Electron transport in quantum wires and its device applications

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Electron transport in quantum wires and its device applications

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Abstract. The electron transport properties in quantum wires are investigated in the ballistic region and the hot-electron region by solving the Boltzmann equations. In the ballistic region, the effect of the scattering due to the surface roughness of a quantum wire on the conductance quantization is studied, and it is made clear how the scattering at the surface roughness destroys the conductance quantization. In the hot-electron region it is shown that the optical-phonon scattering plays an important role in the electron transport, and two types of transport take place as a result. One is electron confinement in a energy region below the optical-phonon energy and the other is electron velocity runaway. With these characteristics the possibility of a velocity modulation field effect transistor is suggested. Finally, a quantum wire resonant tunnelling transistor, which works as a kind of multichannel rotational switch, is proposed. As an application of this transistor, a switch for a superconducting interconnection network on which signals can propagate without attenuation and distortion is proposed to reduce the number of interconnection lines and also to simplify the circuit configuration.

1. Introduction

In semiconductor quantum wires with their cross-sectional length of the order of an electron wavelength (~ 10 nm), electron energies are quantized and quantum subbands are formed. As a result the electron transport properties in quantum wires are expected to be considerably different from those in bulk semiconductors. Thus, novel electron device applications are expected using these quantum transport properties.

In a quantum wire whose length is smaller than the elastic scattering length of the electrons, the conductance is known to be quantized with the value of approximately $2e^2/h$ at low temperature [1, 2]. This phenomenon can be understood on the basis of the ballistic motion of electrons confined in a quantum wire, and is expected to be sensitive to the shape of the wire or to the roughness of the wire surface. Most of the experimental wires are fabricated by focused ion beam implantation or a combination of electron beam lithography and dry etching for the GaAs/AlGaAs heterojunction structure. Thus it is probable that the atomic-order roughness or crystal damage is introduced on the surface of the wires. In the first part of this paper we study the effect of the scattering due to the surface roughness on the conductance quantization by solving a Boltzmann equation.

A quantum wire whose length is larger than the elastic scattering length of the electrons has been predicted to have an excellent low-field electron mobility exceeding 10^7–$10^8\,\mathrm{cm^2\,V^{-1}\,s^{-1}}$ at low temperature [3]. At high electric fields, on the contrary, the optical-phonon scattering plays an important role for the electron transport in a quantum wire. We have studied the electron transport in a quantum wire at low temperature by using computer simulation [4]. The simulation shows that two types of transport take place as a result, that is electron confinement in an energy region below the optical-phonon energy and electron velocity runaway [5]. In the second part of this paper we show the simulation result, and discuss the possibility of a velocity modulation field effect transistor with a quantum wire channel.

In quantum wires or quantum boxes the density of states has sharper peaks at the quantized energy levels than do the quantum wells. Thus, the resonant tunnelling current through the quantum wires or boxes is expected to show a larger peak/valley ratio in the current-voltage characteristics. In the final part of this paper we discuss possible applications of resonant tunnelling transistors [6, 7] where double-barrier structures are formed for a two-dimensional electron gas in GaAs/AlGaAs heterojunction field effect transistors by the field effect of external Schottky dual gates. Here, we propose a transistor working as a kind of multichannel rotational switch and its application to a switch for a superconducting interconnection network where the communications are made between multiple-input and -output terminals by signals. The resonant tunnelling transistors are introduced to reduce the number of interconnection lines and also to simplify the circuit configuration.

2. Ballistic electrons in short quantum wires

We study the electron motion confined in a quantum wire by an infinite potential. We assume that the wire,

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with a length L and width W, is connected adiabatically to the wide regions of two-dimensional electron gas. The wide regions work as reservoirs. The wire is assumed to be narrow enough for the electron motion in the cross-sectional directions to be quantized, and also to be short enough for electrons to go through the wire almost ballistically. The temperature is assumed to be zero for simplicity. When a voltage V is applied between the reservoirs electrons move from one reservoir to another owing to the difference between the chemical potentials $\mu_1 - \mu_2$ $(=eV \ll E_F)$, and be scattered by the surface roughness on the way.

