ELECTRON TRANSPORT IN QUANTUM DOT STRUCTURES

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Abstract

We investigate the quantum transmission of an electron through quantum dot structures using the waveguide-matching technique. The conductance shows peaks and dips as energy is varied due to resonances through zero-dimensional levels. The effects of scattering from a disorder potential is examined using the transfer-matrix technique. If a lead is connected to the quantum dot region through a thin insulating film, the tunneling current leaking out the barrier gives a spectroscopy of quantum states in the cavity region. In a four terminal geometry, the resonances induce a large fluctuation in the energy dependence of the bend resistance.

Introduction

Quantum mechanical effects on transport properties of electrons in GaAs-AlGaAs microstructures have attracted much attention in recent years. If an electron is confined in a small box, the electron motion is quantized in three spacial directions. The transmission coefficients show sharp features when the Fermi energy coincides with the zero-dimensional (0D) levels. In this paper, we investigate the resonant properties in the electron waveguide structures.

The electron waveguide devices are decomposed into a set of uniform waveguide sections. The wave functions in each section, which are described in terms of a superposition of standing wave solutions of the Schrödinger equation, are matched across the boundaries between adjacent waveguide sections. We have calculated the conductance of multi-lead quantum dot structures by means of the Landauer-Büttiker formula [1,2].

Two-Terminal Conductance

We consider the following confinement potential in a wire region ($|x|<L/2$, $|y|<W/2$) to simulate a quantum dot:

$$V(x,y) = V_B(x) + E_F\,[(|y| - y_0(x))/d]^2\,\theta[|y| - y_0(x)] + V_{HW}(y)\,, \qquad (1)$$

where $\theta(t)$ is a step function, defined by θ=0 for t<0 and θ=1 for t>0, and $V_{HW}(y)$ is a hard-wall potential defined by V_{HW}=0 for $|y|<W/2$ and $V_{HW}=\infty$ for $|y|>W/2$. We assume that $y_0(x)$ and $V_B(x)$ are given by

$$y_0(x) = \begin{cases} (W/4)\,[1 + \cos(4\pi x/L)]\,, & L/2>|x|>L/4\,, \\ 0\,, & |x|<L/4\,, \end{cases} \qquad (2)$$

$$V_B(x) = (U/2)\,[1 - \cos(4\pi x/L)]\,. \qquad (3)$$

The potential is divided into N_x=32 segments in the longitudinal direction and the overall transmission is evaluated using the transfer-matrix technique. For each segment, waveguide modes are described in terms of a linear combination of the eigenmodes in the prefect leads, and then a transfer matrix is defined which relates the amplitudes of the left-hand side waves to right-hand side waves. The matrix for the entire system is found by cascading these matrices.

The conductance of the quantum dot is shown in Fig. 1 as a function of the height U/E_F of $V_B(x)$. One can see resonance peaks superposed on the quantized conductance plateaus. In the weak coupling limit [3], the resonance energies approach the 0D levels in an isolated quantum dot. The resonances can be specified as shown in Fig. 1, where (n,m) denote the quantum numbers for a square box in the longitudinal and transverse directions, respectively. The wavefunction is symmetric (antisymmetric) for odd (even) quantum number. Therefore, the resonant states (1,1) and (2,1) only couple with the evanescent modes in the constriction, while the resonant state (1,2) couples with both the propagating and evanescent modes. The resonance appears as a peak if the coupling between the 0D state and a wide lead is dominated by the evanescent modes. On the other hand, if the coupling through the propagating modes becomes dominant, the resonance appears as a dip. Hence, one expects that the resonance (2,1) is sensitive to an impurity, which breaks the symmetry of the potential. In Fig. 2, the examples of the effect of (a) short- and (b) long-range impurity potentials on the resonances is shown as the strength of disorder is increased for a particular impurity configuration. The peak (2,1) turns to a dip or is broadedned in energy as disorder is introduced, while the peak (1,2) only weakly depends on disorder. We also find that the conductance at the plateaus is suppressed below the quantized values for the short-range disorder, while it remains well quantized for the long-range disorder (not shown).

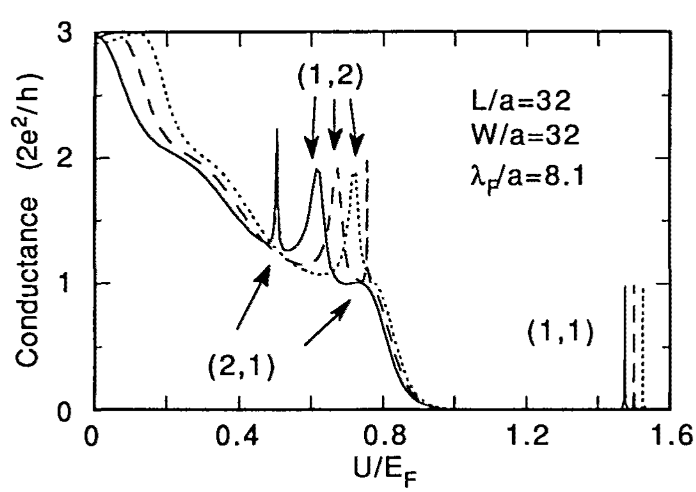

Fig. 1. Conductance of the quantum dot. The solid, dashed, and dotted lines are for d/a=7.7, 8.1, and 8.5, respectively.

