

ANALYSIS OF CURRENT NOISE IN MOSFET-BASED CHARGE-TRANSFER DEVICE

Hiroshi Inokawa, Vipul Singh, Hiroaki Satoh

Abstract:

Low-frequency current noise in the MOSFET-based charge-transfer devices was evaluated at room and cryogenic temperatures. Excessive noise, whose power was 25-50 times larger than that of room temperature, was observed at 20 K, and this hindered the accurate transfer of charge. Interestingly, the noise power was proportional to the square of the pulse frequency that drove the gates in these devices, and an expression for the noise was proposed to correlate it with the frequency, gate capacitance and fluctuation of the threshold voltage at the gate.

Keywords: low-frequency noise, MOSFET, charge-transfer device.

1. Introduction

The charge-transfer device consisting of two serially connected MOSFETs is very important as an element of switched capacitor circuit [1] and as a single-electron turnstile or pump [2]. Since the low-frequency noise in the MOSFET becomes increasingly conspicuous as its size is reduced, it is worthwhile to analyze the noise behavior of the charge-transfer device with small dimensions.

In this paper, Low-frequency current noise in the charge-transfer devices fabricated by 65-nm bulk CMOS process is reported in comparison with the ordinary noise of a MOSFET in direct-current (DC) operation. The noise in the transfer current at a low temperature is evaluated, and is found to show anomaly.

2. Experiments

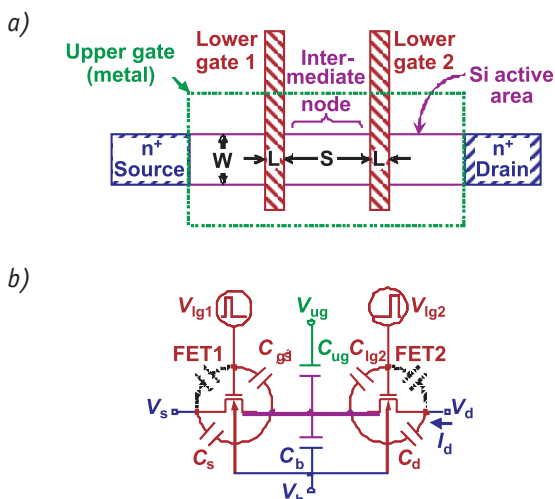


Fig. 1 (a) Device structure, and (b) Equivalent circuit when operating as a charge-transfer device.

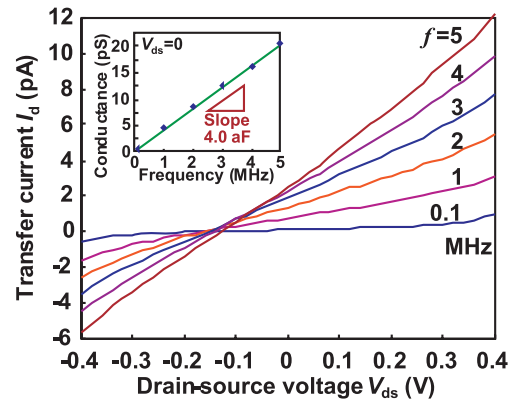


Fig. 2. Charge-transfer (I_d - V_{ds}) characteristics at 295 K. $L=70$ nm, $W=110$ nm, $S=170$ nm.

Figure 1(a) shows the planar view of the fabricated device. Two lower gates cross the Si active area between n^+ - doped source/drain regions. An upper gate made of metal covers the active area to electrically induce an inversion layer that serves as a source/drain extension. The gate length L , channel width W and gate spacing S were 60-80 nm, 100-120 nm and 160-180 nm, respectively, and the gate oxide thickness was 5 nm.

For the charge-transfer operation, as shown in Fig. 1(b), pulses with a phase delay of 180° were applied to the V_{ig1} and V_{ig2} to alternately turn on and off the respective channels. The current was measured with Agilent 4156C, and the data acquired in 600 s with the sampling period of 0.6 s were Fourier transformed to obtain the noise power spectrum.

