Quantum Confinement in Laterally Squeezed Resonant Tunneling Devices

In a recent Letter, Guéret *et al.* [1] investigated the current-voltage characteristics, $I(V)$, of a double-barrier resonant-tunneling device in which the lateral dimensions, and hence the current, are controlled by a Schottky gate. They observed a series of peaks in the conductance dI/dV which moved to higher source-drain voltage (V) with increasing negative gate voltage V_G. They claim that this behavior provides direct proof of a quantum size effect which is governed by V_G. In this Comment, we show that the overall dependence of the peak positions on V_G is qualitatively inconsistent with such a model. We base our argument on an analysis of the resonant-tunneling transitions of electrons from the occupied states of the negatively biased emitter into the quantum well under conditions of lateral confinement.

It is claimed that the confinement provided by the gate potential quantizes the lateral motion, and hence the energy, of the electron states in the emitter and quantum well. The exact form of this quantization depends on the detailed shape of the confining potential. However, the following considerations apply in general. Tunneling transitions from emitter to quantum well can be classified into two types: (1) those in which the lateral quantum numbers are conserved, and (2) those in which they are changed. In both cases, energy is conserved. If the degree of lateral confinement in the emitter and well is the same, the resonance condition for the features due to type-1 transitions is independent of the confinement and therefore they all occur at the same source-drain voltage, independent of V_G. If the length scale (d_w) which defines the lateral confining potential in the quantum well is smaller than that in the emitter (d_e), the features due to the various type-1 transitions will occur at different source-drain voltages, with their separation increasing as the confinement lengths are reduced. Features due to type-2 transitions will exhibit a strong dependence on gate voltage, even if $d_e = d_w$, since they involve a change in lateral quantum number(s). Their shifts, ΔV, in source-drain voltage with increasing negative gate voltage are determined by the energy-level spacing of the quantized levels and by the change in quantum number(s) [2]. This variation is therefore a sensitive test of gate-controlled lateral confinement.

Let us now compare this analysis with the data reported by Guéret *et al.* [1]. They find that the lowest voltage peak in conductance shifts to higher voltages with increasing negative V_G. However, most of the other prominent peaks in the dI/dV shift at a similar rate. This can be seen in Fig. 3 of Ref. [1] and also in Fig. 4 of Ref. [2] which plots the various peak positions for the data shown in Ref. [1] over the full range of gate voltage. In particular, the variation of voltage separation of the lowest two peaks, $\Delta V_{1,2} = \Delta V_2 - \Delta V_1$, is much less than the shift in the voltage of the lowest peak, ΔV_1. From Fig. 4 of Ref. [3] we see $\Delta V_1 \simeq 15$ meV and $\Delta V_{1,2} \simeq 4$ meV as V_g is varied from -1.7 to -2.4 V, although the estimate of $\Delta V_{1,2}$ is complicated by the appearance of an extra peak over this gate voltage range. This is also inconsistent with the model proposed by Guéret *et al.* [1]. We propose that these observations are more consistent with an increase in the potential in the quantum well due to the electrostatic effect of the gate voltage than with a gate-controlled quantum confinement effect. An electrostatic effect would shift both type-1 and type-2 transitions equally, as is observed. In such a description, the peaks in the conductance are more likely to be due to transitions between states localized by random variations in the lateral potential rather than by the gate potential. For example, these might be due to the presence of ionized donors which have diffused or segregated from the doped contact layers. This explanation would also be more consistent with the voltage position of the lowest peak that Guéret *et al.* observe, which is (i) *below* the threshold for resonant tunneling, $V_{\text{th}} \simeq 60$ meV [4], and (ii) found to vary widely (30–50 mV) between different devices [5]. This type of effect has been proposed to explain the sharp peaks in the $I(V)$ curves of similar [6] and related [7] devices.

It is clear that the electrical properties of small devices of this type are sensitive to a number of phenomena such as quantum confinement, potential fluctuations, and Coulomb blockade. An unambiguous observation of a quantum confinement effect controlled by an external gate potential would require evidence of an energy-level spectrum in which the level *separation* increased systematically with increasing confinement. The experiment described by Guéret *et al.* shows only an overall shift of the conductance peaks with increasing negative bias.

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[2] Let us assume an infinite potential well of square cross section, and side length d_w. Guéret *et al.* claim the lateral potential is indeed sharp edged. The energy levels of the quantum well are then given by $E_{\text{QW}} = h^2(p^2+q^2)/8md_w^2 + E_z$, where (p,q) are the quantum numbers for lateral confinement and E_z is the confinement energy provided by the tunnel barriers. The variation with lateral confinement (and V_G) in the source-drain voltage of the resonances is $\Delta V = h^2[(p^2+q^2)/d_w^2 - (p'^2+q'^2)/d_e^2]/em^*f$, where (p',q') are the emitter state quantum numbers and $f \simeq \frac{1}{2}$ is the fraction of the source-drain voltage dropped across the emitter region.

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