ROLL TO ROLL MANUFACTURING OF FLEXIBLE ELECTRONIC DEVICES

By

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ROLL TO ROLL MANUFACTURING OF FLEXIBLE ELECTRONIC DEVICES

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NOMENCLATURE

A	Area of cross-section of web
B_{fe}, B_{fp}	Coefficient of viscous friction
b	Viscous damping coefficient
b_f	Coefficient of friction
c	Specific heat of the web
E	Young's modulus of web material
f	Blasius similarity function
F_c	Disturbing force on the carriage
F_d	Drag Force
g	Acceleration due to gravity
h	Thickness of web
J	Moment of Inertia of the roller
k	Dimensionless empirical constant
L	Length of the web in a bath
L_i	Length of the i^{th} span
m_f	Mass fraction
M	Mass fraction
M_c	Mass of the carriage
m	Mass of the web
N	Number of spans in the accumulator
n	Speed ratio
p	Empirical constant

R	Radius of the roller
R_i	Radius of rollers/pulley
R_{co}	Outer radius of the core-shaft with core on it
s	Blasius similarity function for crosswise flow
T	Temperature
t	Time
t_c	Average Tension in the accumulator
t_i	Web tension in the i^{th} span
U_w	Velocity of the web in the x-direction
U_∞	Velocity of the fluid in the x-direction
U_0	Reference velocity in the x-direction
u	Control torque
u_e, u_p	Control inputs on the entry/process side rollers
V	volume
$\bar{v}$	Average web velocity
v	Web velocity
X	Mixture
x_c	Displacement of accumulator carriage
v_c	Velocity of accumulator carriage
v_i	Velocity of web on i^{th} roller/roll
W_0	Initial velocity of the fluid in the crosswise direction
w	Width of the web
W	Width of the specimen
x	Position in the x-direction
ρ	Density of the web material
ψ	Stream function
η	Similarity Variable

ϱ	Density of the fluid
ν	Kinematic viscosity of the fluid
τ	Shear stress
λ	velocity ratio
ϵ	Strain
σ	Stress

Subscripts

A, B	Layers of webs
c	pertaining to the composite web
i	span or roller number
m	mixture
R	pertaining to the roller
s	stretched state
w	pertaining to the web
W	pertaining to the water

Acronyms

OLED	Organic Light Emitting Diode
PET	Poly Ethylene Terephthalate
AMOLED	Active Matrix Organic Light Emitting Diode
PMOLED	Passive Matrix Organic Light Emitting Diode
HIL	Hole Injection Layer
ETL	Electron Tranport Layer
ITO	Indium Tin Oxide
RTR	Roll To Roll
PFBT	Poly-dihexylfluorene-alt-benzothiadiazole
RFID	Radio Frequency Identification Technology

LCD	Liquid Crystal Display
FOLED	Flexible Organic Light Emitting Diode
TFT	Thin Film Transistor
PECVD	Plasma-Enhanced Chemical Vapor Deposition
UV	Ultra Violet
pps	pulses per second
OVPD	Organic Vapor Phase Deposition
CCM	Color Changing Media
PEN	Poly Ethylene Naphthalate
PC	Poly Carbonate
COC	Cyclic Olefin Copolymer
PI/OMMT	Polyamide/Organoclay nanocomposite
PES	Poly Ether Sulphone
PDMS	Poly Di Menthyl Siloxane
PVDF	Poly Vinylidene Di Fluoride
PEEK	Poly Ether Ether Ketone
IZO	Indium Zinc Oxide
PEDOT:PSS	Poly(3,4-ethylenedioxythiophene) Poly(styrenesulfonate)
OTR	Oxygen Transmission Rate
WVTR	Water Vapor Transmission Rate
RGB	Red Green Blue
TCP	Tape Carrier Package
PCB	Printed Circuit Board
ESA	Electro Static Assist
PSA	Pressure Sensitive Adhesive
PLI	pounds per linear inch

CHAPTER 1

INTRODUCTION

Electronic devices have become an integral part of human life. There are a number of electronic devices that serve different purposes, and many of them improve the quality of life. In some cases, the use of electronic devices has become a requirement than a choice because of their widespread use and part of every day life. This thesis is focused on efficient manufacture of electronic devices in flexible form using roll to roll (RTR) method of continuous manufacturing which is expected to significantly improve productivity and efficiency and reduce manufacturing costs.

1.0.1 Flexible Electronics

Flexible electronics is a technology where the electronic circuits are assembled on flexible substrates for use. These flexible electronics are very thin, light weight, portable, and flexible and have many advantages over rigid electronic devices. Currently, researchers around the globe are trying to build flexible electronic devices in various fields of electronics. The area of flexible electronics includes a wide range of applications such as flexible displays, flexible lighting devices, electrophoretic displays, packaging, textiles, medical devices, flexible sensors, to name a few. The most common feature among these devices is that they can be manufactured in RTR form on flexible substrates such as plastics, stainless steel, thin glass films without losing any functionality. The main reasons behind the possibility of flexible electronics are the development of solution printing techniques that are cost effective and compatible with RTR form of manufacturing and use of polymer materials for substrates along with plastic inks that can be solution printed and coated.

Many researchers, laboratories and companies are trying to develop methods to manufacture these flexible electronic devices in RTR form. Many have already succeeded in developing devices to facilitate manufacture of many parts of flexible electronics in RTR form for some applications. There has been considerable research in this area with respect to the materials that need to be used, manufacturing methods, various processes involved, costs of production, etc. Currently, even though some researchers and companies have succeeded in such manufacturing, the costs involved in the production are quite high compared to batch process method. It is important to optimize the manufacturing of flexible devices with regard to the materials, production methods, etc. These flexible electronics may be flexed, bent and rolled to an extent and would still be expected to function without losing their durability. Flexible electronic devices have already come to the market. For example, Figure 1.1 shows a flexible electronic display prototype developed by HP and the Flexible Display Center at Arizona State University.

Flexible electronic paper promises to replace newspapers in the future. For example, Figure 1.2 shows a thin and flexible electronic paper that has been developed by LG Philips. This type of flexible electronic paper uses wireless communications to update the information and make the news readily available to the consumers.

Flexible OLED television devices have already come to the market. OLED display technology promises to replace the Liquid Crystal Display (LCD) display technology in the near future. Figure 1.3 shows a 14 inch OLED prototype television invented by Samsung company.

Polymer based solar cells are promising alternatives for conventional energy sources. They are energy efficient, flexible, and more easily processed than rigid solar cells. Flexible solar panels are already in the market. Figure 1.4 shows a flexible solar cell panel that is manufactured by silicon solar solutions and is available to the consumers.

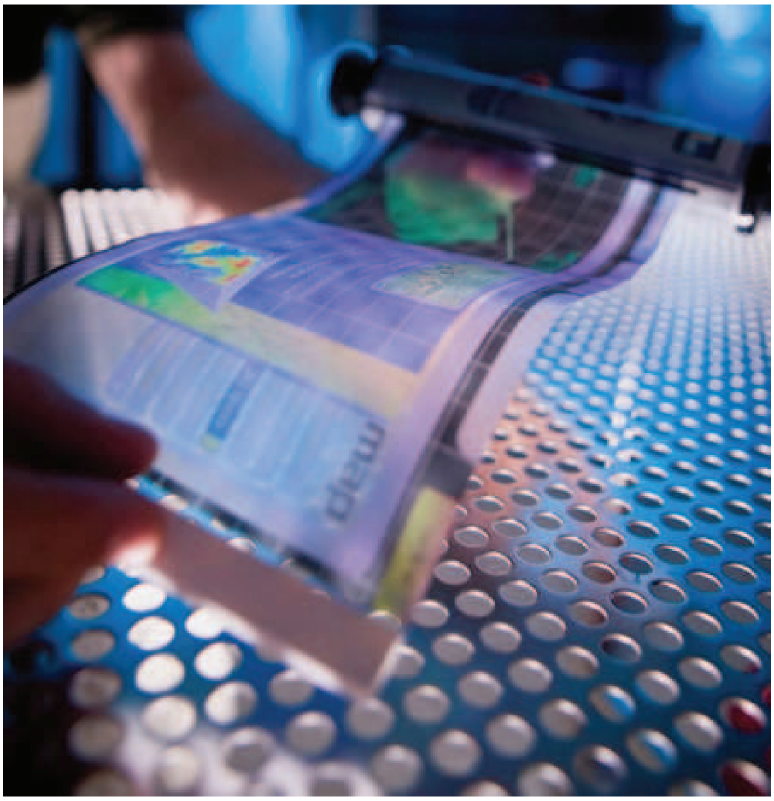


Figure 1.1: Flexible Electronic Display [1]

Figure 1.2: A4-sized Color Electronic-Paper [2]

Figure 1.5 shows how flexible electronics can be a valuable resource for soldiers on

Figure 1.3: Samsung OLED TV [3]

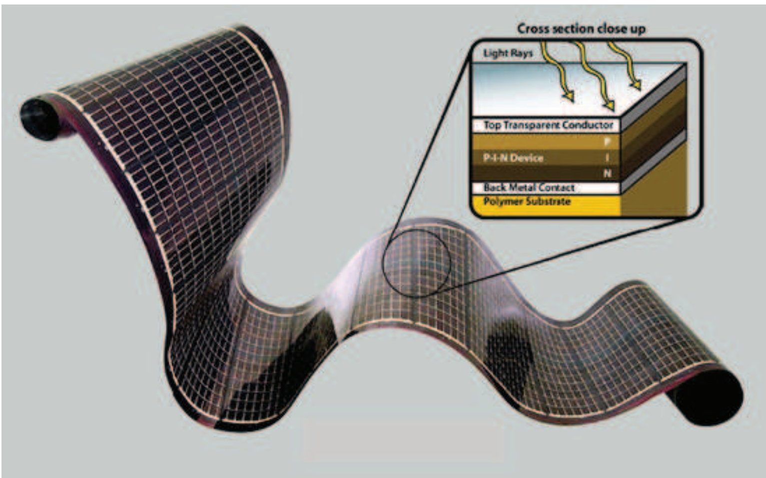


Figure 1.4: Flexible Solar Cell Panel [4]

the battle field. The image shows a military soldier carrying all the required electronic components that are flexible which would reduce the amount of overall weight that the soldier has to carry. The body suit contains components such as GPS, sensors for security, threat detectors, etc. Such wearable flexible devices integrated into the clothes are not only useful in the military but will also be useful in various applications such as construction, security, etc.

Figure 1.5: Flexible Electronics [5]

Display devices have advanced from cathode ray tubes of yesteryear to LCDs of the present. Currently, there is a strong effort to replace LCDs with OLED displays which are flexible, light weight and more durable than LCDs. There has been substantial activity in the field of flexible displays. The change has been very dynamic and rapidly evolving over the last several years. Figure 1.6 shows the advancement in the field of display electronics from the huge and bulky cathode ray tube to LCDs, and to the much awaited thin panel flexible OLED displays.

The advancement in the field of science with the use of flexible electronics is well illustrated in Figure 1.7. This shows artificial muscles which have been made by integrating the printed circuits of electronic devices, which also have the ability to be incorporated within human muscles. These artificial muscles can be used as replacement hands for people who have lost their hands or who have broken limbs, and also can be used for research work related to muscle and tissue behaviors by acting as sensors. The way they work is that these flexible electronics are made to behave like accordions which are able to expand, contract and bend, yet retain the

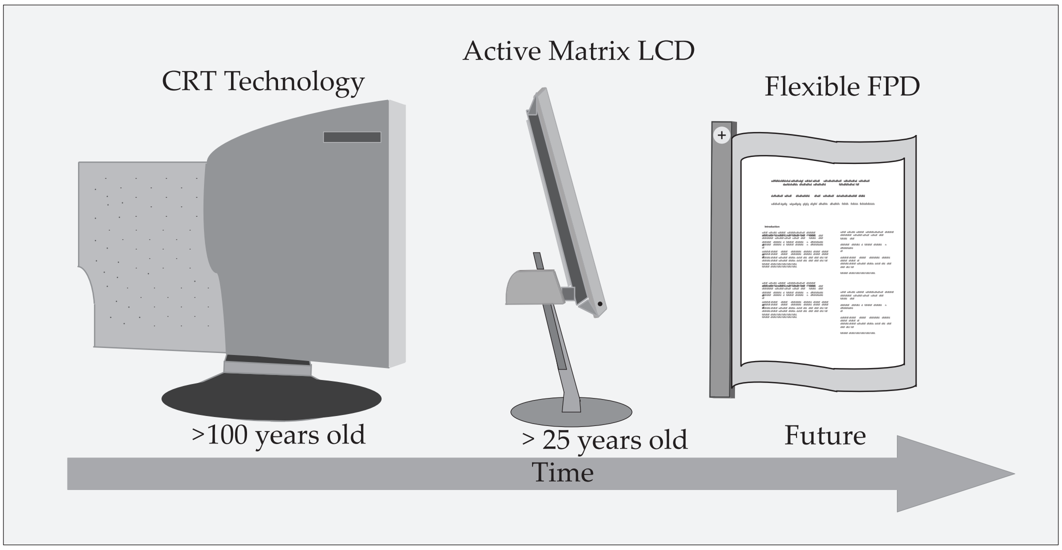


Figure 1.6: Advancement in the Field of Display Electronics [6]

functions of an electronic device.

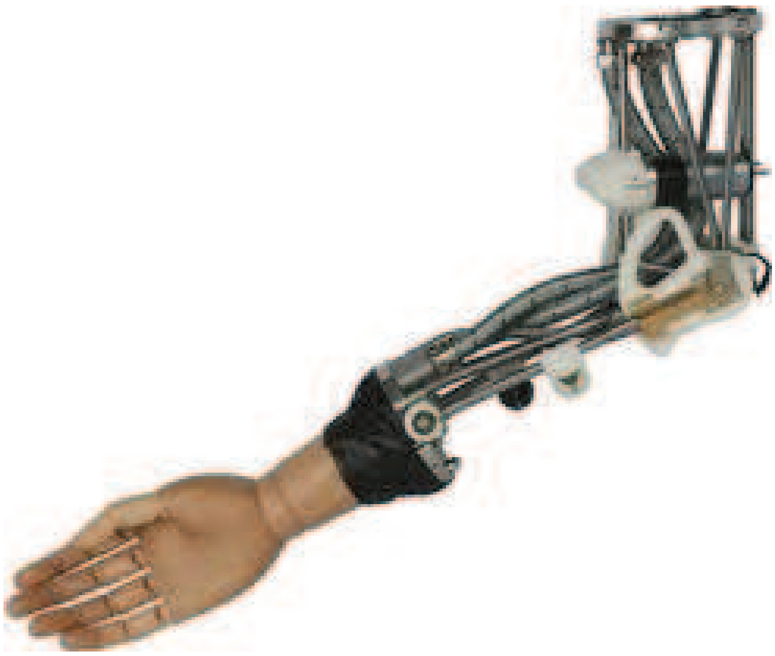


Figure 1.7: Artificial Muscles [7]

Thus, flexible electronics are expected to contribute to mankind in various ways, and an efficient way of manufacturing these flexible electronic devices is of considerable benefit. Needless to say, cost is an important factor in the field of manufacturing. The method developed for the manufacture of these electronic devices should be efficient, economical and cost effective. If these devices are manufactured in a continuous process, it will be beneficial with respect to every regard. Manufacture of flexible electronics using RTR methods over batch process methods is expected to help in reducing the total capital costs of the equipment, display device cost, and substantially increase the throughput of manufacturing. One of the main challenges faced in the development of flexible electronics is in the complete sealing of the devices as these devices have to be protected from entering of environmental permeates such as oxygen and moisture. This is very critical for the long term working of the devices.

Flexible devices such as OLEDs, RFID, polymer solar cells have very thin structure including the active layers deposited on the substrate. The total thickness of the active layers is less than a micron and each of the layers are flexible, which has given rise to a new revolution in the electronics market.

1.0.2 History of Flexible Electronics

The first flexible solar cell array was manufactured in the year 1960 by slimming single crystal silicon wafer cells and combining them together with plastic substrate such that they become flexible. Due to the energy crisis that took place in the year 1973, there was lot of encouragement towards the development of thin film flexible solar cells in order to reduce the cost of producing electricity using photovoltaic materials. In the year 1976, a Schottky barrier solar cell was developed on a stainless steel substrate by Wronski, Carlson and Daniel at RCA laboratories. Plattner et al. and Okaniwa et al. developed solar cells on plastic substrates in the early 1980s. In the year 1985, P. Nath and M. Izu reported the fabrication of flexible solar cells by RTR method. They used glow discharge deposition method to deposit the layers on to stainless steel substrate [8]. In the year 1986, RTR fabrication of solar cells on polymeric substrates were introduced by Okaniwa and his coworkers at their Central Research laboratories in Tokyo [9]. They used continuous glow discharge methods in RTR form in order to deposit the silicon layers on a flexible polymer substrate. The first Thin Film Transistors (TFTs) were made by Brody and his colleagues in the year 1968. They manufactured TFT made of tellurium on paper strip and also proposed the idea of using TFT matrices to address display devices. They also made several TFTs on different substrates such as Mylar, polyethylene, anodized aluminum foil in the succeeding years. Constant et al. demonstrated TFT circuits on flexible polyamide substrates at Iowa State University in the year 1994. In the year 1997, silicon TFTs made on plastic substrates using laser annealing methods were reported. In the year 1996, Smith and his coworkers reported the deposition of thin film silicon films on polyester substrates using excimer laser crystallization and doping methods [10]. In the year 1997, N. D. Young and his coworkers reported the fabrication of poly-silicon TFTs's on polyamide substrates and polyethersulphane substrates [11]. They used excimer laser crystallization technique and PECVD methods for deposition of silicon materials. Over the years, research in the field of flexible electronics has expanded vastly and many researchers have demonstrated the manufacture of flexible devices on various substrates such as plastic, thin glass substrates, stainless steel, etc. For example, in the year 2006, researchers have fabricated a FOLED in a vacuum-free lamination process by laminating an anode component and cathode component of an OLED using a roll laminator [12]. In the year 2005, researchers have demonstrated a flexible OLED using cyclic olefin copolymer (COC) as the substrate [13]. In the year 2008, researchers have fabricated FOLED using an UV-curable epoxy resin as an adhesive between the substrate and the anode [14]. In [15], the authors have demonstrated a FOLED in which polymer layers were deposited by a polymer inking and stamping method that can be employed in a RTR form of manufacturing. In the year 2009, researchers have shown a FOLED using flexible substrate made of polyamide/organoclay nanocomposite [16]. To date, flexible electronic devices such as OLED, polymer cells, LCDs, etc., are manufactured either in a batch method or non-continuous RTR method. These methods are expensive and inefficient. There has been substantial breakthroughs in the field of flexible solar cells too. In the paper [17], researchers have shown that solar cells can be manufactured in a non-continuous RTR form. However, there has been reported activity to date which discusses the web handling aspects of RTR manufacturing of these composite webs. In this thesis, strategies to design web lines and web handling strategies are applied for the manufacture of flexible electronic devices in continuous, composite web form.

1.0.3 Roll to Roll (RTR) Manufacturing

RTR manufacturing involves manufacture of flexible devices in the sheet form. The main criteria is that the substrate material chosen should be flexible. The selection of the material for the substrate is an important factor. The material for the substrate should be selected such that it should be able to be bent, flexed and rolled any number of times without losing its functionality. The suitability of many polymers/plastics are being researched for the substrate material in order to improve the production of flexible devices. The manufacture of electronic devices in RTR form has various advantageous over batch processing methods. It saves time, cost, reduces delay time and increases efficiency, throughput, performance, etc. Figure 1.8 shows a schematic of a typical RTR system for the manufacture of a flexible device.

Currently, most of the printing methods are compatible with RTR manufacturing. For example, there are solution printing methods such as gravure printing, screen printing that are used to print inks on a flexible material in a RTR process. These methods can be used to print a very thin layer of materials on the substrate and are very efficient. Web handling involves improving the storage and transport of web material as the web is transported on rollers through various process sections such as

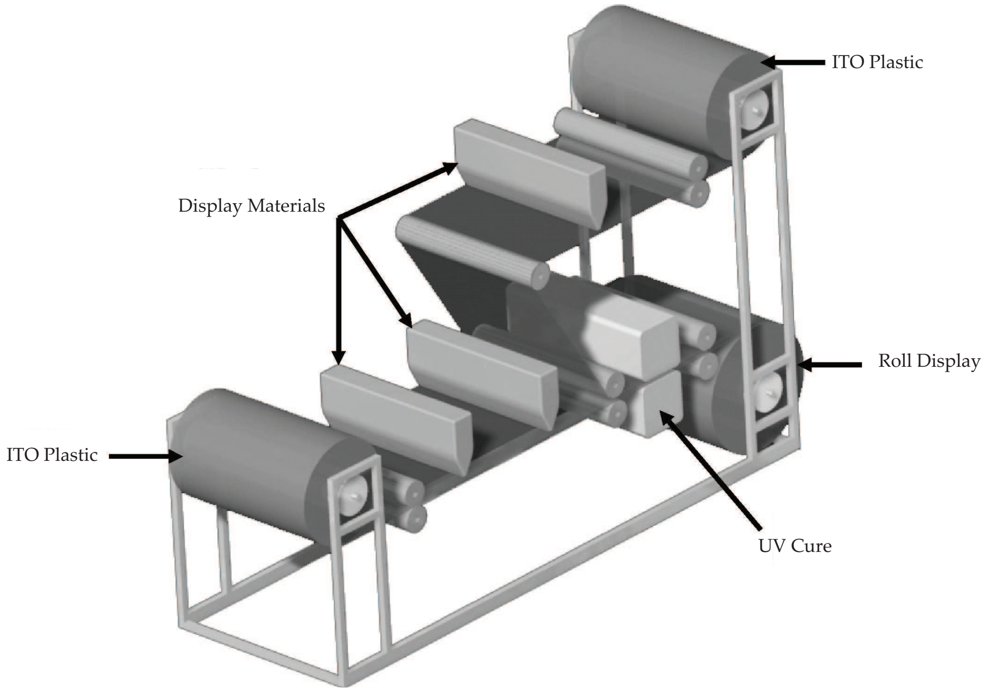


Figure 1.8: Simple Schematic Diagram of RTR Manufacturing Process

coating, printing, lamination, drying, embossing, slitting to name a few.

1.0.4 Web Handling

The thin flexible substrate material used in RTR manufacturing is called a web. It is a flexible thin strip of material that can be passed over the rollers which can be bent, flexed and rolled. Web handling refers to the handling of the web during its movement from an unwinding spool to the winding spool such that there is systematic control of all the processes that takes place on the web. When a web travels from an unwind to a winder, various operations are performed on the web, such as coating, printing, patterning, and drying. It is very important to control the web transport conditions and process variables for accurate processing of the web. The two main parameters that need to be controlled are web tension and web speed. During web transport on rollers the web may experience issues such as wrinkling, unwanted lateral movement, sagging, breakage, slipping on rollers, etc. So, precise handling of the web is very important for the development of a functioning final product. In order to control the movement of the web through a RTR process, it is very important to know the dynamics of the rollers, properties of the web material, operating conditions of the different processes, etc. In a high speed web handling system, as the web goes through dynamic transitions, it might be subjected to stress and strain. The stress developed may exceed the strength of the web material, which would result in web breakage. This would result in an increase in downtime, wastage of material, and would reduce the overall performance of the machine. The quality of the final product is greatly influenced by tension and speed of the web in the web line. The main aim of the web handling process is to transport the web with highest speed and with minimal damage so that overall throughput of the equipment is high.

Web handling machines consist of various tools designed to transport the web through the various processes and machines. Most of these tools are mechanics based but even control theory plays a major role in the web handling system. The mechanics of web handling describes the behavior of a web during its movement between two rollers. The rollers on which the web is moving plays a vital role in maintaining the quality of web that is being processed. Along with the material properties, the roller structure and web's interaction with the rollers should be carefully assessed in order to obtain acceptable productivity. When the web travels over a roller, the roller exerts stress on the web at the point of contact due to the traction between the roller and web. Thus the dimension of roller, its shape and wrap angle of the web on the roller play an important role in the precise movement of the web.

1.0.5 Contributions

The contributions of this thesis is summarized in the following:

- A comprehensive study of the literature was undertaken to understand the various processes involved in manufacture of flexible electronics such as OLEDs and solar cells, and an investigative study was carried out to highlight those processes and methods that are suitable for RTR manufacture of flexible electronic devices.

- Design of web lines for RTR manufacturing of flexible electronic devices was investigated. Three web lines were designed for the manufacture of OLED based flexible electronic devices and polymer solar cells. The first web line was designed for the patterning of the anode layer on a plastic substrate; this web line can be used for manufacture of many types of flexible devices. The second web line was designed for the deposition of active layers of an OLED device on the composite web obtained from the first line consisting of the substrate and the patterned anode layer. The third web line was designed for the lamination of barrier substrate to the polymer solar cell device.

- Solution printing technologies and various web handling techniques were determined such that ITO patterning was done in a continuous process. Various processes and web line parameters were determined for the web line for RTR patterning of ITO material.

- Process parameters and technologies were determined for the web line designed for the deposition of the active layers of flexible OLED device on the ITO patterned anode layer with substrate. The web line parameters and solution printing technologies that assist in RTR manufacturing were determined for the deposition of active layers.

- The application of various aspects of web handling such as registration, guiding, accumulators, etc., were studied and implemented for each of the three web lines.

- A web line was designed for simultaneous lamination of barrier material to both sides of the flexible composite web for OLEDs and polymer solar cell films. The barrier material that protects the devices against oxygen and moisture was identified from a study. Also, web line parameters for the lamination of barrier material to the polymer solar cell device were established.

- A model for web tension for lamination of two webs was investigated. This model was used for studying the tension behavior during simultaneous lamination of barrier materials to both sides of the solar cell substrate.

- Models for tension and velocity were used to develop a model for various spans and rollers of the web line designed for patterning of ITO anode material. Simulations were performed for the entire web line to regulate web velocity and tension in various spans and rollers of the line. Simulations were also conducted for the web line used for lamination of the barrier material.

- The effect of drag force on the web as it passes through liquid bath was investigated. The drag force was calculated based on the crosswise laminar movement of the fluid in the liquid bath through which the web is transported.

CHAPTER 2

ORGANIC LIGHT EMITTING DIODES AND SOLAR CELLS

In this chapter an extensive study was conducted to identify and understand the various technologies and methods available for manufacture of flexible electronics, especially for OLED devices and polymer solar cells. The first section of the chapter focuses on understanding the working of an OLED and its components; the materials used for its different layers; deposition methods of its components and challenges involved in its manufacturing. The second section discusses the operation of polymer solar cells, its components and the function of its components.

This study was critical in understanding the processes involved in OLED and solar cell manufacturing for the proper selection of materials that will enable the manufacture of flexible electronic devices in RTR form. It will help in understanding the function and properties of the materials which will aid in designing the web line to manufacture these flexible electronics in RTR form. This chapter also provides an insight into the construction of flexible electronics and its connection with the electronic circuits in order to form the flexible devices such as OLED lighting, OLED display devices, etc.

2.1 Organic Light Emitting Diode (OLED)

OLEDs emit light by the process of electroluminescence which is an optical phenomenon where certain materials emit light when electric current is passed through them. OLEDs consist of organic materials as the semiconducting materials which produce light when electric current is passed through them. These can provide better displays than any other light emitting diodes that are currently available. They are organic because the emitting materials are made of carbon and hydrogen. An OLED is made of a series of layers of organic material placed in between conducting materials. When current is applied through the organic materials, light is emitted. With an OLED device one can have more control over the colors as it produces pure colors based on the electric current supplied to the corresponding pixel.

2.1.1 Components of OLEDs

OLEDs are made up of the following components:

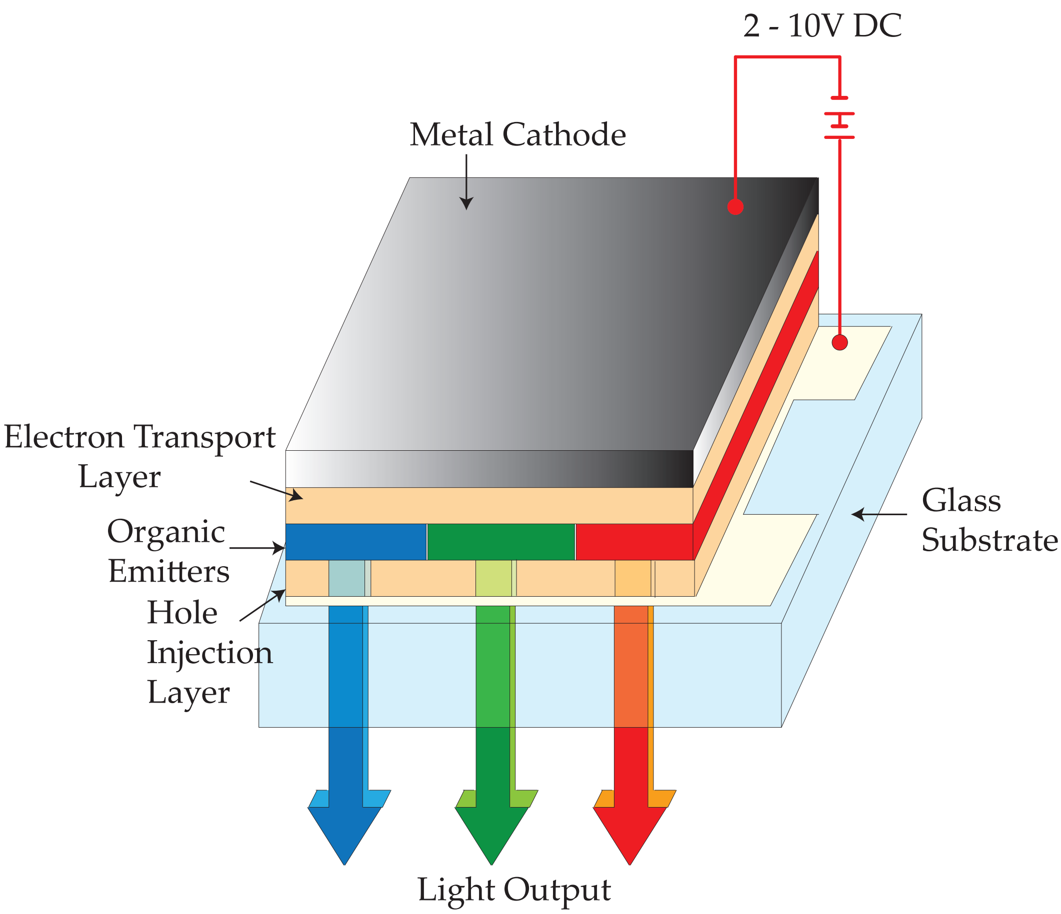


Figure 2.1: Parts of an OLED [18]

- Substrate: The support material of OLEDs, which typically consists of clear plastic, glass, foil, etc.
- Anode layer: This layer is made of materials which inject positive charges (removal of electrons).
- Organic layers: These include the conducting and emissive layers.
- Cathode layer: This layer is made up of materials which release electrons into the emission layer when current is passed through an OLED.
- Encapsulation layer: This is made of barrier material and its function is to protect the OLED device from oxygen and moisture.

The organic layer is typically made of the hole injecting layer (HIL), also known as the conducting layer, and the emissive layer (EL). The former transports the holes from the anode while the latter removes electrons from the cathode layer. The emissive layer is the layer that gets illuminated. The anode is usually made of a transparent material whereas the cathode is usually made of a reflective material. For the anode layer, materials with high work function are chosen. The work function of a material is defined as the minimum energy required to remove an electron from its surface to a point immediately outside the surface. Indium tin oxide (ITO) is commonly chosen as anode material because of its high work function and good transparency. For the cathode, metals with low work function are used.

2.1.2 Light Emission Process of an OLED

The process of light emission by OLED is as follows:

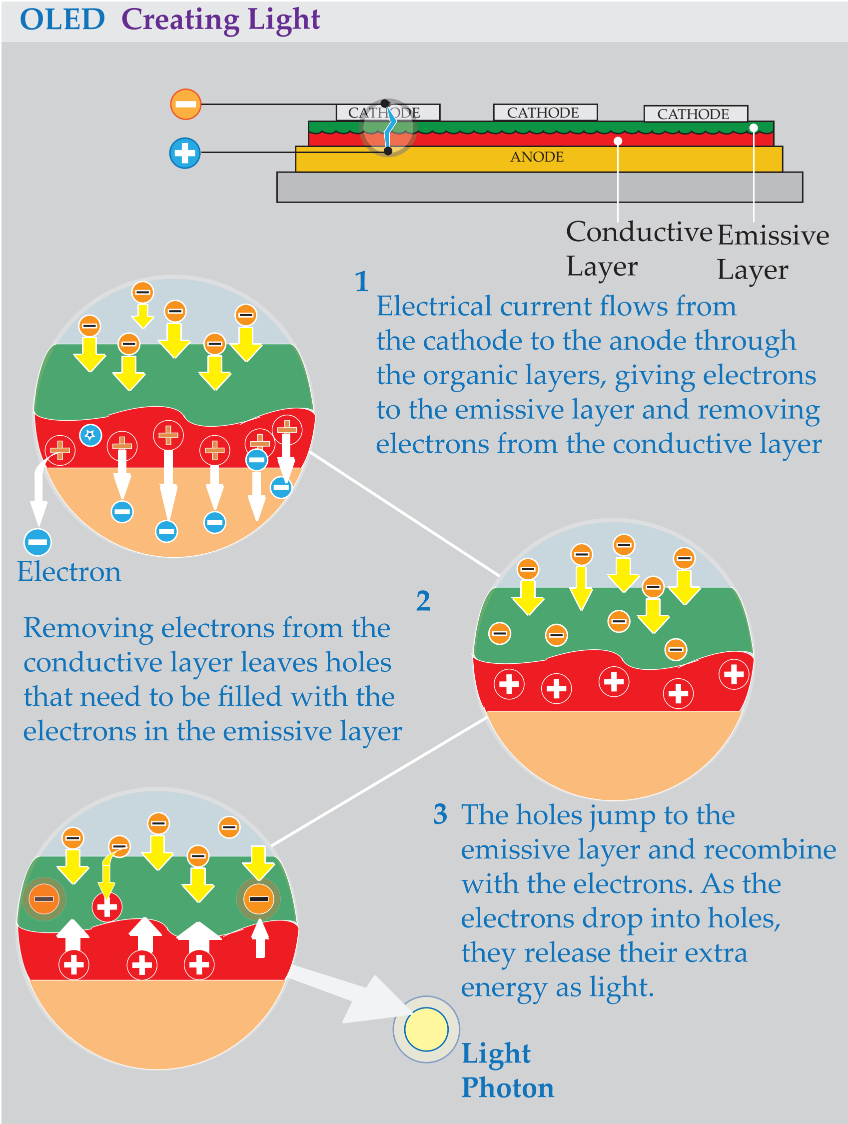


Figure 2.2: Light Emission Process of OLED [19]

1. Voltage is applied across the OLED by a power supply.

2. There is a flow of electric current from the cathode to the anode. The cathode layer releases electrons to the emissive layer whereas the anode layer remove electrons from the organic molecules of the conductive layer.

