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SINGLE-ELECTRON CHARGING OF THE QUANTUM WELLS AND DOTS

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Decrease of the quantum well area should result in a fine structure of its dc I-V curve due to either quantization of the 2-D electron motion in the well, or charging of the well by single electrons, or both. What effect dominates, is determined by a parameter α, the same which determines magnitude of the I-V curve hysteresis due to the multi-electron charging of large-area quantum wells.

1. INTRODUCTION

Low-temperature electron transport in the metallic tunnel junctions of ultrasmall areas (practically, $S<10^{-10}cm^2$) is highly influenced by the single-electron charging effects - for a recent review, see Ref. 1. The objective of the present work was to show that these effects should be observable in semiconductor tunnel structures of equally small areas, in particular in small quantum wells. Here the single-electron charging can coexist and interfere with the quantization of the electron motion in the well.

2. MODEL

We have considered a quantum well with the band edge profile shown in Fig. 1. The Fermi energy ε_F of the degenerate 3-D electron gas in the emitter and collector has been assumed to be much less than height U of the tunnel barriers. In our simple model (very similar to those accepted e.g., in Ref. 2) the average well-emitter voltage φ is a linear function of the voltage V across the whole structure and the charge Q of the tunneling electrons in the well:

$$\varphi=\eta V-Q/C_\Sigma\ , \quad C_\Sigma=C_e+C_c\ , \quad \eta\cong C_c/C_\Sigma\ ,$$
$$C_e=\varepsilon\varepsilon_0 S/(d_e+\frac{w}{2})\ , \ C_c=\varepsilon\varepsilon_0 S/(\frac{w}{2}+d_c+a). \qquad (1)$$

In order to describe the single-electron charging we should take the discreteness of the charge Q into account: $\Delta Q=e\Delta n$.

The rates Γ_e and Γ_c of the sequential electron tunneling to/from each of the quantum states of the electrons in the well (determined by their 2-D motion) can be taken in their Golden Rule form (see Eq. (3) of Ref. 3) which is valid when the tunnel barrier transparencies are low enough (T_e, $T_c \ll w^2/S$). Calculating the transparencies, we have assumed their independence of the 2-D mode and conservation of the 2-D energy during the tunneling. The direct tunneling through the well and scattering processes were neglected.

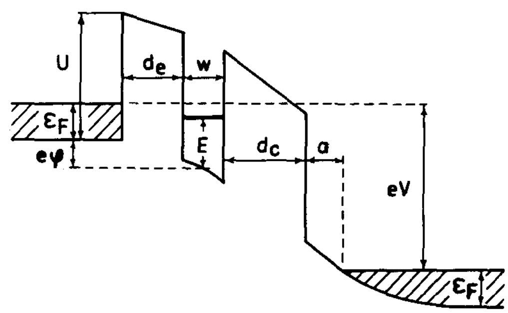

FIGURE 1
Band edge profile model of the quantum well.

3. LARGE-AREA WELL: MULTI-ELECTRON CHARGING

Figure 2 shows our results for the dc I-V curve of a large-area quantum well for which the 2-D quantization is negligible, and the charge Q can be considered as continuous. The hysteresis of the curve is a consequence of the quantum well charging, and its magnitude is determined by the parameter (2)

$$\alpha = \beta\,\frac{\Gamma_e}{\Gamma_e+\Gamma_c}, \qquad \beta = \frac{e^2\rho}{C_\Sigma} = \frac{4d_{ef}}{a_B}\ , \qquad (3)$$

where $\rho=Sm/\hbar^2\pi$ is the 2-D density of states, $a_B=4\pi\varepsilon\varepsilon_0\hbar^2/me^2$ ($a_B\simeq 100$ Å for GaAs) is the Bohr radius, and $d_{ef}=[(d_e+w/2)^{-1}+(w/2+d_c+a)^{-1}]^{-1}$.

This result is quite similar to that of Ref. 2, except that our Γ_e vanishes at $E-e\varphi\Rightarrow 0$, so that the top of the resonant tunneling peak is somewhat rounded within our model. Figure 1b shows that for a fixed α the degree of this rounding depends on the tunneling rates ratio (in all our plots the value of Γ_e/Γ_c at the threshold voltage $V_t=(E-\varepsilon_F)/e\eta$ is indicated).

