TRANSPORT PROPERTIES OF HIGH DENSITY ELECTRON-HOLE PLASMAS AT LOW TEMPERATURES[†]

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ABSTRACT

Measurements of the photoconductivity of germanium single crystals as a function of electron-hole pair density show the effects of carrier-carrier scattering on the mobility, for sample temperatures in the range 48 - 300 K, and for densities up to 2×10^{18} cm^{-3}. Calculations including the effects of carrier-carrier scattering but neglecting conduction band anisotropy appear to underestimate the effect of scattering on the mobilities, especially at the lower temperatures. At 2 K, the photoconductivity shows evidence for the formation of electron-hole drops at intermediate excitation levels.

Although there has been considerable interest in the transport properties of high densities of electrons and holes in semiconductors, there has been limited experimental study which can be compared critically with theory. Experimental studies in germanium,[1-5] silicon[6] and tellurium[7] have been reported, and some inconclusive comparison[8] with theory for the tellurium experiments has been made. Among the other theoretical treatments available, that of Appel[9,10] appears suitable (with modifications) for testing against available data, or newly-generated experimental results. Of particular interest is the regime of electron-hole pair densities sufficiently high that the electron-hole interactions have an appreciable influence on the conductivity.

The work reported here deals with germanium, in basically two different temperature regimes. At temperatures above 10 K, there is no evidence of liquid drop condensation,[11] so that the experiments should deal with a high density electron-hole fluid. In experiments below 6 K,

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the germanium can contain electrons, holes, excitons and liquid condensate, so that the analysis is much more complex. In this paper, the high temperatures chosen for study range from 48 K to 300 K, and the low temperature studies were carried out in the range 1.6 to 2 K.

Samples of germanium of two different kinds were used in the experiments. Group A were single crystals, n-type, with approximately 10^{13} cm^{-3} impurity concentration; group B were single crystals, initially p-type, with initial impurity concentrations less than 10^{11} cm^{-3}. All samples were of dimensions $6 \times 3 \times t$ mm^3 in size, with the thicknesses t ranging from 30 to 525 μm. The large area surfaces were optically polished and etched. The thickness was tapered at about 1^o to reduce multiple reflections of the penetrating laser radiation used in the diagnostics.

The large surfaces were each illuminated simultaneously over the whole area by pulsed optical radiation, to produce electron-hole pairs in a region within about 1 μm of the surface of the sample. In one set of experiments, Xe flash lamps were used as the source of radiation, with their output filtered through water cells to eliminate the infrared. The pulse length was about 3 μsec. In the other set of experiments, the source was a 1.06 μm Nd: glass laser, Q-switched to provide a 25 nsec pulse. Calibrated optical filters varied the intensity falling on the samples.

In addition to this primary source of electron-hole pairs, a 3.39 μm CW He-Ne laser was used to monitor and measure the density of holes produced, since the holes absorb[12,13] at this wavelength, making a transition to the split-off valence band in the process. A fast-response InSb photoconductive detector allowed accurate observation of the time-dependence of this absorption (and thus of the hole density). This enabled independent measurements of carrier density to be made and compared with those estimated from photoconductivity; at the higher temperatures, the 3.39 μm absorption was studied over the whole range

of excitation, and the absorption cross section could thus be checked. We found cross-section values in the range 1.6 - 2×10^{-16} cm^2/hole, which agree fairly well with earlier measurements;[14] we used the values 1.75, 1.75, 1.88 and 1.71×10^{-16} cm^2/hole at 48, 72, 124 and 298 K respectively. At the low temperatures there is some uncertainty[13] in the proper value of the cross section and our measurements were unable to provide an independent test of the value used. We used[12] 1.5×10^{-16} cm^2.

A four-point probe configuration was used to measure the photoconductance. The current contacts covered the sample ends; each consisted of three n^+ and three p^+ alloyed dots, alternately arranged and soldered together to provide ohmic contacts under all conditions of sample injection. The voltage probes on the sides of the crystals were also alloyed contacts. The conductance was measured as a function of applied electric field, and was found to be independent of field below about 1 V/cm at all temperatures and densities. Above 1 V/cm at 2 K and below, increases[4] of photoconductance with electric field were observed, which can be related to the heating of the carriers and the ionization of any excitons present.[15,16] At the high electric fields, the level of conductivity produced would imply that any drops present are also evaporated, although no evidence for this was reported in the work of Nakamura and Morigaki.[5] This is discussed in more detail below.