Here, we introduce distribution functions $f_i^+(x, k_x)$ and $f_i^-(x, -k_x)$ for the electrons moving in the ith quantum subband with longitudinal wavenumber k_x from the reservoir 1 to 2 and vice versa. Let the number of occupied subbands be M. The Boltzmann equation for electrons in the ith subband can be expressed as,

$$\frac{\hbar k_x}{m^*}\frac{\partial f_i^+}{\partial x} = a_{ii}[f_i^-(1-f_i^+) - f_i^+(1-f_i^-)] + \sum_j^M b_{ij}(f_j^+ - f_i^+) + \sum_j^M c_{ij}(f_j^- - f_i^+).$$

The parameters a_{ii}, b_{ij} and c_{ij} represent the surface roughness scattering rates, and can be evaluated by an expression in [8] with a root mean square of wire width fluctuation Δ and a correlation length Λ of the width fluctuation along the wire. These equations are solved under the boundary conditions of

$$f_i^+(x, k_x) = 1 \quad \text{at } x = 0 \quad \text{for } i = 1\text{–}M$$
$$f_i^-(x, k_x) = 0 \quad \text{at } x = L \quad \text{for } i = 1\text{–}M.$$

With these distribution functions, the current flowing in the wire can be expressed as,

$$J = \frac{2e^2 V}{h}\sum_{i=1}^{M}(f_i^+ - f_i^-)$$

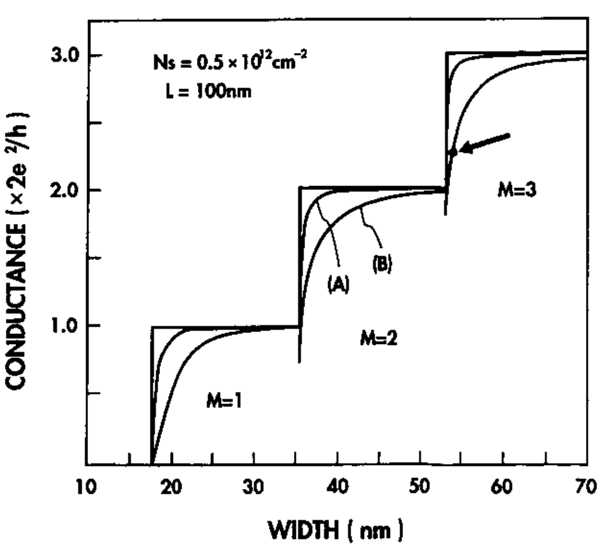

Figure 1. Calculated conductance of a ballistic quantum wire plotted against the width. The wire is formed in GaAs/AlGaAs heterostructures. The curves (A) and (B) correpond to $\Delta = \Lambda = 1.4$ and 2.8 nm, respectively.

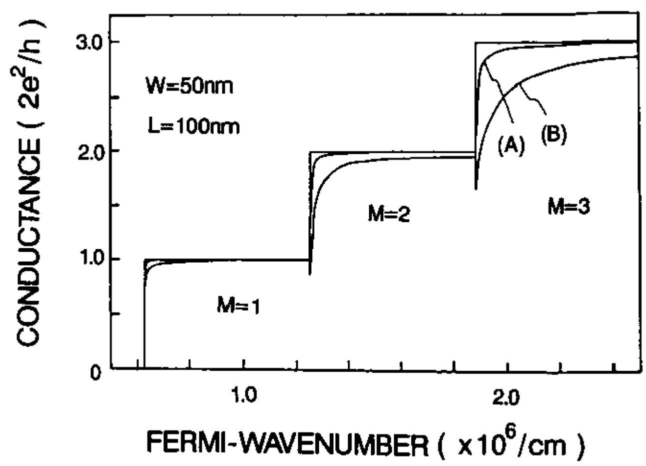

Figure 2. Calculated conductance of a ballistic quantum wire plotted against the Fermi wavenumber k_F. The wire is formed in GaAs/AlGaAs heterostructures. The curves (A) and (B) correspond to $\Delta = \Lambda = 1.4$ and 2.8 nm, respectively.

If the electrons in all the subbands can move in the wire completely ballistically, the distribution functions for backscattered electrons f_i^- becomes zero, and the conductance is completely quantized.

