OSCILLATIONS DUE TO MANY-BODY EFFECTS IN RESONANT TUNNELING

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ABSTRACT. *We analyze the dynamical evolution of the resonant tunneling of a cloud of electrons through a double barrier in the presence of the self-consistent potential created by the charge accumulation in the well. The intrinsic nonlinearity of the transmission process is shown to lead to oscillations of the stored charge and of the transmitted and reflected fluxes.*

In recent years there has been renewed interest in the phenomenon of resonant tunneling (RT) through double barriers. The unique capabilities of molecular beam epitaxy make it possible to investigate fundamental questions on RT through simple man-made potentials by controlling the barrier and well parameters down to the atomic scale[1].

In this paper we investigate the dynamics of RT of ballistic electrons in the presence of the potential created by the charge trapped within the barriers[2]. This problem is interesting not only from a technological point of view but also as a test of quantum mechanical non-equilibrium situations in which many particles are involved. The interest of this type of problem was emphasized some years ago by Ricco and Azbel[3] but as it will appear in the sequel the mechanisms involved are significantly more complicated than envisaged by these authors.

We propose the following model[4] to describe the physical situation. A cloud of electrons is created within a contact layer and launched towards embedded semiconductor layers forming a double barrier potential. The experimental set-up we have in mind puts ideally all the electrons in the same high-energy longitudinal (in the direction perpendicular to the double barrier) state while the transversal degrees of freedom are essentially decoupled[1]. As a consequence, at the starting time, the cloud wave function is factorized in a longitudinal and a transversal component. The longitudinal component is a product state of the same single particle state, $\psi(x,0)$. The cloud state is then symmetric with respect to the exchange of the longitudinal degrees of freedom. The correct antisymmetry of the total wave function is ensured by the transversal coordinates.

At low temperature and when the transversal dimensions of the semiconductor device are large with respect to the screening length in the medium, the decoupling between the longitudinal and transversal degrees of freedom is preserved as the time flows. In fact, theorem 5.7 of Ref. 5 guarantees in the mean field approximation (which is reasonable due to the large number of electrons involved) that the longitudinal state remains a product state during its evolution and allows us to write the following self-consistent equation for the single particle state $\psi(x,t)$:

$$i\hbar\frac{\partial}{\partial t}\psi(x,t) = \left[-\frac{\hbar^2}{2m}\frac{\partial^2}{\partial x^2} + V(x) + W(x,t)\right]\psi(x,t) \tag{1}$$

The external potential, V, is assumed, as customary, to be a piecewise constant function (no electric field is applied) representing a double barrier and admits of a resonance in the transmission coefficient which has an energy width Γ_R. The mean field interaction term, W, can be expressed in terms of the electron density $|\psi(x,t)|^2$ via the Poisson equation. This repulsive feedback effect can be reasonably represented by a simple model in which the bottom of the well between the two barriers of V is shifted to a higher energy proportional to the electron charge, $Q(t)$, trapped in it at time t. In this model the intensity of the repulsive potential is assumed proportional also to a parameter, α, which is inversely proportional to the capacitance of the double barrier and thus takes into account the dielectric constant of the medium.

The 1-particle state, $\psi(x,0)$, which is the initial condition in our mean field equation, has been chosen to be a gaussian shaped superposition of plane waves, with energy spread Γ_0, impinging on the double barrier with a mean kinetic energy close to the resonance energy. At the starting time the cloud is localized distant from the double barrier so that no appreciable charge sits in the well, *i.e.* $Q(0) = 0$. The normalized charge in the well, $Q(t)/Q_0$, where Q_0 is a convenient normalization factor depending on the shape of $\psi(x,0)$, has been calculated as a function of time by numerically integrating[6,7] Eq. (1). The results for different choices of the parameter α are shown in Fig. 1 in the case of electron clouds with energy-spread larger, of the same order and smaller than the resonance width.

When the non linear term is neglected, *i.e.* for $\alpha = 0$, the evolution of the trapped charge, as well as the transmitted and reflected fluxes, presents a smooth increase followed by a decrease. The differences between the two extreme cases $\Gamma_0 \gg \Gamma_R$ and $\Gamma_0 \ll \Gamma_R$ for what concerns the decrease, are simply understood in terms the of decay law of a quantum mechanical state which has a lorentzian or a gaussian shape[7,8].

In the case of a real interacting electron cloud, *i.e.* for $\alpha \neq 0$, the evolution of the trapped charge changes drastically and oscillations can appear. A detailed analysis of our global numerical simulations for different values of α and Γ_0 supports the following considerations. Oscillations appear, for an appropriate strength of the interaction term, *i.e.* for α sufficiently high, only when the cloud energy spread is wider or comparable to the resonance width. No oscillations are seen for a nearly monochromatic cloud, *i.e.* $\Gamma_0 = 0.8\ meV$. When α increases, the oscillations, if present, increase in number but decrease in amplitude.

To understand these results, let us first interpret the dependence of the intensity of the trapped charge as a function of the parameters α and Γ_0. We simplify the question by considering a time-average of the charge dynamically present inside the well. The mean charge Q trapped in the well is determined self consistently by requiring that it is proportional to the asymptotically transmitted charge[8], Q_T, which itself depends on Q:

$$Q \propto Q_T = \int_{-\infty}^{+\infty} dk\ |\widetilde{\psi}(k,0)|^2\ T_Q(k) \tag{2}$$

where $\widetilde{\psi}(k,0)$ is the Fourier transform of $\psi(x,0)$ and $T_Q(k)$ is the transmission coefficient of the potential V modified by the charge Q. The self-consistent relation (2) predicts correctly the decrease of the charge trapped in the well as the self interaction, *i.e.* α, is increased as well as the dependence from the cloud energy spread Γ_0[4].