3. The electrons from the cathode layer move to fill up the electron hole created in the conductive layer and this movement of electrons releases energy in the form of photons which are emitted as light.

4. The type of organic molecules present in the OLED determines the color of light, and the intensity of light depends on the amount of electric current that is passed through the device.

2.1.3 Methods of Deposition of Materials for Different OLED Layers

OLEDs can be fabricated in many ways. Different methods can be used to deposit the materials to form layers of an OLED device. The deposition methods employed depend on the factors such as the layer being deposited, materials, thickness of the layers, resolution of the pixels, etc. Some of the methods used to deposit materials to form the different layers of the OLED device are as follows:

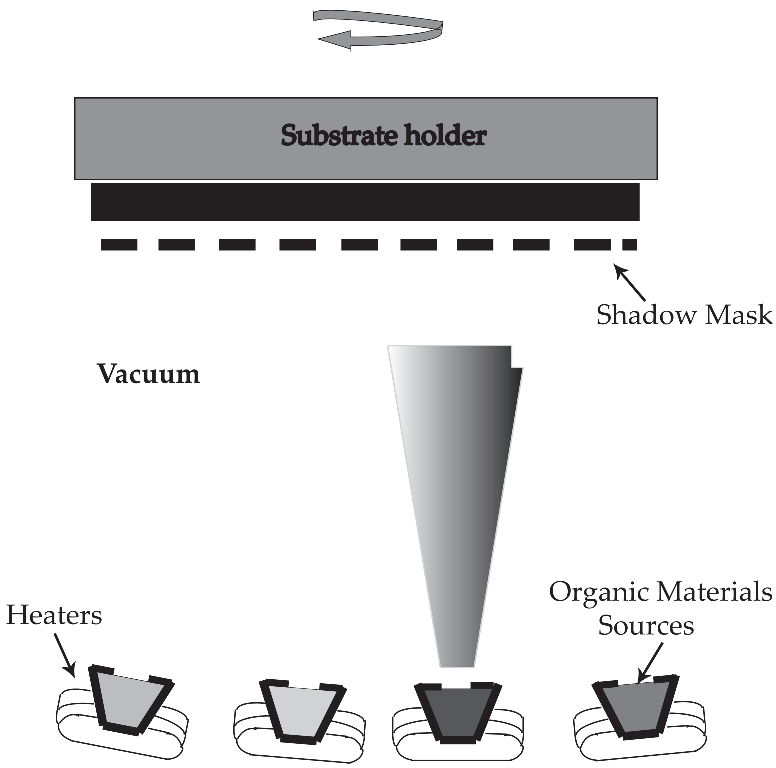


Figure 2.3: Vacuum Deposition Method [20]

- Vacuum deposition or vacuum thermal evaporation (VTE): This process involves heating the organic material in a vacuum chamber so that it condenses onto the substrate as thin film. The organic materials are placed under vacuum in crucibles that are heated to about 100-500^o C. The setup consists of shadow masks placed above the crucibles and has holes for one-third of the pixels. The substrate is placed on top of the masks. When the crucible is heated, organic molecules deposit on the substrate as they evaporate and pass through the mask holes. When one stack of layers of one of the colors is deposited, the substrate gets shifted by one pixel to deposit material for the next pixel. The alignment of the substrate onto the mask should be within ± 5 μm. This technique is widely used for deposition of small organic molecules. It is very expensive to maintain vacuum and obtaining a consistent deposition thickness is a big challenge. When using separate colored emitters, due to the difference in the lifetime of emitters, the overall lifetime of the device is reduced. The lifetime of the blue color emitter is very less compared to the other colors. In order to improve the deposition efficiency, different methods have been designed in industry. One such method consists of moving the substrate perpendicular and as close to the evaporation sources. This process is suitable for making small screen displays, and it is very expensive and inefficient compared to other deposition methods.

- Organic Vapor Phase Deposition (OVPD): This process is cheap and efficient compared to the VTE method. In this method, a carrier gas carries the evaporated organic molecules onto the substrate where it gets condensed to form thin films.

- Spin Coating: This is a common method for deposition of organic materials in OLEDs. It involves deposition of a solution of material onto a substrate and then rotating the substrate at very high speeds such that the fluid spreads by centrifugal force on the substrate. The rotation of substrate is continued until the desired film thickness is obtained. The thickness of the film depends on the speed of rotation of the substrate, concentration of the solution, viscosity and surface tension of the solution, etc. This method can be used to manufacture small OLEDs, but it cannot be scaled to manufacture OLEDs in rolled form.

- Magnetic Sputtering: This method is commonly used for deposition of thin film materials. Sputtering is a process where atoms are ejected from a target material when it is bombarded with high energy particles. Magnetic sputtering involves applying high power to a magnetron which results in a very high negative voltage on the target. This causes positive ions to move toward the target at very high speeds. When the high speed ions hit the target material and if the colliding energy is greater than the binding energy of the atoms in the target material, atoms will be released from the target material which can be directed onto a substrate. This method can be used for deposition of organic materials onto OLEDs in RTR form.

- Lift-up Soft Lithographic Technique: This method is used to pattern the anode layers deposited on the substrate. It can be used over a large area and is known to provide good control over the thickness of the layer on the substrate. It involves a mold with a protruding shape brought in conformal contact with the layer for few seconds and then removed. The material in its aqueous state will be adhered to the mold and leaves the substrate resulting in a required pattern of the layer on the substrate.

- Laser Ablation: This method involves writing directly onto a polymer layer using a high powered laser. This method does not require photo resist coating and wet etching steps involved in a lithography process. It involves using a powerful laser on a polymer layer such that patterned material removal is done by the powerful laser beam. The laser beam breaks the molecular bonding that exists in the polymer layer and the materials are kinetically ejected upon removal. The polymer chains will be broken into chains of lower molecular weight along with liberation of gases like carbon, carbon monoxide, etc., which get ejected from the surface at supersonic velocities. When these gases are released at such speeds, they carry the solid particles of the polymer along with them. The amount of material removed can be controlled by adjusting the wavelength, energy density, and the pulse width of the laser beam used for ablation. This process is faster than reactive ion etching and produces cleaner lines than thermal and mechanical drilling which are the traditional methods of material removal in electronic packaging. When using this method for multilayered devices, short laser pulses are better than long pulses mainly because they reduces the heat in the affected zone. Compared to a thermal ablation process, this method produces a clean surface around the ablation region with minimal material build up whereas the thermal ablation process creates a large heat affected zone with melted material appearing around the ablation region.

- Ink-jet printing: This is a process where the organic material is sprayed onto the substrate in a manner similar to the spraying of ink onto paper during printing. Using this method, OLED layers can be deposited in RTR form which reduces the production cost by a considerable amount. The equipment consists of a substrate that is patterned and has polyamide banks surrounding the pixel area. Ink-jet nozzles are placed above the substrate and consist of ink solution for deposition. The ink solution is dispensed on the substrate through the nozzles and great care must be taken to position the ink-jet tip as a slight difference in the angle will cause considerable error. A high speed camera is used to monitor the ink droplet to ensure proper working of the nozzle. The banks form a well around the pixel area and are water repellent. The pixel area is made hydrophilic so that any sticking of the droplet onto the bank is prevented.

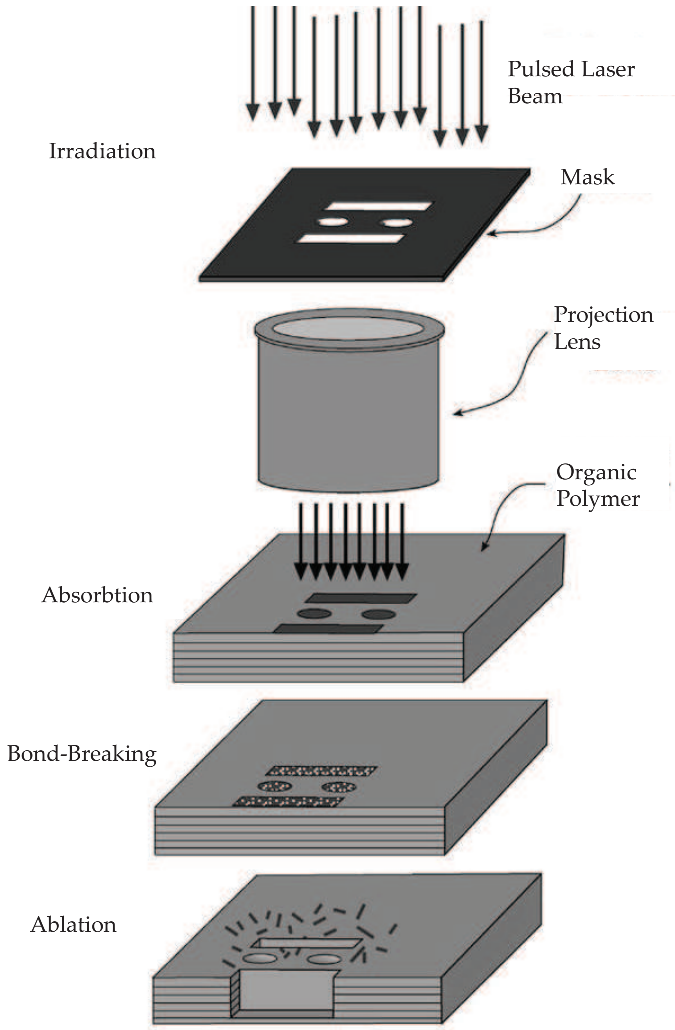


Figure 2.4: Laser Ablation [21]

Once the ink gets deposited, it is dried to form the film. The challenges that are incurred in this method are the pre-patterning of the substrate and obtaining a uniform pattern after drying of the ink droplets on the substrate. This process is highly suitable for the manufacture of large screen displays using polymer organic molecules. It has the advantage of not having any vacuum chamber and mask patterning system. It has the advantage of low temperature processing and results in a low cost manufacturing system. It also has the advantage of depositing a controlled pattern of polymers on the substrate which would be very beneficial for full color displays. This method results in low consumption and wastage of materials compared to the spin coating method and allows for large-area manufacturing of devices.

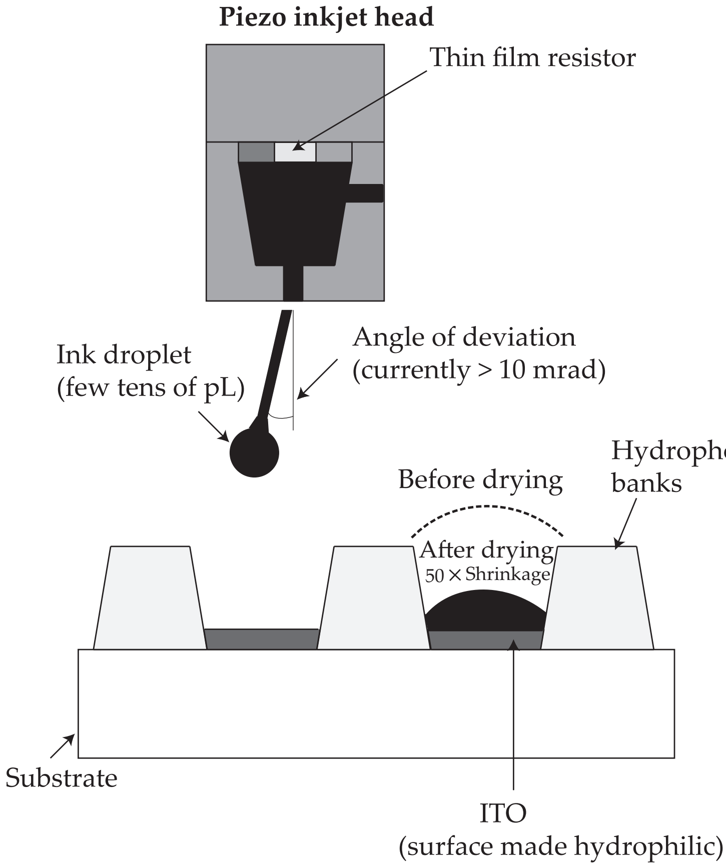


Figure 2.5: Ink-jet Deposition Method [20]

2.1.4 Substrate Materials

It is desirable to have the substrate material exhibit the following features:

- highly transparent;
- low cost and ease of availability;
- resistant to moisture and oxygen;
- low permeability to water and oxygen;

- resistant to chemical attack and dimensionally stable under different cycles of heating processes;
- able to withstand high temperature conditions (as much as 250^o C);
- coefficient of thermal expansion must be similar to the layer being coupled with; any mismatch will result in cracking and high residual stresses during thermal cycling;

Certain plastics tend to shrink when they are cooled after high temperature processes. This can be avoided by pre-annealing the film under high temperature and using minimal web tension when they are rolled. Materials should be flexible enough to be rolled. Flexibility of the materials will enable them to be manufactured in sheet form, which would reduce the overall cost of manufacturing. Most common materials used for the substrate are glass, plastic, and stainless steel.

Glass: Glass has been used as the standard substrate material for OLEDs that are not required to be flexible. It has good optical properties, smooth surface finish and low coefficient of thermal expansion. A major disadvantage of glass is that it is susceptible to breaking and tends to crack near the edges if it is not handled properly. But this problem can be rectified by coating the glass surface and edges with a thin polymer layer. There is also a process called ion exchange where the glass can be strengthened so that breakage can be reduced, but this results in a compression on the external surface and tension in the interior surface of the glass. Using glass as a substrate has the advantage of amended visual appearance, light weight and thinner displays but also faces the challenges of sagging, vibration and edge finishing. There has always been a myth that glass is weaker if its thinner, but glass breakage is dependant on external factors such as applied stress, environmental condition, impact condition, etc. Many researchers have been working on the manufacture of thin glass films that can be rolled in order to reduce the cost of manufacturing.

Plastics: Due to low cost and toughness, plastics have been a major contender for substrate materials. At high temperature condition cycles, these materials undergo change in their physical and mechanical properties. When they reach glass transition temperature, they start to flow as liquid and undergo a great change in dimensional stability. They are permeable to water and oxygen, and hence require barrier layers. The plastic polymeric materials are transparent and can be processed in web form for the manufacture of flexible OLEDs.

Stainless steel: This is suitable as a substrate layer where optical transparency is not required. They are highly impermeable to moisture and oxygen and are flexible, durable, and have much better dimensional stability than plastic under high thermal conditions. They are proven to be a successful substrate material for top emitting active matrix organic light emitting displays (AMOLED) with TFT circuitry. This material has a rough surface and have to be turned into a smooth flat surface by coating a planarization layer on top of it; application of such coatings make them non-conductive. These substrates are very flexible and a promising candidate for the manufacture of OLED devices using RTR manufacturing.

2.1.5 Color Generation

Color generation is an important factor in OLED displays. Colors can be generated mainly in three different ways as described in the following:

- Use of red, green and blue individual pixels (see Fig. 2.6 (a)): Three different color emitters are used for red, green and blue colors. This method is power efficient and the production cost is low. The main problem associated with it

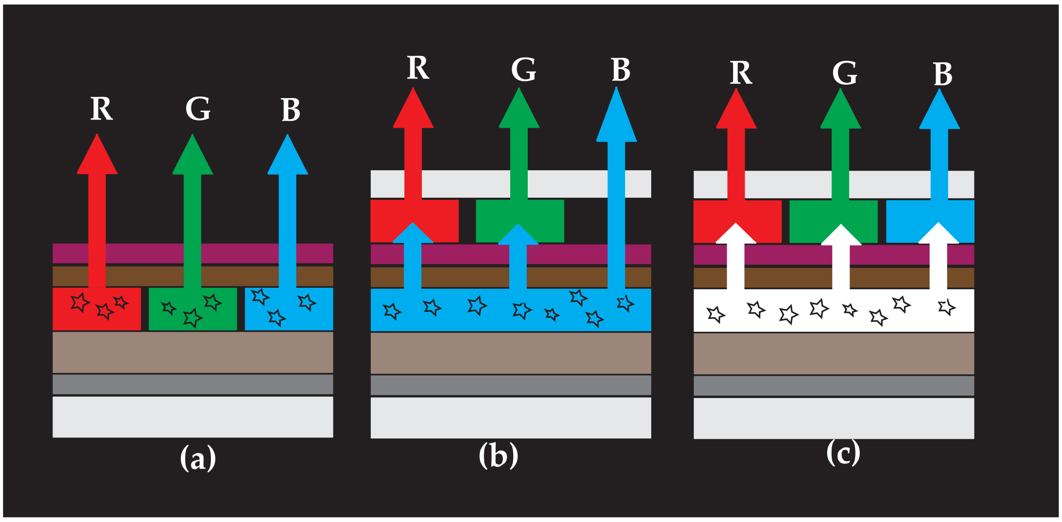


Figure 2.6: Color Generation [20]

is the difference in aging of the emitter materials. The blue emitter has lesser lifetime compared to other emitters. Thus, the overall lifetime of the display depends on the lifetime of the color that has the least lifetime. Also, it is a challenge to maintain constant emission of light by emitting the three colors in a given ratio. This method exhibits good optical performance as different color lights are directly seen without the use of color filters. Another disadvantage is that it requires patterning of the emitters.

- Use of blue emitter and color changing media (CCM) (see Fig. 2.6 (b)): This is a very simple method as it uses only one color of luminescent material. The organic material that emits blue light is deposited on the substrate. Red and green color changing media are then used to provide necessary color in the display. The problem is that the blue emitter should be of very high efficiency since some of the light will be lost during conversion. This method does not require patterning of emitters and is more efficient than using color filters. But this method requires a highly efficient blue emitter and is susceptible to faster aging of CCM's.

- Use of white emitter and color filters (see Fig. 2.6 (c)): In this method, two or more organic materials are combined to generate white light which is then converted to red, green, and blue colors using color filters. This method experiences loss in intensity of light as color filters are used. It does not require patterning of emitter and does not involve problems with differential aging of the emitters. This method is power inefficient and for efficient working of the device, a highly efficient white emitter is necessary.

2.1.6 OLED Emission Types

There are mainly two kinds of emission types that can be seen on a OLED device, namely top emission and bottom emission. In the former, light flows through the top cathode layer and the overall luminance of device depends on the transparency of the cathode material. In the bottom emission type, light flows through the anode layer, and the overall luminance not only depends on the transparency of the anode layer but also depends on the electric circuitry that includes TFT materials. Thus, the top emitting type is preferred for circuitry involving a greater number of TFT's in the pixel circuit. Top emission displays need optically clear barrier films as enclosures. In the top emission type, OLED materials and the pixel circuit will be in tandem configuration which enables smaller pixel size where as in the bottom emission type, the pixel circuit and OLED are placed in side by side configuration. In some applications, OLEDs are required to emit light in both directions. For the manufacture of such OLEDs, both electrodes must be transparent along with the encapsulation layers.

2.1.7 OLED Type Based on Construction

OLEDs are distinguished as active and passive based on the driving method of their display. These are described in the following.

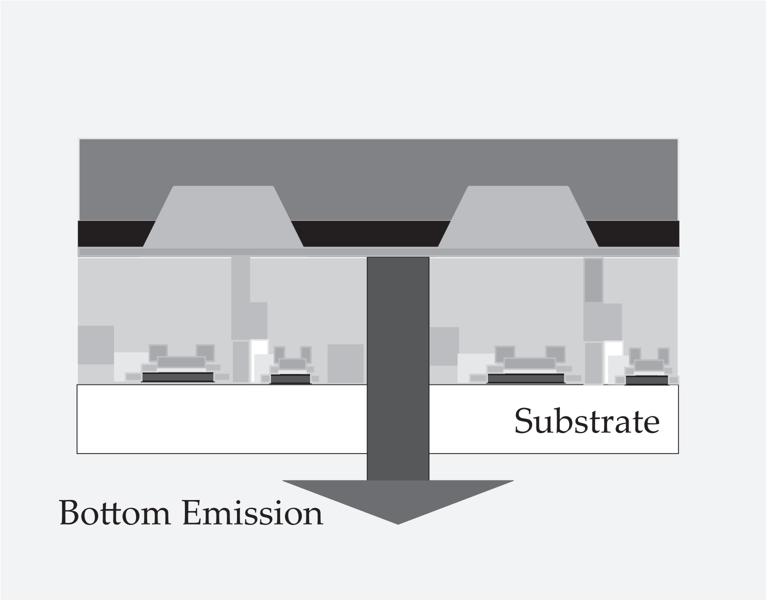


Figure 2.7: Bottom Emitting OLED [20]

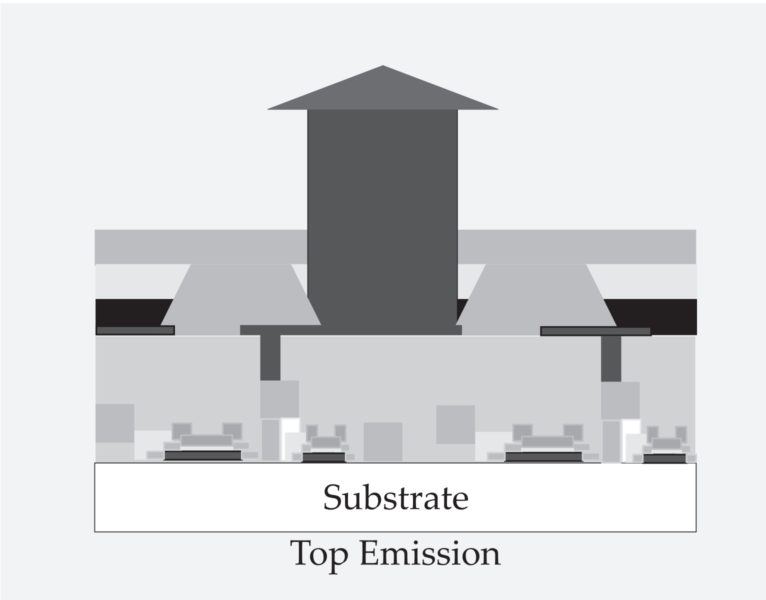


Figure 2.8: Top Emitting OLED [20]

Passive matrix organic light emitting display (PMOLED): This kind of OLEDs are easy to make and have strips of cathode and anode layers arranged perpendicular to each other along with the organic layers. The light is emitted in the pixel formed by the intersection of the cathode and anode. The external circuit applies current across the selected strips of anode and cathode which determines the pixel that needs to be turned on. The turning on and off of pixels quickly in a sequence creates the image. For energizing a certain pixel, certain voltage must be dropped across the emissive material. One of the conductors delivers a part of the voltage while the other conductor delivers the rest. The pixel will be off if it receives only a part of the full voltage. The amount of current applied determines the brightness of each pixel. The display requires high power to drive each pixel, which limits the number of pixels in the device and also limits the use of polymeric material for the substrate as it can get damaged by the heat generated. These displays consume less power than the current LCDs and are mostly suitable for small screens. This method also requires patterning of hole injecting and electron injecting layers. This method limits the size and color contrast of the display.

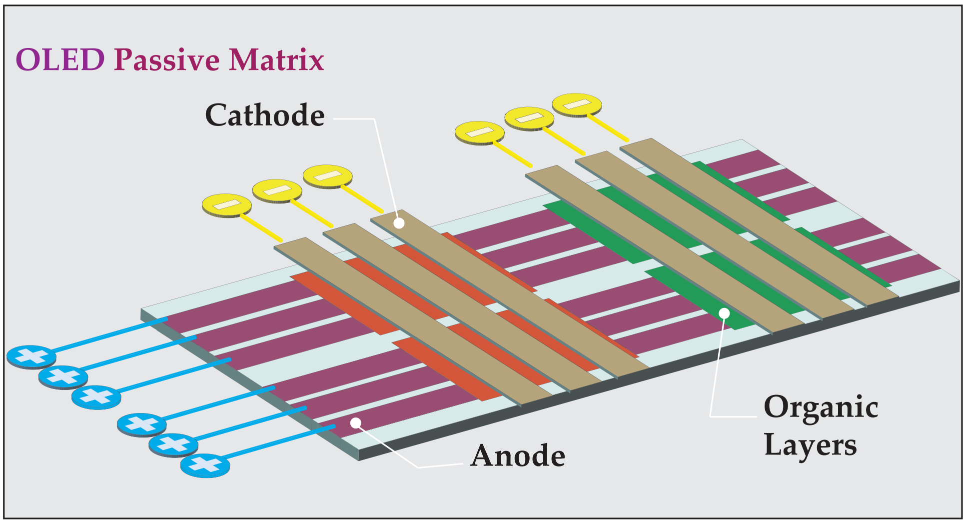


Figure 2.9: Passive Matrix OLED (PMOLED) [22]

Active matrix organic light emitting display (AMOLED): These displays use the TFT technology as their driving circuits. The TFT layer provides the power needed and determines the pixel that gets turned on to form an image. Each pixel is directly controlled to form an image. These are suitable for larger displays and have a faster response rate. As the brightness of the OLED device depends on the amount of

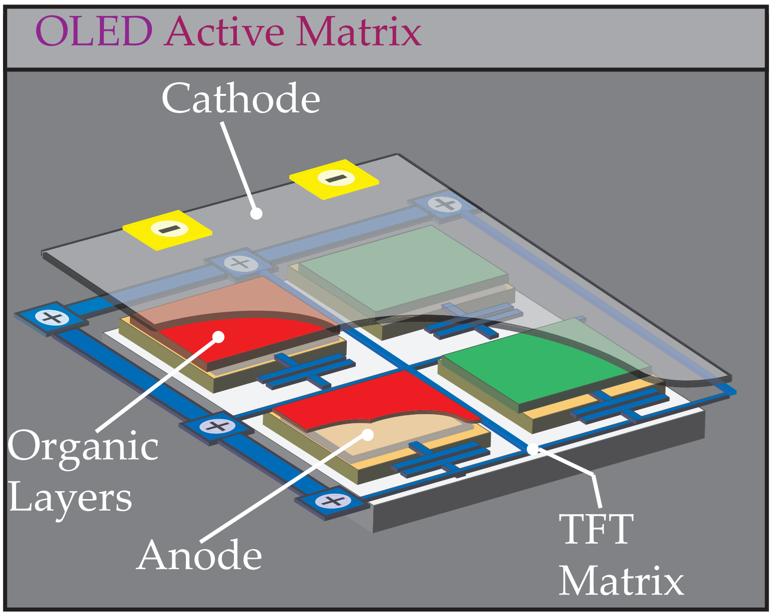


Figure 2.10: Active Matrix OLED (AMOLED) [22]

current passing through it, the pixel circuit needs to pass uniform currents to the OLED layers in order to obtain uniform emission of light from the device. The circuit consists of TFTs integrated into each individual pixel. The number of transistors for each pixel depends on the circuitry which in turn depends on various factors such as required brightness, thickness of the device, etc. It has an advantage of consuming less power compared to the PMOLED since each pixel output is controlled by tiny transistors integrated into it. Since each pixel is driven by a transistor, the image refresh rate is very fast. Organic TFTs use organic semiconductor materials for the active layer. There are various pixel designs for the AMOLED device and the number of transistors used per pixel may vary. Since the amount of current passed through the OLED device is controlled by the transistor, various characteristics of the transistor like threshold voltage, carrier mobility, series resistance, etc., are very important in proper display of the OLED device. Figure 2.11 shows the basic pixel architecture for an AMOLED device.

The circuit shown in the Figure 2.11 consists of two TFT's along with one capac-

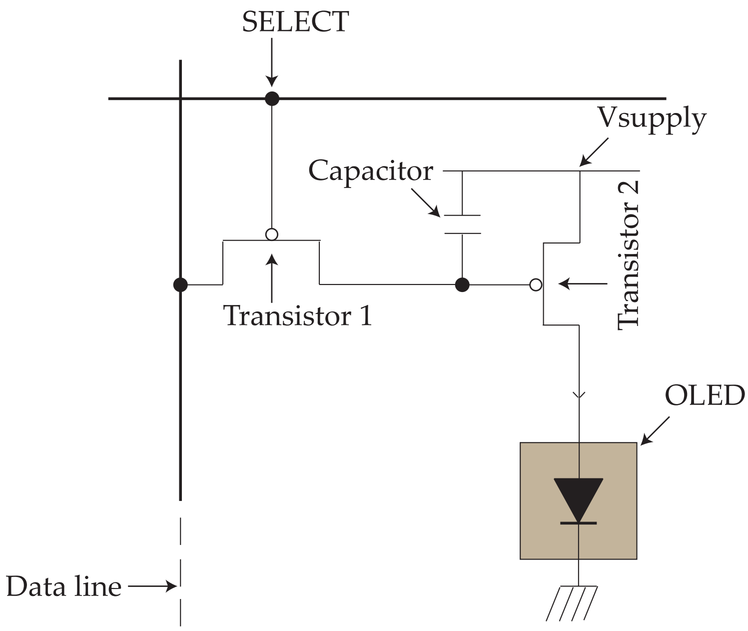


Figure 2.11: Basix Pixel Addressing Circuit for AMOLED [20]

itor. The TFT labeled T1 acts as the drive TFT while T2 controls the amount of current that is supplied to the OLED. The transistor T2 is kept in operation during the entire frame time by the capacitor used in the circuit. When T1 is in operation, the voltage signal from the data line is supplied to the gate of T2 and current proportional to this voltage signal will be transferred to the OLED stack. At the same time, voltage stored in the capacitor will be supplied to T2 which helps to maintain a constant current in the OLED screen during a frame time. Since the capacitor and transistor circuit helps to maintain constant current in each pixel line for the entire frame time, this kind of OLEDs can be manufactured in large sizes and give high color contrast. Researchers have shown that these TFT circuits can be solution processed in rollable form which indicates that these circuits can be used in the manufacture of flexible organic light emitting diodes (FOLED).

2.1.8 OLED Type Based on the Material Type

Based on the type of materials in the organic layer, OLEDs can be divided into small molecule OLEDs (SMOLEDs) and polymer based OLEDs (PLEDs). They are described as follows:

- Small molecule OLEDs consist of materials with low molecular weight. They are deposited mostly by a vacuum thermal evaporation process which is usually a dry process. Vacuum deposition is a very expensive method and therefore SMOLEDs are suitable for small screens and small object displays. The main disadvantage of using small molecule OLEDs is in their manufacturing process as they require extra materials like phosphorus to enhance their performance. Devices formed from small molecule materials allow more layer engineering and have more advanced architecture than the PLED devices. Small molecule OLEDs are very common and are used in applications such as cell phones, digital cameras, etc.

- PLEDs are made of long polymeric organic chains and are deposited by ink-jet or spin cast methods which is usually a wet process. PLEDs can be made by solution based methods in sheet form and are suitable for large screen displays. PLEDs can be produced in large quantities using ink-jet printing methods but current trends show that they are deficient in terms of efficiency and lifetime.

2.1.9 Differences Between Inorganic LEDs and OLEDs

Inorganic LEDs have high brightness point sources and are more like incandescent light devices whereas organic LEDs are area extended sources with wide angle and are more like fluorescent light devices. Inorganic LEDs find applications in spot light areas like flashlights, traffic lights, etc., whereas OLEDs find application in diffuse lighting such as signs, back lights, television, etc.

2.1.10 Differences Between Dry Coated and Wet Coated OLEDs

In dry-coated LEDs, high vacuum is used to evaporate the organic layers whereas in the case of wet-coated technology organic layers are printed with solution. The former are made of more layers whereas the latter are made of fewer layers. It is difficult to scale dry coated LEDs to a large area as they are made of small molecules, whereas wet coated ones are made of larger polymers or molecules and can be manufactured in a large area.

2.1.11 Flexible OLEDs

OLEDs that can be manufactured in rollable form are termed as flexible OLEDs. A crucial requirement for these kinds of OLEDs is that the substrate must be flexible which means that it must be bendable, flexed and also rollable any number of times without degrading its performance. All the materials that are laid on top of the substrate must also be flexible. For transmissive displays, opaque materials for substrate cannot be used as they should be able to transmit light through them.

- Flexible substrate materials: Research is currently active in the testing of suitable materials for substrates that will be flexible, economical and compatible with the other layer materials of OLEDS. The most common materials that have been used as of now are polymeric films, stainless steel foils and ultra-thin flexible glass. Each of them have unique properties which are suitable for certain applications. The ultra-thin flexible glasses cannot be processed in RTR form while stainless steel cannot be used for transparent OLEDs. Metal foils are very expensive and hence cannot be used for large size displays. Polymeric films are best suited to be manufactured in rollable form but they have the disadvantage of not being resistant to oxygen and moisture. Thus, proper encapsulation is required with flexible barrier materials when polymeric materials are being used for the substrate. The polymeric materials chosen for substrate must have very high mechanical, thermal and dimensional stability, high resistance to chemical materials, low coefficient of thermal expansion, high optical transparency, very smooth surface along with being impermeable to oxygen and moisture. The most common materials used for flexible substrates are polyethylene terephthalate (PET), polyethylene naphthalate (PEN), polyamide, polycarbonate (PC), cyclic olefin copolymer (COC), polyamide/organoclay nanocomposite (PI/OMMT), poly ethersulphone (PES), poly dimenthylsiloxane (PDMS), polyvinylidene difluoride (PVDF), polyetheretherketone (PEEK), etc. Table 2.1 and Table 2.2 show some of the important properties of these materials.

Thermal stability of the plastic substrate is also an important requirement as the substrate is subjected to high temperature processes during coating of barrier materials, electrode deposition, patterning, TFT deposition, etc. Mechanical properties of the materials are also an important criteria in the selection of the materials for the substrate. The flexibility of the device depends on factors such as thickness of the device, materials used for each of the layers, arrangement of the layers, mechanical properties of materials, etc. Inorganic materials are generally brittle and require some treatment to improve their flexibility before being used for the manufacture of FOLEDs.

