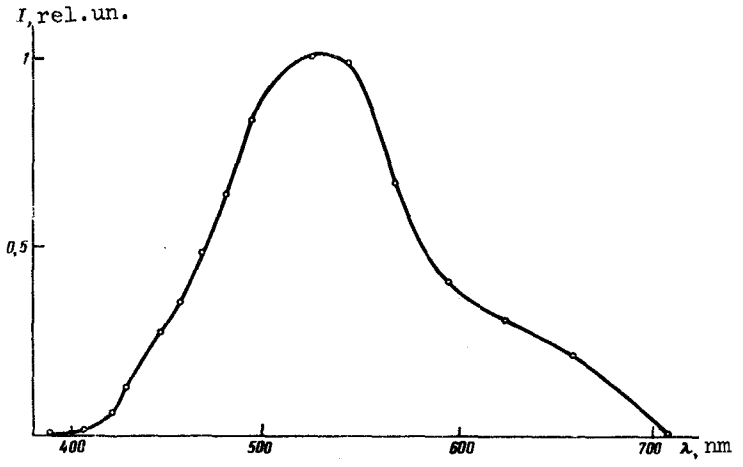

Fig. 2. Spectral distribution of anomalous thermoluminescence.

its rate of change is quite small. Thus, for example, at T = 250°C the brightness decreases 10 - 15% after 30 minutes. The high luminescence intensity and its insignificant variation with time have made it possible to plot the spectral distribution of the luminescence (Fig. 2). The measurements were made with a UM-2 monochromator, an FEU-18A photomultiplier, and an automatic recorder.

The light sum is apparently stored during the formation of the oxide film and is due to the high degree of hydration of the Al_2O_3. The luminescence observed upon heating is apparently due to the release of electrons when the water bound with the Al_2O_3 is desorbed in a definite manner. The release of electrons upon desorption of water from a number of substances was observed in [4] in a study of exoelectronic emission. Favoring this assumption is also the partial restoration of the luminescence by hydration of the aluminum-oxide in water or in its vapor.

The transition from anomalous thermoluminescence to the usually observed peaks (Fig. 1, curves 4) is a result of multiple heating of the samples and subsequent excitation with UV.

[1] J. Kelly and M.J. Laubitz, J. Amer. Ceram. Soc. 50, 540 (1967).
[2] V.V. Mikho, A.L. Fedchuk, and L.M. Stambol'skaya, Fiz. Tverd. Tela 14, 3107 (1972) [Sov. Phys.-Solid State 14, No. 10 (1973)].
[3] V.V. Antonov-Romanovskii, Kinetika fotoluminestsentsii kristallofosforov (Kinetics of Crystal-phosphor Luminescence), Nauka, 1966.
[4] I.V. Krylova, Phys. Stat. Sol. (a) 7, 359 (1971).

INVESTIGATION OF SEMICONDUCTOR PARAMAGNETISM USING LUMINESCENCE POLARIZATION IN A WEAK MAGNETIC FIELD

R.I. Dzhioev, B.P. Zakharchenya, and V.G. Fleisher
A.F. Ioffe Physico-technical Institute, USSR Academy of Sciences
Submitted 22 November 1972; resubmitted 15 January 1973
ZhETF Pis. Red. 17, No. 5, 244 - 247 (5 March 1973)

The paramagnetism of carriers and impurity centers can lead to the appearance of a noticeable circular polarization of recombination radiation of a semiconductor placed in a weak magnetic field. The theory of this effect was considered by D'yakonov and Perel' [1].

