Temperature dependence of shot noise in resonant tunneling structures

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TEMPERATURE DEPENDENCE OF SHOT NOISE IN RESONANT TUNNELING STRUCTURES

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ABSTRACT

Following a recently proposed ɔproach to transport and noise in resonant tunneling structures, we show that useful insights about the dominant causes of shot noise suppression and their connection with the geometrical structure of such devices can be gained from the study of the temperature dependence of the shot noise suppression factor vs bias current.

INTRODUCTION

It is well known that the shot-noise current spectral density S in resonant tunneling devices may be suppressed down to one half of the "full shot noise" value $S_{\text{full}} = 2qI$, obtained in the case of a purely poissonian process. Such suppression is observable when either Pauli exclusion or electrostatic repulsion are effective in introducing correlations between electrons traversing the structure, which make the process sub-poissonian.

We use a recently proposed model which allows us to study transport and noise in generic resonant tunneling structures, in the whole range of transport regimes, from completely coherent to completely incoherent, from a wholly quantum mechanical point of view, and to take into account the combined effects of Pauli exclusion and of electrostatic repulsion. The details of such model are described elsewhere [1,2,3], and will not be repeated here.

In this paper, we focus on the study of the temperature dependence of the the shot noise suppression factor (also called Fano factor) $\gamma \equiv S/(2qI)$, for a given bias current.

MODEL AND APPROXIMATIONS

Let us consider the one-dimensional resonant tunneling structure sketched in Fig. 1: it can be considered as consisting of three isolated regions Ω_l, Ω_w, and Ω_r, i.e., the left reservoir, the well region, and the right reservoir, respectively, weakly coupled through the two tunneling barriers 1 and 2. Let each allowed state in Ω_l, Ω_w, Ω_r be characterized by a set of parameters α_l, α_w, α_r, respectively. The density of states and the occupation factor in region Ω_s ($s = l, w, r$) are $\rho_s(\alpha_s)$ and $f_s(\alpha_s)$, respectively. In our model, transport is described in terms of electron transitions between levels in different regions.

Here, we consider a condition of high bias, in which only transitions from the left reservoir (cathode) to the well, and from the well to the right reservoir (anode) are allowed: we introduce the generation rate g, i.e., the probability per unit time that

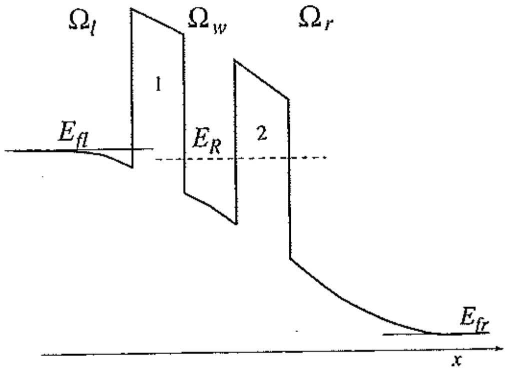

Figure 1: Profile of the conduction band for a typical one dimensional resonant tunneling structure

an electron enters the well through barrier 1, and the recombination rate r, i.e. the probability per unit time that an electron escapes from the well through barrier 2. They can be written, according to the Fermi "golden" rule, as

$$g = \frac{2\pi}{\hbar}\int\int |M_{1lw}|^2 \rho_l \rho_w f_l (1 - f_w) d\alpha_l d\alpha_w, \quad (1)$$

$$r = \frac{2\pi}{\hbar}\int\int |M_{2wr}|^2 \rho_w \rho_r f_w (1 - f_r) d\alpha_w d\alpha_r, \quad (2)$$

where M_{1lw} and M_{2wr} are the matrix elements for a transition from $|\alpha_l\rangle$ to $|\alpha_w\rangle$, and from $|\alpha_w\rangle$ to $|\alpha_r\rangle$, respectively.

It is worth noticing that Pauli exclusion affects g through the term $(1 - f_w)$ in (1), while Coulomb repulsion affects g and r through the transition matrix elements, which depend on the charge density in the device through the Hartree term.

In realistic structures, the well region contains many states, which definitely makes not tractable the problem of considering the transition rates as functionals of the occupation factor of each level in the well. Hence, we shall make a further strong assumption: that generation and recombination rates depend on f_w only through the total number of electrons in the well N, so that $g = g(N)$, and $r = r(N)$. A few drawbacks of these approximation are considered in [3].

In addition, if the distribution of the total number of electrons in the well is narrow enough we can greatly improve the tractability of the problem by linearising recombination and generation rates around the value $N = \tilde{N}$ for which we have $g(\tilde{N}) = r(\tilde{N})$. After such operation the average number of electrons in the well $\langle N \rangle = \tilde{N}$, and the average current through the device is $I = qg(\tilde{N})$.

We can introduce now the caracteristic times τ_g and τ_r for generation and recombination, defined as

$$\frac{1}{\tau_g} \equiv - \left.\frac{dg}{dN}\right|_{N=\tilde{N}}, \qquad \frac{1}{\tau_r} \equiv \left.\frac{dr}{dN}\right|_{N=\tilde{N}}, \quad (3)$$

which allows us, according to Ref. [3], to write the shot noise suppression factor

$\gamma = S/2qI$ as

$$\gamma = \frac{S}{2qI} = 1 - \frac{2\tau_g\tau_r}{(\tau_g+\tau_r)^2}. \tag{4}$$

As can be easily seen, according to (4) γ cannot be smaller than one half: this is a general result which is also valid at different bias conditions.

