Single electron transport and current quantization in a novel quantum dot structure

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We report on single electron transport via a novel quantum dot structure fabricated by a combination of mesa etching and gate formation. In this device electrons are confined in an etched submicron wire and squeezed further by two barrier gates. The resulting dot is of a very small size, and the number of confined electrons can be tuned down to the few electron limit. This novel structure has a large charging energy and an improved current quantization during turnstile operation. In small dots, containing only a few electrons, we found Coulomb oscillations with an unexplained multiple peak structure.

Remarkable advances in microstructure fabrication technology have made it possible to control transport of electrons by fundamental constants of physics. The voltage quantization in Josephson junctions[1] and the resistance quantization in the quantum Hall effect[2] are two major examples, which now provide the voltage and the resistance standards, respectively.

In order to realize quantization of current, charging effects have been used to control current on a single electron level.[3] In metallic tunnel junction systems, external rf signals have been used to obtain a so-called turnstile operation.[4] In a turnstile device an integer number of electrons are allowed to tunnel per cycle of the rf signal. This controlled tunneling process is measured in current-voltage (I-V) characteristics as frequency-determined current plateaus.

The quantization of current has been also observed in a semiconductor quantum dot defined by split gates, where turnstile operation can be performed using barrier modulation.[5] This barrier modulation technique is actively employed to open and close the entrance and exit of the quantum dot for the one-by-one electron transport after setting the initial barrier profile at appropriate condition. However, the precision of the current quantization was actually of the order of a few percent. This was partly due to unwanted tunnel events which causes smearing or disappearance of the quantized current plateaus.

In this letter, we report on novel quantum dot structures fabricated by the combined techniques of mesa etching and gate formation, and describe single electron charging experiments. The number of electrons confined in the dot can be tuned down to less than 10, and an improved control of the barrier modulation is demonstrated by the observation of good current quantization during turnstile operation.

Figures 1(a) and 1(b) show the schematic illustration of a new quantum dot structure and its scanning electron micrograph. In Fig. 1(c) another sample geometry is also shown, where the dot is connected to four leads via tunable tunnel junctions. As for the sample shown in Fig. 1(b), a narrow wire structure with a width W_e=460 nm was defined by wet shallow etching[6] on a selectively doped n-$Al_{0.3}Ga_{0.7}As/GaAs$ heterojunction. The thicknesses of the undoped AlGaAs spacer layer, the n-AlGaAs doped layer, and the undoped GaAs cap layer are 30, 70, and 10 nm, respectively. The mobility and density of the two-dimensional electron gas (2DEG) in the unpatterned wafer were 80 $m^2/V\,s$ and 4.0×10^{15} m^{-2} at 4.2 K, respectively. The top 60 nm layer on the part of the heterostructure uncovered by electron beam sensitive resist polymethylmethacrylate (PMMA) was etched away in an etchant of H_3PO_4:H_2O_2(30%aq):H_2O=3:1:75 for 3 min. at 3 °C. The length of the narrow wire is 10 μm, beyond which it widens into large 2DEG regions. Ohmic contacts were made onto the widened portions by alloying In-Sn in an argon atmosphere at 400 °C for a few minutes. Due to the depletion of electrons at the edge region of the wire, the effective width of the conducting region is less than the geometrical width by roughly 400 nm.

Three gates with a width of 230 nm were fabricated by depositing locally NiCr (5 nm)/Au (50 nm) film with lift-off technique. The position of the gates were precisely aligned with respect to the etched wire [see also Fig. 1(c), where the gate alignment is in the two directions] by using an electron beam lithography system equipped with a backscattered electron detector and an elaborate moving stage with an interferometer for the precise control of the exposure location. Alignment marks on the wafer were made at the first stage of

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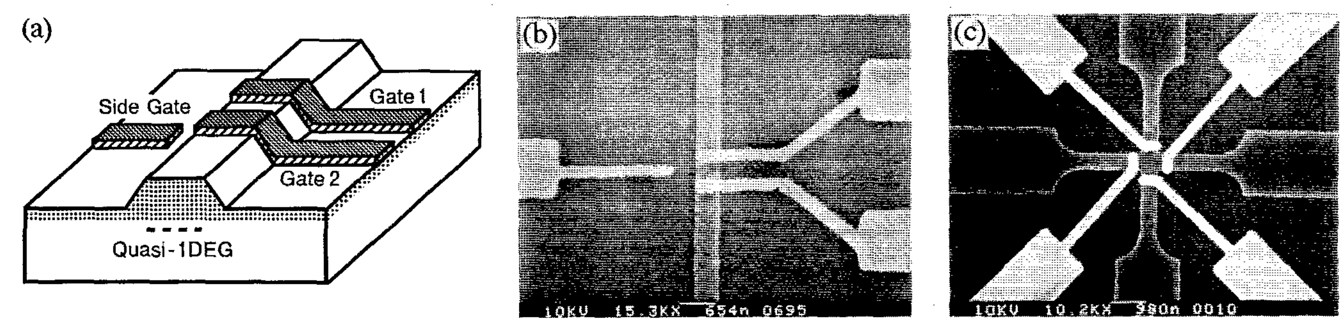

FIG. 1. A schematic illustration (a), and scanning electron micrographs (b) and (c) of two quantum dot samples.

the processing by wet chemical etching with their edges oriented along the crystal axis ⟨011⟩ and ⟨$0\bar{1}1$⟩ to allow a clear pattern definition using the crystal facets.

