# SEMICONDUCTOR STRAIN SENSORS

By

CALVIN O. VOGT

Bachelor of Science

Oklahoma State University

Stillwater, Oklahoma

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Thesis Approved:

Herbert L. Jones
Thesis Adviser

Chas. F. Cameron

Robert MacVicar
Dean of the Graduate School

# PREFACE

The resistance strain gage has greatly simplified the testing of materials and structures. It has made possible great advances in design and design economy. The extremely low level signals available from these gages, however, have continually presented a problem to the instrumentation engineer.

In recent years it has been found that certain semiconductors exhibit very high strain sensitivity. Before practical, high output strain sensors could be made available, it was necessary to carefully measure and study the complete properties of these materials. In addition, it was necessary to develop and perfect manufacturing techniques for producing units with reproducible properties in large quantities.

The purpose of this thesis is to provide a brief discussion of the piezoresistive properties of semiconductors and to describe how they were used in the development of a commercially practical silicon strain sensor having a sensitivity 60 to 70 times that of ordinary wire and foil strain gages.

I should like to express my appreciation to Century Electronics and Instruments, Inc., where this research project was conducted, for the release of this material. I especially thank R. A. Broding and Dr. M. A. Xavier for their guidance and suggestions in this project; Esequiel Zarate for assistance in preparing samples and conducting tests; Dr. Xavier for suggestions and criticism of this thesis.

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# CHAPTER I

## INTRODUCTION

The basic discovery that led to the strain gage was announced in 1856 by Professor William Thompson (later Lord Kelvin) to the Royal Society of London.[1] In this paper, Thompson described numerous experiments that he had performed in investigating the electrodynamic properties of metals. Professor Thompson, as well as the members of the Society, must have had unusual stamina, as he read the 225-page paper in its entirety to the Society. Among other findings, he reported that the electrical resistance of certain wires varied with the tension to which the wires were subjected. Many years elapsed, however, before this principle was put to use.

Early resistance type strain gages were rather crude and quite difficult to install and use. They usually consisted of several turns of fine wire wound around insulated pins fastened to the body under test. The development of the bonded wire resistance strain gage converted this laboratory curiosity into a simple, powerful tool for

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[1] W. Thompson (Lord Kelvin), "On The Electrodynamic Qualities of Metals," Phila. Trans. Roy. Soc. (London), Vol. 146 (1856) p. 649

the stress analyst. Simmons at the California Institute of Technology, and Ruge at the Massachusetts Institute of Technology, working independently, in 1938 almost simultaneously perfected techniques for bonding a length of fine wire to the surface to be investigated. When properly bonded, the strain in the surface immediately beneath the wire was transmitted directly to the wire. No longer was it necessary to employ destructive testing to determine points of maximum stress and maximum loads. Even today this achievement is one of the most important in the field of stress analysis. Before a new model aircraft becomes operational, literally thousands of these gages have been cemented on its many members and the stresses encountered under actual operating conditions determined. Except for such things as extension of the operating temperature limits, stability of characteristics with temperature change, and the number of forms and sizes available, the bonded strain gage has remained relatively unchanged from its beginning.

Research in an entirely different field has provided the next large step forward. The discovery and later high development of the transistor has resulted in some quite thorough investigations into the properties of semiconductors. It was only natural that from these investigations should come a new family of semiconductor devices. Some of these are such things as photodiodes, solar batteries, and Hall effect devices. Among their many other properties, C. S. Smith at the Bell Telephone Laboratories in 1953 investigated and reported on the change in resistance of silicon and germanium as the result of applied stresses.[2]

Smith found that the piezoresistive effect was much larger than in previously studied materials and varied in different directions in the crystal structure. Shortly after these original measurements, efforts were made to utilize this phenomenon in microphones for converting the sound wave induced vibrations of a diaphragm into an electrical signal.[3] Later, a transducer for measuring torque and the possibility of making strain gages of silicon and germanium with sensitivities many times that of conventional ones was demonstrated at the Bell Laboratories.[4, 5] Using this as a guide, commercially practical silicon strain sensors have been developed and tested with sensitivities 60 to 70 times that of ordinary strain gages. These sensitivities make possible the measurement of very small strains. In other cases, they allow a great simplification in the strain measurement instrumentation. In the following chapters, the author

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[2]Charles S. Smith, "Piezoresistance Effect in Germanium and Silicon," Physical Review, Vol. 94, April 1954, pp. 42-49

[3]F. P. Burns, "Piezoresistive Semiconductor Microphone," Journal of the Acoustical Society of America, Vol. 29 (1957) p. 248

[4]W. P. Mason and R. N. Thurston, "Use of Piezoresistive Materials in the Measurement of Displacement, Force, and Torque," Journal of the Acoustical Society of America, Vol. 29 (1957) p. 1096

[5]W. P. Mason, "Semiconductors in Strain Gages," Bell Laboratories Record, January 1959, p. 7

will give a brief review of the important parameters and characteristics of conventional strain gages, followed by a description of the theory, development, testing characteristics, and applications of these silicon strain sensors.

# CHAPTER II

## STRAIN GAGE PARAMETERS

In the design and development of a new type of strain gage, as with any other kind of new product, it is well to begin with a review of the important and desired characteristics and how they are being met by devices now on the market. Detailed discussions of wire and foil strain gage parameters and performance are available in the literature (see Bibliography).

### Size and Configuration

To faithfully measure the strain at the surface of a specimen, a strain gage should lie as close as possible to that surface and be of negligible mass. To fit in a variety of places and on irregular surfaces, it should be reasonably small and flexible. Commercially available strain gages are made in a great variety of configurations and sizes. The most commonly used forms are those of a flat grid of very fine wire (.001 inch in diameter or less), or thin foil imbedded in a matrix of cement to a thin flexible insulating carrier. Some typical examples of these gages are shown in Figure 1. They are available in sizes from several inches in length down to gages with only 1/64 inch of active length.

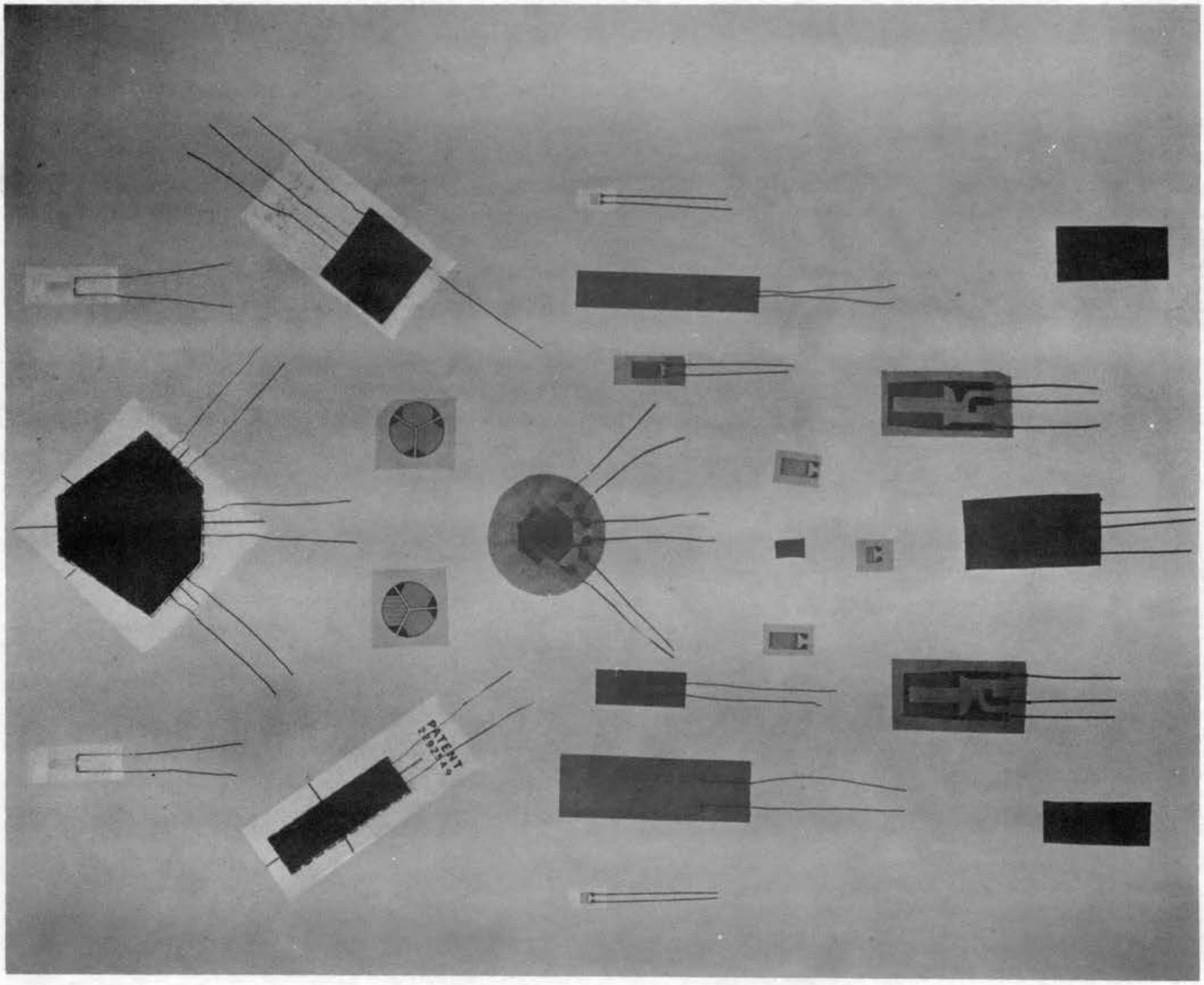


Figure 1. Typical Wire and Foil Strain Gages

(Photo courtesy of Baldwin-Lima-Hamilton Corporation)

## Materials

The materials from which a gage is made should be easy to handle, have stable, repeatable properties with changing temperature, and be relatively inexpensive. The sensitive element should exhibit high strain sensitivity and should be linear over wide ranges of strain magnitude and strain frequency down to and including static conditions.

Two types of wire commonly used as the sensitive element in strain gages are constantan and Iso-elastic. Constantan (more commonly called Advance[6]) is an alloy of 45% nickel and 55% copper. Iso-elastic consists of 36% nickel, 8% chromium, 0.5% molybdenum, and the balance iron and other small constituents. Iso-elastic has a higher strain sensitivity (piezoresistive effect), but is more temperature sensitive than constantan. Strain gages for high temperature use are made of Nichrome wire. Metal foil gages are made of Advance, Nichrome V, and Karma Alloy (composed of approximately 74% nickel, 20% chromium, 3% aluminum, 3% iron).

The materials used for the carrier or backing depend mostly upon the temperature range in which the gage is to be used. For relatively short time tests at room temperature, thin paper has been standard for many years. For higher temperature use and long term room temperature tests, epoxy and Bakelite backings are employed.

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[6] Trade name of wire manufactured by Driver-Harris Corporation

For extremely high temperatures, gages are available with strippable backings that allow mounting the element with only the cement used as support and insulation.

## Sensitivity

A strain sensitivity is defined for the material from which the sensitive element of the gage is made. This strain sensitivity factor is the ratio of the unit change in resistance to the unit change in strain. For a uniform, straight wire, this may be expressed as

$$S_t = \frac{\frac{\Delta R}{R}}{\frac{\Delta L}{L}}$$

where $S_t$ = Strain Sensitivity Factor
$R$ = Resistance
$L$ = Length
$\Delta R$ and $\Delta L$ = corresponding changes in resistance and length, respectively.

Some materials exhibit a linear relationship between unit change in resistance and unit change in strain and, hence, have constant strain sensitivity. In others, the sensitivity varies greatly with strain magnitude. Part of the change in resistance can be accounted for by the strain-induced change in physical dimensions of the material. If this were the only effect, the strain sensitivity for all materials would vary only by the extent to which Poisson's Ratio for that material changes the cross-sectional area. Investigators have found, however, a great difference in the strain sensitivity of different materials. Some, in fact, exhibit negative values (that is, a decrease in resistance with an increase in length). The following analysis will help explain the situation.

For a straight wire of uniform cross section, the resistance in ohms is given by

$$R = \rho \frac{L}{A}$$

where $\rho$ = Specific Resistivity in ohm-cm.
$L$ = Length of Conductor in cm.
$A$ = Area of Cross Section in $cm.^2$

When tension is applied to the wire it will undergo an increase in length and a decrease in cross section. For such an arrangement, it has been shown[7] that the strain sensitivity is given by

$$S_t = \frac{\frac{dR}{R}}{\frac{dL}{L}} = \frac{\frac{d\rho}{\rho}}{\frac{dL}{L}} + (1 + 2\mu)$$

where $\mu$ = Poisson's Ratio.

The quantity $(1 + 2\mu)$ represents the effect of change in dimensions on strain sensitivity. Since, for most metals, Poisson's Ratio is equal to approximately 0.3, the strain sensitivity would be only 1.6 if it were due only to the change in physical dimensions. The great wealth of experimental evidence of strain sensitivities considerably larger than this and the variations found

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[7] W. M. Murray and P.K. Stein, Strain Gage Techniques, (1959) p.4

between metals indicates the significance of the change in resistivity with strain.

