phys. stat. sol. (b) 70, K109 (1975)

Subject classification: 13.5.1 and 20.3; 6; 22.1.1

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Magnetooscillations of the EHD TA-Line in Pure Germanium

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According to Keldysh and Silin (1), electron-hole droplets (2, 3) (EHD) in a magnetic field have a field dependent oscillating equilibrium density, due to oscillating contributions to the free energy (4). This oscillating density causes intensity oscillations of the EHD luminescence in Ge (5, 6). In this paper, we for the first time present time dependent measurements of the intensity oscillations of the TA-phonon assisted line at 729 meV. They show characteristic differences compared to the LA-assisted line (709 meV) which was investigated in a previous paper (7). As we can show, these differences are due to the fact that the TA-assisted radiative transition is a forbidden one at the band extrema (8). The experiments were carried out on Ge samples with an impurity concentration of about 10^{12} cm^{-3}. The samples were immersed in liquid helium which was pumped to about 1.5 K. For carrier excitation a pulsed GaAs laser was used with a peak power of about 5 W, pulse length of 2 μs, and duty factor of 0.2%. The power density on the sample was about 5 W cm^{-2} during the pulse. A magnetic field in Faraday configuration could be applied in (100) direction to the samples by means of a superconducting coil (H $\lesssim$ 35 kOe). The detection system consisted of an MDR-2 grating monochromator used here as a narrow band filter for the different EHD lines, and a Ge photodiode (rise time < 1 μs). The signal-to-noise ratio was improved by conventional boxcar technique. The intensity of the LA- and TA-line, respectively, may be written in the following way:

$$I_{LA,TA} = \text{const}_{LA,TA} \int \left| M_{LA,TA} \right|^2 D(k_e, k_h) d^3 k_e d^3 k_h , \qquad (1)$$

where $D(k_e, k_h)$ is the combined density of the occupied electron and hole states, and M is the total matrix element of the transition.

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1) On leave from Physikalisches Institut der Universität Stuttgart, FRG.

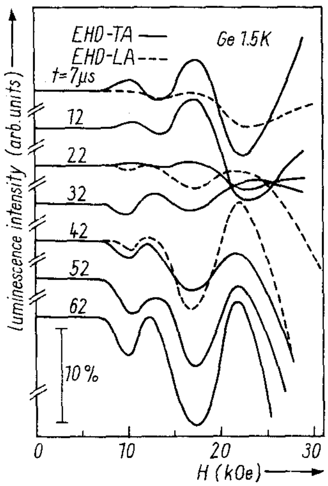

Fig. 1. Magnetooscillations of the EHD TA-line in pure germanium. The parameter to the curves is the delay time between excitation and detection. All curves are normalized to the intensity at H = 0

The LA-line should be allowed (8), so M_{LA} should be approximately constant in the region of integration. In contrast to this, the TA-assisted radiative transition should be forbidden at the band extrema (8), the matrix element M_{TA} should be proportional to $\left(|k_e| + |k_h|\right)^r$, where k_e (k_h) is the momentum of the recombining electron (hole) measured with respect to the band extrema, and r gives the order of forbiddenness. r = 0 would mean that this line also is allowed. The mean value of $|k_e| + |k_h|$ is connected to the density as $\left\langle |k_e| + |k_h| \right\rangle \sim n^{1/3}$.[2)] From equation (1) we can derive the ratio of the intensities of the two lines to be

$$I_{TA}/I_{LA} = \text{const}\; n^{2r/3} \tag{2}$$

As shown in (7) the density inside the EHD oscillates with respect to the magnetic field. These density oscillations cause oscillations of the luminescence intensity of the LA-phonon assisted line according to the equation

$$\left.\frac{\Delta I}{I_o}\right|_{LA} = \frac{\Delta n}{n_o}\left[1 - t(B\,n_o + 2\,C\,n_o^2)\right], \tag{3}$$

where t is the delay time between excitation and detection and B and C are the transition coefficients for radiative and Auger recombination, respectively. For the oscillations of the TA-line we can derive from equation (2)

$$\left.\frac{\Delta I}{I_o}\right|_{TA} = \left.\frac{\Delta I}{I_o}\right|_{LA} + \frac{2r}{3}\,\frac{\Delta n}{n_o}\,. \tag{4}$$

2) This is valid for the non-ultraquantum region of the applied field. In our case only for holes the field is low enough. However, due to the larger k-spread of holes, their influence should dominate, so that the used relation still is a good approximation.

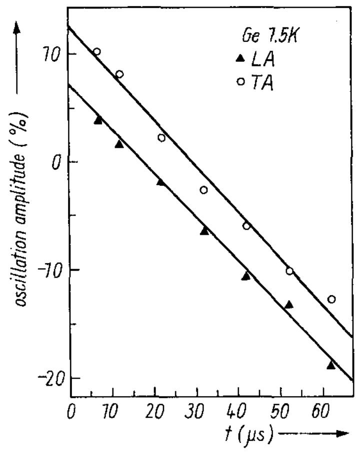

Fig. 2. Plot of the amplitude of the last measured oscillation in Fig. 1 with respect to the delay time t. Values for the LA-line according to (7)

So the measurements of the magnetooscillations of the TA- and LA-lines can directly provide the value of r. Fig. 1 shows the intensity oscillations of the TA-assisted EHD line with respect to the applied magnetic field for different times t. For comparison some equivalent curves for the LA-line are drawn (dashed). The relatively large differences show that $r \neq 0$, and that the TA-assisted radiative recombination also inside the EHD is forbidden at the band extrema. To derive the exact value of r, the amplitudes for the last measured oscillation have been plotted with respect to the delay time for both the TA- and the LA-line (7) (Fig. 2). In agreement with equations (3) and (4) both amplitudes depend approximately linearly on delay time. Within the measurements accuracy the slope of the two dependences is the same which is in accordance with equation (4). The extrapolation to $t = 0$ yields $\Delta n/n_o$ (cf. equation (3)), the mean distance of the two least-meansquare-error fits in Fig. 2 provides $\frac{2r}{3}\frac{\Delta n}{n_o}$. From this r can be derived to be $r \approx 1$. This directly shows that the matrix element for the TA-phonon assisted radiative transition in the EHD in Ge has linear k-dependence. So in spite of its relatively high intensity, the EHD TA-line is in first order forbidden in Ge.[3)]

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(Received April 24, 1975)