Conductivity Above 10 K

The photoconductivity was calculated from the conductance measured, assuming a homogeneous filling of the germanium by the electron-hole plasma. This assumption seemed well verified by the fact that samples of varying thicknesses (30 up to 400 μm) yielded the same values of photoconductivity at the same average carrier density. Measurements of the conductance were made at times of the order of 2-4 μsec after the laser pulse, during a period where the density was varying very little with time (lifetimes were 10 μsec and longer). Measurements made with

Xe flash lamps and with the 1.06 μm laser yielded results which agreed very well with each other; there was also no difference observed at 72 K and higher between A-type and B-type samples. Figure 1 shows the

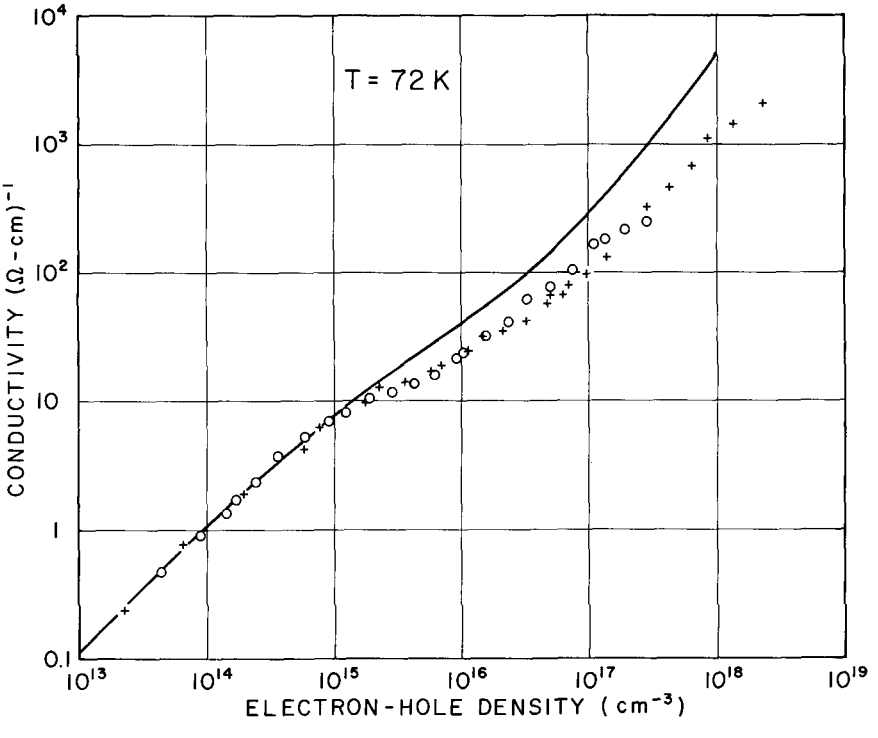

Fig.1. The photoconductivity of germanium as a function of electron-hole concentration at 72 K. Samples of thicknesses ranging from 30 to 400 μm were used. Curve is theoretical.

results of our measurements with several samples at 72 K.

The curve plotted in Fig. 1 is calculated using the expressions[10] of Appel, which in zero-order of the variational solution are:

$$\sigma^{(0)} = \frac{\sigma_e^{(0)} + \sigma_h^{(0)}}{1 + (\sigma_h^{(0)} + \sigma_e^{(0)})\, C\, J_o}$$

$$C = \frac{2^{5/2}\pi^{1/2}e^2(m_e m_h)^{1/2}}{3\, K_o^2 (kT)^{3/2}(m_e + m_h)^{1/2}}$$

$$J_o(y) = \int_o^\infty x \exp(-x^2) \left[\ln(1 + 2x^2/y) - (1 + y/2x^2)^{-1}\right] dx$$

$$y = \hbar^2/4\lambda_D^2(m_e m_h/m_e + m_h)\ kT$$

$$\lambda_D^2 = K_o\ kT/4\pi e^2(n + p)$$

We included both light and heavy holes in the calculation, and took it to first order in the expansion, using[17] $m_e = 0.12$, $m_{lh} = 0.043$ and $m_{hh} = 0.347$; K_o is the germanium dielectric constant, 16. The anisotropy of the conduction band ellipsoids was not included; preliminary calculations which include this anisotropy give reduced conductivities, in better agreement with experiment. The behavior of the photoconductivity is qualitatively as expected: as the density of electron-hole pairs is increased, the mobilities decrease due to electron-hole scattering; further increases in density increase the screening of the Coulomb interaction and decrease the effectiveness of the carrier-carrier scattering.

