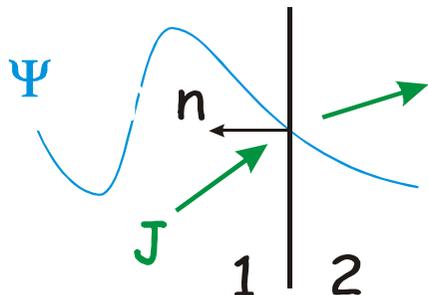


Туннелирование в наноструктурах

1. **Метод матриц переноса.**
2. **Резонансно-туннельный диод.**
3. **Кулоновская блокада и туннельный экситон.**

Вероятность туннелирования и прозрачность барьера



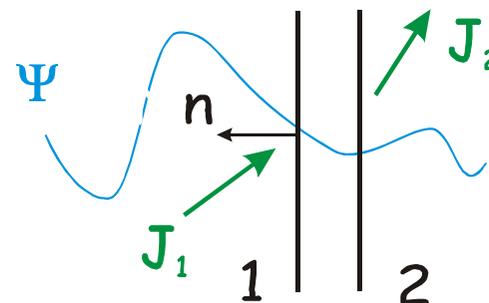
В случае локализованных состояний.

$$\int_{-\infty}^{+\infty} |\psi|^2 dz = 1 \quad P = \int_2 |\psi|^2 dz$$

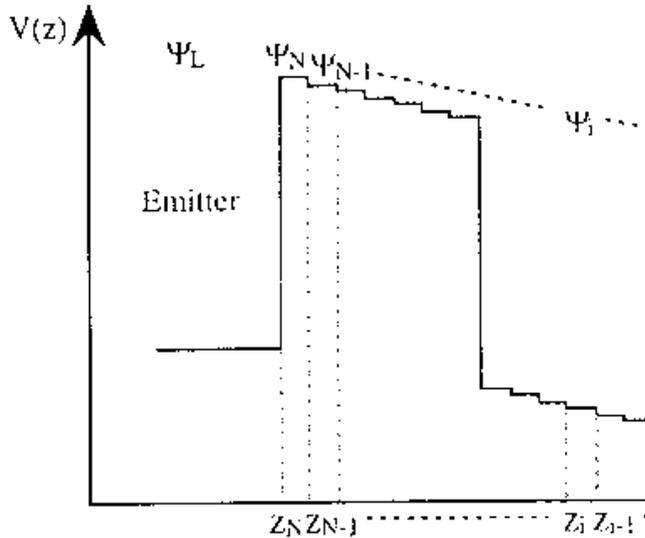
В случае нелокализованных состояний

$$J_i = \frac{1}{2} \left(\psi^* \frac{p_i}{m(z)} \psi + \psi \frac{p_i^*}{m(z)} \psi^* \right) = 1$$

$$T = \frac{J_{2n}}{J_{1n}}$$



Матрицы переноса



$$\Psi_{k_z^{(i)}}^{(i)}(z) = A_{k_z^{(i)}}^{(i)} \exp(ik_z^{(i)}z) + B_{k_z^{(i)}}^{(i)} \exp(-ik_z^{(i)}z)$$

$$k_z^{(i)} = \frac{\sqrt{2m_*^{(i)}(E_z - V^{(i)})}}{\hbar}$$

$$\psi_{k_z^{(i)}}(z_{i+1}) = \psi_{k_z^{(i+1)}}(z_{i+1})$$

$$\frac{1}{m_*^{(i)}} \frac{\partial \psi_{k_z^{(i)}}}{\partial z}(z_{i+1}) = \frac{1}{m_*^{(i+1)}} \frac{\partial \psi_{k_z^{(i+1)}}}{\partial z}(z_{i+1})$$

$$\begin{pmatrix} A_{k_z^{(i+1)}}^{(i+1)} \\ B_{k_z^{(i+1)}}^{(i+1)} \end{pmatrix} = T^{(i)} \begin{pmatrix} A_{k_z^{(i)}}^{(i)} \\ B_{k_z^{(i)}}^{(i)} \end{pmatrix} \quad T^{(i)} = \begin{pmatrix} \alpha_{+}^{(i)} P & \alpha_{-}^{(i)} / Q \\ \alpha_{-}^{(i)} Q & \alpha_{+}^{(i)} / P \end{pmatrix} \quad P = \exp \{i(k_z^{(i)} - k_z^{(i-1)})z_{i+1}\}$$

$$\alpha_{\pm}^{(i)} = \frac{1}{2} \{ 1 \pm (m_*^{*(i-1)} / m_*^{*(i)}) (k_z^{(i)} / k_z^{(i+1)}) \} \quad Q = \exp \{i(k_z^{(i)} - k_z^{(i+1)})z_{i+1}\}$$

