New electronic effects in quantum semiconductor–(magnetic semiconductor) structures

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(Submitted 2 August 1991)
Pis'ma Zh. Eksp. Teor. Fiz. **54**, No. 8, 449–452 (25 October 1991)

Several new effects which arise in quantum-well structures based on a semiconductor–(magnetic semiconductor) system upon magnetization of the magnetic semiconductor are discussed.

Quantum structures based on semiconductor–(magnetic semiconductor) systems,[1–4] in which the layers of magnetic semiconductor can act as either barriers or quantum wells, have recently attracted increased interest. The reason is that by varying the magnetic field B or the temperature T one can substantially change the quasiparticle energy spectrum and thus the physical properties of the overall structure. It has been established that the exchange interaction between free electrons and the magnetic subsystem in the magnetic semiconductor $HgCr_2Se_4$ permits the spin splitting of the conduction band to reach 1 eV. In EuS, this splitting is ~ 0.4 eV. A splitting of the same order of magnitude occurs in dilute magnetic semiconductors such as $Cd_{1-x}Mn_xTe$. It follows from the experimental data that the spin splitting in the thin layers of magnetic semiconductor in quantum structures is essentially the same as in bulk samples. For example, this conclusion was reached in Ref. 5 for a tunnel structure with a EuS barrier.

If the magnetic semiconductor forms barriers, the large splitting of the electron spectrum at these barriers upon magnetization gives rise to potential barriers for electrons (holes) with different spin directions which are substantially different in height in the quantum well of the nonmagnetic semiconductor. The quantum-well levels in the quantum well then shift and split, because of the different depths of the wells for particles with different spin directions. If the magnetic semiconductor plays the role of quantum wells, the quantum–well levels in the wells themselves acquire a spin splitting and undergo a shift.

In this letter we wish to call attention to several new effects which might occur in quantum structures with a magnetic semiconductor.

1. When the barriers in superlattices are magnetized by a magnetic field and/or as a result of a lowering of T below the Curie point T_C, each original miniband converts into two spin minibands, one narrower and the other broader than the original miniband, because of the different heights and thus different tunneling transmission coefficients of the barriers for electrons with opposite spin directions. The midpoints of these spin minibands shift with respect to each other, to the point that they lose their energy overlap. The difference between the widths of the spin minibands, $\Delta_\downarrow$ and $\Delta_\uparrow$, gives rise to different effective quasiparticle masses $m_\downarrow^*$ and $m_\uparrow^*$ in these minibands. As an example, Fig. 1 shows the results of a numerical calculation of this transformation of the spectrum on the basis of the Kronig-Penney model. This particular superlattice consists of semiconductor quantum wells and barriers of a magnetic semiconductor with respective widths of 100 Å and 30 Å. The heights of the barriers are $V_0 = 0.4$ eV at $B = 0$. The change in the barrier height at $B \neq 0$ is $\Delta V = \pm 0.1$ eV, with $m^* = 0.1 m_0$, where m_0 is the mass of a free electron. Figure 1 shows the changes in the widths and positions of the three lowest minibands upon magnetization of a superlattice of this sort. Cases *b* and *c* correspond to barriers which are respectively lowered and raised by the magnetization. This transformation of the spectrum should be seen as changes in the optical and kinetic properties of the structure. In particular, when a system contains quasiparticles with quite different values of m^*, a branch of acoustic plasmons is known to arise in the spectrum of collective excitations. The velocity and damping of these plasmons depend on the mass ratio. We wish to stress that $\Delta_{\downarrow,\uparrow}$ and

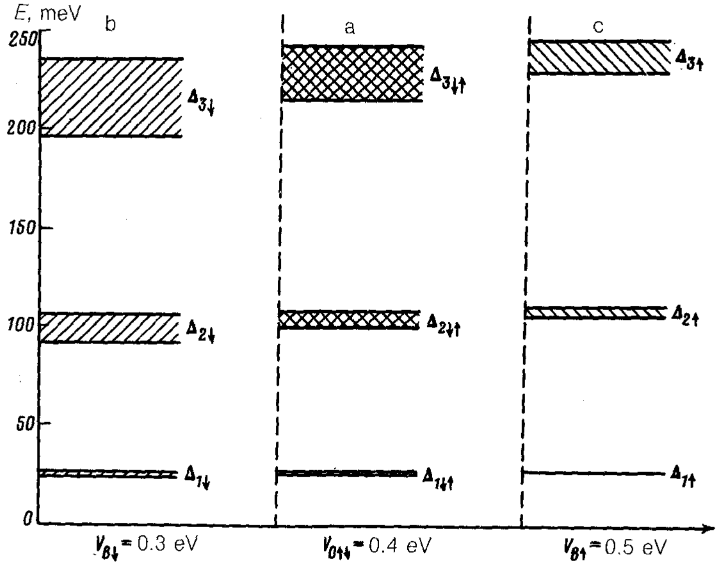

FIG. 1.

$m^*_{\downarrow,\uparrow}$ can be tuned continuously by varying B and T. It is thus possible to tune the properties of devices based on such superlattices.

2. In a structure with isolated quantum wells and magnetic barriers, there can be a situation in which the barriers disappear completely for particles with one spin direction in the wells, if the spin lowering of the barrier is equal to the original height of the barrier. The particles with the other spin direction become more localized, because of the rise of the barriers for them. The result is an unusual system in which 2D and 3D electrons coexist in the same volume. Such a state might be manifested, in particular, by sharp increases in the conductivity and the photoconductivity of the system along the axis of the structure and also in the spectra of plasma absorption, exciton absorption, interband absorption, intraband absorption, and luminescence.

