Letters to the Editor

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Anisotropy of Cyclotron Resonance of Holes in Germanium*

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SEVERAL investigators[1,2] have reported cyclotron resonance of holes and electrons in germanium at liquid helium temperatures. Recently, we have performed similar experiments at 8900 and 23 000 Mc/sec using infrared instead of rf excitation of carriers. This technique considerably improved the quality of the data because very low rf power levels could be used, thus avoiding rf ionization and the resulting changes in carrier concentration with dc magnetic field. These experiments were carried out on oriented single crystal samples of p- and n-type germanium which had room temperature resistivities of about 40 ohm-cm.

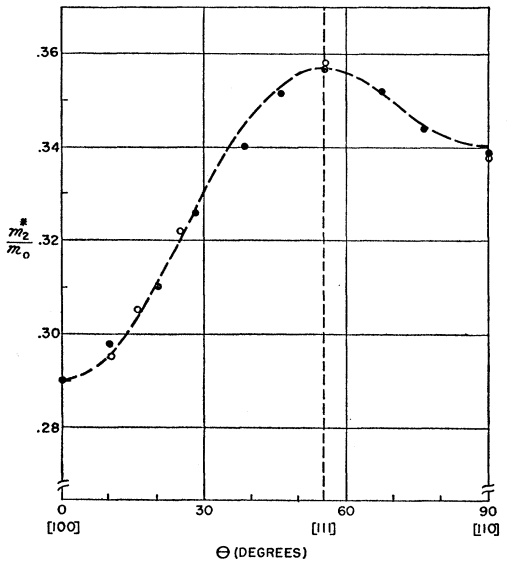

FIG. 1. The ratio of m_2^* to m_0 as a function of the angle θ between the [100] direction and the magnetic field in the (110) plane. The open and solid circles are experimental points taken at 23 000 and 8900 Mc/sec, respectively. The dashed curve is a theoretical function, Eq. (2).

With rf impact ionization, the two hole resonances in germanium, corresponding to effective masses of $m_1^*=0.04$ (m_0 and m)$_2^*=0.3m_0$ (m_0 is the free electron mass) showed no directional effects.[1,2] Under infrared excitation and very low rf excitation, we have observed anisotropy in the cyclotron resonance associated with the holes of effective mass m_2^*, as shown in Fig. 1.

The cyclotron resonance associated with the holes of small effective mass was approximately isotropic with $m_1^*=0.042m_0$. However, there were indications of a slight anisotropy with minimum effective mass when the magnetic field was in the [111] direction.

When infrared excitation was used, the intensity of the high-mass resonance was about eight times that of the low-mass one. The collision times for the two kinds of holes, as calculated from the line widths, were about equal. A typical value of collision time was about 6×10^{-11} seconds.[3]

The two resonances were interpreted in terms of a model for the top of the valence band in germanium[4] in which the energy E as a function of the wave vector, $\mathbf{k}$, is

$$E=(\hbar^2/2m_0)\times\{ak^2\pm[bk^4+c(k_x^2k_y^2+k_x^2k_z^2+k_y^2k_z^2)]^{\frac{1}{2}}\}, \quad (1)$$

where a, b, and c are constants. The plus and minus signs are associated with m_1^* and m_2^*, respectively. The radical was expanded to first order (the second order term in the expansion would contribute about 7 percent) and a perturbation method gave the frequencies for cyclotron motion. To first order, the effective masses for resonance with the magnetic field in the (110) plane, assuming $\mathbf{k}\cdot\mathbf{H}=0$, have the form

$$m^*=m_0\{A+B(1-3\cos^2\theta)^2\}, \quad (2)$$

where A and B are constants depending only on a, b, and c, which appear in Eq. (1). The constants, evaluated by fitting to the low-field peak and the high-field peaks in the [100] and [111] directions, are $a=13.6$, $b=83$, and $c=126$. An anisotropy in m_1^* of about 2 percent was predicted from these values. This prediction is consistent with the observations.

According to the above interpretation, the constant energy surfaces of the Brillouin zone near the top of the valence band in germanium are two sets of surfaces centered about $k=0$. These surfaces are nearly spherical for the holes of mass m_1^*. For the holes of mass m_2^*, they are perturbed spherical surfaces, protruding outward along the [111] axes.

We would like to express our thanks to Professor H. Brooks for his helpful suggestions concerning germanium band structure. We are happy to acknowledge interesting discussions with Drs. E. N. Adams, II,

and Esther Conwell. Thanks are due Dr. D. Tuomi for orienting the samples, and other members of the solid state groups of Lincoln Laboratory for their assistance.

