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Transport through one-dimensional channels

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The oscillatory behavior in the conductance of narrow channels in semiconductor heterostructures interrupted by a finite number of potential barriers can be explained by resonant tunneling of noninteracting electrons in a single one-dimensional subband. A simple and powerful method based on a generalized wave-impedance concept is used to calculate the transmission coefficient for electrons passing through such devices. The results show intriguing similarities with recent experiments.

Suitable lithographic techniques have recently been used to fabricate narrow channels in semiconductors in order to study the dependence of their conductance on the Fermi energy or, equivalently, on the carrier density of the underlying electron gas (EG). Scott-Thomas *et al.*[1] reported the discovery of conductance oscillations periodic in the density of one-dimensional (1D) inversion layers in Si metal-oxide-semiconductor field-effect transistors. Similar results have been reported for 1DEG in GaAs.[2] These oscillations exhibit a complex phenomenology and were originally interpreted in terms of pinned charge-density waves.[3] Later, Meirav, Kastner, and Wind[4] reported a set of experiments in high-mobility nanostructures on GaAs in which they were able to adjust two electrostatically defined potential barriers in the 1DEG. Following the suggestion of van Houten and Beenakker,[5] the periodic oscillations of the conductance with varying density were then associated with a sequential addition of single electrons to the segment defined by the two barriers. Although a resonant-tunneling picture has been considered as a crude model for the experimental findings, no explicit calculation has been presented.

On the other hand, many other phenomena observed in submicrometer semiconductor devices have been successfully analyzed in light of the transmission approach.[6] In view of the absence of a definitive explanation for the oscillations and its current controversial status, we have performed transmission-coefficient calculations and representative results are offered in this paper. For this we have used a simple method recently introduced by Khondker, Khan, and Anwar,[7] to which little attention seems to have been paid. We further present calculations of the electron transmission through a related structure; namely, the finite 1D crystal recently studied by Kouwenhoven *et al.*[8] The results, in spite of their simplicity, can account for many features of the experimental observations.

We first consider the structure shown in Fig. 1(a). The upper panel is a schematic drawing of the physical system described in the experiments of Meirav, Kastner, and Wind.[4] A 1DEG interrupted by two barriers connects two 2DEGs between which a small source-drain voltage V is applied. We model this system with the 1D potential profile (bottom of the conduction band) shown in the lower panel. The squeezing of the 2DEG is taken into account through the barrier U_0, which raises the linearly dropped potential floor along the 1D channel of fixed length (3.2 μm). The squeezing of the 1DEG is simulated with two barriers of length d and height U_b, separated by a segment of length L. An electron is incident from the left-hand side with energy E. It is worth noting that the devices described in Ref. 4 have two independent gate voltages, one defines the geometry via a patterned gate and the other (here referred to as V_g) controls the electron density. The effect of the former is here represented by U_0 and U_b, while V_g is assumed to scale with the Fermi level $E=E_F$. The conductance at zero temperature $G(E_F)$ is related to the transmission coefficient, $T(E_F)$ by the single-channel two-terminal Landauer formula $G(E_F)=(e^2/h)T(E_F)$. Contribution from a single one-dimen-

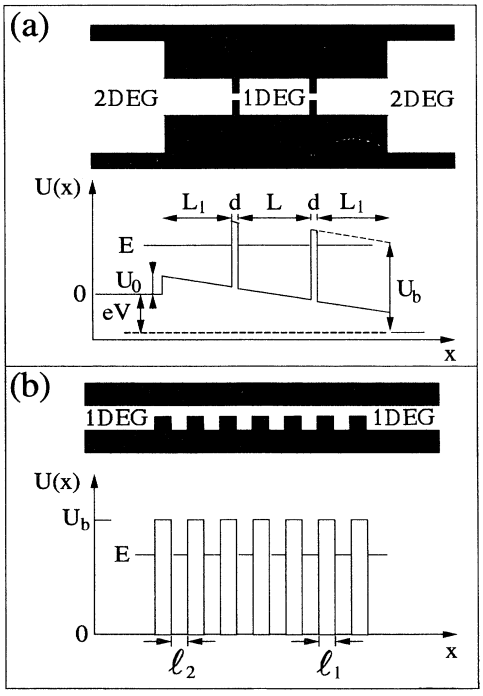

FIG. 1. (a) Schematic representations of the devices investigated in Ref. 4 and (b) in Ref. 8 (upper panels) and corresponding model potentials across the constrictions used here (lower panels).