The same behavior occurs at all of the temperatures studied, with the calculated conductivity being somewhat higher than the measured values at the highest densities. The experimental data are summarized in the form of a plot of the reduced mobilities (the sum of electron and hole mobilities, divided by their value at very low densities) as a function of electron-hole density in Fig. 2. We see that the density of carriers at which the mobilities drop sharply decreases with decreasing temperature.

Conductivity at 2 K

These experiments were carried out with samples of types A and B, and Xe flash lamp excitation. Preliminary results were published earlier.[4] A summary of data taken with type A samples is given in Fig. 3, which is a plot of conductivity as a function of electron-hole density produced. In these measurements, it was not possible to detect the 3.39

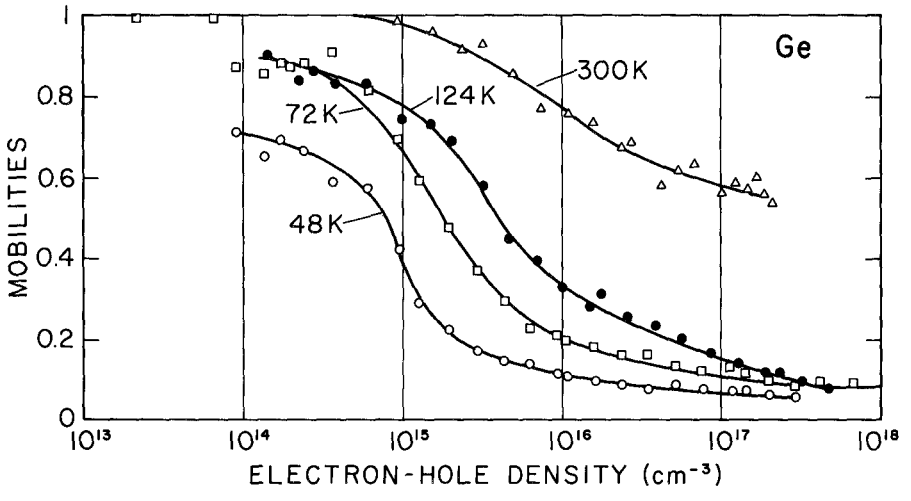

Fig.2. The mobilities of electrons and holes as a function of electron-hole density. The mobilities are normalized to 1 at low density. The curves are drawn to fit the data.

μm absorption over the whole range of excitation; in general this was possible for densities above about 2×10^{16} cm^{-3} only. The abscissa then represents the relative numbers of electron-hole pairs produced for densities lower than this value, since the number of absorbing holes is not known.

As noted earlier, at the highest densities, the data indicate a dependence of conductivity on carrier density somewhat stronger than linear. It should be noted, however, that there is heating of the sample for injection levels above 10^{17} cm^{-3}, so that the actual lattice and carrier temperatures can be appreciably greater[4] than 2 K. As the excitation level is decreased, the conductivity drops sharply, and this is interpreted as due to the formation of electron-hole liquid drops in the sample, now not sufficiently strongly excited to fill the whole sample with the liquid (density about 2×10^{17} cm^{-3}). With further intensity decrease we find the onset of a conductivity "plateau" which appears to have a dependence on sample thickness and some dependence on the purity of the sample. Figure 4 shows the plateau region data for