3. Results and Discussions

The charge transferred in one cycle of the pulse is expressed as [3]

$$Q = C_\Sigma' V_d + C_{ig1}(V_{tho1} - V_{ig1L}) + C_{ig2}(V_{ig2L} - V_{tho2}) \quad (1)$$

where $C_\Sigma' = C_{ig1} = C_{ug} = C_b = C_s = C_d$, V_{ig1L} and V_{ig2L} are the lower levels of the V_{ig1} and V_{ig2} pulses, respectively, and V_{tho1} and V_{tho2} are the threshold voltages of FET1 and 2, respectively, when source/drain is not biased. Note that the noise in the form of the fluctuation in V_{tho1} and V_{tho2} led to the fluctuation in Q , and was reflected to the noise in the transfer current $I_d = Q_f$, where f is the pulse frequency. Specifically, the noise in the transfer current can be expressed as

$$\delta I_d = \sqrt{2} \delta V_{th} C_{ig} f \quad (2)$$

where it is assumed that the noises in the V_{tho1} and V_{tho2}

are independent and have the common standard deviation δV_{th} , and $C_{lg1} = C_{lg2} = C_{lg}$.

On the other hand, the noise in the DC current in the subthreshold region can be related to the V_{th} fluctuation by

$$\delta I_d = I_d (10^{\delta V_{th}/S} - 1) \approx I_d (\ln 10) \delta V_{th} / S \quad (3)$$

where S is the subthreshold swing in the unit of volt per decade.

Figure 2 shows the charge transfer ($I_d - V_{ds}$) characteristics at 295 K for various pulse frequencies. Since the slope of the curve (i.e. conductance) was proportional to the frequency, C_{Σ}' was found to be 4.0 aF.

The current noise spectra have been evaluated at a fixed $V_{ds} = 0.2$ V for various current levels (i.e. various frequencies) as shown in Fig. 3(a). The current noise spectra for DC operation were also obtained with the same device by applying high voltage (2 V) to one lower gate and adjusting the other to attain similar current levels to that of charge transfer measurement (Fig. 3(b)). The spectra for charge-transfer operation showed larger slopes, whereas those for DC operation showed gentler slopes. This difference may be related to the charging and discharging dynamics of the traps modified by the gate pulse in the case of the charge-transfer operation, as is expected from the cycled-gate experiment [4].

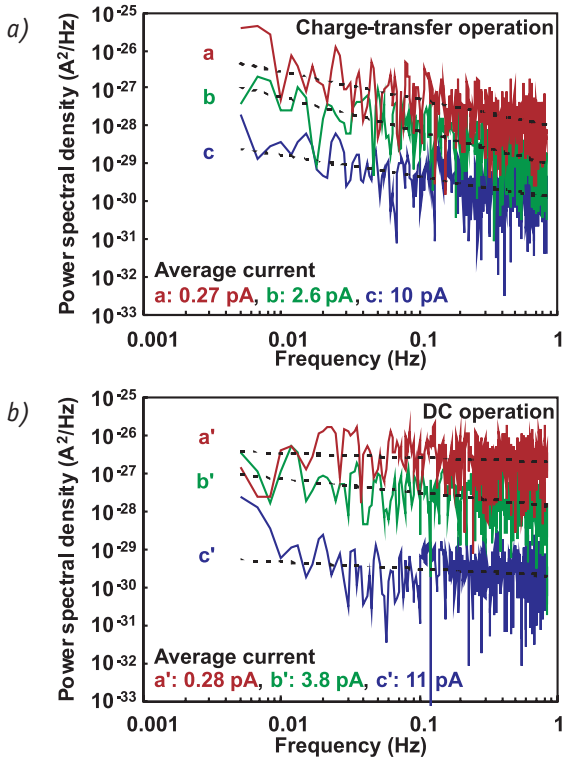


Fig. 3. Noise power spectra in (a) charge-transfer, and (b) DC operations at 295 K. $L=70$ nm, $W=110$ nm, $S=170$ nm.

The total noise powers were obtained by integrating the entire spectrum above 5 mHz, and have been plotted with respect to the average current in Fig. 4. The noise power in the transfer current is comparable to or a little smaller than that of the DC current. This can be attributed to the difference in the conversion factors from δV_{th}

to δI_d (see eqs. (2) and (3)), and the difference in δV_{th} itself. Since the lower gates are frequently switched between inversion and accumulation states in the charge transfer operation, the emission and capture times for the traps are largely reduced, and δV_{th} in the low-frequency range may become smaller [4].

