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Scope of Study: The high school physics teacher must continuously face the problem of trying to keep abreast of new developments in physics. One of the most recent advances has been in the area of semiconductors. Research has led to the production of crystal diodes and transistors on a commercial basis and they are finding many applications in all branches of electronics. In this report, an attempt has been made to present some of the theory of semiconductor operation in such a way that the high school teacher will be able to intelligently answer and discuss questions which students may have concerning semiconductors. In addition, a series of five semiconductor circuits are presented which can be used as projects for those students interested in electronics.

ADVISER'S APPROVAL James H. Zant

SEMICONDUCTOR
THEORY AND PROJECTS

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CHAPTER I

INTRODUCTION

One of the many problems facing the high school physics teacher today is that of maintaining instruction in basic physics and at the same time keeping abreast of the many new developments in physics. In many instances, the teacher can do little more than read current newspaper and magazine articles and to incorporate new ideas into class discussions as an opportunity arises.

However, in the fast growing field of electronics, particularly the area of semiconductors, the availability of transistors on a commercial basis has made possible the actual use of semiconductors in the high school laboratory. It is unlikely that the teacher will want to set up regular class experiments using transistors because of the limited time which can be spent on electronics and the desire to use more basic experiments in electricity. Nevertheless, transistors can offer an excellent series of special class projects which many students will find interesting and fascinating. For the student interested in science fairs, transistors offer a good chance for some original experiments with transistor circuits.

The use of transistors has an added advantage in that costs to the science department or to individual students are nominal for most applications. A box of parts from old radios will yield most of the necessary circuit components and power requirements can usually be satisfied with flashlight batteries.

In this report, an attempt is made to acquaint the teacher with some of the basic theory of semiconductor and transistor operation. In addition, a few of the more common applications of transistors are discussed and circuit diagrams are given in each case. No attempt has been made to design or develop new circuits for transistor application, but only to list applications which a high school student should find interesting and informative. In addition, the physics teacher can find an ever increasing number of other transistor applications in current radio and electronics publications.

CHAPTER II

ELEMENTARY SEMICONDUCTOR THEORY

Semiconductors are defined as materials which exhibit a resistance which is high in comparison to the common metals, but low in comparison to insulating materials. Common examples of such materials are the elements germanium and silicon. Although these elements are similar in atomic structure to insulating materials, they have electrons within the crystal which are free to move and conduct a current. In actual practice, crystals are formed which contain impurities. These impurities serve as either electron donors or electron acceptors and the combination becomes either rich in electrons or lacking in electrons. If the material is rich in electrons, it is called n-type while if it lacks electrons, it is called p-type and is said to be rich in "holes". In either case, the material may serve as a conductor since both the electrons and "holes" can be considered free to move.

Actually, the movement of holes is a consequence of electrons shifting positions among atoms. As an electron moves to fill a hole in one atom, it has left a hole in some other atom. In effect, the hole has been shifted at the same time the electron moved, but it moves in the opposite direction. It becomes just as easy, then, to discuss the movement of holes as it is to consider the movement of electrons. It must be remembered, however, that electrons represent a negative charge while holes, in effect, represent a positive charge. Conduction of current can be accomplished in either case and it becomes possible to consider conduction by holes or conduction by electrons.

When a p-type material, rich in holes, is joined with an n-type material rich in electrons, it would be natural to expect the electrons and holes to cross at the junction and neutralize each other leaving the combination without excess holes or electrons. This is not the case, however, although some neutralization must occur. For example, if one considers the electrons as moving across the junction from the n-type to the p-type material, an area in the n-type material near the junction will become more and more positive. This, in turn, will tend to limit additional electron transfer and only a small area near the junction becomes neutral. The same argument can be advanced for holes moving from the p-type material into the n-type material.

The first semiconductor products to be produced commercially were the germanium crystal diodes. They consisted of a single p-n junction and exhibited the property of high resistance to current flow in one direction, but low resistance in the opposite direction. Figure 1, on the following page, shows a schematic drawing of the p-n junction with a battery connected in the external circuit. In Figure 1 (a), the p-type material, rich in holes, is connected to the negative terminal of the battery. The

FIGURE 1

CRYSTAL DIODE BATTERY CONNECTIONS

positive holes, then, will be attracted away from the p-n junction. Similarly, the excess free electrons in the n-type material will be attracted away from the p-n junction and toward the positive battery terminal. This will leave the junction without either type of current carrier and no current can flow across the junction.