It is interesting to note that investigators[8] have found that in all the materials they investigated, the final strain sensitivity, which corresponds to plastic yielding, was about 2. For yielding without change in volume, $\mu = 1/2$ and the term $(1 + 2\mu) = 2$. Hence, $\frac{d\rho/\rho}{dL/L} \approx 0$, and for high strains with yielding and without volume change, it appears that the specific resistivity $\rho$ remains about constant.

The strain sensitivity of materials from which gages are made should, preferably, be high and should be constant over a large strain range. A list of the strain sensitivities of some metals is given in Table I.

TABLE I

STRAIN SENSITIVITY OF SOME METALS

| Material | Strain Sensitivity Factor |
|---|---|
| Manganin | .47 |
| Nickel | -12.1 (non-linear) |
| Nichrome | 2.1 |
| Phosphor Bronze | 1.9 |
| Advance | 2.1 |
| Copel | 2.4 |
| Monel | 1.9 |
| Iso-Elastic | 3.6 |

[8] E. Jones and K. R. Maslen, The Physical Characteristics of Wire Resistance Strain Gages, Her Majesty's Stationery Office, London, 1952

In order to achieve the necessary total resistance and still maintain a relatively short gage element, the wire is usually wound in a flat grid. Since part of the wire which makes up the end loops is not parallel to the direction of strain, it will undergo proportionally less or no resistance change, depending on its actual direction. Hence, the finished gage will exhibit less sensitivity than the unmounted wire. The gage sensitivity or gage factor is the ratio of the unit change in resistance divided by the unit change in strain for the finished gage.

$$\text{Gage Factor} = \frac{\Delta R/R}{\epsilon} .$$

This is one of the important parameters of a strain gage. It must be known for every gage except for those special cases where a calibration curve can be run on the installed gage, such as is the situation in strain gage type transducers.

Also of considerable importance is the transverse sensitivity of a strain gage; that is, the sensitivity of the gage to strains at right angles to the gage axis. A transverse sensitivity factor is defined which is the ratio of the transverse sensitivity of a strain gage to its axial or longitudinal sensitivity. It is desirable that this quantity be very low. The transverse sensitivity factor in wire strain gages varies considerably with gage size and configuration. Typical values range from 1.5% to 3.5%. In most foil gages, the transverse sensitivity factor is 0.5% or less.

## Resistance

The resistance of a strain gage should be sufficiently high to be large compared to the resistance of interconnecting lead wires, switch contacts, etc. The resistance should be low enough to minimize pick-up. Wire and foil strain gages are available having resistances from 60 ohms to more than 5000 ohms; however, certain resistances have become somewhat standard. These are 60 ohms, 120 ohms, 350 ohms, and 1000 ohms.

## Temperature Effects

The effects of temperature on strain gage properties and operation are of great importance. This is particularly true in view of some of the temperature extremes to which gage installations are subjected as the result of work with guided missiles and rockets. Even at quite moderate temperatures, the temperature-induced zero shift, change in effective gage factor, and creep[9] can be of considerable importance. At more severe temperatures, such things as the insulation resistance of the carrier and adhesive and instability in the resistance of the strain sensitive material must also be considered.

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[9]Creep is the change in gage output with time when under load due to slippage in the cement.

Most materials from which wire or foil strain gages are made show only slight change in strain sensitivity with temperature. The apparent loss in gage factor at high temperature reported by many early investigators has been found in more recent years to be mostly the result of weakening of the adhesive used to mount the gage. Where proper cements are used for the temperatures encountered, the variation of gage factor with temperature can usually be neglected. At moderate temperatures, with the use of the proper cement, creep can be held to less than one percent over periods of several hours. At high temperatures, the selection of cement becomes quite critical, and at extremely high temperatures none of the presently available adhesives are satisfactory for long-time creep-free static tests.

The zero shift or apparent strain resulting from temperature change is the result of several combined effects. The primary ones are:

1. The specimen to which the gage is mounted changes in length with temperature.
2. The gage changes in length with temperature.
3. The resistance of the gage changes with temperature.

The combined result of these effects must be zero to eliminate the apparent strain (zero shift) due to temperature changes. Since different metals have different temperature coefficients of expansion, a particular strain gage cannot be self temperature compensated (show small or zero apparent strain as the result of temperature change) for all materials.[10] Also, the temperature coefficients of expansion and resistance change with temperature so that a particular strain gage can only be self temperature compensated over a limited temperature range for a particular material.

Two of the common methods employed in producing self temperature compensated strain gages are the use of selected melts and dual element units. These techniques are outlined below.

The temperature coefficient of resistance of such alloys as Advance can be altered by repeatedly cycling the metal from room temperature to above 500° F. For use below 500° F, the altered temperature characteristics remain fixed and repeatable. By proper cycling, the temperature characteristics can be adjusted to produce gages matched to most of the materials on which strain measurements are normally made. Using this selected melt technique, the temperature-induced zero shift or apparent strain can be held to less than one micro-inch per inch per degree Fahrenheit over a temperature range of several hundred degrees.

The dual element units are composed of two wires, having different temperature coefficients of resistance, connected in series. By properly proportioning the lengths of each type of wire, the

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[10]For instance, a gage that is self temperature compensated on steel would have an apparent strain of approximately 6 micro-inches per inch per degree Fahrenheit when mounted on aluminum.

temperature coefficient of the composite unit can be adjusted. Gages of this type are produced that have apparent strains of less than 0.25 micro-inches per inch per degree Fahrenheit.

## CHAPTER III

## PIEZORESISTANCE IN SEMICONDUCTORS

The theory of piezoresistance in semiconductors has been outlined by Smith[11] and later enlarged upon by others[12, 13] at Bell Telephone Laboratories.

### Mathematical Explanation

For a three-dimensional medium, Ohm's law is a vector relationship between the current density vector $\vec{I}$ and the potential gradient vector $\vec{E}$ . This relationship can be expressed by assigning subscripts to the various components of $\vec{E}$ and $\vec{I}$ . It will be convenient to choose as reference directions the orthogonal crystal axes. The complete equations then are:

[11] Smith, p. 42

[12] F. J. Morin, T. H. Geballe, and C. Herring, "Temperature Dependence of Piezoresistance of High Purity Silicon, Germanium," Physical Review, Vol. 105 (1957) p. 525

[13] C. Herring and E. Vogt, "Transport and Deformation Potential Theory for Many-Valley Semiconductors with Anisotropic Scattering," Physical Review, Vol. 101 (1956) p. 944

$$E_1 = \rho_{11} I_1 + \rho_{12} I_2 + \rho_{13} I_3 \qquad (1)$$

$$E_2 = \rho_{21} I_1 + \rho_{22} I_2 + \rho_{23} I_3$$

$$E_3 = \rho_{31} I_1 + \rho_{32} I_2 + \rho_{33} I_3$$

where the first subscript of each $\rho_{ij}$ indicates the component of the voltage field to which it contributes, and the second identifies the component of the current making the contribution. The generalized equation is

$$E_i = \rho_{ij} I_j \qquad (2)$$

where all subscripts have the range 1 to 3.

For an isotropic medium, $\rho_{ij} = 0$ for $i \neq j$ and $\rho_{11} = \rho_{22} = \rho_{33} = \rho$, so that the set of equations reduces to $\vec{E} = \rho \vec{I}$ in which $\vec{E}$ and $\vec{I}$ are co-linear. Germanium and silicon have cubic crystalline structure and in the unstressed condition are isotropic.

We now add to the relationship (2) the piezoresistive effects. A set of stresses can be represented by $T_{k\ell}$ where k and $\ell$ have the range of 1 to 3. $T_{11}$, $T_{22}$, $T_{33}$ are the normal stresses along the crystal axes and $T_{12}$, $T_{13}$, $T_{23}$ are shear stresses. Equation (2) then takes the form

$$E_i = \rho_{ij} I_j + \pi_{ijk\ell} I_j T_{k\ell} \qquad (3)$$

where $\pi_{ijk\ell}$ are the piezoresistive coefficients. The four-subscript notation is required since these coefficients are characterized not only by i and j (the directions of the voltage and current, respectively), but by k and $\ell$ (the stress directions) as well. However, due to the symmetry of germanium and silicon crystals, and the fact that the zero stress resistivity is isotropic, considerable simplification is possible. First, a substitution in the notation for the subscripts of the piezoresistive coefficients and the stresses is made according to the following table:

$$11 = 1$$
$$22 = 2$$
$$33 = 3$$
$$23 = 4$$
$$13 = 5$$
$$12 = 6$$

The zero stress resistivity $\rho$ is factored out of the coefficients and a new set of piezoresistive coefficients $\pi_{st}$ defined. These are:

$$\rho\pi_{11} = \pi_{1111} \qquad \rho\pi_{12} = \pi_{1122} \qquad \rho\pi_{44} = 2\pi_{2323}$$ 23

Using these substitutions and observing the symmetry of cubic crystals, the new piezoresistive coefficients are given by the following:

| s\t | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| 1 | $\pi_{11}$ | $\pi_{12}$ | $\pi_{12}$ | 0 | 0 | 0 |
| 2 | $\pi_{12}$ | $\pi_{11}$ | $\pi_{12}$ | 0 | 0 | 0 |
| 3 | $\pi_{12}$ | $\pi_{12}$ | $\pi_{11}$ | 0 | 0 | 0 |
| 4 | 0 | 0 | 0 | $\pi_{44}$ | 0 | 0 |
| 5 | 0 | 0 | 0 | 0 | $\pi_{44}$ | 0 |
| 6 | 0 | 0 | 0 | 0 | 0 | $\pi_{44}$ |

Incorporating these into the general equation (3), the following set of equations is obtained:

$$E_1 = \rho I_1 \left[1 + \pi_{11} T_1 + \pi_{12}(T_2 + T_3)\right] + \rho \pi_{44}(I_2 T_6 + I_3 T_5) \qquad (4)$$

$$E_2 = \rho I_2 \left[1 + \pi_{11} T_2 + \pi_{12}(T_1 + T_3)\right] + \rho \pi_{44}(I_1 T_6 + I_3 T_4)$$

$$E_3 = \rho I_3 \left[1 + \pi_{11} T_3 + \pi_{12}(T_1 + T_2)\right] + \rho \pi_{44}(I_1 T_5 + I_2 T_4)$$

The piezoresistive effect in wires and foils as it is known includes only the coefficient $\pi_{11}$ and, hence, involves only co-linear voltages, currents, and stresses. The more complicated behavior of silicon and germanium is obvious.

For use as strain sensors, specimens of small cross section compared to their length are of interest. For these devices we are concerned with a uniaxial state of stress T', current I', and voltage E' in the direction of the length of the semiconductor bar. If the axis of the bar exhibits direction cosines $\ell$, m, n with respect to the 1, 2, 3 crystal axes, it has been shown[14] that

$$E' = \rho I'(1 + \pi_\ell T') \qquad (5)$$

where $\pi_\ell$ , the "longitudinal piezoresistive coefficient" is equal to

$$\pi_{11} + 2(\pi_{44} + \pi_{12} - \pi_{11})(\ell^2 m^2 + \ell^2 n^2 + m^2 n^2)$$

It can also be shown that the factor $\ell^2 m^2 + \ell^2 n^2 + m^2 n^2$ has a maximum in a direction making equal angles with the crystal axes, i.e., the 111 direction. Hence, the maximum absolute magnitude

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[14] Mason and Thurston, p. 1100

of $\pi_l$ will occur either along a 111 direction or along a crystal axis. The values for the fundamental piezoresistive coefficients of germanium and silicon at room temperature as measured by Smith[15] are given in Table II. The longitudinal piezoresistive coefficients are calculated from these as outlined above. The maximum absolute value for both n- and p-type germanium and p-type silicon occurs along the 111 axis, while the maximum for n-type silicon is along any crystal axis (corresponding to $\pi_{11}$). Equation (4) indicates that these coefficients must have the dimensions of $T^{-1}$. The so-called elasto-resistive coefficient $m_l$ is obtained from $\pi_l$ by means of Young's Modulus in the $l$ direction; i.e., $m_l = Y_l \pi_l$. Replacing the tension, T', in equation (5) with $Y \times \epsilon$, where $\epsilon$ is the unit strain, and substituting for $\pi_l$ gives

$$E' = \rho I'(1 + m_l \epsilon) \tag{6}$$

or $$\frac{\Delta\rho}{\rho\epsilon} = m_l \tag{7}$$

Hence, it is seen that $m_l$ is analogous to the "gage factor" defined for wire and foil strain gages in Chapter II. Typical values for wire and foil gages were given as 2.0. The strain sensitivity of properly doped p-type silicon in the 111 direction is given by Table II as 175, or over 85 times that of materials used in conventional gages.

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[15]Smith, p. 44

## TABLE II

## PIEZORESISTIVE COEFFICIENTS

| Material | $\rho$ | $\pi_{11}$ | $\pi_{12}$ | $\pi_{44}$ | $(\pi_{\ell})_{111}$ | $(m_{\ell})_{111}$ | $(m_{\ell})_{100}$ |
|---|---|---|---|---|---|---|---|
| | ohm cm | (in $10^{-12}$ cm$^2$/dyne) | | | | dimensionless | |
| Ge (n-type) | 16.6 | - 5.2 | - 5.5 | -138.7 | -101.2 | -157 | |
| Ge (p-type) | 1.1 | - 3.7 | + 3.2 | + 96.7 | + 65.4 | +101.5 | |
| Si (p-type) | 7.8 | + 6.6 | - 1.1 | +138.1 | + 93.6 | +175 | |
| Si (n-type) | 11.7 | -102.2 | +53.4 | - 13.6 | - 7.6 | | -133 |

## Physical Explanation

The concepts of charge transport in semiconductors by "holes" and free electrons have been thoroughly explained in the literature[16]. Only the basic ideas in their simplest form will be given here as a background for explaining the piezoresistive effect.

