MEASUREMENTS OF RESISTIVITY
IN POLYCRYSTALLINE THIN FILMS
OF GERMANIUM

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ABSTRACT

Thin films of amorphous germanium were prepared by evaporating 99.999% pure germanium in a vacuum of 10^{-5} torr. Thickness was the only parameter knowingly varied from one evaporation to the next. Resistance measurements were made over a temperature range of 173°K to 373°K. From electron microscope transmission studies, the films were found to contain a large density of grain boundaries. Assuming grain boundary scattering to be the predominant scattering mechanism in films thickner than 800°A, the grain boundary density is found to be 2.59×10^{12} per cm^2. Resistivity versus thickness studies of the films revealed that a thickness dependent scattering mechanism predominated in films thinner than 700°A.

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I. INTRODUCTION

The purpose of this thesis is twofold: first, to describe evaporation techniques for the films and, second, to evaluate the significance of the following temperature dependent scattering mechanisms on the current carriers in a thin film sample:

(1) Lattice scattering

(2) Ionized impurity scattering

(3) Grain Boundary scattering

(4) Thickness dependent scattering

as well as the one temperature independent scattering mechanism:

(1) Neutral impurity scattering.

The samples for which the resistance versus temperature characteristics were studied were thin films of amorphous germanium. The only parameter that was knowingly vaired in the samples was thickness, which varied from 100°A to 10,000°A. The theoretical approach used for this thesis is based upon the band theory[+] of semiconductors

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[+] For the reader unfamiliar with the theory used in the physics of semiconductors, an excellent treatment of the basic measurable parameters can be found in Physics of Semiconductors, by A. F. Ioffe, (8) chapter one. Another detailed approach to basic parameters and a good treatment of the band theory of solids can be found in Introduction to Solid State Physics, by Charles Kittel (10).

which applies not only to single crystal samples but also to poly-crystalline and amorphous films (8, p. 132).[‡] Many correlative examples between theoretical and experimental results for thin film parameters can be found in The Hall Effect and Related Phenomena, a Semiconductor Monograph by E. H. Putley (15).

As will be shown in the theoretical development, the effective relaxation time due to the different scattering mechanisms is given by

$$\frac{1}{\tau} = \frac{1}{\tau_{\text{Lattice}}} + \frac{1}{\tau_{\text{Ionic}}} + \frac{1}{\tau_{\text{Neutral}}} + \frac{1}{\tau_{\text{Grain Boundary}}} + \frac{1}{\tau_{\text{thickness}}} .$$

The mechanisms are usually present in varying degrees in thin film samples. Since mobility and relaxation time are directly proportional, the total mobility can be written as[+]

$$\frac{1}{\mu} = \frac{1}{\mu_L} \quad \frac{1}{\mu_I} \quad \frac{1}{\mu_N} \quad \frac{1}{\mu_{GB}} \quad \frac{1}{\mu_{Th}} .$$

When this expression for mobility is substituted into the equation for resistivity, one obtains the following expression

$$\rho_{\text{total}} = \frac{1}{q\,[N_{ex} e^{-\epsilon_{ex}/2kT} + N_{in} e^{-\epsilon_{in}/2kT}]} \quad \frac{1}{\mu}$$

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‡ First number refers to bibliographical index, second, to page number.

\+ For a quick reference of the final equations of mobility and a brief discussion of their significance, one should consult Solid State Physics by Adranus J. Dekker (3, pp. 329-334).

$$\rho_{total} = \rho_L + \rho_I + \rho_N + \rho_{GB} + \rho_{Th}$$

and since

$$R = \frac{\rho_{total} L}{A} = \frac{L}{A}[\rho_L + \rho_I + \rho_N + \rho_{GB} + \rho_{Th}]$$

letting $N_T = N_{ex}e^{-\epsilon_{ex}/2kT} + N_{in}e^{-\epsilon_{in}/2kT}$

the above expression can be written to show its temperature dependence in the following form

$$R = \frac{L}{AN_T}[\alpha_L T^{3/2} + \alpha_I T^{-3/2} + \alpha_N + \alpha_{GB} T^{-1} + \alpha_{Th} \frac{1}{(thick)} 4T^{-1}] .$$

Many characteristics of the thin films and the procedures used in preparing them have been left unexplored in this thesis. Possibilities for future investigations will be suggested in the section on results.

II. THEORETICAL DEVELOPMENT

The first part of the introduction deals with the development and discussion of several basic parameters used in the study of thin films. The bulk of the theoretical development is devoted to the scattering mechanisms and their evaluation. The mechanisms discussed are lattice scattering, ionic impurity scattering, neutral impurity scattering, grain boundary scattering, and thickness dependent scattering. In the last part of the theory, the expressions for the total effects on resistivity and reciprocal mobility are developed.

It is of interest to the reader to understand the units and their conversions used in this thesis; therefore, a short section has been included in the appendix listing some of the basic parameters in the practical and c.g.s. systems.

Theoretical Parameters

Starting with the electrical definition of force being equal to the charge times the electric field and integrating this expression, one obtains the velocity that an electron acquires in the period of time between collisions.

$$m\frac{d\underset{\sim}{v}}{dt} = q\underset{\sim}{E}$$

$$\int_0^v d\underset{\sim}{v} = \frac{q\underset{\sim}{E}}{m}\int_0^\tau dt$$

$$\underset{\sim}{v} = \frac{q\underset{\sim}{E}}{m}\tau .$$

When the average values of velocity and life time are used, the expression can be written as

$$\underset{\sim}{\bar{v}} = \frac{q\underset{\sim}{E}}{m}\bar{\tau} .$$

Now by using the definition of mobility as the ratio of average velocity to electric field

$$\underset{\sim}{\mu} = \frac{\underset{\sim}{\bar{v}}}{\underset{\sim}{E}} = \frac{q}{m}\bar{\tau} .$$

The average life time $\bar{\tau}$ can also be defined as the mean free path $\bar{L}$ divided by the average velocity $\bar{v}$

$$\bar{\tau} = \frac{\bar{L}}{\bar{v}}$$

which when substituted into the equation of mobility yields,

$$\mu = \frac{q}{m}\frac{\bar{L}}{\bar{v}}$$

substituting the life time dependent mobility term into the equation for conductivity yields

$$\sigma = N_T q \mu$$

$$\sigma = N_T q \frac{q\bar{\tau}}{m} = \frac{N_T q^2 \bar{\tau}}{m} .$$

The average life time for a typical film 1/6-A whose thickness is 2120^{o}A and conductivity is $0.5(\text{ohm-cm})^{-1}$ can be calculated as follows:

$$\sigma(\text{esu}) = \sigma(\text{pract}) \times 9\text{x}10^{11}$$

$$\sigma(\text{esu}) = 4.5\text{x}10^{11}\ \text{sec}^{-1}$$

$$\bar{\tau} = \frac{\sigma m}{N_T q^2} \qquad \text{Assuming } N_T = 10^{18} \text{carriers/cm}^3$$

$$\bar{\tau} = \frac{(4.5\text{x}10^{11})(9\text{x}10^{-28})}{(1.0\text{x}10^{18})(5.0\text{x}10^{-10})^2}$$

$$\bar{\tau} = 1.62\text{x}10^{-15}\ \text{sec.}$$

This value can be understood physically if one assumes that an electron moving with thermal velocity at room temperature is scattered by two grain boundaries every 100^{o}A. Using these physical assumptions