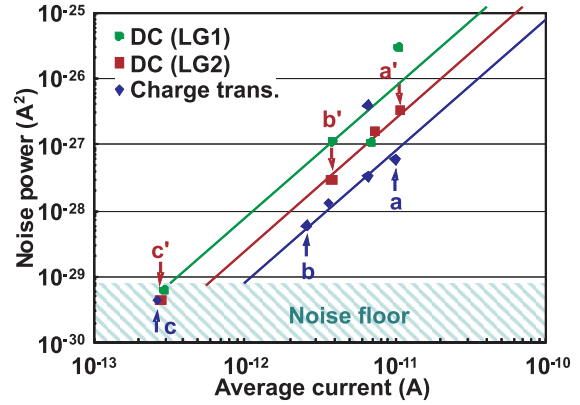


Fig. 4. Total noise power vs. current for DC and charge-transfer operations at 295 K. $L=70$ nm, $W=110$ nm, $S=170$ nm. The data points corresponding to the spectra in Fig. 3 are labeled with a, b, c, etc.

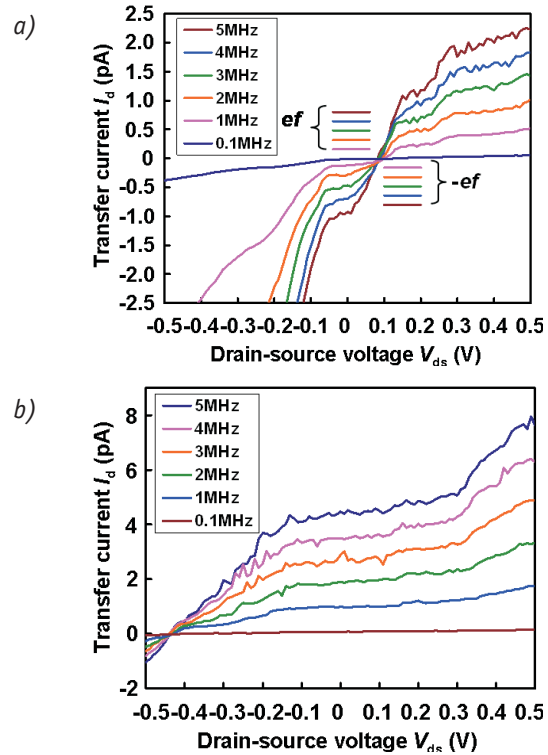


Fig. 5. Charge-transfer ($I_d - V_{ds}$) characteristics at 20 K. (a) $L=60$ nm, $W=100$ nm, $S=160$ nm, (b) $L=80$ nm, $W=120$ nm, $S=180$ nm. For noise characterization, plateau areas in (a) 0.3~0.45 V, and (b) -0.1~0.1 V are analyzed by linear regression.

Figure 5 shows the charge-transfer characteristics at low temperature, where current quantization can be expected as a result of Coulomb blockade [2]. However, the current plateaus do not perfectly match the multiple of ef and large noises were found to be superimposed. For the simple characterization of the noises, plateau areas were chosen, straight lines were drawn by least-square method,

and the square of the deviation from the straight lines were averaged to obtain the noise power, plotted as a function of current in Fig. 6. Fifty times larger noise was observed at 20 K. This excessive noise is estimated to come from the larger δV_{th} , since other terms in eq. (2) are rather independent of temperature. The cause of the large V_{th} noise is not clear at this moment, but the emission and capture times for the traps may become longer at a low temperature, leading to the increase in the low-frequency component of the noise (see eq. (15) in [5]).

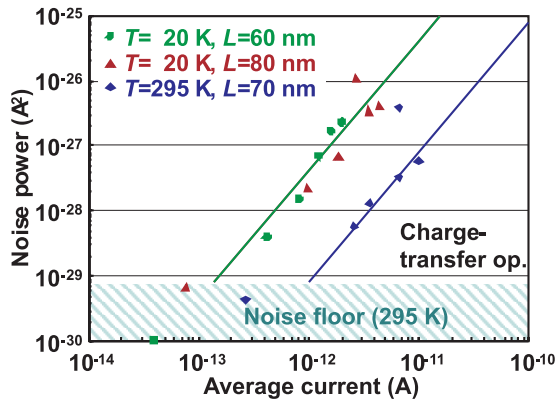


Fig. 6. Total noise power vs. current for charge-transfer operation at 20 and 295 K. Excess noise is observed at low temperature.

