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SUPPRESSION OF BALLISTIC ELECTRON TRANSMISSION THROUGH A SEMICONDUCTOR Π-STRUCTURE BY AN EXTERNAL TRANSVERSE ELECTRIC FIELD*

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We have conducted numerical studies of ballistic electron transport in a semiconductor Π-structure when an external transverse electric field is applied. The device conductance as a function of electron energy and the strength of the transverse electric field is calculated on the basis of tight-binding Green's function formalism. The calculations show that a relatively weak electric field can induce very large decrease in the electron transmission across the structure. When the transverse electric field is sufficiently strong, electrons can hardly be transported through the device. Thus the performance of the device can be greatly improved for it is much easier to control electron transport through the device with an external transverse electric field.

PACC: 7320D; 7340

I. INTRODUCTION

Since the quantized conductance was first observed in point contact structure[1-2], the interference effects in mesoscopic systems have attracted a great deal of interest.[3-9] Especially with recent progress in nanometer-scale lithography and atomic-layer epitaxy, it is possible to fabricate the structures in the size below the phase coherence length of the electron wave. In these mesoscopic systems, the electron transport is ballistic[3] and the systems can be regarded as quantum waveguides.[4] In the ballistic regime, the Fermi wavelength of the incoming electrons is comparable to the characteristic size of the device, so that quantum mechanical analysis is necessary.

In order to investigate the possibility of realizing electronic devices that are directly based on quantum interference effects, the semiconductor T-structure transistor has been proposed by Fowler[5] and Datta.[6] To control the electron transmission across the structure, a method proposed by Sols *et al.*[7] is to apply an external gate voltage that modifies the penetration of the electron wavefunction in a lateral stub. Instead of tuning an electron current, the device switches on and off by changing the related phase of the electron waves leading to a very high switch speed. Their calculations have shown that relatively small changes in the stub length can induce strong variations in the electron transmission. As can be seen from their results, it is easy to let electrons transmitted through the structure while it is

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difficult to switch off the transistor. Because of the high value of the intrinsic resistance of a single channel ($\approx 25\,\mathrm{k}\Omega$), one should stack many quantum modulated transistor structures in a superlattice. If we take the layer-to-layer fluctuations into consideration, the transistor cannot work perfectly. So we should resort to other methods if we want to control the electron transmission more effectively.

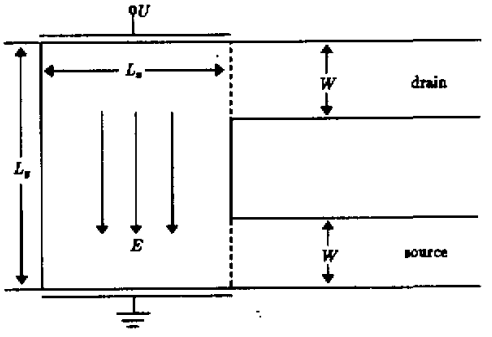

Fig. 1. Schematic view of Π-shaped structure on which an external transverse electric field is applied. The widths of the two perfect leads are W, lateral length is L_y and longitudinal length is L_x.

In this paper we present a method to control the electron conduction. Via the external transverse electric field applied on the structure, the electron transmission through the device can be controlled by the electric field which modifies the potential in the structure. We take a Π-shaped structure as an example to illustrate the effects of an external transverse electric field. The structure we have adopted is schematically shown in Fig. 1. An external electric field is applied on the structure except for two perfect semi-infinite leads.

II. THEORETICAL MODEL AND NUMERICAL METHOD

The effects of the electric field on the conductance are studied numerically within a tight-binding lattice model,

$$\widehat{H} = \sum_{\boldsymbol{R}} \varepsilon_{\boldsymbol{R}} |\boldsymbol{R}\rangle\langle\boldsymbol{R}| + t \sum_{\boldsymbol{R},\boldsymbol{d}_R} |\boldsymbol{R}\rangle\langle\boldsymbol{R}+\boldsymbol{d}_R| \,, \tag{1}$$

where each site $\boldsymbol{R}$ is connected to its nearest neighbors $\boldsymbol{R}+\boldsymbol{d}_R$. The hopping matrix element is given by

$$t = -\frac{\hbar^2}{2m^* a^2} \,. \tag{2}$$

For sufficiently small lattice constant a, this model can describe a continuum system with effective mass m^* very well. The guiding potential and the potential induced by the external transverse electric field are included in the form of $\varepsilon_{\boldsymbol{R}}$

$$\varepsilon_{\boldsymbol{R}} = -4t + V_c(\boldsymbol{R}) + V_{ex}(\boldsymbol{R}) \,, \tag{3}$$

where V_c is the guiding potential and V_{ex} is the transverse electric potential. The boundaries of the device are assumed to be hard walls so that the potential V_c vanishes in the device, and otherwise $V_c = \infty$.

The transmission amplitude t_{nm} and the reflection amplitude r_{nm} for the incident electron of the transverse mode m can be evaluated by the recursive Green's function (RGF) method, where n and m refer to the lateral modes in the two leads. The transverse modes in the region where a transverse electric field exists are modified and should be calculated first. Then the Green's functions in the region can be obtained. Using the recursion procedure[7-14], the Green's function of the structure can be calculated numerically. Via the relation between the Green's function and the S matrix for scattering in the leads[10], one can obtain the relevant amplitudes. The conductance G can be calculated by the two-probe multichannel Landauer-Büttiker formula[12,13]

$$G = \frac{2e^2}{h} T_r(tt^\dagger) . \tag{4}$$

In the numerical calculations, we choose the parameters $m^* = 0.067m_e$ (the value in GaAs) and $L_y = 3W$. Throughout all the calculations, we set the temperature $T = 0$.

