The scattering of charge carriers in large electron-hole drops in germanium

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The temperature dependence of energy absorption from an alternating magnetic field on photoexcitation of germanium, due to excitation of eddy currents in the conducting medium, has been studied. The mobility of free electrons and holes and the mobility in large electron-hole drops are determined from the dependence of this absorption on the strength of the dc magnetic field. It is shown that between 2 and 4.2 K the mobility of both free and condensed charge carriers is determined by scattering by acoustic phonons.

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1. INTRODUCTION

Measurements of the absorption of energy from an alternating magnetic field due to excitation of eddy currents in a nonequilibrium conducting medium have been used in Refs. 1–3 to determine the conductivity and carrier mobility in electron-hole drops (EHD) in germanium. The mobility of nonequilibrium carriers, μ, at $T \approx 2$ K was determined from the dependence of this absorption on the strength of the dc magnetic field, H, which ia analogous to the usual transverse magnetoresistance effect. It was shown[3] on the basis of a study of the kinetics of the absorption that in undeformed germanium, when photoexcitation produces a cloud of fine drops, absorption by free charge carriers predominates. Such a result is to be expected. In fact the power absorbed by a sphere of radius R and conductivity σ is

$$W = \pi R^5 \omega^2 h_0^2 \sigma / 15 c^2, \tag{1}$$

where ω is the frequency and h_0 the amplitude of the alternating magnetic field.[1–3] Although the mobility due to free electrons and holes in the atmosphere surrounding an EHD is several orders of magnitude lower than within an EHD, the characteristic dimensions of the cloud exceeds 10^{-1} cm while $R \approx 10^{-4}$ cm (Ref. 4) and absorption in the atmosphere predominates.

A potential well in which a large EHD is localized, with dimensions which can reach 0.3 to 0.5 mm, at a photoexcitation power of 0.1 to 0.5 W (Ref. 5) can be formed by nonuniform local deformation of germanium crystal. Absorption in a large EHD has then been shown[3] to dominate. The mobility, μ, determined by the magnetoresistance effect,

$$\sigma = \sigma_0 [1 + (\mu H/c)^2]^{-1}, \tag{2}$$

reached 1.3×10^6 cm$^2 \cdot$V$^{-1} \cdot$s^{-1} at 2 K in a large EHD. This value of mobility could be determined by both electron-hole scattering and scattering by acoustic phonons, since both type of scattering lead to values of 10^6 to 10^7 cm$^2 \times$V$^{-1} \times$s^{-1} for the mobility at 2 K (Ref. 3). When electron-hole scattering dominates, however, several effective momentum scattering times $\tau_p = (\tau_{eh} \tau_L)^{1/2}$ where τ_{eh} is the electron-hole scattering time and τ_L is the time for lattice scattering, while the absolute value of the EHD conductivity should be determined by τ_{eh}.[3,6] It has been shown that the value of the mobility determined from absolute measurements of hf absorption and the dimensions of a large EHD and from the magnetoresistance effect are in satisfactory agreement. It was concluded from this[3] that lattice scattering either dominates or is comparable with electron-hold scattering. In the present work the temperature dependence of hf absorption by free charge carriers and by large EHD's is studied and definite conclusions are drawn about the scattering mechanisms.

2. METHOD AND EXPERIMENTAL RESULTS

The main difficulty in using traditional focusing of a laser beam on the side face of a crystal (Fig. 1, *A*) to produce a large EHD is due to scattering of the beam by the bubbles of the boiling helium. Scattering of the light produces an appreciable number of free carriers in the specimen 1, which do not contribute to the formation of a large EHD but lead to considerable hf absorption. In addition, drift from the excitation region to a potential well takes place then over an appreciable distance for relatively small deformation gradient. This reduces the efficiency of feeding a large EHD, especially at higher temperatures when the mobility of drops decreases strongly. To avoid these effects we focused the laser beam (Fig. 1, *B*) onto the lower surface of the crystal through a Plexiglas plunger 2 that produced nonuniform deformation of the crystal. The lower end of the plunger was sealed

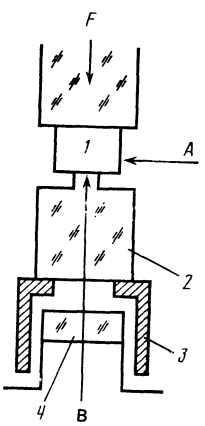

FIG. 1. System for exciting and deforming the specimen 1: 2—plunger; 3—bakelite cap; 4—window; *A* and *B*—laser beam.

