Eddy currents in electron-hole drops in germanium

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We had investigated the absorption due to photoexcitation of germanium at 2°K in crossed alternating (8–30 MHz) and constant magnetic fields. The absorption is due to excitation of eddy currents in the electron-hole drops (EHD). The characteristic relaxation times of the conductivity of the EHD were estimated.

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An alternating magnetic field should excite in electron-hole drops (EHD) eddy currents that lead to the appearance of high-frequency (HF) losses. To measure the losses we used a commercial instrument of the type Sh 1-1, with the germanium samples placed in the inductance coil of its tank circuit. To eliminate the influence of the HF electric field, a slotted screen of brass foil was placed between the sample and the coil; the screen had openings for the entry of the exciting radiation and for the exit of the recombination radiation. The samples of dislocation-free *p*-Ge with residual impurity concentration N equal to 10^{11} and 10^{14} cm^{-3} were in the shape of parallelepipeds measuring

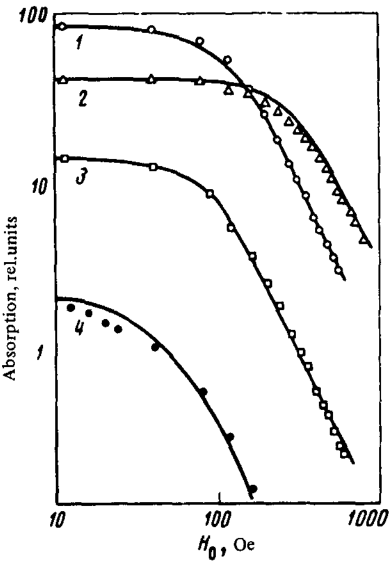

FIG. 1. Dependence of HF absorption of germanium on the magnetic field H_0 at 2 °K under quasistationary excitation by a 70-mW argon laser: 1—$N=10^{11}$ cm^{-3}, $F=20$ kgf, $f=19.8$ MHz, $t=1\times10^{-10}$ sec; 2—$N=10^{14}$ cm^{-3}, $F=20$ kgf, $f=19.8$ MHz, $\tau=3\times10^{-11}$ sec; 3—$N=10^{11}$ cm^{-3}, $F=20$ kgf, $f=8.8$ MHz, $\tau=1\times10^{-10}$ sec; 4—$N=10^{11}$ cm^{-3}, $F=0$, $f=19.8$ MHz, $\tau=2.7\times10^{-10}$ sec. The solid curves were calculated for the indicated values of τ.

4×4×2 mm with faces corresponding to the (100) planes. The samples could be subjected to nonuniform compression with the aid of a caprone pin of 1.6 mm diameter, to which a force F was applied in the (001) direction. Under such a compression, according to[1], what is produced in the sample is not a cloud of minute EHD, but only four EHD located under the pin in the directions ⟨111⟩. The samples were excited either by pulses from a nitrogen laser of wavelength 0.337 μ, pulse energy $\approx 10^{-5}$ J, and pulse duration 40 nsec, or else by radiation of an argon laser of 70 mW power, interrupted with frequency 670 Hz. When the samples were excited, the Q of the tank circuit changed and modulation of the HF oscillations set in. The low-frequency component of the signal was detected, amplified, and displayed on the oscilloscope. At the same time, the signal recombination radiation of EHD was also displayed on the oscilloscope. The constant magnetic field H_0 was applied perpendicular to the coil in the (010) direction relative to the sample.

The magnitude and shape of the recombination-radiation and HF-absorption signals at 2 °K and $H_0=0$ depended strongly on the magnitude of the deforming force F. In the absence of deformation, the HF absorption signal in the sample with $N=10^{14}$ cm^{-3} did not exceed the noise level. In the sample with $N=10^{11}$ cm^{-3}, the relaxation time constant τ_0 of the recombination radiation and of the HF absorption was 40 μsec, which is typical of a cloud of minute EHD.[2] At the optimal force $F\approx 20$ kgf, the value of τ_0 increased to 400 μsec, thus indicating formation of large EHD.[1] Under quasistationary excitation conditions, the intensity of the recombination radiation was approximately tripled, the HF absorption signal increased by 40 times in the sample with $N=10^{11}$ cm^{-3}, and by more than two orders of magnitude in the sample with $N=10^{14}$ cm^{-3}.

