Nuclear electric resonance and orientation of carrier spins by an electric field

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(Submitted 4 October 1989)
Pis'ma Zh. Eksp. Teor. Fiz. **50**, No. 9, 398–400 (10 November 1989)

An orientation of carrier spins arises during the flow of a current through a crystal, in which there is a spin splitting of bands which is linear in the momentum. This orientation effect can be detected from the nuclear resonance which is induced by an alternating electric field and also from the polarization of luminescence spectra.

In this letter it is shown that nuclear magnetic transitions can be caused by an alternating electric field **E** in crystals in which there is a spin splitting of band states which is linear in the momentum. The field gives rise to an average spin of the electrons which varies at the field frequency. The hyperfine interaction of electrons with nuclei results in transitions between nuclear magnetic sublevels at the frequency of the nuclear magnetic resonance in a static magnetic field.

Terms in the effective Hamiltonian of the carriers, which are linear in the wave vector **k**, are allowed by the symmetry of gyrotropic crystals, by that of crystals lacking an inversion center during uniaxial deformation, and also by that of structures with quantum wells and superlattices. Let us examine the effect in deformed III-V crystals.

In the impurity diagram technique, the average spin of the electrons is given by a diagram of the type in Fig. 1. We will assume that the D'yakonov–Perel' spin-relaxation mechanism is predominant. In this case the exact one-particle Green's function of the electrons, incorporating scattering, is

$$G^{R(A)}_{\epsilon,\mathbf{p}} = \frac{\epsilon - \mathcal{H}_0 \pm i/2\tau + \vec{\sigma}\vec{\Omega}}{(\epsilon - \mathcal{H}_0 \pm i/2\tau)^2 - \Omega^2}, \qquad (1)$$

 0021-3640/89/210431-04$01.00

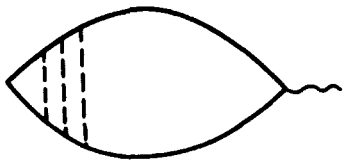

FIG. 1. Diagram determining the average spin of the electrons. Solid lines—Electron Green's functions; dashed lines—interaction of electrons with impurities. The vertex at the left is associated with the carrier spin operator; that at the right is associated with the carrier-field interaction.

where τ is the momentum relaxation time, $\mathcal{H}_0 = p^2/2m$, and $\mathcal{H}' = \vec{\sigma}\vec{\Omega}$ is the Hamiltonian describing the spin splitting of the electron band. In a deformed III-V crystal, this Hamiltonian contains terms which are linear and cubic in $\mathbf{k}$:

$$\Omega_i = \gamma_c k_i (k_{i+1}^2 - k_{i+2}^2) + \frac{C_3}{2}(\epsilon_{i,i+1}k_{i+1} - \epsilon_{i,i+2}k_{i+2}), \tag{2}$$

where $\epsilon_{i,j}$ are the components of the strain tensor, and i are the principal axes of the crystal. A cyclic permutation of subscripts is to be understood. The vertex at the right (the field vertex) in Fig. 1 is not renormalized in this case of point scattering. After the scattering corresponding to spin diffusion is taken into account, with $\omega \ll \tau^{-1}$, $ql \ll 1$, $\tau \ll \tau_{s0}$, where ω is the field frequency, l is the mean free path, and q^{-1} is a length scale of the field variation, the vector vertex at the left is associated with the expression $\sigma_j (1/\tau_{s0})_{ij}^{-1} \tau^{-1}$, where the tensor $(1/\tau_{s0})_{ij}$ is the reciprocal spin-relaxation time. As a result, we find the following expression for the average spin $\mathbf{S}$:

$$S_i = \frac{1}{n}\mathrm{Sp}\left[\sigma_i \int_{-\omega}^{0} \frac{d\epsilon}{2\pi} \int d\mathbf{p}\sigma_j \frac{(1/\tau_{s0})_{ij}^{-1}}{\tau} G^-\left(\frac{e}{c}\nabla_{\mathbf{p}}(\mathcal{H}_0 + \mathcal{H}')\mathbf{A}\right)G^+\right], \tag{3}$$

where n is the density of electrons. In the case of degenerate statistics we would have

$$S_i = \alpha \Delta_i(k_E)/E_F \cdot \quad \mathbf{k}_E = e\mathbf{E}\tau/\hbar, \tag{4}$$

$$\Delta_i = C_3(\epsilon_{i,i+1}k_{i+1} - \epsilon_{i,i+2}k_{i+2}), \tag{5}$$

where E_F is the Fermi energy. If the strain is slight, $C_3\epsilon_{ij}/k^2\gamma_c \ll 1$, we have a factor $\alpha = 9/16$; if the strain is pronounced, we have $\alpha = 3/4$.

The expression for the average spin in nondegenerate crystals differs from (4) in that E_F is replaced by $(3/2)k_B T$, where k_B is the Boltzmann constant, and T the temperature.