In Figure 2-A, a silicon atom is illustrated in which one of the electrons has been separated from its regular location in the structure of lattice bonds. Also shown is an energy diagram. The energy level of an electron in a closed bond is that of the "valance band". The freely moving electron has energy corresponding to the "conduction band". The differential energy (1.11 electron volts for silicon) is liberated in the cancellation or absorbed in the generation of an open bond. When "donor" atoms (elements from the fifth column of the periodic table, such as arsenic) are introduced into the crystal lattice, the situation is as shown in Figure 2-B. The extra electron lacks relatively little energy (0.54 electron volts for arsenic) to be raised into the conduction band. When "acceptor" impurities (elements from the third column of the periodic table, such as boron) are used, an open-bond level is produced that can be reached by a valance electron with the absorption of very little energy (0.08 electron volts for boron). This transfer produces a hole at the location originally filled by the electron.

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[16] C. Herring, "Transport Properties of a Many-Valley Semiconductor," Bell System Technical Journal, Vol. 34 (1955) pp. 251-258

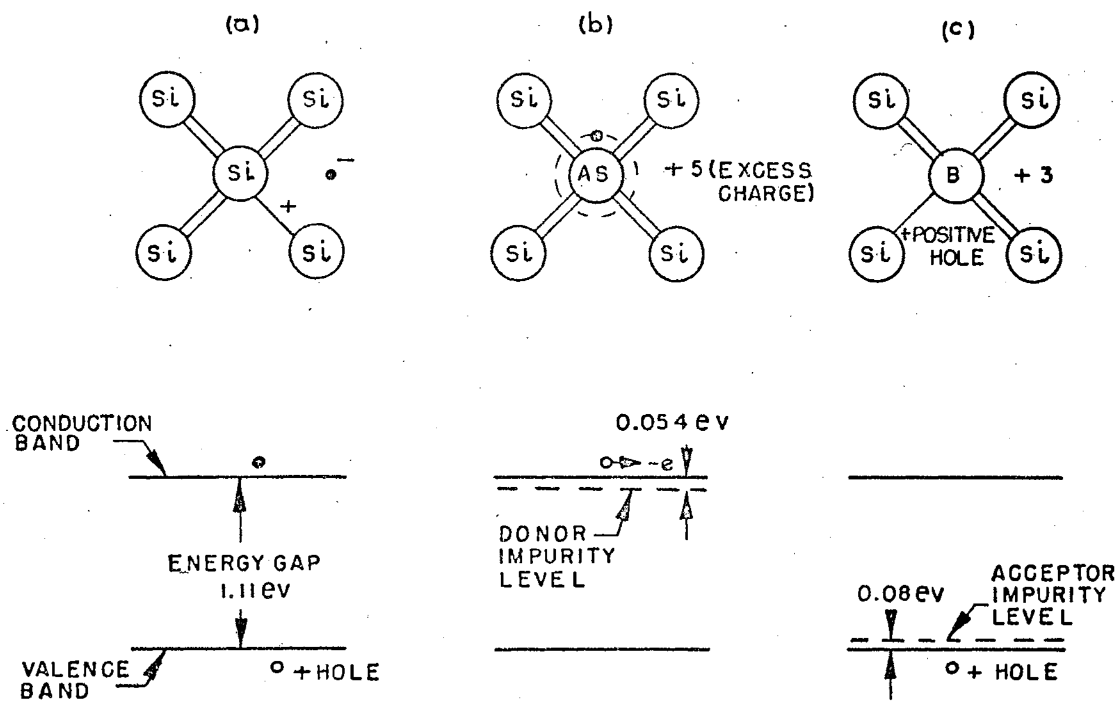


Figure 2. Conduction in Silicon

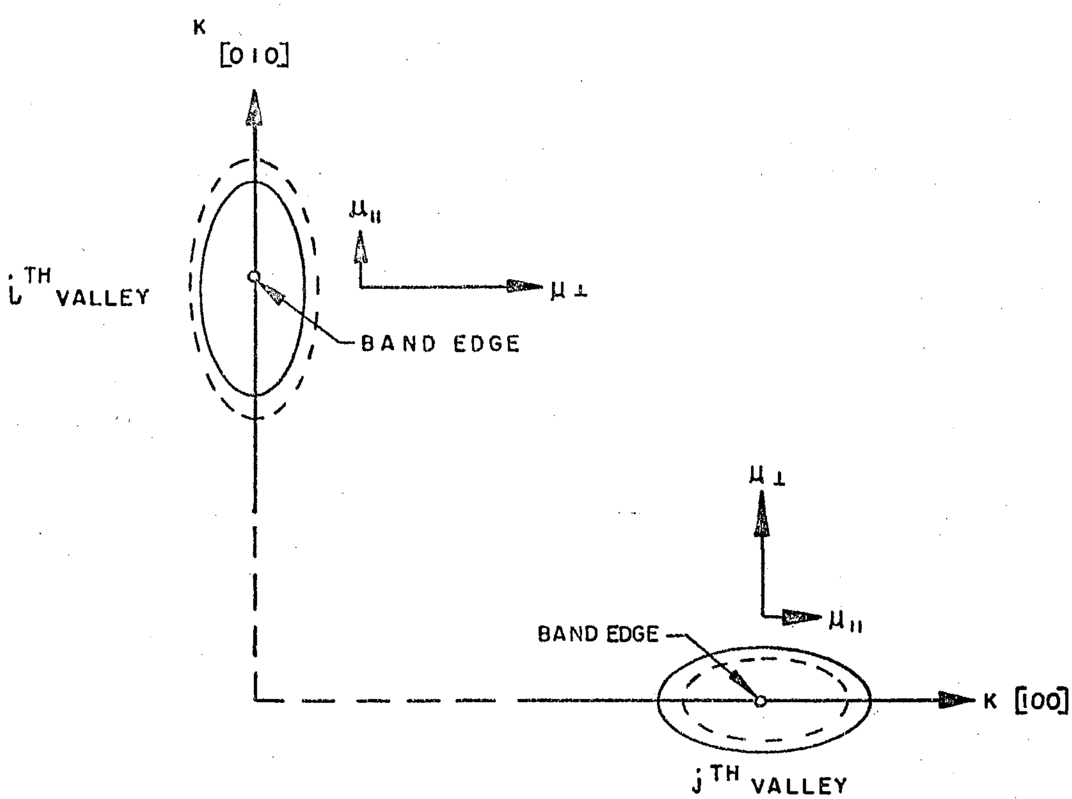


Figure 3. Piezoresistance In N-Silicon

The motion of an electron in the conduction band can be described with quantum mechanics. Wave numbers, $K_1$, $K_2$, $K_3$, are associated with the components of its motion in the 1, 2, 3 directions. An electron may achieve the minimum energy which it requires to remain in the conduction band by several combinations of $K_1$, $K_2$, and $K_3$. These combinations constitute the lower limits of energy required for a free electron. They are thus referred to as "band edge points". These points can be represented by a three-dimensional plot commonly referred to as "K-space", with the three axes corresponding to $K_1$, $K_2$, and $K_3$. Such a plot for n-type silicon is shown in two dimensions in Figure 3 where the $K_1$, $K_2$, $K_3$ axes have been chosen to correspond to the crystal axes. An electron with slightly more energy than that of a band edge point may possess such energy by various combinations of $K_1$, $K_2$, $K_3$. These combinations describe a constant-energy surface surrounding the band edge point. There will be an infinite family of such surfaces about a band edge point. These surfaces define an energy valley in K-space. There are, in general, several band edge points, and, hence, reference is made to a multi-valley model.

In germanium and silicon these constant-energy surfaces consist of prolate ellipsoids of revolution. For the n-type silicon shown, these ellipsoids are aligned with the crystal axes. The elliptical shape of these energy surfaces indicates that the electrons in these valleys have components of effective mass and mobility that vary in different directions. (In Figure 3 the mobility parallel to the crystal axis is indicated by $\mu_{\parallel}$ and that perpendicular by $\mu_{\perp}$ .) Hence, these electrons make anisotropic contributions to the total conductivity of the lattice. However, if all ellipsoids have the same proportions and all valleys are equally populated with electrons, the over-all conductivity of the lattice will be isotropic. This is indeed the case for unstressed silicon and germanium.

The application of an anisotropic stress causes an increase in the minima in some valleys and a decrease in others, as indicated by a shift from the full to the dashed positions of the energy surfaces. Under these conditions electrons will transfer from higher energy valleys to lower energy ones. The total number of electrons in these valleys will also change. The over-all result is the introduction of an anisotropy into the total conductivity of the crystal lattice.

## CHAPTER IV

## DEVELOPMENT OF A 50-OHM SILICON STRAIN SENSOR

P-type silicon was chosen for making the strain sensors since it exhibits the largest piezoresistive effect. A doping concentration of $1.3 \times 10^{19}$ boron atoms per cubic centimeter of silicon melt was selected from curves of resistivity variation with temperature[17]. This value produces p-type silicon with a relatively constant resistivity over the temperature range of -200°C. to 100°C. At room temperature, the resistivity is approximately 0.01 ohm-centimeters.

A silicon ingot was "grown" from a seed crystal in a crystal puller. The ingot was 3/4 inch in diameter and 3 to 4 inches long. The ingot was carefully orientated with x-ray defraction equipment and then slices .006 to .008 inch thick were cut, using diamond saws. From these slices, bars approximately .006 inch wide and .4 inch long were cut. The slices were orientated so that the length of the bar was a 111 crystal direction within ± one degree. As was pointed out earlier, this is the axis of maximum strain sensitivity in p-type silicon.

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[17]W. Shockley, Electrons and Holes in Semiconductors, D. Van Nostrand Co., New York (1950) p. 284

A gold wire .005 inch in diameter and containing 1% of gallium was attached to each end of the bar. The gold was fused to the silicon in a furnace at 500°C. Gallium is a donor material and is necessary to produce an ohmic contact between the gold and the p-type silicon.

The units were then etched in an acid solution to remove irregularities from the surface of the silicon resulting from the sawing. The dimensions of the bar and the resistivity chosen resulted in units with slightly less than 50 ohms resistance. They were left in the etch solution until their cross section had been reduced sufficiently to raise their resistance to approximately 50 ohms.

The units appeared as shown in Figure 4-A. The silicon bars were approximately .006 inch by .006 inch in cross section and had straight, smooth sides. The size of the bars was uniform from end to end. The gold-silicon junctions were ohmic and quite strong. The units themselves were rather fragile and required handling with tweezers. Approximately fifty (50) units of this type were built and tested.

The resistance variation with temperature in the unmounted condition was first measured. The units were placed in a thermostatically controlled oven with lead wires extending outside for making resistance measurements. Approximately 30 minutes were allowed for the temperature to stabilize before making resistance measurements. Temperature was measured with a thermocouple and potentiometer. Low temperatures were obtained by disconnecting the heater and