Under certain conditions, it is possible to obtain information on the g-factors of impurity centers and free carriers from the degree ρ of the circular polarization of the luminescence. To this end it is necessary to separate the cases in which the polarization is determined by one type of carrier or impurity. Thus, for example, in the case of doped semiconductors there are two possibilities: 1) The non-equilibrium carriers cannot become noticeably oriented during the lifetime τ ($\tau \ll \tau_s$, where τ_s is the spin relaxation time). ρ is then determined by the average spin of the equilibrium carriers. Such a situation is realized in nondegenerate p-type semiconductors if the spin relaxation of the non-equilibrium electrons is slow (relative to τ). 2) The non-equilibrium carriers are practically fully oriented ($\tau_s \ll \tau$), and the orientation of the equilibrium carriers is negligible. This case is realized in degenerate n-type semiconductors, since the hole spin relaxation is rapid enough, and orientation of the equilibrium electron is possible only near the Fermi level.

We present below the results of an experimental study of the circular polarization of photoluminescence in n- and p-type GaAs crystals when observed along the magnetic field H. In both p- and n-type GaAs we investigated the recombination radiation with acceptor participation. To estimate the possible contribution of the non-equilibrium electrons in p-GaAs we used the method of optical orientation [2]. By combining the methods of spin orientation by circularly polarized light and by a magnetic field it is possible to separate the contributions of the non-equilibrium carriers and acceptors. The rapid spin relaxation within the lifetime leads to a decrease (by a factor $\tau_s/(\tau + \tau_s)$) of the effect of optical orientation of the nonequilibrium electrons, but to an increase of their "magnetization" in the field H. At a low rate of spin relaxation, to the contrary, the optical orientation increases, but the "magnetization" of the non-equilibrium electrons decreases by a factor $\tau/(\tau + \tau_s)$ in comparison with the equilibrium ones in the nondegenerate semiconductor.

Figure 1 shows, for n- and p-type GaAs crystals, plots of ρ(H) obtained by exciting the photoluminescence with an He-Ne laser. The slopes of the ρ(H) lines depends strongly on the density of the doping impurities and relatively little on their type (n or p). ρ decreases with increasing density. At a doping-impurity density $\geq 3 \times 10^{18}$, the sensitivity of the setup is insufficient to observe the circular polarization.

As shown in [1], the luminescence polarization due to acceptor orientation is $\rho_A = 5g_A\mu_B H/4kT$, where g_A is the g-factor of the acceptors, μ_B is the Bohr magneton, k is Boltzmann's constant and T is the temperature. For the equilibrium electrons in a nondegenerate semiconductor we have accordingly $\rho_e = g_e\mu_B H/4kT$, where g_e is the electron g-factor. For non-equilibrium electrons, ρ_e decreases by a factor $\tau/(\tau + \tau_s)$. Experiments on optical orientation make it possible to estimate $\tau/(\tau + \tau_s)$. Thus,

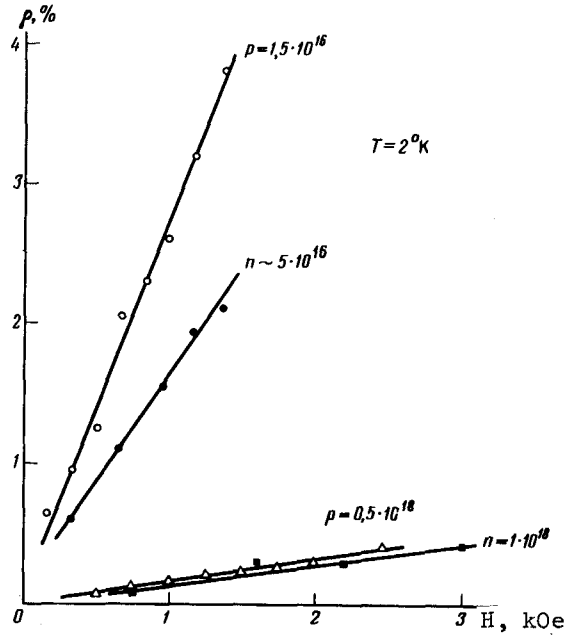

Fig. 1. Degree of circular polarization ρ(H) in excitation of photoluminescence by unpolarized or linearly-polarized light at various densities of the doping impurities in n- and p-GaAs, T ≈ 2°K.

