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Single-electron counting statistics of shot noise in nanowire Si MOSFETs

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1. Introduction

Noises in electronic devices, such as Si MOSFETs, have been widely investigated from the viewpoints of their impact on device performances and circuit applications because they limit minimum operation current and thus lead to increased power consumption in integrated circuits. Among the various noises, shot noise is the most fundamental because it is caused by electrons, the exact origins of current, passing randomly through electric devices in the Poissonian process [1, 2]. In spectrum measurement, one of the familiar techniques for analyzing shot noise, it is likely that shot noise is hidden by other noises and that observed results are averaged behavior of individual electrons.

In this work, we demonstrate real-time monitoring of single-electron (SE) transport, i.e., shot noise, in a Si nanowire-MOSFET, which reveals shot-noise suppression in specified regimes of current characteristics of MOSFETs.

2. Device structure and principle

The fabricated device for real-time monitoring of shot noise is shown schematically in Figs. 1(a) and (b). The device is composed of nanowire Si MOSFETs for SE transfer (TTr) and detection (DTr) fabricated on a silicon-on-insulator wafer [3]. The TTr has a two-layer gate. The upper gate (UG) is used to invert the undoped channel of the TTr and thereby defines a source and drain electrically. The lower gate (LG) turns the TTr on and off as in a conventional MOSFET. Since the drain is terminated at the tip, or storage node (SN), of TTr's nanowire-channel, electrons transferred from the source, or electron reservoir (ER), are stored in the SN. The electrons transferred to the SN are detected as a change in current I_D flowing through the DTr, which is capacitively coupled to the SN, as shown in Fig. 1(d). Since the DTr has a tiny channel close to the SN, its charge sensitivity reaches 0.0017 $e/\sqrt{\mathrm{Hz}}$ even at room temperature [3].

3. Experimental results

Figure 2(a) shows electron injection from the ER to the SN through the TTr when lower-gate voltage V_{LG} was swept in a positive and then a negative direction. The electron injection was monitored as the change in the DTr current I_D. When V_{LG} was changed from -3 V and reached -2.4 V, I_D abruptly decreased because the TTr turned on and electrons entered from the ER to the SN. The subsequent reverse sweep of V_{LG} caused hysteresis in I_D because the TTr turned off at V_{LG} of -2.4 V and electrons were stored in the SN. The hysteresis in I_D indicates that 16 electrons were stored in the SN.

Figure 2(b) shows the time-resolved measurement of SE injection at fixed V_{LG}, which was a little lower than that causing the electron injection shown in Fig. 2(a). I_D decreased stepwise with the same height. This is proof that an SE, which entered the SN from the ER through the TTr, was detected as one step of I_D, owing to the high charge sensitivity of the DTr [3]. In other words, the DTr allows the real-time monitoring of shot noise in the TTr.

Such detection of SEs enables us to measure extremely small current, i.e., shot noise, of the TTr in the deep-subthreshold region, which cannot be detected by conventional ammeters. Figure 3(a) shows TTr current characteristics, which can be fully controlled using V_{LG}. Such high controllability is difficult in conventional MOSFETs due to various kinds of undesirable current leakage, mainly pn-junction leakage [4]. Our MOSFET makes it possible because the electrically formed source (ER) and drain (SN) of the TTr can eliminate pn-junction leakage [5].

Note that TTr current characteristics have temperature-dependent and temperature-independent slopes as respectively indicated by solid and broken lines in Figs. 3(a) and (b). This means that SE transport in the solid-line regimes is based on thermal-activated transport and follows the well-known theory of subthreshold current in the conventional MOSFET. On the other hand, SE transport in the broken-line regimes suggests single-electron tunneling through an energy barrier controlled by V_{LG}, which means that tunneling current can be observed only at extremely low current even in 20-nm-gate MOSFETs.

The time-domain analysis of electron injection in both regimes reveals SE transport based on the Poisson process, i.e. full shot noise, in the TTr. Histograms of time interval δt between each electron injection typically show an exponential decay, as shown in Figs. 4(b), (d), (e), and (g). The fact that the Fano factor, which indicates how ideally electron transport follows the Poisson process, were close to one as shown in Fig. 4(a) and its inset. These results mean that the electron transport is actually shot noise based on the Poisson process, which is theoretically natural.

