Asymmetric nanostructures in a magnetic field

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It is shown that an asymmetric system of quantum wells in a magnetic field oriented parallel to the layers can exhibit anomalously strong photovoltaic and magnetoelectric effects. Abrupt relocation of electrons between the wells can occur in crossed electric and magnetic fields.

The development of methods for engineering of band structure and wave functions opens up the possibility of controlling the physical properties of materials over a wide range. Among ordinary crystals, systems with broken fundamental symmetries with respect to inversion of the coordinates and time reversal are distinguished by unique properties. Quantum structures based on asymmetric quantum wells obviously do not have an inversion center. In this letter we consider the destruction of time-reversal invariance in such a structure by an external magnetic field **H**. We show that an asymmetric quantum structure in a magnetic field is an interesting object with nontrivial macroscopic symmetry and unusual microscopic characteristics. The structure studied exhibits photovaltaic and magnetoelectric effects. These macroscopic effects are caused on a microscopic level by the appearance of quasimomentum asymmetry of the spectrum of elementary excitations, and this effect in turn indicates that a nonzero toroidal moment density exists in the system.

Let us consider spinless charge carriers in a quantum structure described by the potential $V(x)$ and having a symmetry axis 1 parallel to the x axis (Fig. 1). Let the magnetic field **H** lie in the plane of the quantum wells ($\mathbf{H}\| z$). For this orientation of the field and quantum structure the variables in the Schrödinger equation separate:

$$\psi_n(x)=\phi_{nk_y}(x)\exp[i(k_yy+k_zz)],\quad E_n(k_y,k_z)=E_n(k_y)+\hbar^2k_z^2/2m.$$

The components of the wave function $\phi_{nk_y}(x)$ and of the spectrum $E_n(k_y)$, which are related to the motion along the axis of the quantum structure, are determined from the solution of the one-dimensional eigenvalue problem:

$$\left[-\frac{\hbar^2}{2m}\nabla_x^2+\frac{\hbar}{2}\omega_0\lambda^{-2}(x-x_0)^2+V(x)\right]\phi_n=E_n\phi_n, \tag{1}$$

where $\omega_0=eH/mc$ is the cyclotron frequency, $\lambda^2=\hbar c/eH$ is the magnetic length, and $x_0=k_y\lambda^2$ is the coordinate of the center of an electron orbit in the magnetic field.

The main physical properties of the system under study can be illustrated for a simple, analytically solvable model. Consider two different δ-function quantum wells separated by a distance a:

$$V(x)=-V_1(x)-V_2(x)=-V_1\delta(x+a/2)-V_2\delta(x-a/2),\quad V_{1,2}>0. \tag{2}$$

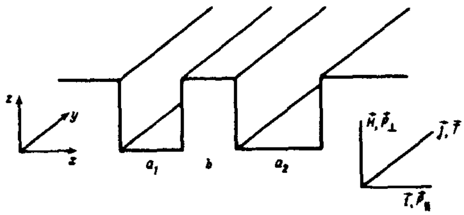

FIG. 1.

The spectrum of free electrons ($V=0$) in a magnetic field is, as we know, degenerate with respect to the position of the center of the orbit: $E_n^0(k_y)\equiv E_n^0(x_0) = \hbar\omega_0(n + 1/2)=\text{const}$. The potential (2) lifts this degeneracy and leads to the appearance of dispersion $E_n(k_y)$. In a strong magnetic field ($V/\hbar\omega_0 \ll 1$) the potential (2) can be regarded as the perturbation. To first order in the potential $V(x)$ we obtain the following expression for the shift in the energy level with $n=0$:

$$E'(k_y)\equiv E'(x_0)=-\frac{1}{\pi^{1/2}\lambda}\left[\Delta_1 \exp-\left(\frac{x_0+a/2)}{\lambda}\right)^2+\Delta_2 \exp-\left(\frac{x_0-a/2)}{\lambda}\right)^2\right], \quad (3)$$

where $\Delta_{1,2}=\int V_{1,2}(x)dx$. The existence of dispersion means that a current flowing along the y axis appears in this quantum state:

$$j_y=ev_y(k_y)\equiv -e\frac{1}{\hbar}\frac{dE(k_y)}{dk_y}. \quad (4)$$

This case is unusual in that the regions along the x axis, where the wave functions corresponding to different quantum states $k_y=x_0\lambda^{-2}$ are localized, are spatially separated. The local current density in the quantum structure in a transverse (with respect to the l axis) magnetic field is therefore different from zero. As follows from Eq. (3), the spectrum of charge carriers in an asymmetric quantum structure ($\Delta_1\neq\Delta_2$) in a magnetic field is asymmetric in the quasimomentum