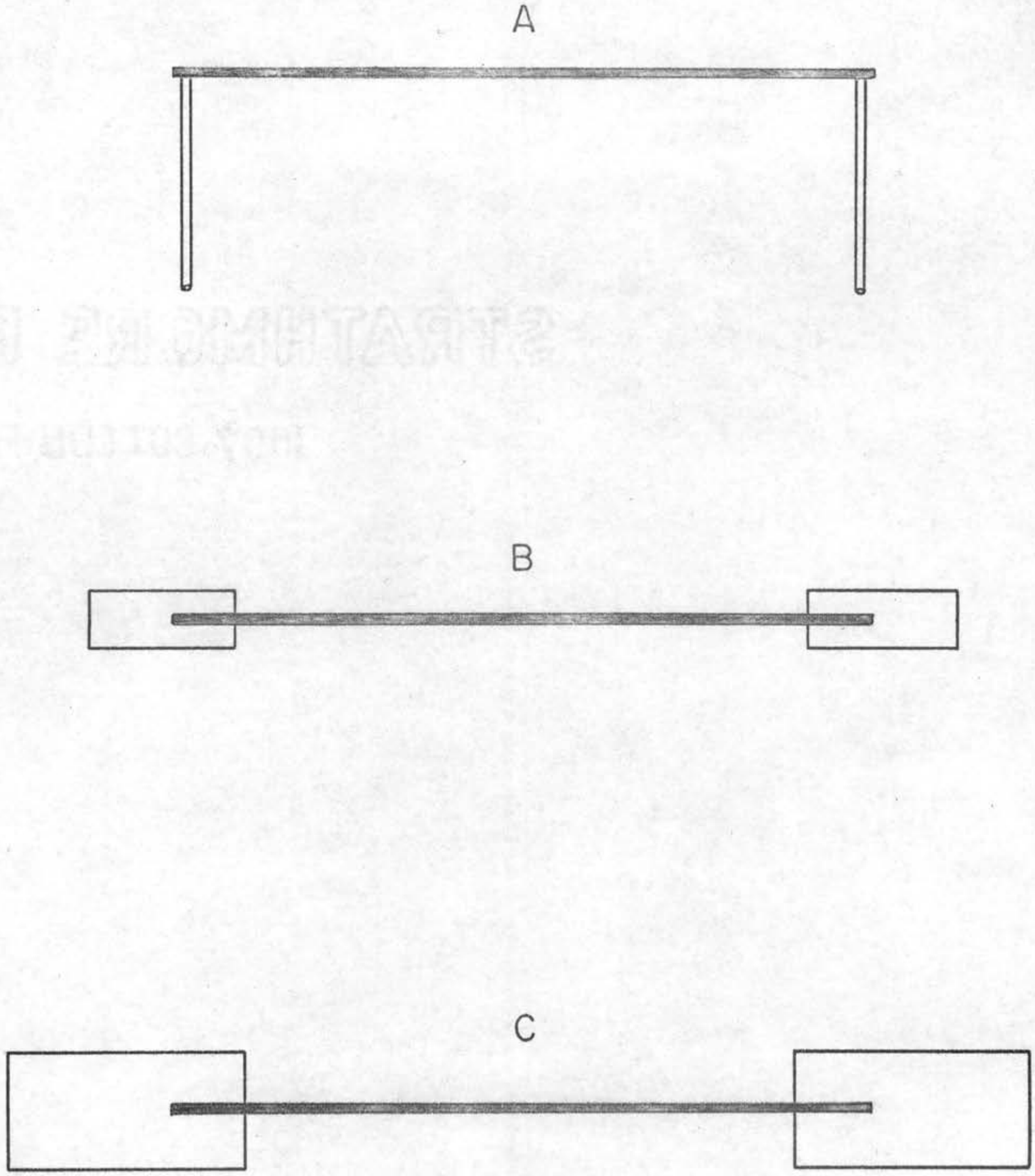


Figure 4. Sensor Configurations

placing dry ice in the oven. The resistance was measured on a Shallcross Wheatstone bridge at a current level of approximately 15 milliamperes. The polarity was reversed during the tests in order to detect the presence of rectifying contacts. The curves of several of these units are shown in Figure 5. There was a maximum difference of resistance with voltage reversal of 0.2 ohms. A sample element of approximately the same configuration was obtained from Dr. Mason of the Bell Telephone Laboratories. Data from this unit (indicated on Figure 5 by "B.T.L.") are shown for comparison. The agreement between units is quite good.

The resistance variation with current was measured on one of the units in free air to determine the effect of self heating. The results are shown in Figure 6. The unit was operated at a current of 200 milliamperes for several minutes. At this current level the silicon glowed red. The current was then reduced to 10 milliamperes and the temperature allowed to stabilize. The resistance returned to very near its original value. It is apparent that the self heating at 15 milliamperes is not sufficient to significantly affect the results of the resistance variation with temperature.

To test the strain properties of the sensors, a test fixture incorporating a cantilever beam was constructed. The beam consisted of an aluminum bar 3/4 inch wide, 1/8 inch thick, and 10-1/2 inches in unsupported length. This bar was clamped in a

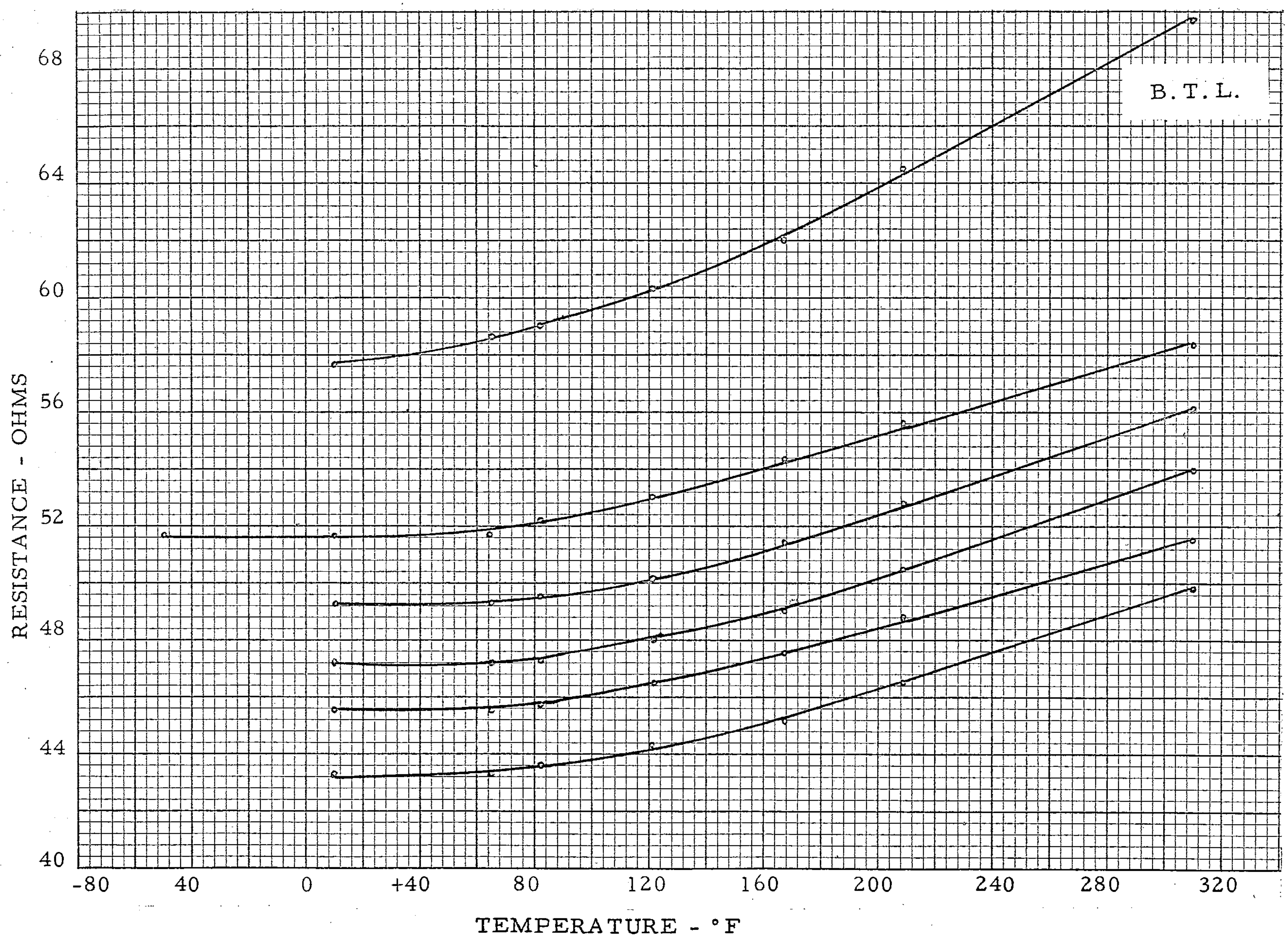


Figure 5. Resistance Temperature Characteristics - Unmounted 50-Ohm Sensor

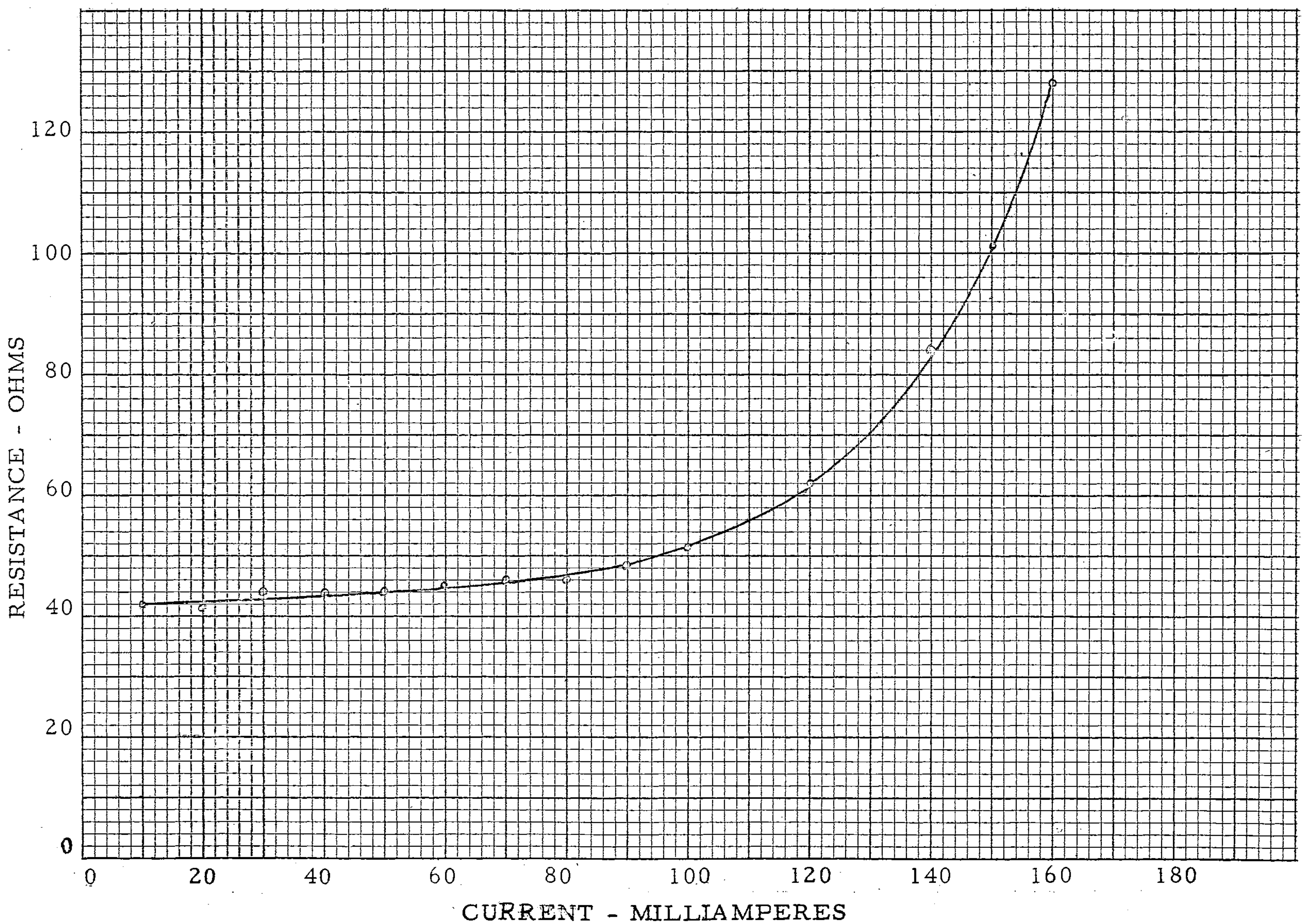


Figure 6. Resistance Current Characteristics - Unmounted 50-Ohm Sensor

rigid support and a means of deflecting the beam the thin way at a point ten inches from the restrained end was provided.

The elastic strain in the outer fibers of a cantilever beam is given by the formula

$$\epsilon = \frac{3/2\ yhx}{L^3} \qquad (8)$$

where
$\epsilon$ = Unit Strain (dimensionless - in. /in.)
y = Deflection of the beam at the point of loading in inches
h = Beam Thickness in inches
x = Distance from the point of loading to the point under consideration in inches
L = Length of the beam from fixed end to the point of loading in inches.

The test units were cemented to the beam at a point approximately 3-1/3 inches from the fixed end. A nitrocellulose cement (Ambroid) was used for bonding and a thin piece of paper was used to insulate the silicon from the aluminum beam. The cement was allowed to cure at least 24 hours at room temperature before testing. The beam was deflected in increments and the resistance measured on a Wheatstone bridge. The average strain in the surface of the beam beneath the test unit is directly proportional to deflection and can be computed from equation (8) above. A plot of resistance change versus deflection for one of the units is shown in Figure 7. The data for the unit obtained from Dr. Mason are included for comparison. The maximum deflection corresponded to a strain of approximately 500 micro-inches per inch of tension.

