Free-carrier cyclotron resonance in nonuniformly deformed germanium

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A nonuniform distribution of free carriers above an electron-hole drop localized in a potential well was evident from the line shape of cyclotron resonance at $T = 4.2$ K in a nonuniformly deformed Ge. The equilibrium concentration of the free carriers and the collision frequency near the surface of the drop were determined from an analysis of this shape. Estimates of the effective layer of the free carriers surrounding the drop are given.

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Investigation of cyclotron resonance (CR) in a nonuniformly deformed Ge produced as a result of pulsed laser excitation was undertaken by us in view of the problem of large, electron-hole drops (LEHD). Although the physical properties of the drops are known in sufficient depth,[1] the information about the properties of the cloud of free excitons (FE) and free carriers (FC) surrounding the drop so far is limited.[2] At the same time, it is clear that both the spatial and kinetic peculiarities of this cloud should greatly influence the behavior of the entire system as a whole.

Analysis of the CR spectra makes it possible to determine many important characteristics of the cloud of FC, their kinetics, and the spatial distribution.

The experiments were performed by using samples of dislocation-free, n-type Ge with a residual impurity concentration of $\sim 7 \times 10^{11}$ cm^{-3} in the form of a 4-mm-diam and 2-mm-thick disk nonuniformly compressed in the $\langle 111 \rangle$ direction. The optical excitation was accomplished by a pulsed YAG Nd^{3+} laser ($\lambda = 1.06\ \mu$m). The sample was placed into a microwave cavity in the area of maximum electric field **E**; the $\langle 111 \rangle$ crystal axis in this case was parallel to the external magnetic field H and perpendicular to the electric field E. The CR spectra were recorded by means of a microwave spectrometer ($\lambda = 3.2$ cm) that had a gate integrator with a different delay (t_d) relative to the exciting light pulse. The magnitude of the applied pressure, ~ 1500 kg/cm^2, was estimated from the line shift of recombination radiation of the LEHD,[3] and the lifetime of the drop was determined from the kinetics of luminescence ($\tau_0 \approx 500\ \mu$sec).

Figure 1 shows a group of CR spectra of a nonuniformly compressed Ge at $T = 4.2$ K, which were taken for different delays after the laser pulse. It can be seen that the shape of the spectra is rather complex: there is a narrow central line and a pronounced, broad, right-hand wing. For relatively short delays ($t_d \leqslant 50\ \mu$sec) the lines in the spectrum are poorly resolved. At long delay times, the CR spectrum has a single, unsymmetric line with a maximum corresponding to the electron effective mass $m^* = 0.08 m_0$. In the interval $t_d = 50$–$1000\ \mu$sec we obtained identical line shapes with a weakly varying amplitude. After increasing $t_d > 1000\ \mu$sec, the right-hand wing of

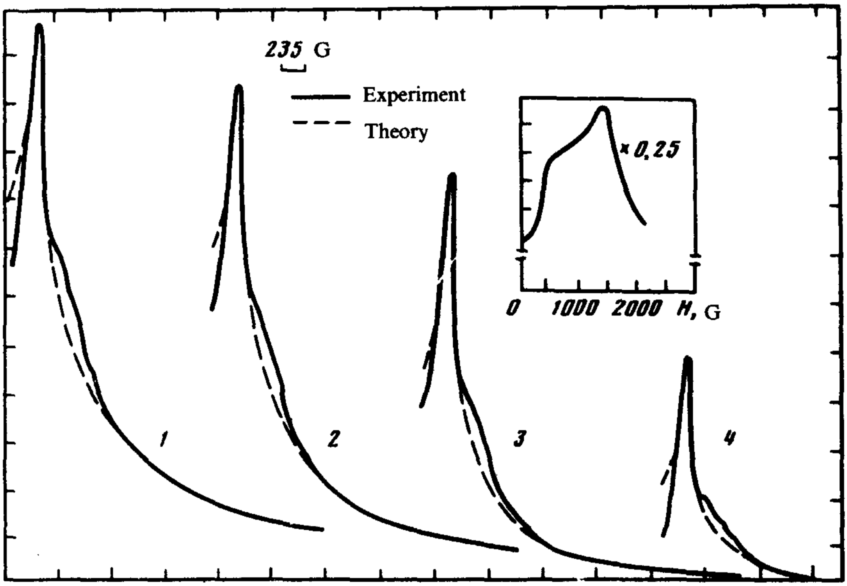

FIG. 1. Cyclotron resonance spectra of nonuniformly deformed Ge for different delays of the laser pulse: in the inset $t_d = 10\,\mu$sec, 1–1000 μsec, 2–1700 μsec, 3–2000 μsec, 4–2300 μsec. $T = 4.2$ K, $P = 1500$ kg/cm^2, $\mathbf{P}\|\langle 111\rangle\|\mathbf{H}_\perp\mathbf{E}$. The initial excitation level -10^{13} electron-hole pairs in the sample. The dashed lines represent the calculation of the line shape of the CR according to Eq. (2).

the line decreased gradually. We assumed that the peculiarities observed in the spectrum are due to a nonuniform density of FC around the drop. The narrow line evidently belongs to the peripheral regions with a relatively low carrier density and collision frquency (ν), and the broad wing belongs to the surface layers directly adjacent to the drop, where the concentration (n_{e0}) and ν have maximum values. The lines corresponding to the other effective masses are missing.