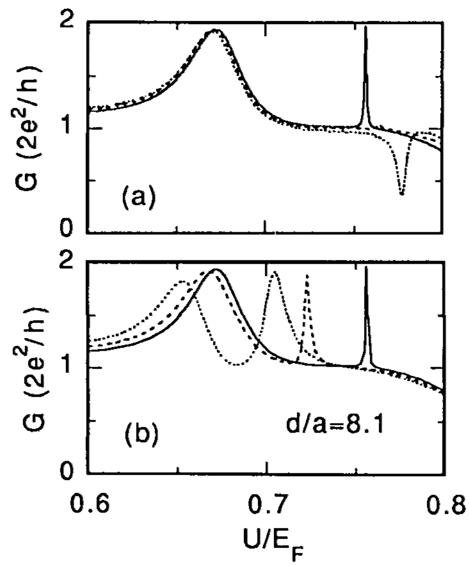

Fig. 2. Random potential correction is increased for dashed and dotted lines. Solid line: no impurities.

Three-Terminal Conductance

A tunneling current leaking out a thin wall of the waveguide can provide useful information on the density of states of the channel. The tunneling probability in a geometry illustrated in Fig. 3 is plotted in Fig. 4 as a function of the energy for L=W. We assume a hard-wall potential for the waveguide and a uniform potential step is assumed in the shaded area (d=0.1W) in Fig. 3 as a tunneling barrier. The solid (dotted) line represents transmission probabilities when an electron is injected through the lowest (first excited) mode in the wire. One can see peaks in the tunneling probability T_S coinciding with the dips due to resonances [4] in the transmission probability T_F. through the main channel The nearly perfect reflection in T_F due to resonances has been found to be robust against the presence of impurities even though the position of the dip in energy is sensitive to the scattering [5]. Increasing the coupling to the side-lead, however, moves the minima in T_F at the resonance away from zero and the resonances are broadened in energy. The coupling to the additional lead may be regarded as inelastic scattering, since the cavity region is subjected to a contact reservoir which is assumed to be in local equilibrium and electrons are absorbed in the reservoir without being reflected [6]. The tunneling probability is insensitive to the subband thresholds in the narrow wire, so that the tunneling current measurement may provide clear evidence of the presence of the quasi-bound states in the mesoscopic structures.

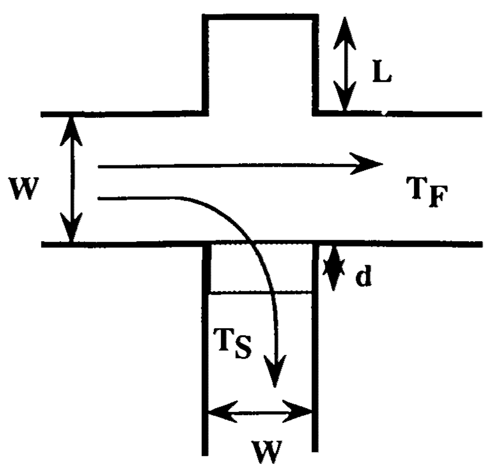

Fig. 3. A schematic illustration of a model geometry.

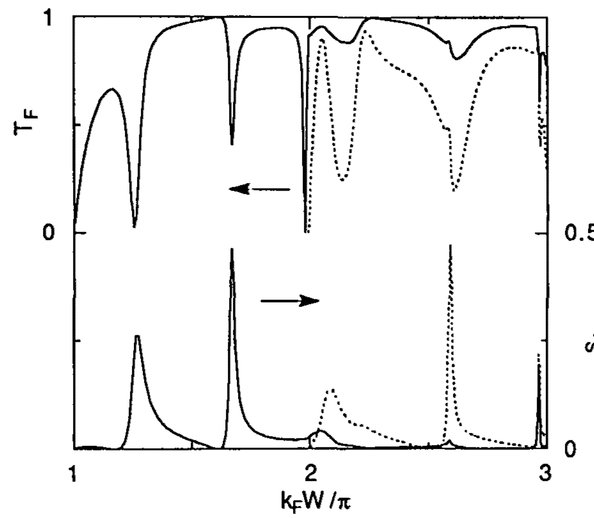

Fig. 4. Tunneling spectroscopy of a quantum resonator.