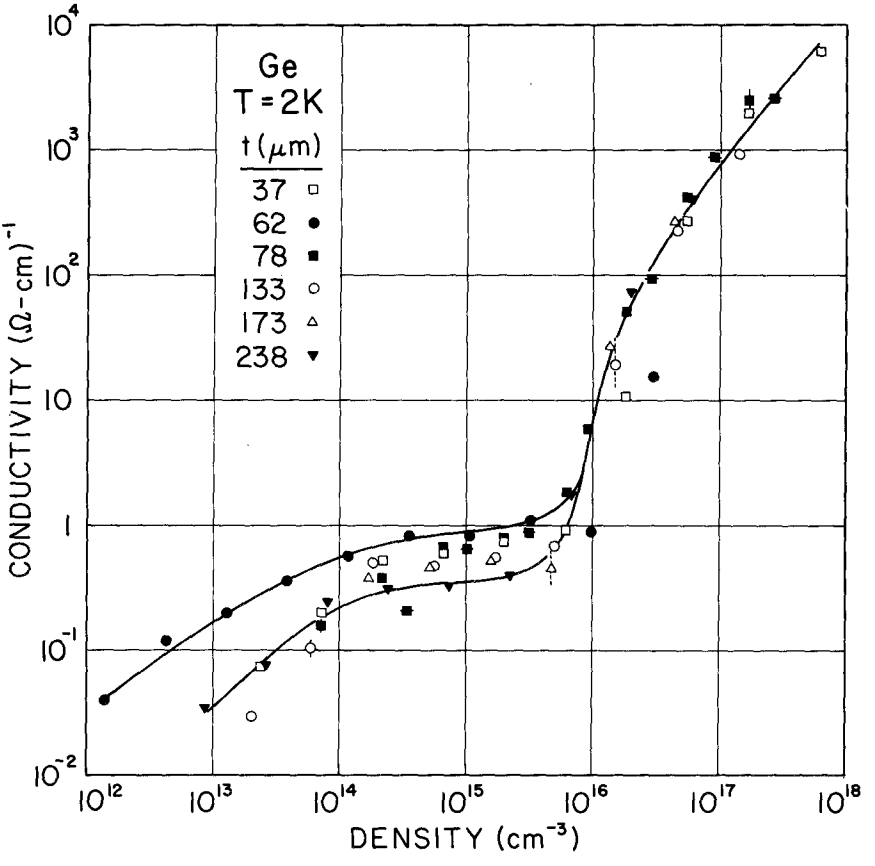

Fig.3. The photoconductivity of germanium at about 2 K (temperatures were in the range 1.8 to 2.0 K), as a function of injection density. Samples were of type A. Curves are drawn to fit the data. The values for the carrier density were calculated from the 3.39 μm absorption using the cross section 1.5×10^{-16} cm^2 (ref. 4 and 12).

samples of type B; the values of the conductivity are very much the same as those in type A germanium samples, but the region of excitation level over which the plateau is seen is greater than $1{:}10^3$, as compared to about $1{:}10^2$ shown in Fig. 3. This may be due to differences in the nucleation conditions for droplets in the two kinds of samples; it could also be due to the difference in carrier mobilities and the stronger effect of electron-hole scattering in the purer samples, with their lower concentration of ionized and neutral impurities. A clearer interpretation of this region should await conductivity measurements on

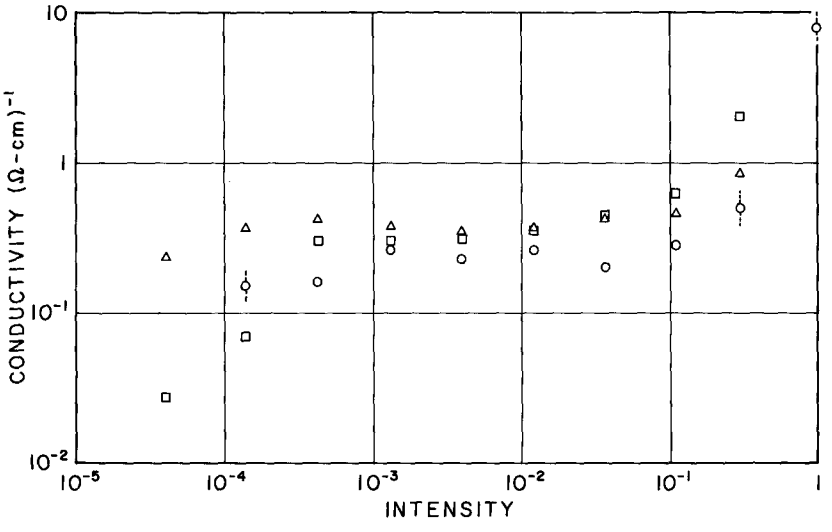

Fig.4. The photoconductivity of type B samples of germanium as a function of injecting light intensity, in the "plateau" region, at 1.9 K.

these samples covering the whole temperature range, so that the second suggestion may be evaluated.

