Single-electron quantization of electric field domains in slim semiconductor superlattices

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It is shown that dc I-V curves of the semiconductor superlattices of small (practically, submicron) cross section should exhibit oscillations with the dc voltage period e/C, where C is the capacitance between adjacent conducting layers. These oscillations are due to the single-electron quantization of electric charge of the boundaries of static high-electric-field domains.

Low-temperature electron transport properties of the multilayer tunneling structures (conductor/tunnel barrier/conductor···) may be dominated by the single-electron charging effects[1,2] if cross-section S of the structure, and hence capacitance C between the adjacent layers ($C \propto S$), are small enough to satisfy the condition $E_c \equiv e^2/2C > k_BT$. Modern nanolithography allows to fabricate submicron substrates for which the above condition is well satisfied at $T < 1$ K. The charging effects may include, in particular, a substantial correlation of the single-electron tunneling events in space and/or time, which are of considerable interest for several electronics applications.[2]

In metallic systems, the single-electron charging effects have been studied in a considerable detail.[1,2] In semiconductor nanostructures, these effects are even more interesting because here the charge quantization can coexist with electron energy quantization. However, these effects are well understood only for the simplest double-barrier structures.[3–7] In this letter we will present the first results on the single-electron charging effects in multilayer semiconductor structures—"slim" superlattices.

We have analyzed superlattices with small miniband width $\delta \ll \max(k_BT, eV_i, \hbar/\tau)$, where eV_i are the voltage drops across the tunnel barriers and τ is the relaxation time of momentum, which is determined by the elastic scattering of electrons in the wells and/or in the barriers.[8] In this limit, electrons are nearly localized in the conducting layers, and electron transport between the layers can be described as a sequential hopping with a complete randomization of the phase of the wave function between consecutive tunneling events. Another assumption is that the elementary charging energy E_c is much larger than the energy scale Δ of the energy quantization due to the lateral confinement. The ratio Δ/E_c is close to $a_B/2d$, where a_B is the Bohr radius in the semiconductor material, and d is the superlattice period,[4] so that our results are strictly valid in the limit $2d \gg a_B$.

Under these conditions, the superlattice can be described exactly as a one-dimensional (1D) array of metallic tunnel junctions[9] by probability rates for tunneling of a single electron through each barrier. The only (but very important) distinction is that the "bare" I-V curve of each junction of the superlattice (i.e., the dc I-V curve in the case of the fixed voltage across it) consists of a series of current peaks. Each of these peaks is due to the tunneling between energy levels in the adjacent conducting layers, that correspond to different minibands. For relatively small voltages, only two peaks (corresponding to the miniband pairs $1 \rightarrow 1$ and $1 \rightarrow 2$) are important, and the junction I-V curve can be approximated as follows:

$$I_0(U) = \frac{U}{R}\left(\frac{1}{1+(U/V_0)^2} + \lambda \frac{1}{(1-U/V_1)^2}\right), \qquad (1)$$

where V_0 is the width of the first peak (determined by momentum relaxation time τ), and eV_1 is the energy gap between the lowest (first) and the next (second) minibands. Coefficients R and λ are determined mainly by the barrier transparency and the structure of the wavefunctions in the first and second miniband. Although we neglected the width of the second resonant current peak in Eq. (1), it is still a good approximation, since characteristic voltages in the simulations below do not come very close to the center of this peak at $U \simeq V_1$.

We have carried out extensive numerical simulations of dynamics of the superlattice using approximation (1) and the Monte Carlo method described in Ref. 9. Figure 1 shows typical results of the simulations for a superlattice of a relatively large cross section ($e/C \ll V_0$). At low voltages, $V < NV_0$, where N is the number of the tunnel junctions in the superlattice), the applied electric field is distributed uniformly, and the dc I-V curve of the whole structure follows the curve (1) for one junction with $U = V/N$. When V/N approaches the position V_0 of the first current peak, the uniform field distribution along the superlattice becomes unstable due to the negative differential resistance of the junction (1), and one tunnel junction is switched into a state with high electric field ($U \lesssim V_1$). This transition leads to a sharp drop of the superlattice current. When the voltage V is increased to $V \simeq V_1 + (N-1)V_0$, one more junction is switched to a high-voltage state, etc. As a result, the I-V curve exhibits a series of branches as the number n of tunnel junctions forming the high-electric field domain increases (Fig. 2). This phenomenon is well understood theoretically[10,11] and experimentally,[10,12–16] although we are not aware of any previous attempt of its quantitative numerical modeling. Our modeling indicates, in particular, that although the transitions between the branches are hysteretic [Fig. 1(a)], this hysteresis can be substantially suppressed at higher values of parameters e/C_0 and λ [Fig.

