Experimental Confirmation of Relation between Pulse Drift Mobility and Charge Carrier Drift Mobility in Germanium

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Experimental data of drift mobilities of minority carriers in germanium are brought into agreement with theoretical predictions by distinguishing between group velocity and particle velocity of a pulse of minority carriers. Corrected high temperature measurements of electron drift mobility are consistent with the theoretical prediction $\mu=AT^{-\frac{3}{2}}$. The experimentally determined value of A is 2.0×10^{7} cm^2 deg$^{\frac{3}{2}}$/volt-sec.

DURING a current investigation of drift mobilities of minority carriers in semiconductors, it has been observed that as the temperature is increased above room temperatures the mobility values apparently decrease much more rapidly than theoretically predicted. Another experimental observation is an apparent decrease in mobility at room temperature as samples of resistivity values near intrinsic are used. This, too, disagrees with the expectation that the mobility should approach the value associated with pure lattice scattering as the samples become more intrinsic. It is the purpose of this paper to point out an explanation for these anomalous experimental results. The basis of the explanation lies in distinguishing between group velocity and particle velocity of a pulse of excess minority carriers in a semiconductor.

The direct experimental measurement of drift mobilities of charge carriers in semiconductors consists of "injecting" a pulse of additional minority carriers at one point into a rod of semiconductor in which there is an electric field and "collecting" some of these carriers at a later time at another point on the rod.[1] From measurements of the distance between the emitter and collector points, the electric field, and the time between emission and collection of the additional carriers, one can determine the mobility of the charge carriers from the definition of mobility $\mu=v/E$, where v=average velocity and E=electric field intensity.

The last statement holds as long as the group velocity of the pulse is equal to the drift velocity of the individual carriers. This condition is met with in most experimental conditions. Herring[2] has solved the general problem of an injected pulse of minority carriers in a semiconductor. Additional studies have been carried by van Roosbroeck[3] with particular emphasis on the effects of minority carriers present under thermal equilibrium conditions. Shockley[4] has given a more elementary discussion of the problem from which it is shown that the ratio of charge carrier drift mobility μ to pulse drift mobility μ_g is given by

$$\frac{\mu}{\mu_g}=\begin{cases}1+\left(1+\dfrac{1}{b}\right)\dfrac{p}{n_e} & \text{for holes in } n \text{ type material;}\\[2ex] 1+(1+b)\dfrac{n}{p_e} & \text{for electrons in } p \text{ type material,}\end{cases}$$

where p=density of holes, n=density of conduction electrons, $n_e=n-p$=density of excess electrons in n type material under conditions of thermal equilibrium, $p_e=p-n$=density of excess holes in p type material under conditions of thermal equilibrium, and $b=\mu_n/\mu_p$ =ratio of electron drift mobility to hole drift mobility. From a physical point of view one can say that the pulse moves as if under the influence of an electric field E_p, which is smaller than the applied electric field E by a factor of σ_e/σ, where σ_e is the conductivity arising from the excess majority carriers (n_e in n type material, etc.) and σ is the conductivity of the sample. This effect is

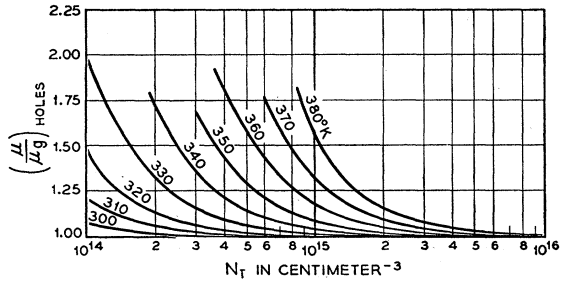

FIG. 1. $(\mu/\mu_g)_{\text{holes}}$ *versus* excess number of impurities (N_I) for various temperatures.

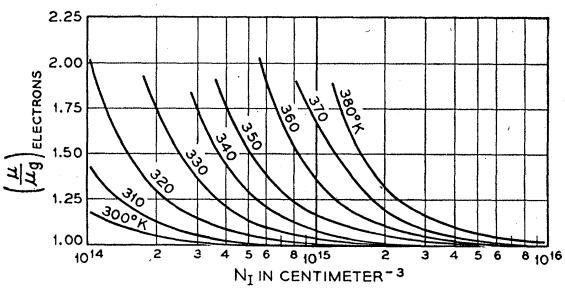

FIG. 2. $(\mu/\mu_g)_{\text{electrons}}$ *versus* excess number of impurities (N_I) for various temperatures.

[1] J. R. Haynes and W. Shockley, Phys. Rev. 81, 835–843 (1951).

[2] C. Herring, Bell System Tech. J. 28, 401–427 (1949).

[3] W. van Roosbroeck, Bell System Tech. J. 29, 560–607 (1950).

