Absolute transparency of an inelastic channel and the photovoltaic effect in the resonance tunneling through the two-well heterojunction

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An inelastic channel of resonance tunneling through a structure comprised of two wells with ϵ_1 and ϵ_2 levels can be completely transparent in the case of a weak interaction with radiation of frequency ω if $|\epsilon_2 - \epsilon_1|$ is close to $\hbar\omega$. The dependence of the current on the applied voltage or frequency ω in this case has a sharp peak. The asymmetry of the structure leads to a strong photovoltaic effect.

The probability of elastic resonance tunneling under certain conditions may be equal, as we know, to unity. With allowance for the interaction with the vibrations, one might ask: can the probability for the resonance tunneling strictly through an inelastic channel be equal to unity? Making use of the calculations,[1,2] it can be shown that the answer is negative for a single well with one or two levels. For a structure consisting of two wells with the levels ϵ_1 and ϵ_2, however, this effect, as will be shown below, does not occur. It turns out that in the case of a weak interaction with the vibrations of frequency ω, when the conditions $|\epsilon_2 - \epsilon_1| \approx \hbar\omega$ is satisfied, we have a case in which the probability for the elastic resonance tunneling will be negligible and the main current will flow solely along the inelastic channel.

Let us consider a two-well heterostructure (Fig. 1), whose distance $|\epsilon_2 - \epsilon_1|$ can be varied over a broad range by applying voltage which is tuned to the frequency ω. First, we will briefly consider a well-known case of elastic resonance tunneling through a two-well structure[3] and then obtain analogous results for the inelastic case.

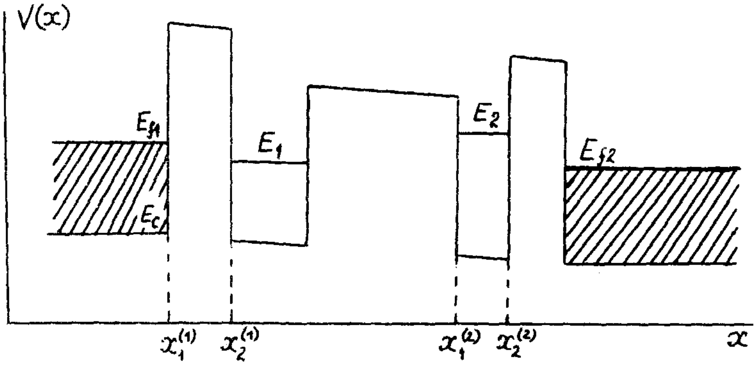

FIG. 1. Energy diagram of a two-well heterostructure.

We assume that E_1 and E_2 are the levels in the first well and the second well, which are considered independently. We also assume that the difference $|E_2 - E_1|$ and the overlap integral δ of the corresponding states and their widths are small in comparison with the energy parameters of the wells. Let us assume that the energy of the incident electrons E is close to E_j. We can then write a Breit–Wigner type equation for the probability of elastic resonance passage through the structure:

$$D_0(E) = \frac{\Gamma_1 \Gamma_2 \delta^2}{|(E - E_1 + \frac{i}{2}\Gamma_1)(E - E_2 + \frac{i}{2}\Gamma_2) - \delta^2|^2}. \qquad (1)$$

Here Γ_j is the width of the decay of the state in the well j with $\delta = 0$. The poles $\lambda_j^0 = \epsilon_j^0 - \frac{i}{2}\lambda_j^0$ of expression (1) determine the levels of the structure under consideration, ϵ_j^0, and also their widths γ_j^0, which can easily be determined by solving the quadratic equation. For $\delta^2 > \Gamma_1\Gamma_2/4$ expression (1), as a function of the parameter $E - E_1$ and $E - E_2$, has two maxima equal to unity. In the opposite case it has only one maximum equal to less than unity.