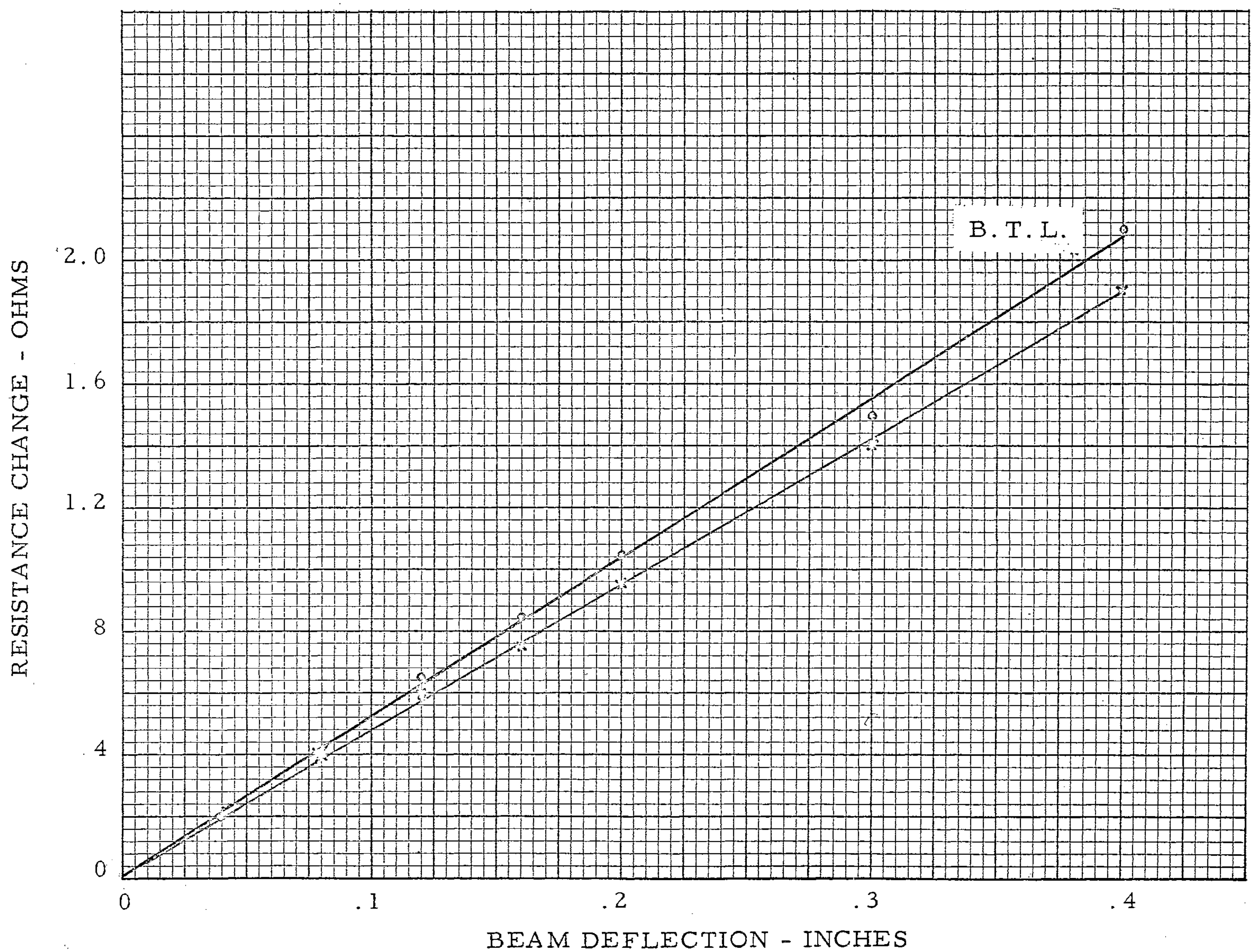


Figure 7. Load Test - Mounted With Nitrocellulose Cement

Approximately ten units were tested. The strain sensitivities of these units were calculated from the formula used for calculating gage factor for wire and foil gages as given in Chapter II.

$$\text{Strain Sensitivity} = \frac{\Delta R}{R} \times \frac{1}{\epsilon}$$

The sensitivities ranged from 61 to 80.

Another group of the elements was mounted on a test beam using Epibond 121. This is a two-component epoxy cement manufactured by the Furane Plastic Company. The cement was cured at 180°F for 30 minutes before testing. The sensitivity of these units varied from 90 to 122. To verify that the higher sensitivity was due to cement strength, some of the units previously mounted with Ambroid were removed with solvent and re-mounted with Epibond 121. All of the units had a higher sensitivity than when mounted with Ambroid cement.

The bond strength for a long, thin member is proportional to the ratio of the surface area per unit length to the cross section area of the element. For the .001 inch and .0005 inch wire commonly employed in wire gages, this ratio is between 4000 and 8000. For the silicon bars, this ratio was only approximately 600.

One method of improving this ratio would be to make the bar thin and wide. For instance, a bar .001 inch thick and .008 inch wide would have a ratio of 2500. Manufacturing difficulties, however, made it impractical to reduce the size below .006 inch.

It was suggested that the surface area could be increased significantly by texturing the surface of the bars. The finished bars were quite smooth as a result of the acid etching. Several of the units were subjected to a very fine sand blast. This produced a roughened surface that appeared knurled. While this increased the bond strength somewhat, it made the units much more fragile and was abandoned for this reason.

The approach that produced the most satisfactory results was that of providing a cementable anchor at each end of the silicon bar. Some units were built in which the gold wires at the ends of the bar were replaced with metal tabs having considerable surface area. Kovar was selected for making the tabs since it has a coefficient of thermal expansion near that of silicon[18]. Hence, there would be no appreciable temperature-induced strain in the connection. In order to obtain an ohmic bond to the silicon, it was necessary to gold-plate the Kovar. The tabs were approximately .035 inch by .092 inch and .0035 inch thick. The units appeared as shown in Figure 4-B. The silicon bar overlapped the tab approximately .050 inch at each end. Ten units of this type were built. The doping and size of the silicon element were the same as the previous units.

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[18] Silicon has an expansion coefficient of approximately 1.4 parts per million per degree F. at room temperature.

Most of these units were found to have rectifying contacts between the gold and silicon. The resistance of some units changed as much as 8 ohms on polarity reversal. Those units with ohmic contacts had temperature resistance curves quite similar to the units with wire leads. The resistance of the units with rectifying contacts varied quite differently with temperature and current. It was determined that the rectifying junctions occurred as the result of improper doping in the gold. No further tests were made on these units because the rectifying contacts made them unsuitable for use as strain gages.

The next elements were constructed using tabs .003 inch thick, .150 inch long, and .075 inch wide. They appeared as shown in Figure 4-C. The tabs were made larger to increase the cementing surface area and to facilitate making solder connections to the elements. The gold was carefully checked to insure proper doping. These units had ohmic contacts. Their temperature resistance curves were very similar to those of the units with wire leads.

The large tabs made it possible to test these units directly in axial tension and thereby determine their true strain sensitivity, independent of cement efficiency. A .003 inch steel wire was soldered axially to each end tab. A jig was constructed for applying different tensile loads to these wires by means of a movable weight on a pivoted beam. The resistance was measured on a Non-Linear Systems, Inc. digital ohmmeter as the load was varied.

The strain in the silicon bar can be calculated from the load and the modulus of elasticity and cross section area of the silicon bar using the following formula:

$$\epsilon = \frac{w}{A} / Y$$

where $\epsilon$ = Unit Strain (dimensionless)
w = Load in lbs.
A = Area in in.$^2$
Y = Modulus of Elasticity = $26.7 \times 10^6$ lbs./in.$^2$

At least 15 units were tested in this manner. For all units the resistance change was essentially linear with strain. The cross sections were carefully measured with a micrometer. The strain sensitivities as determined from the equation of Chapter II ranged from 80 to 91. These values are somewhat below that predicted by the curve of sensitivity vs. doping for p-type silicon.[19]

Since the sensitivity is quite dependent on crystal orientation, another group of elements was made in which the crystal orientation was quite carefully controlled. When tested in tension with the previously described test jig, their sensitivities were found to range from 114 to 125, which is in general agreement with the theoretical curves. The resistance change with load for several of these units is shown in Figure 8. The resistance change with temperature of these units was very similar to that of the wire lead units shown in

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[19] Private communication from Dr. W. P. Mason

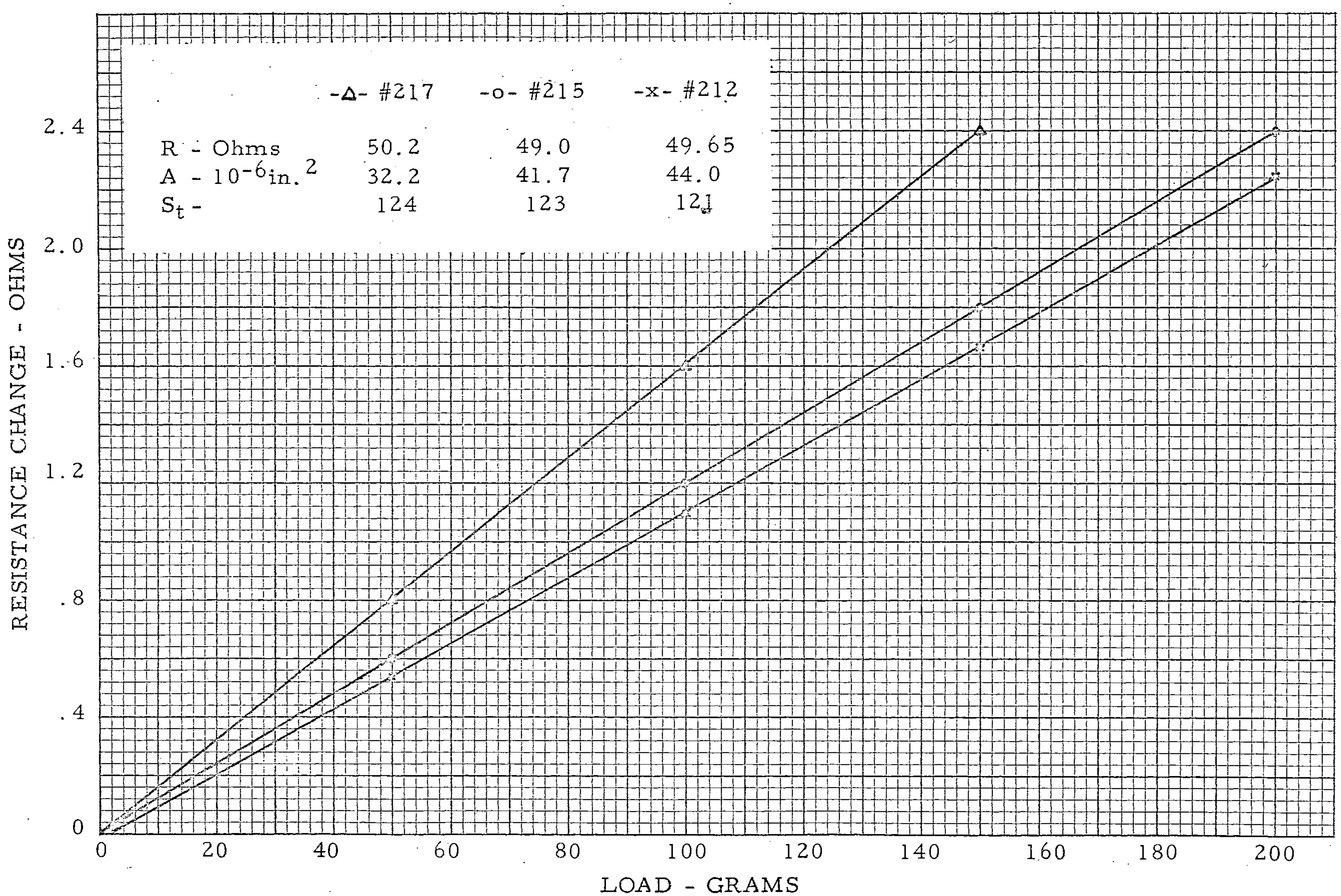


Figure 8. Load Characteristics - 50-Ohm Sensors

Figure 5. The variations between units were small. In Table III below are listed some of the parameters and their variation for this group of 13 units.

TABLE III

50-OHM SILICON STRAIN SENSOR PARAMETERS

| Parameter | No. of Units Tested | Range | Mean |
|---|---|---|---|
| Resistance - Ohms | 13 | 46.9-53.0 | 50.0 |
| Cross Section Area - $10^{-6}$in.$^2$ | 13 | 30.7-44.0 | 37.8 |
| Strain Sensitivity | 11 | 114-125 | 122 |

These results indicated that 50-ohm silicon strain sensitive elements could be manufactured with repeatable characteristics. A survey of strain gage users being conducted simultaneously indicated a 120-ohm unit would be more standard and compatible with existing instrumentation. Hence, development and tests were begun to provide a higher over-all resistance.

## CHAPTER V

## DEVELOPMENT OF A 120-OHM SILICON STRAIN SENSOR

The resistance could be increased by any one of the three following methods or combinations thereof:

1. Increasing the length
2. Decreasing the cross section area
3. Increasing the resistivity of the silicon.

Attempts were first made to decrease the cross section of the silicon bars by leaving them in the etching solution for longer periods of time and by using stronger etching solutions. It was found that while 120-ohm units could be produced in this manner, the bars were no longer uniform. The end portions of the silicon bars reduced in size considerably more than the center portion. This resulted in elements that were too weak to be of general use.

Rather than increase the length of the unit, it was decided to increase the resistivity of the silicon. This can be quite easily done by reducing the amount of doping material (boron) added to the silicon melt in the crystal growing operation.

Twelve groups of elements were made covering the resistivity range of .015 ohm-cm. to .031 ohm-cm. There were at least four units in each group. Each group was etched until the over-all resistance of the individual units was approximately 120 ohms. All of the units with resistivities below .03 ohm-cm. showed some "necking" of the silicon bar at the ends when viewed under a microscope. In the lower resistivity units, the effect was more pronounced from their having been in the etch solution for a longer period of time.

Samples were selected from the entire range of resistivity and tests conducted to determine resistance change with temperature. It was found that in the temperature range of 75°F. to 350°F. with higher resistivity, the resistance increased more rapidly with temperature. At somewhat below room temperature, the resistance had a minimum and increased with further reduction in temperature. This is in general agreement with the curves of resistivity variation with temperature as given by Shockley.