Another noteworthy feature was that TTr current characteristics had a kink at V_{LG}, indicated by arrows in Figs. 3(a) and 4(a), where the slope of the current characteristics changed between the solid and broken lines, especially at 20 K. The time-domain analysis revealed that the Poissonian distribution was disturbed [Figs. 4(c) and (f)] at V_{LG} near the kink. The Fano factors at the kinks also became smaller than one at 20 to 300 K as shown in Fig. 4(a). These features mean that shot noise was suppressed at the kinks. Changes in the shape of the kink (Fig. 3) and δt distribution (Fig. 4) with change in temperature as well as in ER voltage (Fig. 5) mean that shot-noise suppression is intrinsic behavior in MOSFETs, where current flows in the specific regime between thermal-activated and tunnel-event transports, and that the thermal energy and shape of energy barrier between the ER and SN would be key factors in shot-noise suppression. Although the detailed mechanism of such shot-noise suppression is not fully understood, there are some possible models to explain it, e.g., such as Coulomb interaction and Pauli exclusion [6, 7].

4. Conclusions

Shot noise in the transport of single electrons in Si MOSFET is monitored with a real-time measurement using a high-charge-sensitivity electrometer. In the zept- and atto-ampere current characteristics, the current characteristics are found to be divided into two regimes: a temperature-independent regime in the lower current range and a temperature-dependent one in the higher current range. A time-domain analysis reveals that, for both regimes, the SE transport obeys a pure Poisson process with the Fano factor being nearly unity, while the Fano factor is reduced around the boundary.

References

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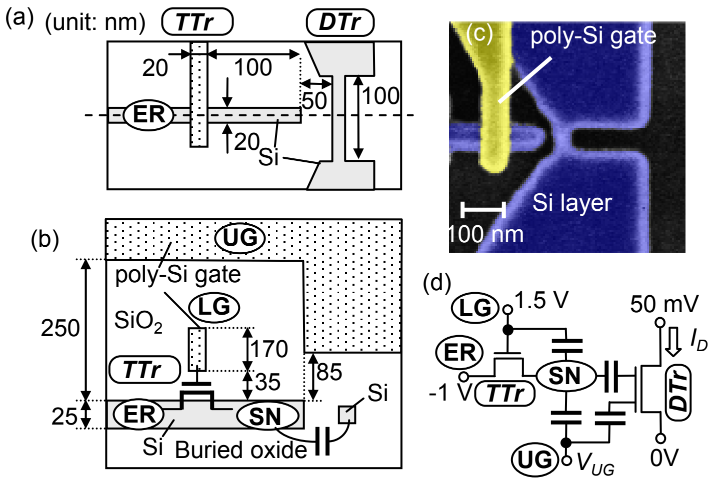

SN: Storage node
TTr : MOSFET for single-electron transfer
DTr: MOSFET for single-electron detection
LG/UG: Lower/Upper gate
ER: Electron reservoir

Fig. 1. (a) Schematic top view of the device that transfers single electrons and detects them in real time. The UG is not shown here. (b) Cross-sectional view along the broken line in (a). (c) Scanning electron microscope image. (d) Equivalent circuit. Voltages for all measurements, except for Fig. 5, are also shown.

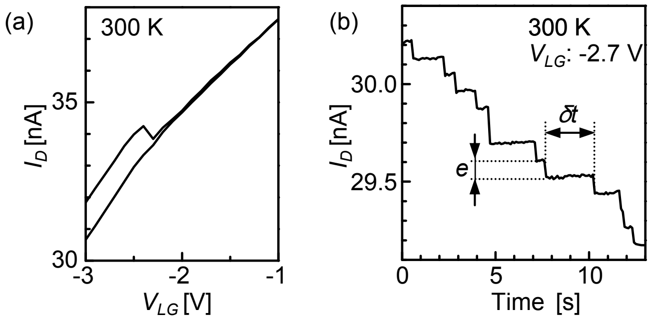

Fig. 2. (a) Electron injection into the SN by turning the TTr on and off. Before the measurement, all electrons in the SN were removed by opening the TTr and applying 2 V to the ER. (b) Single-electron injection into the SN, where δt is defined as the interval between each electron injection into the SN.