sional subband has been justified through self-consistent solution of Poisson's and Schrödinger's equations.[3] In general, the transmission coefficient can be readily obtained with the method described in Ref. 7, which is based upon the analogy between transmission-line theory and quantum mechanics. By impedance-matching the plane-wave solutions of the Schrödinger equation at appropriately chosen potential discontinuities, the reflection (transmission) coefficient can be determined. The reader is referred to Ref. 7 for details. In what follows we present results for $V=0$ (low-bias regime), $U_0=0$, since it was found to be irrelevant within reasonable values, and $m^*=0.07m_0$ (m_0=electron rest mass), appropriate for GaAs-$Al_xGa_{1-x}As$ heterostructures. We estimate U_b from the measured conversion ratio $edV_g/dE_F=3.5\pm0.2$.[4] Since in the experiments the oscillations in the conductance occur in a typical interval of 30 mV in V_g,[2,4] it must appear in a corresponding range of 8–9 meV in E_F, so that a barrier of a few meV is reasonable. In Fig. 2 we present results for T vs E and T vs k, where $k=(2m^*E)^{1/2}/\hbar$, for $L=1$ μm, $d=33$ nm, and $U_b=2.5$ meV. We can clearly see that the resonances spread out with increasing E, but are remarkably periodic in k. The inset in Fig. 2(a) shows the calculated transmission through a single barrier, which modulates the minima of the corresponding double-barrier resonances. The inset in Fig. 2(b) shows an expanded plot of a single peak (dotted line) and a fit with a Lorentzian line shape (solid line). If we take into account temperature effects, the conductance is given by the convolution of the zero-temperature conductance with the energy derivative of the Fermi distribution function, $\partial f(E,T)/\partial E \propto \cosh^{-2}[(E-E_F)/k_BT]$. This functional form is dominant if the natural width of the resonance is $\ll k_BT$.[4] At $T\sim100$ mK, $k_BT\sim10^{-2}$ meV, which is an order-of-magnitude greater than the mean width of the peaks shown in Fig. 2. In contrast with the high-mobility GaAs samples, where the electrons could move ballistically through the constrictions, the oscillatory behavior in the conductance of the Si devices requires—an assumption common to all explanations—the presence of two dominant scattering centers which would define an isolated segment within the 1D channel.[1] An advantage of the resonant-tunneling model is that, since the number of impurities can be arbitrary, it can be easily handled with the wave-impedance method.[7] One important feature of the experiments with the Si transistors is the frequent occurrence of two (or more) oscillatory components in the conductance, in particular for longer (~10 μm) samples.[1] The power spectra in Fig. 3 show how the oscillations in the transmission change by the presence of a third barrier slightly different from the two dominant ones. As in the experiments, we observe in the transmission spectrum of the three-barriers structure the presence of two *competing frequencies*, $f_0=0.33$ μm, —the fundamental harmonic of the $L=1$ μm double-barrier structure—and $f_1=2.45$ μm. Furthermore, the inset in Fig. 3(a) shows that the fundamental harmonic scales linearly with L, as is suggested by the experimental data of Ref. 4. By changing the set of parameters (num-