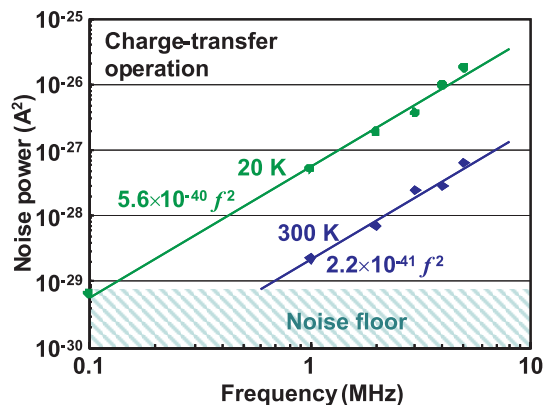


Fig. 7. Total noise power vs. pulse frequency for the charge-transfer operation at 20 and 300 K. These data are obtained from another device with $L=60$ nm, $W=100$ nm and $S=170$ nm, but the same tendency has been observed generally.

In order to see the behavior of the noise precisely, dependence on the pulse frequency at a fixed drain bias was evaluated as shown in Fig. 7. In this case, a single device is measured under a consistent condition both at 20 and 300 K. The noise power is proportional to the square of the gate pulse frequency at both temperatures, supporting eq. (2). The noise at 20 K is 25 times larger than that at 300 K, and the excessive noise at the low temperature is confirmed.

The noise power was also evaluated when the V_{ig1} and V_{ig2} pulses became asymmetric. As indicated by eq. (1), the transfer current can be reduced by increasing the V_{ig1L} while keeping the V_{ig2L} constant. It is remarkable that the noise power does not change even when the current changes, indicating again the validity of eq. (2). Note that the use of the current as the basis of compari-

son between *DC* and charge-transfer operations, as in Figs. 4 and 6, is still acceptable as long as the device structure and the operation condition are symmetric for lower gate 1 and 2, because the current is proportional to f without an offset in such a case. From the slope of the transfer current in Fig. 8, the C_{ig1} is calculated to be 2.2 aF based on eq. (1), and this leads to the δV_{th} as large as 7.6 mV at 20 K.

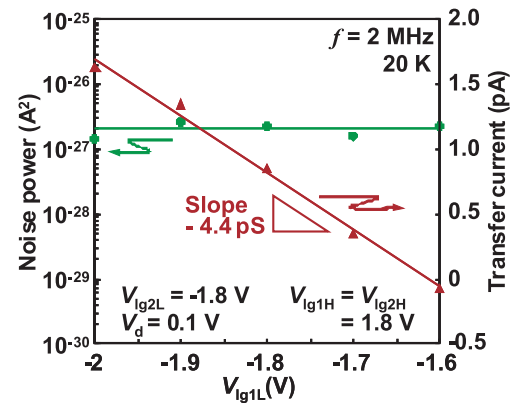


Fig. 8. Noise power and transfer current with respect to the lower level of the V_{ig1} pulse. Transfer current can be changed by the asymmetry in V_{ig1} and V_{ig2} pulses, but the noise power is kept constant as long as the pulse frequency is the same. From the slope of the transfer current, C_{ig1} can be calculated to be 2.2 aF.

4. Conclusions

Low-frequency current noise in the MOSFET-based charge-transfer device has been evaluated. It was found that, at 295 K, the noise power in the transfer current was comparable to or a little smaller than that in the *DC* current. At 20 K, on the contrary, 25–50 times larger noise power was found in the transfer current. In accordance with the proposed expression, the noise power in the transfer current was demonstrated to be proportional to the square of the pulse frequency, and in some device the threshold voltage fluctuation for the lower gates was estimated to be as large as 7.6 mV at 20 K. The reduction of the traps, related to the threshold voltage fluctuation is especially significant for accurate single-electron transfer at low temperatures.

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