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## Nonlinear conductance of quantum wires normally pinched-off by surface potential

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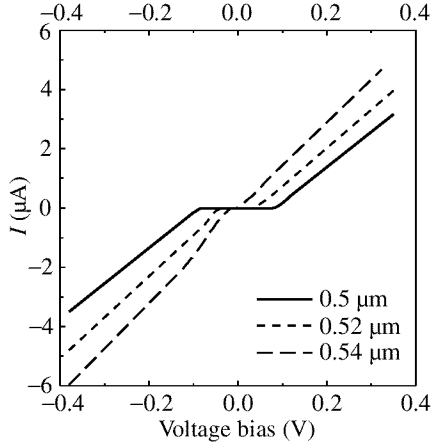
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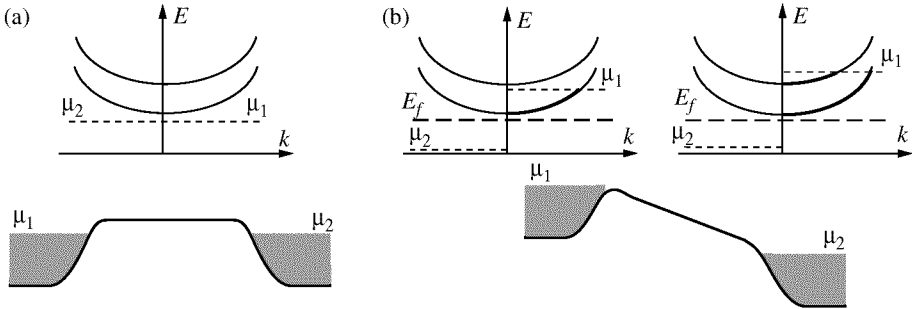
In this work the studies of the nonlinear transport in quantum wires patterned from wafers with a high mobility two-dimensional electron gas by means of E-beam lithography and following chemical etching are presented. The wires studied were normally pinched-off by surface potential under equilibrium conditions. Stepwise increase of the differential conductance  $g = dI/dV$  from zero to a approximately constant value  $G_0$  at a certain critical voltage  $V_c$  was detected. The critical voltage  $V_c$  and  $G_0$  dependence of the wire width was studied. This observation are similar to the findings of L. P. Kouwenhoven *et al.* [1] on quantum point contacts when they were slightly pinched-off by application of the appropriate split-gate voltage. Unexpectedly we also found the change of the magnitoresistance sign with the reverse of the magnetic field direction in the nonlinear conductance regime. It happened only when magnetic field was in the 2DEG plane and normal to the wire. The possible reasons of loosing the inversion symmetry point in the wires under high voltage biases are discussed. The wires with different lithographic width  $0.50 \mu\text{m}$ ,  $0.52 \mu\text{m}$ , and  $0.54 \mu\text{m}$  and  $0.8 \mu\text{m}$  length were fabricated from a GaAs/GaAlAs heterostructure with a high-mobility two-dimensional electron gas (2DEG) located  $100 \text{ nm}$  below the surface (the electron density  $N_{2D} = 3.1 \cdot 10^{11} \text{ cm}^{-2}$  at  $T = 4.2 \text{ K}$  with mobility  $1.4 \cdot 10^6 \text{ cm}^2/\text{Vs}$  corresponding to the mean free of  $9 \mu\text{m}$ ). In fact, the real width of the wire was about  $0.25 \mu\text{m}$  (determined from the scanning electron microscopy micro graph) when lithographic width was  $0.54 \mu\text{m}$ . It should be noted that surface depletion in our samples was about  $150 \text{ nm}$  from the wires sidewalls. Thus the parabolic quantum well was created in the wire with 1D quantization as the result.

Fig. 1 shows the  $I-V$  characteristics for samples with lithographic width  $0.5 \mu\text{m}$ ,  $0.52 \mu\text{m}$  and  $0.54 \mu\text{m}$ . All the measures are held at  $4.2 \text{ K}$ . All of our samples demonstrate a stepwise increase of the differential conductance  $g = dI/dV$  from zero to a approximately constant value  $G_0$  (various for all samples) at a certain critical voltage  $V_c$ . The critical voltage  $V_c$  increases strongly with decreasing of the lithographic width of the wires. Moreover, the value  $G_0$  shows evident correlation with the lithographic width of the samples—slightly increases with increasing width. Note that the  $I-V$  characteristics are not antisymmetric, and the critical voltage  $V_c$  is slightly different (about  $10 \text{ mV}$ ) for positive and negative bias.

It should be marked that critical voltage  $V_c$  and  $G_0$  after heating and following cooling down were slightly different. The degradation of our samples with the number of the temperature cycles led to slight  $V_c$  decrease and  $G_0$  increase.



**Fig. 1.** Current-voltage characteristics for samples with lithographic width  $0.5 \mu\text{m}$  (solid curve),  $0.52 \mu\text{m}$  (dotted curve),  $0.54 \mu\text{m}$  (dashed curve).

