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Acoustoelectric Effect and Intervalley Scattering Rates in Antimony-Doped Germanium*

B. TELL† AND G. WEINREICH
University of Michigan, Ann Arbor, Michigan

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The acoustoelectric effect in antimony-doped germanium has been measured as a function of temperature and doping by a method similar to that used by Weinreich, Sanders, and White for arsenic-doped germanium. The purpose of this experiment was to determine from the acoustoelectric effect the intervalley scattering rates for ionized and neutral antimony donors. Models for the scattering process are discussed, and the antimony rates are compared with those for arsenic. Our main result is that the rate per ionized antimony donor varies by a factor of 50 from 15 to 100°K, following approximately an inverse-square temperature dependence. The rate per ionized donor is a factor of 2 smaller than for arsenic at 20°K, and a factor of 10 smaller at 100°K.

I. INTRODUCTION

THE acoustoelectric effect is the production of a dc electric field under the action of a traveling acoustic wave in a medium containing free carriers. We have measured the acoustoelectric effect in antimony-doped germanium by a method similar to that used previously by Weinreich, Sanders, and White[1] (called W.S.W. hereafter) for arsenic-doped germanium. W.S.W. showed that, under appropriate conditions, the acoustoelectric effect yields directly the intervalley scattering rate (i.e., the mean transition rate between the separate groups of states which lie in the neighborhood of the equivalent conduction-band minima or valleys). This rate was attributed to phonons and to both ionized and neutral donors. Since the impurity rate would be expected to depend on the identity of the donor by virtue of its valley-orbit splitting, we have measured the dependence as a function of temperature and attempted to fit our results and those of W.S.W. with various models. These models and the effect of valley-orbit splitting on the intervalley scattering rates will be discussed in Sec. V. In the temperature and doping regime where the phonon contribution is dominant, our results agree with W.S.W.

In addition to its possible intrinsic interest, the recent developments concerning the use of germanium as a microwave ultrasonic amplifier[2] utilize the deformation potential coupling and the electron transfer mechanism (intervalley scattering) studied here, and lend possible technological value to our measurements.

As a subsidiary result of this experiment and as a definitive check on the experimental procedure, we have found the uniaxial deformation potential of 16.9 eV by the method discussed in W.S.W. This is in good agreement with W.S.W. and the other independent measurements.

II. THEORY

The theory of the acoustic drag is discussed fully in W.S.W. We present here only a physical description and the final form of the equations needed to interpret the experimental data.

In germanium, the electrons are coupled to the acoustic wave by means of a deformation potential, as contrasted to piezoelectric coupling in the recent acoustoelectric experiments on CdS [3] and GaAs.[4] The simplest physical picture is to visualize a sinusoidal potential traveling with the sound velocity with the electrons attempting to attain an equilibrium distribution favoring regions of lower potential. For the case where the electron relaxation time is short but finite with respect to the period of the acoustic wave, the electron sees the traveling potential but cannot attain exact equilibrium. The electrons get behind and tend to bunch on the backward slope of the wave. This implies a net average force (i.e., the local force weighted by the local electron distribution) in the direction of the wave. The magnitude of this force depends on the amount by which the electron distribution deviates from the equilibrium distribution in the presence of the wave.

The acoustoelectric effect thus requires the bunching of electrons on the backward slope of the wave. (In the presence of a sufficiently large external field, this situation can change.)[5,6] The electrons are assumed to move in a uniform positive-charge background due to the ionized donors and bunching would upset the neutrality. However, as shown by W.S.W., a shear wave propagating in a [100] direction permits bunching while maintaining space-charge neutrality. This occurs because the shear raises the energy of two of the valleys and decreases the other two by an amount symmetric with respect to the zero strain energy. This results in a bunching and antibunching between the two sets of valleys (classes) in such a manner that space-charge neutrality is maintained.

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† Present address: Bell Telephone Laboratories, Murray Hill, New Jersey.

[1] G. Weinreich, T. M. Sanders, Jr., and H. G. White, Phys. Rev. 114, 33 (1959).

[2] M. Pomerantz, Phys. Rev. Letters 13, 308 (1964).

[3] W. Wang, Phys. Rev. Letters 9, 443 (1962).

[4] J. R. A. Beale and M. Pomerantz, Phys. Rev. Letters 13, 198 (1964).

[5] G. Weinreich, Phys. Rev. 104, 321 (1956).

[6] A. R. Hutson, Phys. Rev. Letters 9, 296 (1962).