On the other hand, in Figure 1 (b), the battery polarity is reversed and both positive holes and negative electrons will move toward the p-n junction. In this case, there are many current carriers in the vicinity of the junction and the junction offers very little resistance to current flow.

The crystal diode, then, functions in much the same way as the diode vacuum tube and serves as a typical rectifier for many low current radio and television applications.

In 1948, Shockley[1] applied for a patent on a device known as the transistor. It could perform many functions which had formerly been possible only with a vacuum tube. At the same time, the transistor possessed many advantages over the typical vacuum tube. The transistor requires no filament, operates with much smaller voltage requirements, and is much smaller than the vacuum tube. Since 1948, many companies have begun research projects with transistors and have developed techniques for manufacturing them economically. In addition, many new applications for transistors are being found daily.

Generally speaking, the transistor is formed by combining p-type and n-type material in such a way that a thin area of n-type material lies between two areas of p-type material. This will form what is called a p-n-p type junction transistor. Actually, n-p-n type transistors may also be formed and the two types are found to have very similar operating characteristics. The actual procedures used to get desirable and efficient junctions in transistors involve many intricate problems. However, at R.C.A. Laboratories in Princeton, experiments using the element indium as a germanium impurity to form p-type material have proved successful.[2] Indium melts at a very low temperature

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[1] W. Shockley, U.S. Patent 2,569,347, applied for June 26, 1948

[2] E. N. Herold, New Advances in the Junction Transistor, <u>Transistors I</u>, New Jersey: R.C.A. Laboratories, 1956, p. 27.

and will dissolve germanium. Subsequent cooling results in partial recrystallization of the germanium and a desirable junction between the indium-germanium alloy and undissolved germanium.

The general arrangement of the three areas of a transistor is shown in Figure 2 along with the symbol which is normally used to indicate transistors in an electrical circuit. Figure 2 (a) gives a greatly magnified picture of the p and n layers of the p-n-p type junction

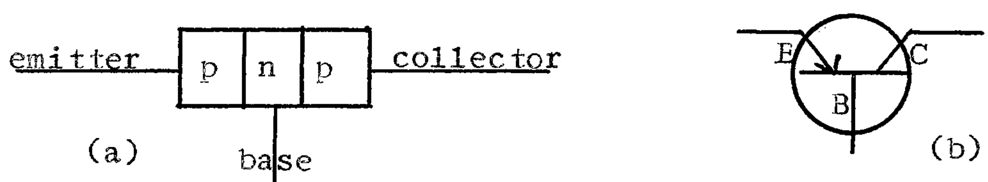

FIGURE 2

THE JUNCTION TRANSISTOR
STRUCTURE AND SYMBOL

transistor. Actually, the transistor is little more than a thin germanium wafer into which three distinct impurity areas have been introduced. As shown in Figure 2, the central area is called the base while the outer layers are called the emitter and collector. Roughly speaking, the emitter, base, and collector can be thought of as corresponding to the cathode, grid, and plate, respectively, of the triode vacuum tube.

Figure 3 shows the bias and signal connections which could be used in a typical transistor circuit. The collector is biased negatively with respect to the base and this results in current carriers being drawn away from the

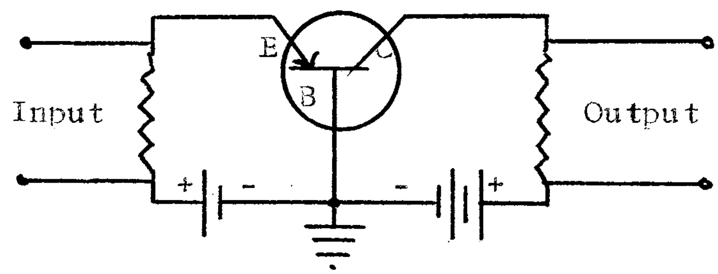

FIGURE 3

TRANSISTOR BIAS AND SIGNAL CONNECTIONS

collector-base junction. The transistor, therefore, offers high resistance to current flow in the collector-base circuit. On the other hand, the emitter and base are biased such that the n-type base is negative with respect to the emitter. In this case, current carriers will move to the junction and the transistor offers very low resistance in the emitter-base circuit.