The physical mechanism for the orientation of the spins of free carriers by an electric field can be seen clearly in a solution of the problem which starts with the semiclassical kinetic equation for the spin density matrix ρ:

$$\frac{\rho}{\tau_L} + \frac{i}{\hbar}[\mathcal{H}', \rho] + e\mathbf{E}\frac{\partial \rho}{\partial \mathbf{p}} = \mathrm{St}\rho. \tag{6}$$

Here, τ_L is the lifetime, and the collision integral $\mathrm{St}\rho$ for elastic scattering and for a precession mechanism for spin relaxation is[1]

$$\mathrm{St}\rho = \sum_{\mathbf{p}'} \frac{2\pi}{\hbar} N_i |V_{\mathbf{p}'\mathbf{p}}|^2 \{\delta(\mathcal{H}_{\mathbf{p}}^0 + \mathcal{H}_{\mathbf{p}}' - \mathcal{H}_{\mathbf{p}'}^0 - \mathcal{H}_{\mathbf{p}'}'), \ \rho_{\mathbf{p}} - \rho_{\mathbf{p}'}\}, \tag{7}$$

where N_i is the impurity concentration, and $\{\ \}$ means a symmetrization of the matrix product. Equation (6) can be solved easily by an iterative method under the condition $\Omega\tau \ll 1$ and in the diffusion approximation, $\omega\tau \ll 1$, $ql \ll 1$. The first-approximation density matrix is

$$\rho^{(1)} = e\mathbf{E}\nabla_{\mathbf{p}}\rho_0\tau \tag{8}$$

where for simplicity we have ignored the difference between the momentum relaxation times of the components of ρ which are described by the various spherical harmonics, and ρ_0 is the equilibrium density matrix, which is a function of the total energy $E = \mathscr{H}_0 + \mathscr{H}'$. Although matrix (8) depends on the spin, it describes only the appearance of an electric current. After a summation over all directions of the momentum and an integration over the energy, the average spin vanishes. The spin orientation arises when the spin relaxation of carriers with different momenta during the flow of a current is taken into account. In this case the average spin is determined by a density matrix which is cubic in Ω. Significantly, however, since we have $1/\tau_{s0} \sim \Omega^2\tau$ for the spin-relaxation mechanism under consideration here, the spin polarization of the carriers is determined in order of magnitude by the first power of the spin splitting. It constitutes the ratio of the splitting $\Delta(p_E)$, which corresponds to the characteristic momentum $p_E = eE\tau$ in the electric field, to the characteristic energy of the electrons.

The rf field causes the average spin to vary in time at the frequency ω. As a result, the hyperfine interaction of the electrons and nuclei,

$$\mathscr{H}_{int} = a\mathbf{IS}, \tag{9}$$

where $\mathbf{I}$ is the nuclear spin, gives rise to nuclear magnetic transitions at a frequency $\omega_N = \gamma_I H_0$, where H_0 is the static magnetic field which produces the nuclear sublevels, and γ_I is the gyromagnetic ratio.

The ratio of the rates of the transitions of the nuclear electric resonance and the nuclear magnetic resonance is

$$\left[\frac{aS}{\gamma_I H_\sim}\right]^2 = \left[K\ \frac{E_\sim}{H_\sim}\ \frac{m_0 c}{p_F}\Delta(p_F)(\tau/\hbar)\right]^2, \tag{10}$$

where $K = \alpha\chi_S/gN\mu_B\gamma_I$ is the Knight shift, μ_B is the Bohr magnetron, g is the g-factor of the electrons, $\chi_S = \mu_B^2\nu$ is the paramagnetic susceptibility of the electrons, ν is the state density, $\Delta(p_F) \sim (C_3/\hbar)p_F\epsilon_{ij}$, and $H_\sim$ is the strength of the alternating field which causes the transitions between nuclear sublevels in the NMR case. Substituting into (10) parameter values characteristic of AlGaAs ($C_3 = 5.2$ eV·A, $N_i = 10^{18}$ cm^{-3}, $\tau = 10^{-12}$ s, $\epsilon_{ij} = 10^{-3}$, and $K_{Al} = 0.75\%$), we find that the rates of the nuclear electric and nuclear magnetic resonances are comparable at $E_\sim \sim 0.1H_\sim$.

In the case of a pronounced deformation, in which the tensor nature of the spin-relaxation time becomes important, the time $\tau_{s0}^{\perp}$, i.e., the spin-relaxation time of the electrons in the plane perpendicular to the vector $\mathbf{N} = (\epsilon_{yz}, \epsilon_{xz}, \epsilon_{xy},)$ enters the expression for the average spin.

A spin orientation of carriers in an electric field can also be detected in the polarization of luminescence spectra.

We wish to thank V. F. Masterov and D. N. Mirlin for useful discussions.

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Translated by Dave Parsons