A nominal resistivity value of .024 ohm-cm. was selected to insure that the elements would etch uniformly and to maintain as low as possible a resistance change with temperature. Experience had shown that by accepting a resistivity range of .004 ohm-cm. the major portion of the silicon crystal could be used. Thus, the resistivity range was established at .022 ohm-cm. to .026 ohm-cm.

In handling the units, a number had been broken due to the sharp corners of the tab becoming caught during handling. Accordingly, it was decided to provide tabs with rounded corners on the final units.

In order to verify the characteristics and reproducibility, a pilot production run of 500 units was completed. The physical configuration of these units was as shown in Figure 9. From this group, a random sample of 50 units was selected for extensive testing. Table IV lists some of the properties measured and the results obtained.

TABLE IV

120-OHM SILICON STRAIN SENSOR PARAMETERS

| Parameter | No. Tested | Result |
|---|---|---|
| Bar Thickness | 50 | .0055 in. - .0064 in. |
| Bar Width | 50 | .0053 in. - .0068 in. |
| Resistance | 50 | 120 ohms ± 5% |
| Strain Sensitivity | 25 | 122 ± 5% |
| Maximum Strain | 5 | All units exceeded 2000 micro-in. /in. |
| Linearity | 8 | |
| 500 micro-in. /in. | | Better than 1% |
| 2000 micro-in. /in. | | Better than 2-1/2% |
| Hysteresis | 8 | None detectable |
| Bending Radius | 4 | All units would conform to a radius of 3 inches |

In addition, such things as temperature characteristics and self heating effect were measured. A curve of resistance variation with current for one of the units installed on a test bar is shown in

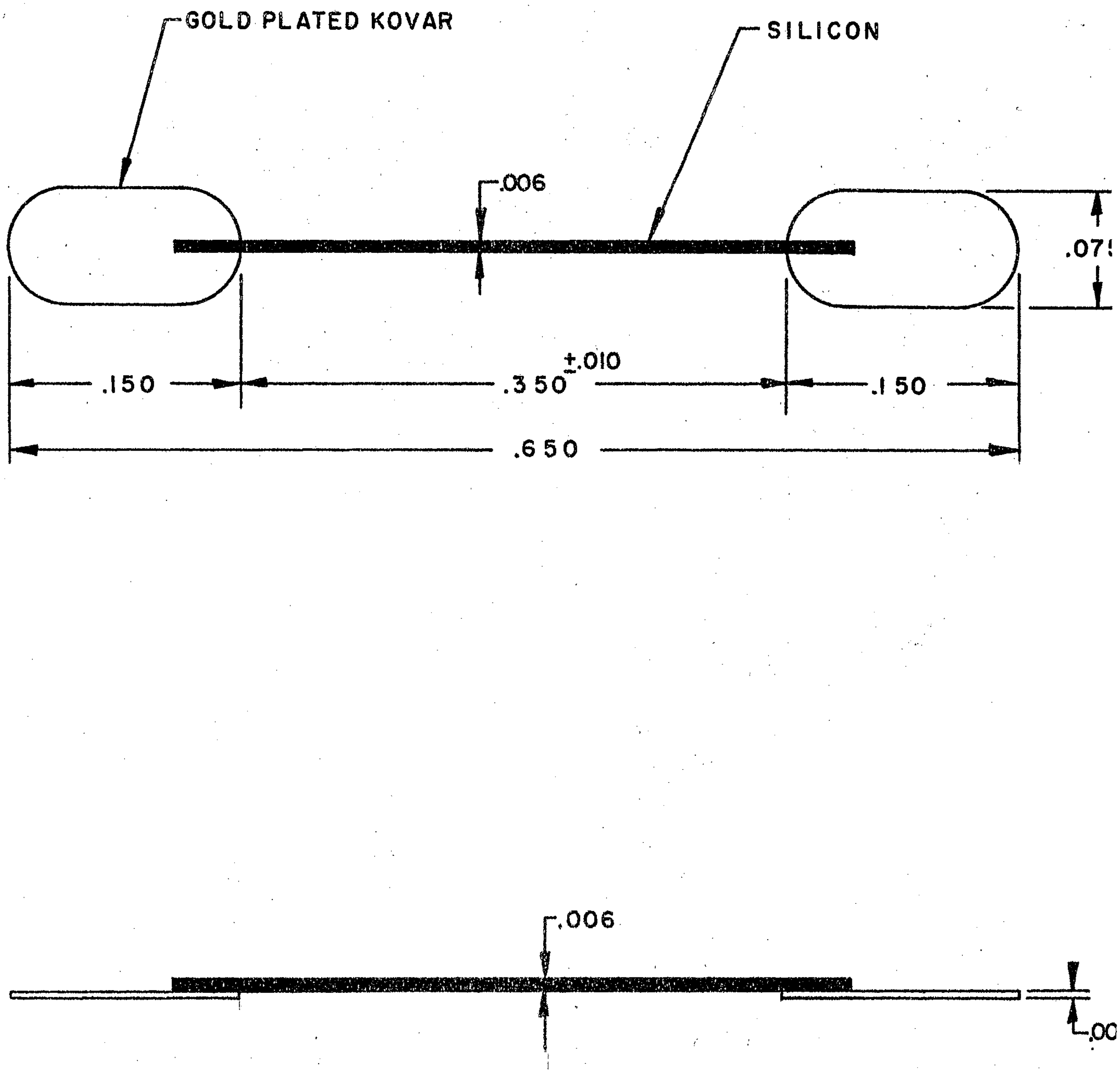


Figure 9. Dimension Drawinq 120 Ohm Sensor

Figure 10. There is very little self heating effect at current levels below 30 milliamperes. Above this value, the resistance increases quite steeply. The temperature characteristics are discussed in detail in a later chapter.

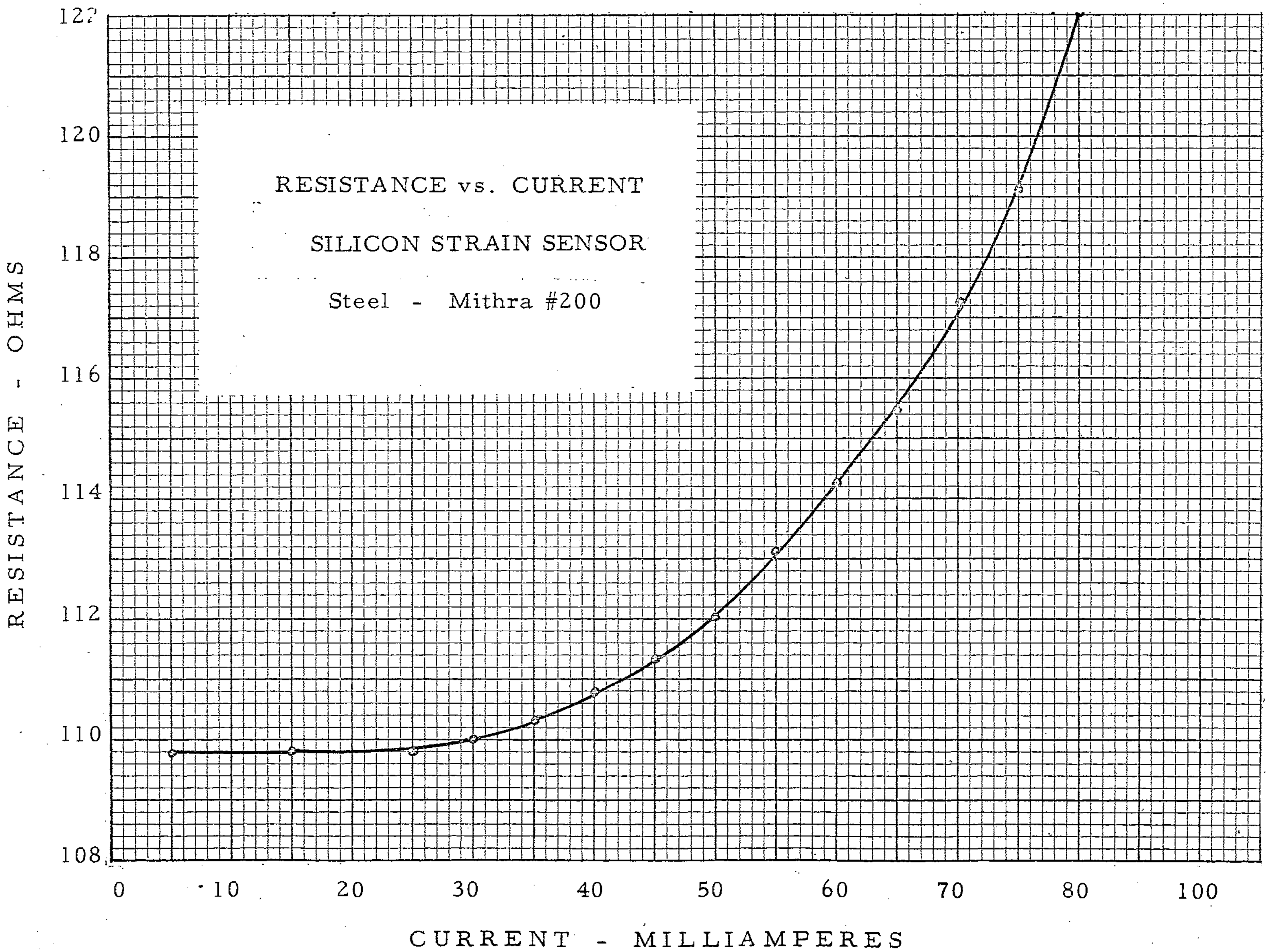


Figure 10. Resistance Current Characteristics - Mounted 120-Ohm Sensor

## CHAPTER VI

## ADHESIVES AND INSTALLATION TECHNIQUES

The adhesive used to attach the strain sensor to the test specimen is an important part of the system. It must faithfully transmit the strain from the specimen to the sensor and provide adequate insulation resistance over the temperature range to be encountered. Concurrently with the development of the silicon sensors themselves, tests were conducted to evaluate adhesives and develop simple, reliable installation techniques.

Numerous adhesives have been evaluated with wire and foil strain gages. Some have been developed specifically for this purpose. Table V lists some of the adhesives tested and evaluated with the silicon sensors.

One of the primary means of evaluating the adhesives was to test their creep properties. Sensors were cemented to a cantilever beam test bar following the manufacturer's recommended instructions and cure schedule. A constant load was applied and the resistance change with time at a constant temperature was measured. Tests were conducted at elevated as well as room temperature. Tests were also made to determine mounting efficiency. The

TABLE V

ADHESIVES TESTED

| Adhesive | Type | Manufacturer |
|---|---|---|
| SR-4 | Nitrocellulose | Baldwin-Lima-Hamilton, Inc. |
| EPY-150 | Epoxy | Baldwin-Lima-Hamilton, Inc. |
| EPY-400 | Epoxy | Baldwin-Lima-Hamilton, Inc. |
| Ambroid | Nitrocellulose | Ambroid Company |
| Eastman 910 | Modified Cyanoacrylate | Eastman Chemical Products, Inc. |
| Armstrong A-2 | Epoxy | Armstrong Products Company |
| Areldite 502 | Epoxy | Ciba Company, Inc. |
| Bondmaster 620 | Epoxy | Rubber & Asbestos Corporation |
| Bondmaster 648T | Epoxy | Rubber & Asbestos Corporation |
| Bondmaster 688 | Epoxy | Rubber & Asbestos Corporation |
| Mithra 200 | Epoxy | Mithra Engineering Company |
| Epibond 121 | Epoxy | Furane Plastics, Inc. |
| RX-1 | Ceramic | Baldwin-Lima-Hamilton, Inc. |
| H Cement | Ceramic | W. T. Bean Jr. Company |

unmounted strain sensitivity was measured as outlined previously. The units were then installed and the mounted sensitivity measured.

The most consistently good results were obtained with the following adhesives in the temperature ranges noted:

EPY-150 - well below zero to 150° F.

Eastman 910 - 0° F. to 200° F.

Mithra 200 - room temperature to above 450° F.

Both EPY-150 and Eastman 910 can be cured at room temperature. Mithra 200, as most high temperature cements, requires elevated temperatures to develop sufficient bond strength.

In all installations that were cured at elevated temperature, the sensor was found to be in compression when cooled to room temperature. This occurred because at the temperature at which the cement hardened, the test bar was expanded more than the silicon. Upon cooling, the bar contracted, carrying the sensor with it. This can be used to an advantage as outlined below.

One of the things that can limit the high temperature use of these silicon strain sensors is their relatively low expansion coefficient. On some materials, at high temperatures, the differential expansion between the silicon and the test specimen can be sufficient to introduce considerable strain. This will limit the magnitude of the strain level which can be used. By using a cement that cures at a temperature near the middle of the range to be encountered, the temperature-induced strain will be only one-half as much as would result from use of a cement that cured at one end of the temperature range. Since most high temperature cements require elevated temperature cure, this condition is ordinarily achieved. In addition, for room temperature tests that are known to involve only tensile strains, the strain range can be extended by the pre-compression resulting from elevated temperature cure. The magnitude of this pre-compression can easily be made as high as 1400 micro-inches per inch.