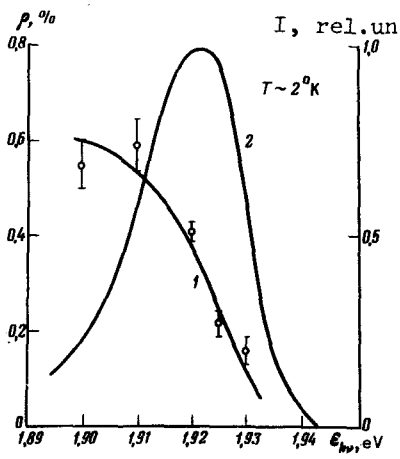

Fig. 2. Dependence of ρ on the recombination-radiation quantum energy $\varepsilon_{h\nu}$ for a p-GaAlAs crystal with acceptor density ~5 × 10^{17} cm^{-3} (curve 1) at H = 2.5 kOe and T ≈ 2°K. Curve 2 illustrates the dependence of the photoluminescence intensity I on $\varepsilon_{h\nu}$ for this crystal at ~2°K.

for example, for p-Ga with acceptor density N_A = 15 × 10^{16} cm^{-3} we have $\tau/(\tau + \tau_s) \lesssim 0.4$. At g_e = 0.5 [3], H = 1 kOe, and T = 2°K we have $\rho_e \lesssim 2 \times 10^{-3}$, which is much less than the observed value. Thus, the polarization of the luminescence was determined by the "magnetization" of the acceptors. When photoluminescence is excited with unpolarized light, right-circular polarized luminescence is observed in the positive direction of the field H. This corresponds to a predominant contribution of -1/2 → 3/2 transitions.

From the slopes of the ρ(H) lines we can determine the effective acceptor g-factor $g_A' = 4kT\rho/5\mu_B H$, which decreases with increasing impurity concentration. For a sample with N_A = 1.5 × 10^{16} cm^{-3} we have g_A' = 0.67 ± 0.11. The corresponding paramagnetic susceptibility is $\chi_A = \mu_B^2 (g_A')^2 j(j+1) N_A/3kT$ = (1.79 ± 0.29) × 10^{-9}. Here j is the total angular momentum quantum number. Obviously, the true acceptor g-factor is $g_A \geq$ (0.67 ± 0.11). The value of χ_A determined in this manner varies little with doping in p-type crystals, since the product $(g_A')^2 N_A$ varies little, and in n-GaAs is decreased with increasing donor density in proportion to $(g_A')^2$ (since $N_A \approx$ const).

From the fact that at close doping-impurity concentrations the slopes of the ρ(H) lines are also close, it can be concluded that non-equilibrium holes in n-GaAs acquire during a time τ a practically equilibrium orientation. Similar plots of ρ(H) were observed in GaAlAs and GaInP crystals.

The dependence of g_A' on the doping is probably due to the influence of the electric fields of the ionized impurities or of the static deformations connected with the impurities on the relative positions of the acceptor magnetic sublevels. One can use the estimates given in [4] for the splitting $\Delta\varepsilon_E$ of the acceptor levels by the electric field E. In that reference they estimated the linear and quadratic (in the field) effects ($\Delta\varepsilon_E \sim N_i^{2/3}$ and $N_i^{4/3}$, respectively, where N_i is the concentration of the ionized impurities). At $\Delta\varepsilon_E$ comparable with the splitting $\Delta\varepsilon_H$ in the magnetic field, the relative position of the magnetic sublevels is altered in such a way that the average acceptor spin is decreased and ρ and g_A' are decreased accordingly. Estimates show that $\Delta\varepsilon_E$ becomes comparable with $\Delta\varepsilon_H$ (at H = 1 kOe) if N_i is of the order of 10^{17} cm^{-3} (then the effect quadratic in E exceeds the linear effect). Obviously, the greatest influence is exerted by the centers closest to the acceptors. In the case of donor-acceptor recombination one can expect an influence of the donor belonging to the recombining pair. Then pairs with shorter distances R between the donor and acceptor should correspond to a lower luminescence polarization. Such a relation was indeed observed in the experiments. Figure 2 shows a plot of $\rho(\varepsilon_{h\nu})$, where $\varepsilon_{h\nu}$ is the quantum energy of the recombination radiation. The

