

III. SOLID STATE PHYSICS

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RESEARCH OBJECTIVES

1. Soft X-ray Spectroscopy

The soft X-ray spectroscopy program has as its objective the experimental study of the structure of the conduction band of electrons in a series of metals, particularly the alkalis, alkaline earths, and some of the transition metals. The filled portion of such a band can be studied by observing the emission spectrum produced by transitions from this band to the nearest sharp levels below this band. In most metals this corresponds to an energy in the range of 15-250 ev (wavelengths in the range 50-900A), so that the technique of extreme ultraviolet vacuum spectroscopy is applied. The energy width of these bands usually lies in the range of 2-10 ev. Present effort is directed to the measurement of the copper and nickel bands in a series of copper-nickel alloys of various compositions. A more detailed description of the procedures will be found in the Quarterly Progress Report of January 15, 1954, page 9.

G. G. Harvey

2. Microwave Study of Semiconductors

One of the general aims of the research on microwave study of semiconductors is to apply the methods and general point of view of the microwave gaseous discharge work to those problems involving semiconductors wherever it seems profitable.

S. C. Brown

3. Elastic Constants of Single Crystals

The development of high-speed computers and the accuracy of experimentally obtained low-temperature specific heats have led to a revival of interest in the theory of lattice dynamics. The vibrational frequency spectrum and the bulk thermodynamic properties of a crystalline material can be computed by a Born-von Kármán calculation based on interatomic force constants derived from the adiabatic elastic constants of a single crystal. Since the specific heat at low temperatures is most sensitive to the parameters of the lattice model employed, calculations that use the elastic constants at liquid-helium temperatures are of the greatest interest.

The adiabatic elastic constants of a crystalline substance can be calculated from the velocities of propagation of ultrasonic waves along various crystallographic axes. Pulsed-circuit techniques provide a convenient method for measuring these velocities. Measurements of elastic constants for hexagonal close-packed metals and alkali halides are in progress. Data on magnesium, an almost ideally packed metal, are complete, as reported in the Quarterly Progress Reports for 1956. Work is almost complete on zinc, which is highly anisotropic, and has been started on sodium iodide.

C. W. Garland

4. Liquid Helium Research

Two experiments are under way in the low temperature laboratory. We hope to round out our previous measurements of the attenuation of sound in liquid helium below

1° K at 12 mc, as a function of pressure, by acquiring data at 2 mc and 6 mc. A second project is concerned with measuring the velocity of pulsed sinusoidal waves of second sound in the temperature range from 1° K, where there is very little dispersion, to approximately 0.3° K, where the dispersion is so great that second sound can no longer exist as a wave motion.

The results of both of these experiments should help clarify the nature of the elementary relaxation processes that lead to the establishment of thermal equilibrium in liquid helium at these temperatures, and possibly explain the behavior of other properties of the liquid.

W. M. Whitney

A. RECOMBINATION OF ELECTRONS AND DONORS IN GERMANIUM

1. Recombination

In studying the direct recombination of electrons with donors in germanium we are using a sample of germanium which is mounted in a microwave cavity in such a way that a voltage pulse can be applied to it. When the sample is at 4.2° K, a large portion of the donors are not ionized. When we apply a dc (or microwave) field of sufficient intensity, we raise the temperature of the electrons so that they ionize the remaining donors by impact. This is our breakdown picture.

We are studying the manner in which the number of electrons returns to the number that corresponds to equilibrium in the absence of a field

We write

$$\frac{dn}{dt} = -an(n + N_a)$$

where N_a is the number of acceptors in our sample, which is, however, of type n, and the number of ionized donors is $(n + N_a)$; a is a proportionality constant $= \sigma v$, where σ is the cross section for recombination, and v is the velocity of the electrons.

If we impose as initial conditions $n = N_d - N_a$ at $t = 0$, and $n = n_\infty$ at $t = \infty$, we can solve Ricatti's equation:

$$n - n_\infty = \frac{N_a}{\frac{N_d - n_\infty}{N_d - N_a - n_\infty} e^{aN_a t} - 1}$$

For $n_\infty \ll N_d - N_a$, the formula becomes

$$n - n_\infty = \frac{N_a}{\frac{N_d}{N_d - N_a} e^{aN_a t} - 1}$$

Developing the denominator in series, we obtain

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$$n - n_{\infty} = \frac{N_a}{\frac{N_d}{N_d - N_a} (1 + \alpha N_a t) - 1} \approx \frac{1}{\alpha t}$$

for $N_d \ll N_a$.

The unloaded Q of a cavity is inversely proportional to the conductivity, and hence to n , and thus we can write

$$\frac{Q_{\infty}}{Q} - 1 = \frac{1}{\alpha n_{\infty} t}$$

We were justified in disregarding diffusion because during the time involved, $t \approx 0.1 \mu\text{sec}$, there is no possibility of its having an appreciable effect.

In Fig. III-1 ($Q_{\infty}/Q - 1$) is plotted as a function of t for two different samples. The exponent of t is approximately -1 (within 10 per cent). We disregarded the points in the graph of sample 3 that correspond to $t > 0.2 \mu\text{sec}$, because they seem to be related to a phenomenon which we do not yet understand.

We believe that even by using a pulsed probing field whose duration is $0.2 \mu\text{sec}$ and whose incident power is approximately $10 \mu\text{watts}$, we have produced a partial breakdown which is evidenced by the low Q of our cavity. From the measurement of Q in the absence of a voltage pulse, we can evaluate n_{∞} , which is approximately 10^8 cm^{-3} , and hence the corresponding cross section for recombination in sample 3 is $\sigma \approx 10^{-9} \text{ cm}^2$.

