Optical orientation of electrons and holes in semiconductor superlattices

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A study has been made of the effect of longitudinal and transverse magnetic fields on the optical orientation of the spins of free carriers in a GaAs/AlGaAs superlattice. The increase in the degree of spin polarization of photoelectrons in a classical longitudinal magnetic field is explained on the basis of a suppression of spin relaxation caused by a splitting of an electron miniband which is linear in **k**.

Optical orientation of free carriers in semiconductor superlattices with three-dimensional minibands has been achieved for the first time. A study was made of the circular polarization of the (conduction band)—acceptor photoluminescence[1] in a superlattice grown by molecular beam epitaxy and consisting of fifty double layers of GaAs and $Al_xGa_{1-x}As$ ($x \approx 0.35$) with a period of 30–60 Å.

Figure 1 shows the spectra of the intensity and the degree of circular polarization, P_c, of the luminescence found during excitation with the circularly polarized light beam from a krypton laser with $\hbar\omega = 1.916$ eV at $T = 1.6$ K. To determine the relaxation times which control the optical orientation of the free carriers, we measured P_c as a function of the magnetic field, both longitudinal (Fig. 2) and transverse (Fig. 3) with respect to the direction of the exciting beam. This direction coincided with the principal access of the structure, $z \parallel [001]$. In the longitudinal field, we separately determined the contribution to P_c from the optical orientation, $P_c^\sigma = [P_c\ (\sigma_+, B_\parallel) - P_c\ (\sigma_-, B_\parallel)]/2$, and the signal representing the magnetic circular polarization of the luminescence, $P_c^H = [P_c\ (\sigma_+, B_\parallel) + P_c\ (\sigma_-, B_\parallel)]/2$.

The increase in the circular polarization P_c^σ in a classical magnetic field can be linked in a natural way with an attenuation of the spin relaxation of photoelectrons. It

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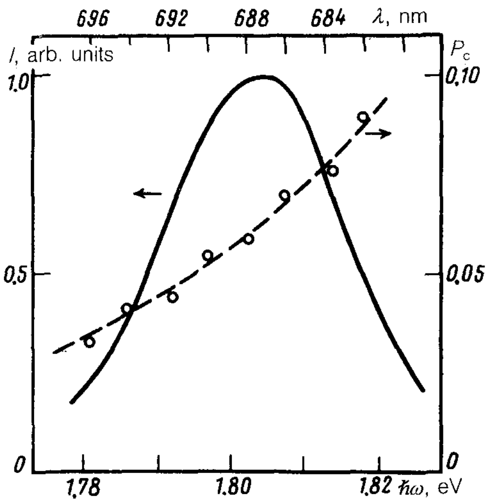

FIG. 1. Spectra of the intensity I and the degree of circular polarization, P_c, of the photoluminescence of a GaAs/AlGaAs superlattice with a period ~30 Å in the case of circularly polarized excitation ($T = 1.6$ K).

was shown in Ref. 2 that the D'yakonov-Perel' precession mechanism for spin relaxation is effectively suppressed in III–V crystals in a field $\mathbf{B} \| [001]$ or $[111]$. The D'yakonov-Perel' mechanism involves a contribution $(A/2)\sigma[\mathbf{k}\times\pi]$, which is cubic in the wave vector $\mathbf{k}$, to the effective Hamiltonian of the electrons ($\pi_j = k_{j+1}k_{j+2}$). A study of this suppression in optical-orientation experiments made it possible to determine the momentum relaxation time of the photoelectrons and also the coefficient A in GaAs crystals.[3] The symmetry of this system is lower (class D_{2d}) than that of the bulk crystal (of class T_d), and the spin splitting of the conduction band contains a component which is linear in $k_\perp$: $\Delta E = \beta k_\perp$, where $\mathbf{k}_\perp$ is the component of the wave vector in the plane of the interface. The coefficient β was calculated in Refs. 4 and 5 for isolated quantum wells. As for an isolated well, in a superlattice with $z \| [001]$ the longitudinal