It should also be noted that our measurements of the electric-field dependence of the conductivity indicate an inappreciable number of excitons present in the lowest region of excitation. If we refer to Fig. 3, measurements of the I-V characteristic showed essentially linear dependences up to fields in excess of 10 V/cm, except in the region we have called the "plateau". In that region, a rise in conductivity was observed between 2 and 4 V/cm, followed at higher fields by ohmic behavior. These results lead to the conclusion that, in this region, there are carriers which do not contribute to the conductivity unless the average energy of the carriers is increased to about the energy required to ionize excitons,[15] or presumably to evaporate the electron-hole drops. Since this is not observed for lower excitation levels, it is believed this is evidence for the negligible fraction of the excitation, under our conditions, present in excitons in this region.

Figure 5 plots the range of values of the plateau "conductivity" observed as a function of thickness. The curve is calculated for a

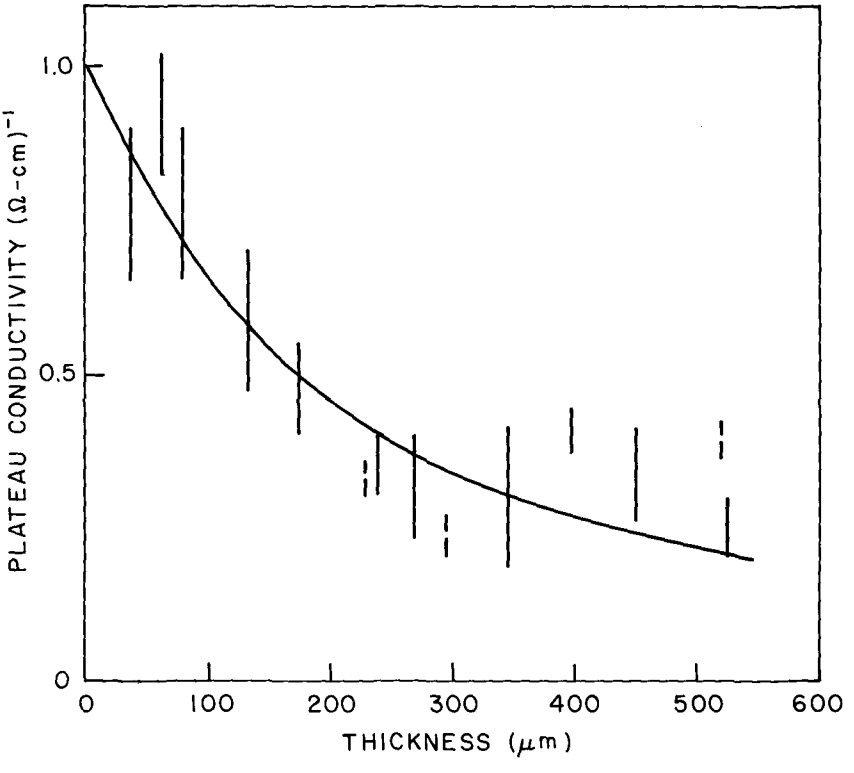

Fig.5. Values of the "plateau" conductivity as a function of sample thickness, for germanium crystals at about 2 K. Curve is calculated for an ambipolar diffusion length of 110 μm.

steady-state distribution of electrons and holes present, with an ambipolar diffusion length of about 110 μm, under the assumption that the conductivity does not vary with density. This would lead us to conclude that the variation of plateau conductivities with thickness is due to the inhomogeneous electron-hole plasma distribution. The density of electrons and holes is here then directly related to the presence of liquid drops, and its value is determined by the evaporation of electrons and holes from the drops.

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Notes Added in Proof:

According to our recent infrared measurements of absorption (unpublished), the value of 1.5×10^{-16} cm^2 for the absorption cross section quoted from ref. 12 should be replaced by 4.5×10^{-17} cm^2/hole. Hence the scale of the abscissa for the density in Fig. 3 should be multiplied by the factor 3.3.

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