In actual operation, holes from the p-type emitter region are injected into the base region. However, the base region is very thin and most of the holes pass on into the collector region and become part of the collector circuit. The few holes which are neutralized in the base region make up the base current. This current is very small and is measured in microamperes. If all the holes injected into the base region passed through the base into the collector region, the emitter and collector currents would be equal and the emitter to collector current gain would be equal to one. In most commercial junction transistors, however, the current gain will be slightly less than one and usually falls in the range of 0.80 to 0.99.

From the preceding statements, it is fairly easy to see how power amplification is possible with the transistor. In measuring power, the formula $P = I^2R$ can be used and since the current in the emitter and collector circuits is very nearly the same, the power in each circuit will be approximately proportional to the circuit resistances. The biasing shown in Figure 3 will result in high collector resistance and low emitter resistance and the power amplication will be high. The actual power amplication will also depend upon other circuit components used in conjunction with the transistor.

Voltage amplification is also possible with the transistor and it occurs in much the same way as power amplification. From Ohm's Law, $V = IR$, and here again the amount of voltage amplification essentially depends on the ratio of collector resistance to emitter resistance.

Transistors may be connected into circuits in a number of ways depending on the function which the transistor is expected to perform. Figure 4 shows the three basic methods of connecting transistors into a circuit for signal amplification.

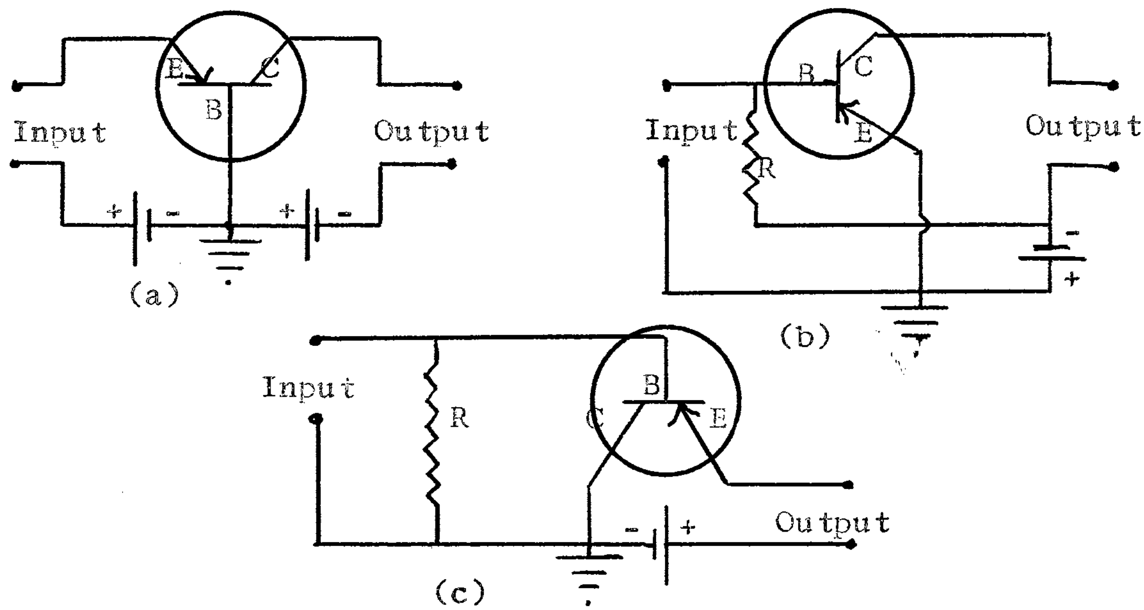

FIGURE 4

BASIC TRANSISTOR CIRCUIT CONNECTIONS

Figure 4 (a) is called a grounded base circuit and offers low input impedance and high output impedance. This circuit corresponds to the grounded grid circuit used with vacuum tubes.

Figure 4 (b) shows the grounded emitter circuit which exhibits input and output impedances which are about the same order. Only one bias supply is needed in the circuit as base collector bias is obtained from the voltage drop across the resistance in the base-collector circuit. The circuit corresponds to the grounded cathode vacuum tube amplifier and is probably the most commonly used method of connecting the transistor in a circuit.