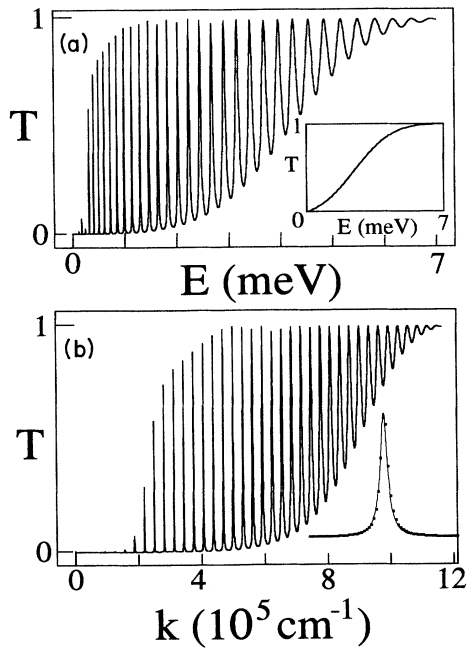

FIG. 2. (a) Transmission coefficient T vs energy E for the potential profile shown in 1(a), with $L=1$ μm, $d=33$ nm, $U_b=2.5$ meV, and $eV=U_0=0$. The inset shows the corresponding single-barrier transmission. (b) Transmission-coefficient T vs wave number k, for the same set of parameters as in (a). The inset shows a single peak (dotted line) and a fit with a Lorentzian line shape (solid line).

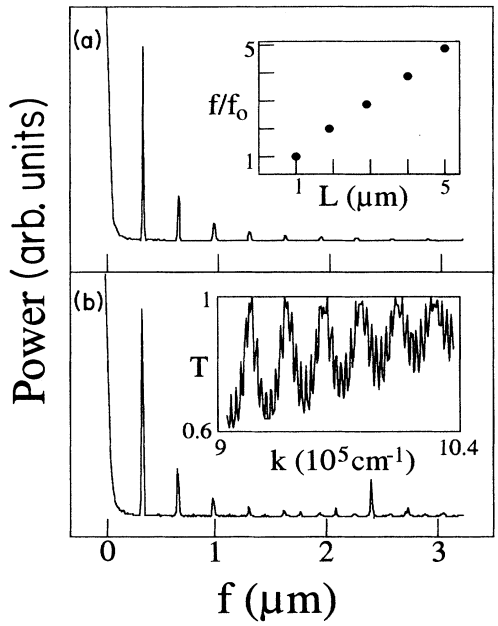

FIG. 3. (a) Power spectrum of the oscillation shown in 2(b). The inset shows the behavior of the fundamental harmonic with L. (b) Same as (a) with the addition of a third barrier with the same height, 10 nm in width, and 7.7 μm apart from the original structure. The inset shows the corresponding oscillation in the transmission.

ber, width, height, and separation of the barriers) we can obtain a variety of different shapes for $T(E)$ as observed in the experiments. An example is given in Fig. 4. Figure 4(a) reproduces experimental data from Ref. 2, corresponding to a segment between scattering centers of length ~ 1 μm. In Fig. 4(b) we show the calculated conductance for a double-barrier structure with $L=1$ μm, $d=66$ nm, and $U_b=2.5$ meV. The similarity of the two results is impressive; not only is there good qualitative agreement for the conductance modulation, but, in addition, the oscillation periods are in excellent quantitative agreement given the conversion ratio experimentally determined in Ref. 4.

Another important and related experiment on narrow channels in GaAs has recently been reported by Kouwenhoven *et al.*[8] They have studied the transport properties of an artificial crystal, i.e., a linear sequence of fifteen quantum dots electrostatically defined in a 2DEG by means of two independent split-gate electrodes. The geometry of the electron system is depicted in Fig. 1(b) (upper panel), together with the potential profile chosen to model the system (lower panel). For clarity, only seven barriers (six dots) are shown. Again we neglect the connections with the 2DEG as well as the small source-drain voltage. The application of the wave impedance method for a sequence of sixteen barriers (fifteen dots) of length l_1 a distance l_2 apart from each other and of height U_b is straightforward. Some results are shown in Fig. 5 for $l_1=l_2=0.1$ μm and $U_b=0.5$ meV. The period of 0.2 μm was chosen from Ref. 8 and the value of U_b is a reasonable one. The calculated transmission-coefficient exhibits a band structure from which the first two gaps and the first two minibands are shown in Fig. 5. Within each miniband, as a result of the finite extent of the periodic lattice, there are fifteen peaks in the transmission, reflecting the discrete states of the fifteen dots. These results are again in good qualitative agreement with those found in experiments and numerical calculations.[8]

