QUANTUM OSCILLATIONS OF THE INTENSITY OF RECOMBINATION RADIATION OF ELECTRON-HOLE DROPS IN SILICON

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Submitted 20 June 1973
ZhETF Pis. Red. 18, No. 2, 114 - 118 (20 July 1973)

We investigate recombination radiation of silicon single crystals at high density of the non-equilibrium carriers produced by laser pumping in strong magnetic fields at T = 1.4°K. Quantum oscillations of the intensity were observed at the "blue" edge of the band connected with carrier recombination in the electron-hole drop. The carrier density in the drop is determined. The heating of the carriers and excitons is studied.

We have investigated the recombination radiation of single-crystal Si at high density of the non-equilibrium carriers produced by pulsed laser excitation, in strong magnetic fields. Oscillations of the integral intensity of recombination radiation of electron-hole drops (EHD) in Ge in a magnetic field was first reported in [1]. In the case of Si, varying the magnetic field smoothly, we observed intensity oscillations at fixed frequencies near the "blue" edge of the band connected with the EHD radiation [2, 3]. No noticeable changes in the shape and position of the EHD band maximum were observed in fields up to about 40 kOe. A small shift towards lower energies (approximately 0.5 meV at 40 kOe) was observed only in the exciton band.

The meaning of our experiment can be seen from Fig. 1. The EHD comprise a degenerate two-component Fermi system, in which the energies of the electrons and holes become quantized when a magnetic field is applied. When the magnetic field is varied, the number of Landau levels under the Fermi surface changes jumpwise and periodically in the reciprocal field, as do the distributions over the states themselves. It is therefore natural to expect the intensity of the recombination radiation at fixed frequencies to oscillate within the limits of the EHD band. This effect should be most appreciable in the region of the "blue" edge of the EHD band, e.g., at the points 2, 3, and 4 marked by the arrows in Fig. 1a, where the contribution to the intensity is made by the transitions between states in a certain layer ΔE directly under the Fermi surfaces of the electron and hole bands (Fig. 1c). The effect should decrease near the maximum of the EHD band, for in this case the intensity is determined by transitions between practically all the Landau levels.

We investigated the recombination radiation of pure Si crystals of n- and p-type ($\rho = 4 \times 10^3 \Omega$-cm and 2.5×10^4 Ω-cm, respectively). The samples were fastened without being stressed inside a superconducting solenoid placed in a specially constructed optical cryostat; the entire setup had a sufficiently high transmission with sufficiently high homogeneity of the field along the sample. The samples were in superfluid helium at T = 1.4°K. The optical pumping was with the second Stokes component of SRS by liquid nitrogen ($\hbar\omega$ = 1.2104 eV) excited witha pulsed ruby laser. Such volume excitation (the absorption coefficient of Si at T = 1.4°K and at 1.2104 eV is $\sim$0.5 cm^{-1}) generates e-h pairs practically near the extrema of the corresponding bands, and the heating of the electron system is due mainly to the relaxation of the TA and LO phonons produced in the optical transitions. The e-h pair concentration averaged over the volume was $n \sim 10^{18}$ cm^{-3} at the maximum pumping.

Let us discuss first the temperature of the electron system under pulsed excitation of such carrier densities. A direct determination of the drop temperature T_d from the EHD spectrum is difficult, because the shape of the spectrum is a complicated function of the temperature and of the Fermi energies of the carriers. We determined the exciton-gas temperature T_{exc} under the assumption that $T_d \approx T_{exc}$.

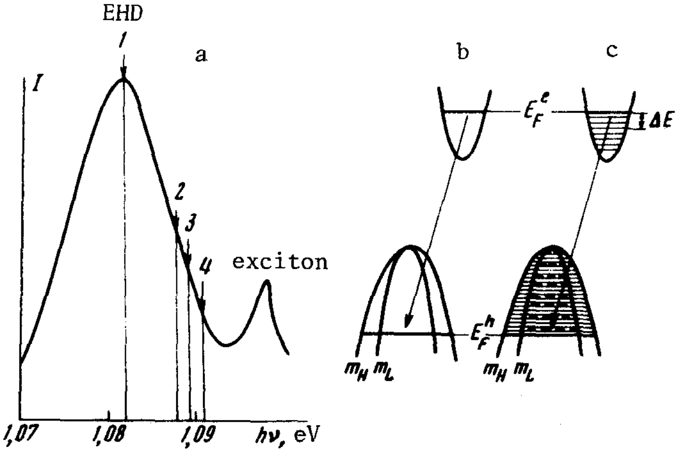

Fig. 1. a) Si recombination radiation at 1.4°K; b, c) EHD level scheme at H = 0 and H ≠ 0.