Расчет прозрачности барьера

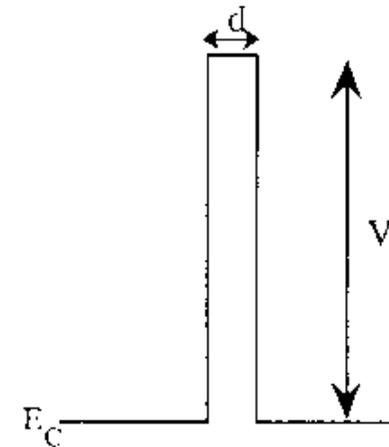
$$\begin{pmatrix} A_{E_z}^L \\ B_{E_z}^L \end{pmatrix} = T \begin{pmatrix} A_{E_z}^R \\ B_{E_z}^R \end{pmatrix} \quad T = T^{(N)} T^{(N-1)} T^{(N-2)} \dots T^{(2)} T^{(1)}$$

$$T(E_z) = \frac{m^{*L} k^R |A_{E_z}^R|^2}{m^{*R} k^L |A_{E_z}^L|^2}$$

$$\frac{A_{E_z}^3}{A_{E_z}^1} = e^{-ik_z d} \left\{ \cosh(\kappa_z d) - i \frac{2E_z - V}{2\sqrt{E_z(V - E_z)}} \sinh(\kappa_z d) \right\}^{-1}$$

$$T_{SB}(E_z) = \left\{ 1 + \frac{V^2}{4E_z(V - E_z)} \sinh^2(\kappa_z d) \right\}^{-1}$$

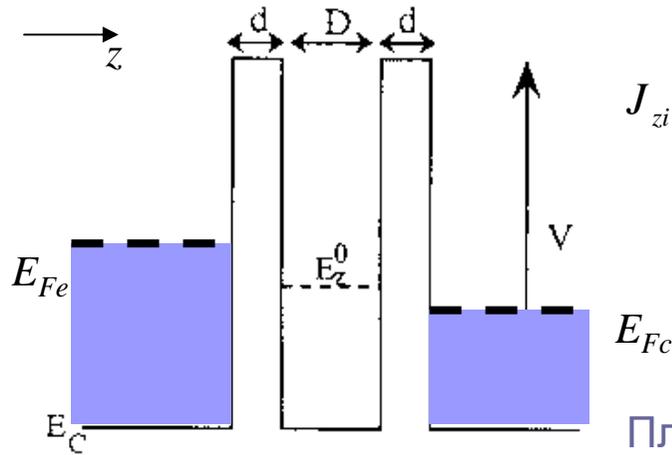
$$\kappa_z = \frac{\sqrt{2m_*(V - E_z)}}{\hbar}$$



При $E_z \ll V$

$$T_{SB}(E_z) \approx \frac{16E_z(V - E_z)}{V^2} e^{-2\kappa_z d}$$

Резонансно-туннельный диод



$$J_{zi} = \frac{1}{2} \left(\psi^* \frac{\hat{p}_z}{m(z)} \psi + \psi \frac{\hat{p}_z^*}{m(z)} \psi^* \right) = v_z$$

$$J_{zt}(E_z) = T(E_z) J_{zi} = T(E_z) v_z$$

Плотность туннельного тока имеет следующий вид:

$$J_T = e \iiint J_{zt} [f_e(1 - f_c) - f_c(1 - f_e)] \frac{2dp_x dp_y dp_z}{(2\pi\hbar)^3}$$

$$v_z = \frac{dE_z}{dp_z}$$

$$J_T = \frac{e}{h} \iiint T(E_z) [f_e(1 - f_c) - f_c(1 - f_e)] \frac{2dp_x dp_y dE_z}{(2\pi\hbar)^2}$$