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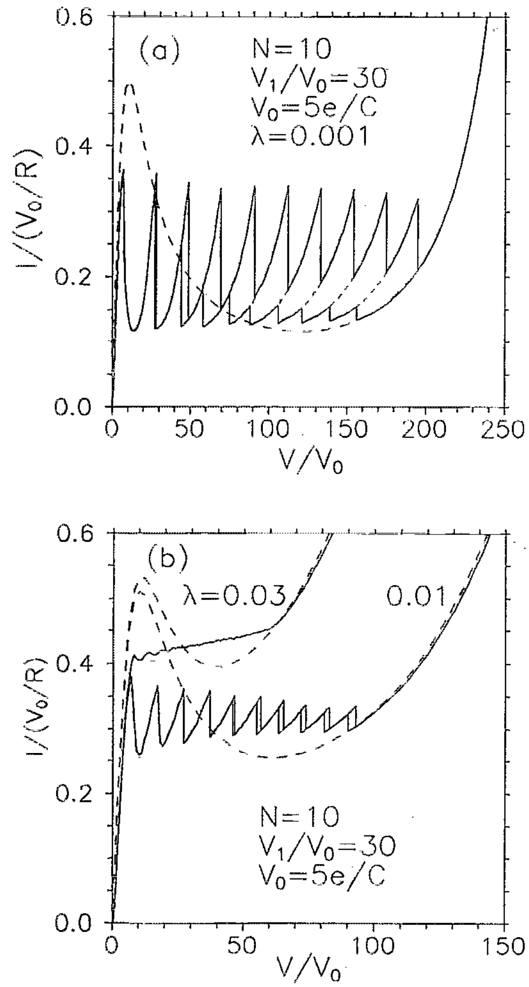

FIG. 1. The dc I-V curves of a usual (large cross section) superlattice with small single-electron charging effects. The quasiperiodic structure is due to formation of the high-field domain embracing increasing number n of tunnel barriers ($0<n<N$). Dashed curve shows the "bare" I-V curve of the individual tunnel junction scaled up in the voltage by the total number N of the junctions in the superlattice. Temperature is assumed to be small ($k_BT \ll e^2/C,\ eV_0$).