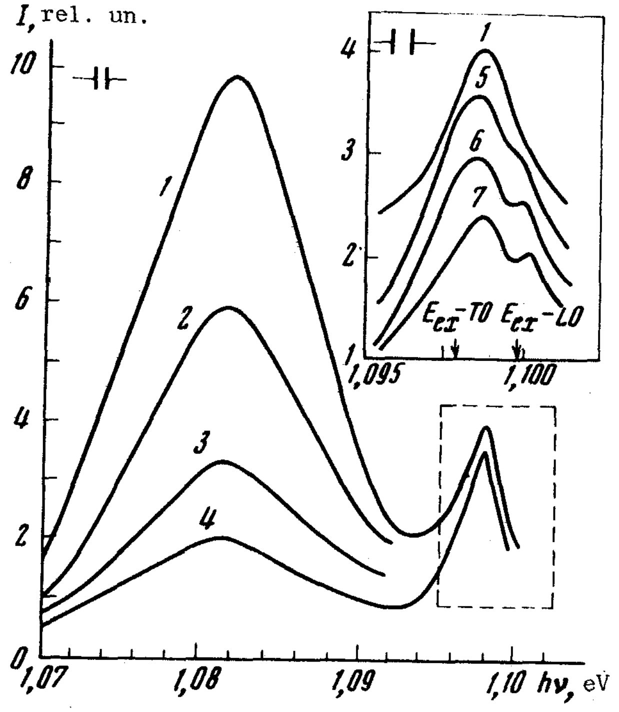

Fig. 2. Distributions of the intensity in the emission spectrum of EHD and free excitons with emission of TO and LO phonons, obtained at different instants after the arrival of the exciting pulse. Curves 2, 3, and 4 of the EHD spectrum correspond to delays of 0.2, 0.4, and 0.6 μsec. Curves 5, 6, and 7 of the exciton spectrum correspond to delays of 1, 2, and 3 μsec (insert, upper right). Curve 1 was plotted without a delay and shows the distribution of the maximum intensity in the spectrum.

Figure 2 shows the intensity distributions in the spectrum of the EHD and the free excitons with emission of TO and LO phonons, obtained (without a field) at different times after the arrival of the excitation pulse. The observed exciton-luminescence band is a superposition of two lines with participation of TO and LO phonons ($\hbar\omega^{TO} = 57.3$ meV, $\hbar\omega^{LO} = 55.3$ meV) [4]. With increasing delay relative to the excitation pulse, the TO-LO structure of the exciton spectrum becomes more distinct, as illustrated by the "cooling" of the exciton gas after the instant of pumping (upper right insert of Fig. 2). We determined T_{exc} by analyzing the shape of the exciton-phonon spectrum, by separating the contours of the lines with participation of the TO and LO phonons. For the maximum intensity of the exciton line, corresponding to $n \sim 10^{18}$ cm^{-3}, T_{exc} amounted to 11 ± 2 °K. For delays of 1, 2, and 3 μsec we obtained $T_{exc} = 10.6$, 9.4 and 8°K. The values of T_{exc} obtained in this manner agree well with the exciton line widths ($\sim 2kT_{exc}$) and evidently exceed 1.4°K appreciably. Such a high value of T_{exc} is due, from our point of view, to the overheating in the system of the long-wave acoustic phonons produced upon decay of the optical phonons and upon relaxation of the Auger electrons, and also when the excitons become bound into drops. We estimate the damping time of such phonons at $\sim 10^{-5}$ sec. Thus, in the case of pulsed excitation with $\bar{n} \sim 10^{18}$ cm^{-3} we have $T_d \simeq 10$°K (assuming that $T_d = T_{exc}$).

We call attention, in addition, to the invariance of the shape, width, and position of the maximum of the EHD spectrum, owing to the constancy of the damping time over the entire EHD spectrum. This result is convincing evidence of the constancy of the Fermi levels and hence of the carrier density n_0 in EHD at different values of $\bar{n}$. The damping of the EHD recombination radiation is itself connected with the decrease in the drop dimensions.

The lifetimes τ_d and τ_{exc} determined from Fig. 2 are 0.4 and 2.6 μsec, respectively.