The first silicon strain sensors were handled and installed using tweezers. This was rather tedious and required considerable skill. A number of the units were broken. To remedy this, a handling fixture was developed that permitted simple installation without having to touch the sensor itself. A photograph of a handling fixture and attached strain sensor is shown in Figure 11. The fixtures were coated with a release agent to which the cements would not adhere strongly. The strain sensors were lightly attached to the fixture with a weak adhesive such as watch crystal cement. The installation procedure is as follows.

The area to which the sensor is to be attached is first thoroughly and carefully cleaned and degreased. A thin coat of cement is applied to the test area and at least partially cured. Another layer of cement is applied on top of the first coat and the strain sensor is pressed into the cement, handling it by the attached fixture. The cement is then cured. After cooling, the

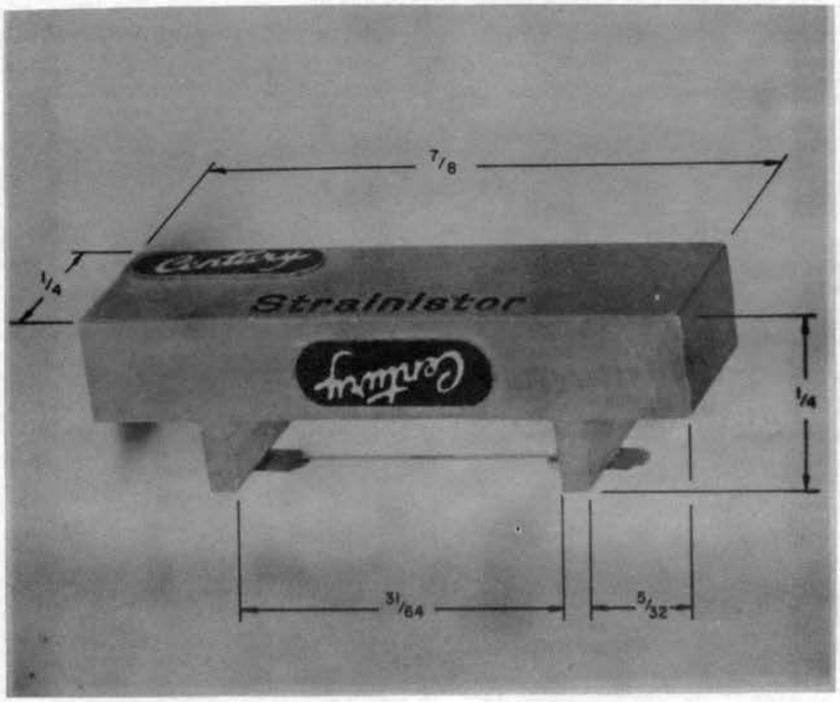


Figure 11. Handling and Installation Fixture

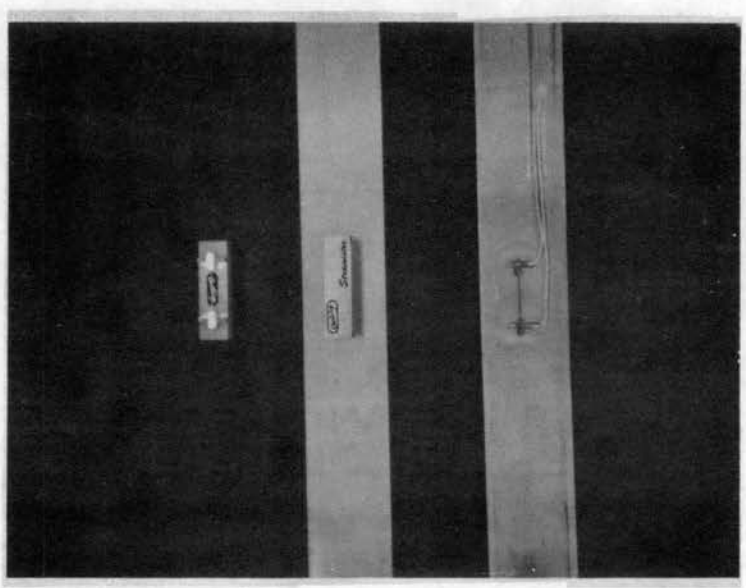

Figure 12. Installation Procedure

fixture can be removed with a slight pull. Lead wires can be attached by soldering or spot welding (for high temperatures) directly to the end tabs in the areas exposed by removal of the fixture. These steps are illustrated in Figure 12.

A curve of resistance variation with load for a sensor mounted with Mithra 200 cement using the above procedure is shown in Figure 13. The specimen was tested in tension in a Dillon Tensile Testing Machine. The maximum load corresponded to a strain of approximately 890 micro-inches per inch.

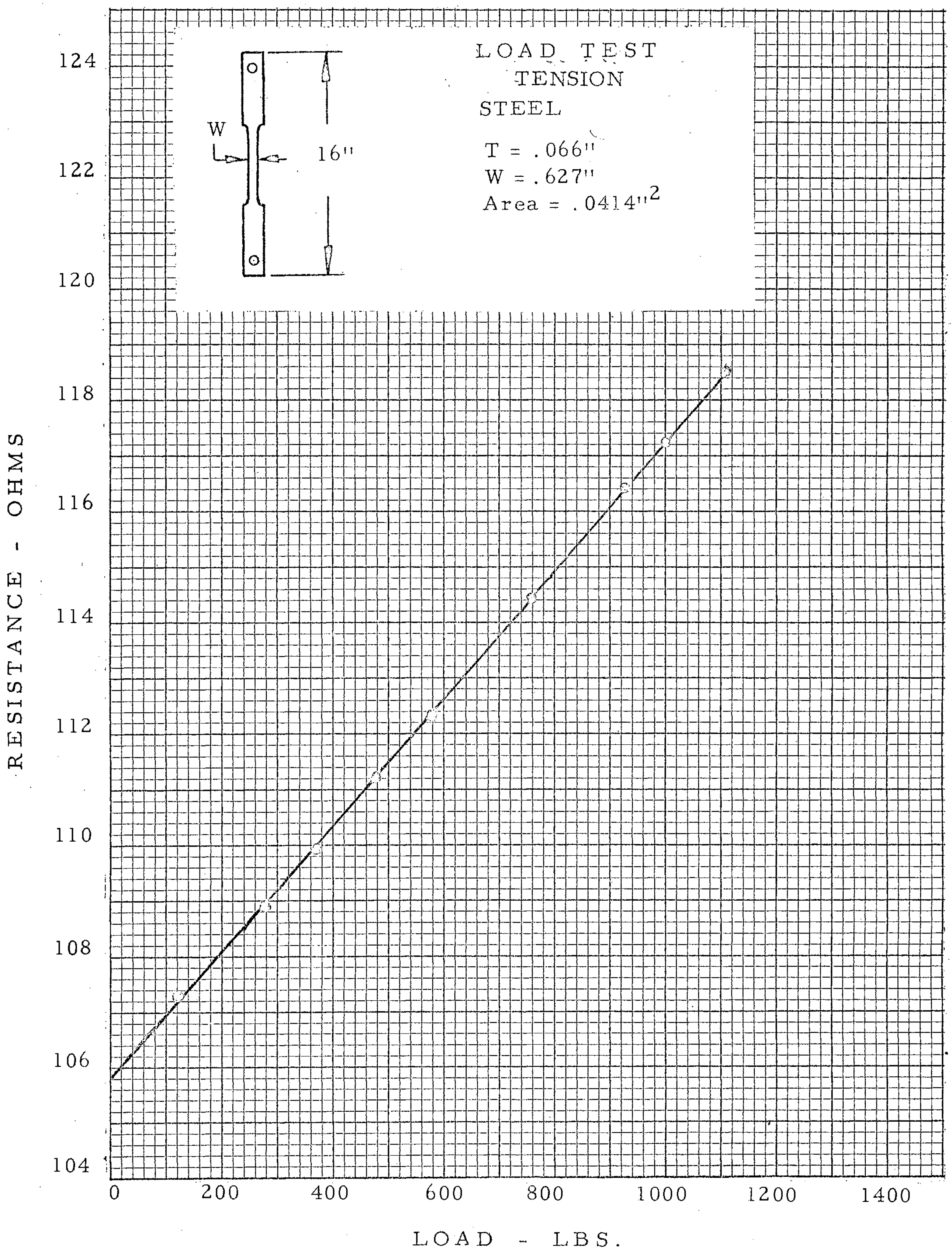


Figure 13. Resistance-Load Characteristics - Mounted 120-Ohm Sensor

# CHAPTER VII

# TEMPERATURE EFFECTS

The manner in which the properties of the silicon strain sensors change with temperature is discussed below. Some schemes for compensating these effects are suggested. The temperature limits within which the sensors can be used are also discussed.

## Temperature Characteristics

With change in temperature, there is both a change in resistance and a change in strain sensitivity in the silicon. The manner in which the resistance changes with temperature for the 50-ohm units is shown in Figure 5, and the differences for the 120-ohm unit were noted in Chapter V. As was pointed out in Chapter II, the total resistance change, or zero shift, with temperature for an installed sensor is the combined result of this change and the strain-induced change due to the difference in expansion between the silicon and the test material. Figure 14 shows the resistance change with temperature, as a percent of the 75°F. resistance, for typical 120-ohm silicon sensors when mounted on both aluminum and steel. In the room temperature and above region,

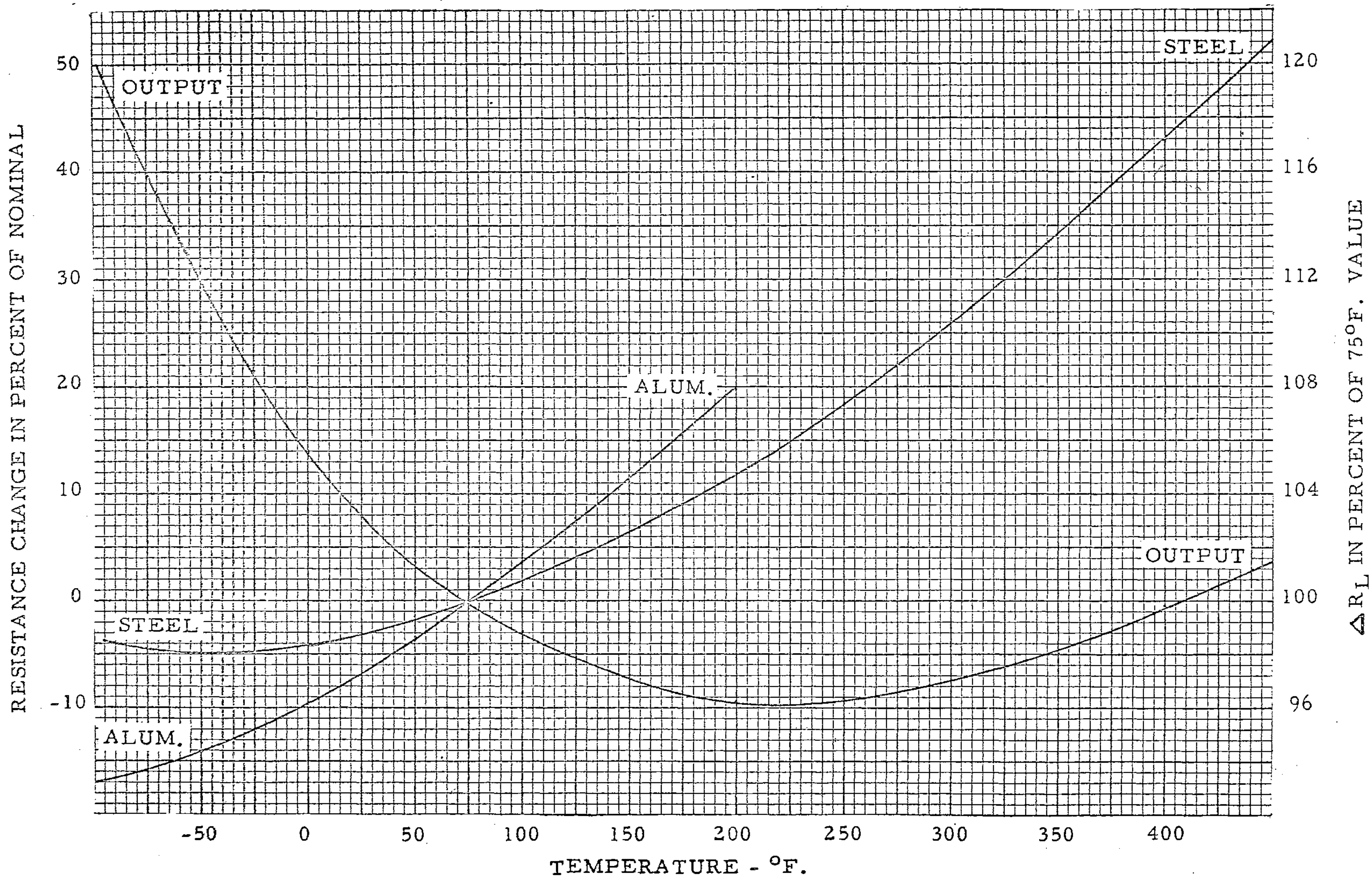


Figure 14. Mounted Temperature Characteristics

both effects produce an increase in resistance with temperature. From approximately 25° F. to below -100° F., the sensors are self temperature compensated on steel. In this region, the resistance increase with decreasing temperature is cancelled by the resistance decrease due to temperature-induced compression. At room temperature, the apparent strain is approximately 6 micro-inches per inch per degree Fahrenheit on steel, and 12 micro-inches per inch per degree Fahrenheit on aluminum. This is comparable to typical uncompensated wire and foil strain gages.