The acoustoelectric field $\bar{E}$ as derived by W.S.W. is given by

$$e\bar{E}=\frac{q^2S}{c^2kT}\frac{\omega^2\tau_r}{1+\omega^2\tau_r^2}, \tag{1}$$

where S is the acoustic power density, c is the sound velocity, kT is the Boltzmann constant times the absolute temperature, ω is 2π times the acoustic frequency, τ_r is the relaxation time, and q the effective acoustic charge.

The total relaxation time τ_r is given by

$$\frac{1}{\tau_r}=\frac{4}{3\tau_{\text{iv}}}+\frac{1}{\tau_D}, \tag{2}$$

where τ_{iv} is the intervalley scattering time, τ_D is the spatial redistribution or diffusion time, indicating the two available relaxation mechanisms.

The effective acoustic charge q is defined as $\frac{1}{2}\sqrt{2}$ times the deformation potential in a strain of unit energy density. For the present experiment, the valleys are divided into two classes having equal and opposite acoustic charges given by[1]

$$q=\pm\Xi_u/3(C_{44})^{1/2},$$

where Ξ_u is the uniaxial deformation potential and C_{44} is the appropriate elastic constant.

III. EXPERIMENT

The experimental setup and procedure was similar to that of W.S.W. However, a brief description is given in the interest of self-containment.

The basic arrangement consists of an acoustic wave (usually at 60 Mc/sec) injected at the driving end of the sample and dissipated in an indium absorber at the far end. The sample is locked into a massive copper holder as seen in Fig. 1, and is thermally isolated except at the ground contact. The acoustoelectric voltage was measured in a pair-wise fashion between the three signal contacts. The rf was amplitude modulated (at a known modulation index) and the component of the acoustoelectric voltage at the 10-kc/sec modulation frequency was amplified and narrow-band detected. The absorbed acoustic power produces a thermal gradient with a resulting dc thermoelectric voltage between the absorber end and the ground contact, and this voltage is measured between the same contacts as the acoustoelectric voltage. The absolute acoustic power is determined by removing the rf drive and reproducing the thermoelectric voltage by putting a known amount of power into a heater thermally anchored to the absorber.

The procedure was to stabilize the system at a given temperature, measure the acoustoelectric voltage, the thermoelectric voltage, and the temperature, and then remove the rf drive and determine the absorbed acoustic power by means of the heater. The temperature was then raised 2 or 3°K and a new set of measurements were taken.

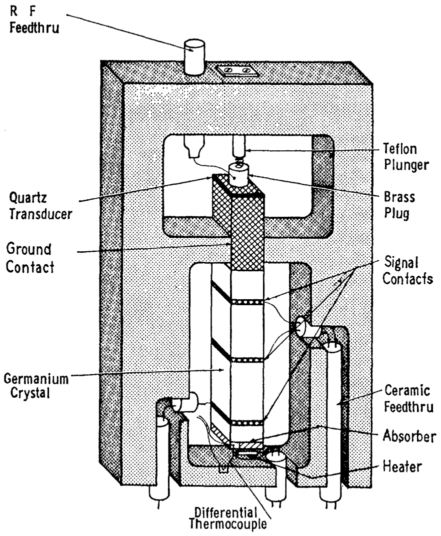


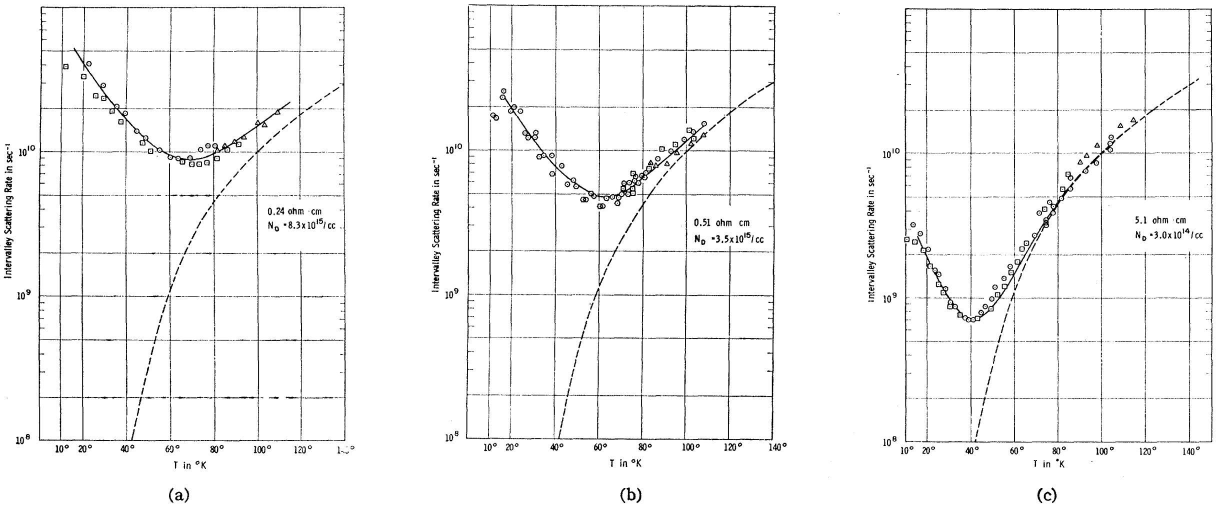
FIG. 1. A typical germanium sample mounted in sample holder. The sample was plated with Au+1% Sb at the ground and signal contacts (cross hatched areas). The signal contacts were 0.1 cm wide and spaced at approximately 1-cm intervals. The total length (in a [100] direction) was about 5 cm and the width and thickness were around 0.6 cm. A Y-cut quartz transducer was acoustically coupled to the sample with stopcock grease and placed as shown.