[4] W. Shockley, *Electrons and Holes in Semiconductors* (D. Van Nostrand Company, Inc., New York, 1950), p. 328.

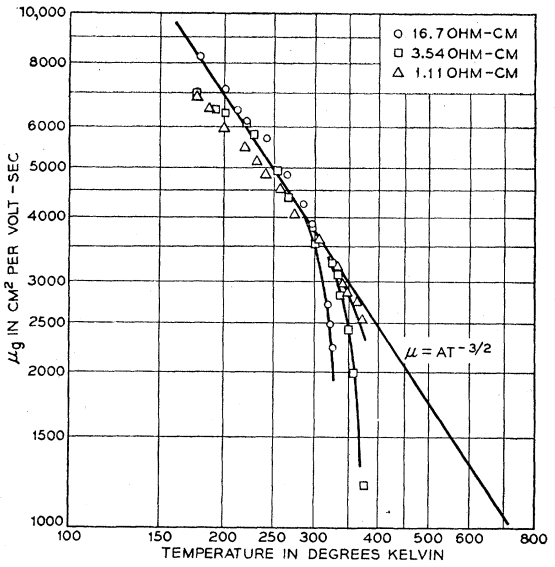

FIG. 3. Pulse drift mobility *versus* temperatures for several samples.

not caused by conductivity modulation resulting from the injected-pulse, which can be eliminated experimentally by reducing the injected pulse to zero height, but instead is caused by minority carriers present under thermal equilibrium conditions.

For the case of germanium, with the best available numbers,[5] and if one uses the relation $np=n_i^2$, these formulas reduce to

$$(\mu/\mu_g)_p=1+0.74[(1+\varphi)^{\frac{1}{2}}-1] \text{ for } n \text{ type material,} \quad (1)$$

$$(\mu/\mu_g)_n=1+1.54[(1+\varphi)^{\frac{1}{2}}-1] \text{ for } p \text{ type material,} \quad (2)$$

where

$$\varphi=\frac{4n_i^2}{N_I^2}=\frac{3.26\times10^{32}}{N_I^2}T^3e^{-8680/T},$$

n_i=density of electrons or holes in intrinsic material, T=absolute temperature, $N_I=|N_d-N_a|=p_e$ or n_e, N_d=density of donors (cm^{-3}), and N_a=density of acceptors (cm^{-3}).

Thus for $\varphi<0.01$, the mobilities of the minority carriers equal the measured pulse drift mobilities within 1 percent. This occurs for low temperatures and high impurity concentrations. Curves showing the ratio μ/μ_g *versus* impurity concentration for various temperatures are given in Figs. 1 and 2 for holes in n type material and electrons in p type material, respectively.

As an example of where this correction must be applied in order to obtain the correct charge carrier mobility, consider Fig. 3. Figure 3 shows some experimental data of pulse drift mobility *versus* temperature on logarithmic scales for several different resistivity p-type samples. It can be seen that for the higher resistivity (smaller impurity concentration) samples, the apparent mobility falls off more rapidly than for the lower resistivity samples. When the corrections are applied to the data one obtains the information given

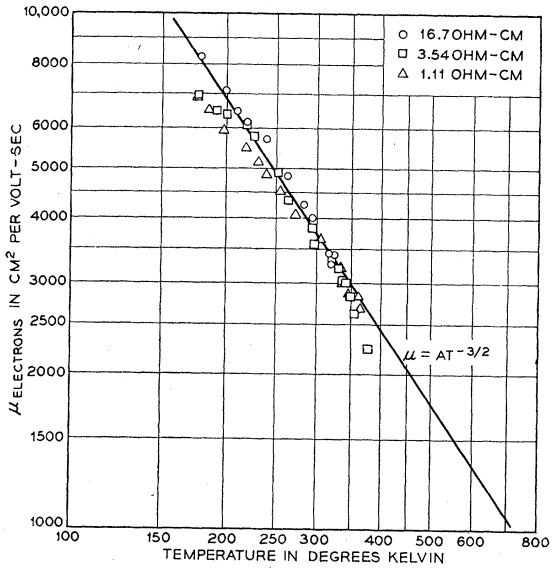

FIG. 4. Electron drift mobility *versus* temperature for several samples.

in Fig. 4. It is seen that the high temperature data are consistent with the line

$$\mu=AT^{-\frac{3}{2}},$$

with

$$A=2.0\times10^7 \text{ cm}^2 \text{ deg}^{\frac{3}{2}}/\text{volt-sec},$$

which is the theoretical prediction for the case in which lattice scattering is the important scattering mechanism. The low temperature deviations from this line can be shown to be due to the more effective scattering by impurity centers at these temperatures.

I would like to thank Dr. W. Shockley for suggesting the treatment of the experimental data as given in this paper.

[5] M. B. Prince (unpublished); see also E. M. Conwell, Proc. Inst. Radio Engrs. **40**, 1327–1337 (1952).