$$f_{e,c} = \frac{1}{1 + \exp\left(\frac{E - E_{Fe,c}}{k_B T}\right)}$$

$$J_T = \int_0^{\infty} T(E_z) S(E_z) dE_z \quad S(E_z) = \frac{m^* e k_B T}{2\pi^2 \hbar^3} \ln \left[\frac{1 + \exp\left\{\frac{1}{k_B T} (E_{Fe} - E_z)\right\}}{1 + \exp\left\{\frac{1}{k_B T} (E_{Fc} - E_z)\right\}} \right] - \text{функция подачи электронов}$$

ВАХ вблизи резонанса узкой квантовой ямы при низкой температуре

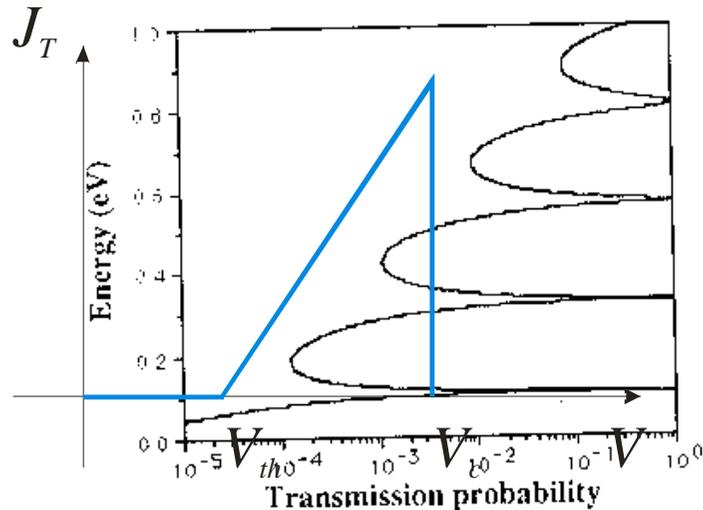
$$T(E_z) = T_0 \delta(E_z - E_0) \quad \text{при} \quad E - E_0 \ll E_1 - E_0$$

что выполняется лучше в случае узкой квантовой ямы

$$k_B T \ll E_{Fe,c} \Rightarrow f_{e,c} = 1 - \theta(E_{Fe,c})$$

$$J_T = \frac{2e}{h} T_0 \int_0^{E_{Fe} - E_0} \frac{dp_x dp_y}{(2\pi\hbar)^2} = \frac{2e}{h} T_0 g_{2D}(E_{Fe} - E_0)$$

при $E_{Fc} < E_0 < E_{Fe}$



В случае $d \gg D$ можно пренебречь поляризацией квантовой ямы и считать что:

$$E_0(V) = E_0(0) - eF \langle z \rangle = E_0(0) - eV \frac{d + D/2}{2d + D} = E_0(0) - e\alpha V \Rightarrow J_T = \frac{2e^2}{h} \alpha T_0 g_{2D}(V - V_{th})$$

$e\alpha V_{th} = E_{Fe} - E_0(0)$ Линейный рост тока будет до тех пор пока $E_0 > E_c$

при $E_0 < E_c \quad f_{e,c} = 0 \Rightarrow J_T = 0$

НанОРТД

Асимметричный РТД

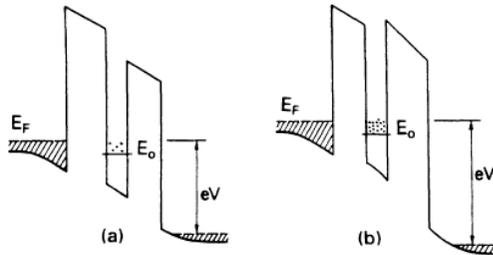


FIG. 1. Schematic energy diagrams of a large asymmetric DBRTS device under (a) positive and (b) negative bias. Hatching represents electron population of the emitter (left) and the collector (right) electrodes; dots represent the electron population in the well. E_0 is measured from the bottom of the well to the bottom of the subband of the 2D resonant states.