A third circuit used for transistor connections is shown in Figure 4 (c) and is similar to the cathode follower circuit used with vacuum tubes. It is called the grounded collector circuit and exhibits high input impedance and low output impedance. This circuit is probably the least used of the three circuit types.

Transistors presently in commercial production have two major limitations. The first is based on the fact that the transistor tends to overheat if the rate of power dissipation is not held to reasonably low values. Overheating, of course, may alter the transistor characteristics or break it down entirely. Transistors have been described which are capable of power dissipations of five watts when used singly and up to twenty watts when two transistors are used in push-pull output circuits.[3] These transistors employ an emitter which is a gallium-silver-indium alloy.

The second limitation of transistors is that of frequency response. Most transistors presently in production find uses in audio circuits and in low frequency radio applications although some transistors are now available which have cut-off frequencies as high as four megacycles.

[3] B. N. Slade, Recent Advances in Power Junction Transistors, Transistors I, New Jersey: R.C.A. Laboratories, 1956, p. 153.

Transistors are rapidly finding applications in many commonly used electronic circuits. The fact that they have small power requirements and are small physically make them highly desirable for such applications as hearing aids and portable radios. The ever increasing number of applications for transistors as well as improved transistor designs may soon make the vacuum tube obsolete!

CHAPTER III

SEMICONDUCTOR PROJECTS

The use of semiconductors in both junior high and high school science classes offers a valuable source of projects which will be interesting and informative. Furthermore, the number of projects which can be used is practically unlimited as new circuit ideas as well as variations in old projects are constantly being published. The circuits on the following pages are relatively simple and students should find little difficulty in getting the desired operation.

The simple crystal radio set which students have always found interesting has an equally interesting counterpart in the crystal diode and transistor radio receiver. The circuits on the following page show two simple radio receivers. In Figure 5, the crystal diode is used as a detector while the transistor serves to amplify the signal. Adjustment of the variable condenser serves the same purpose as tuning the dial of a regular radio receiver and will make it possible to adjust the receiver to the frequency of a local radio station. For best results, a good ground and antenna are most important.

Figure 6 shows a second radio receiver circuit which is very similar to the first except that two transistors are used for greater amplification. It should be noted that two types of transistors are used in this circuit. The first amplifier

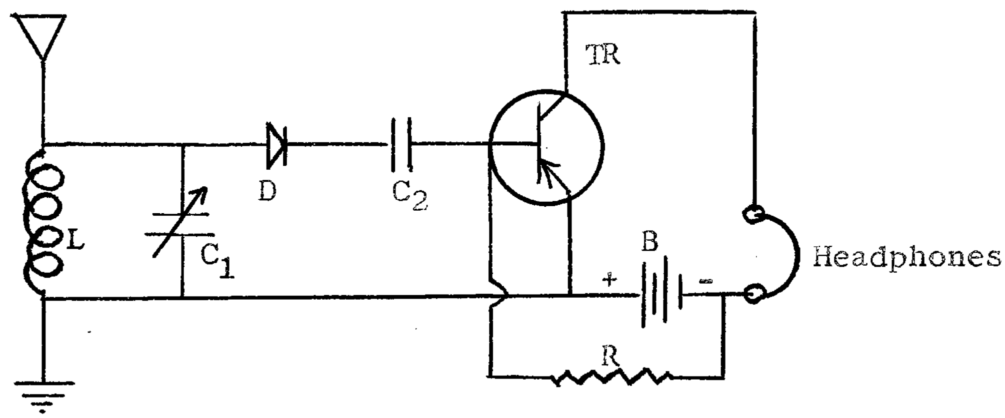

FIGURE 5

A SIMPLE RADIO RECEIVER

R -- 220,000 ohm, ½ watt resistor
C_1-- 365 mmf. variable condenser
C_2-- .02 mfd. condenser
L -- Miller loopstick, # 6300
D -- 1N64 crystal diode
B -- 3 volt dry battery
TR-- 2N107 transistor