The piezoresistive coefficients have been shown to vary as 1/T (where T is in degrees Kelvin), both experimentally and theoretically.[20] The jig used for measuring the unmounted sensitivity was modified so that the load could be varied while the sensor was enclosed within an oven. The strain sensitivity of a 120-ohm unit was measured at several temperatures between 75° F. and 250° F. A curve of the calculated theoretical change in sensitivity with temperature is shown in Figure 15. The experimentally determined points are marked. The agreement is quite good.

The sensitivity at each temperature was determined by dividing the resistance change due to load by the unstrained resistance at that temperature. In a properly designed circuit, the voltage or

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[20] Morin, Geballe, and Herring, p. 525

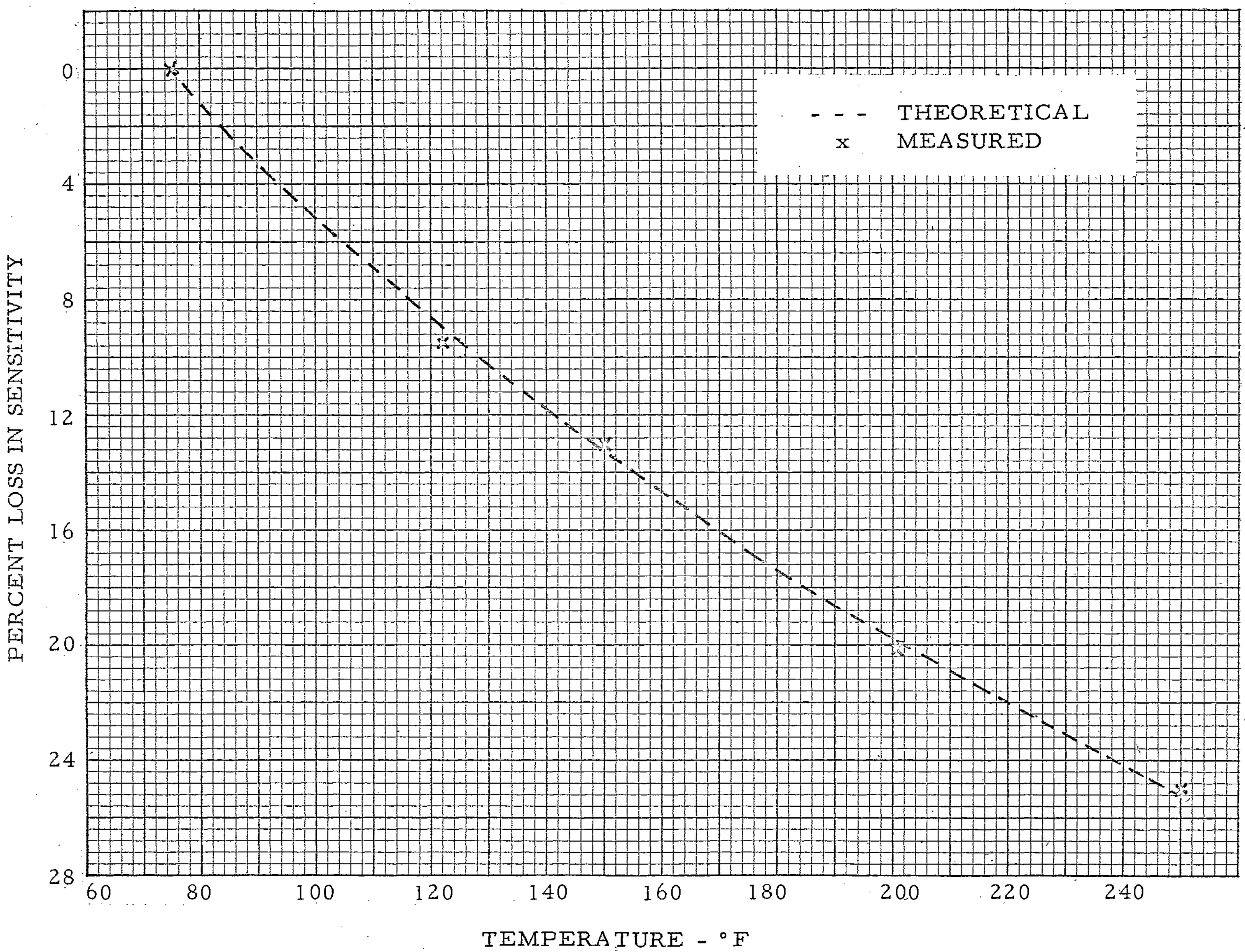


Figure 15. Sensitivity Change With Temperature

current output will be proportional to the actual change in resistance rather than the percentage change. Since the unstrained resistance increases with temperature, the loss in output with temperature will not be as great as indicated by Figure 15. A curve of percent change in load-induced output with temperature for a typical 120-ohm silicon strain sensor mounted on a test bar is shown in Figure 14. At somewhere near 225° F. the rate of increase in resistance is equal to the rate of decrease in sensitivity. Above this temperature, the actual resistance change per applied strain begins increasing even though the absolute sensitivity continues to decrease. Below room temperature, the sensitivity increases fairly rapidly down to at least -100° F. (no tests were conducted below this temperature).

## Temperature Compensation

There are several ways in which the zero shift or apparent strain due to temperature change can be compensated. The one most straightforward and simple is the use of a "dummy gage". This technique is employed quite extensively with wire and foil strain gages. A gage is mounted on the same material and near the active gage in such a manner that it is subjected to the same temperature as the active gage, but is not subjected to strain. Placing these two gages in adjacent arms of the Wheatstone bridge circuit will cause the resistance changes due to temperature to cancel at the output. This procedure is equally applicable to silicon strain sensors.

Other techniques that can be used include the following:

1. The use of a small thermistor mounted near the sensor to provide a resistance change with temperature that can be employed in the circuitry to balance out the resistance change in the sensor.

2. The use of a small thermocouple mounted near the sensor to provide a voltage that can be used to cancel the voltage at the output due to temperature-induced resistance changes in the sensor.

When measuring dynamic strains, the strain will ordinarily change more rapidly than the temperature. The resistance change due to temperature can be easily filtered out and no compensation for zero shift is necessary. One method for compensating the change in sensitivity due to temperature is to control the voltage applied to the circuit by the use of a temperature-sensitive device, such as a thermistor, mounted near the sensor. This control could also be introduced at the output of the bridge, but would have the disadvantage of changing the effective source impedance as seen by the indicating instrument.

In almost all instances a small thermocouple can, of course, be mounted near the sensor for recording temperature directly, simultaneously with strain, and the appropriate corrections made for both zero shift and sensitivity change, using the curves of Figure 14.

Some of the temperature effects that are important with wire and foil gages are almost insignificant with the silicon strain sensors. The zero shift or bridge unbalance due to the resistance change with temperature of the lead wires of a wire or foil gage installation can be considerable. The magnitude of these changes is usually insignificant, compared to the resistance change in the silicon when measuring strains of average magnitude. This is also true of other parasitic resistances such as slip rings and switching boxes. With wire and foil strain gages, the leakage resistance of the cement may significantly affect readings at high temperatures. With the silicon sensors, lower insulation resistance can be tolerated.

## Temperature Extremes

The materials from which these sensors are made can withstand very high temperatures. The melting points of both gold and silicon are above 1000° C. The "intrinsic" temperature of silicon is near 700° C., above which it loses its piezoresistive characteristics. However, the maximum operating temperature of these sensors is limited by the gold-silicon junction. The eutectic temperature is approximately 450° C. Above this temperature, there will be a migration of the gold into the silicon, changing the doping level. A maximum operating temperature of 700° F. (371° C.) is quoted to provide a good margin of safety.

The piezoresistive properties extend well into the cryogenic temperatures. The piezoresistive coefficients vary as 1/T (where T is in degrees Kelvin) well down into this temperature region.

## CHAPTER VIII

## APPLICATION

The silicon strain sensors can be employed in the conventional strain gage circuits and with the instrumentation used with wire and foil gages. The high sensitivity makes it possible to measure very low strains with the conventional instrumentation. In cases of higher strains, it many times makes possible a simplification in the instrumentation.

It has been shown[21] that the maximum voltage sensitivity of a strain gage, regardless of the circuit in which it is used, is given by the following relationship:

$$S_{v_{max}} = R_g \times I_{g_{max}} \times G.F.$$

where $S_{v_{max}}$ = Maximum Voltage Sensitivity in microvolts per micro-inch per inch

$R_g$ = Gage Resistance in ohms

$I_{g_{max}}$ = Maximum Gage Current in amperes

G. F. = Gage Factor or Sensitivity

[21] Murray and Stein, p. 141

Using a current of 30 milliamperes, the maximum voltage sensitivity of the 120-ohm silicon sensor is .45 millivolt per micro-inch per inch. The actual sensitivity will be less than this maximum, but can easily reach 90 percent with proper circuit design. For an equal arm Wheatstone bridge, the sensitivity is always 50 percent of maximum. With one active sensor in an equal arm Wheatstone circuit, the output would be .225 millivolts per micro-inch per inch. For a 2000 micro-inch per inch strain, the open circuit output would be .45 volts. This can be read directly with a high impedance sensitive voltmeter without the need of amplification. With a properly designed bridge circuit, this output can be as high as .81 volts. Similarly, the maximum current sensitivity in microamperes per micro-inch per inch is given by:

$$S_{I_{max}} = I_{g_{max}} \times G.F.$$

For the 120-ohm silicon sensor, this quantity is 3.75. As before, the efficiency of an equal arm bridge is 50 percent. For one active sensor and a 2000 micro-inch per inch strain, the current output is 3.75 milliamperes and, by proper circuit design, can be made as high as 6.5 milliamperes. This can be read without amplification on a simple meter. In the case of dynamic strains, it is also large enough to drive many high-frequency galvanometers directly.

Some precautions concerning circuitry must be observed in the use of these sensors. In the use of strain gages, it is ordinarily assumed that the output of a Wheatstone bridge circuit is linear with strain (that is, resistance change in the strain gage or gages). For the small resistance changes involved in wire and foil gages, this is ordinarily a fair assumption. For resistance changes of over 20 percent, as are possible with the 120-ohm silicon sensors, this is not always true. For an equal arm Wheatstone bridge circuit with one active sensor, the open circuit output voltage can depart from linearity by as much as 10 percent at full scale strain (2000 micro-inches per inch). For an equal arm bridge with two active sensors (one in tension and the other in compression), the departure from linearity will be only 2 percent for full scale strain.

In either case, the linearity can be improved by the use of higher resistance in two arms of the bridge. For instance, using a value nine times that of the sensor resistance, the linearity will be improved by a factor of five; that is, to 2 percent for one active sensor and less than .5 percent for two active sensors. These circuit conditions which improve linearity are the same as those that improve circuit efficiency, which is indeed fortunate.

## CHAPTER IX

## SUMMARY AND CONCLUSIONS

In the foregoing chapters, the parameters and characteristics of wire and foil strain gages were first outlined as a background. The piezoresistive properties of semiconductors were presented and the manner in which they were employed in the development of an ultra-sensitive silicon strain sensor was reported. Several problems, such as lead attachment and obtaining high bond strengths, were overcome. In addition, a simple means for handling and mounting these relatively fragile elements was devised.

The properties of these strain sensors were investigated and reported. The temperature characteristics were discussed in detail and some schemes for compensating these effects were suggested.

A few of the properties of these sensors (notably the conformability and temperature characteristics) fall slightly short of wire and foil gages. However, their many advantages greatly outweigh these undesirable characteristics. Their high sensitivity overcomes the problems encountered with the low level signals associated with wire and foil strain gages. In many cases, they can eliminate the need for expensive DC amplifiers. Using these silicon strain sensors, it is possible to construct transducers with a full scale output of five volts, sufficient to drive a telemetry channel directly. As has been the case with other semiconductor devices, as experience in their usage increases and the ingenuity of circuit and instrumentation engineers is brought to bear, additional ways to overcome or compensate the temperature effects will be found.

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# VITA

Calvin Oscar Vogt

Candidate for the Degree of

Master of Science

Thesis: SEMICONDUCTOR STRAIN SENSORS

Major Field: Electrical Engineering

Biographical:

Personal Data: Born in Guthrie, Oklahoma, March 19, 1931, the son of Oscar B. and Freda A. Vogt.

Education: Attended grade school in Arkansas City, Kansas, and Mulhall, Oklahoma; graduated from Guthrie High School, Guthrie, Oklahoma, in 1949; received the Bachelor of Science Degree from the Oklahoma State University in May, 1953, with a major in Electrical Engineering; completed requirements for the Master of Science Degree in August, 1960.

Experience: Bell Telephone Laboratories, Member of Technical Staff, 1953-1954; Signal Corps, Microwave Operation and Maintenance Officer, 1954-56; Century Electronics and Instruments, Inc., Project Engineer, 1956 to present.

Organizations: Member of Eta Kappa Nu, Institute of Radio Engineers, and American Physical Society.