Taking into account the strong heating of the EHD, the magneto-optical measurements were made with the <100> axis directed along the magnetic field H. Light masses $m^e = 0.19\, m_0$ were then effective in two valleys of the conduction bands, so that $\hbar\omega_c/kT \gtrsim 3$ in fields on the order of 40 kOe. The dependence of the intensity on H was measured at the maximum of the EHD band and at several fixed frequencies near its blue edge (arrows on Fig. 1a). In the latter case, intensity oscillations were observed with variation of the magnetic field at all the frequencies. The spectrum sections separated by the double monochromator did not exceed 0.8 meV in width. Figure 3 shows the measurement results for the frequency $\hbar\omega = 1.082$ eV, corresponding to the maximum of the EHD band and for $\hbar\omega = 1.089$ eV on its blue edge (arrows 1 and 3 in Fig. 1a). At the maximum of the band (curve 1), there are practically no oscillations, whereas on the blue wing the curve shows oscillations with a period that is constant in terms of 1/H (curve 3). The oscillation depth does not exceed about 6 %. The experimental points are the result of averaging a large number of measurements at each value of the field, with the corresponding error indicated. The sensitivity of the setup enabled us to observe oscillations with depth not less than 2%.

Oscillations of the recombination-radiation intensity were observed by us also when the

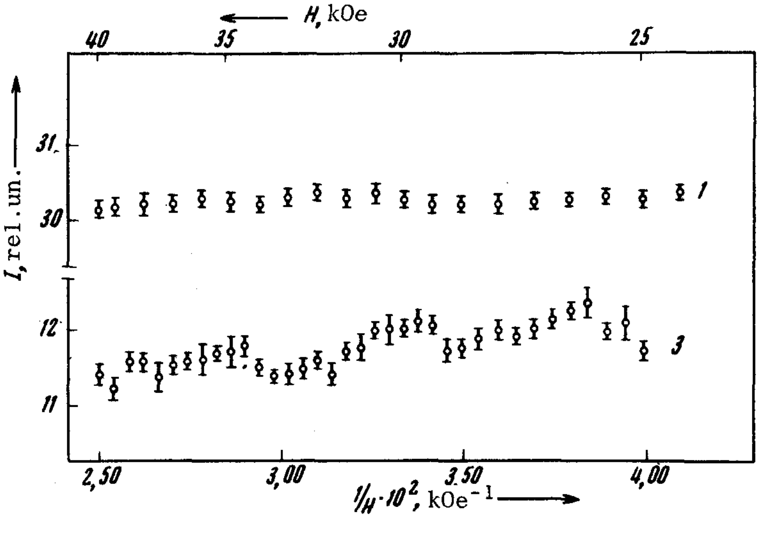

Fig. 3. Intensity of EHD recombination radiation vs the magnetic field at the maximum of the band (curve 1) and near its blue edge (curve 3).

excitation was produced directly by a ruby laser. At the same $\bar{n} \sim 10^{18}$ cm^{-3}, however, judging from the value of T_{exc}, the overheating of the carrier was at least 1.5 times larger than in the case of volume excitation. The depth of the oscillations was much smaller ($\sim$3%).

The constancy of the period of the oscillations a d the dependence of the depth on the temperature indicate that they are of quantum origin, in accord with the arguments advanced above. The value of the period observed at the orientation H $\parallel$ <100> is due, in our opinion, to the light masses of the electrons, $m^e = 0.19m_0$, in two out of the six valleys. In the remaining four valleys the cyclotron mass is large enough, $m_c = \sqrt{m_\parallel m_\perp} = 0.42m_0$, and we believe that the contribution from these valleys to the intensity takes the form of a non-oscillating background that is smeared out by the high temperature. This applies equally well to the heavy holes, $m_H^h = 0.48m_0$ (the light holes, $m_L^h = 0.16m_0$, constitute only 16% of all the holes).

From the period of the oscillations ($\sim 5\times10^{-3}$ kOe^{-1}) we estimated directly the Fermi energy of the electrons, and then the equilibrium concentration of the e-h pairs in the EHD, which turned out to equal $n_0 \simeq 5\times10^{18}$ cm^{-3}.

Oscillations are observed also at an orientation H $\parallel$ <111> (with depth $\sim$4%). The period observed in this case, however, is approximately 1.5 times smaller than the expected value, if it is assumed that at this orientation only one electron cyclotron mass, $m_c = 0.28m_0$, is effective. The reason for this discrepancy is still unclear.

We note in conclusion that the described results, which can be satisfactorily interpreted within the framework of the EHD concept, cannot be simply explained on the basis of the biexciton concept [5], or on the basis of an unstable e-h plasma.

The authors thank V. F. Gantmakher for useful discussions during the course of the work.

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