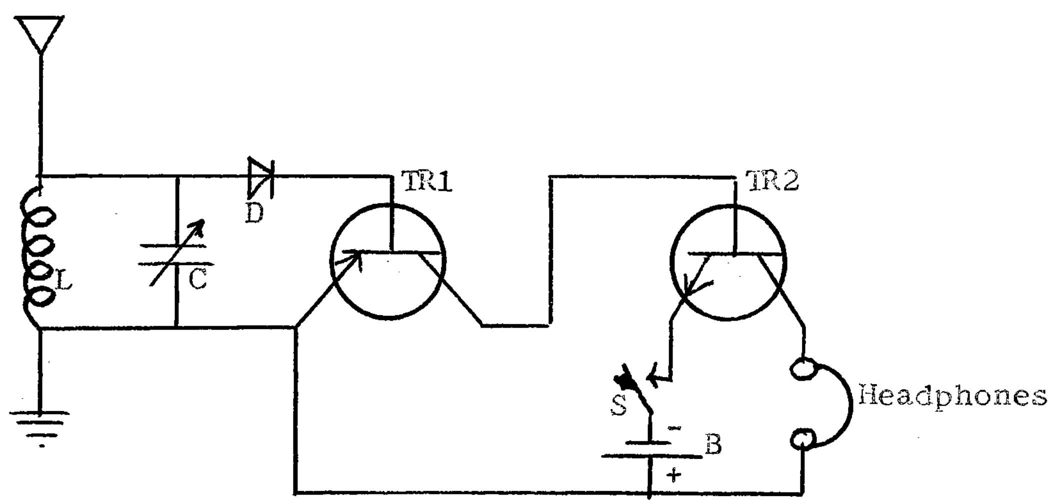

FIGURE 6

A TWO TRANSISTOR RADIO RECEIVER

C -- 365 mmf. variable condenser
L -- Miller loopstick, # 6300
D -- 1N64 crystal diode
B -- 3 volt dry battery
S -- On-off switch
TR1 -- 2N107 transistor
TR2 -- 2N170 transistor

is a p-n-p type transistor while the second is a n-p-n type. This is necessary if a single battery is to be used to power the circuit. Again, a good ground and antenna is necessary for best results and the receiver should be capable of picking up several stations.

For the student interested in amateur radio, the code practice oscillator circuit of Figure 7 will be of some value.[1] The use of a speaker makes it possible for several students to practice code at the same time and the tone can be varied to any desired frequency by adjustment of the potentiometer in the circuit at R_1. The power required by the oscillator can be supplied by two $4\frac{1}{2}$ volt batteries or by six $1\frac{1}{2}$ volt penlite cells wired in series to form a battery pack. The low current requirements of the transistor will result in long battery life.

An interesting transistor circuit for a wireless broadcast band phono oscillator was shown in a recent issue of Radio and Television News magazine.[2] The circuit diagram is shown in Figure 8 and the oscillator will function as a small radio transmitter which will tune to the broadcast band of any radio. The range of the transmitter is approximately twenty feet and is well with in the maximum range set by the

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1 Louis E. Garner, "Transtopic Experiment No. 15", Popular Electronics, Volume 6, No. 2, February, 1957, p. 85.

