Influence of parallel magnetic field on the tunnel current between dimensionally quantized films

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The presence of a resonance and a decreasing region in the I-V characteristics of a tunnel junction consisting of two, dimensionally quantized films in nonquantizing magnetic fields is predicted theoretically.

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This paper deals with the influence of a constant magnetic field, which is parallel to the junction plane, on the tunnel current between dimensionally quantized semiconductor films separated by a potential barrier. As is known, the magnetic field, alters the shape of the energy spectrum, which is reflected in the I-V characteristics.[1] However, the electron spectrum in a sufficiently thin film for a parallel geometry is altered only in strong magnetic fields in which the magnetic length $r_H = (e/cH)^{1/2}$ is shorter than the film thickness d_0. But the condition of a classically strong magnetic field $\omega_H \tau > 1$, when the conductivity of bulk semiconductors strongly depend on the magnetic field, can be satisfied in lower fields. Here $\omega_H = eH/m^*c$ is the cyclotron frequency, τ is the momentum relaxation time, and m^* is the effective mass. In particular, at $\omega_H \gg 1$ the conductivity along the electric field decreases as $1/H^2$.[2] We show that the conductivity of the tunnel junction consisting of two, dimensionally quantized films behaves in an entirely different manner. It decreases as $1/H$ in strong magnetic fields. A maximum with an amplitude proportional to $\phi^{1/2}$ exists in the I-V characteristics when the resonance condition $\omega_H d_0 p_0 \approx e\phi$ is satisfied. Here, ϕ is the potential difference between the film centers and p_0 is the characteristic electron momentum in the film plane.

As a model we take two wells that are separated by a potential barrier. We choose a coordinate system with its origin at the center of one of the wells; the $0y$ axis is directed along the normal to the junction plane and the magnetic field, which is specified by the vector potential $\mathbf{A}(-Hy, 0, 0)$, is directed along the $0z$ axis. We assume that $\psi_{n\mathbf{p}}(\mathbf{r})$ are the wave functions of an electron in the well with an energy $\zeta_{n\mathbf{p}}$, if the barrier thickness approaches infinity, where n is the number of the dimensionally quantized level and $\mathbf{p}$ is a two-dimensional momentum in the xz plane. The Hamiltonian of the system in the secondary-quantization representation can be written as follows:

$$\mathcal{H} = \Sigma \zeta_{n\mathbf{p}} a^+_{n\mathbf{p}} a_{n\mathbf{p}} + (\zeta_{n\mathbf{p}} + \omega_H d p_x + e\phi)\, b^+_{n\mathbf{p}} b_{n\mathbf{p}} + T_{n\mathbf{p},n'\mathbf{p}}\, a^+_{n\mathbf{p}} b_{n'\mathbf{p}} + T^*_{n'\mathbf{p},n\mathbf{p}}\, b^+_{n'\mathbf{p}} a_{n\mathbf{p}}\,, \tag{1}$$

where $a^+_{n\mathbf{p}}$ is the creation operator of an electron in the well in which the origin was chosen, $b^+_{n\mathbf{p}}$ is the creation operator of an electron in the other well, and $d(\approx d_0)$ is the distance between the well centers. The matrix elements $T_{n\mathbf{p},n'\mathbf{p}}$ describe the electron transitions between the wells. We assumed that the longitudinal momentum is conserved during tunneling. Nonspecularity may be regarded as the consequence of specular tunneling followed by scattering at the boundary. The collision of carriers with the scattering centers is taken into account via the relaxation time. This corresponds to a ladder approximation in alloy theory, a valid assumption if the the mean free path length is much greater than the de Broglie wavelength of electrons.[3]

We can see from the structure of the Hamiltonian that in the basic approximation d_0/r_H the influence of the magnetic field is equivalent to the action of the p_x-dependent, effective, potential difference $\phi^* = \omega_H p_x d/e$. Thus, in sufficiently strong magnetic fields the electrons for which $e\phi^* > 1/\tau$ cannot tunnel between the wells with longitudinal-momentum conservation, since the energy conservation law is not realized for them. As a result, only electrons with $|p_x| < 1/\omega_H \tau d$ contribute to the current, i.e., the junction conductivity decreases as $1/H$. If the potential difference between the wells is increased, then the electrons with $p_x \neq 0$ will contribute to the current, i.e., those electrons for which the condition $e|\phi + \phi^*| \leqslant 1/\tau$ is satisfied. The number of such electrons increases with increasing p_x, and this increases the tunnel current. If, however, $e\phi$ is so large that the energy conservation law cannot be realized for any electrons, then the tunnel current will vanish. We can see, therefore, that the I-V characteristics have a maximum as well as a decreasing re-region. We assume here that we are dealing with tunneling in which the number of the dimensional qunatization level is not changed in the well.

These results can also be obtained from a rigorous calculation. The tunnel current can be determined by using the known expression[1]

$$I = 2e\Sigma|T_{n\mathbf{p},n\mathbf{p}}|^2 \int \frac{d\omega}{2\pi}\frac{d\mathbf{p}}{(2\pi)^2} N(\omega, \zeta_{n\mathbf{p}}).$$

$$N(\omega + e\phi, \zeta_{n\mathbf{p}} + \omega_H d p_x)(f(\omega) - f(\omega + e\phi)),$$

$$N(\omega, \zeta) = \frac{\nu/2}{(\omega + \mu - \zeta)^2 + \nu^2/4}, \quad \nu = 1/\tau, \qquad (2)$$

where $f(\omega)$ is the Fermi distribution function and μ is the chemical potential. The quantity ν takes into account the electron collisions with the scattering centers that are located in the film and on the surface.[4] In zeroth approximation with respect to d_0/r_H, $\zeta_{n\mathbf{p}} = \epsilon_n + p^2/2m$, where ϵ_n is the energy of transverse motion of an electron in the well. After integration with respect to the two-dimensional vector **p** and with respect to ω (at first, it is more convenient to calculate the integral with respect to p), we obtain

$$I = \frac{\phi}{R}\left|\mathrm{Re}\,\frac{\nu}{\sqrt{\omega_H^2 d^2 p_0^2 - (e\phi + i\nu)^2}}\right|, \qquad (3)$$

where the matrix elements $|T_{n\mathbf{p},n\mathbf{p}}|$ are expressed in terms of the junction resistance R for $H = 0$ and $\phi = 0$. Expression (3) reveals all the peculiarities that were discussed above.

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