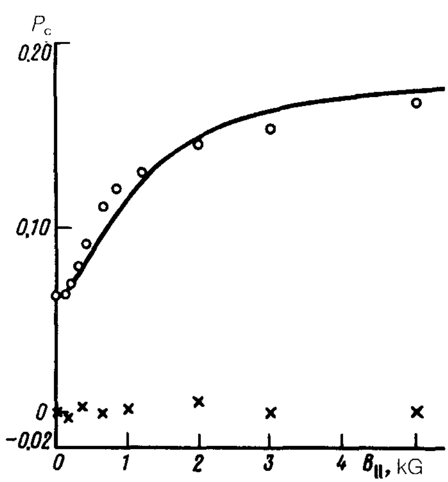

FIG. 2. Change in the circular polarization of the photoluminescence at the maximum of an (energy band)—acceptor spectral band in a longitudinal magnetic field. ○—P_c^σ; ×—P_c^H; solid line—calculation of P_c^σ with $\tau_p = 13$ ps.

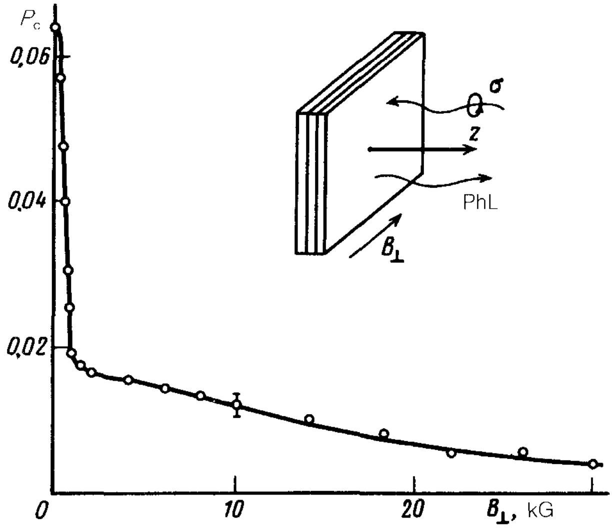

FIG. 3. Change in the circular polarization at the maximum of the photoluminescence band in a transverse magnetic field. The inset shows the experimental arrangement.

(τ_{s1}^e) and transverse (τ_{s2}^e) spin relaxation times of the electrons are related by $\tau_{s2}^e = 2\tau_{s1}^e$. The cyclotron revolution of the electrons in a field $\mathbf{B}\|z$ leads to an averaging of the depolarizing effect of the splitting of the spin branches, and the dependence of τ_{s1}^e on $B_\|$ is described by

$$\frac{1}{\tau_{s1}^e(B_\|)} = \left(\frac{\beta}{\hbar}\right)^2 \left\langle \frac{k_\perp^2 \tau_p}{1+(\Omega_c \tau_p)^2} \right\rangle. \tag{1}$$

Here $\Omega_c = eB/m_\perp c$, $m_\perp$ is the effective mass for the motion of the electrons along the layers, τ_p is the momentum relaxation time, and the angle brackets mean an average over the steady-state distribution function of the photoelectrons.

The observed behavior $P_c(B_\perp)$ can be explained by assuming that not only the photoelectrons but also the nonequilibrium holes at acceptors are partially spin-polarized. In this case the Hanle effect is described by a sum of two Lorentzian functions:

$$P_c(B_\perp) = \sum_{\lambda=e,h} \frac{\rho_\lambda(0)}{1+(\Omega_L^\lambda)^2 T_1^\lambda T_2^\lambda}. \tag{2}$$