- Flexible electrode materials: These are the materials that are required for passage of electrical signals between the power supply, driver circuitry, and display pixels. Selection of these materials is important as they provide the necessary conduit by which electric signals are passed that will result in the display of an image in applications such as televisions, display screens, etc. Some of the materials that are available for electrodes include Indium Tin Oxide (ITO), carbon nanotube films, polymers, thin metal films, hybrid organic-inorganic films, etc.
  - ITO: This is the most commonly used material for the electrode layer as

Table 2.1: Minimum Requirement for Polymeric Materials to be used for FOLEDs

Material	**Properties**	**Requirement**
Polymer substrates	Total light transmittance over 400−800nm (%)	> 85
	Haze (%)	< 0.7
	Average surface roughness (nm)	< 5
	Chemical resistance	Resistance to acid, alkali and solvent
Barrier coated substrates	Water vapor transmission rate ($g/m^2/day/atm$)	OLED $<10^{-6}$
		LCD$<10^{-3}$
		TFT$<10^{-3}$
Transparent anode coated substrates	Resistance (Ω/sq)	< 20
	Total light transmittance (%)	> 80
	Flexibility	Ability to bend over a 1 inch diameter 1000 times

it has very good transparency, environmental stability, low electrical resistivity. But it tends to crack when the substrate is bent, it is susceptible to corrosion, and moreover it is costly. The ITO material is brittle and

Table 2.2: Important Properties of Some Polymeric Materials

Properties	**PET**	**PEN**	**PC**	**COC**	**PES**	**PI**
Thickness (mm)	0.1	0.1	0.1	0.1	0.1	0.1
Total light transmittance (%)	90.4	87.0	92.0	94.5	89.0	30−60
Retardation (nm)	Large	Large	20	7	<10	Large
Refractive index	1.66	1.75	1.56	1.51	1.6	−
Glass transition temperature (°C)	80	150	145	164	223	>300
Coefficient of thermal expansion ($ppm/°C$)	33	20	75	70	54	8−20
Water absorption ratio (%)	0.5	0.4	0.2	<0.2	1.4	2.0−3.0
H_2O barrier ($g/m^2/day$)	9	2	50	−	80	−
Elastic Modulus (GPa)	2− 5.34	5 − 6.08	2.6	2.6−3	2.8	2.5−5

lacks the mechanical flexibility required for flexible displays, however, researchers have successfully processed ITO coated on polymeric substrates so that they can be used for flexible displays. They have low sheet resistance and are more environmentally stable compared to some other electrode materials. Oxygen plasma treatment of an ITO material enhances the hole injection property, and thus makes it more suitable for use as an anode material.

– Indium Zinc Oxide (IZO): These materials show good electrical and mechanical properties like ITO. They do not require substrate heating or any post-deposition annealing process as required for the deposition of ITO. Similar to ITO, IZO is brittle and thus it is a challenge for using it in flexible display applications.

– Carbon Nanotubes: These materials are formed from graphite sheets and have excellent thermal, mechanical and electrical properties due to which these materials are finding application in thin electronic applications. They have high elastic modulus and are very strong compared to other materials used for the electrode layer. They can be processed in vacuum at very high temperatures without losing their thermal stability. They have very high thermal conductivity and electrical properties. But researchers have shown that their efficiency is less compared to ITO.

– Polymer Materials: Most of the polymeric materials are insulating in nature but there are conductive polymers that have good electrical properties, which can be easily flexed and have very high optical transparency. They also have the ability to be solution processed at room temperature. One of the most used conductive polymeric materials is poly (3,4-ethylenedioxythiophene), poly (styrene sulfonate) which is also known as PEDOT:PSS. There are other conducting polymers that can be used for the anode layer which have better properties than the ITO material. PEDOT:PSS is one of those conducting polymers which appears to be a good material to be used for the electrode mainly because of its excellent thermal stability and high transparency than the other conducting polymers. It also has the advantage of easy deposition, less surface roughness, less cost compared to ITO material. Even though it has lower transparency than the ITO material, this problem can be resolved by adding dimethylsulfoxide (DMSO) to an aqueous solution of PEDOT:PSS material. It has an advantage that it can be easily solution coated onto substrate materials. PEDOT:PSS is also used as a material for HIL as it improves the electromechanical performance of an ITO coated poly ethylene terephthalate (PET) substrate.

There are several challenges faced in the manufacture of flexible electronics. Two of the main challenges for flexible electronic devices are obtaining a suitable thin barrier layer for polymeric substrates and improving the flexibility of brittle inorganic films like ITO. Polymeric substrates must be encapsulated with flexible barrier materials that would prevent permeation of oxygen and moisture which otherwise may cause degradation of the device. All OLEDs must be sealed on the top and bottom sides of the device which is termed as encapsulation. Usually, OLEDs have been encapsulated using a metal in an inert atmosphere such as oxygen or nitrogen and using calcium oxide or barium oxides to stop any water diffusing into the device. But this kind of encapsulation is not applicable for flexible OLEDs. Flexible OLEDs can be encapsulated mainly in two ways, one is by using barrier-coated polymer substrate which provides a multilayer structure and has the advantage of providing a mechanically robust device and the second method is by coating a thin-film multilayer directly on the device. For transparent devices, these barrier materials must be transmissive in nature along with being flexible. The common materials used for forming barrier layers are aluminium, aluminium oxides or silicon oxides.

The selection of barrier materials is important for successful manufacture of an OLEDs. It is found that for an OLED with a lifetime of 10,000 hours or more, water vapor transmission rate (WVTR) and oxygen transmission rate (OTR) must be less than 10^{-6} (g/m^2/day) and 10^{-5} (mL/m^2/day), respectively. Figure 2.12 shows a comparison of these requirements for an OLED with other electronic devices [23].

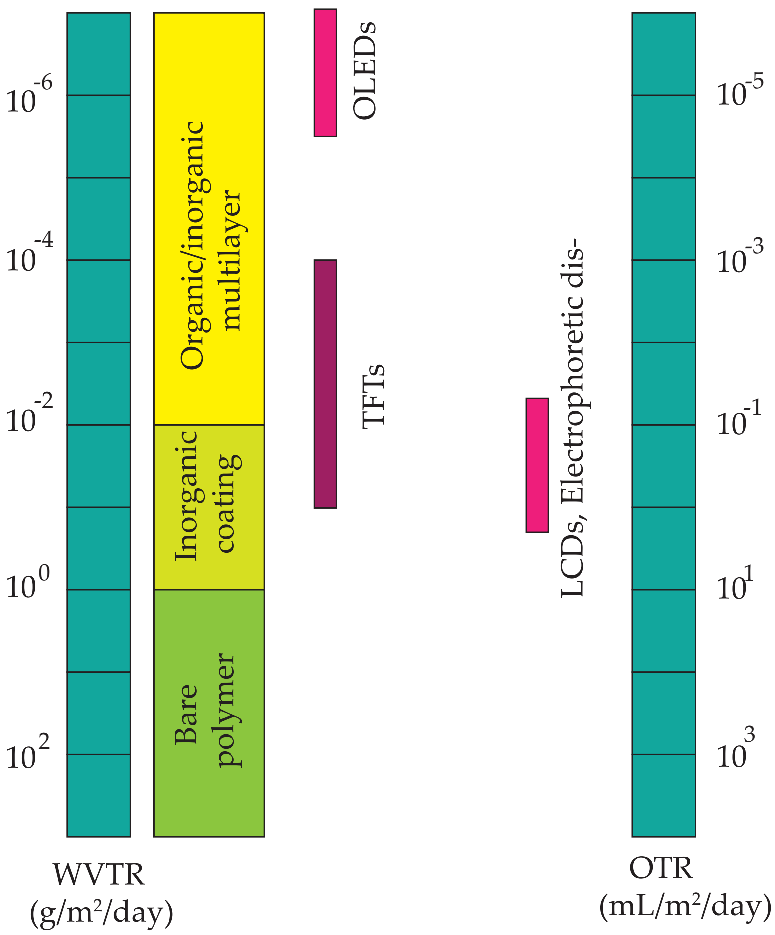


Figure 2.12: WVTR and OTR requirement for Electronic Devices [23]

Flexible electronic devices are thin, robust, lightweight, mechanically flexible due to which they find their applications in a variety of places. Some of their applications include:

- Portable display screens
- Wearable displays
- Electronic papers

- Decorative lighting
- Flexible window panes
- Automobile accessories
- Television displays
- Cameras, mobile phone displays, etc.

2.1.12 Advantages and Disadvantages of OLED Devices

Advantages:

1. In OLEDs, the organic layers are plastic and hence are lighter, thinner and flexible compared to the crystalline layers of LED or LCD.

2. OLEDs are brighter than LEDs. The substrate used to support OLEDs can be made of plastic rather than the glass substrates used for LEDs. The glass substrate absorbs light, but that problem does not exist in OLED.

3. OLEDs consume less power than LCDs since there is no back lighting in OLEDs. This is one of the major advantages of OLED over LCD. OLED being emissive, can be turned off to remain completely dark whereas LCD being transmissive does not allow for the complete blocking of its backlight. This reduces the power required and also the number of layers of the substrate required which would make it thin and more efficient. LCD consumes the same power regardless of the image being fully black or white but OLEDs power consumption depends on the image being displayed. Darker images consume less power while white images consume more power.

4. OLEDs have a wider viewing angle of upto 170 degrees and can operate at very low voltage ranges ($2-10$ volts). Thus the image can be seen from any angle clearly without having problems of blurring or color contrast.

5. OLEDs have a better contrast and faster refresh rate, as a result motion blur is minimized.

6. OLEDs are flexible and can be manufactured in large quantities using RTR manufacturing. They can be produced in different shapes. Very thin and transparent OLEDs can be prepared.

7. OLEDs have vast color range compared to the other currently available displays.

8. As they are flexible, they are not affected by shock or twisting forces.

9. They can work in a much greater operating temperature range than LCDs.

10. In the case of AMOLEDs, there is no backlighting and each pixel can be turned on by the TFT matrix. Thus there are no limitations to the resolution, pixel count and size of the display.

11. Flexible OLED displays can be rolled, bent, conformed to any shape. Such properties can be used to produce portable rollable displays, irregular shaped displays, wristband displays, etc.

Disadvantages:

1. It is currently expensive to manufacture OLEDs. But many companies are trying to develop RTR technologies to manufacture OLEDs in web form which would reduce the cost of manufacturing to a great extent.

2. OLEDS have a problem of operating in direct sunlight because of their emissive nature. Since they are emissive, when they are viewed under direct sunlight, they face readability problems. Research is being actively pursued to resolve this problem.

3. Indium is a rare earth element and thus expensive to mine and difficult to recycle. Low temperature conditions must be accommodated when using ITO

with glass substrate in order to obtain low sheet resistance and high optical properties. ITO may also undergo cracking under tensile strain when it is placed on a polymeric substrate which would result in failure of the flexible display.

4. OLEDs tend to get dimmer within several hours of working. The problem is mainly with the blue component of the OLED that tends to fail within 5000 hours of working. Research is being actively pursued to resolve this problem.

5. Most of the OLED materials are chemically unstable in the presence of moisture and oxygen which can lead to the formation of dark spots in the display. Proper barrier encapsulation should be provided in order to overcome this issue.

2.1.13 Challenges Faced in Manufacturing of OLEDs

The main challenge is in manufacturing of large size OLED displays with reasonable cost. Material lifetime and efficiency are also a matter of concern. The overall lifetime of the OLED device is calculated as the mean time to half brightness. Due to the difference in aging of the different color emitters, the overall lifetime of the device is greatly reduced. Initial investments in the manufacturing of OLEDs have been high and this should be reduced in order to compete with other technologies. Depositing the organic molecules to the substrate to obtain the different colored pixels has been a major challenge faced by the manufacturers. Small molecule based OLEDs have been experiencing problems such as catastrophic failure, dark-spot degradation, and intrinsic degradation. By using adequate methods of fabrication, the first two problems can be solved but the third problem has been of considerable challenge to the OLED manufacturers. Also, the lifetime of organic materials drop significantly with increase in temperature. This will be a major problem mainly when choosing the organic materials for the television displays, computer screens, etc.

Accurate methods must be adapted for the encapsulation of organic materials when using a flexible substrate. Planarization of ITO material that is used as an anode is also posing problems in the manufacture of OLED which would require deposition of additional layers for better performance. Planarization is defined as the process of improving the flatness of a semiconductor material.

Other challenges in RTR manufacturing of OLEDs include inter-layer damages, maintaining cleanliness, etc. It is very important to select the materials with similar coefficients of thermal expansion when forming the organic layers on the substrate; a large mismatch would result in cracking and failure of the deposited layers during thermal cycling. Maintaining an accurate fine-line registration of the process when using RTR manufacturing technique is very challenging. Also, maintaining web tension; proper handling of the web during transport, and maintaining the purity of organic layers are important when using RTR manufacturing.

2.1.14 OLED Based Light Sources

As discussed previously, OLEDs can be used as light sources with the integration of some electrical circuits and drivers along with the OLED layers. A method for obtaining colored light from the OLED light source with the integration of OLED layers and a control unit having electronic components has been described in [24]. The active layers of the OLED device are segmented and these segments may contain series of stripes or color lines. The control unit may be used to drive these stripes individually or separate color lines may be controlled. Sometimes even a region of the panel consisting of the color lines may be separately controlled. Figure 2.13 shows the manner in which drive electronics can be integrated with the OLED layers in order to give a OLED light source [24]. Active layers may be made of different colors like RGB or only one color emitting material may be used. If the yellow color emitting material is used as the active layer, a light source having yellow light may be obtained.

Likewise, individual color lines of the active layer having RGB color emitting material lines may be controlled in order to obtain different shades of RGB colors. Different shades of these colors may be controlled in order to obtain white light or any other necessary color lighting device. In order to create a flexible light source from the

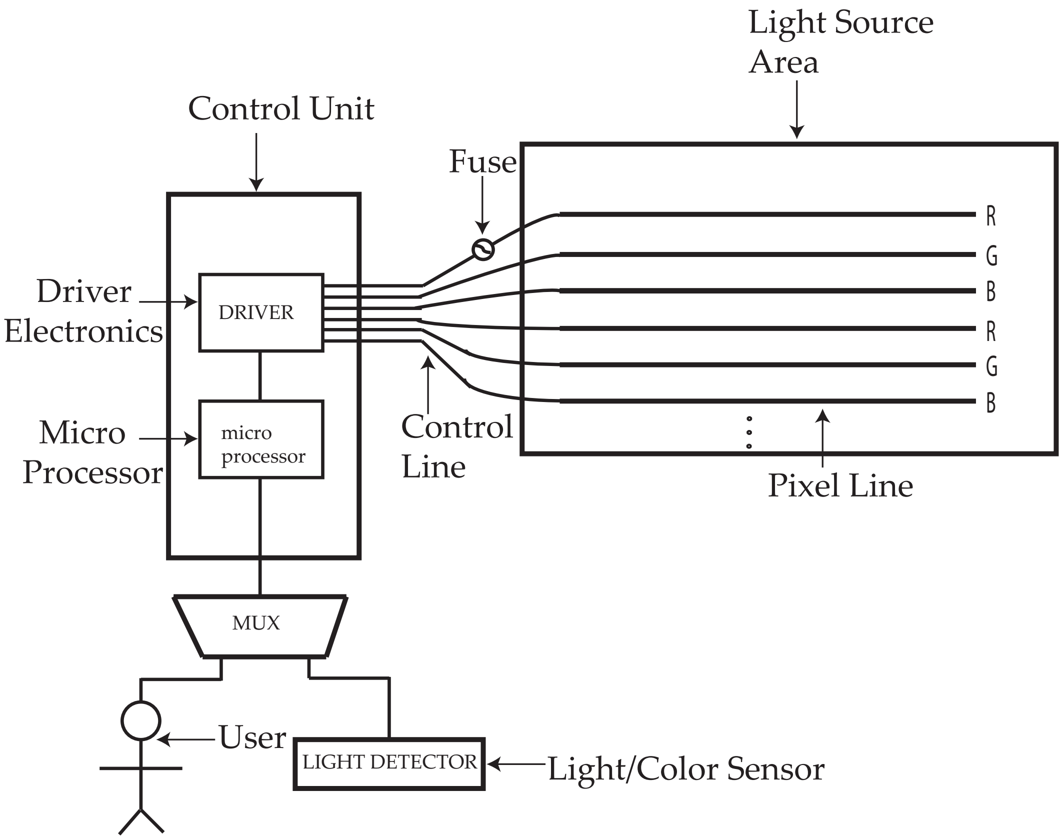


Figure 2.13: OLED Light Source [24]

OLED layers, the following materials and layers are required.

- Substrate: The substrate has to be transparent and flexible. Any of the plastic material like PET, PEN, PC or semi rigid thin glass can be used for the substrate.

- Anode: The anode material is deposited and patterned on top of the substrate. Material such as ITO, IZO etc., may be used as the anode material.

- Bus line: An optional bus line may be deposited on top of the anode in order to decrease the overall resistance of the anode stripe across the panel. This can be of any metal or metal alloy material. This is sometimes necessary if the resistance of the anode material is large which would require a large amount of voltage to drive the current.

- Insulating separators: These may be deposited on top of the above mentioned layers in order to provide proper electrical isolation. It is optional and it can be of any insulating materials like photo resist, SiO_x, SiN_x, etc. These are used to provide proper separation between the stripes of the light panel. Sometimes, just patterning of the anode material is enough to obtain electrical isolation.

- Hole injection layer: This layer is used to complement the anode layer in hole creation and can be made of PEDOT:PSS, Pani or any other conducting polymers.

- Active layers: This layer is made of emitting material. Any material or combination of materials may be used in order to obtain specific colored light.

- Cathode layer: Finally, on top of the active layers, cathode material is deposited which can be made of any low work function metal or alloy. The cathode layer can be segmented similar to the anode stripes. Sometimes, only the cathode layer may be patterned and the anode layer need not be patterned or cathode can be deposited on top of the substrate and the anode layer may be deposited on top of the emission layer.

The above layers are shown in the Figure 2.14. Sometimes, an insulating or electron injection layer may be deposited between the emission layer and the cathode layer which would supplement electron injection. For a light source, the thickness and the resolution of the layers are larger compared to the display devices. At the light output side of the device, a brightness enhancement layer may be laminated to the substrate. As shown in Figure 2.13, the individual red, green and blue color stripes may be directly addressed by the current source. The current to this source can be controlled by a circuit in order to avoid excess current flows. Figure 2.13 shows a light source area and a control unit used to control the current input to the individual stripes of the layers. The location of the control unit depends on the demands of the light source. It may be separately constructed or it may be integrated with the light source layers on the same substrate. A part of the control unit may be integrated with the light source on the substrate and the rest may be constructed separately. The control unit consists of driver electronics, microprocessor, light sensor, etc. If three different colors are used in order to obtain the white light, then a sensor can be used to check the color obtained from the light panel based on the temperature of white light required. A microprocessor can be used to obtain the signal from the sensor based on which it can send the required control signals to the driver circuits. Any combination of the stripes can be turned on/off and any color can be obtained from the light source. Even a fuse can be integrated with each control line so that if the current to that particular stripe exceeds the limit, then the fuse would blow and would prevent failure of the entire device. The segmentation of the layers in the light source can be done in different ways. The stripes for the segmentation can be in the form of rows, columns or in the form of the pixels or any other shape or combination can also be employed.

2.1.15 OLED Display Device

One of the most important application of OLEDs is in the display industry. Having benefits of wide viewing angle, better quality, thinner display, light weight and flexibility, OLED is a promising technology to replace other current technologies such as LCDs in the field of display devices. Many researchers have described how an OLED can be integrated with the electronic components in order to obtain a display device.

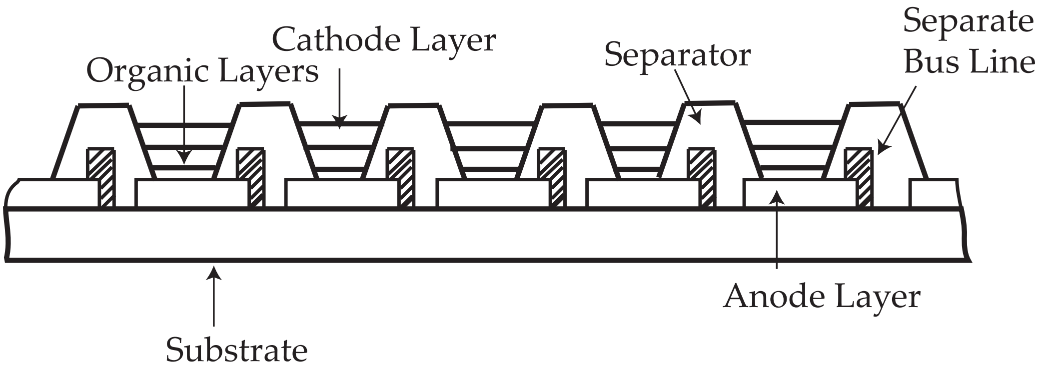


Figure 2.14: OLED Layers for the Light Source [24]

In [25], a display device made of OLED integrated with printed circuit board and other electronic circuits has been discussed. This device is shown in Figure 2.15; scan lines, data lines, and TFT circuits present in the pixel region are not shown. The

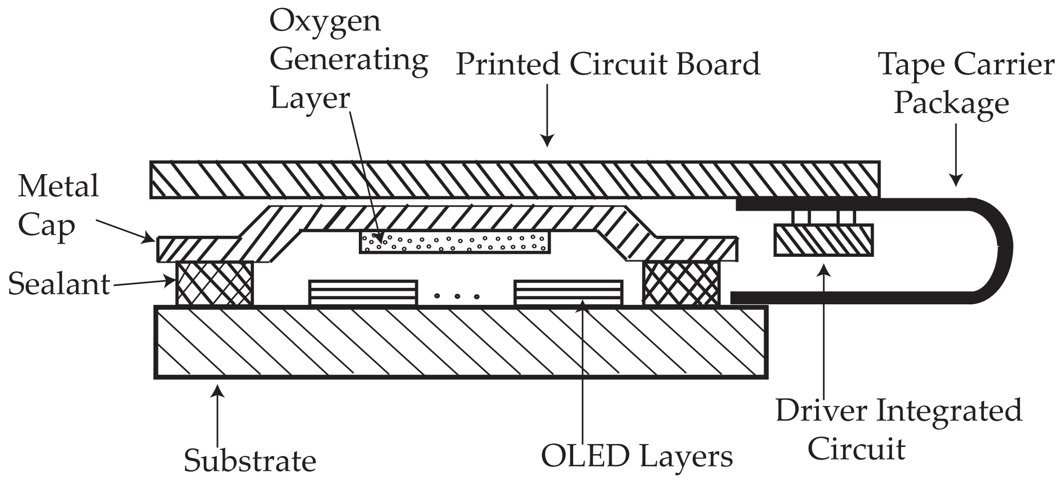


Figure 2.15: OLED Display Device [25]

device described in [25] consists of the following regions and parts:

- A substrate that is divided into pixel and non-pixel region.
- The pixel region consists of at least one OLED deposited on it. The OLED consists of two electrode layers with light emission layers between them.
- The non-pixel region consists of the sealant deposited on it which is used to

seal a cap on top of the pixel region in order to provide protection against environmental permeates like water, oxygen, and dust. It is better to adhere the cap in an inert atmosphere like nitrogen or argon to obtain better protection from air and moisture.

- An Oxygen generating layer and an absorbent layer that are located between the cap and substrate. The oxygen generating layer might help in absorbing the moisture and may be made of materials like peroxides of alkali metals or a catalyst such as manganese dioxide. The absorbent layer is deposited between the oxygen generating layer and the sealing cap. It may be made of calcium or calcium oxide. The absorbent layer helps in reducing the incursion of moisture, oxygen and hydrogen into the sealed shell.

- A circuit for the display which includes printed circuit board (PCB), driver integrated circuit, tape carrier package (TCP). The printed circuit board is used to send electrical signals to the OLEDs of the display device. The function of the TCP is to provide signal wirings between the PCB and OLEDs for transmission of the electrical signals. The driver IC is used to drive the OLEDs by sending the required data and scan signals to them.

In [26], a method of manufacturing OLED display panels has been described. Figure 2.16 shows the different parts of the display panel device. The functionalities of each of the parts shown in Figure 2.16 is described as follows:

- Display panel consists of the display area and peripheral area.

- The display area includes the emission layers and plurality of (TFT) circuits deposited on top of the substrate.

- The peripheral area is around the display area at its circumference and consists of at least one driver and a voltage pad.

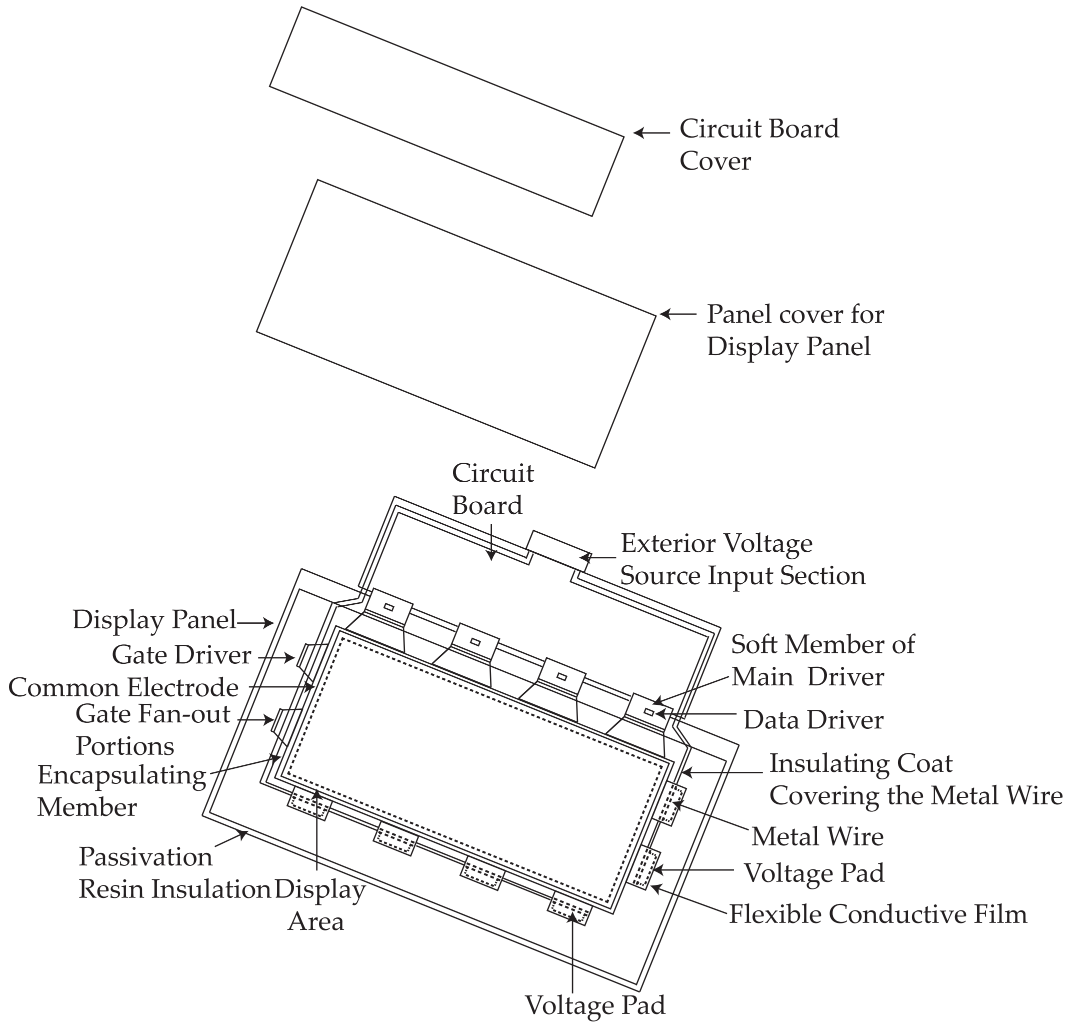


Figure 2.16: Exploded View of the Display Device [26]

- A driver is used to drive the display signal, i.e., it sends the data signal and gate signals to each of the TFTs. The driver comprises a circuit board needed to generate the display signal; a soft member used to connect the display panel and circuit board; and a data driver for applying a data signal to the TFTs. The circuit board supplies this data signal to the data driver. The drive may also include at least one gate driver in order to send the gate signal to the TFTs. The circuit board is connected to the exterior voltage source input.

- The function of the voltage pad is to apply a driving voltage required for the display area.

- The necessary driving voltage and common voltage to the voltage pad is provided by an outer voltage source input section which are connected to each other using a metal wire. The metal wire is fixed to the voltage pad with the help of a conductive fixing member.

- In the peripheral region of the display panel, the driving voltage pads are connected to driving voltage lines while the common electrode is electrically connected to common voltage pads. In Figure 2.16, there are many driving voltage pads at intervals in the peripheral area. The function of each of them is to apply a predetermined level of driving voltage to the driving voltage line. This voltage is sent to the driving voltage line through a metal wire of the driving voltage cable. The voltage required by the driving voltage pad is supplied by the exterior voltage source input section. These voltage pads are formed opposite to the data drivers with the display area in between them.

- The peripheral region also consists of many common voltage pads which are placed at intervals opposite to the gate drivers with the display area in between them. The common voltage pad applies a predetermined level of common voltage to the common electrode via metal wire of common voltage cable. This voltage is supplied from an exterior voltage input section to the common voltage pad.

- The main drivers required for generating the data and the gate signals are also placed in the peripheral area opposite to the region where the driving voltage pads are located.

- A substrate for encapsulation of the display panel is provided at the front side of the panel. Encapsulation is necessary to prevent the moisture and oxygen from entering the emission layers causing it to degrade.

- On top of the encapsulation substrate, a panel cover is formed. This panel cover supports the display panel and helps in easy transportation of the display device. It is better that the panel cover is made of an insulating material such that it is electrically isolated from the electrical lines formed on the display panel.

- A circuit board cover is placed on top of the panel cover in order to protect the circuit board present on the peripheral region of the display device. This cover is fixed to the panel cover with the help of screws or any other fixing methods.

The display area that contains the emission layers and plurality of the TFTs is shown in Figure 2.17.

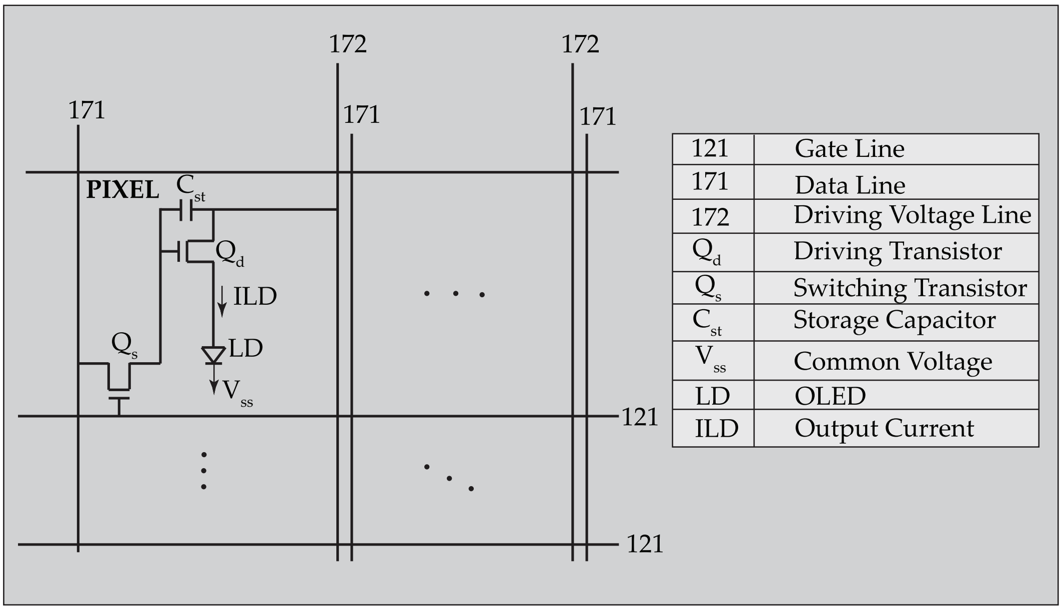


Figure 2.17: Schematic Diagram of Circuit in the Display Area [26]

The circuit diagram in Figure 2.17 shows the electrical circuit that is formed in the display area of the device. The various circuit lines present in it are explained as follows:

- The signal lines includes a multitude of gate lines, data lines and driving voltage lines. The gate lines are used to send gate signals, data lines are used for sending data signals while the driving voltage lines are used for sending a driving voltage.

- It can be seen that gate lines are considerably in the row direction and are mostly parallel to each other while the data lines and driving voltage lines are in the column direction and mostly parallel to each other.

- There will be many pixels in the display area of the device, depending on the application. Each pixel includes various components like switching transistor, driving transistor, storage capacitor, and an OLED.

- The switching transistor consists of a control terminal which is connected to the gate line, an output terminal connected to the driving transistor, and an input terminal connected to the data line.

- The driving transistor consists of a control terminal, an input terminal, and an output terminal. The control terminal is connected to the output terminal of the switching transistor while the input terminal is connected to a driving voltage line. There is also an output terminal which is being connected to the OLED.

Table 2.3 shows typical values of layer thickness for an OLED material [27].

2.2 Solar Cells

2.2.1 Introduction

A photovoltaic device consists of semiconducting materials which produces electric current under the action of light. A device which converts the sun's energy into electricity by photovoltaic effect is known as a solar cell; they are also known as photovoltaic cells. These cells are made of semiconductor materials which absorb part of the solar energy when light strikes the cell. The energy absorbed in the

Table 2.3: Typical values for OLED layer thickness

Application	**Layer Thickness**
Opaque and Semitransparent Layers	
OLED active material	80 − 300 nm
Metal inks used in electrodes and wiring	50 nm − 10 μm
Insulators	100 nm − 20 μm
Transparent Layers	
ITO anode	50 nm − 1 μm
Hole transport / injection layer	50 − 100 nm
Insulators	80 - 2000 nm

semiconductor material causes the electrons present in the material to flow freely. These cells contain one or more electric fields that will direct the electrons released by the absorption of light to move in a certain direction. This flow of electrons results in current and by using proper metal contacts on top and bottom of the cell, current generated can be stored or used to power any other device. The total power or wattage of the solar cell will be defined by this current along with the cell's supply voltage provided by the in-built electric field of the device. Silicon is the most common semiconductor material that is currently used in the industry.

