Letters to the Editor

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Electron Multiplication in Germanium at Low Temperature

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IN measurements on germanium and silicon at 300°K and 77°K, Ryder[1] has found that the current density is proportional to the electric field E provided the drift velocity is below a critical value, which for electrons in germanium is 3.2×10^6 cm/sec. For higher drift velocities the current density becomes proportional to $E^{\frac{1}{2}}$ and this has been explained by Shockley[2] as caused by the heating of the electron gas. Ryder's data at 30° differed from that at 77° and 300° in that the transition to the $E^{\frac{1}{2}}$ behavior showed an initial steep rise with field. This steep rise has been seen in new data on n-type germanium at 12.1°, 13.9°, and 20.3°. A similar effect was observed by Gerritsen[3] at 1.7° in p-type germanium at fields above 4.1 volt/cm. Recently Sclar, Burstein, Turner, and Davisson[4] have observed such an effect at 4.2° and 6.4 volt/cm which they[5] interpret as a breakdown by the mechanism of impact ionization of neutral donors. In the explanation of Ryder's 20° data advanced by Conwell,[6] the rise in current is attributed to an increase in mobility. This theory is based on the assumption that at low fields the mobility is limited by impurity scattering, so that when the electrons are heated with increasing field the impurity scattering decreases and the mobility increases until it becomes limited by lattice scattering. In a recent private communication Miss Conwell says that she now believes that the acceptor density required to explain the Ryder data as a mobility change is implausibly high. She has gone on to suggest[7] that measurements on different samples at the same temperature, or on the same sample at different temperatures, should reveal whether electron multiplication is taking place.

Figure 1 shows the current density as a function of electric field for one sample of n-type germanium at the temperatures 12.1°, 13.9°, 20.3°, 77°, 300°. The sample was in the form of a bar 0.194 in.×0.026 in.×0.026 in. with very heavily doped n-type ends on which copper was plated. This type of contact has been found to be nonrectifying and noninjecting at all the temperatures studied. The current and voltage was measured by

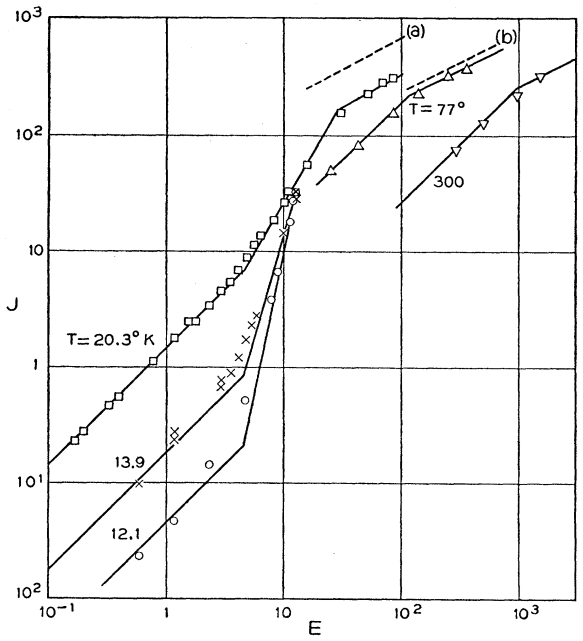

FIG. 1. Current density (amp/cm²) as a function of electric field (volt/cm) in n-type germanium.

Ryder's pulse technique and the current density and electric field calculated from the dimensions of the sample. Normal behavior was found at 300° and 77°. The previously reported steep rise with field at 20° is confirmed by the new data. We find in addition that at 12° and 14° the rise is even steeper, and the current densities at 13 volt/cm are about the same for all three temperatures. If the rising portions of the curves are extrapolated to meet the low-field portions the intersections are all at 4.5 volt/cm. The effective conductivities at 12 volt/cm are greater than the low-field values by the factors 2.1, 13, 50 for 20°, 14°, 12°, respectively.

Table I gives the low-field resistivities of our sample for the five temperatures. It turns out that our sample is very similar to sample No. 49 of Debye and Conwell,[8] as shown in the table, which provides a basis for estimating the carrier density. The carrier density at 300° can be estimated independently from the observed current density 240 amp/cm² at the knee of the curve and the previously measured critical drift velocity 3.2×10^6 cm/sec, which gives 4.7×10^{14} cm^{-3} in good agreement with sample No. 49. Were it not for the freezing out of carriers at lower temperatures the critical current density would be constant in temperature. Since the critical current density at 77° seems to be 200 amp/cm², we conclude that the uncompensated donors are about 83 percent ionized at 77° in our sample. According to the Conwell theory the current is limited by lattice scattering in the $E^{\frac{1}{2}}$ region. Assuming that lattice mobility varies at $T^{-\frac{3}{2}}$ and that ionization is complete at 300°, we find that the $E^{\frac{1}{2}}$ lines correspond-

TABLE I. Resistivity of our sample compared with sample No. 49 of Debye and Conwell (see reference 8) and the carrier density of sample No. 49 by Hall effect.