Let us now consider the effect of the monochromatic radiation with a polarization of the electric field along the tunneling direction which is described by the Hamiltonian

$$H = -\frac{\hbar^2}{2m}\frac{\partial^2}{\partial x^2} + V(x) + W(x)\cos(\omega t), \qquad (2)$$

where $V(x)$ is the potential of the heterostructure (see the discussion below, where the three-dimensional nature of the problem is taken into account). The difference $\epsilon_2^0 - \epsilon_1^0$ is assumed to be approximately equal to $\hbar\omega$. The main contribution to the resonance tunneling will then come from the electrons with energies lying close to ϵ_1^0 and ϵ_2^0. Let us assume that the widths γ_j^0, the splitting δ, and the magnitude of the interaction in the wells

$$q_j = <\psi_j^0|W(x)|\psi_j^0> - \frac{1}{2}[W(x_1^{(j)}) + W(x_2^{(j)})] \qquad (3)$$

[ψ_j^0 are the normalized eigenfunctions in the wells with $\Gamma_j = \delta = W(x) = 0$] are small in comparison with the quantum of the vibrational energy $\hbar\omega$. The interaction with the vibration is taken into account only in the wells, which is justifiable according to (4) near the resonance when $|q_2 - q_1|\delta/\hbar\omega \gtrsim \Gamma_j$. We will use the perturbation theory for the interaction not to fully solve the unperturbed problem (the condition under which such an approximation would be valid is $|q_j| \ll \Gamma_k$), but just for the basic solutions of the type $\exp(\frac{i}{\hbar}\int p dx)$ inside the wells. For the quasi-energy line near the lower level we will take into account the transition in which $\hbar\omega$ is acquired and for the quasi-energy line near the upper level we will take into account the transition in which $\hbar\omega$ is lost. The basic solutions obtained in this manner are joined at the boundaries $x_k^{(j)}$ and with the incident wave. As a result, we find the amplitudes of the elastic and inelastic transitions with allowance for the multiquantum processes inside the wells.

In the case under consideration $\delta \ll \hbar\omega$, the unperturbed states are localized in one of the wells. Let us assume that in the case $-\infty$ the initial electron energy E is close to E_1, so $|E - E_1| \ll \hbar\omega$. We then see that if $\hbar\omega \gg |q_2 - q_1| \gg \Gamma_j$, then at resonance the main current flows only through the inelastic channel. This gives rise to multiquantum inelastic transitions from the state in the first well to the state in the second well and back again. We introduce $\theta = \mathrm{sgn}(E_2 - E_1)$. For the probability of a transition to the state with an energy $E + \hbar\theta\omega \approx E_2$ for $+\infty$ we find in this case

$$D_{\rightarrow}(E) = \frac{\Gamma_1\Gamma_2\beta^2}{|(E - \epsilon_1 + \frac{i}{2}\gamma_1)(E + \hbar\theta\omega - \epsilon_2 + \frac{i}{2}\gamma_2) - \beta^2|^2}, \ (|E - E_1| \ll \hbar\omega), \quad (4)$$

$$\beta = (q_2 - q_1)\delta/\hbar\omega, \ \epsilon_{1,2} \approx \epsilon_{1,2}^0 \pm \theta q_{1,2}^2/\hbar\omega, \ \epsilon_{1,2}^0 \approx E_{1,2} \mp \theta\delta^2/\hbar\omega, \ \gamma_j \approx \Gamma_j.$$

Expression (4) is the same in form as (1), so the passage through an inelastic channel is completely the same as the elastic resonance tunneling. For $\beta^2 > \Gamma_1\Gamma_2/4$, expression (4) has two maxima equal to unity. At the same time, the resonance transparency for E close to E_2 is always low. This is attributable to the fact that in order to achieve a resonance tunneling, it is necessary in this case to generate a preliminary single-quantum transition of low amplitude. In the case of tunneling in the opposite direction with an initial energy close to E_2, inelastic resonance transparency apparently is $D_{\leftarrow}(E) = D_{\rightarrow}(E - \hbar\theta\omega)$.

