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Electronic transport through very short and narrow channels constricted in GaAs by highly resistive Ga-implanted regions

Y. Hirayama, T. Saku, and Y. Horikoshi
Nippon Telegraph and Telephone Basic Research Laboratories, Musashino-Shi, Tokyo 180, Japan
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Very short and narrow channels are fabricated by use of focused-ion-beam implantation into a $Al_xGa_{1-x}As/GaAs$ modulation-doped epilayer. The channels are constricted by highly resistive Ga-implanted regions. The electron transport experiments exhibited a prominent quantization of conductance characteristics, which is peculiar to ballistic transport through one-dimensional subbands. These quantized conductance characteristics are observed until the temperature is raised to approximately 10 K. In addition to the quantized conductance, large conductance fluctuations are observed at low temperatures.

Recently, extensive work has been done on the transport properties of one-dimensional wire structures.[1–5] When the wire length (L) is less than the elastic mean free path (l_e), a ballistic electron transport occurs through one-dimensional subbands and conductance is quantized at multiples of $2e^2/h$. Recently, van Wees and co-workers[6,7] and Wharam *et al.*[8] clearly demonstrated this quantized conductance using a separated metal-gate structure on top of a modulation-doped $Al_xGa_{1-x}As/GaAs$ epilayer. In their experiments, channel width, carrier density, and confinement potential all varied with gate voltage.

This Rapid Communication describes the fabrication of an extremely short and narrow channel structure by use of a highly resistive p-type region formed in an $Al_xGa_{1-x}As/GaAs$ modulation-doped structure by Ga focused-ion-beam (FIB) scanning.[9] This structure is equivalent to the quantum point contact proposed by van Wees and co-workers.[6,7] The electrical transport on this structure showed a prominent quantized conductance phenomenon caused by ballistic transport through one-dimensional subbands. Also observed was a conductance fluctuation at low temperature, which is probably caused by a quantum interference of electrons scattered in the short and narrow channel or reflected at the boundary between the one-dimensional channel region and the two-dimensional ohmic region.

The extremely short and narrow channel structure was fabricated as follows: The starting modulation-doped wafer had GaAs(Si-doped, 2 nm)/$Al_{0.3}Ga_{0.7}As$(Si-doped, 100 nm)/$Al_{0.3}Ga_{0.7}As$(undoped, 10 nm)/GaAs(undoped, 500 nm) structure on a semi-insulating GaAs substrate. The electron density (n) and mobility (μ) at 4.2 K were $n = 5\times10^{11}$ cm^{-2} and 1.4×10^5 cm^2/Vs, respectively. This relatively large electron density suppresses the lateral spread of the depletion layer and maintains an effective channel length (L_{eff}) with a small value. The estimated elastic mean free pass was $l_e = 1.6$ μm.

The scanning pattern of Ga FIB is shown in Fig. 1. The channel structure was fabricated by our scanning Ga FIB, whose diameter was about 100 nm, and leaving a space of W_s at the center. The nominal channel length was, therefore, about 100 nm which is denoted by L_s in Fig. 1. The implanted Ga dose was 2.5×10^{12} cm^{-2}. Following implantation, samples were annealed at 700 °C for 15 s. The Ga-implanted highly resistive region and the surrounding depletion region formed the potential barriers. The high resistivity induced by the Ga ion implantation was maintained even after annealing above 800 °C,[9] although implantation-induced crystalline damage was almost completely recovered in this annealing process. The lateral depletion region that spread into the channel region due to implantation-induced damage was, therefore, expected to be very small. Indeed, the lateral depletion region spreadings less than 300 and 30 nm were obtained with use of modulation-doped heterostructure wafers with original two-dimensional electron densities of $\sim10^{11}$ and $\sim10^{12}$ cm^{-2}, respectively. A long (1.4 μm) one-dimensional channel with effective width of 50 nm fabricated by this process showed the channel mobility of greater than 7×10^4 cm^2/s.[10] The confinement potential was approximately equal to the band gap ($\sim$1.5 V), because the resulting highly resistive region exhibited very weak p-type conduction.[9]

The conductance of the channels was measured as a function of W_s and is shown in Fig. 2. The measurement was performed under a constant dc current (10^{-8} A).

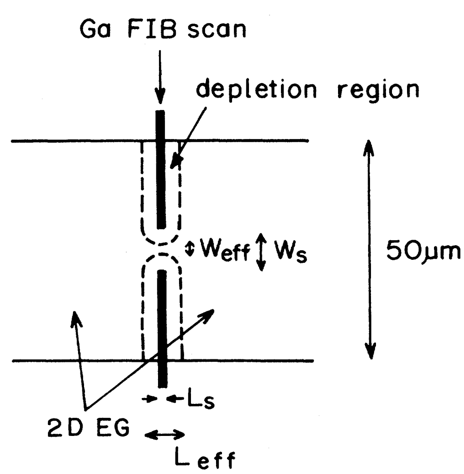

FIG. 1. Schematic diagram of FIB scanning. (2D EG denotes two-dimensional electron gas.)