The semiconductor materials are actually insulators in their original form. They have to be doped with other materials or heated in order for them to be conducting. As mentioned earlier, silicon is the most common semiconductor used. When a semiconductor is doped with phosphorus atoms, it will give rise to an excess of free electrons and this is termed as n-type semiconductor. When a semiconductor is doped with materials like boron, it will result in electron holes and the semiconductor with holes is termed as p-type semiconductor. Solar cells consist of p-type and n-type semiconducting materials with a layer known as a junction between them. There is small amount of electron flow from the n-type to p-type material across the junction even in the absence of light. This will result in a small voltage across the cell. When light falls on the cell, large amount of electrons will flow from the n-type to p-type material across the junction which will result in a large amount of current in the device. This current can be utilized to power other electrical devices.

2.2.2 Flexible Solar Cells

Polymer solar cells are flexible solar cells which are made of very thin active layers, and these layers can be solution printed at low processing temperature. Similar to flexible OLEDs, the active materials along with the electrodes in polymer solar cells are deposited on top of the plastic substrate. Thus, the manufacturing of polymer solar cells can be achieved by RTR methods. In [28], a solar cell manufactured using a RTR method is described. In order for the light to be passed to the active layer of the solar cell, one of the electrodes should be transparent. Presently, ITO is used as the anode material as it is transparent and can be deposited on flexible plastic substrates like PET foil along with having the properties desired for being the anode material. As the sheet resistance of ITO material is high, it can be patterned so that smaller cells can be connected in series. This would reduce the ohmic loss and improves the efficiency of the device. In [28], silver material is used for the cathode layer, zinc oxide is used as an electron transport layer and PEDOT:PSS is used as the hole conducting layer. In [28], active layer is made of an ink formed by dissolving P3HT and PCMB ink in a certain ratio in 1,2-dichlorobenzene at around 120^o C temperature. The active layer along with the ZnO and PEDOT layer were slot die coated onto the ITO-PET substrate. On top of the PEDOT layer, silver cathode layer is RTR screen printed. The entire device is encapsulated with a flexible barrier layer using an adhesive. The manufacturing procedure used in [28] is explained below.

Techniques such as slot die coating and screen printing are used to print layers in the form of stripes. By serially connecting these stripes, device modules are created. These printing methods are performed using RTR manufacturing. The PET substrate with a width of 300 mm and total roll length of 200 m is used. Finally the device is encapsulated with a barrier layer using an adhesive in a RTR lamination process. In this paper, researchers have used flat bed screen printing for printing of etch resistant material during anode patterning. The flat bed screen printing is a non continuous process resulting in the intermittent movement of the substrate. This also limits the passing of web directly into the liquid bath after the drying of screen printed etch resistant material.

2.2.3 Anode Layer Fabrication

One of the main requirements of the solar cell is that sunlight has to pass into the active layers. Due to this, at least one of the top or bottom outer layer of the device should be transparent along with the electrode layer which is in contact with the outer layer. In this paper, ITO is used as the anode layer which is sputter deposited on top of the PET substrate by using vacuum RTR technique. The ITO material has high sheet resistance as a result of which ohmic losses will be more. Therefore it is of advantage to pattern the ITO layer. The ITO anode layer is patterned into stripes and serial connection between smaller cells is obtained in the last printing step. There can be continuous pattern of ITO on the substrate, but in the paper [28], the ITO pattern is divided along the length of the substrate. It is extended for the length of the typical module. To enable the printing of subsequent layers on top of the ITO anode layer, registration and cutting marks are appropriately printed along the web. These marks would also help in final cutting of the modules. Researchers in this paper tried different lengths (200, 225, 250 mm) for the ITO stripes. The stripes maintained a repetition gap of 25 mm to enable the cutting of modules. The ITO anode layer has a thickness of 80 nm. As shown in figure 2.18, the ITO anode layer is patterned into 16 stripes each of them about 225 mm in length and with a gap of 25 mm between the stripes along the length of the web. Each of the stripes are 13 mm wide. There should be an optimum width for the ITO stripe. This is because in order to minimize the ohmic loss, it has to be as narrow as possible and in order to increase the active area of the device, it has to be as wide as possible.

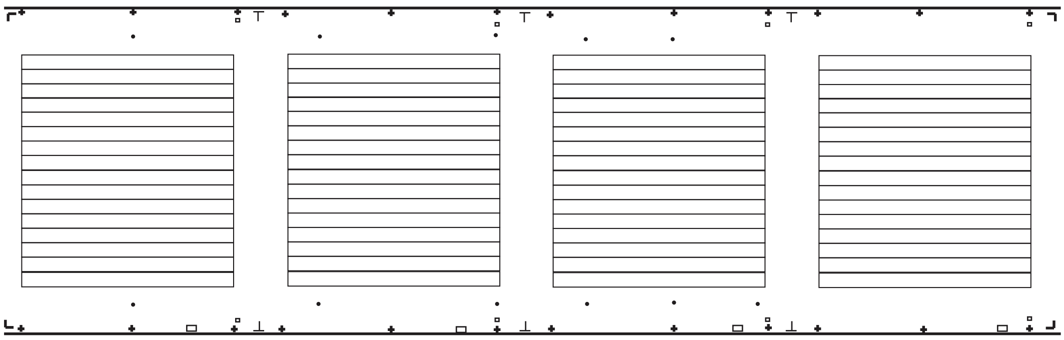


Figure 2.18: ITO Patterning for the Solar Cell Anode Layer [17]

Figure 2.19 depicts the electric contacts deposited on top of the ITO anode layers for different module lengths. In the figure, first patterning shown is for 225 mm long module length, center one is for 100 mm long module length and the last one is for 60 mm long module length.

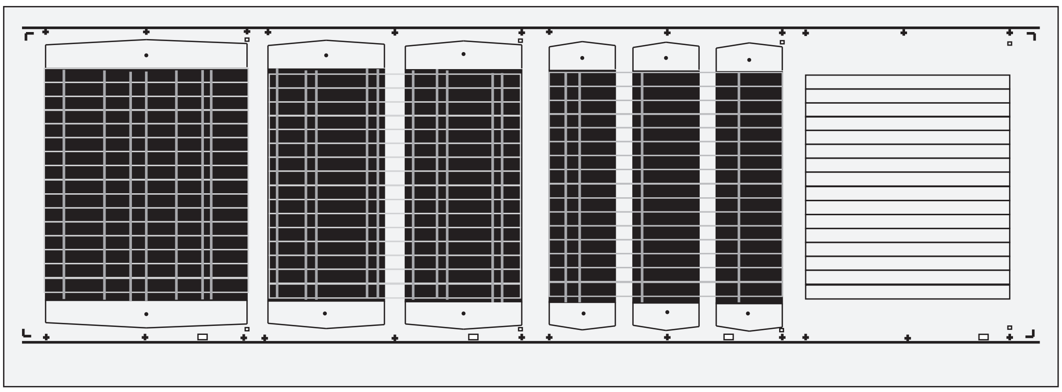


Figure 2.19: Silver Print on top of ITO Pattern for Three Different Module Lengths [17]

After the patterning of the ITO layer, the substrate is cleaned by passing through corona treatment. It is followed by cleaning the web and washing it using isopropanol and then drying it at 140^o C. The ITO layer is patterned using a flat bed screen printing technique. The etch resistant material which is UV curable is screen printed on top of the raw PET-ITO layer on parts of the substrate where ITO anode is required. After screen printing, etch resistant material is cured using UV drying method. A web speed of 3.3 m/min is used for screen printing of etch resistant material and UV drying method. It is a non-continuous process, as flat bed screen printing is used. The unprotected areas of the ITO anode layer is then washed away by passing it through an etching bath which is followed by stripping of the etch resistant material using a stripping bath. The substrate is then dried at around 140^o C. A web speed of 3 m/min is used for etching, stripping and drying of the substrate. During the screen printing of etch resistant material, a hole is punched along the substrate to enable registration during the printing of cathode layer.

2.2.4 Fabrication of active layers

The ZnO solution is slot die coated on top of anode substrate with a speed of about 2 m/min. The thickness of the dry layer obtained is 23 nm. The active layer is also slot die coated on top of ZnO layer at a speed of 1.4 m/min to obtain a dry layer thickness of 127 nm. It is then followed by slot die coating of PEDOT:PSS layer on top of it with a thickness of 20 μm. It is coated at a speed of 0.3 m/min. The slow speed employed in slot die coating of PEDOT:PSS layer is due to slow drying of PEDOT:PSS material. A drying length of 1 m and a drying temperature of 140^o C are used for drying these layers.

2.2.5 Fabrication of cathode layer

The cathode layer is screen printed using a RTR screen printer on a flat bed RTR screen printing machine. The position of cathode pattern on the substrate is in reference with the hole punched during screen printing of the etch resistant material for the anode layer. In order to print the motif on the substrate, the position is determined by the registration marks printed during screen printing of the cathode layer. Based on these registration marks, the substrate is moved to the vacuum table for printing where it is fixed and printed with the motif. It is then passed through drying oven at a temperature of 130^{o} C and for a drying length of 120 cm. The web speed is maintained at 1 m/min.

2.2.6 Lamination of the barrier layer

This is the last step in the fabrication of a solar cell. At first, barrier foil with a thickness of about 55 μm is coated with an adhesive. The barrier foil has a width of 305 mm and the adhesive is lined on the foil for a width of 298 mm. The foil with adhesive is then cut into 250 mm width in order to laminate on the active areas such that the silver bus bars are exposed for electrical connection. The barrier foil with the adhesive is laminated on both the sides of the device in order to protect it from moisture and oxygen. The side with the active layer is laminated first. After testing of the roll, solar cell sheets are cut using a knife which is triggered when the registration mark is reached. A camera is employed which recognizes the registration mark on the substrate that was printed during screen printing and then sends the signal. Based on this signal, movement of the substrate is stopped and the module is cut with the knife. These modules are passed over the belt which are then collected and packed. The length of the ITO stripe does not affect the performance of the device as the current flow is across the stripes and not along them.

Figure 2.20 shows the entire structure of solar cell module. It can be clearly seen from the figure the manner in which electrical connection is made with anode and cathode layers.

In [30], development of a flexible solar cell in RTR form that can be used to charge a polymer lithium ion battery through a blocking diode is described. These solar cell

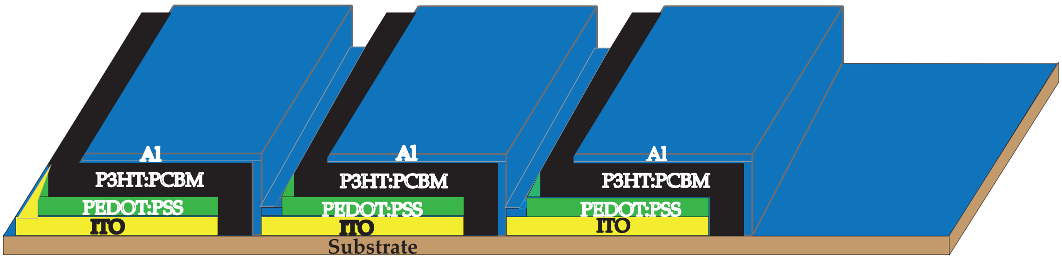


Figure 2.20: Solar Cell Structure [29]

modules are used to light a small LED based pocket lamp by using a polymer battery which is charged by using the solar cell module. All the layers are patterned in stripes having a width of 5 mm and spaced by 1 mm. In order to charge the lithium ion battery, a voltage of 4.7 volts is required and it was found out by a trial and error method that in order to achieve that voltage about 16 individual solar cells have to be connected in series.

Figure 2.21 shows the front side, side view and back side of the lamp that is assembled with solar cell module and lithium ion battery to provide light. Figure 2.22 shows the solar lamp in operation.

The following steps are used in the manufacturing of the solar cell lamp module.

- ITO on PET substrate is patterned. The ITO pattern has two sets of 16 parallel stripes and each of the stripe has a gap of 1 mm between them. Each stripe has a length of 285.5 mm and a repetition length of 305 mm.
- ZnO nano particle is slot die coated to achieve a dry layer thickness of 28 nm.
- The active layer of P3HT:PCBM is slot die coated on top of ZnO layer to a thickness of 129 nm.
- A layer of n-octanol is then coated on top of active layer using flexographic printing. This will wet the entire surface which is necessary for sound coating of PEDOT:PSS layer on top of active layer. This is essential as the PEDOT:PSS layer has high surface tension and the active layer has a low energy surface.

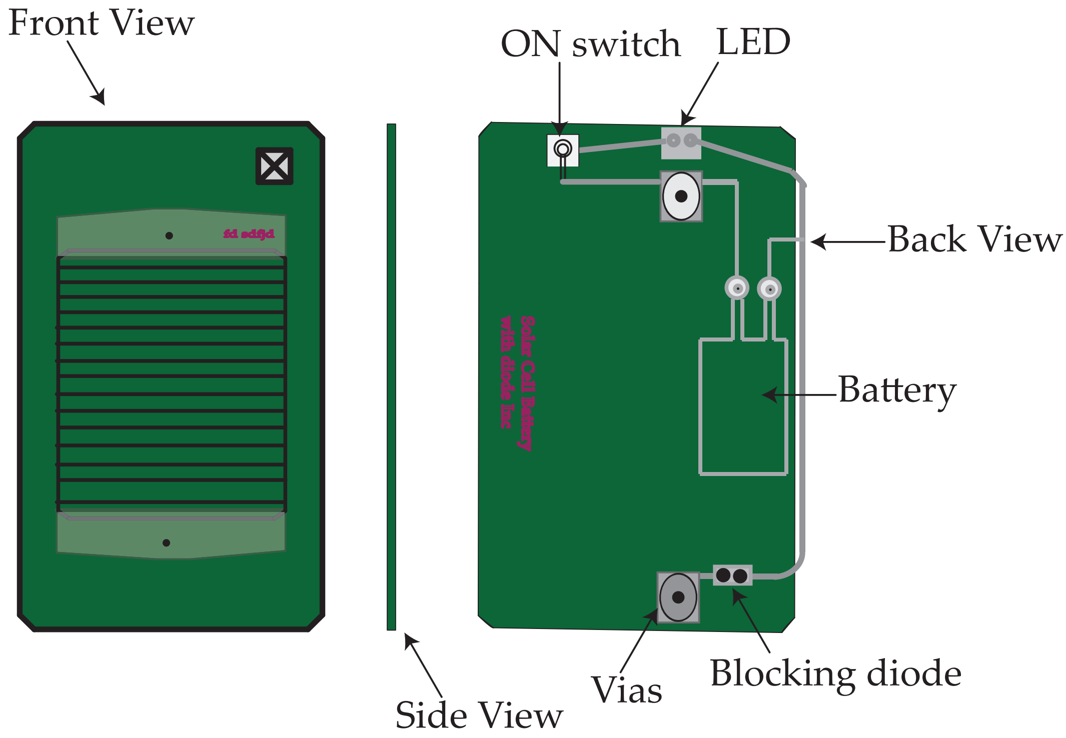


Figure 2.21: Front View, Side View and Back View of a Solar Lamp [30]

- PEDOT:PSS is slot die coated.
- It is then followed by rotary screen printing of silver cathode layer.
- After screen printing of the cathode layer, registration marks are printed for future processing and cutting of the modules.
- A barrier foil is laminated on both the front and back side of the device. In the front side of device, it covers the substrate completely while in the back side of device, it is laminated only to an extent such that about 5 mm silver cathode will be allowed free for an electrical contact.

The solar module prepared above is then assembled with other electronic components like blocking diode, white LED, battery, etc., in a process line. In order to make room for the battery, a spacer made of PET substrate of about 1.5 mm is used. Finally, contact is made between the solar cell and the circuit by crimping and by using

Figure 2.22: Solar Cell Lighted Lamp [30]

adhesive between the layers. After the deposition of each layer, it is dried directly in order to deposit the following layer on top of it. This requires accurate patterning and registration. Metals which are highly conductive like aluminum, silver, and copper can be used for the contact pad. Typical thickness of the layer for the contact pad is about 1−10 μm which will result in efficient conductivity. The contact pad and bus bars need to be aligned with the electrodes which necessitates the requirement of resolution and registration. Due to high metal content and viscosity of ink, rotary screen printing would be the method suitable for deposition of the ink for the contact pad layer.

An electron transport layer is often preferred between the cathode and active layer to prevent their interfacial mixing. It is usually made of thin organic material. They also help in charge transport and defending the photoactive layer from oxidation. The electron transport layer is typically made of materials like LiF, Ca, Li, ZnO, TiO_x, etc., and some of them are even printable. When they are used for ETL, they are often dissolved into polar solvents which will assist in wetting and spreading of the cathode ink and prevent breaking up of the active layer. This layer must be very thin as the thicker layers can increase the resistance which in turn decrease the efficiency of the cell. This requires ink to have low viscosity and a printing process such as gravure printing would be the method suited for deposition.

The transparent barrier layers are usually made of a single layer of oxides or nitrides. Sometimes they are also made of multiple layers of organic and inorganic materials. The barrier layer that is laminated is usually made of plastic film coated with metal or barrier materials.

The transparency of the substrate should be over 90 percent in order to obtain efficient absorption of the solar light into the active layers of the cell. The photoactive layers are typically made of low viscosity inks as they have very poor solubility to solvents. The adhesive layer is printed over the cathode and wiring, after which a barrier foil is laminated onto it.

Table 2.2.6 show various requirements of each layer of a solar cell device [27].

Figure 2.23 depicts the assembly of a solar cell with the corresponding electrical circuitry. In addition to the encapsulation of the barrier layers, contact pads must be

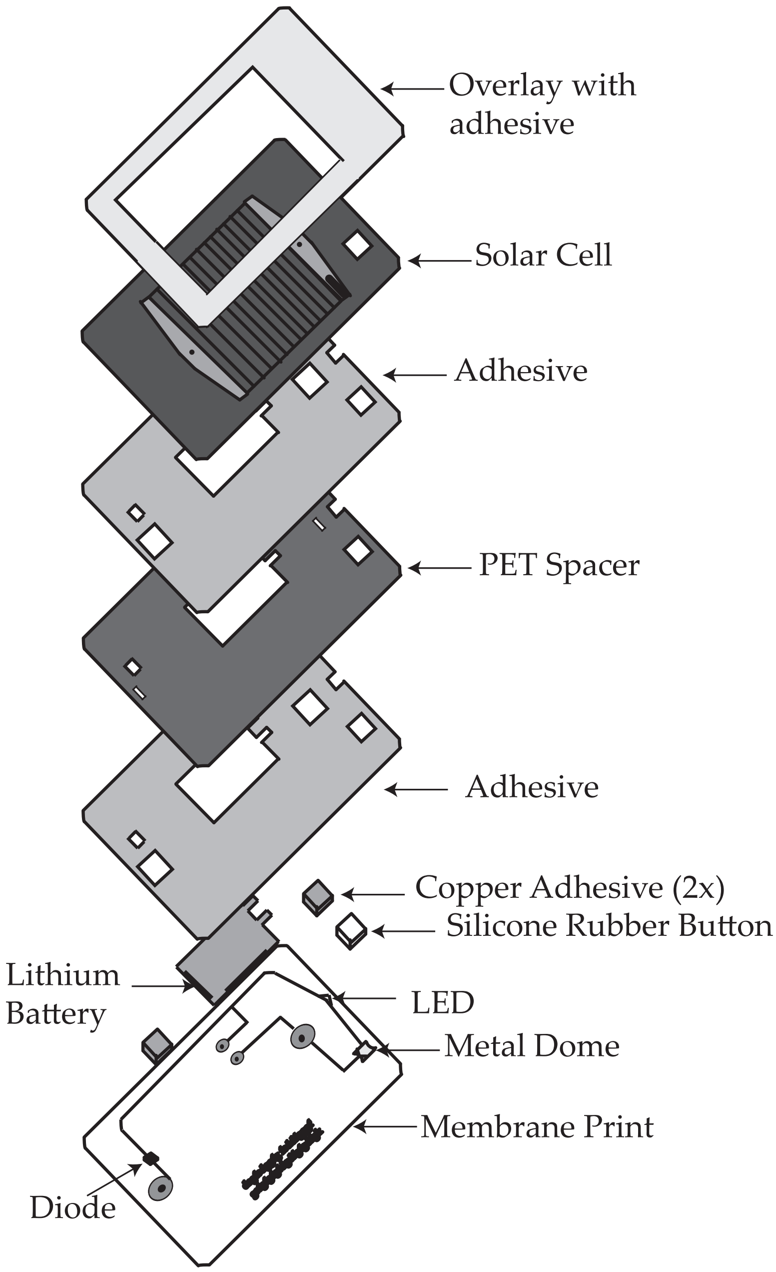


Figure 2.23: Exploded view of the solar lamp assembly [30]

printed in order to provide electrical contacts to the electrode and make modules out of individual cells. The electrode layer deposition must be done in the presence of inert atmosphere as they are prone to oxidization which would reduce their conductivity [29].

A single solar cell does not provide large voltage output. It produces an output voltage of about 0.5 V [29]. Thus, many solar cells have to be connected in series in order to obtain higher output voltages. As shown in the figure 2.20, the anode of the first cell is connected to the cathode of the next cell to form a series connection. As the output current is directly proportional to the active area of the device, the active area of the device has to be increased to obtain higher electrical power.

The parallel connection of solar cells provides a reliable connection compared to the series connection. This is because failure of a single solar cell does not affect the functioning of an entire module. After RTR manufacturing of solar cells or modules, these sheets must be converted. These solar cells or modules in web form are converted into desired applications by cutting and slitting. For a solar cell to function properly for 10,000 hours, it is estimated to have a WVTR value of 10^{-6} g/m^2/day and OTR value of 10^{-3} cm^3/m^2/day. The HIL layer can be printed on top of the patterned anode layer as a solid patch to avoid the necessity of strict resolution and register requirements.

Table 2.4: Requirements and function of each layers of a solar cell

Requirements	**Functions**
Barrier Layer	
Thickness of the layer should be $> 10\ \mu$m	Protect the cell from moisture and oxygen absorption
Layer must be smooth and homogenous	It must maximize light absorption
Layer transparency must be > 90 percent	
The target value for WVTR is $10^{-6}\ g/m^2/day$	
The target value for OTR is 10^{-3} $cm^3/m^2/day$	
Anode Layer	
Layer must be smooth and homogenous and made of high conductive material	It must maximize light entry to the cell
Layer transparency must be > 90 percent and must be of optimum thickness	It must provide efficient charge transport and generation
It must have a resistance of under 50 Ωm and it must not oxidize	
HIL Layer	
It must provide optimum conductivity and made of smooth and homogenous material	It must maximize light entrance to the cell
Layer should be thin lesser than < 50 nm	It must provide effective and stable transport of charges without any losses
Layer must be transparent > 90 percent	

Table 2.5: Requirements and function of each layers of a solar cell

Photo Active Layer	
This layer must be smooth, homogenous and have a optimum layer thickness of about 80-300 nm	It must provide effective light absorption and charge generation
Cathode Layer	
This layer must be smooth, homogenous and have high conductivity	It must provide maximum amount of electron injection to the photoactive layer
The layer thickness is about 1 μm and should be of material which is not prone to oxidation	
Contact Pad and Bus Bars	
This layer must also be smooth, homogenous and have high conductivity	It has to connect the components to form modules
The layer must be thin (about 1 μm)	It must provide electrical contact to the electrodes
Adhesive Layer and Backside Barrier Layer	
The layer must be smooth, homogenous and must have a thickness of around $2-20$ μm	It must prevent oxygen and moisture absorption
It must have a WVTR value of 10^{-6} $g/m^2/day$ and OTR value of 10^{-3} $cm^3/m^2/day$	It must provide proper encapsulation to the solar cell

CHAPTER 3

Roll to Roll Manufacture of Flexible Electronic Devices

Flexible electronic devices such as flat panel displays and solar cells are not currently manufactured in rolled form. Although some elements during the manufacturing of these devices may currently involve roll to roll processing, RTR manufacturing of the entire production of these devices has not been accomplished yet. Designing and developing an RTR process line that is capable of producing these devices in rolled form is expected to significantly improve productivity and reduce the cost of manufacturing. As a result there is a strong research and development effort towards achieving this goal in commercial companies, research laboratories, and academic institutions. Current manufacturing of these devices involves a considerable amount of batch processing. In order to manufacture the flexible electronics in RTR form, proper selection of materials along with processing methods which assist in RTR manufacturing must be used. Materials for the layers of flexible electronic devices must be chosen such that they can be deposited on the substrate using the techniques that are compatible with RTR manufacturing. Similarly, process methods and devices must be selected to be compatible with RTR manufacturing. Understanding of the various key methods of web handling is key to developing RTR methods and design of RTR machines for manufacture of flexible electronic devices.

Although manufacture of many flexible electronic devices are being envisioned, the focus in this chapter is on manufacturing of OLEDs, which is expected to be applicable for flat panel displays and flat panel lighting. In first section of this chapter, materials that are suitable for RTR manufacturing of flexible OLED devices and their properties are discussed. One such material is indium tin oxide (ITO), which is used in many flexible devices such as LCDs, OLEDs, plasma displays, and solar cells. The ITO material cannot be solution printed directly on a web substrate; it is deposited on the surface by different techniques which were described in the previous chapter. After deposition it is patterned using different techniques. The currently available patterning techniques are expensive and cannot be performed in a continuous manner. The flexible electronics industry could benefit a great deal if such patterning could be successfully performed using solution printing techniques that are compatible with RTR manufacturing. From the literature it appears that there has been substantial progress in recent years on developing these solutions in appropriate composition which will facilitate patterning of the ITO anode on a plastic substrate. Design of a web line for patterning of ITO anode on a plastic substrate is discussed in the second section of this chapter. Appropriate patterning of the anode layer is critical to the working of an entire device. It reduces the overall resistance of the conducted and helps in obtaining better resolution devices. Various key technologies, processes and devices are selected for the web line such that ITO patterning can be performed as continuous process in this web line. The ITO patterned substrate can be used for manufacturing of flexible electronic devices such as OLEDs, polymer solar cells, LCDs, etc. The third section of this chapter discusses the design of a web line that is capalbe of depositing the active layers of OLED lighting devices on an ITO patterned PET substrate. The web line processing conditions, parameters, and printing technologies are chosen such that the layers can be deposited in a continuous manner during transport of the flexible material. Although flexible OLED lighting devices is the focus for the development of this web line, similar web line designs can be used for fabrication of other flexible devices also, except that the materials and process parameters may change.

3.1 Solution Printed Flexible OLEDs

Based on a comprehensive and investigative study of available literature, materials and process that make the different components of flexible OLED lighting devices are determined and are summarized below. Further discussions are provided in subsequent sections when the design of the two web lines are discussed.

- Indium tin oxide (ITO) is used as an anode layer on polyethylene terephthalate (PET) substrate. The ITO material can be deposited by a sputter deposition process on PET substrate to obtain the ITO-PET layer. ITO anode may be patterned depending on the application of the OLED device.

- PEDOT:PSS ink is used for the hole injection layer. This layer is made of about 40 nm thickness and is gravure printed on top of anode layer on the PET substrate.

- Poly-dihexylfluorene-alt-benzothiadiazol (PFBT), a yellow color emitting polymer layer is deposited onto the hole injection layer. The thickness of this layer is about 70 nm and is gravure printed on top of the PEDOT:PSS layer.

- An insulating layer is screen printed on the emissive layer in order to separate it from the cathode layer and to complement electron transport from the cathode layer.

- Aluminum is used as the cathode material and is rotary screen printed on top of the insulating layer. As the printed cathode material is sensitive to air when in liquid form, it is required to print the cathode layer in the inert atmosphere.

- Silver wiring is then rotary screen printed on top of the aluminium cathode layer.

- Finally, the OLED device is encapsulated with a barrier layer in order to protect it from moisture and oxygen. This is achieved by laminating the substrate with a barrier layer using a suitable adhesive.

3.2 Design of a Web Line for Patterning of ITO Anode Layer on PET Substrate

In this section, design of a web line for patterning of anode material on a PET substrate is discussed. The ITO deposited PET substrate is unwound from a roll and passed through the following series of operations to obtain a desired pattern of the anode on the substrate.

- An etch resistant material is rotary screen printed on the ITO-PET substrate on the areas where ITO pattern is required.
- It is then passed through an UV curing process where the etch resistant material is cured.
- The resulting substrate is then passed through an etching bath of aqueous cupric-chloride (CuCl2) in order to remove the ITO from the unprotected areas of the substrate.
- The web is then passed thorough a stripping bath of sodium hydroxide in order to remove the etch resistant material from the substrate, which will result in an ITO patterned substrate.
- Finally, the web is washed by passing through demineralized water and dried by passing through a section of hot air.

The following subsections provide detailed discussion of various available technologies used in the web line for ITO patterning, and the reasons for the selection of some technologies that are appropriate for RTR processing.

3.2.1 Screen Printing of Etch Resistant Material

Researchers have used flat bed screen printing machines to print etch resistant materials on top of the ITO layer [28]. This is not a continuous operation as it requires intermittent stopping of the web. Due to the use of flat bed screen printer, the web has to be wound after UV drying of etch resistant material on the web and cannot be passed directly for further processing. The reason for this is that further processing involves passing the web through various baths such as etching bath and stripping bath for which the web has to be passed continuously through them. In the web line proposed in this paper for ITO patterning, rotary screen printing is used in place of a flat bed screen printing machine in order to print the etch resistant material on the web. Rotary screen printing is a continuous process which would overcome the limitation of winding the web after UV drying of an etch resistant material on the web. After rotary screen printing and UV drying the web can be transported in a continuous manner through an etching bath. This would decrease the system downtime and increase the throughput of the process. There are also many other advantages of using rotary screen printing over flat bed screen printing machines which are described in the following.

There are mainly two types of screen printing techniques, flat bed screen printing and rotary screen printing. Flat bed screen printing is a solution printed deposition technique where ink is deposited onto the substrate thorough a screen attached to a frame. The screen is a woven mesh fitted onto a frame under tension. The pattern that needs to be obtained on the ITO layer of the substrate is defined on the screen by using specific emulsion coatings. These coatings fill the open areas of the screen where the ink deposition is not required. During printing, screen will be placed at a certain offset distance from the substrate. Ink is poured on the screen and is spread over the screen by using a squeegee. During printing, the screen is either deflected downward to make contact with the substrate by using sufficient pressure on the squeegee or ink is just passed onto the substrate through the screen without the screen making contact with the substrate. As the squeegee passes a given point on the screen, screen fabric tension moves the screen back leaving the ink on the substrate. The wet thickness of the film that can be obtained on the substrate thorough this process can be controlled by the volume defined between the threads of the screen and thickness of the emulsion coating. Usually rectangular screens are used for printing, but rotary screens in cylindrical shape are used in a rotary screen printer. The selection of the screen type depends on various factors such as viscosity of the ink and accuracy of pattern required, etc. Mesh size of a screen is measured by the number of threads of mesh per square inch. Mesh sizes selected for a particular screen depend on the application. It defines the detail of the image that needs to be printed and also the thickness of ink. As the mesh count increases, the threads and holes in the screen are finer. An image with a very high detail cannot be printed by using a lower mesh screen and also if the ink is thinner, it will easily pass through the screen holes which may result in a blurry image. Figure 3.1 shows an illustration of the flat bed screen printing process; please note that all the figures and tables for this chapter are shown at the end of the chapter. Currently available screen printing machines are capable of producing a screen print of 10-20 micron lines and spaces. Some of the key terms associated with screen printing are given in the following.

- Stroke: The stroke is defined as the one complete movement of the squeegee across the screen. Generally, there are two types of strokes involved in screen printing, namely, flood stroke and print stroke. Both these strokes have different purposes and are defined below.

    1. Flood Stroke: It is the first stroke and it spreads the ink across the screen and prepares it for the execution of the print stroke. The mesh opening will be filled with ink during this stroke. The squeegee cannot be moved

with a high pressure during this stroke when compared to the print stroke but sufficient pressure is applied to spread the ink across the screen.

2. Print Stroke: During this stroke the ink is forced through the mesh openings by the squeegee moving across the screen. A single movement of the squeegee across the screen is considered as one stroke. During this stroke, three important actions are performed. The mesh is brought down onto the surface of the substrate, then the squeegee moves across the substrate forcing the ink through it, and lastly, excess ink remaining on the screen will be carried away to the far end of the screen. When the squeegee applies pressure on the screen, it actually adds extra tension into the screen. Initially, the screen will be at some tension due to stretching of the screen as it is fitted into the frame, which is referred to as static tension. The additional tension caused by the squeegee pressure is called the dynamic tension. The mesh tries to resist this dynamic tension and tries to return to its original position which is an important factor in the working of screen printing. During printing, only the line of mesh underneath the squeegee comes in contact with the substrate at any point of time and as soon as the squeegee blade passes that point, the mesh recoils back to its original position due to its static tension. During the second part, squeegee forces the ink through the mesh by applying a force and finally as it moves through the screen, it also cuts any extra ink present above the mesh thread.

- Double Stroking: Sometimes, if the print is not good with the first pass, the squeegee is passed over the screen twice during the print stroke which is termed as double stroking. It does not necessarily improve the quality of the print but it will produce a thicker print.

- Squeegee Speed: There is no specific speed for the squeegee; it depends on factors such as ink viscosity, mesh count, substrate, screen tension, etc. One of the important criteria for determining squeegee speed is that there should be enough time for the ink to flow into the substrate. If the ink takes a longer time due to its viscosity, the print stroke has to be very slow.

In the case of rotary screen printing, the screen is in cylindrical shape with the squeegee on the inside of the rotating cylinder. This cylindrical shaped screen rotates in a fixed position unlike the flat bed screen printing machine, where it has to be raised and lowered during printing. As the web is passed through the rotary screen, ink is deposited on the web, based on the pattern defined on the screen. The screen rotates with the same speed as the web. Thus it is a faster process compared to flat bed screen printing. The substrate is moved at a constant speed between the rotary screen and an impression roller which is placed below the rotary screen. This impression roller may be made of rubber or steel, depending on the application, and it functions similar to the press bed in a flat bed screen printing. In rotary screen printing, the squeegee does not move but rather is fixed with its edge contacting the inside surface of a screen exactly at a point where the impression roller, rotary screen and the web make contact. The ink required for printing is fed automatically to the screen and gets collected into a well that is formed by the inner surface of the screen and the guiding side of the squeegee. As the screen rotates, this ink is forced through the openings of the stencil thus deluging the screen with ink. This ink is swerved by the squeegee onto the web as the screen and the web come into contact. The image is repeated for every revolution of the screen printer. The thickness of the layer printed is dependent on the size of mesh in the screen and amount of pressure applied by the squeegee. A thickness of about 20-100 μm can be obtained using rotary screen printing. Figures 3.2, and 3.3 show two illustrations of rotary screen printing, and Figure 3.4 shows the inside geometry and the support tube used in rotary screen printing.