Figure 1 shows the calculated conductance of a wire plotted against the width. We have assumed here that the wire is formed in GaAs/AlGaAs heterostructure. The wire is 100 nm long and the sheet density, N_s, of the two-dimensional electron gas is 5×10^{11} cm^{-2}. The curves (A) and (B) correspond to $\Delta = \Lambda = 1.4$ and 2.8 nm, respectively. With the increase of Δ, the quantization of the conductance becomes incomplete, the steps become rounded and a sharp dip appears at each step edge position.

Figure 2 shows the calculated conductance of a wire plotted against the Fermi wavenumber k_F. The wire is 100 nm long and 50 nm wide. We can see that the deviation from the ideal step function becomes smaller with the decrease of k_F. This is because the occupied subband number M is smaller for smaller values of k_F, and the resulting number of possible states to be scattered becomes smaller, resulting in weaker scattering. It is also because the surface scattering rate for electrons with smaller values of k_F becomes smaller due to a smaller amplitude of the wavefunction near the surface.

Figure 3 shows the spatial variation of the distribution functions for a quantum wire with the parameters pointed out by the arrow in figure 1. We can see that the electrons in the highest-order subband are strongly scattered at the surface and more than half of them are backscattered to the reservoir 1. This is because the scattering rate for electrons in the highest-order subband is large owing to the divergent nature of the state density of the one-dimensional electron gas, and also because the electrons in the highest-order subband have a small momentum in the longitudinal direction and are scattered many times at the surface as they pass through the wire.

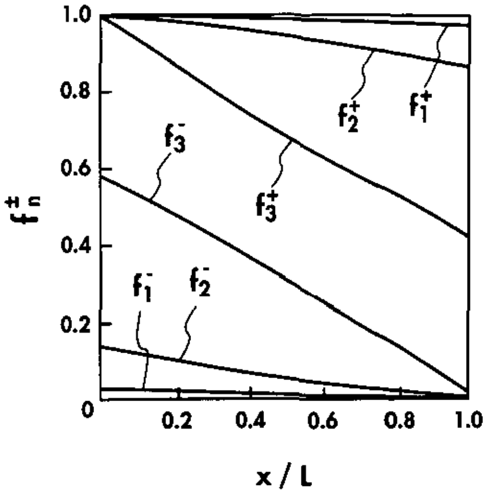

Figure 3. Spatial variation of the distribution functions for a ballistic quantum wire.

3. Hot electrons in long quantum wires and their applications to devices

At high electric fields the electrons in a quantum wire undergo strong optical-phonon scattering and the electron transport properties become considerably different from those at low fields. The optical-phonon scattering rate has an energy dependence shown schematically in figure 4. It diverges when electrons have a kinetic energy corresponding to the optical-phonon energy δ and decreases with an increasing electron energy. These features are attributed to an energy dependence of the state density of the one-dimensional electron gas. The electron transport in a quantum wire at high electric fields has been studied by solving a time-dependent Boltzmann equation with a collision term that results from intersubband and intrasubband optical-phonon scattering [4]. The calculations show that two types of transport occur, depending on the electron line density and the field strength. One is electron velocity runaway, which results from the scattering rate decreasing as the electron energy increases. This occurs when the electron density in a quantum wire is large and the Fermi energy at equilibrium exceeds δ. The other is electron confinement in an energy region below δ, owing to strong optical-phonon scattering at the energy region around δ. This occurs when the electron density is small and the Fermi energy at equilibrium is smaller than δ and the electric field is small, such that electrons are hardly allowed to have kinetic energies above δ owing to the strong scattering at the energy region around δ.

Figure 5 shows the calculated result for the drift velocity of electrons in a quantum wire as a function of the electric field. The wire is assumed to be made of GaAs with a impurity line density of $10^5\,cm^{-1}$ surrounded by selectively doped AlGaAs. The cross section of the wire is 10 nm × 10 nm. The electron line density is assumed to be varied by the field effect of a Schottky metal gate on the AlGaAs and is represented by the Fermi energy at equilibrium in the figure. Electron confinement in an energy region below δ occurs for the Fermi energy of 0.3δ in a field of 10^2 to $10^3\,V\,cm^{-1}$, where the velocity increases slowly with the field. When the Fermi energy is 1.2δ electrons with energy above δ run away and the velocity increases monotonically with the field. Some electrons begin to populate the second subband at a field around $10^3\,V\,cm^{-1}$.