In summary, we have presented transmission calculations for electrons in 1D channels using a simple resonant-tunneling model. These calculations give a general and surprisingly good explanation of the oscillatory behavior in the conductance of submicrometer semiconductor devices observed in recent experiments. One important feature remains unclear, namely, the conductance behavior in the presence of a magnetic field. Beenakker and van Houten[9] argue that one dimensionality can only be achieved with a magnetic field, since only the highest-index edge channel has an appreciable backscattering probability, and that this would be an important reason why Kouwenhoven *et al.*[8] did not observe any band-structure effect at zero magnetic field. On the other hand, the lack of observation of spin splitting in the Si samples has been used against the resonant tunneling model.[1] However, it is not clear how the gyromagnetic factor depends on the magnetic field and on the carrier density for these samples and no result has been presented for the GaAs samples so far.[2,4] For all these reasons, our purpose here is to provide some results which could give us an understanding of a complex phenomenology in its simplest form. Actually, resonant tunneling has been widely used to explain a great number of different experiments on electronic transport, and its transparency seems to have been lost in the Coulomb-blockade and charge-density-wave models.

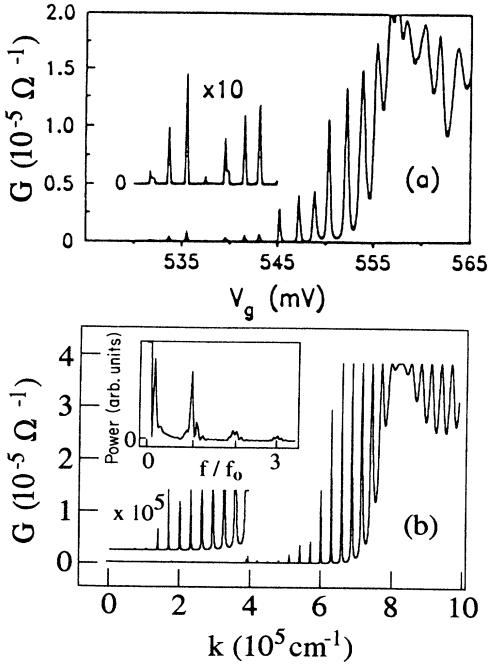

FIG. 4. (a) Measured conductance as a function of the gate voltage, from Ref. 2, and (b) calculated conductance for a double barrier structure as described in the text. The insets show the corresponding power spectrum and an expansion of the sharp peaks close to the onset of oscillation.

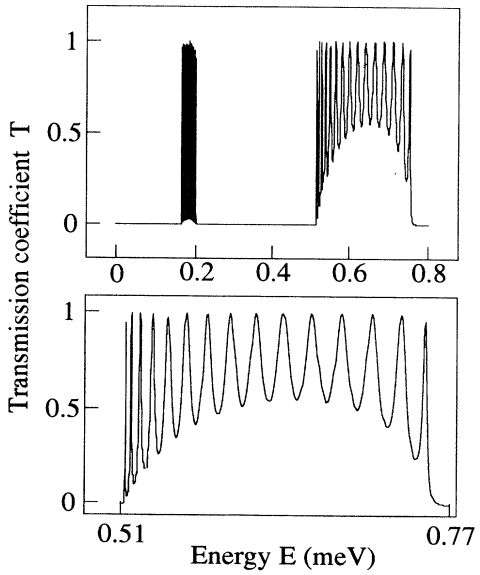

FIG. 5. Transmission coefficient T vs energy E for the potential profile shown in 1(b), for a chain of sixteen barriers (fifteen dots). The lower panel shows an expansion of the energy range corresponding to the second miniband, exhibiting fifteen maxima in the transmission.

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