A copper can containing charcoal was attached to the sample holder for added thermal stability, and the system was held in a conventional helium double Dewar by a 30-cm stainless steel tube which also served as the outer conductor for the rf input. The procedure for regulating the temperature was to saturate the charcoal with liquid helium and to boil off the helium with a heater attached to the copper can until the desired temperature was reached. The heater was then turned down until the system stabilized. (A 0.5°K drift was allowable during the course of a set of measurements.) The heater was then turned up until a new temperature was reached.

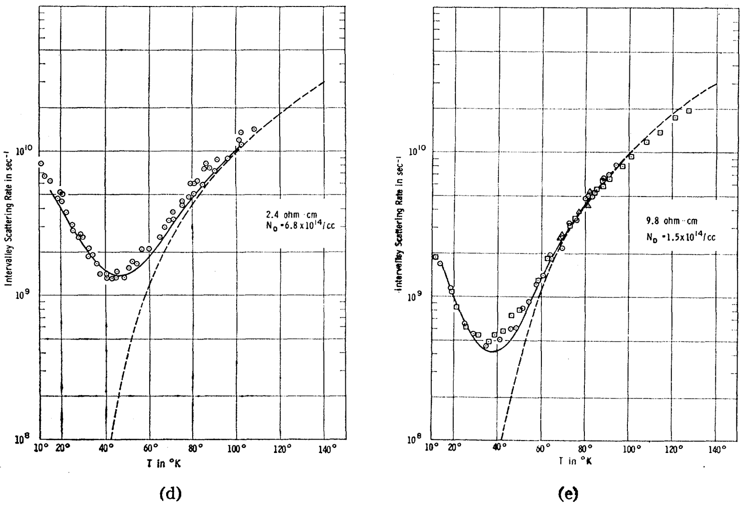
A calibrated copper-constantan thermocouple was used to measure the absolute temperature and a differential thermocouple was used to measure the temperature difference between the absorber and the sample holder due to the absorbed acoustic power. When good thermal contact was made at the ground end, the temperature difference was usually less than 2°K. From the two temperatures, an average sample temperature was determined.

IV. RESULTS

From the measured acoustoelectric voltage, the intervalley scattering rate is determined from Eqs. (1) and (2). The results of a least-squares fit for the rate $R=1/\tau_{\text{iv}}$ are presented in Fig. 2 as a function of temperature for five antimony-doped germanium samples



(a) (b) (c)



(d) (e)

FIG. 2. Intervalley scattering rate for five samples as a function of temperature. The dashed lines are the phonon contribution, and the solid lines include contributions from ionized and neutral donors. The symbols are the experimental points with different symbols denoting different runs. N_D is the total donor concentration which is equal to $N_+ + N_0$.

ranging in resistivity and room-temperature carrier concentration from 0.24 ohm cm with 8.3×10^{15} cm^{-3} to 9.8 ohm cm with 1.5×10^{14} cm^{-3}. This rate is again attributed to both phonons and ionized and neutral donors, and is given by

$$R(T)=R(\text{phonons})+R(\text{ionized donors})+R(\text{neutral donors}), \quad (3)$$

with

$$R(\text{ionized donors})=N_+(T)A(T), \quad (4a)$$

$$R(\text{neutral donors})=N_0(T)B(T), \quad (4b)$$

where N_+ and N_0 are the ionized and neutral donor density and $A(T)$ and $B(T)$ are the intervalley scattering rates per ionized and per neutral donor at temperature T. N_+ and N_0 were determined for each sample as a function of temperature from resistivity measurements and known mobilities.[7] $A(T)$ and $B(T)$ are plotted as a function of temperature in Fig. 3. The phonon rate, as mentioned, agrees well with W.S.W. and will not be further discussed.