Rotary screen printing has many advantages over flat bed screen printing. Both rotary and flat bed screen printing have the same basic operation of printing the ink onto the substrate by applying pressure using a squeegee. However, the major difference is that the flat bed screen printing is not continuous where as the rotary screen printing is a continuous process. The rotary system is similar to flat bed in the sense that it can be considered to be formed by sealing the two ends of the rectangular flat screen into a cylindrical roll. Flatbed screen printing requires two stages. In the first stage, ink will be spread over the mesh by passing the flood bar over the screen and in the second stage, squeegee will be passed such that it presses the mesh to come in contact with the web. In the case of a rotary screen printer, there is no flood bar and both flooding and printing of the ink comes under same continuous movement. The rotary screen print machine is more compact than the flat bed screen printing machine for printing a pattern with same number of colors. Even though flat bed screen printing machine is compatible with roll to roll manufacturing, it is more time consuming because stoppage of the substrate is needed after printing of each image as it requires time for the squeegee to move back.

In a screen printing operation, thickness and opaqueness of the film depends on many factors. A list of key factors is given below [31]:

1. Screen mesh: If the screen mesh is higher, the amount of ink deposited is less. But the thickness of the film does not depend only on the screen mesh but also on other factors.

2. Squeegee durometer and squeegee sharpness : If the squeegee is softer, it will yield thicker ink. If the squeegee is dull, it will result in thicker deposited film.

3. Squeegee angle and pressure: A sharper angle between the squeegee and the screen along with high pressure from the squeegee will result in thicker film

deposition.

4. Viscosity of the ink: The thickness of the deposited film increases with viscosity of the ink.

5. Squeegee position: The thickness of the film printed also depends on the position of the squeegee with respect to the print cylinder.

High speed screen printing operation may have an adverse affect on the surface finish of the cured film. As an example, if the web speed of 100 m/min is used, it might result in bubbling of the ink on the substrate, and if there is not enough time between the printing station and the curing unit, then optimum leveling of the film on the substrate may not be achieved. This will lead to a lower surface finish of the printed film on the substrate. Thus, it is important to optimize the speed of the web and the time between the printing and UV curing station during the screen printing process.

Rotary screen cylinders are usually made of nickel. The ink to be printed or coated is forced through the holes of the cylindrical screen. The cylindrical screen is driven and rotates at the same speed as the web. The flexible squeegee blade forms a converging geometry with the screen. This creates hydrodynamic pressure when the screen rotates which causes the liquid to flow through the screen. The web moves between the nip provided by the rotary screen and the backup roll. The backup roll is usually made of rubber. This type of rotary screen can be used to print various shapes, intricate detail or even print a continuous layer on the substrate. The squeegee is replaced by flexible blades made of stainless steel. This is due to the fact that it is easy to manipulate the blade angle using the blade instead of squeegee. This enables varying the pressure profile required for the ink passage and in turn will affect the print quality. The use of such metal blades also reduces friction and will provide for operation at higher speeds than that can be achieved by using rubber squeegees. The screen is maintained at a required tension by pneumatic means with the help of rotating wheels made of nylon and a system of arms. The screen can be easily removed for cleaning or replacement, and also if the photo emulsions are used, they can be easily washed away by pressurized water and the same screen can be used for printing different patterns. The coating thickness depends mainly on the five factors such as the screen permeability, location of the blade tip in relation to nip between the rotary screen and the backup roll, the force with which the blade is pressed against the screen surface, and web speed and properties of the liquid being printed [32]. The ink flows out of the screen based on liquid contact theory. Accordingly, as the screen rotates, hydrodynamic pressure is developed due to converging gap in the blade flow and there is ambient air outside the screen. This difference in pressure causes the liquid to ooze out through the holes of the rotary screen onto the substrate. The distance between blade tip and nip produced by the rotary screen and the backup roll is known as the tip-to-nip offset which primarily controls the average coating thickness during the screen printing operation. The loading of the blade is controlled using a blade mount. Instead of moving the blade perpendicular to the web, it is moved at an angle. This is done to maintain the tip position at the same point in relation to the roll-gap nip. The amount of force that the blade applies to the inner surface of the screen is known as blade loading. The blade loading is not measured but it is controlled by keeping the blade tip closer or farther from the screen which can be measured from a neutral position. The neutral position is the location of the blade tip when it just touches the inner surface of the screen. With higher blade loading, there is an increase in the average coating thickness [32]. This is because as the blade loading increases, it also increases and widens the pressure profile in the blade flow area. Under light loading of the blade, the blade flow gap widens which results in low pressure upstream of the blade tip such that the flow of ink through the screen is small. This will result in a thinner film. When higher blade loading is used, the blade gap flow is narrower which will result in higher pressure upstream of the blade tip such that the flow on ink through the screen is large. This will provide a thicker film. Rotary screen printing is a robust and reliable method as the thickness of the layer printed is consistent if the quantities such as squeegee pressure or angle are not changed during the printing process. Currently, the range of line widths that can be achieved with rotary screen printing is 50-100 μm. Since this method uses very little nip pressure, it a safer method to print multilayered structures.

After rotary screen printing of the etch resistant material onto the substrate, it is passed through an UV drying chamber in order to cure the printed etch resistant material. The following section describes the UV drying process.

3.2.2 Ultra Violet (UV) curing

Ultra-Violet light is a part of the electromagnetic spectrum with wavelengths between 200-400 nanometers. UV curing is a process where the wet film that is deposited on a substrate is solidified by exposing high energy radiation. Unlike conventional drying, UV curing involves a cross-linking reaction along with the evaporation of a solvent. It also results in superior physical properties than obtained using conventional drying. UV curing system gives good physical properties and solvent resistance to the cured film. It is a very fast process of curing and just takes a few seconds to dry a film. UV spot lamps or UV flood lamps can be used to cure the film depending on the application. The former one provides a high intensity UV light on a smaller area whereas the latter one provides moderate intensity UV light over a larger area. Mercury vapor lamps are the most common source of UV light used for UV curing processes and produces light either by passing electric current into a quartz containing mercury or by energizing mercury using microwaves. UV cured films will have a very smooth finish as a result of very fast curing. In the case of screen printing with conventional drying inks, the ink may dry on the screen itself which is always a problem. This happens due to the evaporation of the solvent present in the ink.

This requires frequent cleaning of the screen whenever there is a break in the printing process. In the case of UV curing inks, this problem does not occur and the screen need not be cleaned every time the press is stopped. Generally, screens are cleaned once a week when UV cured ink is used for screen printing. Labor is always a key factor in a printing press. If the conventional inks are used for screen printing, there are problems involved in racking and stacking of the prints whereas if the ink used is UV curable, as soon as it exits the curing unit, it can be either stacked up immediately or can be used for further processing without any waiting time. Thus, both labor and time is reduced in the case of screen printing operations with UV curing inks. Since, the UV curing system consumes less space, space savings can also be achieved by using UV curing system instead of conventional drying units or ovens. UV cured films are biodegradable and are environmentally safe. They provide very high curing speeds and web speeds of up to 100 m/min are possible. It generates less heat and therefore is suitable for heat sensitive substrates. As the film cures fast, the turnaround time is greatly increased. It is reported that the capital investment for UV-curing unit is substantially less compared to conventional drying unit and a complete installation of a UV curing setup does not involve more than one-half of that used for a conventional drying unit [31].

The curing speed depends on many factors. It depends not only on the curing unit but also on the color of the substrate color and the color of ink. If the substrate is white or light in color, it has the ability to reflect the unabsorbed UV light back onto the film. Thus the curing speed will be higher for the substrate which is white or light in color compared to black or dark colored substrate. Also, printing on transparent films with reflective support will increase the curing speed. It is know that ink cures faster with UV curing if it is red or yellow in color than black or white colored ink [31]. This is because of the low transmission of the UV light by pigments present in the white or black colored ink than the red or yellow ones. The curing speed depends on the following factors of an UV curing unit.

1. Intensity of the UV light: In order to double the curing speed, intensity of the light has to be increased by four times.

2. Number of UV sources: The curing speed is directly proportional to the number of UV lamps and the exposure time. As the exposure time is increased, the curing speed can be increased also. But the web speed is inversely proportional to the exposure time. Thus, the curing speed, web speed and number of UV lamps required for curing are interrelated. Lower web speeds for very fast curing UV inks will result in over curing of the ink which will affect the flexibility of the film layer, adhesion of coating, etc.

3. Temperature: Very high temperature during curing will cause problems, especially in the case of substrate made of paper and some of the plastic materials. These materials undergo change in their dimensional property when they are subjected to high temperature conditions. It is very crucial to maintain a low optimum curing temperature when using heat sensitive plastic substrates during an UV curing process. The temperature of the substrate can be controlled by using low powered UV lamps, by increasing the web speed or by using an UV unit with efficient cooling systems. But in the case of non-heat sensitive material substrate such as steel, thick plastics, glass etc., a higher temperature is beneficial. In such cases, higher temperature will increase the adhesion property and will also increase the curing speed of the ink.

4. Effect of inert atmosphere: During the UV curing process, the oxygen in air reacts with atoms that causes curing of the ink and thus inhibits the curing process. So, the presence of inert atmosphere during UV drying will overcome this problem. Nitrogen is generally used as the gas for maintaining inert atmosphere.

The UV curing process reduces air pollution and also reduces solvent vapor generation as compared to other thermal curing processes. Reducing solvent vapor generation saves a significant amount of energy. For the web line that is designed in this thesis, a pulsed UV curing device that cures the material on the substrate at low temperature is used. UV curing of a material can be done on a substrate using a pulsed UV curing device at a very low temperature and in a continuous manner. The process involves passing the substrate after screen printing the UV curable etch resistant material into the UV chamber where it is subjected to a high intensity pulsed UV light in order to cure the material on the substrate. When conventional UV curing devices are used, the process of curing is complicated because of high temperature involved with conventional UV curing devices. The conventional UV curing light sources such as mercury lamps operate at a high temperature of up to 1000^o C. Even though cooling equipments are associated with conventional light sources, a substantial amount of infrared heat is formed which will heat the substrate. Due to this heat, the pattern printed on the substrate may be damaged or distorted. It may even melt if the heat developed is higher. The UV curing device is placed soon after the screen printing device such that the web is pushed or pulled through the section of coating and curing by mechanical means without any contact of the pattered material on the mechanical support after printing until it is cured. Driven pull rollers are placed before the screen printing device and after the UV curing device such that the web continuously passes through these processes with a desired tension. Conveyor belts cannot be used due to the fact that screen printing operation is used for printing the etch resistant material and screen printing involves the use of impression roller along with the screen printer [33]. It is desirable to place the UV drying chamber close to the screen printing machine. This will avoid problems such as unwanted oxidation, evaporation or maturing of the uncured printed material. It is also better to keep the distance between the screen printed and UV drying machine within one meter.

The temperature is not increased much during this cold curing operation and is typically not more than 50^o C. The pulsed UV curing light is supplied to the substrate at the ambient temperature or at low temperature. There might be some heating involved in this process but it is exothermic heat which does not heat the substrate. Even cold inert gas may be supplied in order to lower the temperature within the curing chamber. The temperature of cold UV curing process may be between 10-33^o C. Even a temperature lower than the ambient temperature may be obtained during a cold UV curing operation [33]. Sometimes there might be a striping effect when passing a web continuously under a UV lamp. Striping effect involves partial cured and uncured sections of the material which needs to be cured after the web leaves the UV curing section. In order to avoid striping effect, the pulsed UV source should at least have a flash frequency of 10 pulses per second (pps). The flash frequency value of even 100 pps may also be desired. Multiple pulsed UV lamps within the UV chamber for curing may be also be desirable. Whenever more than one lamp is used, it is necessary to coordinate the pulsing of the lamps such that faster and better curing is obtained without any striping effect. The use of a cold UV curing device will result in better curing of the material on the substrate, as there is not much heat involved compared to the conventional UV lamps. Moreover, the substrate will not be subjected to any thermal stresses and also any problems such as discoloration that occurs due to the scorching of the plastic substrate is eliminated. Unlike conventional lamps, pulsed UV lamps do not require any warm up period prior to operation. This saves time and energy, especially when there is a break involved in the process such as for maintenance or any other operator breaks. With this process, the web may be transported at speeds between 20 to 90 m/min.

After the curing of etch resistant material, the web is passed through an etching bath of aqueous Cupric Chloride solution where the unprotected anode material present on the substrate is etched. The process of etching is described in the section below.

3.2.3 Etching

Etching is a process of having a liquid carrier called etchant into which an unwanted material from a substrate is dissolved by oxidizing it first. It involves the removal of a specific material from the web by using an etching material. The parts of the substrate where the material is needed are protected with an etch resistant material. The etch resistant material should not be marred or influenced by the etchant and vice versa. There are mainly two divisions of etch resistant materials: metallic resists that are based on pure metal and organic resists that are made of organic chemicals or mixture. The former is mainly used for etching the outer layers whereas the latter used for etching the inner layers. Etching can be done by different methods such as spraying, passing through an etching bath, etc. When etching any circuitry that involves close dimensional tolerances between the patterns, it is better to use an etching bath. For cupric chloride etching baths, the operating temperature is generally maintained at 44^o C or less. After etching, the substrate has to be rinsed with deionized water and dried before any further processing can take place. Materials can be etched by dry etching or wet etching. Generally wet etching is simpler, less costly and produces a high throughput compared to dry etching. The etching rate is generally calculated by dividing the thickness of the film by etch duration. During etching, the concentration of the etchant and temperature of the etching bath should be coordinated with web speed to ensure complete etching of unprotected areas of the web when it leaves the etching bath. The glass transition temperature of the PET substrate is about 69^o C. Therefore, it is safe to pass the PET web through an etching bath at temperature below 44^o C.

As the web exits the etching bath, it is moved to a rinsing bath where it is rinsed with deionized water. The web is then dried by passing it through a drying section consisting of hot air or any other drying method available can be used. After drying of the web, it is passed through a stripping bath where the etch resistant material, which was printed earlier to protect the anode material, is stripped from the substrate. Sodium hydroxide solution is used for the stripping bath. The next section gives an insight into the stripping of etch resistant material from the substrate. Wet etching is usually preferred when patterning the metal layer as etching will stop as soon as the substrate material is reached. Also, dry etching process uses high temperature and vacuum processing which makes it unsuitable for roll to roll manufacture of flexible electronics.

3.2.4 Stripping

Stripping is defined as the removal of etch resistant material from the web using a stripping liquid. Generally, sodium hydroxide is used as the stripping liquid. Similar to etching, stripping can also be done in many ways such as spray stripping, splash stripping, using a stripping bath, etc. The temperature of the stripping bath should always be maintained below 44^o C. It is always recommended to use a temperature of about 27-33^o C. It is ideal to thermostatically control the stripping bath. Immersion strippers involve chemicals to remove material by the process of dissolution where as the anodic strippers remove materials by a process of electrolysis. Immersion strippers are generally preferred over others as they can uniformly strip the complex parts, and easier to operate, and electricity is not required. After passing the web through the stripping bath, it is rinsed by passing it through a rinsing bath where it is rinsed by using demineralized water. It is then dried by passing it though a dryer. The dried web which consists of anode material patterned on it can be passed either directly to another coating section for coating of the next layer or it can be wound onto a roll.

Figure 3.5 shows a sketch of the web line that is proposed for RTR patterning of an ITO anode material onto a PET substrate. The ITO deposited PET substrate is unwound from an unwind roll and is passed through a displacement guiding system in order to maintain the lateral position of the web. It is then passed through an accumulator which helps in continuous supply of the web material to process sections during an unwind roll change. The web from an accumulator is passed over a master speed roller which sets the line speed and to the screen printing operation. The screen printing setup consists of a rotary screen printer which prints a layer of UV curable etch resistant material on those parts of the web where the ITO pattern is required. The pattern dimension such as width and space between the patterns depends on the specific application. During printing, the web material is passed between the rotary screen and an impression roller which will assist in providing the necessary pressure in obtaining the print on the web. The web is passed through a UV drying unit where the printed material is cured by UV lamps. The web is then passed through an etching bath of necessary acidic solution to remove the ITO material from the unprotected areas of the web. An aqueous solution of cupric chloride can be used to etch the ITO material. Rollers within the bath are used to enable transport of the web in the bath. Lateral movement of the web is expected in the bath as there is fluid flow in the etch bath. A web guide is used subsequent to the etch bath and prior to the rinsing bath. A discussion of how to transport the web through a liquid bath is given in [34]. Vacuum rollers can be used to pass the wet substrate and thus avoid the use of nip rollers. After rinsing of the web with water, it is passed through hot air drying and then to the stripping bath. The stripping bath consists of the solution necessary to strip off the etch resistant material from the top of the ITO layer. The most commonly used stripping agent is a solution of sodium hydroxide. The amount of time the web is within the etching and stripping baths depends on the web speed, concentration of the solution, and temperature of the bath. It is necessary to agitate the solution to expedite the process. After the stripping bath, it is passed through deionized water to rinse it such that no solution or etch resistant material remains on the web. After this, the web is passed into a hot air dryer via a displacement guide. The dried and patterned web is passed onto as accumulator from the dryer. The web from the accumulator is passed through displacement guide onto the rewind roll. The patterned ITO on PET can be transferred to the next section where it can be coated with necessary materials depending on the applications.

3.3 Design of a Web Line for Deposition of Active and Cathode Layers

In the first web line discussed in the previous section, patterning of the ITO anode layer on a PET substrate is accomplished. After the patterning of anode layer, other layers such as the hole injection layer (HIL), the active layer, the insulation layer, the cathode layer, and silver wiring need to be deposited on the anode layer. As mentioned previously, gravure printing is used to print the HIL layer and active layer where as rotary screen printing is used to print the insulation layer, cathode layer and silver wiring. The rotary screen printer similar to the one used in the printing of etch resistant material can be used to print these layers. The web line that is proposed for the deposition of these layers is shown in Figure 3.6 (page 102).

3.3.1 Gravure Printing

Gravure printing is a process where an etched cylinder is used to print ink onto a substrate. The excess ink present on the gravure cylinder is removed by a doctor blade before that part of cylinder makes contact with substrate. The main feature of gravure printing which distinguishes it from other printing techniques is the fact that the image to be printed is engraved on the cylinder surface. The cylinder surface is dipped in the ink before printing. The engraved cells on the surface of the cylinder are filled with ink that needs to be printed onto the substrate. Any excess ink or ink that is present on the non-engraved parts of the cylinder is wiped off using a doctor blade or a wiper. During printing, the cylinder rotates as the substrate moves.

During printing, the ink is transferred from the cells of the cylinder onto the substrate due to high printing pressure and an adhesive force developed between the ink and the substrate. Figure 3.7 illustrates the principle of gravure printing (page 102). As shown in the figure, the print cylinder rotates on the ink tank and as it does ink is filled into the engraved cells of the cylinder. Excess ink is removed by the doctor blade. The ink is printed on the substrate as it passes between the printing cylinder and the impression cylinder.

The screening surface of gravure printing is divided into two parts. One is the image containing part having the engraved cells and the other is the non-image part of the printing surface which is the cell walls. After the doctor blade swipes on the cylinder surfaces, ink should be present only in the engraved cells. The image is generally engraved on the print cylinder using an etching method. In the case of multi-color printing, the first gravure printed ink must be dried before passing the substrate for gravure printing of next ink. A good quality image can be obtained with the gravure printing technique. A web speed of about 5 m/min can be obtained with gravure printing and the print cylinder circumference can be between 800 - 1600 mm and a web width of about 2.40 m can be used during gravure printing [35]. Gravure printing cylinders are made of chrome-plated, copper-coated steel cylinders. The minimum value of line width that can be obtained with gravure printing is about 20-50 μm but with the advances being made in cylinder engraving, line widths are expected to be reduced to about 10 μm. As the gravure printing cylinders are made of solid metal, they are durable and are suitable for mass production. The problem associated with gravure printing is that as the doctor blade wipes off excess ink from the gravure cylinder, tiny particles may detach from it and fall into the ink bath which may contaminate the ink. If the doctor blade is made of metal, then these tiny metallic particles will degrade the layer performance. A non-metallic doctor blade could be used in the manufacture of electronic devices, as they do not have the same effect on the electrical performance of a printed layer as much as metallic particles. In gravure printing, the ink transfer can be improved by creating an electric field across the nip which lifts the ink from the vessel to make better contact with the web. This system is known as electrostatic assist (ESA). However this system cannot be used with metallic or conductive inks [29].

3.3.2 Drying Methods

After the deposition of ink for each of the layers such as HIL, active layer, cathode layer, the composite web must be dried before deposition of the next material. As the active materials are sensitive to UV, hot air drying method must be used to dry these layers. Typical drying temperatures that can be employed for these layers is in the range of 80-140^o C. The performance of the drying process can be improved by increasing web speed or drying temperature, but very low speed can lead to excessive ink spreading and high temperature can damage the plastic substrate. As discussed in [29], PEDOT:PSS ink that forms the HIL layer of an OLED device, needs a drying time of more than two minutes at a temperature of 140^o C which requires a longer drying chamber or slower web speed when the device is manufactured in roll to roll form.

3.3.3 Web Handling

As the web has to be transported on rollers through series of processes, handling of the web on rollers with appropriate transport speed and tension is very important. Appropriate handling of the composite web on rollers is critical to proper manufacturing and functioning of the device. As the web is passed through various processes like screen printing operation, UV curing, etching bath, stripping bath etc., various factors will influence the transport of the web. It is important to determine the factors that may cause tension and velocity variations and determine the steps to eliminate the causes of such variations. The following are some terms and phrases that are used in the web handling literature, which are required to understand the web line that is been proposed in this paper.

- **Web Span:** The free web between two adjacent rollers.

- **Roll:** A solid or hollow core onto which the material is wrapped.

- **Idle Roller:** A roller that is used to support the web material during transport. It is the cylinder over which the web is moved for transportation, coating and other processes.

- **Driven Roller:** A roller whose speed is controlled by a motor and is used to transport the material.

- **Winding:** It is the process of wrapping the web onto a core.

- **Unwinding:** It is the process of unwrapping the web from a roll.

- **Master speed roller:** A master speed roller is a driven roller which is responsible for setting the line speed. The velocity of this roller is set at a predefined value. Traditionally there is only one master speed roller in the entire web line. The velocities of the other driven rollers are set with respect to the velocity of the master speed roller in order to maintain the desired tension levels in the various spans of the web line.

- **Pull Rollers:** These are the driven rollers that help to maintain the tension forces of a web in a web line. There can be any number of pull rollers in the web line depending on the manufacturing process. There are different arrangements of the pull rollers. They can be nip rollers, s-wrap rollers, omega-rollers, and vacuum rollers.

- **Guide Rollers:** These are rollers that will help in guiding the web on rollers. Web guides are placed in sections of the web line where accurate lateral positioning is required. There are basically four different types of edge guiding systems. They are as follows:

  - **Unwind Sidelay Guide:** These guides help to maintain proper positioning of the web entering the machine from an unwind roller. These guides help to correct for lateral shifting of the web due to improper positioning of web in an unwind roll or due to problems like telescoping in the roll.

  - **Displacement Guide:** These are used to guide the web in sections of the web line where span lengths are shorter. The guide consists of two rollers as shown in Figure 3.8. It is also important to appropriately locate the entry and exit rollers to the guide in the line. The sensor in the displacement guide system must be placed at a location immediately downstream of the displacement guide between the last shifting roller and the subsequent non-shifting roller. It is recommended that the entry, exit and displacement spans must be greater than one web width. There are two kinds of layouts for a displacement guide system, U−shaped and Z−shaped.

  - **Steering guide:** This guide is used in sections of the web line where there are long free spans. It consists of single roller but the the additional three rollers adjacent to the guide roller determine the entry, pre entry and exit span, which must be located appropriately.

  - **Winder Sidelay Guide:** This is a chasing type guide as it helps in chasing the web position due to which the sensor used for this guide has a different purpose compared to the web edge displacement sensors used in the previous three guides.

- **Vacuum Rollers:** In the web line designed for ITO patterning, vacuum rollers are used for transport of the web downstream of the liquid baths. The use of nip rollers or S-wrap rollers to pull the web will affect the ITO material as the web is wet when it is transported out of the liquid baths. Vacuum rollers provide better functionality than nip or S-wrapped rollers by reducing web slippage over a roller and by providing greater operational safety. Thus, vacuum rollers assist in reducing the air entrainment effect in the wrap region. As shown in Figure 3.9, a vacuum roller consists of a rotating shell whose surface is designed to let the air pass through it and a specially designed pathway to evacuate air from the shell. There is a stationary tube at the center of the roller that helps in evacuating air. The area of web wrap around the roller is decided by the vacuum zone present in the roller. These rollers are often used to either pull the web or hold it back to provide good tension control.

- **Accumulator:** Accumulators are provided in both the web lines discussed previously to allow for both unwind and rewind roll change. In the first web line for patterning of ITO anode, there are liquid baths in the line and accumulators must be present in the line in order to ensure continuous movement of the web through the baths during roll change. In the second web line, there are various printing sections and drying chambers, and accumulators assist in maintaining the process speed to be constant through the print sections during unwind/rewind roll change. An accumulator is a combination of rollers on a carriage. They are used with unwinders or winders in order to complement zero-speed splicing of the web such that other processes such as coating, printing or drying are not interrupted during roll changes. Figure 3.10 gives an illustration of an accumulator.

- **Cooling rollers:** In order to cool the web after transporting through heating and drying sections, the web is generally transported over chilled rollers. A chilled roller will have an outer chrome plated surface inside of which cold water or a coolant is passed in order to cool the outer surface. The web passing over a cooling roller will be cooled only in the contact area of the web with the roller. Construction of a typical rotary cooling roller is described in [36]. A rotary cooling roller is made of two inner and outer cylinders as shown in Figure 3.11. The two end plates are connected to the outer cylinder on both ends. An inner supporting shaft protrudes from the end plates. There is a cylindrical space between the inner and outer cylinder and through holes are provided in the inner space of the inner cylinder. The coolant is passed in the inner space of the inner cylinder and also flows in the cylindrical space. A volatile working liquid is contained in the outer cylinder and cooling tubes are provided for the circulation of the coolant. Spacers are provided in the cylindrical space between the outer and inner cylinders. This helps to transfer the external pressure exerted on the outer cylinder by the web to the inner cylinder. This type of arrangement helps in keeping very low thickness for the outer cylinder as it will be supported by the inner cylinder.

3.3.4 Determination of Web Tension and Speed in the Two Web Lines

Web Line for ITO patterning

The main objective of web handling is to transport the web with tensions that result in strains which are below the elastic limit so that there is no damage to the web. When choosing a reference tension value for the web line for ITO patterning, it is recommended that web tension be set at a level of 10 to 20 percent of the web's ultimate tensile strength which results in safety factors of 10:1 to 5:1. It is important to control web tension as it is directly related to problems such as web wrinkles, slack regions, web breaking or deformation, unwanted displacement of the web, etc. In the web line for patterning of the ITO anode, the thickness of the anode layer deposited on the PET substrate is small compared to the thickness of the substrate and does not add much stiffness to the substrate. Thus, in order to determine the tension with which the web can be run in these web lines, the ultimate tensile strength of PET web which is about 55 MPa [37] needs to be considered. The value of ten percent ultimate tensile strength of the web is 5.5 MPa. If we consider a substrate width of 280 mm and the thickness of the substrate to be around 130 μm, the value of tension of the web that needs to be maintained considering a safe limit of ten percent ultimate tensile strength of the web is 200 N. It is reported in the literature that such a PET substrate can be transported with a tension in the range of $125 - 376$ N [38]. The calculated value for web tension is within this suggested range.

In this line, the web has to pass through various processes such as screen printing, UV curing, various liquid baths, etc. As the web passes through UV curing and etching baths, the temperature of the baths and the chamber is limited by the material properties of the web. Since the web is a plastic substrate, the temperature of these processes has to be selected appropriately. The web speed must be chosen appropriately considering all the factors that influence the various processes in the web line. The web speed in this line can be in the range between 20 m/min to 50 m/min and very high speed is not preferred as enough time should be given for the web to dry in the UV chamber before it is transported to liquid baths. If the web speed is very high, etch resistant material may not dry well in the UV chamber. It may also lead to improper etching and stripping in the baths. Thus, web speed must be carefully chosen to obtain accurate patterning which would result in a better final product.

Web Line for Active and Cathode Layers

In this web line, the HIL and active layers are deposited followed by the deposition of insulation layer, silver wiring and the cathode layer. As the thickness of these layers is small compared to the thickness of the plastic substrate, the tension with which it should be run during this deposition is same as the tension of the web to be maintained during the first web line. The thickness of the aluminum layer is significant when compared to the thickness of the substrate. After the deposition of the aluminum cathode layer, the PET substrate is wound before it is laminated with the barrier material. Deposition of the cathode layer will change the modulus of the composite web by a significant amount. Thus, the tension with which the web has to be run for lamination of the barrier layers needs to be different.

Table 3.1 shows typical values for various parameters involved in rotary screen printing, gravure printing and ink jet printing technologies [27]. However, for flexible electronics, printing speeds are lower compared to the ones given in the table due to the limitations in the properties of inks used for the layers. There is ongoing research to optimize the ink quality used in the manufacture of flexible electronic devices. PEDOT:PSS ink does not dry fast and requires a longer drying chamber which restricts the speed of the web line.

3.3.5 Encapsulation of Barrier Layer

As discussed earlier, OLED devices require protection against moisture and oxygen intrusion which would degrade their performance and also reduce their lifetime. For achieving longer lifetimes from OLED based devices, the values for oxygen and moisture permeability must be less than 10^{-3} cc/m^2/day and 10^{-6} g/m^2/day, respectively [39]. A number of methods have been considered for encapsulation of the flexible OLED devices. One such method is by using a barrier layer of inorganic materials which is coated to the flexible polymer substrates using vacuum deposition methods. These inorganic layers are made of oxides, nitrides or carbides and are impermeable to moisture and oxygen diffusion. The main reason for this is that the polymeric substrate by itself is inherently porous and has high permeability level for oxygen and moisture. Researchers have considered the possibility that even with the coating of an inorganic barrier layer to polymeric substrate, the required criteria of minimum permeability levels may not be met for OLED devices. This may be due to intrinsic holes created during the deposition process or impurities contained during the vacuum chamber or those present in the substrate itself. In the case of rigid OLEDs, encapsulation of the device is made by using a glass or metal lid which provides a hermetic protection against water and moisture [40]. They cannot be used as encapsulation layer for flexible OLEDs because of their rigidity, thickness and heavy nature.

Encapsulation can be made by many methods such as lamination, coating or any other vacuum deposition methods. Lamination method is preferred as it can be easily performed using roll to roll form of manufacturing, which will reduce the overall cost and also results in the manufacturing of flexible devices. Lamination can be done using different methods such as adhesive lamination, extrusion coating, etc. In the following section, different methods of lamination will be discussed briefly.

Adhesive lamination can be achieved by dry bonding, wet bonding, UV/EB curing and by a hot melt adhesion process. In the extrusion method, two dissimilar materials such as polymer film, paper or foil are bonded together by using a thin layer of plastic material. Several polymers layers can be extruded simultaneously followed by pressing or cooling them together which results in co-extruded materials. In the case of incompatible layers, thermoplastic adhesive is used as a tie layer for laminating them together. Table 3.2 (page 106) provides a comparison between mainstream lamination and coating process [41].

Adhesive lamination is the bonding of two or more substrates with the help of adhesives. Adhesive lamination can be performed using different methods depending on the type of adhesive or method of application of adhesive. It is a preferred method of lamination when the substrates cannot be laminated using the co-extrusion process.

A co-extrusion process may thermally damage the substrate. Table 3.3 (page 107) provides an insight into different types of adhesive lamination [41].

Extrusion is a process of coating and lamination where a resin is formed into a hot film by melting which is coated onto a substrate. Complete contact is obtained by passing this coated substrate along with the other substrate to be laminated between counter rotating heated rolls. The coating is used as an adhesive layer between number of substrates. The second substrate is laminated onto the first coated substrate when the extrusion coating is still hot which are pressed together using the pressure rolls. This extruded layer also acts as a moisture barrier layer.

Similar to the lamination of the solar cells, the composite web produced for OLED devices has to be laminated on both sides with a barrier layer with the help of an adhesive. Researches are studying the suitability of barrier materials, adhesives and methods of encapsulation to an OLED device that would provide a longer life time to the device with efficient barrier property to oxygen and moisture. The adhesive material should have faster curing and very low curing temperatures to avoid any damage to the OLED device. The adhesive layer can be either patterned or deposited as a continuous layer on top of the cathode. Typical layer thickness of the adhesive layer must be about $2-20$ μm in order to provide firm sealing of the barrier layer. Rotary screen printing method would be the most suitable method for the deposition of the adhesive layer as it requires the deposition of a thick layer with high viscosity inks under low nip pressure.

The lamination of barrier layer to both sides of an OLED device has to be done using a nip, but the rollers must not be heated as they will affect the already deposited layers of the device. UV drying of adhesive cannot be done as high temperature might damage the active layer. In the next chapter, a web line for lamination of barrier material to a solar cell substrate is designed. Lamination is done at room temperature using pressure sensitive adhesive which is highly suitable for the encapsulation of electronic devices as no heat or higher temperatures are involved. The same web line can be used for the lamination of barrier material to the OLED device and other flexible electronic devices. However, the barrier material used and the parameters used for lamination would be different as they depend on the material properties.

3.3.6 Registration

Registration is the ability with which multiple layers can be printed on top of each other on a substrate. It is defined as the process of obtaining accurate alignment of successful print patterns on the web substrate. In the case of flexible electronics, few of the layers may be patterned and during the deposition of successive layers on top of the patterned layers, it is very important that the registration is properly maintained. There are many ways to obtain registration of subsequent patterns. The selection of an appropriate method depends on the accuracy needed with regards to the cost of the equipment. Registration in the machine direction is defined as the relative difference in distance between the two successive printed patterns. It measures the superposition of accuracy of each ink when inks for multiple layers are printed in succession. In the case of flexible electronics, very high accuracy is needed in the alignment of successive layers when inks for the layers are printed in the web line. In order to maintain good registration accuracy, registration errors must be automatically controlled during the printing of successive layers.