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with vacuum grease to a cap 3 which covered the sapphire windown of a helium cryostat chamber 4, so that a gas bubble was formed between the plunger and the window. This eliminated the scattering of the exciting beam by boiling helium. In addition, with this means of excitation the carriers arrived immediately in the region of large deformation gradient, while the distance to the potential well was reduced to ≈ 0.3 mm. The plunger of diameter ≈ 1 mm was pressed onto the germanium crystal with a force $F \approx 5$ to 10 kg and was maintained under load at room temperature for several hours. Good contact was achieved thanks to the plasticity of the Plexiglas so that a potential well for a large EHD could be produced. The dc magnetic field H, parallel to the alternating field h_0 in the (111) direction of deformation of the crystal, was provided by a two-section superconducting solenoid which had a window for letting out the recombination radiation. The remaining features of the experiment have been described earlier.[2,3]

The intensity of recombination radiation I_r, a signal proportional to the magnetic hf power absorption ΔU, and the dependence of ΔU on the strength of the dc field H were measured at each fixed temperature. Since the last dependence was always well described by Eq. (2), the values of ΔU for $H = 0$ and for such a value of H that ΔU was roughly halved were usually used to determine the mobility μ and then μ was calculated from Eq. (2). In addition, the time dependences of I_r and ΔU were studied at some temperatures. The dominance of absorption by either large EHD's or by free carriers in the atmosphere surrounding a drop could be judged from this dependence. In the absence of deformation the rapid decrease of I_r in the temperature range from 2 to 4.2 K corresponded to a cloud of fine drops, and the absorption ΔU was determined by free carriers.[3] On deforming the crystal between 2 and 3.5 K both I_r and ΔU fell according to an exponential law with time constant 300 to 500 μs, which indicated the dominance of absorption by a large EHD. Under the same conditions but at 4.2 K, only a small fall in I_r was a feature of large EHD's. A rapid drop in ΔU indicated the dominance of absorption by free carriers.

The temperature dependence of I_r, ΔU and μ are shown in Fig. 2 for an undeformed specimen of p-type germanium without dislocations, with excess acceptor density 1.5×10^{11} cm^{-3}. The radiation intensity I_r from the EHD cloud was reduced by almost two orders of magnitude on raising the temperature from 2 to 4.2 K. At the same time, the absorption ΔU passed through a minimum at $T = 2.7$ K and then increased more than fivefold. Such a behavior of I_r and ΔU is reasonable since the evaporation of an EHD increases on raising the temperature, leading to a fall in I_r and to a growth in the density of free electrons and holes. It is noteworthy that the mobility μ decreases monotonically according to a law close to $T^{-3/2}$ which is typical for free electrons and holes.

The temperature dependences of I_r, ΔU and μ for nonuniform deformation of the same germanium specimen by a force $F \approx 10$ kg are shown in Fig. 3. It can be seen that the radiation intensity I_r from a large EHD decreases insignificantly in the region of 4 K, while the absorption ΔU de-

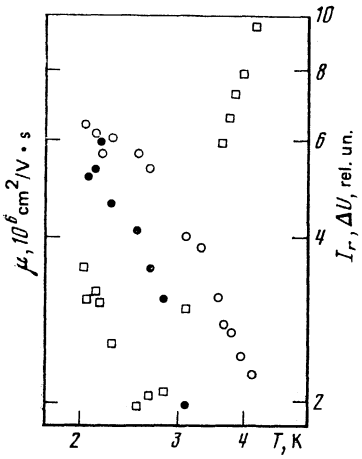

FIG. 2. Temperature dependences: ○) of mobility μ, ●) of recombination radiation intensity I_r, □) of absorption ΔU in undeformed germanium.