To induce two tunnel barriers in the wire and to form an isolated dot in-between, negative voltages were applied to the two barrier gates [gate 1 and 2; see Figs. 1(a) and 1(b)], which are separated by the distance W_g=330 nm. The dot between the gates can be isolated from or weakly coupled to the leads by adjusting the two tunnel barriers under the gates. This situation differs from the case of metal-insulator tunnel devices in which tunnel conductance are not tunable. The use of comparatively wide barrier gates (230 nm) on top of the wire allows us to control the tunnel conductance over a very wide range with only small changes in the gate voltage. This type of barrier can be changed with very little influence on the potential of the other barrier. This mutual influence or the cross-talk effect is much larger in conventional split gate devices. The side gate is employed to tune both the effective channel width and the electron density in the dot.

The conductance is measured at the device of Fig. 1(b) as a function of side gate voltage. Figure 2 shows the experimental result, where clear Coulomb oscillations[7,8] with very sharp peaks are observed with a period of 26 mV; each period corresponds to a change of one electron in the dot. We also observed a clear Coulomb staircase in the I-V characteristic.

We have performed turnstile experiments on the same device, where two out-of-phase rf signals with frequency f=10 MHz and an amplitude of about 5 mV are applied to gates 1 and 2 besides the dc gate voltages. The I-V characteristics measured in this manner are shown in the inset of Fig. 3, where all expected current steps are clearly observed. The magnitude of the steps is close to the electron charge times the frequency of rf signals ef=1.6 pA, which is in good agreement with the transfer of a precise integer number of electrons per turnstile cycle. The inset of Fig. 3 shows that unless rf signals are given, the current is virtually zero on a pA scale. This indicates that the barrier resistances are at least 500 GΩ. This condition minimizes unwanted tunnel events[5] including co-tunneling which limits the accuracy of the metallic structures.[4] However, from the slope of the current plateaus in the inset, it seems that the rf signals induce a conducting path which corresponds to a parallel resistance of 150 MΩ. This parallel path is most likely induced underneath the shallow etched region between the barrier and side gates. A deeper etch should be sufficient to suppress this parallel conduction.

If we correct the data for this parallel resistance, the current plateaus become even clearer as shown in the main part of Fig. 3. The observed plateaus agree very well with the predicted quantized values which are indicated by the dotted lines. The current steps achieved in this novel device are much more distinct than those obtained with split gate devices mainly because the smearing due to unwanted tunnel events is now strongly suppressed. The width ΔV of the plateaus in Fig. 3 reflects the charging energy: $e\Delta V = e^2/C = 1.7$ meV, which gives a total capacitance C=96 aF. This charging energy is a few times larger than obtained in previous split gate devices. This is due to the reduction both in dot size and in the amount of metal that can screen the Coulomb interaction in the dot. From the separation of the plateaus, we can estimate the electron charge $e=(1.602 \pm 0.006)\times 10^{-19}$ C. This accuracy, which is limited by the accuracy of the current measurement at present, is about as high as the best value achieved in four junctions metallic systems.[4]

Coulomb oscillations were studied in another device which is similar to that in Fig. 1(b) except its dimensions (W_e=640 nm, and W_g=120 nm). The results are shown in

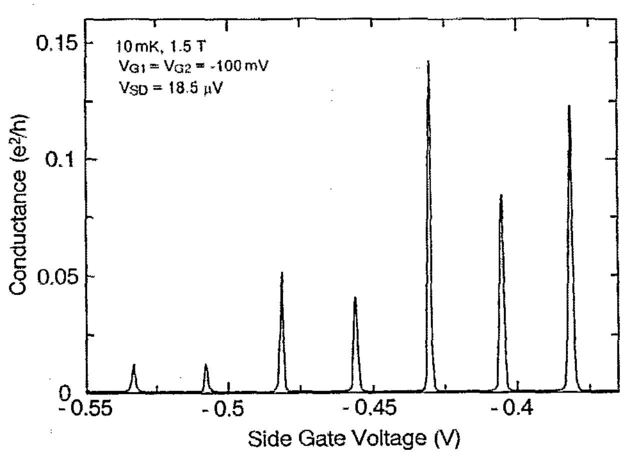

FIG. 2. Conductance vs side gate voltage V_{GS} of the sample shown in Fig. 1(b) measured at 10 mK for a source-drain voltage V_{SD}=18.5 μV and at a magnetic field of 1.5 T. Both of voltages on the gate 1 V_{G1} and gate 2 V_{G2} are set at −100 mV.