Four-Terminal Conductance

In a crossed-wire junction, the wires gradually widen approaching the junction. The quasi-bound states in the rounded junction induces a rapid oscillation of the transmission probabilities as the width of the channel is varied. We consider the effect of the rounded geometry in its simplest form and assume hard-wall confinement for the waveguide potential. Figure 5 shows the forward transmission probability T_F in a cross junction, where a box region with width D, is placed at the intersection of the wires (see the inset of Fig. 6). With increasing D/W, T_F is increased due to the collimation effect [7]. If the electron transport is nearly adiabatic, the transverse mode number is conserved when passing through a gradually widened wire. The lower-lying modes, which have a larger longitudinal momentum component, are preferentially occupied and hence the electron motion is collimated into the forward direction. As D/W is further increased, strong mode mixing occurs at the abrupt junction. The phase accumulation during the multiple reflections in the box region induces a large fluctuation. This can be interpreted in terms of the resonances through the quasi-bound states in the cavity region, which split off from one of the evanescent modes in the wire region as seen in Fig. 5.

In Fig. 6, we show the bend resistance R_B as a function of the number of modes in the wire. The bend resistance is defined as a four-probe measurement of the cross junction, where two adjascent leads at right angles are used for current and the other two leads are used as voltage probes [8]. In terms of the Büttiker formula [2], R_B is given by

$$R_B = -\frac{h}{e^2} \frac{T_F - T_S}{4\, T_S\, (T_F + T_S)} . \tag{4}$$

If the electron transport is ballistic, the transmission probability in the forward direction T_F is larger than that to turn the corner T_S, and thus R_B is negative [8]. Since the voltage difference is measured at nearly the same point, R_B is usually expected to be almost zero and positive. If D=W, the oscillation in T_F and R_B as $k_F W/\pi$ is varied solely arises from the subband thresholds in the narrow wire [9]. However, a large fluctuation is superposed when $D>W$ due to the junction resonances [10,11].

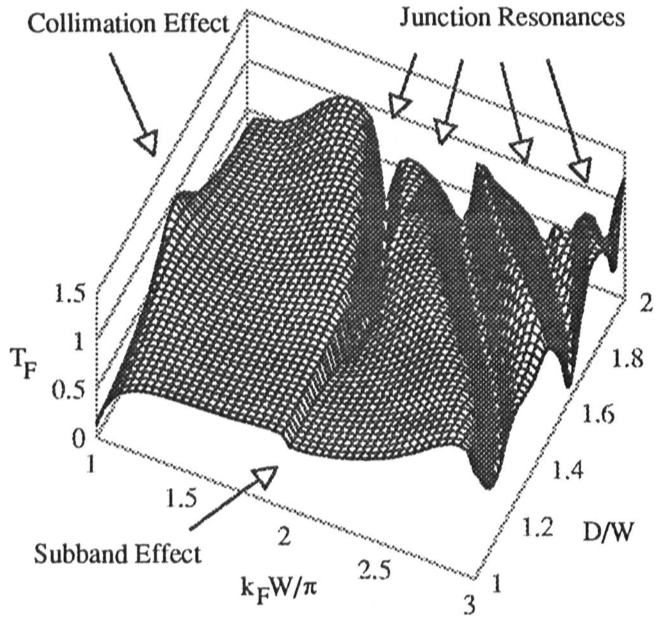

Fig. 5. Forward transmission probability in the crossed wire junction with the box region.

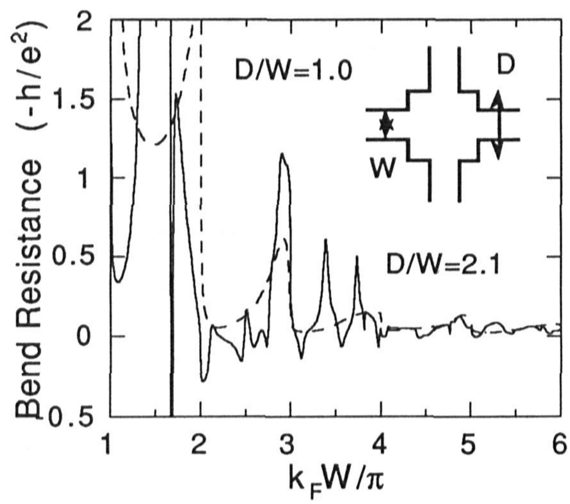

Fig. 6. Bend resistance in a junction with and without the presence of the box region.

Summary

We have presented the results of simulations on multi-terminal cavity structures. The transmission coefficients are evaluated by means of the waveguide-matching technique. We are able to include a smooth waveguide geometry and arbitrary confinement potential in the simulation using the transfer matrix technique. The quasi-bound states formed in the cavity region have been shown to induce significant effects on the quantum mechanical transmission in the waveguide structures.

Acknowledgments

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