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MAGNETIC-FIELD DEPENDENT INTENSITY OSCILLATIONS OF THE EHD LUMINESCENCE IN PURE GERMANIUM

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The magnetic-field dependence of the EHD luminescence in pure germanium is investigated using pulsed laser excitation. Intensity oscillations are found, which vary with the delay time of the detection. A fit to a reaction-kinetic model yields a quantum efficiency of $Q \approx 25\%$. The main nonradiative process in the electron–hole liquid is found to be the Auger-recombination.

AT HIGH DENSITIES and low enough temperatures, excitons in Ge condense into electron–hole droplets (EHD),[1–3] which can be described as a quasimetallic plasma. In a magnetic field Landau levels in this plasma are formed, which influence the density of states and free energy of the carriers in the EHD.[4] In contrast to metals, where the electron density is fixed, in the EHD not only the free energy but also the total density of electrons and holes may have a magnetic field dependent oscillatory part. This gives rise to oscillations of the luminescence intensity.[5,6] In this paper we present time dependent measurements of these intensity oscillations. They will alow conclusions on the quantum efficiency and the nonradiative processes as well as a determination of the carrier density in the EHD.

The measurements were carried out on Ge samples with $N_D \approx 10^{12}\,\mathrm{cm}^{-3}$ to which a magnetic field ($H <$ 40 kOe) in (100) direction could be applied by means of a superconducting coil. $H \parallel (100)$ is the simplest situation for Ge, as all conduction band valeys are equivalent for this direction of field. The samples were immersed in liquid helium which was pumped to about 1.5 K. For carrier excitation a pulsed GaAs laser was used having a peak power of 5 W, pulse duration of 2 μsec and repetition rate of 1 kHz. The power density on the sample was about 5 $\mathrm{W.cm}^{-2}$. The detection system consisted of an MDR-2 grating monochromator used as a narrow band filter for the LA-phonon assisted EHD-line at 709 meV and a Ge photodiode with a rise time of about 1 μsec. For signal registration a conventional boxcar technique was applied.

At the temperature of 1.5 K and the above excitation conditions practically all non-equilibrium carriers are condensed into EHD. This can be proven by the strongly exponential decay of the EHD luminescence over a wide range.[7,8] So the time dependence of the mean carrier density in the sample after excitation can be described by one equation, only taking into account the carriers inside the EHD:

$$\frac{\mathrm{d}}{\mathrm{d}t}(NVn) = -NV(An + Bn^2 + Cn^3) \qquad (1)$$

where N and V are density and mean volume of the droplets, n is the carrier density inside the EHD, and A, B, and C are the recombination coefficients for impurity induced non-radiative, radiative, and Auger-like nonradiative processes, respectively. Higher order processes as for instance two-electron band-to-band transitions (four-particle recombination process) can be neglected because of their extremely low recombination coefficients.[9]

From (1) the total lifetime τ and the internal

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quantum efficiency Q can be defined:

$$\tau^{-1} = A + Bn + Cn^2 \quad (2)$$

$$Q = Bn(A + Bn + Cn^2)^{-1}. \quad (3)$$

According to Keldysh and Silin[4] the total free energy in the EHD has a magnetic-field dependent oscillatory part caused by the varying positions of the density-of-states peaks (Landau levels). This gives rise to an oscillatory density $n(H) = n_0 + \Delta n(H)$ which shows up in a time dependent oscillating luminescence intensity $i(H, t) = i_0(t) + \Delta i(H, t)$. For the relative oscillations the following equation can be derived:

$$\frac{\Delta i(H, t)}{i_0(t)} \int_0^\infty = \frac{\Delta n(H)}{n_0}[1 - t(Bn_0 + 2Cn_0^2)] \quad (4)$$

where t is the time between excitation and detection. The time-integrated intensity

$$I(H) = \int i(H, t)\,dt = I_0 + \Delta I(H)$$

should oscillate with respect to density as

$$\frac{\Delta I(H)}{I_0} = \frac{\Delta n(H)}{n_0}(A - Cn_0^2)(A + Bn_0 + Cn_0^2)^{-1}. \quad (5)$$

Equations (4) and (5) are valid for the region of strongly exponential decay and for small deviations from the equilibrium values at $H = 0$.