2 Anon., "New Transistor Circuits", Radio and Television News, Volume 56, No. 3, September, 1956, p. 98.

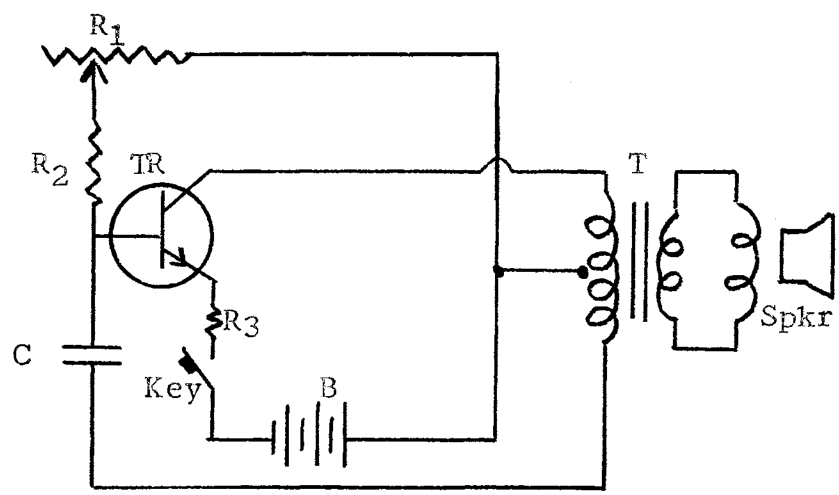

FIGURE 7

CODE PRACTICE OSCILLATOR

R_1-- 1 megohm potentiometer
R_2-- 10,000 ohm, ½ watt resistor
R_3-- 100 ohm, ½ watt resistor
C -- .25 mfd. condenser
B -- 9 volt dry battery
T -- Audio transformer
TR-- 2N170 or 2N35 transistor

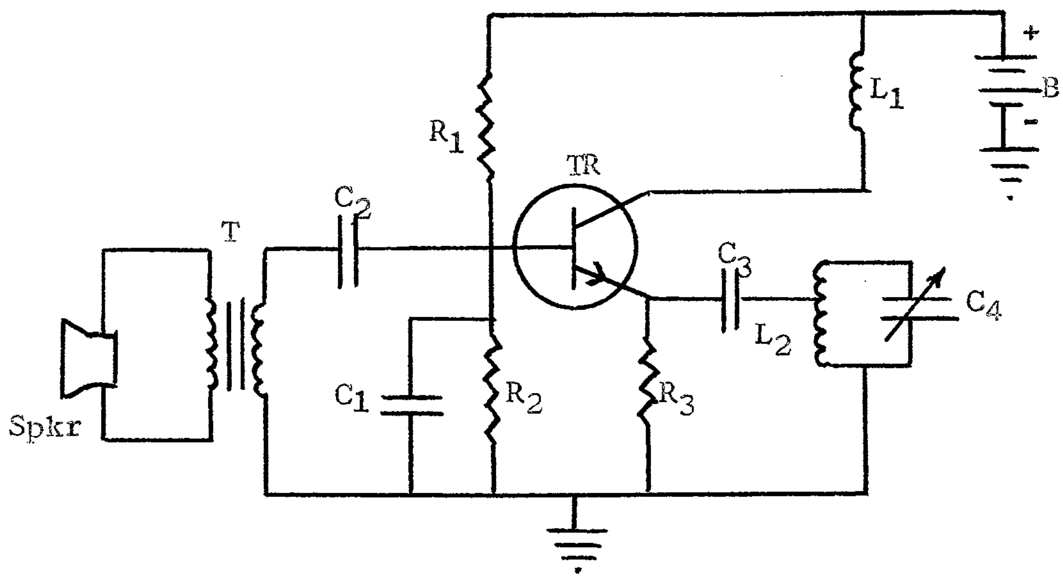

FIGURE 8

WIRELESS BROADCAST BAND PHONO

OSCILLATOR

R_1-- 100,000 ohm, $\frac{1}{2}$ watt resistor
R_2-- 22,000 ohm, $\frac{1}{2}$ watt resistor
R_3-- 1000 ohm, $\frac{1}{2}$ watt resistor
C_1-- .005 mfd. condenser
C_2-- 1 mfd. condenser
C_3-- .01 mfd. condenser
C_4-- 365 mmf. condenser (variable)
L_1-- 60 microhenry inductor
L_2-- 225 microhenry inductor
B -- 6 volt dry battery
T -- 3.2 - 250 ohm audio transformer
TR -- 2N170 transistor

Federal Communications Commission. To put the transmitter in operation, a regular radio receiver should be tuned to a frequency where no stations can be heard. Then, by adjusting the variable condenser C_4, the output circuit of the phono oscillator can be tuned to the same frequency. A regular carbon microphone can be used in place of the speaker, but some experimentation with matching transformers may be necessary to get good results.

For those students interested in photography, the transistorized photo flash unit shown in Figure 9 will be of some interest.[3] In many instances, a photograph could be improved considerably by the use of an additional flash unit properly placed and made to flash at the same time as the flash bulb at the camera. In most instances, the additional flash unit requires bulky equipment and the use of wires connecting the camera and the remote flash unit. With the transistor, however, the unit requires no more space than the camera itself and the wires connecting the flash unit are eliminated by the use of a photocell or sun battery. In actual operation, the photocell or sun battery must be placed such that it will receive part of the light energy from the flash unit at the camera. The energy generated in the circuit will be amplified by the transistor and the relay will close. With the relay

[3] R. L. Winklepleck, "T.S.F. Unit - Transistorized Slave Flash", Popular Electronics, Volume 6, No. 4, April, 1957, pp. 73-74.