III. RESULTS AND DISCUSSION

To check our results, we have compared our results with those in Ref. [11]. No significant discrepancy is found between our results and theirs when the transverse electric field does not exist. We have also calculated $|t_{nm}|^2+|r_{nm}|^2$, which should be unity by current conservation. In the results presented here, the maximum deviation from this expectation is about 10^{-6}. Throughout the calculations we limit ourselves to the single-mode regime, in which electrons can only propagate along the two leads in the fundamental transverse mode.

For several different values of the electric field intensity, we have calculated the conductance for the Π-structure with a longitudinal length $L_x = W$. The results are shown in Fig. 2. Without the transverse electric field, the conductance is given by the solid line. For the relatively low and very high intensities of the electric field, the results are given by the dashed line and dot-dashed line respectively. For energy below the first threshold, there is no propagating states, and thus the conductance is identically zero. When there is no applied transverse electric field, we can see two peaks which are due to the resonant transmission through the quasibound states. When the transverse electric field is present, even at low intensity, the conductance for almost all values of electron energy decreases abruptly. Except several sharp peaks, the conductance is well below 0.04. These peaks are due to tunneling through the quasibound states induced by the transverse electric field. As can be seen from these results, the device are switched off for most electron energies by the applied transverse electric field. At very high intensity of the transverse electric field, the conductance almost vanishes except one resonant peak. From Fig. 2, we find that the electron transmission is suppressed by an external transverse electric field.

In order to illustrate the effects of the transverse electric field on electron transmission more clearly, we have calculated the conductance with $L_x = W$ at a given electron energy $k_F \cdot \omega/\pi = 1.28$ as a function of the electric field strength, as shown in Fig. 3. In the absence of electric field, the conductance is at its peak value of unity. When the electric field intensity increases slightly, the conductance decreases very steeply. As the electric field strength further increases, several sharp peaks with decreasing amplitudes appear. Except these resonant peaks, the conductance is well below 0.04 as the electric field intensity is greater than 130 kV/cm.

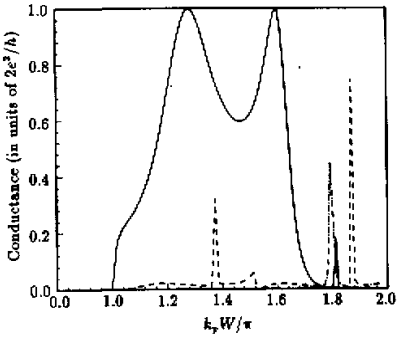

Fig. 2. Conductance G (in units of $2e^2/h$) vs $k_F W/\pi$ with the longitudinal length $L_x = W$ for several different values of the electric field strength: $E = 0$ (solid line), $E = 167$ kV/cm (dashed line), $E = 1000$ kV/cm (dot-dashed).

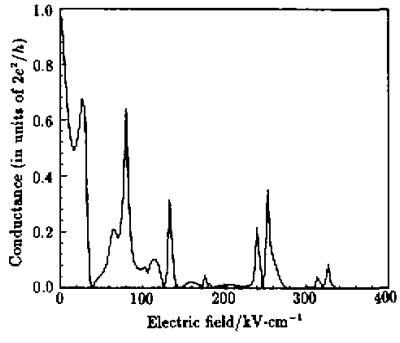

Fig. 3. Calculated conductance G (in units of $2e^2/h$) as a function of electric field strength (in units of kV/cm) for $k_F W/\pi = 1.28$ and $L_x = W$.

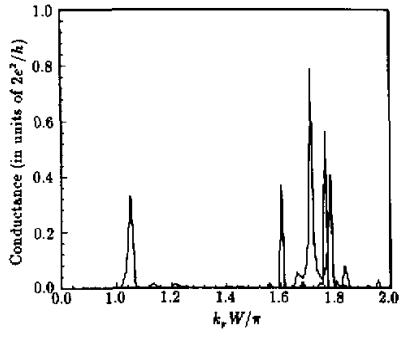

Fig. 4. Conductance G (in units of $2e^2/h$) vs $k_F W/\pi$ with the longitudinal length $L_x = L_y$ for two values of the transverse electric field strength: $E = 0$ (solid line), $E = 266$ kV/cm (dashed line).

For several different values of the transverse electric field strength, we have calculated the conductance for the Π-structure with different longitudinal length ($L_x = 3W$) to illustrate the effects of the longitudinal structure on the electron transmission. For two values of the electric field intensity, the results are shown in Fig. 4 in solid line and dashed line respectively. The resonant peaks look sharper than those in Fig. 2. Both in Fig. 4 and Fig. 2, for the high intensity of the transverse electric field, the number of peaks is less than that for the low intensity. As can be found from the two figures, even the transverse electric field of very high intensity cannot quench the electron transmission completely though the conductance almost vanishes for most values of electron energy.

From the results shown above, we see that the effects of an external transverse electric field on electron transmission are remarkable. When a transverse electric field is applied on the structure, the conductance features are no longer dominated by the scattering from the sample boundaries, instead they are strongly dependent on the transverse electric potential. In this case the structure supports more quasibound states above the first threshold. So the dependence of conductance on electron energies or the transverse electric field strength exhibits more resonant peaks.

IV. CONCLUSION

In conclusion, using the recursive Green's function method, we have investigated the effects of an external transverse electric field on ballistic electron transmission through a Π-shaped structure. For different values of the longitudinal length, the conductance as a function of the incident electron energy and the transverse electric field intensity has been calculated. We find that the effects of the transverse electric field are remarkable even at low intensity. The electrons cannot be transported through the device except those with energies corresponding to resonant peaks when the transverse electric field is strong enough. We believe that the electron transmission through the device can be controlled very easily and effectively by using this technique.

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