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[1] Dresselhaus, Kip, and Kittel, Phys. Rev. **92**, 547 (1953).

[2] Lax, Zeiger, Dexter, and Rosenblum, Phys. Rev. **93**, 1418 (1954).

[3] This is an approximate upper limit since the resonance line is presumably broadened by distribution of velocities in the direction of the magnetic field.

[4] C. Kittel, Phys. Rev. **94**, 768 (1954); H. Brooks (private communication); W. Shockley, Phys. Rev. **78**, 173 (1950).

Kinetic Properties of the Domains in Rochelle Salt*

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AS has been previously reported by the present writers,[1] the relation between the propagation velocity v of the domain wall in Rochelle salt and the electric field E is in general given by

$$\gamma v = 2P_s(E-E_0),$$

where P_s is the saturation polarization and both γ and E_0 are constants. Further investigations have proved that γ is structure-sensitive as well as E_0 and that the temperature dependency of the relation is as shown in Fig. 1. The fact that the curves are almost parallel to each other suggests that γ is roughly proportional to P_s, i.e.,

$$\gamma = \alpha P_s,$$

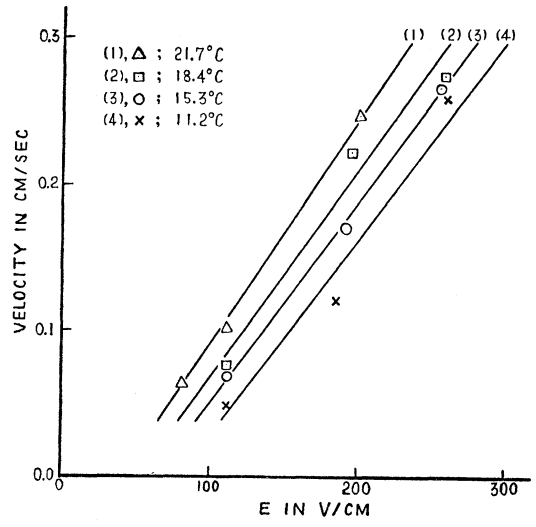

FIG. 1. Propagation velocity of the domain wall as a function of the electric field and the temperature.

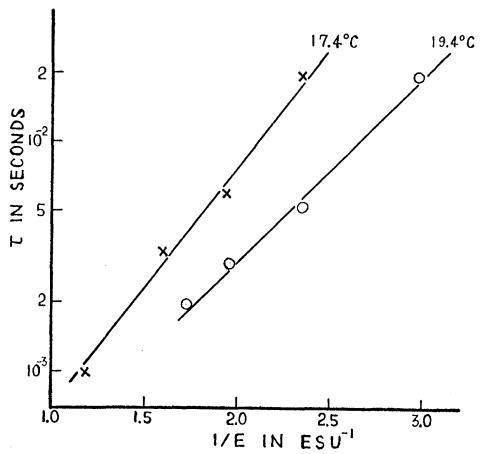

FIG. 2. Relation between the relaxation time for nucleation of the domain, τ, and the electric field, E. The ordinate, is scale logarithmic.

where α is a structure-sensitive constant. This relation implies that γ is proportional to the structure change of the crystal due to the passage of the wall, since the spontaneous deformation y_{zs} is proportional to P_s.

As has been reported by M. Marutake[2] and T. Nakamura,[3] many new domains appear when an electric field is applied along the a axis. The writers' observations have revealed that the new domains come into view at the same places in the crystal when application and withdrawal of the field are repeated, a fact suggesting that the nucleation of the domain takes place at some crystal imperfections. The relaxation time of the appearance of the new domains was measured by means of a rotating sector and a square-wave voltage as in the case of the study of the propagation velocity of the wall.[1] It has been found that the relaxation time τ can be expressed well by the equation

$$\tau = \tau_0 \exp(C/E),$$

where both τ_0 and C are constants, analogously to the results obtained by Merz[4] for $BaTiO_3$ (see Fig. 2). The measured values of C have the same order of magnitude with each other and in general decrease with increasing temperature above 15°C.

A detailed discussion of these results will appear in the *Journal of the Physical Society of Japan*. The writers wish to thank Dr. P. W. Anderson for his valuable discussions and for information on the research at the Bell Telephone Laboratories.

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[1] T. Mitsui and J. Furuichi, Phys. Rev. **90**, 193 (1953).

[2] M. Marutake, J. Phys. Soc. Japan **7**, 25 (1952).

[3] T. Nakamura, Repts. Inst. Sci. and Technol., Univ. Tokyo **7**, 113 (1953).

[4] W. J. Merz, Phys. Rev. (to be published).