Here $\rho_\lambda(0) = \rho_\lambda^0 \tau_{s1}^\lambda / T_1^\lambda$; $\rho_{e,h}^0$ is the degree of spin polarization (along the z axis) of the electrons which reach the bottom of the conduction band as a result of thermalization or of holes which are captured by an acceptor; $T_j = \tau_0 \tau_{sj}/(\tau_0 + \tau_{sj})$: τ_0^λ is the lifetime; and $\Omega_L^{e,h}$ is the frequency of the Larmor precession of the spin of the electron or hole. Expression (2) has been derived under the condition $|\rho_\lambda| \ll 1$ and also under the assumption that the ground state of a hole at an acceptor in the superlattice corresponds to a z projection of the angular momentum equal to $\pm 3/2$. The dependence P_c $(B_{\parallel})$ is described by the sum $\rho_h(0)+\rho_e^0(\tau_{s1}^e/T_1^e)$, and the effect of the magnetic field on the time τ_{s1}^e is taken into account.

The solid lines in Figs. 2 and 3 have been plotted for $\tau_p = 13$ ps, $\rho_c(0) = 1.6\%$, $\rho_h(0) = 4.8\%$, $\rho_e^0 = 13.2\%$, $g_\perp^h T^h = 4.2\times10^{-10}$ s, $g_\perp^e(T_1^e T_2^e)^{1/2} = 6.7\times10^{-12}$ s, and $\tau_0^e/\tau_{s2}^e(0) = 3.6$ ($g_\perp^\lambda$ is the transverse g-factor of the electron or hole). The fast and slow decreases in P_c in Fig. 3 are attributed to the Hanle effect involving holes and that involving electrons, respectively. The opposite assumption leads to an electron lifetime, which is clearly too high, and to a hole lifetime at acceptors, which is clearly too low. The absence of a magnetic circular polarization ($P_c^H \approx 0$) under these experimental conditions means that the spin relaxation of the holes (bound at acceptors and participating in radiative recombination at the measured frequency) can be ignored, and we have $T^h \approx \tau_0^h$.

We calculated the coefficient β in the Kronig-Penney model, using as boundary conditions the requirement that the envelope of the electron wave function $\psi(\mathbf{r})$ be continuous at the interfaces and the requirement that one of the following functions be continuous:

$$\partial\psi/\partial z \text{ (I)};\; m^{-1}\partial\psi/\partial z \text{ (II)}, \qquad m^{-1}[1+\hbar^{-2}A(\sigma_y k_y - \sigma_x k_x)]\partial\psi/\partial z \quad \text{(III)},$$

where m is the effective mass of the electrons in the corresponding bulk material. Under boundary condition I or II, the coefficients β and A are related by

$$\beta = \frac{A_a q^2 - A_b \kappa^2 \eta}{1+\eta}, \quad q^2 = \frac{2m_a}{\hbar^2}E_0, \quad \kappa^2 = \frac{2m_b}{\hbar^2}(V - E_0), \tag{3}$$

where η is the ratio of the probabilities for finding an electron with $k = 0$ in layer b (Al) and layer a (GaAs), V is the height of the barrier, and E_0 is the energy of an electron at the bottom of the miniband. Incorporating the dependence of boundary condition III on the spin leads to an additional contribution to β, which has the sign opposite that in (3). An estimate for $m_a = 0.067m_0$ (m_0 is the mass of a free electron), $m_b = 1.43\ m_a$, $V = 0.249$ eV, $A_b/A_\alpha = 0.5$, and equal layers thicknesses ($L_a = L_b = 15$ Å) leads to $\beta/A_a = 7\times10^{-4}$, 4×10^{-4} and 0.9×10^{-4} Å^{-2} for boundary conditions I, II, and III, respectively. Assuming $|g_\perp^e| = 0.05$, we find $\tau_{s2}^e(0) = 2\times10^{-10}$ s and $\beta/A_a = 2\times10^{-4}$ Å^{-2} from the experimental data given above. The simple Kronig-Penney model thus yields a value which is correct in order of magnitude for the splitting of the electron miniband which is linear in $k_\perp$ in a short-period GaAs/Al_xGa_{1-x}As superlattice.

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