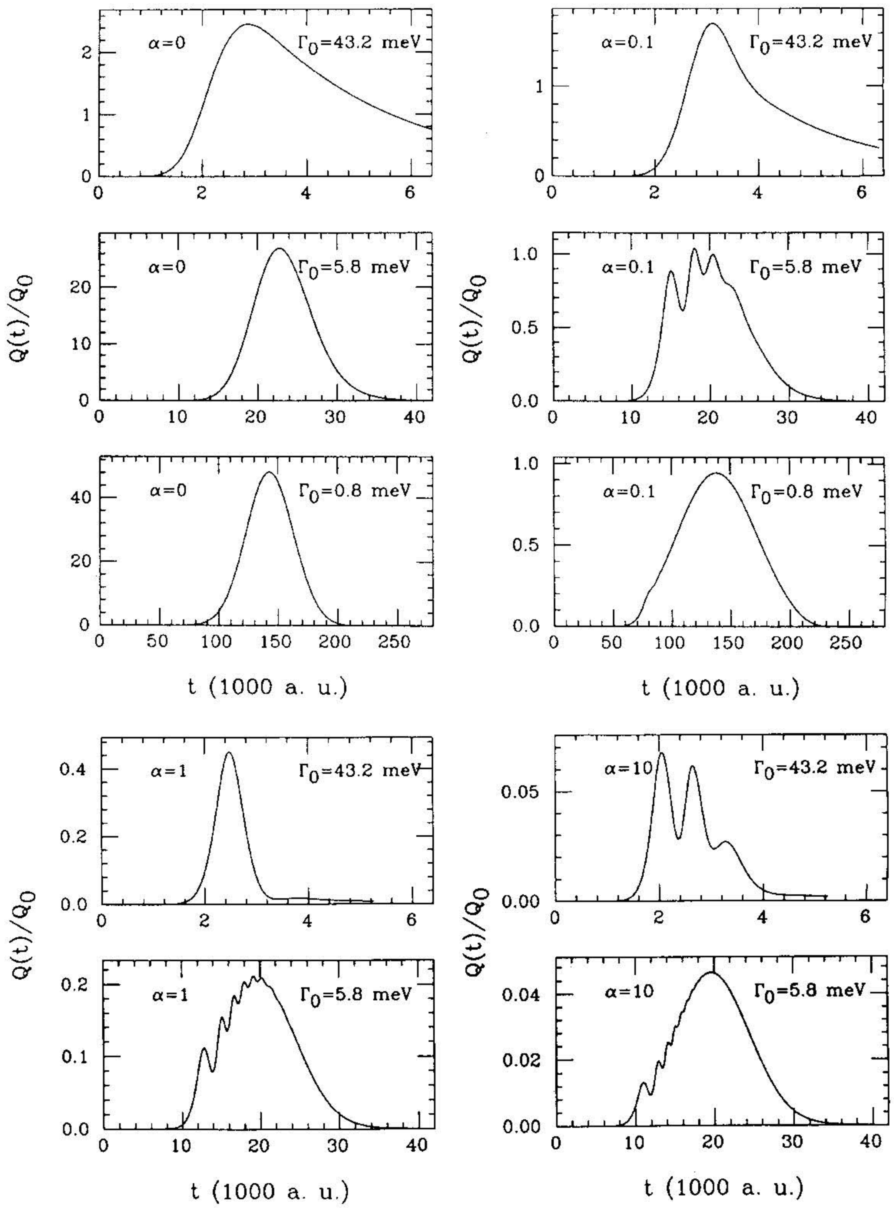

Figure 1. *Time development of the normalized charge trapped in the well for electron clouds with energy spread much wider ($\Gamma_0 = 43.2$ meV), of the same order of ($\Gamma_0 = 5.8$ meV) and much smaller ($\Gamma_0 = 0.8$ meV) than the resonance width ($\Gamma_R \simeq 5$ meV). The results are shown for various values of the feedback intensity parameter, α. The conversion of the atomic units of time to seconds is* $1\ a.u. \simeq 4.83\ 10^{-17}\ s$.

We then consider the oscillating behavior. Let us assume that this phenomenon is due to the competition of two processes: *(a)* the filling up of the well by the incoming cloud and *(b)* the natural decay of the trapped charge. For the process *(a)* the time scale is of the order of $\hbar/\Gamma_0$. For the process *(b)* a reasonable time scale is $\hbar/\Gamma_Q$, where Γ_Q is the energy spread of the function to be integrated in Eq. (2), *i.e.* the width of the spectral decomposition of the charge present in the well. Oscillations are then expected if a substantial crossover of Γ_Q and Γ_0 is realized for the Q values reached during the time evolution. The analysis of Γ_Q as a function of Q shows[7] that when $\Gamma_0 \ll \Gamma_R$, its value is very close to Γ_0 and nearly independent of Q. As a consequence no oscillations are possible in this case for any value of α. On the other hand, when $\Gamma_0 \geq \Gamma_R$, Γ_Q crosses Γ_0 at a some Q; oscillations are then realized for a sufficiently high value of α. This critical value of α increases with the ratio Γ_0/Γ_R. These predictions agree with the results of the simulations reported above.

Experimentally, the geometry considered here can be implemented by ballistically launching electrons into a double barrier inserted in the thin (< 1000 Å) base of a unipolar transistor[9]. The predicted range of oscillations (≤ 1 ps) should be detectable with electro-optic sampling techniques[10].

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