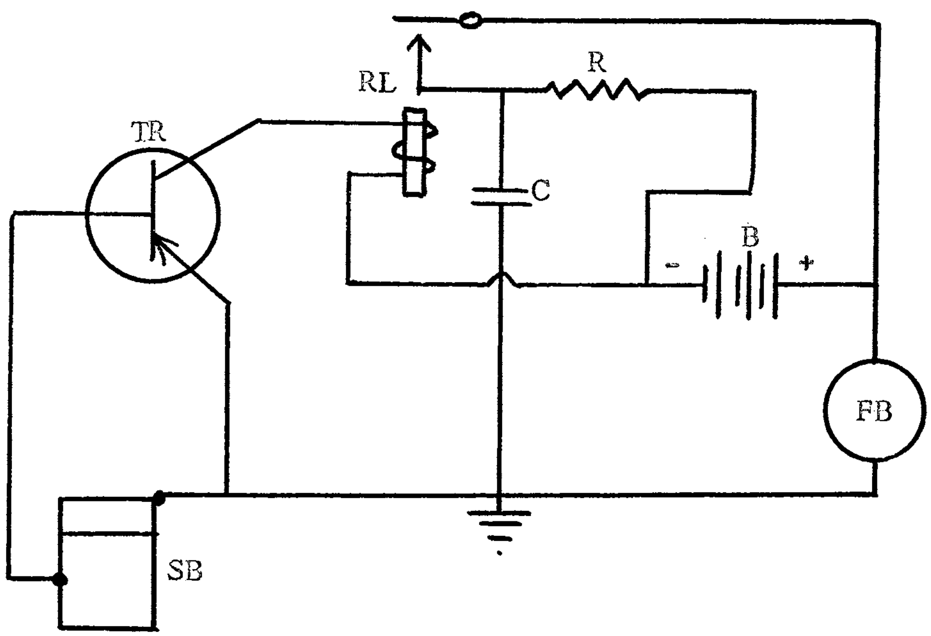

FIGURE 9

THE REMOTE FLASH UNIT

R -- 2500 ohm, $\frac{1}{2}$ watt resistor
C -- 100 mfd, 25 volt electrolytic condenser
B -- 22$\frac{1}{2}$ volt dry battery
RL-- Relay (Advance type SO with 10,000 ohm coil)
SB-- Sun battery - International Rectifier Corp., Type 132 M
FB-- Flash Bulb
TR-- 2N107 or CK722 transistor

closed, the condenser at C_1 will discharge through the flashbulb causing it to flash.

It would be impossible, of course, for the flash at the remote unit to occur at exactly the same instant as the flash at the camera. The greatest delay, however, is in the inertia of the relay and it has been found that two similar bulbs will reach peak light output only about fifteen milliseconds apart.[4] At common camera shutter speeds, this delay will not be serious if the shutter is properly synchronized.

The preceding projects are but a few of the many projects which students will find interesting as well as useful. In addition, the student who is interested in electronics and would like to carry the study of transistors further will find a field which is open to new ideas and experiments.

[4] R. L. Winklepleck, "T.S.F. Unit - Transistorized Slave Flash", Popular Electronics, Volume 6, No. 4, April, 1957, pp. 73-74.

BIBLIOGRAPHY

Albert, Arthur L., Electronics and Electron Devices, New York: The Macmillan Company, 1956.

Garner, Louis E., "Transtopic Experiment No. 15," Popular Electronics, Volume 6, No. 2, February, 1957. p. 85.

Harold, E.N., New Advances in the Junction Transistor, Transistors I, New Jersey: R.C.A. Laboratories, 1956.

Hellman, Charles I., Elements of Radio, New Jersey: D. Van Nostrand Company, Inc., 1956.

Slade, B. N., Recent Advances in Power Junction Transistors, Transistors I, New Jersey: R.C.A. Laboratories, 1956.

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