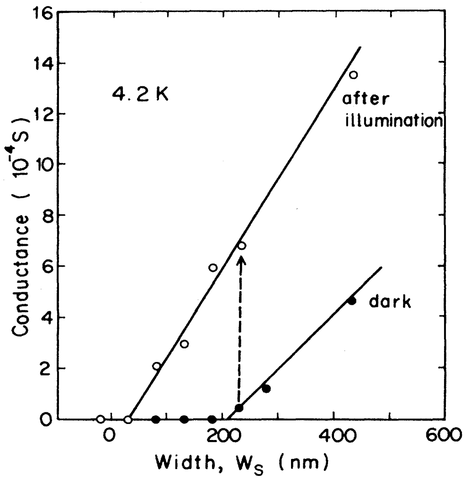

FIG. 2. Channel conductance as a function of structural width W_s. "After-illumination" data were measured in darkness after being illuminated.

Conductance data after illumination, which were obtained in darkness after illumination, are also shown in this figure. After illumination, there was a steady increase in the electron density ($n \sim 7\times10^{11}$ cm^{-2}) and a decrease in the lateral depletion region, increasing the effective width of the channel (W_{eff}) and conductance. The estimated lateral spread of the depletion region in darkness (before illumination) was 100 nm and after illumination was 25 nm. From these data and $L_s \sim 100$ nm, the effective channel length was estimated to be $L_{\text{eff}} \lesssim 300$ nm (before illumination) and $L_{\text{eff}} \lesssim 150$ nm (after illumination). Although the electron density and mobility in the narrow channel structure might slightly decrease during processing, ballistic electron transport is expected in this channel because of an extremely small L_{eff}.

The conductance variation of the channel when illuminated with a weak red light ($h\nu \sim 2$ eV) was measured, and the results are shown in Fig. 3. In this experiment, the electron density in the channel and W_{eff} increased with time along the broken line in Fig. 2. The measurements were performed with an ac current of 0.4 nA. The influence of background resistance was corrected in these figures. The measured conductance is indicated by the unit of the quantized value of $2e^2/h$. Conductance steps occurred near the quantized values ($2e^2m/h$, m is an integer). This implies that the number of one-dimensional subbands (m) contributing to the ballistic conduction increases with electron density and W_{eff}. Therefore, an observed steplike conductance change may correspond to the variation of the subband number. This phenomenon, as shown in the figure, was observed even when the temperature was raised to 10 K. This indicates that one-dimensional confinement remained up to approximately 10 K. As shown in Fig. 3(c), however, the conductance steps can be observed only for small m values at 10 K. This is because W_{eff} should be small for small m values. Therefore, more distinct one-dimensional characteristics can be observed for small m values.

It should be pointed out that marked conductance fluctuations were observed in the step regions at 1.5 K [Fig. 3(a)]. The amplitude of this fluctuation drastically decreases with temperature as $T^{-1.8}$. This temperature dependence is different from that reported for the universal conductance fluctuation (UCF) of wires.[4,5]

Magnetoconductance characteristics were also measured at steps of $m=2$, $m=4$, and $m=6$, and the results are shown in Figs. 4(a), 4(b), and 4(c), respectively. The measurement was performed after termination of the illumination at each step. Although a wire structure with a longer L_s ($L_s = 1.4$ μm) fabricated by the same process exhibited positive magnetoconductance,[10] the result shown in Fig. 4 indicates a strong tendency towards negative magnetoconductance. Figures 4(a) and 4(b) were measured at 4.2 K and Fig. 4(c) was measured at 1.5 K. The quantized conductance is also shown by broken lines in the figure. As reported previously,[1,7,8] the observed negative magnetoconductance can be explained by consideration of the depopulation of one-dimensional subbands under a magnetic field. For the magnetic field greater than 0.7 T in Fig. 4(c), Shubnikov–de Haas (SdH) oscillation was clearly observed. These magnetoconductance characteristics showed conductance fluctua-

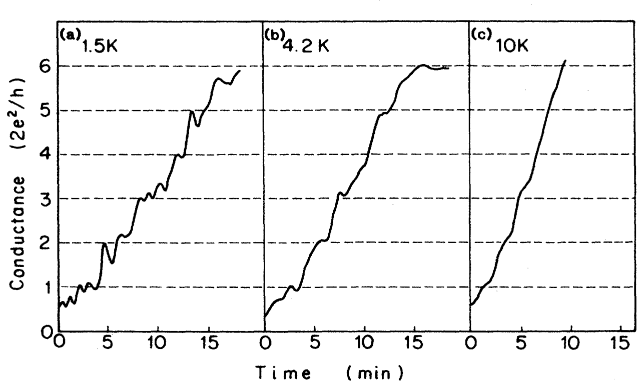

FIG. 3. Channel-conductance change during weak-light illumination at (a) 1.5 K, (b) 4.2 K, and (c) 10 K. Conductance is represented as the unit of the quantized conductance ($2e^2/h$).