3. In systems with a resonant tunneling, a magnetization of the barriers of wells may cause qualitative changes in the current-voltage characteristics (the appearance of new N-shaped regions and the switching of resonant tunneling on or off). The reason would be changes in the number and positions of the levels in the quantum well. If the particles tunnel through only one spin-split resonant level, there should be an essentially total spin polarization of the transmitted flux (Fig. 2). In this case the resonant system plays the role of a tunable spin filter. In the regime of rf generation of a resonant tunnel diode, the generation frequency depends strongly on the electron lifetime in the resonant level, τ_n. A change in τ_n caused by a variation in the positions of the quantum-well levels in the quantum well should cause a change in the generation frequency.

We know that an electric field applied along the axis of a superlattice will, by arranging conditions for a resonant tunneling of electrons between different quantum-well levels in neighboring wells, initiate IR emission associated with interlevel transition.[6,7] In the case of tunneling between spin-polarized levels in structure with magnetized quantum wells or barriers, one can control the frequency and the polarization of this emission by means of a magnetic field.

4. A situation which makes it possible to observe the oscillator pumping of a wave packet between two tunneling-coupled quantum wells, known from quantum mechan-

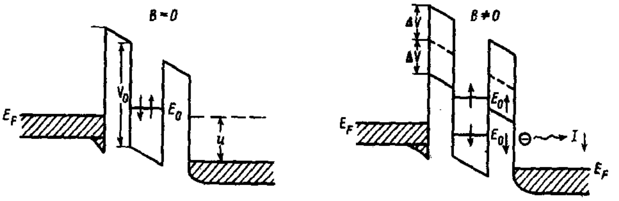

FIG. 2. Energy diagram of a resonant tunnel diode with barriers of a magnetic semiconductor. U—Applied voltage; E_F—Fermi energy; E_0—energy of a low-lying resonant level in a quantum well in the $B=0$ case; $E_{0\downarrow,\uparrow}$—energies of low-lying resonant levels for different spin directions in the $B\neq 0$ case; ΔV—change in the height of the magnetic-semiconductor barriers during magnetization; $I_\downarrow$—tunneling current of spin-polarized electrons. The effect of the weak field B on the particle spectrum in the nonmagnetic semiconductor is not indicated in the part of the figure on the right.

ics, has recently been realized for the first time in a GaAs–GaAlAs structure.[8,9] In the absence of scattering, the period of these oscillations is $\tau = 2\pi\hbar/\Delta$, where Δ is the magnitude of the splitting for a tunneling hybridization of two levels from different quantum wells. In structures with magnetic quantum wells or barriers, this period becomes a function of B. For $\tau_{\downarrow,\uparrow}$, for example, in a structure with magnetic barriers of width L and tunneling-coupled levels of the same spin direction, a semiclassical estimate yields

$$\tau_{\downarrow,\uparrow}(B) = \frac{m^* L \lambda_{\downarrow,\uparrow}(B)}{\hbar} \exp(2\pi L/\lambda_{\downarrow,\uparrow}(B)), \tag{1}$$

where

$$\lambda_{\downarrow,\uparrow}(B) = h/\sqrt{2m^*\{[V_0 \mp \Delta V_{\downarrow,\uparrow}(B)] - [E_0 \mp \Delta E_{\downarrow,\uparrow}(B)\}}]$$

is the de Broglie wavelength of the tunneling electrons with the different spin directions, V_0 and $E_0 \equiv E_0^{(1)} = E_0^{(2)}$ are the heights of the barriers and the energies of the low-lying quantum-well levels in the wells in the case $B = 0$, and $\pm \Delta V_{\downarrow,\uparrow}$ and $\pm \Delta E_{\downarrow,\uparrow}$ are the changes in the barrier heights and the level energies in the case $B \neq 0$. Estimates show that for two identical coupled quantum wells of width 100 Å, with $V_0 = 0.4$ eV, $L = 30$ Å, $m^* = 0.1 m_0$, $\Delta V_{\downarrow,\uparrow} = \pm 0.1$ eV, and $\tau_0 = 0.38$ ps ($B = 0$), we would have $\tau_\downarrow = 0.28$ ps, $\tau_\uparrow = 0.49$ ps ($B \neq 0$).

5. The magnetization of barriers or wells in structures with tunneling-coupled quantum wells differing in width gives rise to a special situation. This difference leads to different changes in the positions of the spin-split quantum-well levels as B and T is varied. It thus becomes possible to bring the levels in nieghboring wells to resonance and to move them away from resonance. We know that in nonmagnetic structures these conditions can be arranged only by applying an electric field along the axis of the structure. In particular, in superlattices consisting of pairs of quantum wells differing in width a variation of B or T may result in the appearance and destruction of isolated minibands in various parts of the spectrum.

6. We also note that in a variable magnetic field $B(t)$, which is oscillating in a symmetric fashion with a period τ_B with respect to a zero level, the magnitude of the current through the tunneling structure should oscillate with a period of $\tau_B/2$ upon a complete magnetization reversal of the barriers. The degree of spin polarization of the transmitted flux, on the other hand, will oscillate with a period of τ_B. This behavior of the tunneling current in magnetic-barrier structures can be taken as evidence of the realization of effects caused specifically by a magnetization of the barriers.

In isolated (magnetic semiconductor)-semiconductor heterostructures in which a 2D electron channel has been produced in the nonmagnetic material, magnetization of the magnetic semiconductor will cause radical changes in the energy spectrum of the 2D gas in the ordinary semiconductor and in all the physical properties associated with this energy spectrum.

We wish to thank A. V. Nikitin for assistance in the numerical calculations.

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Translated by D. Parsons