Observation of optical orientation of holes in semiconductors

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A luminescence band near 1.86 eV is observed in n–GaAS crystals and is due to electronic transitions from the conduction band to the split-off valence band. The presence of circularly polarized luminescence in the case of circularly polarized pumping offers evidence of optical spin orientation of the holes in the split-off band.

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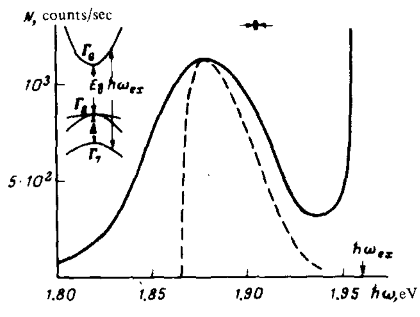
We present here preliminary results of an investigation of the spectrum and polarization of photoluminescence due to transitions of electrons in GaAs crystals into the valence band Γ_7, which is split off as a result of a spin-orbit interaction (see the figure). The luminescence was excited in n-GaAs crystals by He-Ne laser radiation ($\hbar\omega_{ex} = 1.96$ eV, 40 mW), and was registered with a DFS-24 spectrometer and a photon-counting system. The measurements were performed both on epitaxial films with $n \approx 10^{14}$ cm^{-3} and on doped crystals with electron density from 2×10^{17} to 2×10^{18} cm^{-3} at 90 °K. The figure shows the experimental luminescence spectrum for a sample with $n = 6.7\times10^{17}$ cm^{-3}, and also a spectrum calculated by the formula

$$I(\epsilon) = A\epsilon^{1/2} \frac{\exp\left(-\frac{m_c}{m_c + m_{sh}} \frac{\epsilon}{kT}\right)}{1 + \exp\left\{\left(\frac{m_{sh}}{m_c + m_{sh}}\epsilon - \mu\right)\Big/kT\right\}} . \qquad (1)$$

Here $\epsilon = \hbar\omega - (E_g + \Delta)$, m_c and m_{sh} are the effective masses of the electrons in the conduction band and of the holes in the Γ_7 band, respectively, and μ is the chemical potential of the electrons. It is proposed that the photoexcited holes in the Γ_7 band satisfy Boltzmann statistics, and the luminescence spectrum is determined by the direct transitions. The theoretical curve was plotted at values $m_{sh}/m_c = 3$ and $m_c = 0.07\, m_0$. Superposition of the maxima of the theoretical and experimental curves leads to a value $E_g + \Delta = 1.865$ eV, which corresponds to the values of E_g and Δ known from other experiments. [1]

In samples with $n \approx 10^{18}$ cm^{-3}, the intensity of the investigated luminescence is lower than the intensity of the edge luminescence $\Gamma_6 \to \Gamma_8$ by approximately 10^5 times. With decreasing electron concentration, the luminescence intensity decreases, the band becomes narrower and shifts towards lower frequencies, and at $n < 10^{15}$ cm^{-3} there is practically no luminescence in the $\Gamma_6 \to \Gamma_7$ band. We note that the experimental spectra are noticeably compressed in comparison with the calculated ones, not only in the low-frequency direction but also on the high-frequency side. The latter circumstance indicates that the distribution function of the holes excited by the light in the Γ_7 band is not at equilibrium, i.e., the observed luminescence is "hot" in this sense.



Luminescence spectrum in the region of the $\Gamma_6 \to \Gamma_7$ transitions in a GaAs crystal ($n = 6.7\times10^{17}$ cm^{-3}, $T = 90$ °K). Solid curve—experiment, dashed—calculated from formula (1) at $m_{sh}/m_c = 3$ and $m_c = 0.07 m_0$. [4] The increased intensity at $\hbar\omega \sim 1.95$ eV is due to the "tail" of the exciting line. The upper left corner shows the band structure of GaAs in the vicinity of $k = 0$.

One could expect the luminescence in the $\Gamma_6 \to \Gamma_7$ band to be convenient for observation of optical orientation of optical orientation of free holes. In experiments on optical orientation of free carriers in semiconductors, it was possible to observe so far only the orientation of the electron spins in the conduction band.[2] Owing to the spin-orbit interaction in the band Γ_8, which is degenerate at the point $k=0$, the hole spin relaxation time τ_s is much shorter than their lifetime τ_0. Therefore the effect of the optical orientation of the holes in the band Γ_8, which is proportional to $\tau_s(\tau_s+\tau_0)^{-1}$, is negligibly small.[3] A different situation can occur for holes in the split band Γ_7. Indeed, in this case the lifetime τ_0 is determined mainly by the relatively large probability of the $\Gamma_7 \to \Gamma_8$ transitions between the step-bands of the valence band and can be quite small. Therefore the holes produced in the band Γ_7 upon excitation with circularly polarized light do not have time to lose their directed angular momentum within the time τ_0, and consequently the luminescence due to the $\Gamma_6 \to \Gamma_7$ transitions turns out to be circularly polarized to a considerable degree.

Indeed, under circularly polarized excitation, we have observed circular polarization of the luminescence in the $\Gamma_6 \to \Gamma_7$ band. Measurements in the maximum of the band for the sample with $n=1.6\times10^{18}$ cm^{-3} (approximately 6500 Å) yielded a degree of circular polarization $\rho=0.90\pm0.02$. Close values of ρ were obtained also for other samples. At the same time, ρ is close to zero for the $\Gamma_6 \to \Gamma_8$ edge luminescence. This indicates that the spin orientation of the majority carriers—electrons—is negligibly small in this case and the observed circularly polarized luminescence $\Gamma_6 \to \Gamma_7$ is due to spin-oriented holes in the Γ_7 band. For the $\Gamma_6 \to \Gamma_7$ transitions, in analogy with[3], the degree of circular polarization of the radiation in a direction opposite to that of the exciting light

$$\rho = -P_{sh}\exp(-\Phi)\tau_s(\tau_s+\tau_0)^{-1}, \qquad (2)$$

where P_{sh} is the degree of spin polarization of the holes at the instant of production, τ_0 is the lifetime of the holes in the Γ_7 band, τ_s is the time of their spin relaxation near the extremum, and the factor $\exp(-\Phi)$ takes into account the losses of the directed hole spin as the holes become thermalized inside the Γ_7 band. It can be shown that P_{sh} coincides exactly with the degree of spin polarization P_c of the electrons excited by circularly-polarized light from the Γ_7 band and calculated in[3]. An estimate shows that $P_{sh}=0.99$ under the conditions of our experiment. Using the experimentally measured value of ρ, we obtain in accordance with (2) an estimate for the quantity $\exp(-\Phi)\tau_s(\tau_0+\tau_s)^{-1}\approx 0.9$, from which it follows that $\tau_s/\tau_0 \gtrsim 10$.

[1]C. Hilsum, Progr. in Semicond. 9, 136 (1965).
[2]G. Lampel, Proc. 12th Intern. Cont. Phys. Semicond. Stuttgart, 1974, p. 743.
[3]M.I. D'yakonov and V.I. Perel', Zh. Eksp. Teor. Fiz. 60, 1954 (1971) [Sov. Phys.-JETP 33, 1053 (1971)].
[4]M. Cardona, transl. in: Opticheskie svoĭstva poluprovodnikov (Optical Properties of Semiconductors), Mir, 1970, p. 162.