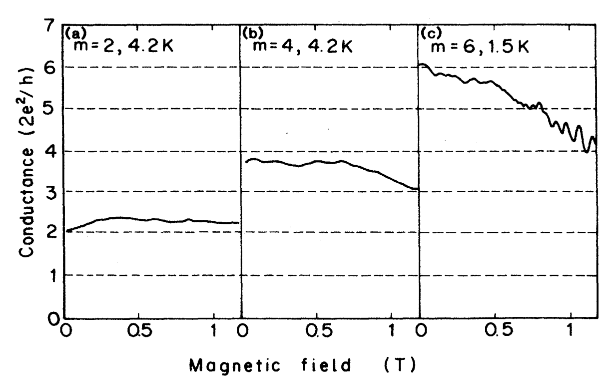

FIG. 4. Change of the channel conductance as a function of magnetic field. The zero-magnetic-field conductance was set at steps of approximately (a) $m=2$, (b) $m=4$, and (c) $m=6$. In (c) the SdH oscillation was observed in the region of $B \gtrsim 0.7$ T.

tions in addition to the magnetodepopulation effects. However, the amplitude of the fluctuation is smaller than that observed in Fig. 3, as clearly shown in the results measured at 1.5 K [compare Fig. 3(a) with Fig. 4(c)]. This result combined with the temperature dependence mentioned before suggest that the conductance fluctuation observed in Fig. 3 is different from so-called UCF.

The origin of this fluctuation is not yet clear. The first candidate is the quantum interference of electrons scattered by impurities or unintentionally formed structural disorders in the very short and narrow channel. The sizes of the channel are smaller than l_e (ballastic regime), so that, at most, very few impurities exist in the channel. Therefore, the present phenomenon may be caused by the fewer impurities in the channel. Indeed, Chang *et al.*[11] reported an anomalous quantum interference effect in the ballistic channel. The contribution of impurities in the transition regions on both sides of the channel is also conceivably due to the nonlocal impurity scattering effects. In addition, the shift of the conductance at the step region away from the quantized values is predicted from the recent theoretical calculation for the ballistic wire including impurities.[12] Therefore, the conductance fluctuation in Fig. 3(a) may reflect a repetition of electron trapping and detrapping at the impurity centers in the channel during weak red-light illumination.

Another hypothesis to explain the conduction fluctuation in Fig. 3 is the effect of electron wave reflection at the boundary between the one-dimensional short channel and the two-dimensional ohmic region. On the analogy of microwave or optical waveguide, the reflection effect becomes important when the de Broglie wavelength of a one-dimensional electron (λ) is larger than the length of a transition region between the one-dimensional channel and the two-dimensional ohmic region. This length is about 100 nm in the dark and about 25 nm after illumination in the present structure, as mentioned previously. Though the number of subbands below E_F is constant in the conductance-step region, $\lambda_n = h/[2m^*(E_F - E_n)]^{1/2}$ varies with E_F, where n and E_n indicate the one-dimensional subband number and corresponding subband energy, respectively. $E_F - E_n$ is less than a few meV in the highest one-dimensional subband, then λ_n becomes larger than the transition region length and the reflection effect could occur. If we take into account the reflection at both sides of the channel, transmission probability is equal to 1 under the condition of $\lambda_n \times (\text{integer}) = 2L_{\text{eff}}$. The transmission probability is less than 1 under different conditions. Therefore, the conductance probably fluctuates with its maximum at the quantized values according to the change of λ_n with E_F. Though the peak conductance of the observed fluctuation in Fig. 3 does not necessarily agree with $2e^2/h \times (\text{integer})$, the number of fluctuations will be explained by this hypothesis. Moreover, the subband structure modulation from one- to zero-dimensional-like may occur if the reflection effect becomes large.

In summary, transport properties of the extremely short and narrow channels constricted by Ga-implanted highly resistive regions have been studied. Quantized conductance characteristics and magnetodepopulation of one-dimensional subbands were observed in conduction measurements that were performed under light illumination and under a magnetic field. The quantized conductance characteristics were observed until the temperature was raised to approximately 10 K. In addition, large conductance fluctuations were observed, especially at low temperatures.

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