$$E(k_y)\neq E(-k_y). \quad (5)$$

Since we are considering spinless charge carriers, the asymmetry of the spectrum (5) is in no way related to the relativistic spin-orbit coupling. It is attributable exclusively to orbital effects and can be large. In a system with an asymmetric spectrum the velocities in the states k_y and $-k_y$ do not add up to zero [$v(k_y)+v(-k_y)\neq 0$]. However, since the expression for the current has the form of a total derivative (4), upon integration over filled states with a distribution function which depends only on the energy, the total current vanishes. On the other hand, upon integration with a nonequilibrium distribution function, the total current along the y axis can be different from zero. If the nonequilibrium is produced by optical excitation, then the photovoltaic effect (PGE) can appear in the system. A detailed exposition of the theory of PGE in crystals with a spectrum which is asymmetric with respect to the quasimomentum is given in Ref. 1. The spontaneous current is formed by nonequilibrium charge carriers in a wide energy interval, in contrast with conventional mechanisms of PGE,[2] which are based on scattering asymmetry and, consequently, are very sensitive to the symmetry of the initial and final states of the charge carriers and to the spectral composition of photoexcitation. The PGE in an asymmetric quantum well in a magnetic field oriented parallel to the plane of the well was observed in Ref. 3, where the effect was attributed to the quasimomentum asymmetry, due to spin-orbit coupling, of the elementary-excitation spectrum. As we have indicated in this letter, a much stronger nonrelativistic orbital effect occurs in quantum structures.

A macroscopic characteristic of systems with quasimomentum-asymmetric spectrum is the toroidal moment density[4,5] **T**. Using the expression given in Ref. 6 for the toroidal moment density, we easily see that the toroidal moment of a given magnetic-quantization level ($n_z=\text{const}$) is different from zero in our system:

$$T=\frac{1}{10c}\int [r(rj)-2r^2 j]dr=\frac{2e}{c}\frac{\lambda^2 aS}{(2\pi\hbar)^2}(\Delta_1-\Delta_2)\sqrt{mE_F}. \tag{6}$$

Here S is the cross-sectional area of the sample in the yz plane, and E_F is the Fermi energy. We note that each level of magnetic quantization in a nonuniform quantum structure carries a magnetic dipole moment.

The symmetric state, which describes the photovoltaic effect in a system with quasimomentum asymmetric spectrum and nonzero toroidal moment density, has the form

$$j_{\text{PGE}}=\beta T,$$

where β is the dissipation constant which arises as a result of the nonequilibrium. In our system the toroidal moment is induced by a magnetic field

$$T\propto [Hl] \tag{7}$$

and is directed along the y axis. With respect to its transformation properties, the toroidal moment is a polar t-odd vector, dual to the antisymmetric component of the magnetoelectric (ME) tensor which determines the electric polarization induced by the magnetic field:

$$P\propto [TH]. \tag{8}$$

It follows from Eqs. (7) and (8) that two types of ME effects, which are nonlinear in the magnetic field, occur in the quantum structure under consideration: a longitudinal (with respect to the axis **l** of the structure) ME effect, in which the electric polarization along the x axis, present in the absence of a magnetic field, in weak fields is a quadratic function of the field:

$$\delta P_x=a_{\parallel} H_z^2$$

and a transverse ME effect, in which the electric polarization

$$P_z=\alpha_{\perp} H_z H_x,$$

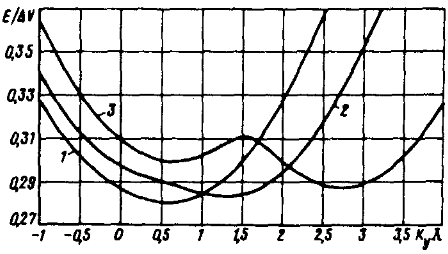

FIG. 2. Dispersion curves for a two-well structure with $a_1=0.58\Lambda$, $a_2=0.60\Lambda$, $b=0.50\Lambda$ in a magnetic field $H=0.5$ (1), 1.0 (2), and 2.0 (3).

arises in the plane of the wells in the structure in crossed magnetic fields, one of which (H_x) is oriented along the l axis and the other (H_z) is oriented in the plane of the wells.

The magnitude of the electric polarization of the quantum structure is very sensitive to the degree of nonequilibrium of the system. In a strong magnetic field, to first order in the potential $V(x)$ [Eq. (2)], we obtain the following expression for the matrix element of the dipole moment:

$$d_x(x_0)=-\frac{\lambda^2}{h\omega_0}\frac{dE'}{dx_0}=-\frac{1}{h\omega_0}\frac{dE'}{dk_y},$$

where $E'(k_y)$ is the correction to the energy (3). Thus, in this approximation the dipole moment, just as the spontaneous current (4), reduces to a derivative and vanishes when summed over filled states with an equilibrium distribution function. In the presence of dissipation, which arises, for example, as a result of optical excitation, the electric polarization should change abruptly. The equilibrium electric polarization in the limit of a strong field arises in higher orders in the potential (2).