short-wave edge of the line corresponds to smaller R (larger energy of Coulomb interaction in the final state). As R increases towards the long-wave edge of the luminescence line, ρ increases. A change of ρ induced by uniaxial compression was also observed.

An investigation of the exciton orientation in a weak field H has shown that ρ of the annihilation radiation of exciton is several times smaller than that of recombination radiation with participation of oriented acceptors, other conditions being the same.

We note, in conclusion, that simple methods of measuring circular polarization make it possible to "sense" magnetic-sublevel energy shifts on the order of 10^{-5} - 10^{-6} eV.

The authors thank M.I. D'yakov and V.I. Perel' for a number of remarks.

[1] M.I. D'yakonov and V.I. Perel', Fiz. Tverd. Tela 14, 1452 (1972) [Sov. Phys.-Solid State 14, 1245 (1972)].
[2] R.R. Parsons, Phys. Rev. Lett. 23, 1152 (1969).
[3] W. Duncan and E.E. Schneider, Phys. Lett. 7, 23 (1963).
[4] G.L. Bir, E.I. Butikov, and G.E. Pikus, I. Phys. Chem. Solids 24, 1475 (1963).

OBSERVATION OF THE DRAWING OUT OF NEEDLES BY ELECTRIC FIELDS

V.G. Pavlov, A.A. Rabinovich, and V.N. Shrednik
A.F. Ioffe Physico-technical Institute
Submitted 23 January 1973
ZhETF Pis. Red. 17, No. 5, 247 - 250 (5 March 1973)

It has been observed that when tungsten needles are heated to 2300 - 2700°K in an electric field (3 - 6) × 10^7 V/cm, the needles become sharper and elongated in directions normal to the close-packed faces, in contrast to earlier observations. The experiments were performed by field-emission electron microscopy with needles having radii 0.1 - 1.5 μ.

When a metallic needle is heated it becomes blunter - its length is decreased and the radius of curvature of the tip is increased [1, 2]. By applying an electric field it is possible to decrease the rate of blunting, and to stop it at a certain field value E_0 [3]. Herring's classical macroscopic theory [4], simplified by assuming an isotropic needle material [3], predicts for the motion of the tip of the needle a field dependence that agrees well with the one obtained experimentally for tungsten [3]. According to this theory, the needle should become drawn out by the field at $E > E_0$ (its length should increase and the radius of curvature decrease). Experiments, however, have never revealed such a growth of the needle in an electric field (see, e.g., [5]). This was attributed either to the difficulty of growing new atomic layers on the smooth close-packed faces [3] or to the absence of appreciable

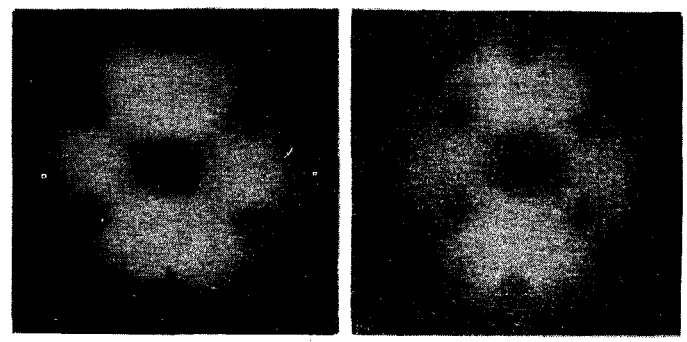

Fig. 1. Field-emission electron micrograms of needles: a) initial, b) elongated by the field ("sharpened") and annealed.