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Experimental Determination of the Conduction Width in Quasi Ballistic Wires

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Many works have been studied on the transport phenomena in split gate wires. However, it is difficult to find the beginning of quantization, for instance, when we change the mean free path of the propagating electron wave in the gate. In order to determine the actual conduction width of the wire region in the gate, we have studied an experimental determination of the conduction width in quasi-ballistic narrow wires constructed on the 2-dimensional electron gas system of GaAs/AlGaAs heterojunction.

1. Introduction

The conductance quantization in a quantum point contact is easily realized in a scale-controllable quantum wire with a split-gated confinement on the 2-dimensional electron gas (2DEG) system.[1,2] Many works in such wires have been studied on the transport phenomena in ballistic or quasi-ballistic regime.[3] When the mean free path ℓ of electron wave propagating in the wire is much longer than the wire scale, the split-gated wire behaves as a pure ballistic system and the conductance quantization occurs. When ℓ is shorter compared with the wire scale, on the other hand, the transport in the wire is diffusive (classical) and the conductance is not quantized but obeys the ohmic law. For practical, it would be difficult to find the beginning of the conductance quantization when we proceed from the classical transport regime to the quantized one by increasing ℓ.

The transport behavior is determined also by the conduction width of the wire. Thus, in order to find the boundary between the classical and quantum transport regimes, it is very important to determine the actual conduction width of split-gated wires. We consider that two types of the width determined at the both transport regimes does not agree with each other and that there may exist the crossover between the both regimes.

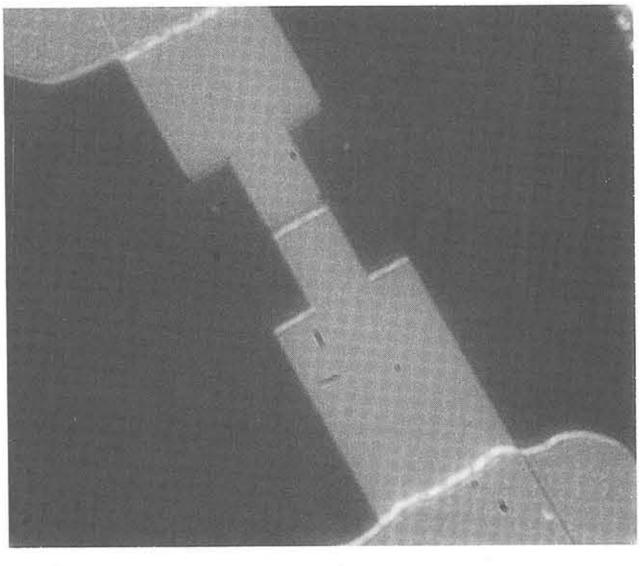

Figure 1. The top veiw of the split gate is shown in the SEM photograph. The designed gap and width of the gate are 0.6 and 6μm.

2. Experiments

The split-gated wires were fabricated on GaAs/AlGaAs wafers with a typical low-temperature mobilities μ=10~40m^2/Vs. The wafers were patterned into the Hall bar geometries with a width of 100μm and a voltage probe separation of 120μm. The sample lithographic length of the gates is ranged from 1 to 6μm. However, the lithographic gap between the gates was kept constant at 0.6μm and then the low-temperature transport was expected to be almost in the quasi-ballistic regime. The SEM photograph of the top view of the split gate for the 6μm length wire is shown in Fig.1.

The low-temperature magnetoresistance measurements were performed at 1.2K. In order to obtain a narrow quantum wire, a negative voltage was applied to the gates so as to deplete the region of a 2DEG underneath them. The carrier concentration of the wires was determined from the periodicity of the high-field SdH oscillations and is ranged from 3 to $7\times10^{11}\mathrm{cm}^{-2}$. The concentration is essentially independent of the applied gate voltage and also almost independent of the source-drain bias. As for a classical determination of the width, the effective conduction width of the wire could be calculated by assuming a uniform, gate-voltage-dependedent, depletion layer to exist around the gates and by associated the change in the channel resistance with a change in the width of this layer when the gate voltage varies. We can find the formation of the split-gated wire at the sharp resistance bend of the dependence on the gate voltage. The gate voltage and the resistance at the bending point on the formation of the wire weakly depend on the carrier concentration, mobility and the wire length. Since values of those parameters change consistently among each other in our study, we consider that the actual width at the bending point has a constant value close to 0.6μm of the designed width even at any slight change in our carrier concentration, mobility or wire length.

3. Results and Discussion

We can determine the two kinds of the conduction width of the wire, whose length scale is L, from the two different view points of classical (ohmic)[4] and quantum[1,2] concepts. In the first, as for the classical width W_c, we use the ohmic transport condition,

$$R_g = \rho\frac{L}{W_c} \quad . \tag{1}$$

Here, R_g is the gate resistance and ρ the resistivity of the wire, both of which are determined by the resistance measurement of the 2DEG region at the zero gate voltage. Under this ohmic transport condition, we obtain R_g from a small correction for the measured value of the resistance by considering the ratio of the gate area $W_c \cdot L$ to the rest area of the 2DEG region. Although L is the designed length, it does not differ largely from the practical value. By using Eq.(1), we can estimate W_c as shown in Fig.2, according to which W_c is almost constant around 0.5~0.6μm for $\ell/L\leq0.6$ and it decreases as ℓ/L increases above 0.6. The result that W_c is almost constant in the range of 0.5~0.6μm implies the validity of the above ohmic transport condition in the case of $\ell/L\leq0.6$. From Fig.2, it is also clear that those W_c can be scaled with ℓ/L even at different length from 1 to 6μm.