To determine the values of n_{e0} and ν for FC from the experimental results, we approximated the shape of the spectrum on a computer. A detailed description of the theoretical model for calculating the line shape of the CR for a nonuniformly deformed Ge will be published later. Here, however, we shall discuss the main aspects of this calculation.

The spatial distribution of FC above the surface of the drop in the potential deformation hole with the energy $E_s = -\alpha r^2$, where α is the pressure parameter and r is the distance from the center of the hole, can be described by the relation[4]:

$$n_e(r, R) = n_{e0}\exp\left[-\frac{\alpha(r^2 - R^2)}{kT}\right], \qquad (1)$$

where R is the radius of the drop and n_{e0} is the carrier concentration near the surface of the LEHD at $r \gtrsim R$.

The line shape of the CR of the free carriers in the presence of LEHD is described by the following integral:

$$P_{\mathrm{Cr}}=\int_R^{\infty}\left\{\frac{\sigma'(H)E_{\perp}^{2}(r)}{\left[1+\kappa\epsilon_{0}-\kappa-\dfrac{4\pi\sigma'(H)\kappa}{\nu}\right]^{2}+\left[\dfrac{4\pi\sigma'(H)\kappa}{\omega}\right]^{2}}\right. \tag{2}$$

$$\left.+\frac{\sigma'(0)E_{\parallel}^{2}(r)}{\left[1+\kappa\epsilon_{0}-\kappa-\dfrac{4\pi\sigma'(0)\kappa}{\nu}\right]^{2}+\left[\dfrac{4\pi\sigma'(0)\kappa}{\omega}\right]^{2}}\right\}4\pi r^{2}dr.$$

Here, $\sigma'(H)$, $\sigma'(0)$ is the conductance of the sample in a magnetic field (with allowance for the plasma shift) and without a magnetic field (see, for example, Ref. 5), the denominator is governed by the total, dielectric constant of the lattice ϵ_0 and of the carriers,[6] κ is the depolarization factor, and $E_{\perp}$ and $E_{\parallel}$ are the average fields that are perpendicular and parallel to the magnetic field due to distortion of the external electromagnetic field by the conducting sphere (drop).[7]

It is known that at large concentration of FC the collision frequency ν is a function of n_e. Manenkov *et al.*[8] obtained the $\nu(n_e)$ dependence in Ge at $T = 4.2$ K without a pressure: $\nu(n_e) = \nu_p + bn_e$ is the collision frequency with phonons and $b = 0.08$ cm^3/sec. In our calculation we varied the coefficient b. The integral (2) was calculated on a computer by varying three parameters: b, n_{e0}, and R. We obtained a satisfactory agreement between the observed spectra and the calculation at $b = 0.1$ and $n_{e0} = (3.5 \pm 0.5)\times 10^{12}$ cm^{-3} for $R = 0.4$ mm, $R = 0.22$ mm, and $R = 0.188$ mm; $n_{e0} = (2.8 \pm 0.4)\times 10^{12}$ cm^{-3} for $R = 0.08$ mm, and $n_{e0} = (2.4 \pm 0.4)\times 10^{12}$ cm^{-3} for $R = 0.05$ mm. The pressure parameter α, which was obtained under analogous conditions, was assumed to be equal to 7 meV/mm^2.[9] The obtained concentration of the FC at the surface of the drop $n_{e0} = 3.5\times 10^{12}$ cm^{-3} is in good agreement with the calculation of the work function $E_0 = 4.6$ meV.[10]

Figure 1 compares the calculated CR spectra with the experimental. Notice that there are two regions of the spectra in which a deviation from the experimental curves is observed; in the initial and the middle part of the spectrum. The first deviation, which can conceivably occur at small t_d when the drop size is comparable with that of the potential well, is apparently attributable to nonsphericity of the drop. As for the second region, it can be attributed to the weak line of the holes with $m^* = 0.13m_0$, which is characteristic of Ge that has been deformed in the $\langle 111\rangle$ direction.[11]

The obtained results allow us to conclude that there is a spatial distribution of FC in the sample in the presence of LEHD. The presence in the spectra of a single electron line in the indicated orientation means that all the electrons belong to a single valley and that the carriers in the sample are located near the drop. A satisfactory description of the spectrum shape using the given model confirms the correctness of expression (1), from which the effective size of the layer of the FC (the distance at which the carrier density decreases by a factor of e) can be calculated: $\delta r \approx 60\,\mu$m at $R \approx 400\,\mu$m.

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