Temperature	Resistivity Our sample	Resistivity Sample 49	Carrier density Sample 49
12.1°K	23 ohm-cm	16 ohm-cm	3×10^{12} cm^{-3}
13.9	5.5	4.3	9×10^{12}
20.3	0.71	0.67	9×10^{13}
77	0.53	0.55	
300	3.8	4.0	4.8×10^{14}

ing to complete ionization are the lines (a) and (b) in Fig. 1 for 20° and 77°, respectively. Comparing (a) with the 20° data shows that ionization is about 50 percent in the $E^{\frac{1}{2}}$ region, whereas at low fields we estimate from sample No. 49 that ionization is about 19 percent. This is our most direct evidence for electron multiplication. Indirect evidence is provided by the large increase in conductivity with field at 14° and 12°. We believe that this cannot be attributed to an increase in mobility. A simple interpretation can be given for a steady-state ionization of 50 percent at high fields. Let n be the electron density, v the velocity, N_0 the density of neutral donors, N_+ the density of ionized donors, and σ_0 the cross section for impact ionization, σ_+ the cross section for recombination with an ionized donor. We shall neglect the acceptors. Then if R is the thermal rate of production of carriers we have

$$R+vn\sigma_0N_0-vn\sigma_+N_+=0.$$

At high field we may assume R is small compared to the other terms, so we have

$$\sigma_0N_0=\sigma_+N_+.$$

Now 50 percent ionization corresponds to

$$N_0\sim N_+\sim\tfrac{1}{2}N_D,$$

where N_D is the donor concentration. Thus our simple interpretation is that σ_0 and σ_+ are approximately equal,

$$\sigma_0\sim\sigma_+.$$

[1] E. J. Ryder, Phys. Rev. **90**, 766 (1950).
[2] W. Shockley, Bell System Tech. J. **30**, 990 (1951).
[3] Gerritsen, Physica **15**, 427 (1949).
[4] Sclar, Burstein, Turner, and Davisson, Phys. Rev. **91**, 215 (1953).
[5] Sclar, Burstein, and Davisson, Phys. Rev. **92**, 858 (1953).
[6] E. M. Conwell, Phys. Rev. **90**, 769 (1953).
[7] E. M. Conwell, Phys. Rev. **94**, 1068 (1954).
[8] P. P. Debye and E. M. Conwell, Phys. Rev. **93**, 693 (1954).

Electron Spin Resonance in Beryllium*

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THE electron spin resonance in beryllium was observed at 300 and 9000 Mc/sec. The sample was in the form of particles embedded in paraffin. The particles were large in comparison to a skin depth (of the order of 1 mm) so that Dyson's[1] theory for the absorption in bulk metals could be applied. A typical trace of the derivative of the power absorption *vs* field at 300 Mc/sec and room temperature is shown in Fig. 1. The ratio of the maximum to minimum deflection A/B (see Fig. 1) depends on T_D/T_2, where T_D is the time it takes an electron to diffuse through the skin depth and T_2 is the electron spin relaxation time. T_2 was found to be 2×10^{-8} sec and taking the velocity of the electrons at the Fermi surface, we find $T_D/T_2=0.14$. Corresponding to this value, A/B should be [1,2] 7.0. The observed value is 7.5 ± 0.5. This agreement is a definite proof that the observed resonance is due to conduction electrons rather than to stationary paramagnetic impurities throughout the metal, which for a Lorentzian line would give a value for A/B of 2.7 and for a Gaussian 2.0.

At 300 Mc/sec the temperature was varied between 296°K and 4°K. T_2 was found to be temperature independent for the entire range and had a value of

$$T_2=2.0\times10^{-8}\text{ sec.}$$

The same value was obtained at 9000 Mc/sec at room temperature.

The electronic g value was determined at 9000 Mc/sec by comparison with the free radical α,α-diphenyl β-picryl hydrazyl. Taking Hutchison and Pastor's[3] value of $g=2.0037$ for the hydrazyl we found the g for beryllium to be

$$g=2.0032\pm0.0001.$$

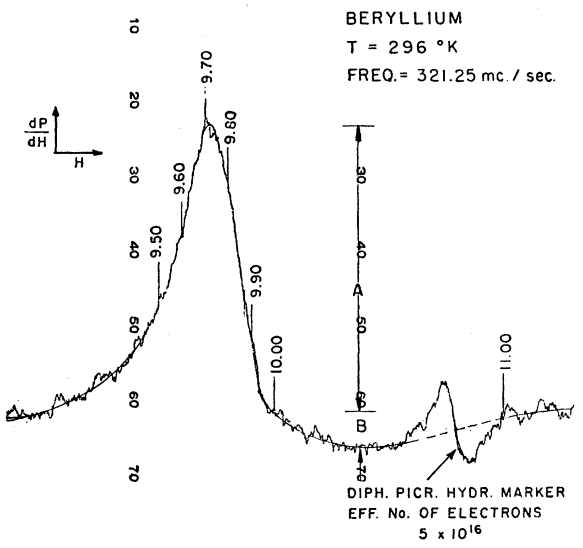

FIG. 1. The derivative of the power absorption *vs* field in beryllium. Vertical markers are proportional to magnetic field. 1 unit = 11.77 oersteds. The free radical resonance is displaced in field to avoid interference with the main line.