Figure 1 shows the measured relative intensity oscillations for different delay times t in the magnetic field region between 5 and 30 kOe. Two maxima and two minima can be clearly identified. A change in sign and an increase of the relative amplitude to longer delay times is in good qualitative agreement with equation (4). In order to get quantitative results, the positions of the maxima and minima were plotted with respect to the reciprocal magnetic field (insert of Fig. 2), and, from the measured curves, those for $t = 0$ and for the oscillations of the integral intensity were calculated (Fig. 2). The plot of the maxima and minima positions can be fitted by a straight line according to the condition for the index of maxima (minima)[4] $m = \mu/\hbar\omega + \text{const.}$ where μ is the Fermi energy and ω the cyclotron frequency of the electrons.[10] From this fit, the carrier density in the EHD at 1.5 K is derived to be $n = 2.3 \times 10^{17}\,\text{cm}^{-3}$ (bandstructure parameters see reference 4). This value is in excellent agreement with calculations of n from the lineshape.[11] The curve for $t = 0$ directly

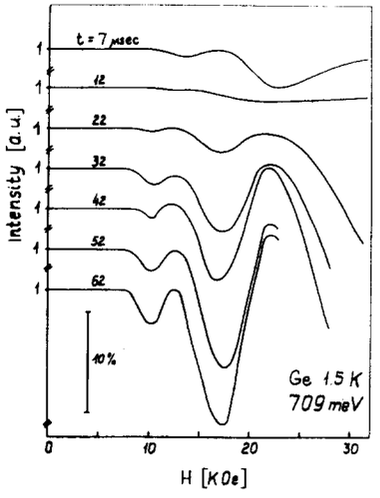

FIG. 1. Intensity oscillations of the LA-phonon assisted EHD line for different times t between excitation and detection.

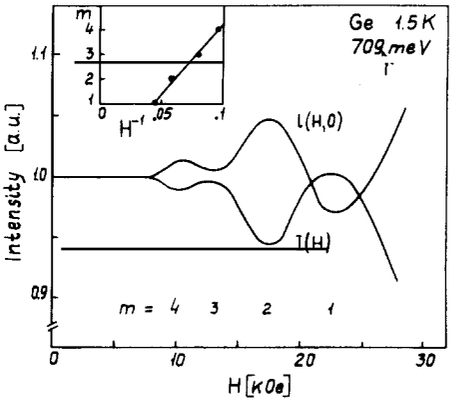

FIG. 2. Oscillations of the luminescence intensity at $t = 0$ and of the time integrated luminescence intensity (calculated from the measurements in Fig. 1). In the insert the maxima and minima are plotted with respect to the reciprocal field.

gives the density oscillations [cf. equation (4)], which are less than those calculated by Keldysh and Silin[4] by a factor of 10.

A fit of the two calculated curves in Fig. 2 to the equations (4) and (5) results in a condition for A and C: $A : Cn^2 < 0.1$. That means, that in the EHD in Ge the main nonradiative process is the Auger recombination and that impurity induced nonradiative processes can be neglected at least to doping regions of about $10^{16}\,\text{cm}^{-3}$, until which the total lifetime is nearly unchanged.[12]

Assuming $A = 0$, equations (3), (4), and (5) yield the quantum efficiency in the EHD to be $Q \approx 25\%$ (for $A > 0$: $Q < 25\%$). This is less by a factor of 2 and 3 respectively than earlier estimations by Benoit a la Guillaume *et al.*[13] ($Q = 50\%$) and Pokrovskii *et al.*[14] ($Q = 80\%$). With this new value of Q and the total lifetime of electrons and holes in the EHD[7,8] of 36 μsec, we are able to calculate the Auger coefficient C for the EHD in Ge:

$$C = (1-Q)n^{-2}\tau^{-1} = 4 \times 10^{-31}\,\mathrm{cm}^6\,\mathrm{sec}^{-1}.$$

As the Auger recombination in Ge is phonon assisted, C should not be temperature dependent below the Debye-temperature of the phonon involved, and at higher temperatures should increase with temperature. So a comparison of the EHD value of C with the room-temperature value of $2 \times 10^{-31}\,\mathrm{cm}^6\,\mathrm{sec}^{-1}$ [15] shows that in the EHD the Auger recombination is enhanced by a factor $\rho > 2$. This is in good agreement with theoretical calculations of the enhancement factor in the EHD[16,17] ($\rho \approx 3$).

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