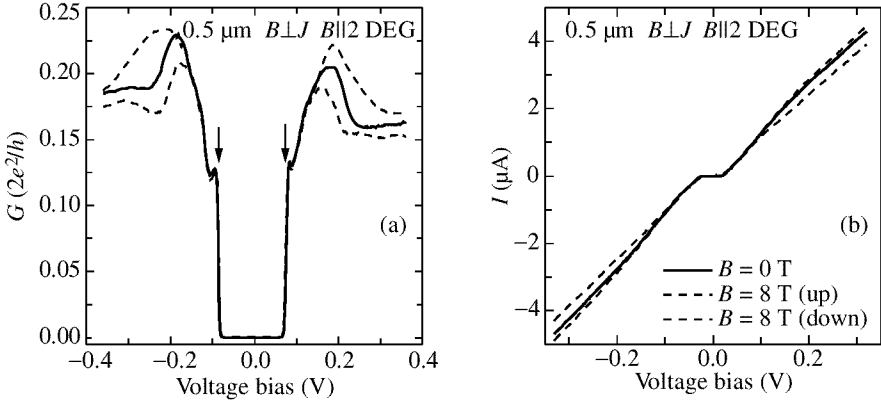


**Fig. 2.** Upper picture—subband occupation at the bottleneck in the absence (a) and in the presence (b) of the voltage bias. Lower picture—the schematic band diagram of our samples bottleneck in the absence (a) and in the presence (b) of the voltage bias.

To understand the main features in the  $I$ – $V$  characteristics we use a simple model following the work of L. P. Kouwenhoven *et al.* [1]. Fig. 2(a) shows the schematic zone structure of our samples at zero voltage bias. Due to the lateral confinement 1D subbands are formed. Apart from the lateral confinement, the surface depletion reduces the electron density in the wire. On entering the wire, in the absence of the voltage bias, the bottom of the 1-st subband rises relative to the bulk 2DEG Fermi level, as a combine result of the increased lateral confinement and electrostatic barrier.

In the presence of the voltage bias the bottom of the 1-st subband descending relative to the chemical potential in the emitter— $\mu_2$ . At the critical voltage bias  $V_c$  the maximum of the potential barrier, where the 1-st subband bottom has an energy  $E_1$ , occurs lower than  $\mu_2$ . Extrapolating an approach valid in the linear transport regime, following Kouwenhoven, the current is given by

$$I = \frac{2e}{h} [\mu_1 - E_1]$$



**Fig. 3.** Differential conductance of the samples with lithographic width  $0.5 \mu\text{m}$ , solid curve—without magnetic field, dotted and dashed curve—in the magnetic field 8 T (a). Current-voltage characteristics for the samples with lithographic width  $0.5 \mu\text{m}$ , solid curve—without magnetic field, dotted and dashed curve—in the magnetic field 8 T (b). For the dashed curves magnetic field is oriented in the 2DEG plane and normal to the wire, whereas for the dotted curves the direction of magnetic field was reversed.

and the conductance is given by

$$G = \frac{dI}{dV} = m \frac{2e^2}{h}.$$

Here  $m$  is a phenomenological parameter between 0 and 1, describing the fraction of total voltage  $V$ , which drops on the left of the bottleneck.

It should be noted, that according with calculation in our samples the distance between 1D levels is about 0.8 meV. Thus we can expect that even at voltages just slightly over the  $V_c$  there are a number of 1D levels lying under the chemical potential in the emitter— $\mu_2$ . So we can write, that at voltage bias, where the linear regime is approached the differential conductance is given by  $G = m \frac{2e^2}{h} n$ . Here  $n$  is the number of subbands lying under the  $\mu_2$ .

In Fig. 3(a) the solid curve shows the differential conductance versus voltage bias for the sample with lithographic width  $0.5 \mu\text{m}$ . One can see the local maximum close to the pinch-off voltage. At higher voltages the differential conductance reaches maximum ( $\approx 0.2 \frac{2e^2}{h}$ ), and then falls down to the constant value  $\approx 0.15 \frac{2e^2}{h}$ .

At the moment we can't explain the peaks on the curve of the differential conductance versus voltage bias. But we can propose, that at so high voltage bias (0.2 V) the real space transfer could be included into the consideration. Electrons get energy in the electric field and can be transferred from the quantum well into the AlGaAs modulated doped region above or below the 2DEG layer. For example, electrons can be transferred into the doped region close to the surface, where the electron mobility is smaller than for the electrons in the quantum well. Thus the differential conductance drops into the constant value.

The behaviour of our samples in the presence of a magnetic field is rather unexpected. In Fig. 3(b) the  $I$ – $V$  characteristics for the sample with lithographic width  $0.5 \mu\text{m}$  in the absence (solid curve) and in the presence (dashed and dotted curve) is shown. For the dashed curve the magnetic field is oriented in the 2DEG plane and normal to the

wire, whereas for the dotted curve—in the reverse direction. At low voltage bias near the pinch-off no magnetoresistance is detected. But at higher voltages, when the conductance reach maximum value, the magnetoresistance can be easily seen. As one can see the magnetoresistance change it's sign as the magnetic field change it's direction to the opposite. Besides this, the sign of the magnetoresistance depends of the current direction. The relative negative magnetoresistance is approximately 4%, whereas the positive is about 12%.

For magnetic field parallel to the wire the magnetoresistance does not change sign with reversing magnetic field direction.

At voltages, when the magnetoresistance is obvious, part of the electrons is out of the quantum well, and the transport is not one dimensional. Depending on its direction magnetic field (when perpendicular to the current and in plane of the 2DEG) shifts the maximum of the electron density in the real space up or down with respect to the surface. If the maximum of the spatial electron density located closer to the scattering centres the electron mobility decreases, the magnetoresistance is positive and *vice versa*.

Thus we have investigated the conductance of the quantum ballistic transport pinched off in equilibrium. Our data are explained by simple model of L. P. Kouwenhoven *et al.* The effect of magnetoresistance sign reversing with reversing the current flow or magnetic field direction in nonlinear region has been found.

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## References

- [1] L. P. Kouwenhoven, B. J. van Wees *et al.*, *Phys. Rev. B* **39**, 8040 (1989).