We assume here that the ohmic transport can be applied also near the crossover between classical and quantum regimes. Under this semi-classical assumption, the Drude conductivity σ is written by

$$\sigma = 2\pi\frac{e^2}{h}\frac{\ell}{\lambda_F} \quad , \tag{2}$$

where λ_F is the Fermi wavelength of electron wave. Since W_c is much larger than λ_F as in our wires, the channel number is roughly $2W_c/\lambda_F$ and then the channel conductance g per channel and per spin is given by

$$g = \frac{1}{4W_c/\lambda_F}\frac{W_c}{L}\sigma = \frac{\pi\,\ell\,e^2}{2L\,h} \quad . \tag{3}$$

Therefore, since we have $g\leq e^2/h$ near the boundary between the classical and quantum regimes, the maximum value of ℓ/L is given by

$$\left(\frac{\ell}{L}\right)_{\max} = \frac{2}{\pi} \simeq 0.64 \quad . \tag{4}$$

In Fig.2, a sudden decrease of the classical width W_c is found at $\ell/L\approx0.6$, which almost agrees with the value of $(\ell/L)_{\max}$.

Next, we determine the conductance width of the wire by using the conductance quantization. The quantum width (gate width) W_q of a point contact in 2DEG is given by

$$W_q = \frac{\lambda_F}{4R_g}\frac{h}{e^2} \quad . \tag{5}$$

If we can ignore effects due to the boundary scattering and the mixing between channels, the wire width does not deviate so largely from the value of W_q. In Fig.2, we show the value of W_q which was estimated by using Eq.(5). The width W_q increases as ℓ/L tends to 0.6, and it has a maximum value at the crossover $\ell/L\approx0.6$. Near the crossover, a similar increase of the width has been observed in the magnetic field dependence of the universal conductance fluctuations.[5] When ℓ/L becomes larger than 0.6, the width W_q has a sudden decrease down to 0.3μm. A simple analytic calculation for the quasi-one dimensional

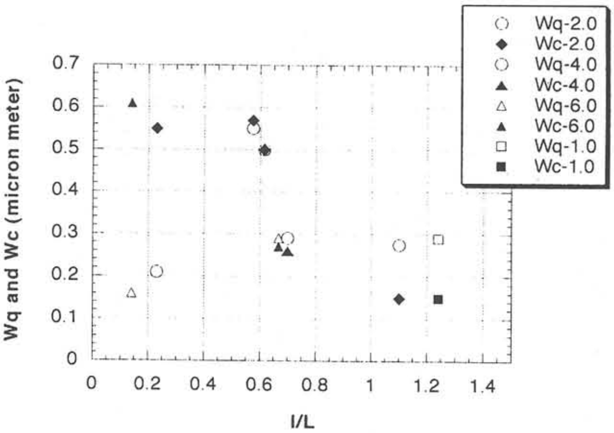

Figure 2. The W_q and W_c are plotted with opened and closed symbols, respectively. The designed length of the wire is indicated in the inset numerically together with its symbol.

transport with a finite scattering time in a confinement potential gives us the transmission probability of electron wave. Although a detailed discussion will be published later, we will show the results briefly as following.

In our wire system, the interference effect between propagating electron waves becomes more remarkable as ℓ/L increases. We consider that the propagating of electron wave can be decreased by the Schrödinger equation,

$$\left(\frac{d^2}{dx^2}+\frac{d^2}{dy^2}+k^2+i\frac{m}{\hbar\tau}\right)\Psi(x,y)=0 \quad , \qquad (6)$$

where $k=2\pi/\lambda_F$ is the wave number and τ is a finite scattering time. If we assume that the y-direction confinement is a hard wall potential located at $y\approx0$ and W_q, and that there exists no confinement in the x-direction, we can put the wavefunction $\Psi(x,y)$ into the form of

$$\Psi(x,y)=\sum_{n=1}^{\infty}\Phi_n(x)\sqrt{\frac{2}{W_q}}\sin\frac{n\pi y}{W_q} \quad ,$$

and then calculate the transmission probability.

The solution of Eq.(6) has a spatial dumping factor $\exp(-2k'|x|)$ when $|x|$ becomes sufficiently large, where k' is the imaginary part of k. At the crossover $\ell/L\approx2/\pi$, it is found that $k'\approx\sqrt{2k/\ell}$ From our experimental data around $\ell/L\approx2/\pi$, we can estimate the transmission probability and the calculated value is about 0.2μm. Since our experiments were performed in the conventional split-gated wires at T=1.2K, it is natural that the analytical calculation does not agree with the experimental measurement. In order to get more agreement between them, we must take account of the finite temperature effect in the analytical calculations. Nevertheless, we can consider the appearance of the peak of W_q in Fig.2 with the transmission probability. Considering the crossover $\ell/L\approx2/\pi$, the actual width of classical or quantum transport regime can be estimated by Eq.(1) or Eq.(5), respectively. However, we can not determine the width near the crossover more exactly because of a clear transition from classical two-dimensional to quantum quasi-one-dimensional transports.

4. Conclusion

We have observed a clear evidence on the crossover between classical and quantum transport in the estimation of the width of the quasi-ballistic split-gated wire. By decreasing the wire length L with keeping constant the wire width and the mean free path ℓ of electron wave, we can realize a clear dynamical change from classical to quantum behaviors in the two terminal measurement of the resistance. We have found that the crossover regime is given by $\ell/L\approx2/\pi$. Especially, near the crossover, we have observed a sudden decrease of the quantum width W_q. As we have discussed by using the quasi-one-dimensional Schrödinger equation, this effect is considered to be the result from two dimensional to quasi-one-dimensional transports. We also consider that those dynamical behaviors can be explained by taking account of the phase coherent region in the wire.

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