creases by almost an order of magnitude as the temperature increases from 2 to 3.5 K. The effective mobility μ in the region 2 to 2.5 K decreases faster then linearly, then linearly as T is raised, and passes through a minimum at 3.5 K. If the absorption ΔU and the mobility μ were determined by processes in a large EHD, we would expect $\Delta U \sim \mu I_r^{5/3}$ since $I_r \sim R^3$ (EHD volume), while $\Delta U \sim \sigma_0 R^5$, $\sigma_0 \sim \mu$ (Eq. (1)). In fact, it can be seen from Fig. 3 that ΔU and $\mu I_r^{5/3}$ correlate well up to 3.5 K. The breakdown in the correlation above this temperature is presumably related to the dominance of absorption by free carriers. The time dependences of I_r and ΔU also confirm this conclusion. We should note that the noticeable evaporation of a large EHD at $T \gtrsim 3.5$ K is to be expected since the critical temperature for condensation in germanium deformed in the (110) direction is unlikely to be above 4.5 K (Ref. 4).

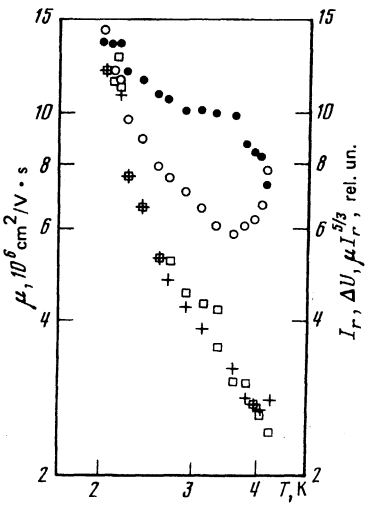

FIG. 3. Temperature dependences: ○) of mobility μ, ●) of recombination radiation intensity I_r, □) of absorption ΔU, +) of $\mu I_r^{5/3}$ in nonuniformly deformed germanium.

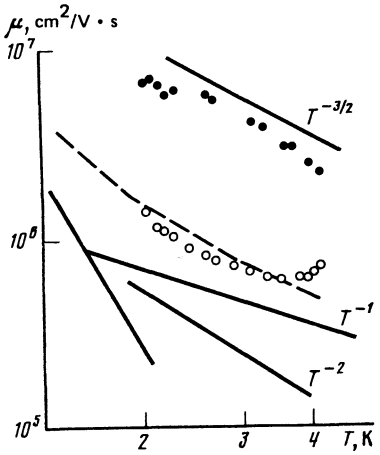

FIG. 4. Temperature dependence of mobility μ: ●) in undeformed, ○) in deformed germanium. Dashed lines calculated according to Eq. (3); Solid lines according to Eq. (4) to (6).

3. DISCUSSION OF THE RESULTS

We consider first the temperature dependence of the mobility in undeformed germanium, when absorption is determined by free charge carriers. Experimental and calculated μ dependences, extrapolated from the temperature region above 40 K (Ref. 7) according to the $\mu \sim T^{-3/2}$ law, are compared in Fig. 4. It can be seen that both the form of the dependence and the absolute value of μ obtained experimentally agree well with those calculated. The small departure at the lowest temperatures is understandable since mechanisms other than scattering by acoustic phonons can occur at such high values of the mobility $\mu \approx 10^7$ cm^2·V·s^{-1}, for example scattering by vacancies always present in dislocation-free germanium. There seems to be no effect of impurities present in the specimen with a density on the order of 10^{11} cm^{-3}, since intrinsic photoexcitation neutralizes the impurity atoms via optical charge exchange. The cross section for scattering by neutral impurities is quite small.[2,7]