If the tension is maintained at a constant desired value in the web span between two successive printing units, one can expect no registration error. However, in practical situations there may be several factors such as strain induced web elongation, mechanically induced disturbances, variations in print cylinder velocities which would lead to a registration error. Thus, active control of registration error is a must when printing multiple layers in a web line.

After the patterning of an ITO anode on PET substrate in the first web line, active layers are deposited on it in the second web line. In the second web line where there is deposition of layers such as HIL, emission layer followed by screen printing of subsequent layers, high quality registration is required in the longitudinal direction in order to obtain a quality product. In [42], methods for obtaining accurate registration by using a registration compensator roller are described. The same method can be used in the second web line for maintaining registration when the different layers are printed on the substrate. In the second web line, as the inks are deposited to form the different layers of the electronic component, it is necessary to align them accurately in order to obtain a quality device. Gravure printing of the HIL layer is followed by gravure printing of the emission layer. Gravure printing of the emissive layer must be aligned with respect to the HIL layer. This can be achieved by using a compensator roll as mentioned in [42]. During the gravure printing of HIL layer, a registration flag is printed along the edge of the web. It is followed by the printing of the emissive layer. In order to obtain accurate alignment of the emissive layer with the HIL layer, the length of the web between two gravure printing units must be an integral multiple of circumference of the first gravure cylinder. This is true when both the print cylinders are suitably aligned. As the substrate is elastic, there will be an elongation of web which would result in stretching of the printed layer. This will cause mis-registration which will require active registration control in order to obtain good quality print of the layers.

As discussed in [42], registration control can be achieved by using a compensator roll. A compensator roll is provided in the web path between the two printing units. A registration flag is printed during the gravure printing of emission layer too along the edge of the web at a proper location. A registration error sensor is placed in the web line soon after the second printing unit. This sensor measures the distance between the flags that were printed by the two successive printing units. Depending on the registration error measured by the sensor, the compensator roll is moved up or down in order to vary the web path length between the two successive printing units. The compensator roll is thus used to ensure proper registration. A motor is used to provide necessary linear motion to the compensator roll depending on the signal from the registration sensor. This method of obtaining registration using the compensator roll is also used during the printing of successive layers in the second web line.

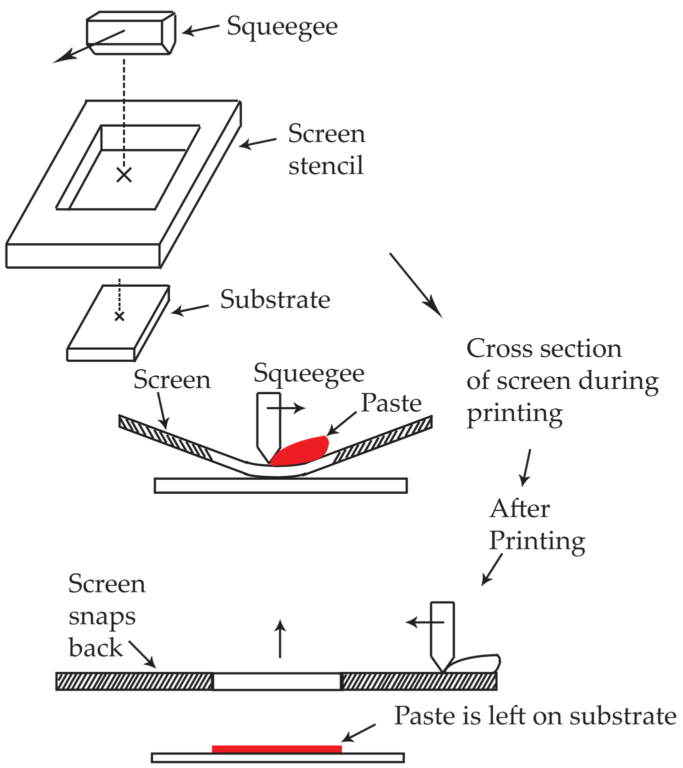


Figure 3.1: Flat Bed Screen Printing

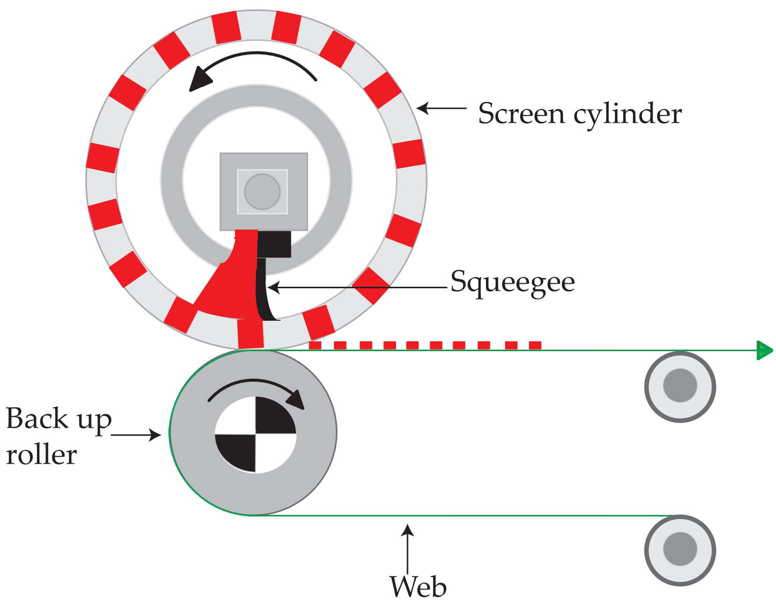


Figure 3.2: Rotary Screen Printing [43]

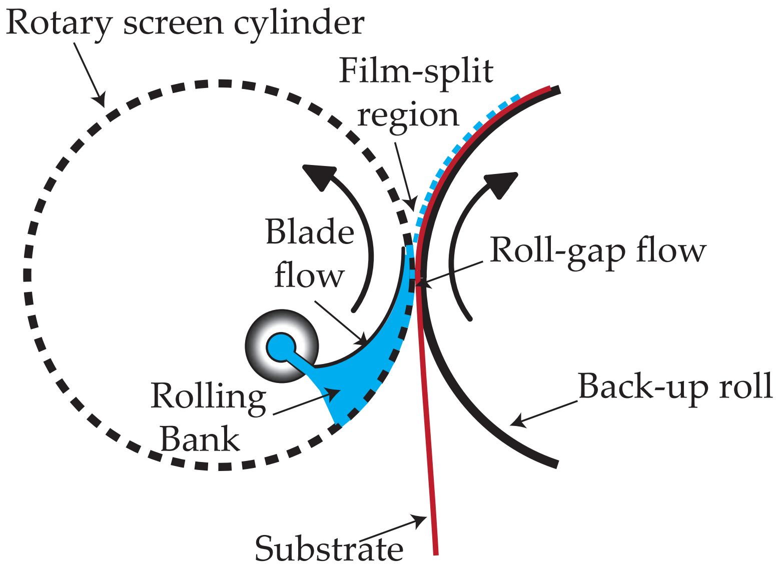


Figure 3.3: Rotary Screen Printing [32]

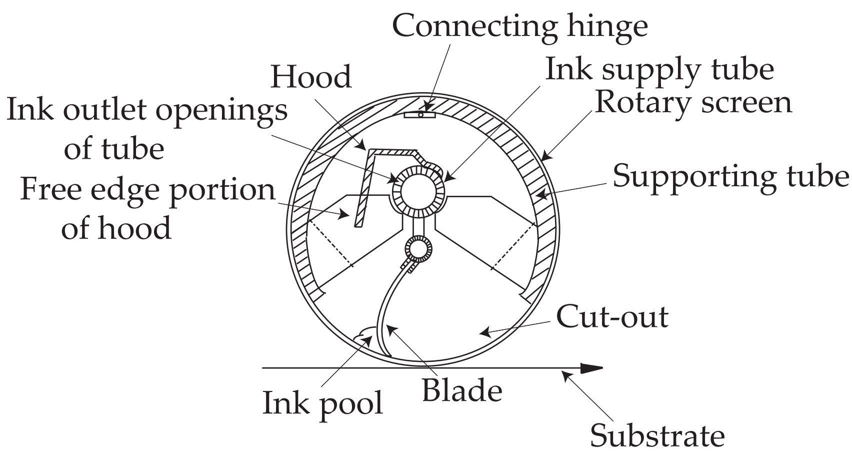


Figure 3.4: Support Tube for Rotary Screen Printing [44]

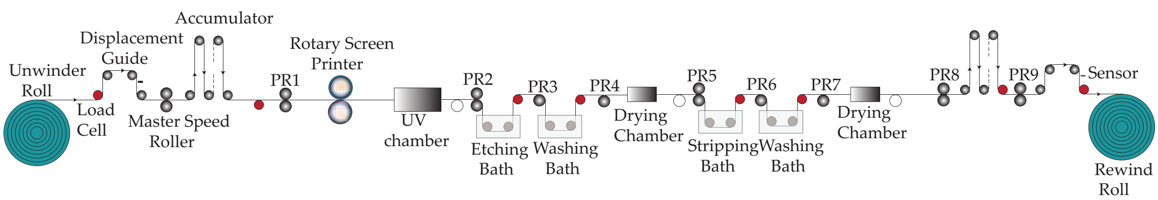


Figure 3.5: Web Line for Patterning ITO

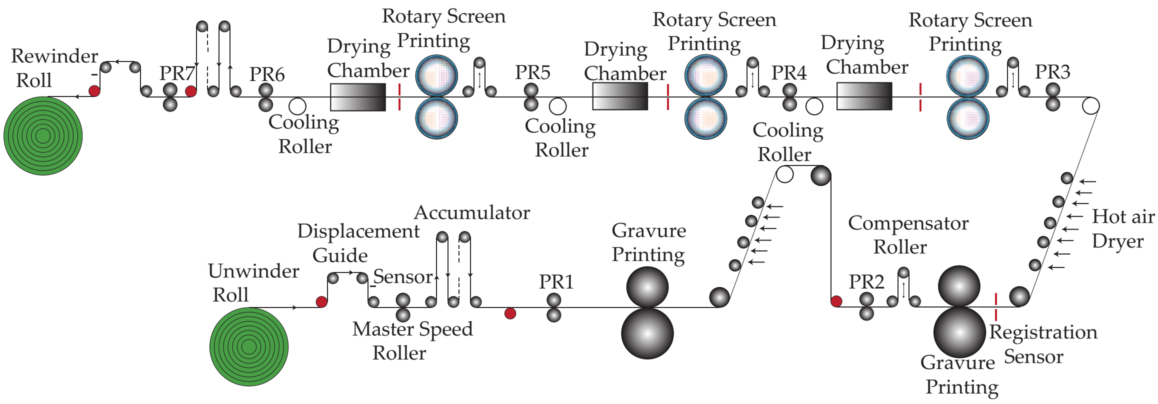


Figure 3.6: Web Line for Deposition of Active Layers and Cathode

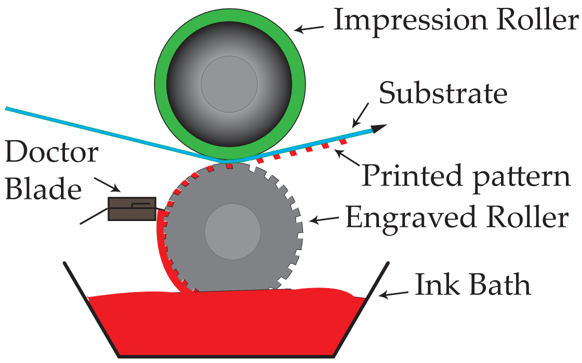


Figure 3.7: Gravure Printing [45]

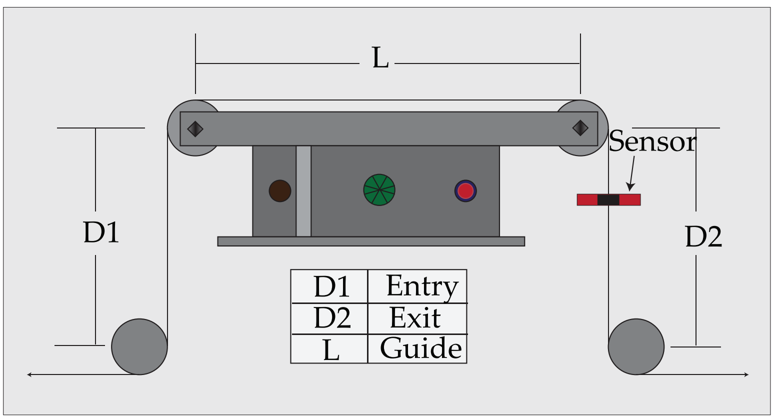


Figure 3.8: Displacement Guide [46]

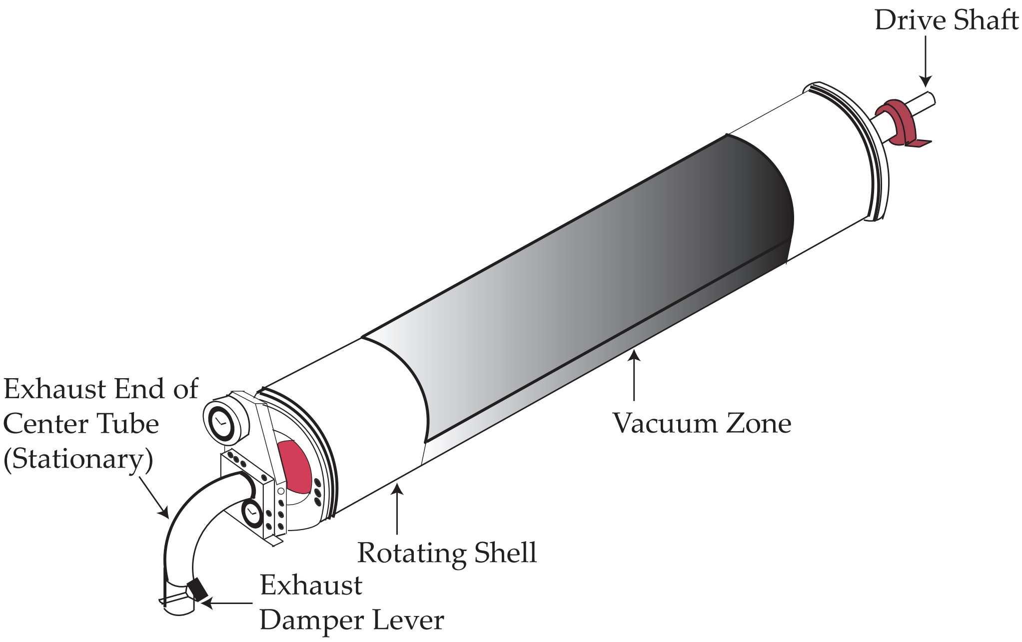


Figure 3.9: Vacuum Rollers [47]

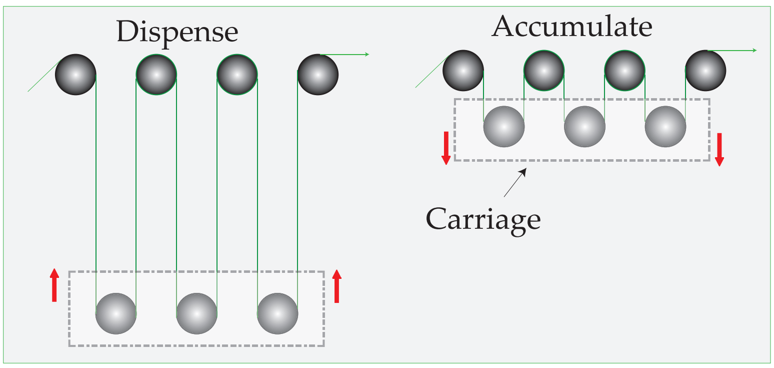


Figure 3.10: Accumulator [48]

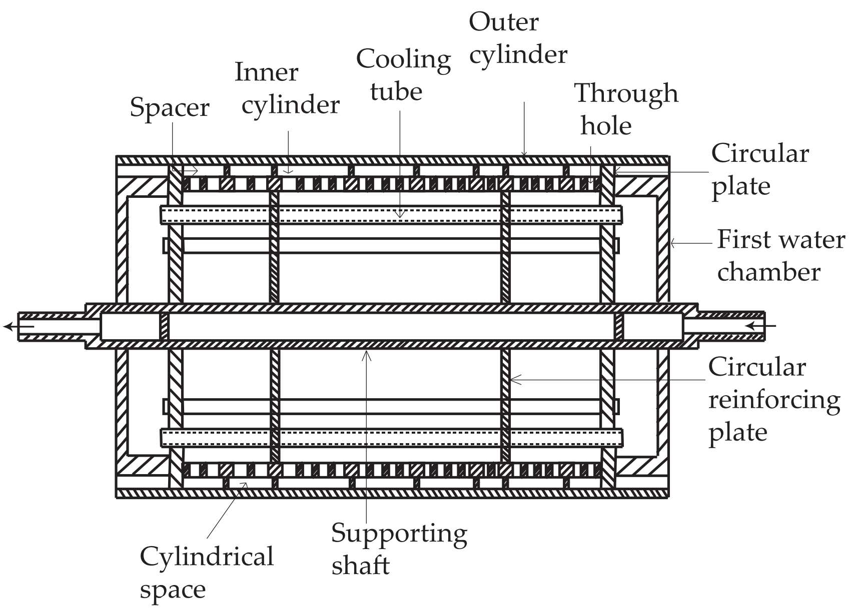


Figure 3.11: Cooling Roller [36]

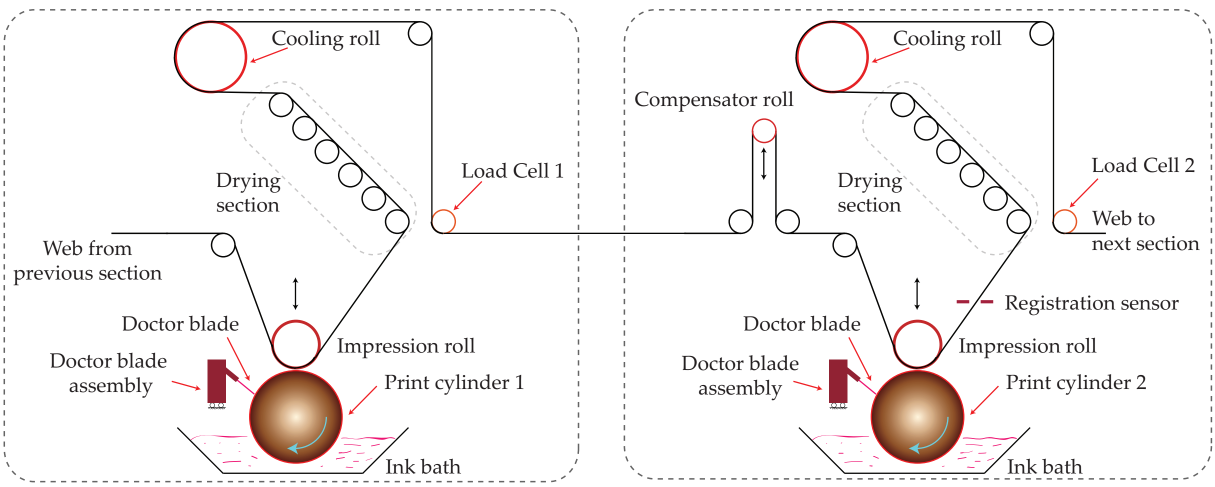


Figure 3.12: Schematic of Two Successive Print Units with Compensator Roller [42]

Table 3.1: Typical values for printing parameters

Method	**Minimum line width** (μ**m**)	**Ink viscosity** ($Pa.s$)	**Ink layer thickness** (μ**m**)	**Printing Speed (m/min)**	**Nip pressure (MPa)**	**Start up cost for a new job**
Rotary Screen	50−100	1−700	1−100	120	very low	High but the screen is not expensive compared to gravure cylinder
Gravure	10−50	0.01−0.20	0.02−12	600−960	1.5−5	High
Ink jet	10−50	0.001−0.03	0.01−0.5	60−300	−	Low but expensive ink cartridge/print heads

Table 3.2: Comparison of mainstream lamination and coating processes

Advantages	**Disadvantages**
Hot Roll Lamination	
Applies to a wide variety of films	Speed of operation is medium
Low capital costs	Possibility of printing deformation during lamination
Low energy consumption	
Ability to apply thin skins	
Superior graphics	
Simple technology	
Low energy consumption	
Extrusion Coating	
Raw materials are inexpensive	Poor gauge control
Improved structural stability	High capital costs
Ability to apply thin skins	Less flexibility in coating type
	High energy consumption
Adhesive Lamination	
High speed operation	High capital costs
Applies to a wide variety of films	Energy consumption is medium
Ability to apply thin skins	Adhesives are needed to bond films
Quality print registration is possible	

Table 3.3: Comparison between wet and dry adhesive lamination

	Process	**Description**	**Application Equipment**
Dry Processes	**Dry Bond Laminating**	Liquid adhesive coated on substrate, dried with heat/air flow, and laminated to a second substrate via heated compression nip	Gravure application cylinder
Dry Processes	**Hot Melt Seal Coating**	Low viscosity hot melt adhesives are applied to substrate	Heated rotogravure cylinder, extruder
Dry Processes	**Cold Seal**	Liquid Adhesive applied, dried with heat/air and bonded with slight pressure so tack to non-cold seal surface is minimized	Gravure application cylinder
Wet Processes	**Wet Bonding Laminating**	Liquid Adhesive applied to substrate, then immediately laminated to a second substrate via nip, followed by drying with heat/air flow (one surface must be porous to allow evaporation of water or solvent)	Gravure cylinder or smoother roll
Wet Processes	**Solventless Laminating**	Adhesive is metered onto substrate in liquid form, then mated to a second substrate via heated nip	Multiple application roll configurations

CHAPTER 4

Modeling and Simulation of Web Lines Designed for Manufacture of Flexible Electronic Devices

4.1 Introduction

In the first section of this chapter, drag force generated as the web is transported in a liquid bath is calculated. In the second section, tension and velocity dynamic models for the web line for patterning of the anode layer on flexible substrate are formulated and simulations are conducted to regulate web tension and web velocity during its transport from the unwind roll to the rewind roll. In the third section, a web line for simultaneous lamination of barrier substrate to the substrate of the flexible electronic device is designed. Also, a web line is designed for the lamination of adhesive material to the barrier substrate. In the fourth section, a model for web tension for lamination of two webs is investigated and simulations are done to regulate web tension and web velocity across various spans and rollers for the web line designed for lamination of encapsulation layers.

4.1.1 Calculation of Drag Force on the Web During Transport Through a Liquid Bath

In RTR manufacturing of flexible panel devices, the substrate is passed through various processes such as printing, coating, etching, stripping, washing bath, etc. Web tension and web velocity need to be controlled precisely when transporting the web through these processes in a web line. When the web is passed through a liquid bath for operations such as etching, stripping, washing and rinsing, the tension and movement of the web will be affected by fluid movement in the bath. In this section, effect of fluid drag on web tension is studied.

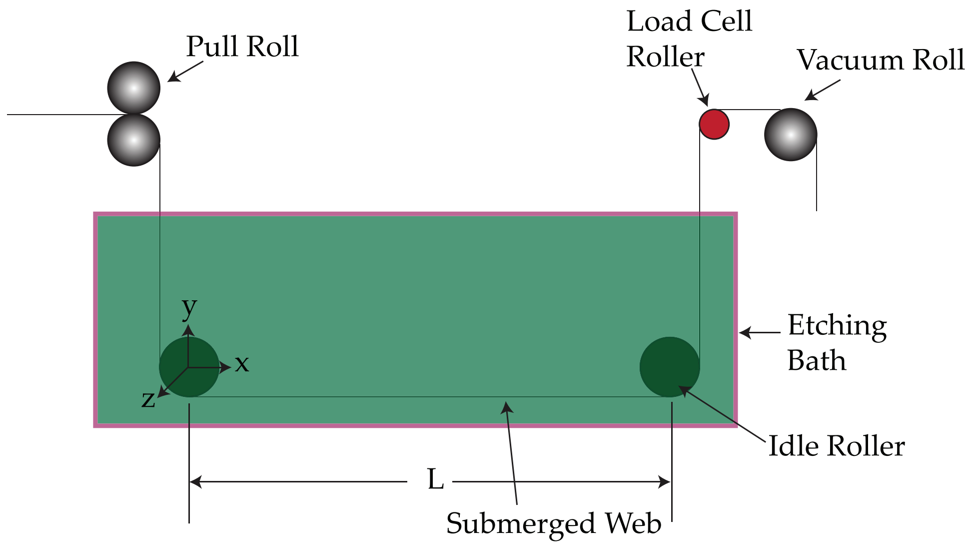


Figure 4.1: Liquid Bath

Etching is a process where unwanted materials are removed from the surface of a substrate using liquid chemicals termed as etchant. Etching can be done by passing the web material through an etching bath having chemical etchant in it. The rate of etching depends on the concentration of etchant, temperature of etchant, speed of movement of the web through an etching bath, amount of time the web remains in the bath, etc. Etching will be better if there is uniform movement of fluid in the bath [49]. Uniform laminar motion of the etching fluid across the web movement is preferred for controlled uniform etching of unwanted materials from the substrate. With the use of web handling technology, etching of a web by passing the web through an etching bath can be done in a continuous manner. The goal is to remove unwanted materials from the surface of the substrate by an etchant so that the required anode pattern is obtained on the web as it comes out of the etching bath. Tension and velocity of the web should be maintained properly in order for the accurate movement of web through the bath which results in better etching of the web. Any factors causing the variation in tension and velocity should be eliminated. If the parameters that cause tension variation or affect the velocity of the web cannot be eliminated, then compensation should be provided for such variations.

As the web moves through the fluid, it will experience a drag force in opposition of the movement of the web. This drag force is mainly due to shear stress caused due to the viscosity of the etchant fluid. The drag force will oppose the free movement of the web through the etching bath which might affect web tension. The web can be passed through the liquid bath with the use of rollers [50]. Idle rollers can be placed inside the liquid bath for guiding the web through it and web is transported into the bath with the help of a driven roller. Web tension is maintained by using driven rollers before and after the bath and using suitable tension control systems in either or both the driven rollers. While considering the tension of the web, effect of drag force on the tension must be calculated. Based on the drag force calculation, suitable changes can be made to the governing equation for tension in a web span to account for fluid drag forces. Over the years, many researchers have studied the effect of fluid movement on a moving wall. This research has focused on the movement of the fluid to be either in the direction of the moving wall or opposite to the direction of the moving wall. In the year 1997, P.D. Weidman [51] formulated the shear stress on the moving wall by laminar fluid flow in the cross flow direction. All the problems with respect to moving wall in the fluid are considered to be boundary value problems and solution was found using Blasius similarity variable conditions.

4.1.2 Drag Force Calculation

Consider the Cartesian coordinates (x,y,z) as shown in the Figure 4.1. Let the web be moving in the direction of x-axis and let the span wise fluid flow be in the z-direction and y be the direction normal to both these axes. Let u, v, w be the components of velocity in the x, y and z directions respectively. In this problem formulation, fluid density and viscosity of the fluid are assumed to be constant. It is assumed that there is uniform steady flow in the cross wise direction. It is assumed that all flows are of infinite extent in the z-direction and thus fully developed. It is also assumed that the pressure gradient in the web direction and in the crosswise direction are zero. Therefore the Navier Stoke equations can be written as follows [51]:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{4.1}$$

$$u\frac{\partial u}{\partial x} + v\frac{\partial v}{\partial y} = \nu\frac{\partial^2 u}{\partial y^2} \tag{4.2}$$

$$u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y} = \nu\frac{\partial^2 w}{\partial y^2} \tag{4.3}$$

Application of Blasius similarity form gives the following similarity conditions:

$$\psi(x, y) = \sqrt{2\nu U_0 x} f(\eta) \tag{4.4}$$

$$\eta = \sqrt{\frac{U_0}{2\nu x}} y \tag{4.5}$$

The similarity function f(η) is found by solving the Blasius boundary value problem which satisfies the following differential equation:

$$f''' + ff'' = 0 \tag{4.6}$$

$$f(0) = 0 \tag{4.7}$$

$$f'(0) = \lambda \tag{4.8}$$

$$f'(\eta \to \infty) = 1 \tag{4.9}$$

When there is uniform cross flow above the moving web, the similarity form can be given as follows [51]:

$$s'' + fs' = 0 \tag{4.10}$$

$$s(0) = 0 \tag{4.11}$$

$$s(\eta \to \infty) = 1 \tag{4.12}$$

The shear stress for a fluid flowing in the span wise direction to the moving plate can be calculated using the following equation [51].

$$\tau = \varrho\sqrt{\frac{\nu U_0}{2x}}[U_0 f''(0)i + W_0 s'(0)k] \tag{4.13}$$

In the above equation, the first term on the right hand side gives the component of shear stress in the x-direction and second term on the right hand side equation gives the component of shear stress in the z direction. So, it is the component in the x-direction that opposes the motion of the web through the bath. The drag force can be calculated by substituting the value of shear stress obtained using (4.13) in the equation (4.14).

$$F_d = W\int_0^L \tau(x)dx \tag{4.14}$$

where the integration is from $x = 0$ to $x = L$. This drag force acts in the direction opposite to web motion and opposes the motion of web through the bath. In the liquid bath, since there is no fluid movement in the x-direction,

$$\lambda = \frac{U_\infty}{U_w} = 0 \tag{4.15}$$

Assuming that there is negligible fluid motion in the direction of the web movement results in

$$U_0 = U_w + U_\infty = U_w \tag{4.16}$$

The value of $f''(0)$ and $s'(0)$ in the equation (4.13) for calculating the shear stress value can be found by solving the Blasius boundary value equations which are given by (4.6) and (4.10). To solve the equation (4.6) which is of third order, only two initial and one final boundary conditions are given. Since it is difficult to use the final boundary condition to solve this equation, a random initial value for $f''(0)$ is assumed and a shooting method is used to find a suitable value that would fit $f''(0)$ which would satisfy the final condition given by the equation (4.9). Similarly, even the value for $s'(0)$ is calculated such that it satisfies the boundary condition given in the equation (4.12).

For solving the above equations, density and viscosity of the solution must be calculated. Table 4.1 provides the preferred solution composition when etching with cupric chloride solution [52].

Table 4.1: Composition of Cupric Chloride Solution

Component Name	**Mass**
Cupric Chloride solid	200 g
Hydrochloric acid	100 g
Water	1000 mL

Viscosity and density for such a mixture is calculated using the following equations [53, 54]:

$$\rho_X = \frac{1}{m_{fH_2O}V_{H_2O} + \sum m_{fi}V_i} \tag{4.17}$$

$$V_i = \frac{m_{fi} + p_2 + p_3 T}{(p_0 w_i + p_1)e^{(0.000001(T+p_4)^2)}} \tag{4.18}$$

$$\eta_i = exp\left[\frac{k_1(1-m_{fW})^{k_2} + k_3}{(k_4 T + 1)(k_5(1-m_{fW})^{k_6} + 1)}\right] \tag{4.19}$$

$$\eta_W = \frac{T + 246}{(0.055594T + 5.2842)T + 137.37} \tag{4.20}$$

Using the above equations, the calculated density of the cupric chloride solution is 1057.964 kg/m^3 and the viscosity of the solution is 6.42×10^{-7} m^2/s. If the solution is assumed to be moving in laminar flow in the crosswise direction to the web at a speed of 3 m/min, for a web moving at a speed of 25 m/min, the value of drag force in the web direction is calculated to be 0.0589 N, and in the transverse direction, the drag force value is calculated to be 0.0071 N. The drag force value calculated is substantially small compared to the reference web tension, and thus has very little effect on the behavior of the web. The same condition applies when it is passed through other liquid baths as laminar movement of fluid in the crosswise direction is preferred.

4.2 Modeling and Simulation of the Web Line for Patterning of the Anode Layer on PET Substrate

The web line is a dynamic system with various control zones to control the movement of the web as it passes thorough different process sections. In the simulation of the web line, a speed-based tension control system is employed. This type of control strategy involves a two loop system in which the tension measuring device such as load cells provide the tension feedback based on which the outer tension loop provides correction to the inside velocity loop.

In the previous chapter, a web line for patterning of ITO anode layer on a PET substrate is designed. In this section, tension and velocity dynamic models are formulated for the same line and simulations are conducted to regulate web tension and velocity as it passes through various sections for patterning of anode material.

The designed web line consists of an unwind roll, unwind/rewind accumulators, several web spans supported by driven/idle rollers, screen printer, UV chamber, cooling rolls, various liquid baths, drying chambers, etc. It is very important to control the tension of the web as it is transported from the unwind to the rewind section having various process sections between them. Thus, it is necessary to control the speed of the unwind roller, rewind roller and all the driven rollers of the web line so that the tension and velocity of the web will be maintained at the necessary reference values. Except for one of the driven rollers which is termed as the master speed roller, all the other driven rollers are used to regulate both web velocity and web tension in their respective spans. The master speed roller is used to regulate web velocity only, and effectively sets the line speed. The motor controller used for driving the master speed roller uses only velocity feedback whereas the motor controllers for driving all the other driven rollers use tension feedback as well as velocity feedback. Figure 4.2 shows the control scheme used for controlling web tension and web velocity. As shown in the figure, the control scheme consist of two loops i.e., outer tension loop and inner velocity loop. Each of the loop has a controller and tension measured by the tension sensor such as load cells in the span is used as feedback for the outer loop such that it provides velocity reference correction to the inner velocity loop. For simulations in this thesis, PI controllers are used. Each of the driven rollers along with the unwind and rewind roller except the master speed roller are provided with two PI controllers for the motors that drive them. The motor for driving the master speed roller has only one PI controller as it regulates web velocity only. For simulation purposes, dynamic models have been developed considering that a tension zone is between two consecutive driven rollers. Dynamic models have been developed for this web line excluding the idler rollers. For the web line, the master speed roller sets the web reference velocity whereas the unwind motor sets the web tension. The control strategy used in the simulation is shown in the Figure 4.2.