As is evident from Eq. (6), T decreases with increasing H, because the localization of the wave function increases and an electron feels increasingly less the presence of the second well. At $H=0$, the current $j=0$, and hence $T=0$. Thus, the function $T(H)$ should have a maximum in an intermediate field H. In this region, which is of most interest, information about the behavior of the system can be obtained by solving Eq. (1) numerically. Such calculations have been performed for unsymmetric structures containing a different number of wells separated by tunneling transparent barriers. For systems containing square wells of the same depth and barriers of the same height it is convenient to introduce the dimensionless coordinate $\tilde{x}=x/\Lambda$, where $\Lambda=\sqrt{2\pi^2\hbar^2/m\Delta V}$ (ΔV is the barrier height, and the dimensionless wave number $\tilde{k}_y=k_y\Lambda$). We present for the example in Fig. 2 the results of a calculation of the dispersion relation $E(k_y)$ for a system of two wells with the dimensions $a_1=0.58\Lambda$ and $a_2=0.5\Lambda$, which are separated by a barrier $b=0.5\Lambda$. As is evident from the figure, the energy spectrum is strongly asymmetric: $E(k_y)\neq E(-k_y)$. As the strength of the magnetic field increases, the dispersion curve changes and an additional minimum appears. The appearance of the second minimum corresponds to a change in the connectedness of the surface of constant energy for energies close to the second minimum. The change in the topology of the energy surface can be recorded by galvanomagnetic and optical measurements. The magnetic field in which a second minimum

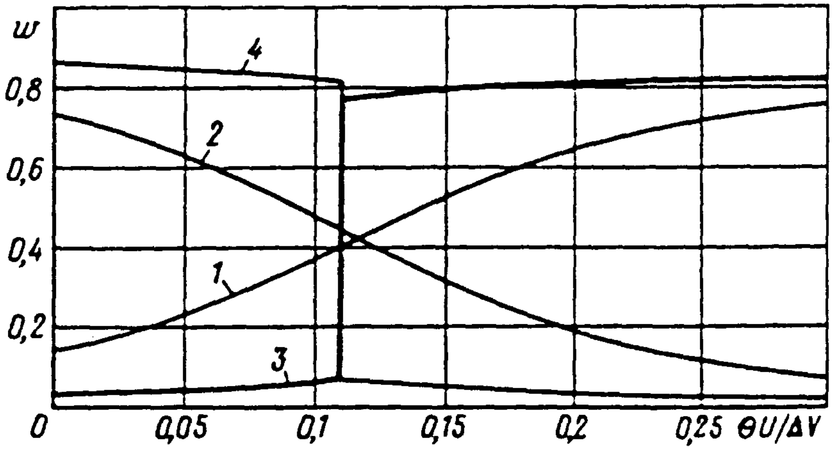

FIG. 3. Electron density in the wells w as a function of the potential difference U applied to the structure with $H=0$ (curve 1—w_1, 2—w_2) and with $H=3$ (curve 3—w_1, 4—w_2) for a two-well structure with $a_1=0.5\Lambda$, $a_2=0.6\Lambda$, and $b=0.3\Lambda$.

appears decreases with increasing width of the barrier between the wells. For the two-well structure under consideration, with $m=0.067m_0$ and $\Delta V=0.1$ eV, which corresponds to a jump in the conduction band for $GaAs/Al_xGa_{1-x}As$ with $x=0.1$, two minima appear with $H=5$ T.

The hole dispersion curves are similar. The positions of the minima of $E(k_y)$ for electrons and holes are generally different. Thus, application of a magnetic field changes a direct-gap semiconductor into an indirect-gap semiconductor; this was observed experimentally in Ref. 7. Despite the fact that the extremum k_{y0} does not lie at the center of Brillouin zone, the k_{y0} star contains only one component and the space group of the vector k_{y0} contains only a one-dimensional irreducible representation due to the inhomogeneity along l and due to the lifting of Kramers degeneracy by the field H.

Figure 3 displays the probabilities of finding an electron in the well, w_1 and w_2, as a function of the potential difference U applied to the structure for a two-well structure with the dimensions $a_1=0.5\Lambda$, $a_2=0.6\Lambda$, and $b=0.3\Lambda$ (in the absence of a magnetic field—curves 1 and 2 and with a magnetic field $H=(\Lambda/\lambda)^2=3$—curves 3 and 4) for k_y corresponding to an absolute minimum on the curve $E(k_y)$. In the presence of a magnetic field the $w(U)$ curves become more abrupt. At a critical value U_c the localization of the wave function changes abruptly. For U close to U_c application of a magnetic field significantly changes the ratio between w_1 and w_2. This change leads to an abrupt change in the resistance in the separate layers and in parallel layers whose carrier mobilities are markedly different.

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