The magnetic field H_0 decreased greatly the HF absorption (see Fig. 1). It is seen from the figure that in strong fields the absorption decreases in proportion to H_0^2. The field region in which the absorption begins to decrease depends on the magnitude of the deforming force F and on the impurity concentration N in the samples. A decrease at minimal fields H_0 was observed for the pure germanium sample in the absence of deformation. In the sample with $N=10^{14}$ cm^{-3}, at $F=20$ kgf, the decrease of the HF absorption signal began with a field stronger by one order of magnitude. The absolute magnitude of the modulation of the HF signal, due to the photoexcitation of the samples at $H_0=0$, corresponded to a figure of merit $Q=2\times10^5$ for curve 1 and $Q=8\times10^{16}$ for curve 4.

The foregoing results can be naturally explained as being due to excitation of eddy currents in small and large EHD. Indeed, using the expression for the loss to eddy currents in a uniform sphere of radius R and conductivity σ,[3] and neglecting the skin effect, we can represent the figure of merit for the low-frequency region in the form

$$Q = \frac{5}{2\pi}\,\frac{V_L}{V_k}\,\frac{c^2}{2\pi f \sigma R^2}\,. \tag{1}$$

Here $V_L \approx 1$ cm^3 is the volume of the inductance coil of the tank circuit, V_k is the volume occupied by all the EHD, c is the speed of light, and f is the frequency. Using the expression for the conductivity of an intrinsic semiconductor in a magnetic field,[4] we can write

$$\sigma = \frac{\sigma_0}{1+\left(\dfrac{eH_0\tau}{m^x c}\right)^2};\quad \left(\frac{\tau}{m^x}\right)^2 = \frac{\tau_e\tau_h}{m_e m_h};\quad \sigma_0 = \left(\frac{\tau_e}{m_e}+\frac{\tau_h}{m_h}\right)e^2 n_0, \tag{2}$$

where n_0 is the density of the electrons or holes in the EHD, τ_e and τ_h are the electron and hole momentum relaxation times, $m_e=1.2\times10^{-28}$ g and $m_h=2.5\times10^{-28}$ g are the effective masses of the electrons and holes in germanium for the (100) directions. From expressions (1) and (2) and from the figure we can estimate, from the dependence of the absorption on the magnetic field H_0, the characteristic conductivity relaxation times τ in the EHD. The curves calculated in accordance with (1) and (2) for the optimal values of τ are shown in the figure by the solid lines. From these values of τ calculated the radii R of the EHD corresponding to the experimental values of Q at $H_0=0$. In the absence of deformation (curve 4) we have $\tau=2.7\times10^{-10}$ sec and $V_k=g\tau_0/n_0$, where the photoexcitation intensity g under the experimental conditions is equal to 1.5×10^{16} sec^{-1}, $\tau_0=4\times10^{-5}$ sec, and $n_0=2.4\times10^{17}$ cm^{-3}.[2] A numerical estimate shows that for the indicated parameters and for the experimental value $Q=8\times10^6$ the EHD radius is $R\approx8\times10^{-4}$ cm, which agrees with the EHD dimensions determined from light scattering.[2] We note that the conductivity of the EHD in undeformed pure germanium, calculated in accordance with (2) for $\tau=2.7\times10^{-10}$ sec is $\sigma_0=2\times10^5$ Ω^{-1}cm^{-1}, which is larger by two orders of magnitude than the value determined in[5] from measurements of the static conductivity of germanium at high levels of pulsed photoexcitation. In the case of nonuniform deformation, only four EHD drops are produced and $V_k=4(4/3)\pi R^3$, $\tau_0=4\cdot10^{-4}$ sec, $n_0=6\cdot10^{16}$ cm^{-3},[1] $\gamma=1\cdot10^{-10}$ sec, $Q=2\cdot10^5$, whence $R\approx10^{-2}$ cm, which agrees with[1]. The fact that the frequency f does not influence the dependence of the absorption on H_0 is natural, inasmuch as in the frequency range 8—30 MHz the condition $2\pi f\tau \ll 1$ is satisfied. The decrease of τ in germanium that is not uniformly deformed can be due both to the decrease in the degeneracy of the EHD plasma[6] and to the increase of the thickness of the skin layer in the large EHD as a result of the decrease of σ in the magnetic field. The smaller value of τ in doped germanium is apparently due to the scattering of the carriers in the EHD by neutral impurities. An estimate shows[4] that at $N \approx 10^{14}$ cm^{-3} the contribution due to such scattering corresponds to $\tau \times 10^{-10}$ sec.

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