When the quantum wire is applied to a channel in a field effect transistor, the high electron velocity at high fields in addition to the excellent high mobility at low fields suggest that high performance can be achieved. Furthermore, the gate potential can modulate not only the electron density but also the electron velocity through the density variation as shown in figure 5. These features could result in a high transconductance g_m and

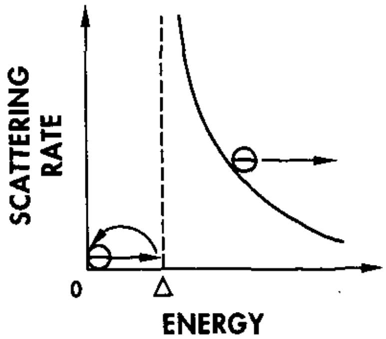

Figure 4. Schematic energy dependence of the optical-phonon scattering rate for electrons in a quantum wire.

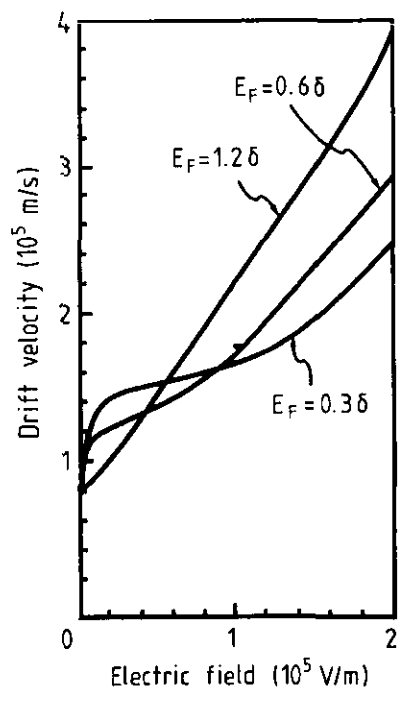

Figure 5. Electron drift velocity for a quantum wire plotted against electric field with an electron line density of the quantum wire varied. The cross section of the wire is 10 nm × 10 nm. The electron line density is represented by the Fermi energy at equilibrium.

also a high-cut-off frequency f_T of the transistors, as is shown by

$$g_m = \frac{dJ}{dV_G} = qv_d \frac{dn}{dV_G} + qn \frac{dv_d}{dV_G}$$
$$= C \frac{v_d}{l}\left(1 + \frac{n}{v_d}\frac{dv_d}{dn}\right)$$
$$C = ql \frac{dn}{dV_G}$$

where J is the current density, n the electron line density, v_d the drift velocity, C the line capacitance and V_g the gate voltage. Here, we can see that the term of $(n/v_d)dv_d/dn$ works as an enhancement factor for the drift velocity, and results in a higher transconductance and a higher cut-off frequency of the transistor.

4. Applications of quantum wire resonant tunnelling transistors

In quantum wires or quantum boxes the density of states have sharper peaks at the quantized energy levels than that do the quantum wells. Thus, the resonant tunnelling current through the quantum wires and boxes is expected to show a larger peak/valley ratio in the current–voltage characteristics. Quantum wire resonant tunnelling transistors have been proposed and fabricated by forming ultra-narrow Schottky metal dual gates on modulation-doped GaAs/AlGaAs heterostructures [6, 7]. In these transistors double barriers for the two-dimensional electron gas are formed by the field effect of the external Schottky dual gates. The spacing of the dual gate is of the order of the electron wavelength and the quantum subbands are formed. The resonant levels in the quantum wire surrounded by the double barriers can be varied by the gate voltage.

Here, we propose a quantum wire resonant tunnelling transistor working as a kind of multichannel rotational switch and its application as a switch in a superconducting interconnection network. Figure 6 shows a plan view of the transistor, which has single source and electrically isolated multiple drains (three drains D1 to D3 in this case). The spacing of the dual gate is varied spatially and a transistor sub-block with a single drain has different resonant values from each other. As a result the drain current flows sequentially from D1 to D3 by changing the on-resonant state and the off-resonant state mutually at each transistor sub-block when the gate voltage is varied monotonically. Therefore the transistor works as a kind of multichannel rotational switch.