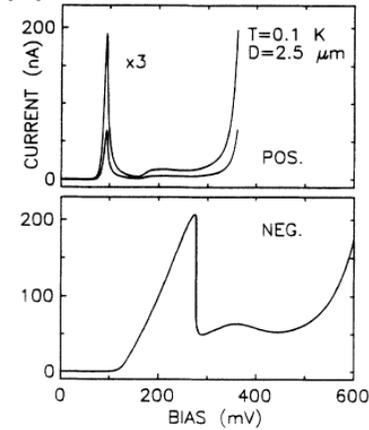
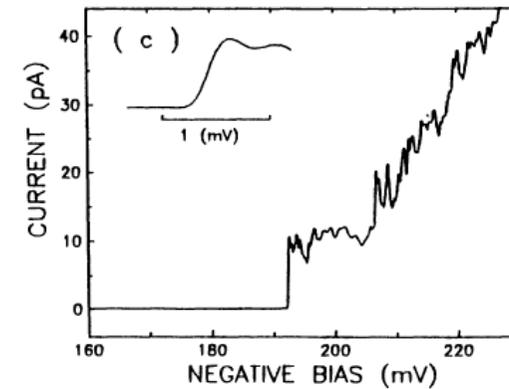
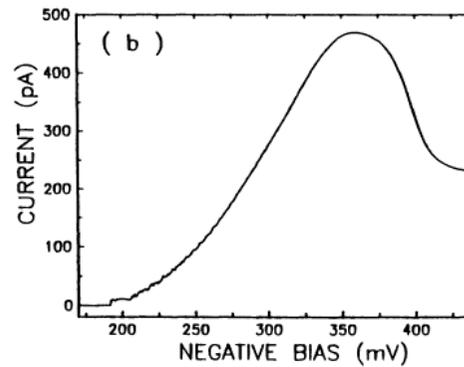
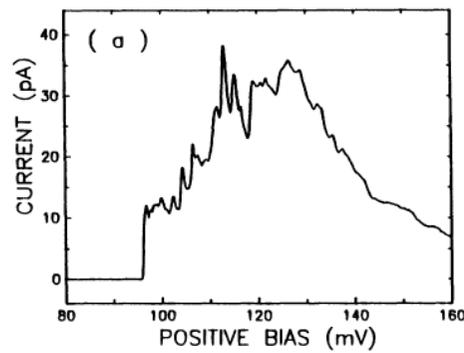


FIG. 2. I - V curve of a large-area device. The asymmetry of the I - V curve for positive/negative bias is due to the asymmetry of the barriers. Positive PTV ratio is 54.

Асимметричный нанОРТД



Кулоновская блокада

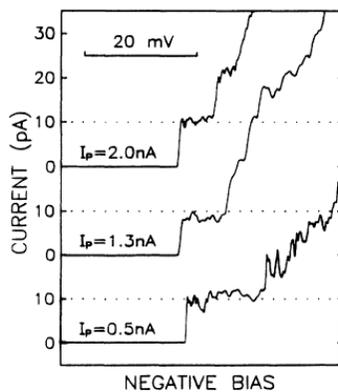


FIG. 5. I - V curves of several devices made from the same DBRTS wafer. I_p gives the peak current; it is a measure of the “electrical size” of a device at V_p (Ref. 30). The first current step height $I^{(1)}$ is independent of I_p .

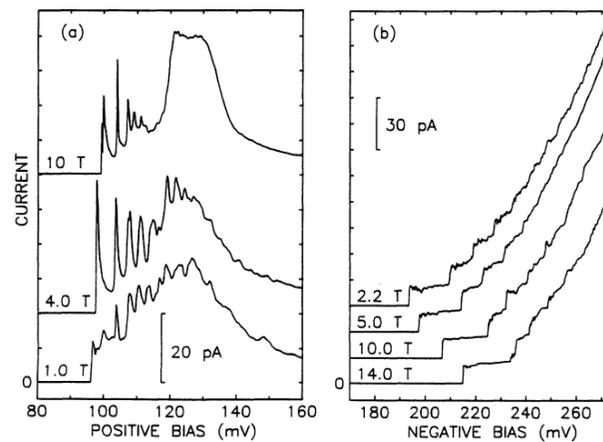


FIG. 6. Representative magnetotunneling data at 20 mK (B perpendicular to the barriers). Note the striking difference in the character of the data (peaks vs steps) in the two bias polarities.