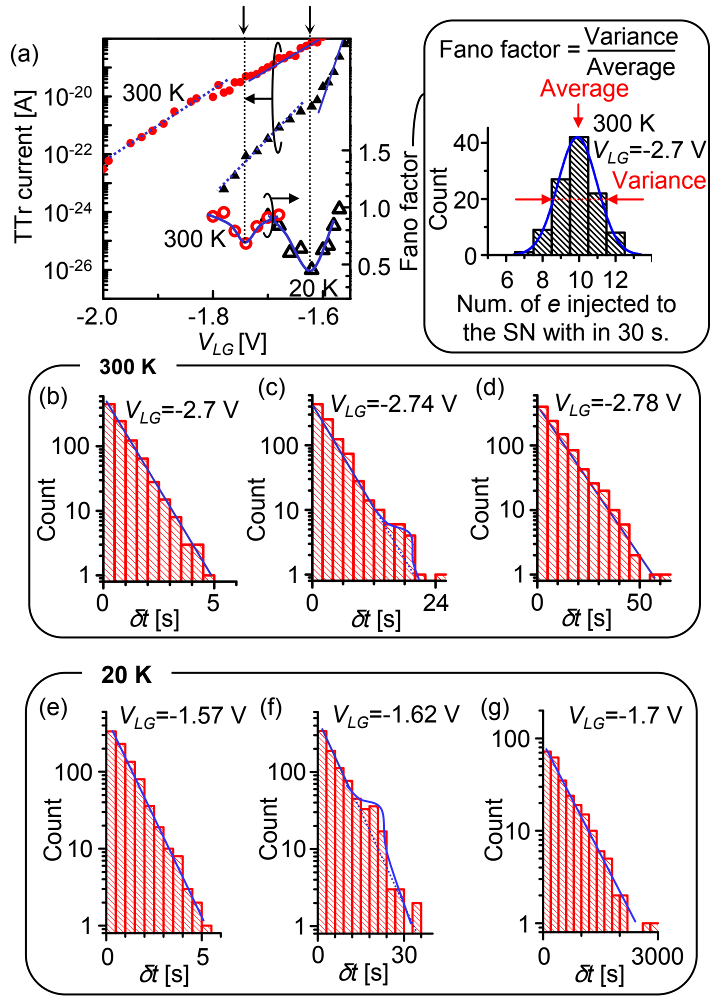

Fig. 4. (a) TTr current and Fano-factor characteristics as a function of V_{LG} at 300 and 20 K. For clarity, data at 300 K are horizontally shifted by 1 V. The Fano factor is defined as the ratio of the variance to the average of the number of electrons injected in the SN within a particular time as shown in the inset. (b-g) Histograms of time interval, δt in Fig. 2(b), between each electron injection in the SN at 300 and 20 K. respectively. V_{LG} for the histogram in (c) and (f) is indicated by arrow in the characteristics at 300 and 20 K, respectively, in (a).

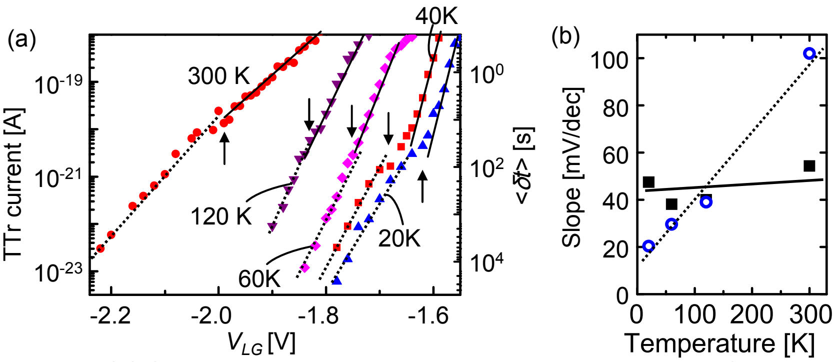

Fig. 3. (a) Sub-atto-ampere TTr current characteristics as a function of V_{LG} at various temperatures. Current, that is the total charges transferred from the ER to the SN for one second, is evaluated from e/<δt>, where e is the elementary charge and /<δt> the average of 30 samples of δt shown in Fig. 2(b). For clarity, data at 300 K are horizontally shifted by 0.8 V. (b) Change in the slopes of solid and dashed lines (open circles and closed squares, respectively) shown in (a).

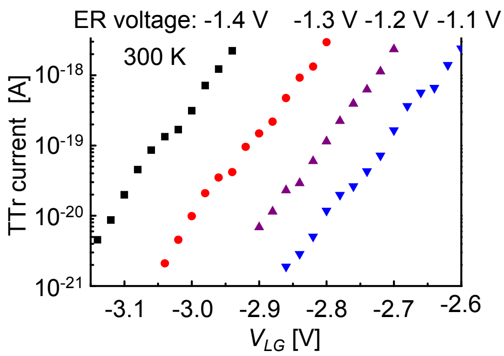

Fig. 5. Sub-atto-ampere TTr current characteristics as a function of V_{LG} at various ER voltages.