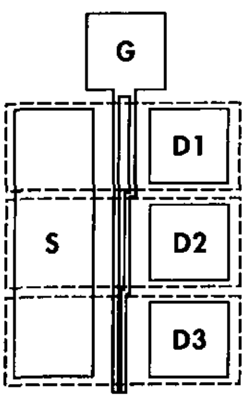

Figure 6. A plan view of the proposed quantum wire resonant tunnelling transistor. The transistor has a narrow Schottky dual gate whose spacing is spatially varied, and a single source and electrically isolated multiple drains.

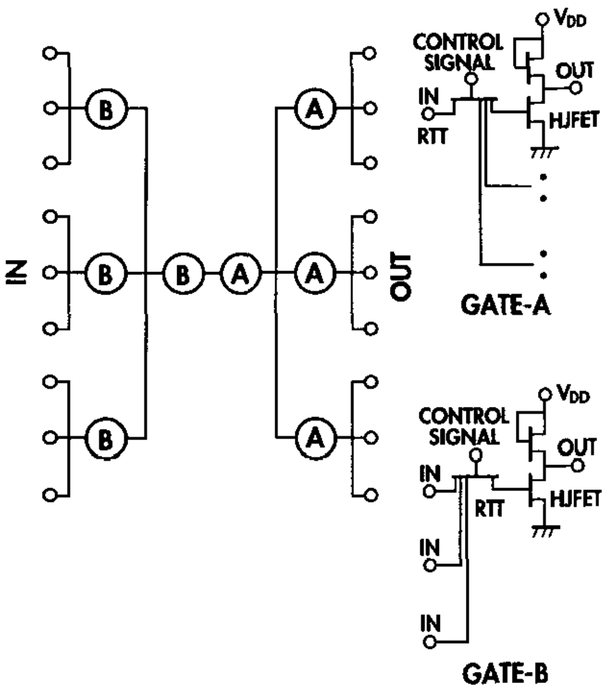

Figure 7. Superconducting interconnection network where a resonant tunnelling transistor is used as a functional transfer gate to switch the signal propagating on superconducting lines without attenuation and distortion. Two types of gates, A and B, are used to collect and to distribute the signals.

Figure 7 shows an application of the transistor where the transistor is used as a switch in a superconducting interconnection network. The circuit configurations of the switches are shown in the same figure. The resonant tunnelling transistor is used as a functional transfer gate to simplify the circuit configuration and also to reduce the number of interconnection lines. The transistor is integrated with ordinary heterojunction field effect transistors on the same substrate. The ordinary heterojunction field effect transistors operate as invertors to regenerate the signal with standard voltage levels. The signal can propagate on the superconducting lines without attenuation and distortion.

In the network two types of gates, A and B, are used. Gate A outputs the signal to one terminal selected among the three output terminals by adjusting the amplitude of the gate voltage. Gate B selects the signal on one terminal among three input terminals also by adjusting the amplitude of the gate voltage. Both gates utilize the resonant tunnelling phenomena to propagate the signal.

Thus, the signal in any input terminal of the interconnection network can be transmitted to any output terminal of the interconnection network by adjusting the gate voltage of the gates located between these two terminals.

5. Conclusions

We have studied the electron transport in quantum wires in the ballistic region and in the hot-electron region. In the ballistic region the effect of the scattering due to the surface roughness of the quantum wire on the conductance quantization has been studied and it has been made clear how the scattering at the surface roughness destroys the conductance quantization. In the hot-electron region it has been shown that the optical-phonon scattering plays an important role in the electron transport in a quantum wire, and two types of transport take place as a result, that is electron confinement and electron velocity runaway. The possibility of a velocity modulation field effect transistor using these characteristics has been shown. Finally, we have proposed a quantum wire resonant tunnelling transistor working as a kind of a multichannel rotational switch. As an application of this transistor a switch for a superconducting interconnection network has been suggested to reduce the number of the interconnection lines and to simplify the circuit configuration.

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