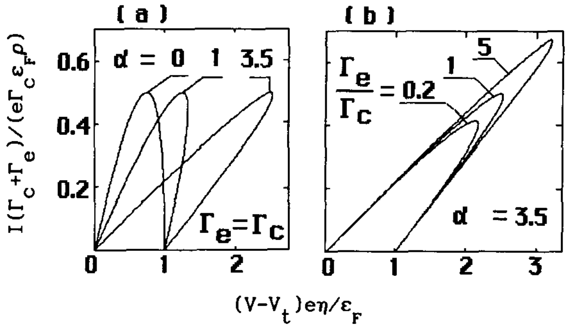

FIGURE 2

DC I-V curve of a large area quantum well with: (a) different α and (b) different Γ_e/Γ_c; $V_t=(E-\varepsilon_F)/e\eta$.

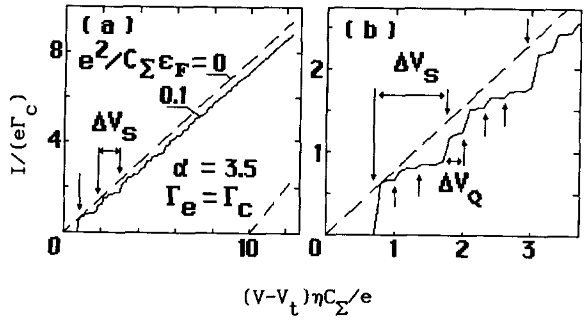

FIGURE 3

DC I-V curve of a quantum dot with $\Gamma_e=\Gamma_c$, α=3.5, and $e^2/C_\Sigma\varepsilon_F$=0.1 for $T=0.01e^2/C_\Sigma$: (a) global shape of the curve, with only the single-electron charging structure ($\Delta V_S=e/C_\Sigma\eta$) visible; (b) blowup of the initial part of the curve, where the energy quantization ($\Delta V_Q=2/e\rho\eta=2\Delta V_S/\beta$) can be distinguished as well. Dashed lines show the DC I-V curve of a similar but large-area quantum well, formally scaled to the same area.

4. QUANTUM DOT WITH $\alpha \ll 1$: ENERGY QUANTIZATION

If the area of a quantum well with $\alpha \ll 1$ is reduced below the point where $\rho^{-1} \simeq T$, the 2-D quantization shows up as a staircase structure in the DC I-V curve (as soon as $\rho^{-1} \ll \varepsilon_F$, the global shape of the curve remains intact). The intervals ΔV_Q between the steps reproduce the energy quantization, and can be either equal (e.g., for a 2-D-parabolic quantum well (4)), or different (e.g., for a rectangular flat well). If the states degeneracy is due to the electron spin alone, the average interval ΔV_Q between the steps is $2/\rho e\eta$ (in all our results below, the states are assumed to be equidistant and doubly degenerate).

5. QUANTUM DOT WITH $\alpha \gg 1$: SINGLE-ELECTRON CHARGING

In the opposite limit of strong charging effects ($\alpha \gg 1$), decrease of the area should lead to a periodic fine structure (see Fig. 3a) with $\Delta V_S=e/C_\Sigma\eta$ due to the discreteness of Q (1). The shape of this structure (as well as the condition of its observability, $e^2/C_\Sigma \gtrsim T$) coincides with that for the similar metallic system (1,3). In particular, the threshold is moved to the right by the "Coulomb blockade range" $\Delta(\eta V_t)=e/2C_\Sigma$ with respect to its position in the similar but large-area well.

6. QUANTUM DOT WITH $\alpha \simeq 1$: INTERFERENCE OF THE FINE STRUCTURES

In small-area wells with $\alpha \simeq 1$, the both fine structures should exist and form a rather complex interference pattern. At $\alpha \lesssim 1$ and $\Gamma_e \gtrsim \Gamma_c$, this pattern can be most readily interpreted as the staircase structure due to the 2-D energy quantization, with a small splitting of each current step by ΔV_S due to the single-electron charging.

On the contrary, at $\alpha \gtrsim 1$ the energy quantization provides a "superfine" structure on each step of the single-electron staircase (Fig. 3b), with increase of each even period by ΔV_Q.

7. DISCUSSION

Possible deviations of a real structure from our simple model (in particular, nonvanishing elastic and inelastic scattering of the electrons in the well, comparability of ε_F with U, effects of V upon the tunnel barriers heights and the depletion width a, *etc.*) would affect our quantitative results but hardly the qualitative conclusions of our analysis.

According to our results, the fine structure observed in the experiments (4) with GaAs quantum well of $S \simeq 10^{-10}$cm^2, $\beta \simeq 1.2$, $\Gamma_e \ll \Gamma_c$, $\alpha \ll 1$ was due to the 2-D quantization rather than the single-electron charging. Nevertheless, the latter effect can be presumably observed in almost similar GaAs structures, but with a thicker collector barrier providing $\Gamma_e \geq \Gamma_c$ and $\alpha \geq \beta/2$.

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