V. DISCUSSION

As previously mentioned, intervalley scattering should depend on the identity of the donor by virtue of its valley-orbit splitting. As is well known,[8] the hydrogen-like donor states in germanium are fourfold degenerate in effective mass approximation, reflecting the fourfold degeneracy of the conduction-band minima or valleys. The central cell correction, which is due to the breakdown of the effective mass approximation, splits the donor states into a singlet and triplet by an amount given by the valley-orbit splitting. The splittings for the ground state are 4.1 MeV for arsenic and approximately 0.6 meV for antimony in germanium, these values representing the extremes of the commonly employed Group V donors.

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[7] P. P. Debye and E. M. Conwell, Phys. Rev. 93, 693 (1954).

[8] See, for example, W. Kohn, *Solid State Physics* (Academic Press Inc., New York, 1957), Vol. V.

Several models have been proposed for the ionized donor scattering. None of the models are in agreement, at least in regard to antimony, with experiment. The intervalley scattering rate per ionized arsenic is twice that of antimony at 20°K, and about 10 times that of antimony at 100°K. The antimony rate follows a T^{-2} temperature dependence. The two models which appear most reasonable to us are direct transitions caused by the central cell potential[9] and the compound-capture re-emission process proposed by W.S.W. The first model predicts a rate which depends on the square of the valley-orbit splitting with a $T^{-1/2}$ temperature dependence. This fits the arsenic data for temperatures above 40°K, but is negligibly small over the entire measured temperature range for antimony. The compound-capture re-emission process in its simplest form predicts a linear dependence on the splitting. We have, in unpublished work, extended this model using a technique suggested by Ascarelli and Rodriguez.[10] This model gave approximately the T^{-2} temperature dependence, but was an order to magnitude too small for antimony. It appears possible, however, to fit the arsenic data with the sum of the two models.

It might also be worth mentioning that Mason and Bateman[11] have determined intervalley scattering rates for high donor concentrations (greater than 10^{17} cm^{-3}) from ultrasonic-attenuation measurements. They find that the rates for both donors, particularly antimony, saturate at these concentrations, with the arsenic saturation value being about 100 times that of antimony.

For neutral donors, the process envisioned is an exchange scattering which results in a change in valley between the incoming and outgoing electron. The difference between the two donors presumably arises mainly from the difference in effective radii. We have attempted a fit for neutral donors by scaling the similar problem of scattering of electrons from neutral hydrogen.[12] This calculation omits refinements such as the anisotropy in effective mass, which would be needed for more than a semiquantitative fit. We have, in unpublished work, achieved an order of magnitude agreement.

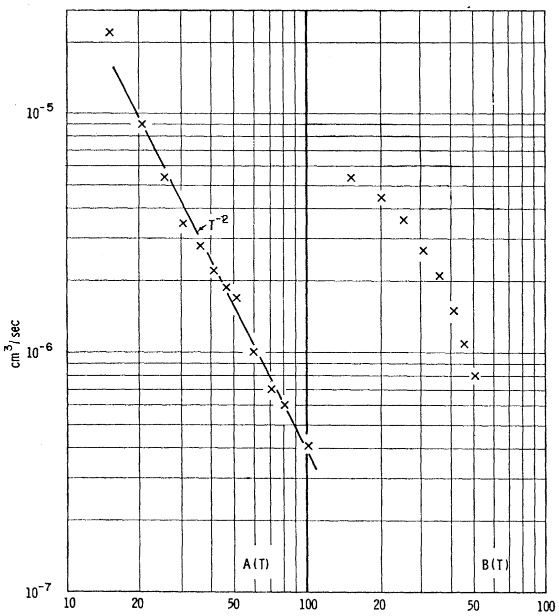

FIG. 3. Intervalley scattering rate per ionized antimony $A(T)$, and per neutral antimony $B(T)$.

VI. CONCLUSION

The intervalley scattering rates for antimony donors in germanium have been determined from the measurement of the acoustoelectric effect. The rates for antimony do not agree with the proposed models, although the arsenic results might be fit with a combination of models.

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[9] P. J. Price and R. L. Hartman, J. Phys. Chem. Solids **25**, 567 (1964).

[10] G. Ascarelli and S. Rodriguez, Phys. Rev. **124**, 1321 (1961).

[11] W. P. Mason and T. B. Bateman, Phys. Rev. **134**, A1387 (1964).

[12] P. G. Burke and K. Smith, Rev. Mod. Phys. **24**, 458 (1962).