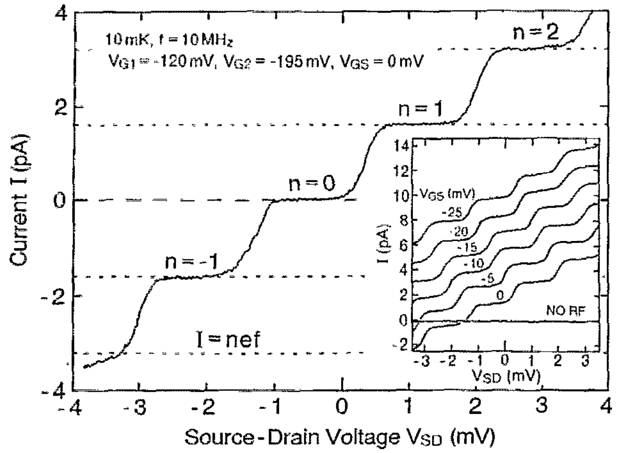

FIG. 3. Turnstile I-V characteristics measured at 10 mK with rf signals of $f=10$ MHz, where dc gate voltages on the gate 1 V_{G1} and gate 2 V_{G2} are set at -120 and -195 mV, respectively. Original data shown in the inset are obtained for various side gate voltages V_{GS} with and without rf signals, and the curves are offset for clarity. As a constant parallel resistance of 150 MΩ is present, it is subtracted to give a series of very clear steps of quantized current as shown in the main figure. The observed current steps correspond to $I=nef(=n\times 1.602$ pA, $n=$integer), which are indicated by dotted lines.

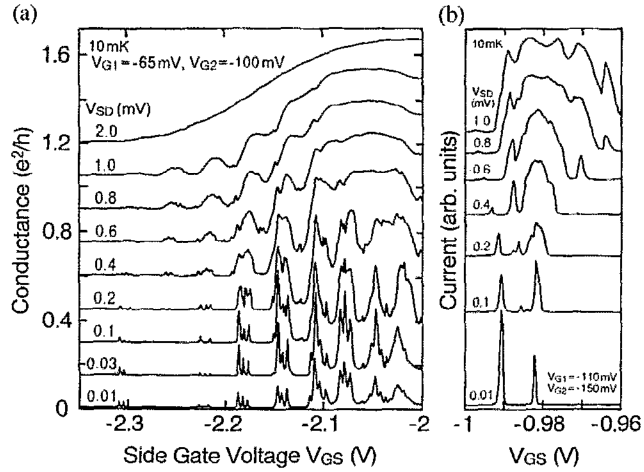

FIG. 4. The conductance of the dot sample measured at 10 mK as a function of side gate voltage V_{GS} at various source-drain voltages V_{SD} (a), where the wire width is 640 nm and the separation between gate 1 and 2 is 120 nm, and gate voltages on the gate 1 V_{G1} and gate 2 V_{G2} are set at -65 and -100 mV, respectively. The current of the same sample as a function of V_{GS} (b), where V_{G1} and V_{G2} are set at -110 and -150 mV, respectively. The curves in both (a) and (b) are offset for clarity.

Fig. 4(a) for various source-drain voltage V_{SD}. The traces show normal Coulomb oscillations with a period of 35 mV, but strikingly the oscillations in the lower traces show fine structure with a smaller period of typically 5 to 10 mV.[9] *While the Coulomb oscillations correspond to a change of one electron in the dot, the fine structure must represent extra structure in the energy spectrum.* The observed fine structure has minima going to zero for small V_{SD} but it gradually smears out at higher V_{SD}, resulting in only the normal Coulomb oscillations at $V_{SD}>0.4$ mV. Figure 4(b) shows a more expanded measurement but under different condition for gate voltages. In this figure one of the fine structure peaks at -0.991 V simply disappears on increasing V_{SD} while the other peak at -0.982 V evolves into a broad oscillation with even more structure. This last substructure is known to arise from the presence of zero-dimensional quantum confined states.[10]

From careful measurements of the conductance quantization and the pinch-off voltages for the different gates, we deduce that in this regime the number of electrons localized in the dot is less than ten. Transport through such a few-electron system has been reported also by Ford *et al.*,[11] who also observed extra structure, and by Weis *et al.*[12] The origin of the fine structure is not yet understood. We note, however, that in the few electron regime where the screening is strongly reduced, the electron distribution in the dot may become inhomogeneous, as correlations or potential fluctuations resulting from doped impurities may now become important. This could cause a break up of our quantum dot in a few smaller dots, each having its own electrochemical potential. Tunneling between the subdots does not change the total number of electrons in our quantum dot, but it can change the transport from being on to off resonance.

In conclusion, novel semiconductor quantum dot structures have been developed with improved single electron tunneling characteristics and also in turnstile operation. This new device scheme can induce smaller sizes and reduces screening of the Coulomb interaction.

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