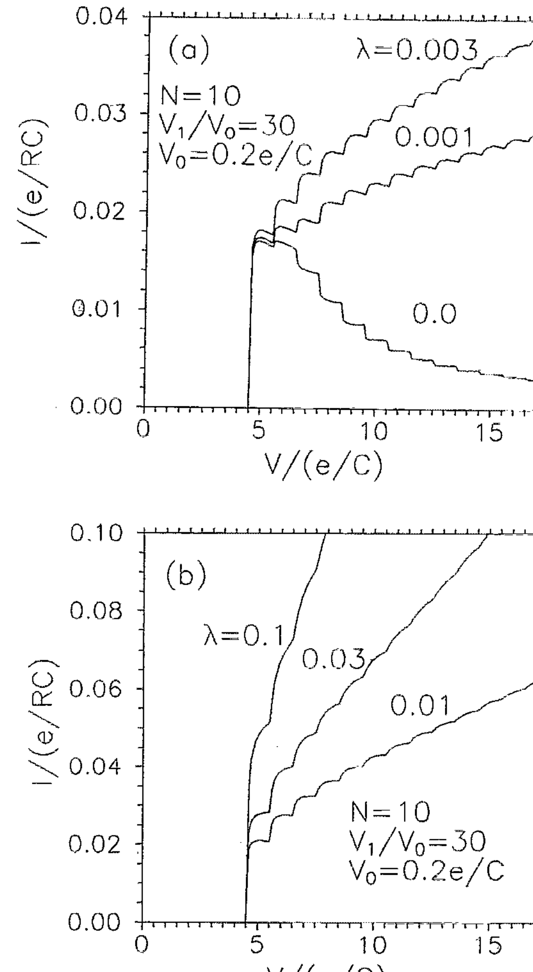

FIG. 3. The dc I-V curves of a "slim" (small cross section) superlattice for several values of the parameter λ. Such superlattices exhibit strong single-electron charging effects: the Coulomb blockade of tunneling at $V<V_t=(N-1)e/2C$, and a structure with the period $\Delta V=e/C$ due to quantization of electric charge of the high-field domains at $V>V_t$.

1(b)]. This effect can be readily explained by the fact that the shot noise of the tunneling electrons causes random switching between the branches.

For slim superlattices of a very small cross-section S (and hence of small capacitance $C \ll e/V_0$) our modeling predicts an entirely different behavior (Fig. 3). First of all, current is suppressed at voltages V below the threshold value $V_t=(N-1)e/2C$. This is a typical manifestation of the Coulomb blockage of tunneling, which was repeatedly observed in various metallic systems.[1,2] Even more important, at $V>V_t$ the superlattices show a new phenomenon: a very distinct structure with the voltage period $\Delta V=e/C$ (Fig. 3). These steps are a result of the quantization of the electric charge Q of the (stationary) boundary of the high-field domain (Fig. 2): each new step corresponds to an increase of Q by e. This picture resembles the so-called Coulomb staircase in metallic double-junction systems,[1,2] but in semiconductors this effect can be observed even for large N, since the effect is strongly enhanced by the negative-slope part of the junction I-V curve.

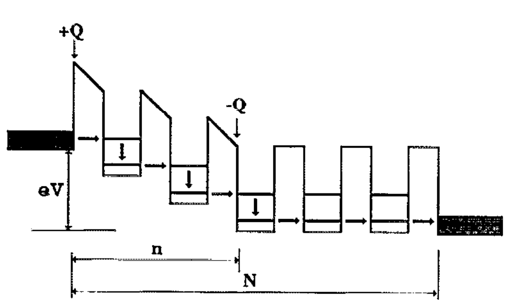

FIG. 2. Schematic band diagram of a superlattice with a high-field domain embracing n tunnel barriers (of the total number N).

The mth step of the pattern corresponds to the following dynamics of the system: m electrons are forming the stationary charge $Q=me$ of the high-field domain boundary (for small $V-V_t$, this domain embraces just one tunnel junction). An additional electron enters the superlattice, and is rapidly moving along it by successive tunneling through the junctions with low voltage (and hence large conductance), until it reaches the high-field domain boundary. Here the voltage is high and effective conductance low, so that the "new" electron joins m "old" electrons sitting on the boundary, until one of them eventually tunnels through the high-field region.

This picture, where the domain boundary is a bottleneck for the electron motion, is strictly valid for $\lambda \ll 1/N^2$. For larger values of λ, there is no well-defined single domain boundary in the superlattice (it splits into several domains which are not correlated at least within our simple model), but numerical simulations show that the periodic modulation of the dc I-V curve is visible until quite high values of λ [Fig. 3(b)]. In this regime, however, it is better interpreted as manifestation of the quantization of the total charge of the superlattice. All calculation results are also qualitatively independent of the position of the second resonant peak, provided that $V_1 \gg V_0$.

To summarize, slim semiconductor superlattices of a small cross-section S should exhibit a new phenomenon: single-electron quantization of electric charge boundary of the high-field domains. Experimentally this effect may be observable at reasonable values of S and T (say, $S < 1\ \mu\text{m}^2$ and $T < 1$ K for GaAs/AlGaAs structures with the period $d \simeq 20$ nm). Such superlattices can presumably be fabricated both in free standing and buried geometries (see, e.g., Ref. 17). Besides experimental confirmation of domain quantization, the most important issue to be addressed in experiment would be the possible coexistence of the charge quantization with the electron energy quantization due to their lateral confinement in the conducting layers (this effect was not considered in this work).

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