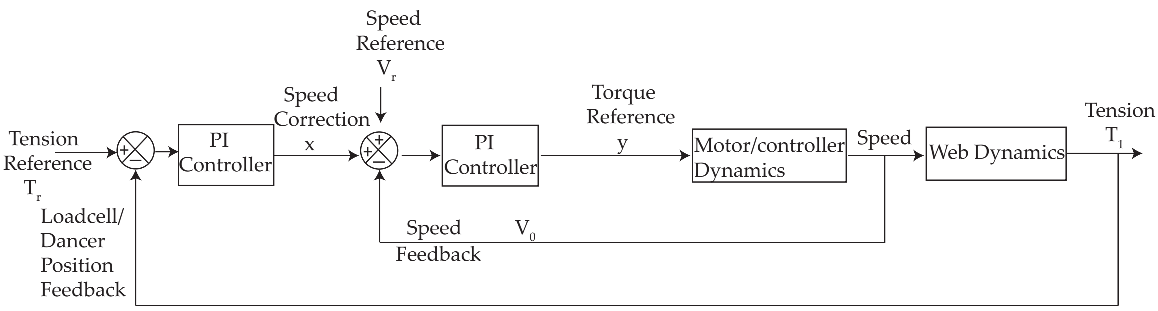


Figure 4.2: Control Scheme for Regulating Web Tension and Web Velocity

The mathematical models representing the dynamics of the web have been derived. These models are developed to provide an understanding of the longitudinal tension and velocity behavior of the web as it passes through screen printing, UV chamber, cooling section and various liquid baths for patterning of ITO anode material that is present on it. For simulation purposes and analysis, the web line is simplified. The simplified web line for which the simulation is conducted is shown in Figure 4.3. As shown in the figure, only the unwind accumulator is considered for simulation. In the original web line for patterning of ITO anode, there are multiple liquid baths through which the web is passed. But for the simulation, only one section of the liquid bath is considered.

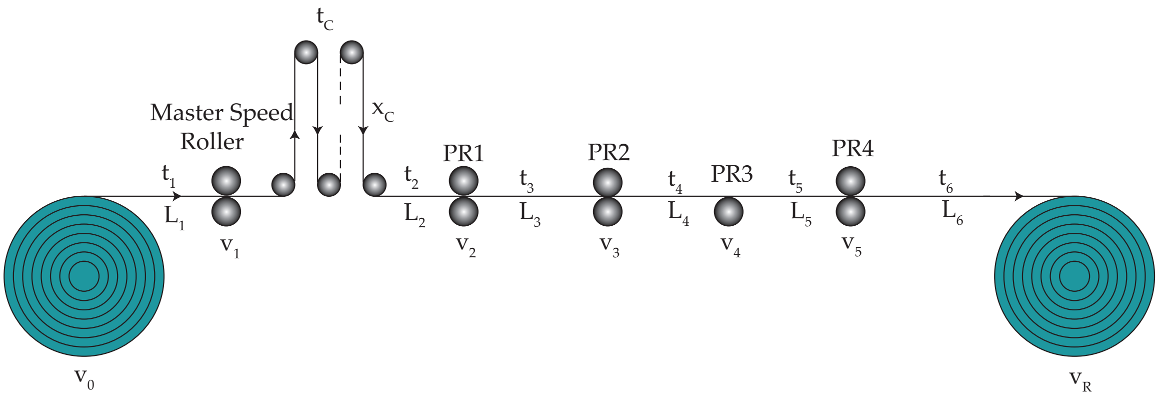


Figure 4.3: Simplified Web Line for Modeling and Simulation

The following section gives the mathematical models for various rollers and web spans of the web line [55]. It is assumed that density of the material remains the same throughout the web line. The governing equation for web velocity leaving the unwind roll is given by

$$\frac{J_o}{R_o}\dot{v_o} = t_1 R_o - n_o u_o - \frac{b_{fo}}{R_o} v_o - \frac{h}{2\pi R_o}\left(\frac{J_o}{R_o^2} - 2\pi\rho R_o^2\right) v_o^2 \tag{4.21}$$

The governing equation for tension in the span downstream of the unwind roller is given by

$$L_1 \dot{t_1} = AE[v_1 - v_o] + t_o v_o + t_1 v_1 \tag{4.22}$$

The radius of the unwind roll changes with time as the web is being unwound according to the equation

$$\dot{R_o} \approx -\frac{h}{2\pi}\frac{v_o(t)}{R_o(t)} \tag{4.23}$$

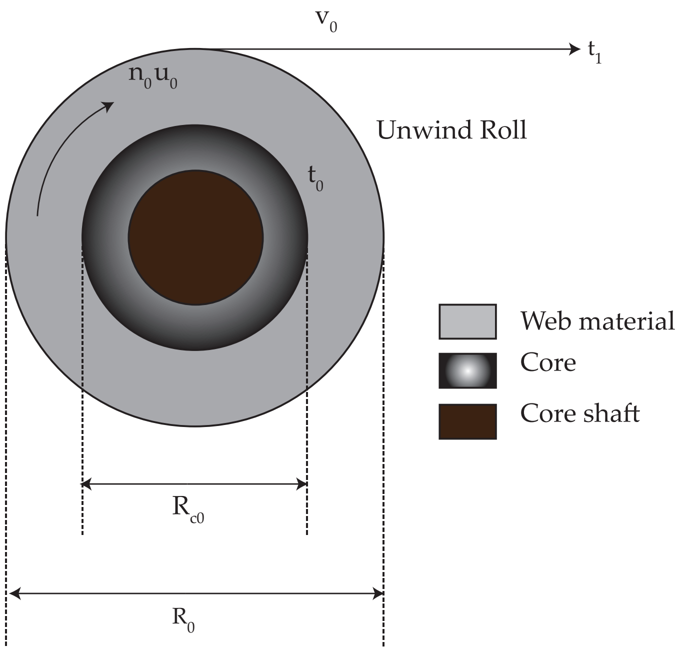


Figure 4.4: Cross-sectional View of Unwind Roll

The web velocity and web tension governing equations for the web span between the two driven rollers in the web line are given by the equations (4.24) and (4.25), respectively.

$$\frac{J_i}{R_i}\dot{v}_i = (t_{i+1} - t_i)R_i + n_i u_i - \frac{b_{fi}}{R_i}v_i \tag{4.24}$$

$$L_i\dot{t}_i = AE[v_i - v_{i-1}] + t_{i-1}v_{i-1} - t_i v_i \tag{4.25}$$

A web accumulator consists of several web spans. In order to obtain a simpler governing tension equation for all the web spans in the accumulator, the average tension is considered according to the equation (4.26). According to this equation, the tension in each span of the accumulator will be equal to t_c.

$$t_c(t) = \frac{1}{N}\sum_{j=1}^{N} t_j(t) \tag{4.26}$$

The tension dynamics in the accumulator span is given by the equation

$$\frac{dt_c(t)}{dt} = \frac{AE}{x_c(t)}\frac{1}{N}\left(v_e(t) - v_p(t)\right) + \frac{AE}{x_c(t)}\dot{x}_c(t) \tag{4.27}$$

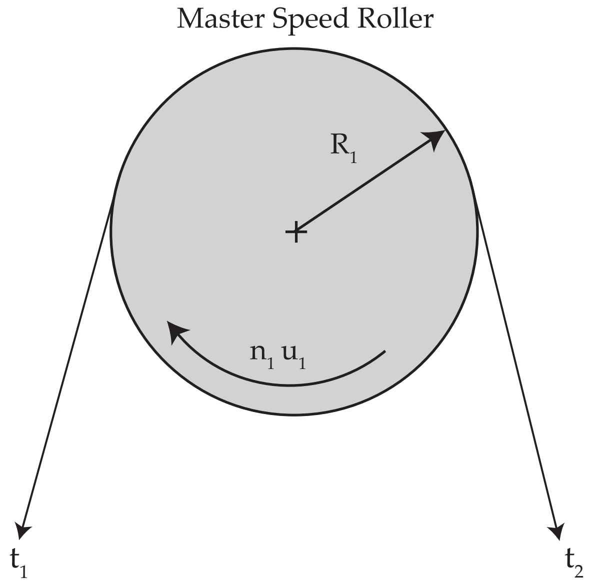


Figure 4.5: Free-body Diagram of Master Speed Roller

The length of the web span in the accumulator varies as it accumulates and releases the web during the roll changeover. It is determined by using the carriage dynamics given in the equation (4.28).

$$M_c \frac{d^2 x_c(t)}{dt^2} = u_c(t) - F_c(t) - M_c g - \sum_{j=1}^{N} t_j(t) \tag{4.28}$$

The position and speed of the carriage in the accumulator depends on the entry-side and exit-side driven roller velocities. It is given by the equation (4.29).

$$v_c(t) = \frac{v_p^d(t) - v_e^d(t)}{N} \tag{4.29}$$

PI controllers were used for the motors of all the sections except for the entry side driven roller, process side driven roller and accumulator carriage. The controllers designed for the accumulator carriage, entry-side driven roller and process-side driven roller which are given by the equations (4.30), (4.31) and (4.32), respectively.

$$u_c(t) = M_c \left(\dot{v}_c^d(t) + g + \frac{v_f}{M_c} v_c^d(t) + \frac{N}{M_c t_c^d} \right) \tag{4.30}$$

$$u_e(t) = \frac{J}{Rn_e}\left(B_{fe}v_e^d(t) + \dot{v}_e^d(t) - k_{pe}e_{ve}(t) - k_{ie}\int e_{ve}(t)d\tau\right) \tag{4.31}$$

$$u_p(t) = \frac{J}{Rn_p}\left(B_{fp}v_p^d(t) + \dot{v}_p^d(t) - k_{pp}e_{vp}(t) - k_{ip}\int e_{vp}(t)d\tau\right) \tag{4.32}$$

The above dynamic models and web line parameters given in Table 4.2 have been used for the simulation of web line used for patterning of ITO anode on PET substrate. The unwind accumulator tension dynamics is also included in the simulation. Simulations were conducted for the simplified web line shown in Figure 4.3. In order to simulate the accumulator carriage movement, very small change in radius is considered for a roll change. The plots in the Figure 4.5, shows simulations conducted for the web line for ITO patterning. The plots in the figure shows the carriage position and velocity profile of the entry side pull roll with respect to the change in the unwind radius. During an unwind roll change, velocity of the pull roll in the entry side of the accumulator will be zero. The change in velocity of the unwind roll and entry side pull roller during the unwind roll change is simulated. It can be seen that the carriage position varies in order to release the web during roll change.

The plots in Figure 4.5 show the tensions in various spans of the web line. Figure 4.13(a) shows the oscillations in the unwind tension due to change in unwind velocity. The plots clearly shows the oscillations in the tensions in the successive spans which is caused due to the tension oscillation in the unwind span. It can be clearly seen that the tension oscillation induced in the unwind span have propagated to the following spans causing the oscillations in tension in those spans.

Figure 4.5 shows the variations in tension in various spans of the web line when a sinusoidal disturbance with a frequency of 0.2 Hz and amplitude 1.82 N is introduced to spans in either sides of the accumulator. The plot in the Figure 4.15(c) clearly shows that the tension in the span immediately after the accumulator has very large variations in the tension compared to the tension in the span before the accumulator

(Figure 4.15(a)). This is caused by the variations in accumulator span tension. Since the accumulator span tension is not controlled, the variation in the accumulator span tension magnifies the tension disturbances in the span immediately downstream of the accumulator. This tension variation propagates to the following spans but will be eventually attenuated in successive spans. Thus, it is very important to have good control of tension before the accumulator spans.

Figure 4.5 represents tension variations in the various spans of the web line, when a sinusoidal disturbance of amplitude 0.25 m/s^2 and frequency of 0.5 Hz is introduced into the accumulator carriage dynamics. Low frequency disturbances are used as they are typical disturbances in the accumulator carriage [56]. It can be clearly seen that the propagation of tension disturbances to the spans downstream of the accumulator. The plots in the Figure 4.5 show the reduction in the tension variations in the successive spans downstream of the accumulator.

4.3 Tension Models for Lamination of Webs

In this section, tension dynamics for lamination of two webs using a nip roller is described [57]. In order to determine the tension dynamics, the mechanical and physical properties must be developed for the laminated web material which is derived by using the rule of mixtures. To determine the elastic modulus of a laminated web, constant stress or constant strain condition can be used. As the laminated material is required to have a uniform displacement in the longitudinal direction in order to obtain perfect bonding between the webs and also to avoid the problems such as curling of the laminated web, constant strain condition is used for determining the modulus of elasticity of the laminated web in the machine direction. In order to formulate the tension dynamics, consider the web lamina made of two materials A and B as shown in Figure 4.6. In this formulation, the width of the webs to be laminated are considered to be the same. The total stress experienced by the lamina in the machine direction is given by

$$\sigma_{cx} = \frac{\sigma_{Ax} h_A + \sigma_{Bx} h_B}{h_A + h_B}. \tag{4.33}$$

Constant strain condition in the longitudinal direction gives

$$\varepsilon_{cx} = \varepsilon_{Ax} = \varepsilon_{Bx}. \tag{4.34}$$

The stress in individual webs is given by

$$\sigma_{Ax} = E_A \varepsilon_{Ax}. \tag{4.35}$$

$$\sigma_{Bx} = E_B \varepsilon_{Bx}. \tag{4.36}$$

Using the above three equations, the modulus of elasticity of the laminate web is given by

$$E_{cx} = \frac{\sigma_{cx}}{\varepsilon_{cx}} = \frac{E_A h_A + E_B h_B}{h_A + h_B}. \tag{4.37}$$

In a similar way, an equation for density of the laminate can be derived which is as follows:

$$\rho_c = \frac{\text{Total mass per unit length}}{\text{Total volume per unit length}} = \frac{\rho_A h_A w + \rho_B h_B w}{(h_A + h_B) w} = \frac{\rho_A h_A + \rho_B h_B}{h_A + h_B}. \tag{4.38}$$

Consider a laminated web formed by laminating two webs by passing through a nip roller as shown in Figure 4.7. The law of conservation of mass can be used to develop the governing equation for tension.

For the control volume of the laminated web span between two rollers shown in Figure 4.7, using the law of conservation of mass, results in

$$\frac{d}{dt}\left[\int_0^{L_c} \rho_{c,s}(x,t) A_{c,s}(x,t) dx\right] = (\rho_{A,s} A_{A,s} v_1 + \rho_{B,s} A_{B,s} v_1) - \rho_{c,s} A_{c,s} v_2. \tag{4.39}$$

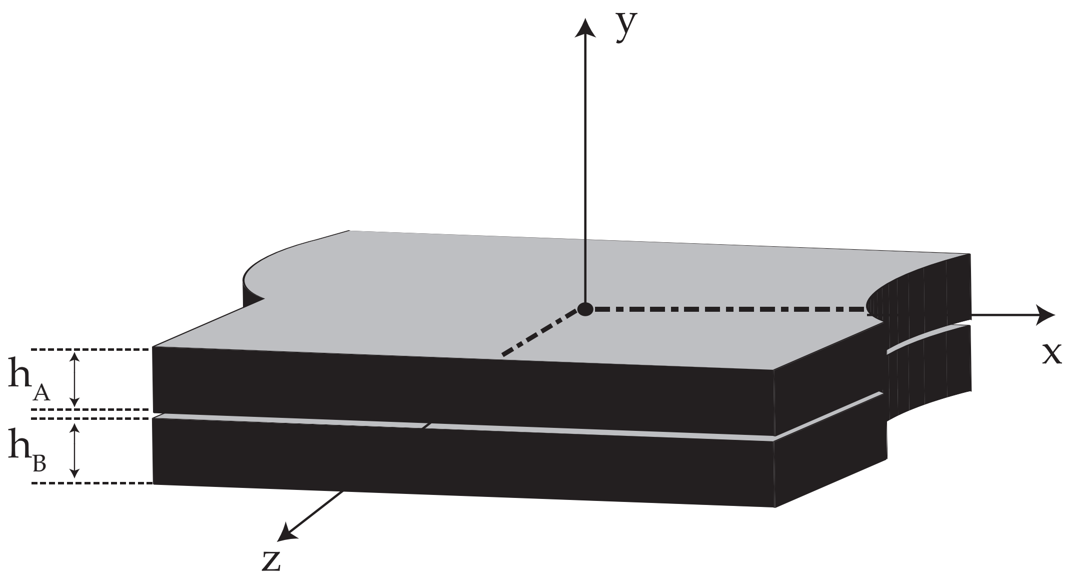


Figure 4.6: Lamination of Two Webs

The mass of a volume element of a web in the stretched state is equal to the mass of web in the same volume element in the unstretched state, i.e., $m_i = m_{i,s}$.

$$m_{i,s} = \rho_{i,s} A_{i,s} \Delta L_{i,s} = m_i = \rho_i A_i \Delta L_i. \tag{4.40}$$

From the above equation, we can write

$$\frac{\rho_{i,s} A_{i,s}}{\rho_i A_i} = \frac{\Delta L_i}{\Delta L_{i,s}}. \tag{4.41}$$

Since,

$$\Delta L_{i,s} = (1 + \varepsilon_i(x,t))\Delta L_i \tag{4.42}$$

equation (4.41) can be written as

$$\frac{\rho_{i,s} A_{i,s}}{\rho_i A_i} = \frac{\Delta L_i}{\Delta L_{i,s}} = \frac{1}{1 + \varepsilon_i(x,t)}. \tag{4.43}$$

Using the above condition for the individual web layers and the web laminate shown in Figure 4.7 gives

$$\frac{\rho_{A,s} A_{A,s}}{\rho_A A_A} = \frac{1}{1 + \varepsilon_A(t)}, \frac{\rho_{B,s} A_{B,s}}{\rho_B A_B} = \frac{1}{1 + \varepsilon_B(t)}, and \frac{\rho_{c,s} A_{c,s}}{\rho_c A_c} = \frac{1}{1 + \varepsilon_c(x,t)}. \tag{4.44}$$

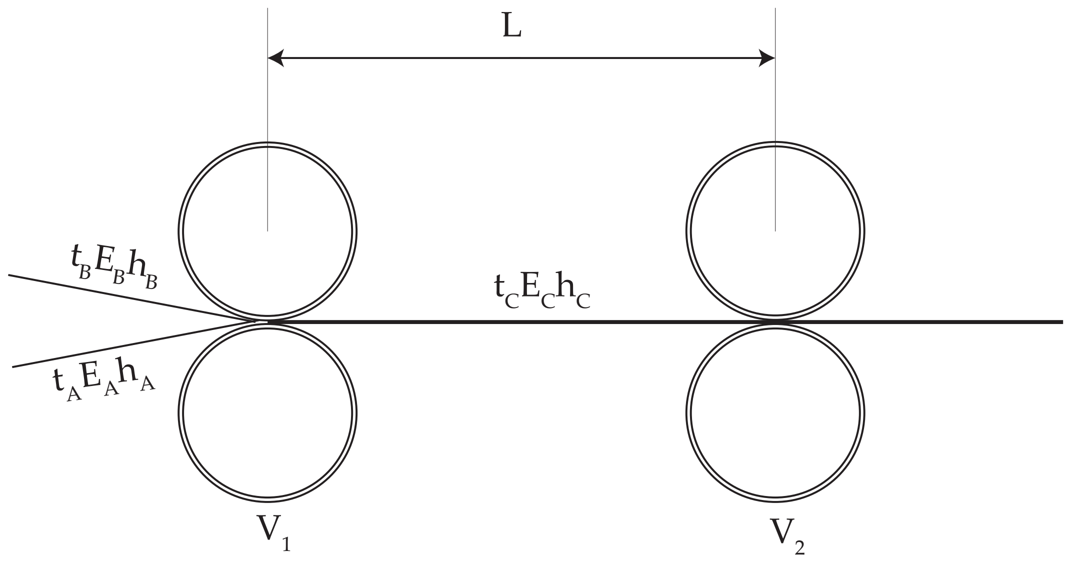


Figure 4.7: Lamination of Two Webs

Using (4.44) in (4.39) results in

$$\frac{d}{dt}[\int_0^{L_c} \frac{\rho_c(x,t)A_c(x,t)}{1+\varepsilon_c(x,t)}dx] = \frac{\rho_A A_A v_1}{1+\varepsilon_A(t)} + \frac{\rho_B A_B v_1}{1+\varepsilon_B(t)} - \frac{\rho_c A_c v_2}{1+\varepsilon_c(t)}. \tag{4.45}$$

Assuming the density and area of laminated and individual webs remains the same within any span, results in

$$\rho_c(x,t) = \rho_c, A_c(x,t) = A_c, \tag{4.46}$$

Using the above condition in (4.45) gives

$$\rho_c A_c \frac{d}{dt}\left[\int_0^{L_c} \frac{1}{1+\varepsilon_c(x,t)}dx\right] = \frac{\rho_A A_A v_1}{1+\varepsilon_A(t)} + \frac{\rho_B A_B v_1}{1+\varepsilon_B(t)} - \frac{\rho_c A_c v_2}{1+\varepsilon_c(t)}. \tag{4.47}$$

Assuming that the strain is small, i.e, $1-\varepsilon^2 \approx 1$, equation (4.47) can be written as,

$$\rho_c A_c \frac{d}{dt}\left[\int_0^{L_c} (1-\varepsilon_c(x,t))dx\right] = (\rho_A A_A v_1)(1-\varepsilon_A(t)) + (\rho_B A_B v_1)(1-\varepsilon_B(t)) - (\rho_c A_c v_2)(1-\varepsilon_c(t)). \tag{4.48}$$

Assuming that there is only mechanical strain, $\varepsilon_c(x,t) = \varepsilon_{t,c}(t)$. Simplifying the equation (4.48) using the above condition results in

$$(-)L_c \frac{d\varepsilon_{t,c}(t)}{dt} = \frac{\rho_A A_A v_1}{\rho_c A_c} - \frac{\rho_A A_A \varepsilon_A(t) v_1}{\rho_c A_c} + \frac{\rho_B A_B v_1}{\rho_c A_c} - \frac{\rho_B A_B \varepsilon_B(t) v_1}{\rho_c A_c} - \frac{\rho_c A_c v_2}{\rho_c A_c} + \frac{\rho_c A_c v_2 \varepsilon_c(t)}{\rho_c A_c} \tag{4.49}$$

Simplifying the above equation gives

$$L_c \frac{d\varepsilon_{t,c}(t)}{dt} = (v_2 - v_1) + \left(\frac{\rho_A h_A \varepsilon_A(t) + \rho_B h_B \varepsilon_B(t)}{\rho_A h_A + \rho_B h_B} \right) v_1 - v_2 \varepsilon_c(t) \tag{4.50}$$

Replacing the velocity term by average velocity in the terms involving the product of strain and velocity in (4.50) gives

$$L_c \frac{d\varepsilon_{t,c}(t)}{dt} = (v_2 - v_1) + \left(\frac{\rho_A h_A \varepsilon_{t,A}(t) + \rho_B h_B \varepsilon_{t,B}(t)}{\rho_A h_A + \rho_B h_B} \right) \bar{v} - \bar{v} \varepsilon_{t,c}(t) \tag{4.51}$$

The governing equation for web tension can be obtained by assuming a constitutive relation between web strain and web tension. By assuming the individual layers as well as the laminated web to be linearly elastic,

$$\varepsilon_{t,c}(t) = \frac{t_c(t)}{E_c A_c}, \varepsilon_{t,A}(t) = \frac{t_A(t)}{E_A A_A} \, and \, \varepsilon_{t,B}(t) = \frac{t_B(t)}{E_B A_B} \tag{4.52}$$

Using the above condition given in (4.52) in (4.51), the governing equation for web tension in the laminated web span can be written as

$$\frac{dt_c}{dt} = \frac{E_c A_c}{L_c}(v_2 - v_1) + \frac{E_c A_c}{L_c} \left(\frac{\frac{\rho_A h_A}{E_A A_A} t_A + \frac{\rho_B h_B}{E_B A_B} t_B}{\rho_A h_A + \rho_B h_B} \right) \bar{v} - \frac{\bar{v} t_c}{L_c} \tag{4.53}$$

Using the condition in (4.37) and area $A = (h_A + h_B)w$ in the above equation and simplifying gives

$$\begin{aligned} \frac{dt_c}{dt} =& \frac{(E_A h_A + E_B h_B)}{L_c} w(v_2 - v_1) - \frac{\bar{v} t_c}{L_c} + \frac{\bar{v}}{L_c} \left(\frac{E_A h_A + E_B h_B}{E_A h_A} \right) \left(\frac{\rho_A h_A t_A}{\rho_A h_A + \rho_B h_B} \right) \\ &+ \frac{\bar{v}}{L_c} \left(\frac{E_A h_A + E_B h_B}{E_B h_B} \right) \left(\frac{\rho_B h_B t_B}{\rho_A h_A + \rho_B h_B} \right) \end{aligned} \tag{4.54}$$

The above tension dynamic model for the laminated web can be applied for the lamination of any number of webs. In the lamination of barrier material to the flexible electronic component, this tension dynamic model can be used.

4.4 Web Line for Barrier Lamination to the Substrate for Flexible Electronics

During the manufacture of flexible electronic devices such as OLED, solar cell, LCDs, etc., final encapsulation of the device is important. It is a critical stage in the manufacture of the device. This is due to the fact that encapsulation is done to obtain barrier against moisture, oxygen and other environmental impermeants. Any wastage at this stage would be costly. Appropriate selection of barrier materials, encapsulation methods and bonding materials are crucial for the effective functioning of the final device. It is always better to perform the adhesive and barrier lamination in the presence of inert atmosphere. This is due to the strict barrier requirements for the active layers of flexible electronic devices.

A good barrier material that would provide longer life for a flexible OLED device has not yet been found. Currently, there are active investigations on this topic. The requirements for the barrier layer for polymer solar cells is not as stringent as in flexible OLED devices. Therefore, barrier materials for the encapsulation of polymer solar cells are available, and have been used recently in the manufacture of films for solar cells. In this section, lamination of barrier material to a flexible solar cell will be discussed. A web line for lamination has been designed. The same line and similar lamination methods could be used for the lamination of flexible OLED devices in the future. A barrier material made of silicon oxide coated PET substrate can be used for the encapsulation of the solar cell device [17]. However, in this thesis a barrier material which is better than the barrier material used in [17], has been considered for lamination of the solar cell device.

When laminating the electronic components with the barrier layer, cold lamination is preferred as the electronic device substrate will be coated with active layers prior to its lamination. If heat is involved during lamination, then it would affect the performance of the device as most of the active layers will be sensitive to heat.

Thus, pressure sensitive adhesives are the most suitable choice of adhesives to be used during cold lamination as there will be no higher temperatures involved. The pressure sensitive adhesives are used in the form of transfer adhesives where component substrate can be laminated on both sides of it, while the adhesive can be applied simultaneously with a peel away liner material which is used to protect the adhesive before lamination [58]. It would not have been possible to attain simultaneous lamination if materials with different thermal properties were laminated on each side of the electronic component substrate. Simultaneous lamination of the barrier material is advantageous compared to sequential lamination. It would reduce the overall cost, time, space, and equipment needed.

The flexible solar cell panel is formed by laminating it with a flexible barrier material along with a pressure sensitive adhesive during its final stage of manufacturing [17]. Various barrier materials are available and companies are conducting research on the barrier material which would be more efficient than the barrier materials currently available. The efficiency of the barrier material is directly related to the longer lifetime of the device. Along with the barrier material, a suitable selection of the adhesive material to laminate it with the solar substrate is also important. Even the adhesive material, should provide considerable sealing against moisture and oxygen. It should not degrade under various processing and environmental conditions. A pressure sensitive adhesive (PSA) with a release liner is considered for lamination of the barrier material. In this section, a web line has been designed for lamination of barrier material to a solar cell substrate, the barrier layer. In the next section, tension dynamic models have been developed for simultaneous lamination of webs. Simulation using these models were conducted for the proposed web line.

Table 4.3 gives the different layers of flexible solar cell developed in [17] along with their thickness and density values. Lamination of barrier layers on both sides of the solar module substrate is considered. The barrier substrate to be laminated to the back side of the substrate that contains the active layers, has its width reduced in order to allow a part of the silver bus exposed for electrical connection [17]. The front side of the substrate has the barrier substrate laminated across its full width.

4.4.1 Pressure Sensitive Adhesive (PSA) tape

With a pressure sensitive adhesive, as the name suggests, application of light pressure will cause it to stick to most of the surfaces. It usually consists of four layers. Out of the four layers, two of the main components are adhesive mass which helps in sticking to other surfaces and backing or carrier which provides a support to it. The adhesive is usually made of synthetic or natural rubber, acrylic polymer, etc., and the backing is usually made of a foil, paper or any kind of flexible material. The other two layers are primer coat and release coat. The primer coat is used to provide good adhesion between the adhesive and backing layer whereas release coat is applied to the backing side opposite to that of the adhesive side to protect the adhesive when it is wound on a roll and to assist in easy unwinding.

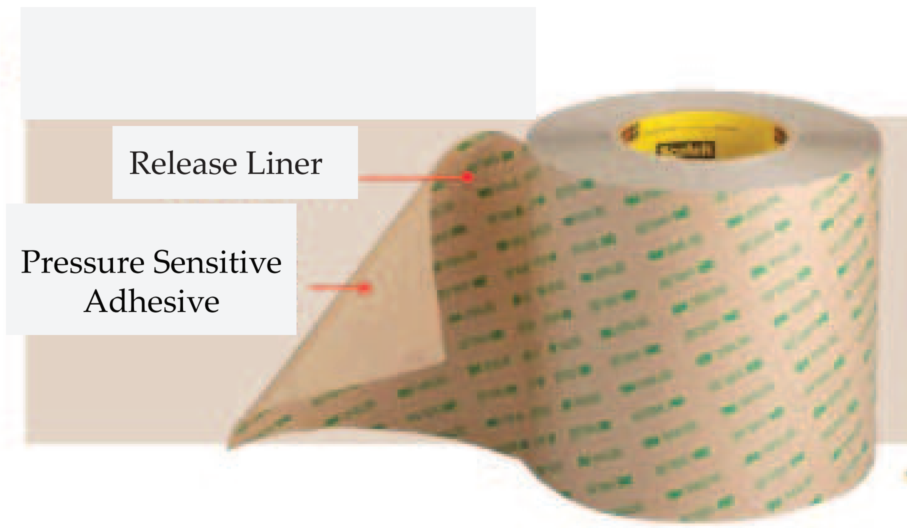


Figure 4.8: Pressure Sensitive Adhesive Tape [59]

There are several reported advantages of using PSA over other liquid adhesives and fasteners.

- Along with the primary function of bonding of two materials, they help in dampening vibration and shock, noise reduction and also help in obtaining a highly effective sealing.
- As they do not require any drilling or welding such as mechanical fasteners, it results in a smooth surface finish.
- PSAs eliminate the galvanic corrosion which can occur when two dissimilar metallic materials are bonded and exposed to moisture.
- They avoid formation of concentrated stress areas by distributing the stress uniformly over the bonded area.
- They also allow lamination of thinner substrates and materials with different coefficients of thermal expansion.

Sometimes, an adhesive tape is made of just a release liner and an adhesive tape. A release liner is a web of thin material which is used to cover the adhesive side of a PSA to protect it during storage and transport as well as to provide support during manufacturing and conversion. It is very important to choose a suitable release liner as it will lead to an expensive process downtime if the liner material fails to protect the adhesive material or releases prematurely. Thus, release liners must be reliable.

The release liners are made of suitable thin substrates with release coatings which allow for easy delamination from the adhesive layer when needed. Release liner material should be such that it should allow easy delamination from the adhesive without scraping any adhesive part and also provide the necessary support for the adhesive during its storage and transportation. Silicon coated release liners are very popular in the industry as it requires less release forces than other materials. Lower nip pressure is preferred for softer adhesives and fragile substrates whereas higher pressure is preferred for firm adhesives and substrates. Usually, softer material such as rubber or elastomer is preferred for the top nip roller while steel or hard rubber is preferred for the bottom nip roller. The bottom roller may be nickel or chromium plated to avoid corrosion and cuts and to be easy to clean.

4.4.2 Barrier Material

The barrier film made of silicon oxide coatings provide very good barrier properties; Dupont company has barrier material made of silicon coatings deposited on their Teonex Q65FA substrate. The silicon dioxide on Teonex Q65FA barrier material has a density of 2.52 g/cm^3 [60] and Teonex Q65FA has an elastic modulus of 5 GPa at room temperature. The silicon coated PEN material has better barrier properties than the silicon coated PET material [61]. Also, biaxially stretched PEN material is superior in mechanical, thermal and gas barrier properties than biaxially stretched PET material.

The thickness of silicon dioxide deposited on the film is about $90-120$ nm. Teonex Q65FA has an ultimate tensile strength 220 MPa and thickness of the film can be around 100 micron. As the thickness of the barrier film increases, its flexibility decreases. So, it is better to keep the thickness of the film at minimum. As the thickness of silicon coating on the Teonex film is minimal, it does not provide much stiffness. Thus, in order to calculate the tension to run this web, the ultimate tensile strength of Teonex film is considered.

4.4.3 Lamination of Barrier Material to Adhesive Layer

Before the lamination of barrier material to the solar cell substrate, an adhesive layer must be laminated to the barrier material which is shown in Figure 4.9. The adhesive material is protected by the liner material during the entire process. The liner material is made in such a way that the adhesive does not stick to the inner layers when it is wound on a roll. The speed of lamination is less due to the involvement of PSA which requires low speed transport to achieve good lamination quality. The speed of lamination is about 4 ft/min. After the lamination of barrier material to the adhesive layer, it must be rewound onto a roll. Curing takes place when it is wound such that the bonding of the adhesive to the barrier material becomes strong. The liner material must be run at a tension of about 6000 psi which is about 640 N for a width of 305 mm and a thickness of 2 mils. Considering the ultimate tensile strength of the barrier material, it can be run at a tension of 671 N for a web width of 305 mm and thickness of 100 μm.