ONE-DIMENSIONAL STRUCTURE

We consider here the case of a structure in which transport can be considered a one-dimensional problem, for example that of large area double barrier structures obtained by epitaxial growth of layers of different gap materials. A state in any region can be decomposed in its longitudinal component $|E\rangle$, its transverse component $|\mathbf{k_T}\rangle$, and its spin component $|\sigma\rangle$, i.e., for $s = l, w, r$, $|\alpha_s\rangle = |E_s\rangle \otimes |\mathbf{k_T}\rangle \otimes |\sigma\rangle$. Electron transitions through either barrier preserve spin, longitudinal energy, and transverse wave vector, therefore the problem of calculating generation and recombination rates can be solved just in the longitudinal direction, and the results can be then integrated over transverse wave vectors $\mathbf{k_T}$ and doubled to account for spin degeneracy. Therefore, (1) and (2) become (a detailed derivation can be found in [3])

$$g = 2\int_{E_{\rm cbl}}^{\infty} dE\nu_w(E)T_1(E)\rho_w(E)\int d\mathbf{k_T}\rho_T(\mathbf{k_T})f_l(E,\mathbf{k_T})[1-f_w(E,\mathbf{k_T})] \tag{5}$$

$$r = 2\int_{-\infty}^{\infty} dE\nu_w(E)T_2(E)\rho_w(E)\int d\mathbf{k_T}\rho_T(\mathbf{k_T})f_w(E,\mathbf{k_T})[1-f_r(E,\mathbf{k_T})] \tag{6}$$

where ρ_T is the transverse density of states, T_1 and T_2 are the tunneling probability of barriers 1 and 2, $E_{\rm cbl}$ is the conduction band edge; ρ_w is the longitudinal density of states in the well, and has a narrow peak at the energy E_R of the resonant level of the well. The shape of ρ_w is strongly affected by phonon scattering, i.e., by temperature; in particular, as temperature (and therefore phonon scattering) increases, the peak of ρ_w lowers and widens (a compact formula for obtaining ρ_w is derived in [2]). ν_w is the inverse of the round trip time of the well: since it is a slowly varying function of energy, it can be substituted with its value ν_w^R at $E = E_R$.

In conditions of high bias we can reasonably suppose that there is a strong accumulation of electrons at the cathode (left electrode) and depletion at the anode, so that, for energies at which f_w is not negligibly small, we have $f_l \approx 1$, and $f_r \approx 0$. In this case (5) and (6) are greatly simplyfied, and reduce to

$$g = 2\nu_w^R T_1^g(N_{l0} - N), \qquad r = 2\nu_w^R T_2^r N, \tag{7}$$

where N_{l0} is defined as

$$N_{l0} = \int_{E_{\rm cb}}^{\infty} dE\rho_w \int \rho_T f_l d\mathbf{k_T}. \tag{8}$$

T_1^g is an average of T_1 over suitable couples of states for transition from the cathode to the well, and T_2^r is analogously defined for transitions from the well to the anode, i.e.,

$$T_1^g \equiv \frac{\int_{E_{\rm cbl}}^{\infty} dE\nu_w T_1\rho_w \int d\mathbf{k_T}\rho_T f_l(1-f_w)}{\nu_w^R\int_{E_{\rm cbl}}^{\infty} dE\rho_w\int d\mathbf{k_T}\rho_T f_l(1-f_w)} \tag{9}$$

$$T_2^r \equiv \frac{\int_{-\infty}^{\infty} dE\nu_w T_2\rho_w \int d\mathbf{k_T}\rho_T f_w}{\nu_w^R\int_{-\infty}^{\infty} dE\rho_w\int d\mathbf{k_T}\rho_T f_w} \tag{10}$$

As can be seen from (7) the rates depend on N both explicitly and through the tunneling coefficients T_1^g and T_2^r.

If the effect of the charge accumulated in the well is negligible, (3) and (7) yield

$$\frac{1}{\tau_g} = 2\nu_w^R T_1^g, \qquad \frac{1}{\tau_r} = 2\nu_w^R T_2^r, \tag{11}$$

which, substituted in (4), give

$$\gamma = 1 - \frac{2T_2^r T_1^g}{(T_2^r + T_1^g)^2}. \tag{12}$$

It is straightforward to see from (12) that γ depends only on the ratio T_2^r/T_1^g. In particular, has just one minimum ($\gamma = 0.5$) when that ratio is unity.

DISCUSSION

For very low temperatures the hypothesis of narrow density of states is valid, because inelastic collisions are rare, therefore T_1^g and T_2^r are very close to the tunneling probabilities at the resonant energy $T_1(E_R)$ and $T_2(E_R)$, respectively, and (12) reduces to the well known results of [4,5].

When the temperature increases, the peak of ρ_w widens, causing T_1^g to increase and T_2^r to decrease. In fact, collisions with phonons make electrons in the well relax to lower energy states, so that generation occurs more easily at higher energies, where T_1 is greater, while recombination occurs at lower energies, where T_2 is smaller.

Now, we must consider two different cases. If $T_1(E_R) < T_2(E_R)$ the Fano factor at low temperatures is greater then 0.5; when the temperature increases the ratio T_1^g/T_2^r approaches unity, making γ reach its minimum of 0.5; then, T_1^g/T_2^r becomes greater then 1, and γ approaches unity again.

If, on the other hand, $T_1(E_R) \geq T_2(E_R)$, we expect $\gamma \geq 0.5$ at low temperatures, increasing towards unity as the temperature is increased. This is the case,for example, of the experimental results shown in Ref. [6], where, at temperatures up to 155 K, shot noise suppression is smoothly dependent on temperature, while it rapidly vanishes at higher temperatures.

Significant deviations from this behaviour are to be expected if the effect of the charge accumulated in the well is predominat, i.e., if Coulomb repulsion has an effect greater then Pauli exclusion in suppressing shot noise.

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