Let us consider as an example the case shown in Fig. 1. We assume that $E_1 < E_{f1}$ and $E_2 > E_{f2}$ (E_{fj} is the Fermi energy on the left and on the right). The applied voltage $U = (E_{f1} - E_{f2})/e = \alpha(\epsilon_2 - \epsilon_1)/e + U_0$, where $\alpha \sim 1$. In accordance with the preceding discussion, in the case of inelastic resonance, when $U - U_0 \approx \hbar\theta\omega\alpha/e$, a strong photovoltaic current may be generated: for $E \approx E_1$ the transparency $D_{\rightarrow}(E)$ is high and $D_{\leftarrow}(E)$ is negligible. At a low temperature we obtain the following temperature for a 3D density of the current I near the inelastic resonance:

$$I(U) = \frac{me}{2\pi^2\hbar^3}\int_{E_C}^{E_{f1}} dE \int_{E_C}^{E} dE' D_{\rightarrow}(E')$$

$$= \frac{2em\beta^2(E_{f1} - E_1)\Gamma_1\Gamma_2}{\pi^2\hbar^3(\Gamma_1 + \Gamma_2)[((U - U_0)\frac{e}{\alpha} - \hbar\theta\omega)^2 + \frac{1}{4}(\Gamma_1 + \Gamma_2)^2 + 4\beta^2]}, \quad (5)$$

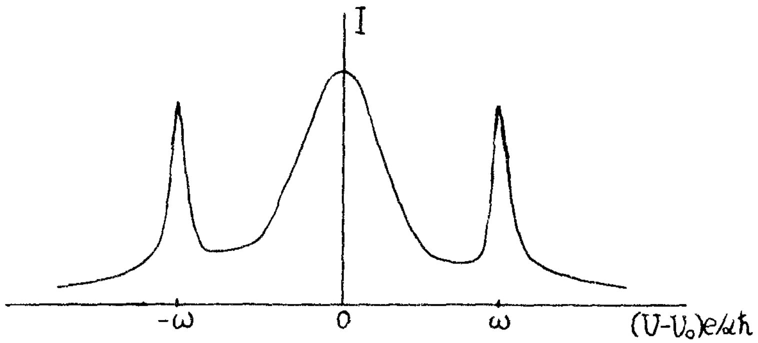

FIG. 2. Characteristic behavior of the $I(U)$ curve for a two-well heterostructure near resonances under conditions indicated in the text. The central peak corresponds to elastic resonance tunneling with a pseudo-crossing of ϵ_1 and ϵ_2 and the lateral peaks correspond to an inelastic resonance tunneling with a pseudo-crossing of $\epsilon_1 + \hbar\theta\omega$ and ϵ_2.

where e is the electron charge. We see from (5) that in the case of inelastic resonance the current-voltage characteristic reveals a sharp Lorentz peak. For $|\beta| > \Gamma_j$ this peak is about the same height as the peak attributable to inelastic resonance tunneling upon a pseudo-crossing of the ϵ_1 and ϵ_2 levels [see Eq. (1)]. The width of the inelastic peak, however, is on the order of β/e, a low value compared with the width of the elastic peak δ/e (Fig. 2).

Let us briefly consider the general case, $\hbar\omega \sim \delta$. It can be shown that for $|\epsilon_2^0 - \epsilon_1^0| \approx \hbar\omega$ the elastic and inelastic channels contribute to the current of generally the same order of magnitude. With an increase in δ, the maximum value of $D_-(E)$ decreases and for the maximum permissible $\delta = \hbar\omega/2$ is 1/4.

We note in conclusion that the system under consideration is a tunable infrared detector with remarkable physical characteristics. It is quite conceivable that such a detector will be built in the nearest future.[4] Effects such as those considered here occur even when the interaction of electrons with the molecular vibrations are taken into account.

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