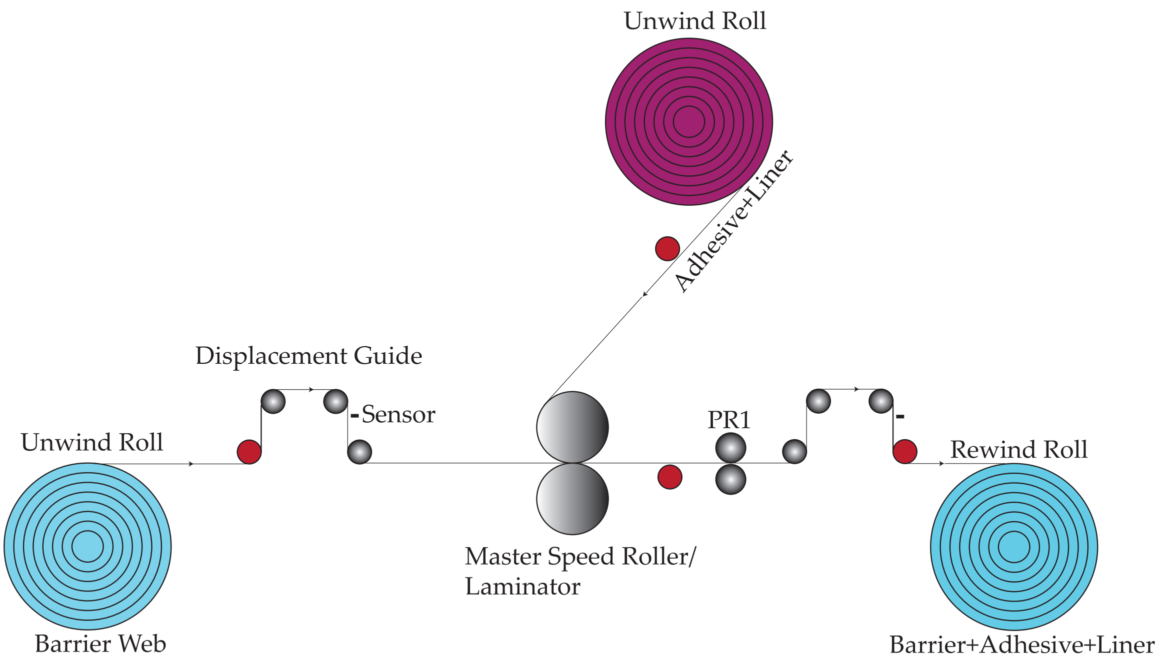


Figure 4.9: Web Line for Lamination of Barrier Layer to the Adhesive Material

Finally, the encapsulation of solar cell substrate with the barrier material using PSA adhesive can be obtained using lamination method as depicted in the Figure 4.10. Pressure sensitive adhesives laminate better at slower speeds of between 3 to 5 feet per minute. During simultaneous lamination of webs, the speed of all the webs must be the same in order to obtain good lamination quality. A nip pressure of value between $1\frac{3}{4}$ - 20 PLI is suggested for lamination using PSA [62].

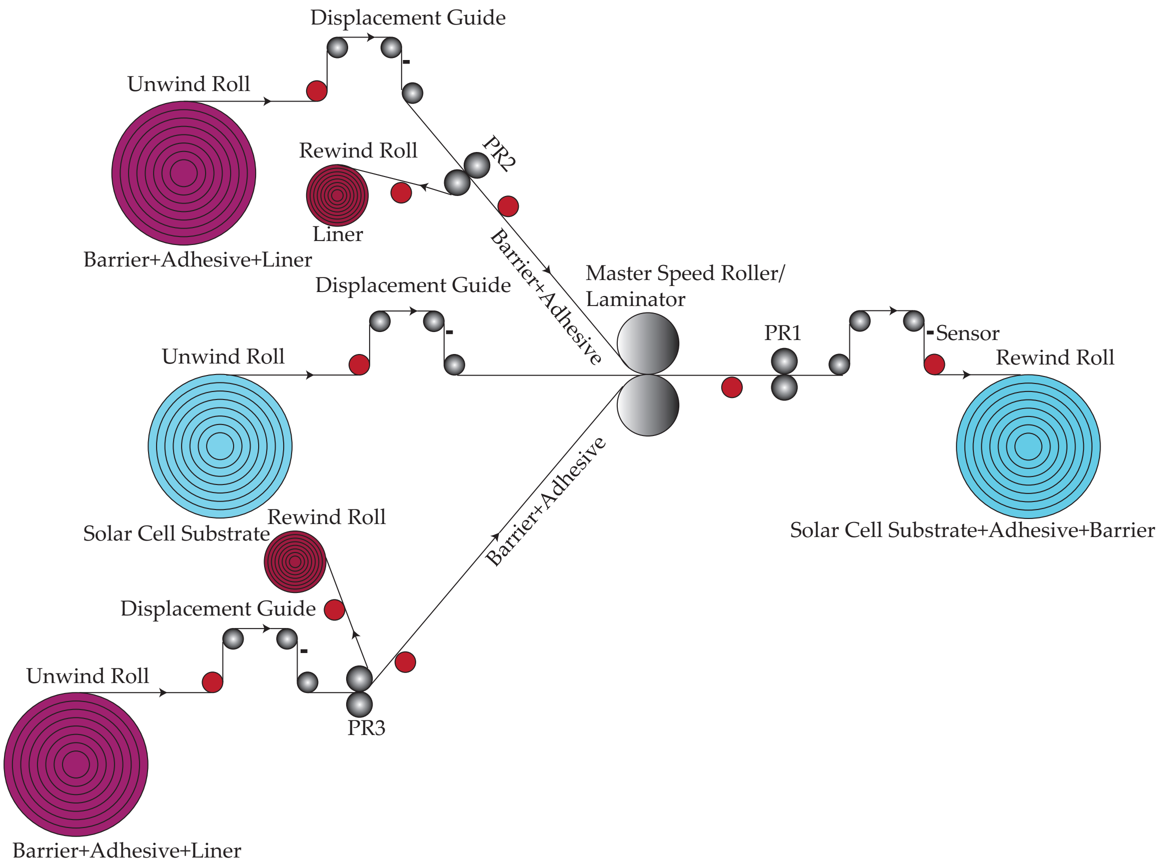


Figure 4.10: Web Line for Lamination of Barrier Layer to the Solar Cell Substrate

The total density of the solar cell substrate after deposition of all the layers on the PET substrate can be calculated using the equation (4.38). Substituting the values as per the Table 4.3 in the equation (4.38), the total density of the substrate with the solar cell module is calculated to be around 1865 kg/m^3. The liner for the adhesive is a polyester film which can be run at a tension of around 6000 psi. The solar cell is made of PET substrate as the base on top of which the active layers are deposited along with the electrodes. In order to calculate the tension required to run this web, ultimate tensile strength of the substrate has to be determined. Since the active layers and electrodes are coated onto the substrate, they do not provide significant stiffness to the substrate. Thus, tension at which this web should be run is calculated based on the ultimate tensile strength of the substrate material.

Consider the web line shown in the Figure 4.10 for lamination of barrier material to the solar cell substrate. In this section, simulations are conducted to regulate the web velocity and web tension of this line during the lamination process. For the purpose of simulation, the web line has been simplified. Controllers are designed for driven rollers, unwind and rewind rolls. Idle rollers are neglected for simulation purposes. The tension dynamics developed for lamination of webs in the previous section has been used. The simplified web line is as shown in Figure 4.11.

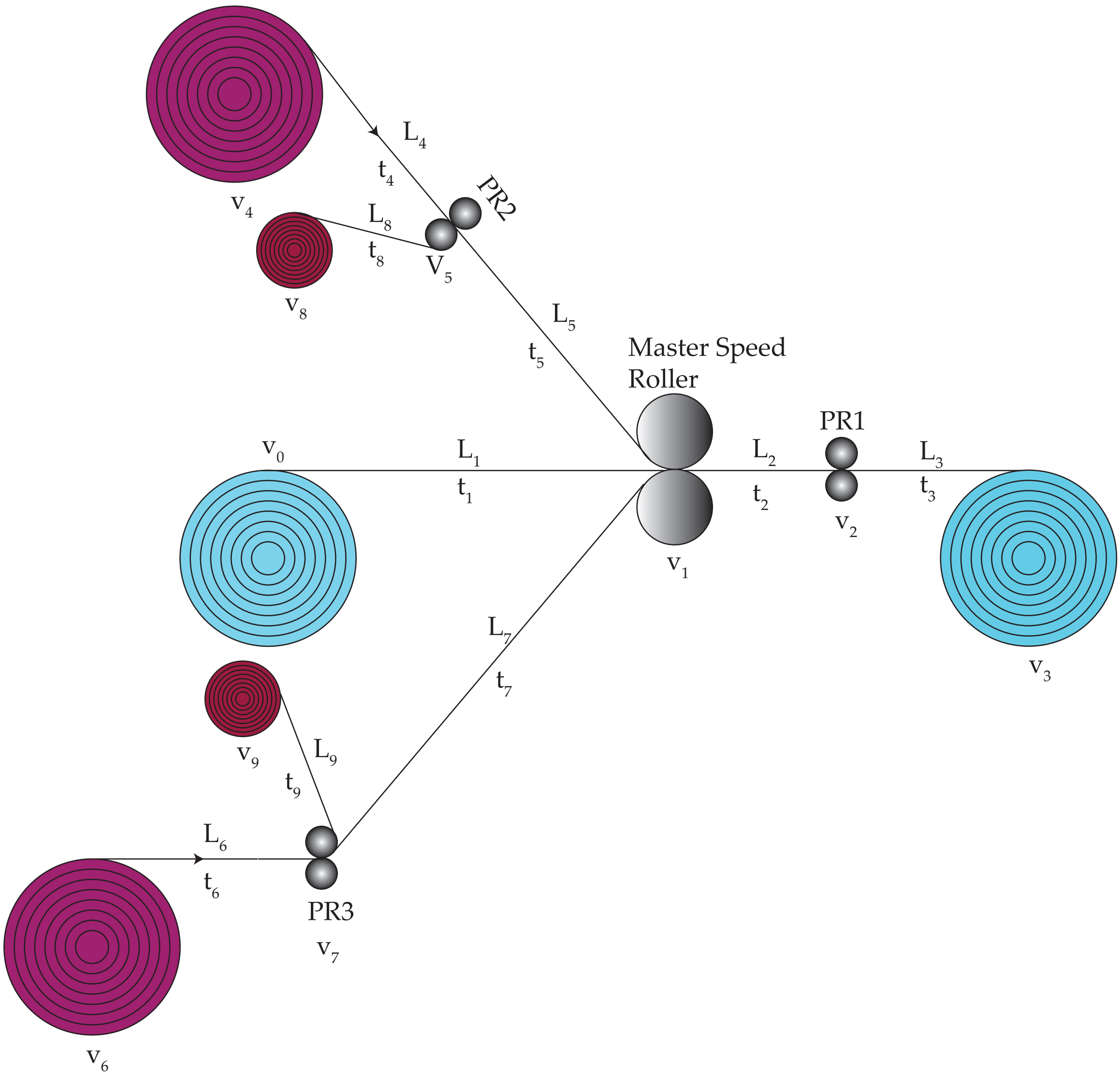


Figure 4.11: Simplified Line for Modeling and Simulation of Lamination Web Line

The tension and velocity dynamic models for all web spans between the driven rollers, unwind roll and rewind roll are same as given in section 4.2 except for span

L8 which is the span after the lamination of the three webs. The tension dynamic equation for that particular span is obtained according to the equation (4.55).

The barrier material is laminated on both sides of the solar cell substrate for encapsulation. However, the width of the solar cell substrate is about 305 mm and width of the barrier substrate for lamination to the back side of the substrate is about 250 mm whereas front side of the substrate has the lamination to its entire width. This is to allow the silver bus bars in the back side of the substrate to be exposed for electrical connection during later stages.

4.5 Calculation of Reference Tension

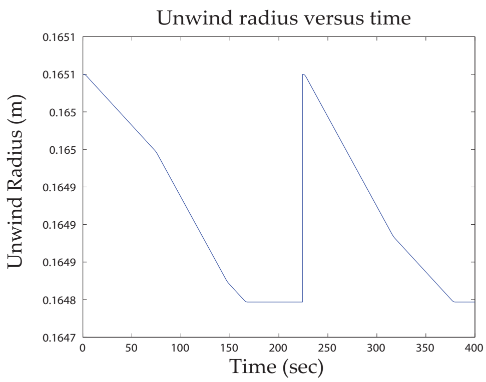
For a web width of 305 mm, the PET substrate must be run at a tension of around 218 N. Since the liner material is already laminated to the barrier material, it has to be run at a tension value which is the sum of the tensions required to run those two web materials individually; although this is what is reported in literature, further study must be conducted to verify this aspect. For the liner material of width 250 mm and thickness 2 mils, a tension value of 525 N is required. For the liner material of width 305 mm and thickness 2 mils, a tension of around 640 N is required. For a web width of 305 mm and thickness of 100 micron, tension required to run the barrier material is about 671 N whereas for a web width of 250 mm, reference tension of about 550 N is required.

Since the liner material with the barrier substrate is of reduced width on the back side compared to the solar cell substrate, the tension dynamic equation (4.55) which is derived should be modified to include the changes in the widths of the webs. The lamination line includes simultaneous lamination of three webs i.e., barrier substrates with adhesive laminated on either sides of the solar cell substrate. Thus, the tension dynamic equation for this particular case involving lamination of three webs having different widths is given as

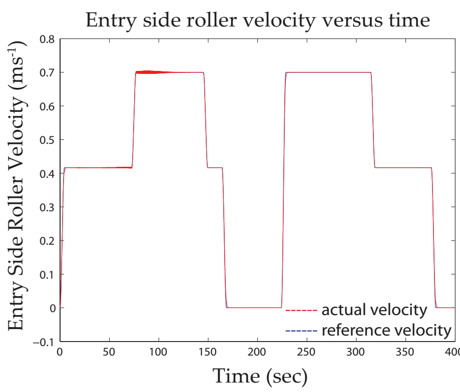
$$
\begin{aligned}
\frac{dt_c}{dt} =& \frac{(E_A h_A w_A + E_B h_B w_B + E_C h_C w_C)}{L_c}(v_2 - v_1) - \frac{\bar{v} t_c}{L_c} \\
&+ \frac{\bar{v}}{L_c}\left(\frac{E_A h_A w_A + E_B h_B w_B + E_C h_C w_C}{E_A}\right)\left(\frac{\rho_A t_A}{\rho_A h_A w_A + \rho_B h_B w_B + \rho_C h_C w_C}\right) \\
&+ \frac{\bar{v}}{L_c}\left(\frac{E_A h_A w_A + E_B h_B w_B + E_C h_C w_C}{E_B}\right)\left(\frac{\rho_B t_B}{\rho_A h_A w_A + \rho_B h_B w_B + \rho_C h_C w_C}\right) \\
&+ \frac{\bar{v}}{L_c}\left(\frac{E_A h_A w_A + E_B h_B w_B + E_C h_C w_C}{E_C}\right)\left(\frac{\rho_C t_C}{\rho_A h_A w_A + \rho_B h_B w_B + \rho_C h_C w_C}\right)
\end{aligned}
\tag{4.55}
$$

Simulations are conducted using the tension dynamic model developed above, and PI controllers are used to regulate web tension and web velocity at various spans and rollers of the web line for lamination of the barrier substrate to the solar cell substrate. Figure 4.16(c) shows the velocity of the master speed roller. The PI controller has been successfully tuned such that the velocity at the master speed roller follows the reference velocity which is about 1.2192 m/min.

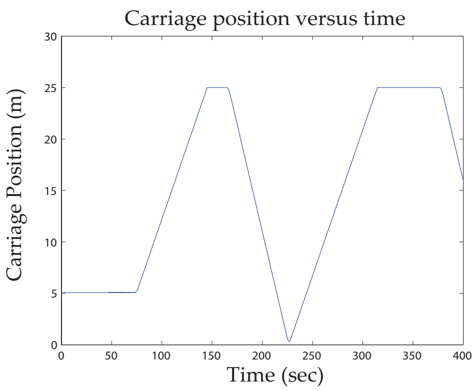
The plots in Figure 4.5 show tension and velocity in various spans of the web line. The plots clearly show that the tension and velocity follow the reference values and controllers are well tuned.



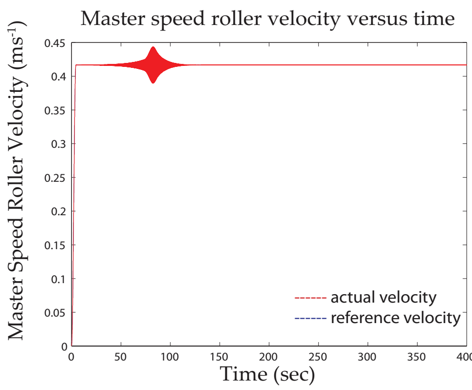
(a) Unwind Radius



(b) Entry Side Roller Velocity



(c) Carriage Position



(d) Process Side Roller Velocity

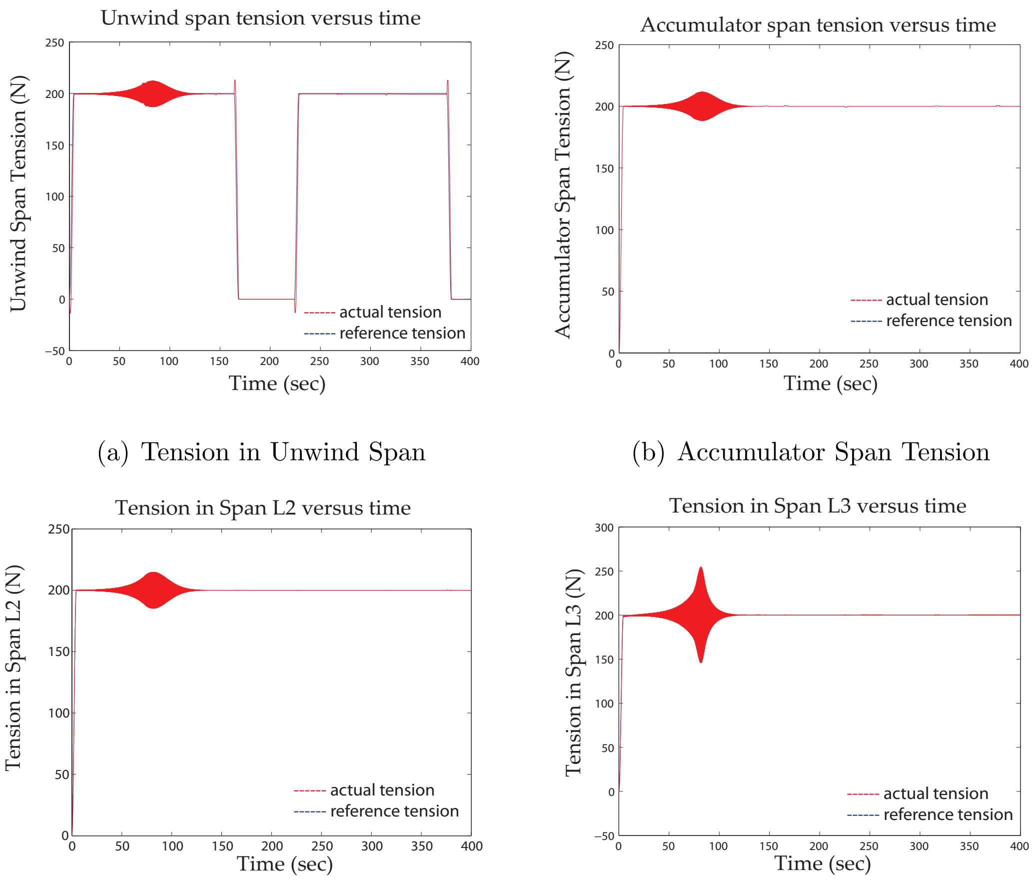
Figure 4.12: Simulations for the Web Line for Patterning ITO

Table 4.2: Simulation Parameters

Width of the web	0.28 m
thickness of the web	0.0001301 m
Radius of unwind/Rewind roller	0.16510065 m
Tension in the web	200 N
Elastic Modulus of web	4 GPa
Cross sectional area of the web	0.000036428 m^2
Gear Ratio of the unwind/rewind roller	3.795
Gear Ratio for other driven rollers	6.82
Moment of Inertia for unwind motors	0.359058348 kgm^2
Moment of Inertia for other driven motors	0.096922253 kgm^2
Moment of Inertia for rewind motors	0.358577276 kgm^2
Radius of other driven rollers	0.0762 m
Length of each span other than unwind, rewind and span 4	2.5m
Length of span 4	3m
Length of span downstream of unwind	0.92710365 m
Length of span upstream of rewind	0.9144 m
Number of accumulator spans	10
density of web	1350 kgm^{-3}
Mass of accumulator carriage	36.2873896 kg
Coefficient of viscous friction	0.02

Table 4.3: Layers of Polymer Solar Cell and their Properties

Material	Thickness	Density (gm/cm^3)
PET	130 μm	1.4
Indium Tin Oxide	90 nm	7.14
ZnO	23 nm	5.6
P3HT:PCBM	127 nm	1.1
PEDOT:PSS	20 μm	1
Silver	5−10 μm	9.6



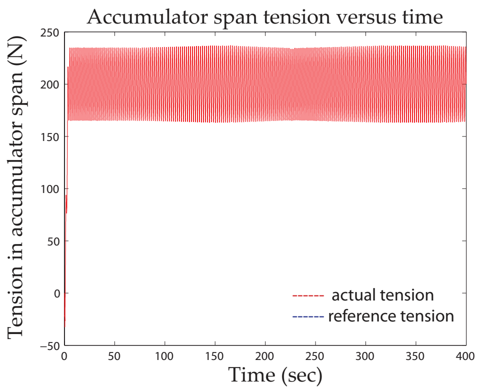
(a) Tension in Unwind Span

(b) Accumulator Span Tension

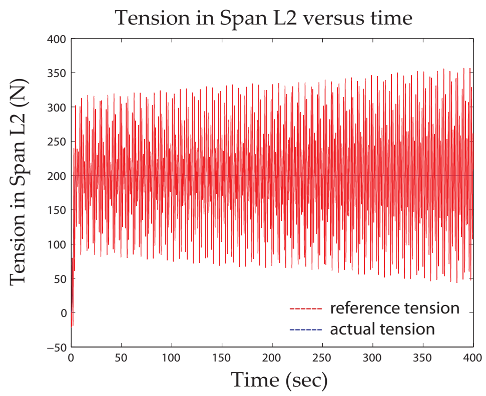
(c) Tension in L2 Span

(d) Tension in L3 Span

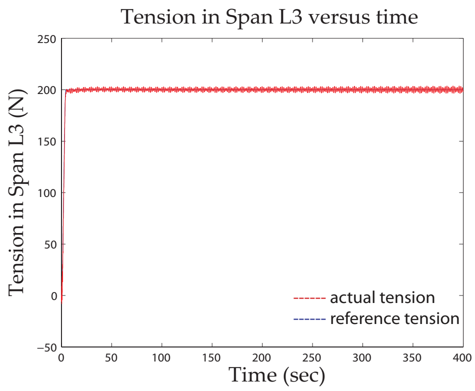
Figure 4.13: Simulations for the Web Line for Patterning ITO



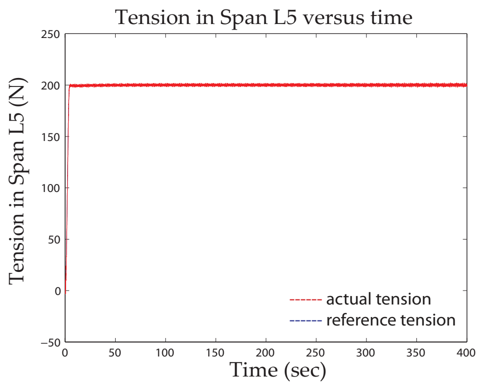
(a) Tension in Accumulator Span



(b) Tension in Span after Accumulator

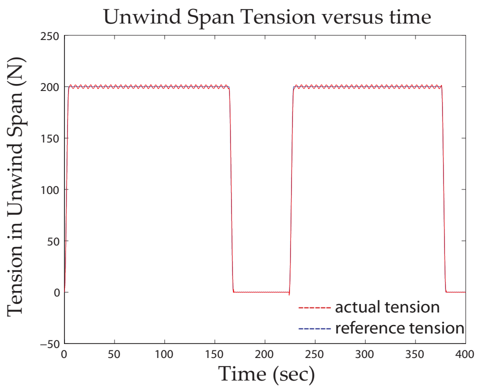


(c) Tension in L3 Span

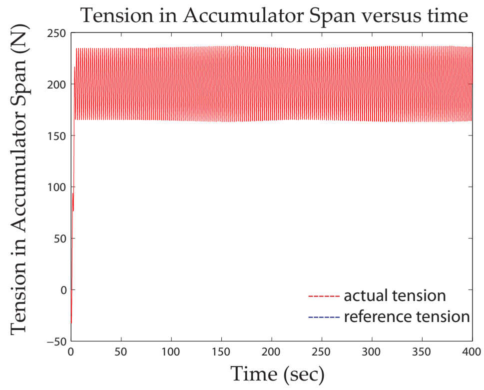


(d) Tension in L5 Span

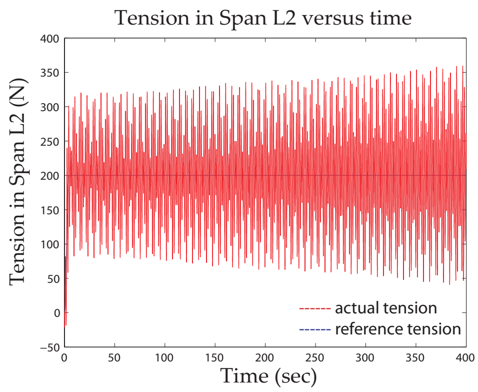
Figure 4.14: Simulations for the Web Line for Patterning ITO



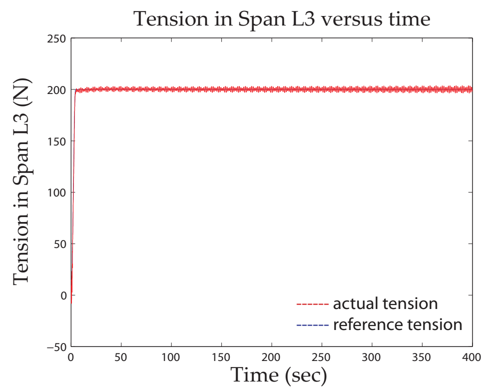
(a) Tension in Unwind Span



(b) Accumulator Span Tension

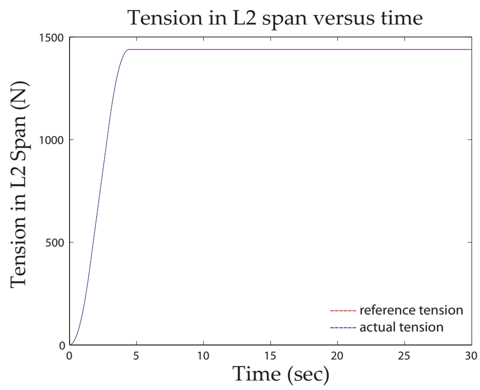


(c) Tension in L2 Span

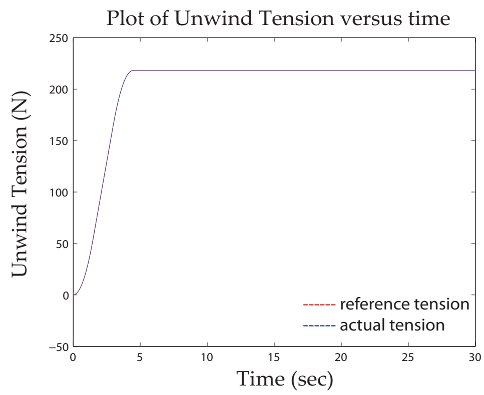


(d) Tension in L3 Span

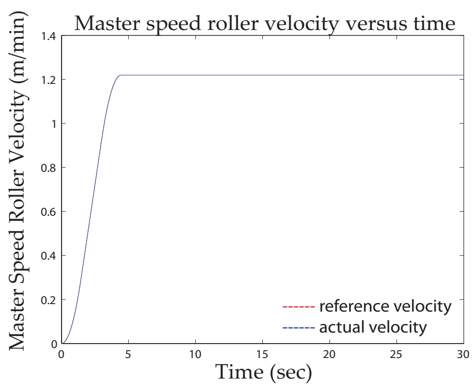
Figure 4.15: Simulations for the Web Line for Patterning ITO



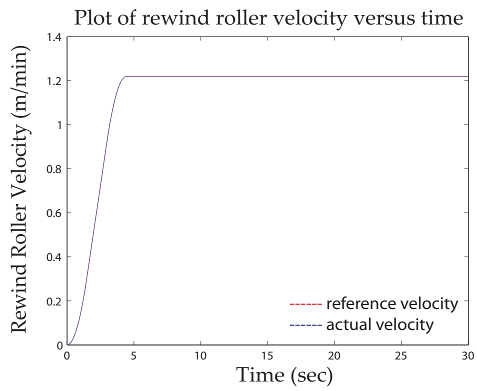
(a) Tension in the span L2 of Lamination Web Line



(b) Tension in Unwind Span L1 of Lamination Web Line



(c) Master Speed Roller Velocity of Lamination Web Line



(d) Rewind Roller Velocity of Lamination Web Line

Figure 4.16: Simulations for the Lamination Web Line

CHAPTER 5

Summary and Future Work

5.1 Summary

Flexible electronics may be bent, flexed and rolled to an extent and still be expected to maintain their functionality. The components of flexible electronic devices can be printed using solution printing technologies such that the entire manufacturing can be done using RTR manufacturing. The main focus of this thesis was on manufacturing of flexible electronics using RTR methods. Based on a comprehensive study of the various processes involved in manufacturing of flexible electronic devices, OLEDs and polymer solar cells in particular, web handling strategies and parameters were determined for continuous processing of flexible electronic devices using several web lines. It is important to regulate web tension and velocity during its transport from the unwind roll to the rewind roll. In this thesis, simulations were conducted for the web lines for regulating web tension and velocity. Lamination of webs is a very important process, especially in flexible electronics manufacturing. This is because the barrier layer must be laminated to the flexible electronic substrate on both sides of it to prevent it from being degraded by the environmental permeates such as oxygen and moisture. In this thesis, a web line for simultaneous lamination of barrier material to both sides of the substrate was designed. A chapter by chapter summary is given below.

Chapter 2 provided detailed discussions about two of the main flexible electronic devices, OLEDs and polymer solar cells. The first section of this chapter provided details about OLEDs; insights into various parts of OLED, their functions, deposition methods, advantages and disadvantages of OLEDs, etc., was given. A discussion on different OLED types and insights into the manufacture of flexible OLEDs was given. The second section provided insights into polymer solar cells, its components and functionalities. In the last part of this chapter, the manner in which polymer solar cell can be used to charge a battery to light a solar lamp was presented.

In chapter 3, a web line was designed for RTR patterning of ITO anode layer on the PET substrate. Various process parameters and technologies are determined for the ITO patterning in the web line. Solution printing technologies and various web handling techniques were discussed such that ITO patterning can be performed in a continuous manner. Web line parameters such as web tension and velocity were determined for the web line. In the second part of this chapter, a web line for the deposition of active layers on the anode layer of the plastic substrate was designed and discussed. The manner in which the web can be passed through liquid baths was discussed. In the last part of this chapter, the manner in which the longitudinal registration between two successive printing units can be obtained using compensator rollers was presented.

In chapter 4, drag force on the web as it passes through a liquid bath was calculated. Laminar flow for the fluid in the bath in the crosswise direction to the web movement is considered for drag force calculation. Tension and velocity dynamic models for various web spans, accumulators and rollers of the web line for patterning of ITO anode were presented. Simulations were conducted to regulate tension and velocity of the web using the tension and velocity dynamic models. Modeling of the tension dynamics for lamination of two webs was discussed. A barrier material that protects the polymer solar cell against oxygen and moisture was identified. A web line was designed for the lamination of barrier material to the pressure sensitive adhesive. A web line was also designed for simultaneous lamination of barrier material onto both sides of the flexible electronic substrate. Web line parameters and lamination conditions were determined for the web lines designed for lamination. Using the tension dynamic model developed for lamination of webs, simulations were conducted to regulate web tension and velocity for lamination of barrier material to the flexible electronic substrate.

5.2 Future Work

Web lines designed in this thesis can be modified to manufacture other flexible electronic devices using RTR methods. The designed web lines must be modified to manufacture other flexible electronic devices. As the manufacturing of electronic devices requires high precision, registration in the lateral direction is necessary along with longitudinal registration. Thus, proper methods must be developed for obtaining accurate registration in the lateral direction of the web movement. Future research should focus on optimizing the process and web line parameters for the designed web lines for the manufacturing of flexible electronic devices. Research must be conducted on the materials such that only solution printing technologies could be used for deposition of all the components of flexible electronic devices. For example, the ITO anode material on the substrate is not deposited by solution printing technology, only the patterning is done using RTR method. So, research must be conducted on selection of materials that would replace the ITO as the anode material which can be deposited by solution printing techniques. The drag force calculation was done for the laminar flow of the fluid in the bath. It was determined that the laminar flow of fluid does not result in a drag force that is significant. However, the flow may not be laminar in many situations, and drag force may not be insignificant in such situations. Therefore, further study on this aspect must be conducted.

Research must be focused on technologies that would assist in increasing web speed and yet obtaining a good quality product. The lamination tension dynamic model was developed using rule of mixture considering the web to be isotropic; both these assumptions weakly reflect practical situations. Research should be done on developing tension dynamic model for simultaneous lamination of non-isotropic material webs. Research must be conducted on finding better barrier materials for the encapsulation of flexible electronic devices. Future work must focus on finding electrode materials for the flexible electronics which do not get oxidized in air eliminating the need for an inert atmosphere during their deposition. The presence of an inert atmosphere poses problems during RTR manufacturing and also increases the cost. Finally, several test web platforms must be developed to conduct experimentation which will help validate the proposed designs, and also help in making improvements to the proposed techniques.

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Scope and Method of Study: Flexible electronics may be bent, flexed and rolled to an extent and still be expected to maintain their functionality. The focus of this thesis is on efficient manufacture of electronic devices in flexible form using roll to roll (RTR) method of continuous manufacturing, which is expected to significantly improve productivity and efficiency and reduce manufacturing costs. A comprehensive study of the literature was undertaken to understand the various processes involved in the manufacture of flexible electronics such as organic light emitting diodes (OLEDs) and solar cells, and an investigative study was carried out to highlight those processes and methods that are suitable for RTR manufacture of flexible electronic devices. Design of three web lines for RTR manufacturing of different stages of flexible electronic devices was investigated.

Summary: Based on a comprehensive study of the various processes involved in manufacturing of flexible electronic devices, OLEDs and polymer solar cells in particular, web handling strategies and parameters were determined for continuous processing of flexible electronic devices using several web lines. The drag force on the web material was calculated based on the crosswise laminar movement of the fluid in the liquid bath through which the web is transported. Simulations were conducted to regulate tension and velocity of the web using the governing equations for web tension and velocity. The web process lines designed in this thesis for OLEDs and solar cells can be modified to manufacture other flexible electronic devices using RTR methods. A model for web tension for lamination of two webs was investigated. This model was used for studying the tension behaviour during simultaneous lamination of barrier materials to both sides of a solar cell substrate material.

ADVISOR'S APPROVAL: ____________________________________