Experimental values for the mobility μ in large EHD's are also shown in Fig. 4 together with the calculated mobility in an electron-hole liquid for scattering by acoustic phonons[8] and for electron-hole scattering.[9] The relaxation time for electron and hole momentum for scattering by acoustic phonons, τ_L, is given by

$$\tau_L^{-1} = \frac{1}{12\pi^3} \frac{m_e^2 D_e^2 + m_h^2 D_h^2}{m_e + m_h} \frac{1}{n\hbar^2 \rho s} \left(\frac{kT}{\hbar s}\right)^5 \int_0^{\xi_0} \xi^5 \frac{e^\xi}{(e^\xi - 1)^2} d\xi. \tag{3}$$

Here $\xi_0 = 2\hbar s\Phi/kT$; m_e and m_h are the effective masses; D_e and D_h are the deformation potentials for electrons and holes respectively; Φ is the Fermi energy; $s = 4\times 10^5$ cm·s^{-1} is the velocity of sound; $\rho = 5.46$ is the density of germanium; n is the carrier density in the EHD. For a large EHD we can put $n = 6\times 10^{16}$ cm^{-3} and $\Phi_e = \Phi_h = 3\times 10^{-3}$ eV.[5] Substituting $m_e = m_h = m^* = 2\times 10^{-28}$ g, $D_e = D_h = D = 12$ eV,[5] we calculated the mobility $\mu = e\tau_L/m^*$ according to Eq. (3). The dependence obtained is shown by the dashed line in Fig. 4. At low temperature $T \lesssim 1$ K, Eq. (3) is approximated by

$$\tau_L^{-1} = \frac{10 m^* D^2}{\pi^3 \hbar^2 \rho s n} \left(\frac{kT}{\hbar s}\right)^5, \tag{4}$$

and at high temperatures by

$$\tau_L^{-1} = \frac{(2m^*)^{1/2} D^2}{2\pi\hbar^4 \rho s^2} \Phi^{1/2} kT. \tag{5}$$

These approximate relations $\mu \sim T^{-5}$ and $\mu \sim T^{-1}$ are also shown in Fig. 4. It can be seen that the experimental and calculated values of μ agree both in absolute magnitude and in temperature dependence in the temperature range from 2 to 3.5 K. As has been noted, the apparent increase in μ at temperatures above 3.5 K is caused by the effect of the free carriers on the hf absorption, since their mobility is greater than in large EHD's.

The following expression obtained[9] on intuitive grounds can be used to estimate the contribution from electron-hole scattering:

$$\tau_{eh} = \left(\frac{3}{4\pi n}\right)^{1/3} \left(\frac{m_e m_h}{4\Phi_e \Phi_h}\right)^{1/4} \frac{\Phi_e \Phi_h}{(kT)^2}. \tag{6}$$

The temperature dependence $\mu \sim T^{-2}$ calculated from Eq. (6) for the same values of n, m^*, and Φ are also shown in Fig. 4. It can be seen that this mobility is the smaller and must, therefore, dominate the resulting mobility. It should, however, be remembered that Eq. (6) only gives the order of magnitude of τ_{eh}. This value can be appreciably reduced since in deriving Eq. (6) the collision frequency of electrons and holes was taken as the mean distance between carriers $(3/4\pi n)^{1/3}$, divided by the Fermi velocity $(2\Phi/m^*)^{1/2}$, and the scattering probability was taken as unity. Moreover, it was shown[6] that electron-hole scattering can determine the conductivity of a neutral electron-hole plasma, but should not show up in the transverse magnetoresistance effect. However, it can be seen from Fig. 3 that the temperature dependence of the hf absorption ΔU in large EHD's agrees well with $\mu I_r^{5/3}$, where μ is in fact determined by the transverse magnetoresistance effect.[2] Such agreement would hardly be possible if μ were determined by τ_{eh}, which has a very different temperature dependence.

The results thus indicate the dominance of scattering of electrons and holes by acoustic phonons in large EHD's. The situation can be appreciably different for small EHD's in undeformed germanium. In the latter case the carrier density is in fact $n \approx 2\times 10^{17}$ cm^{-3}, while Φ_e and Φ_h are approximately the same as in germanium compressed along the (111) axis.[4] According to Eq. (3) and (6) this should lead to an increase in τ_L and a reduction in τ_{eh}, which can produce a change in the dominant scattering mechanism.

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