2. Breakdown

We also measured breakdown fields in sample 3 by a method similar to that used by Madan, Gordon, Buchsbaum, and Brown (1). We observed the necessary time for breakdown as a function of the electric field. The result is shown in Fig. III-2.

By observing recombination as a function of the duration of the breakdown pulse, for an applied field of approximately 60 v/cm , we found that there was no heating effect in the sample or in the contacts. Breakdown was detected by looking at a microwave signal that was on continuously. The beginning of breakdown corresponded to a sudden change of the reflection coefficient of the cavity.

When the delay between the application of the breakdown field and the breakdown itself is approximately $T = 2 \mu\text{sec}$, we find that the field has practically reached its asymptotic value. If we assume that $T \approx 2 \mu\text{sec}$ is the time necessary for n_{∞} electrons to ionize $N_d - N_a \approx N_d$ donors, we can write

$$T = \frac{1}{n_{\infty} v \sigma} \quad \text{or} \quad \sigma = \frac{1}{T n v}$$

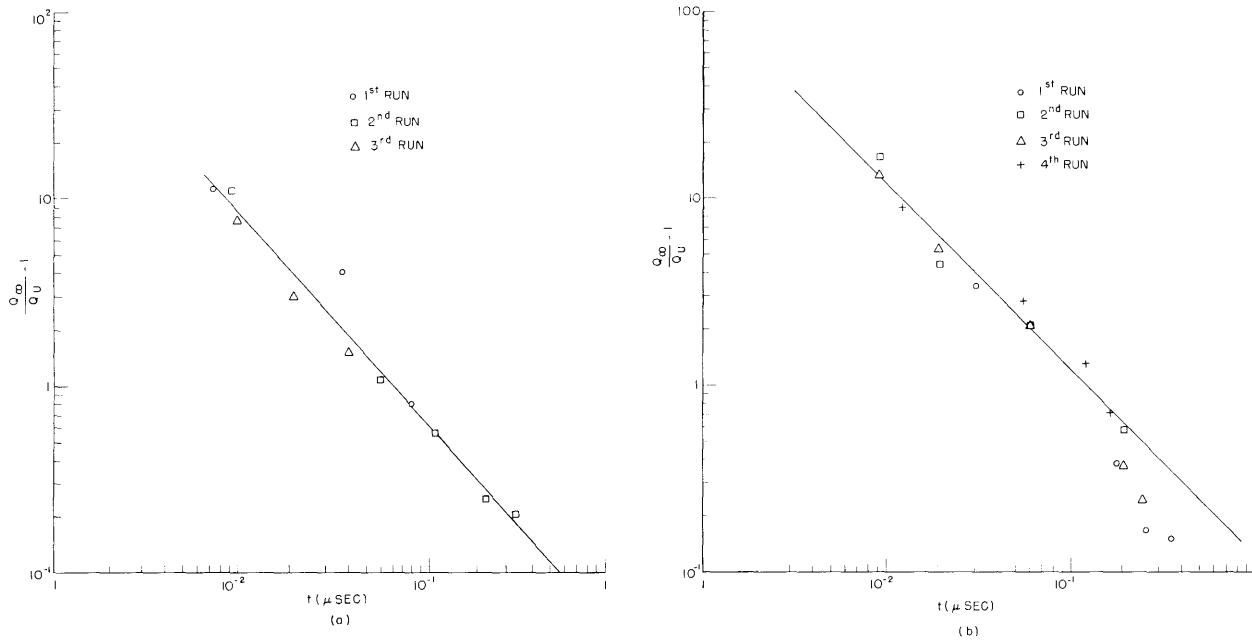


Fig. III-1. Decay of electron density as a function of time. (a) Sample 1, pulse duration $0.2 \mu \text{ sec}$. (b) Sample 3, pulse duration $2 \mu \text{ sec}$.

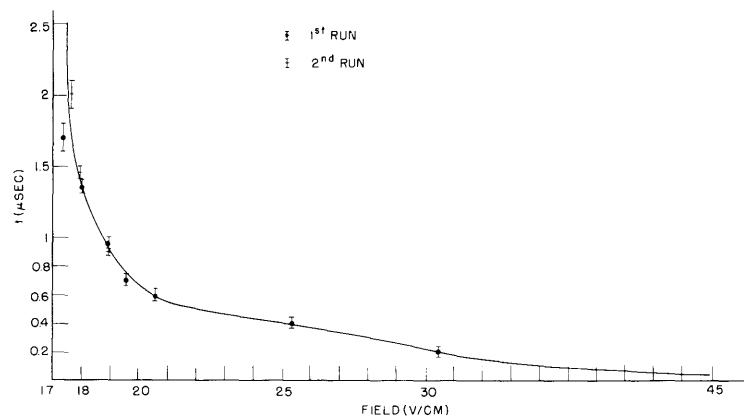


Fig. III-2. Beginning of breakdown as a function of applied field.

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Taking $v = 5 \times 10^6$ cm/sec as corresponding to a temperature of approximately 10° K and $m^* = 0.22 m_0$, $n_\infty = 10^8$ cm⁻³, we obtain $\sigma = 10^{-9}$ cm², which is in agreement with the data from recombination.

G. Ascarelli

References

1. M. P. Madan, E. I. Gordon, S. J. Buchsbaum, S. C. Brown, Determination of the coefficient of diffusion and frequency of ionization in microwave discharges, *Phys. Rev.* 106, 839 (1957).