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Study of Charge Retention Mechanism for DNA Memory FET

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1. Introduction

The number of transistors fabricated on an ultralarge scale IC (ULSI) has doubled approximately every 2 years, which is known as Moore's law. Although a complementary metal oxide semiconductor (CMOS) circuit has been produced via top-down process technology, the fabrication process faces difficulty in the coming generation whose gate length is smaller than 20 nm. The Moore's law is confronted with a limitation with an increase in integration. New materials such as carbon nanotubes [1] and graphene [2] are expected to be substituted for Si [3]. DNA has a characteristic of flowing electric current, and forms nanostructures with self-organization [4,5]. Poly (deoxi (d) G) – poly (dC) DNA molecules behave as a p-type semiconductor, while poly(dA)-poly(dT) DNA molecules behave as an n-type semiconductor [6]. DNA is one of the potential candidates for materials beyond CMOS. The control of the drain current flowing through the DNA channel by gate voltage application and the single electron transistor with multi-islands utilizing DNA have also been reported [7-9].We reported that DNA showed the charge retention characteristics [10]. The purpose of this research is to examine the charge retention mechanism of the DNA utilizing a DNA channel/SiO_2/Si(gate) structure.

2. Experimental

Figure 1 shows a schematic configuration of the DNA Memory FET. A 4-μm-thick, n-type silicon-on-insulator (SOI) with a resistivity of 40-60Ωcm was used to fabricate the DNA Memory FET. Top Si layer of SOI was thinned from 4.0μm to 0.15μm by the chemical dry etching (CDE). The single crystal Si source/drain electrodes were formed using a lithography process. Al electrodes were fabricated on Si thin film by a sputtering. The distances between the source and drain, which are the channel lengths of the FET, is 120 nm. The width of the source/drain, which is the channel width, is 100 μm. The inset shows the connection area of Si electrodes and the DNA molecule. We attached an epoxy function through hydrosilylation of allyl glycidyl ether (AGE) on the Si surface of the source and drain electrodes [11]. Double stranded DNAs (400 bp) were connected between the Si electrode surfaces via DNA-SH terminals. The length of the DNA is 136nm. Long-SH-DNA was prepared by a polymerase chain reaction (PCR) technique using 5'-disulfide-modified DNA primers and λ-DNA as a template. The DNA devices were washed with pure water, dried, and then characterized by a Keithley 6430 semiconductor analyzer at room temperature in air (50 - 60% humidity conditions). By applying the source to drain voltage, V_D, of 0 to 1.0V and the refresh voltage to the gate of -5 to -50V for 10 and 30 s, the refresh characteristics were examined.

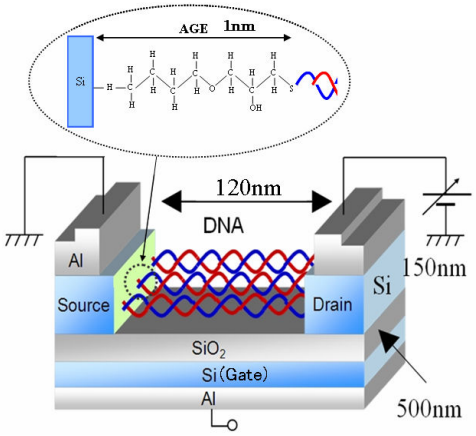

Fig.1 Schematic configuration of DNA Memory FET.

3. Results and discussion

Figure 2 shows the relationship between the derivative of the drain current to the drain voltage, dI_D/dV_D, and the drain voltage. The inset is the I_D-V_D characteristics at the gate voltages of 0 to -5 V. The dI_D/dV_D shows the maximum value at the drain voltage of approximately 0.3 V. The guanine (G)-base generates the hole carriers frequently, because the ionic potential of it is the smallest of the other DNA base [12,13]. By capturing the electrons in the guanine-base, the generated holes dominate the conduction of the DNA. The reason why the maximum of dI_D/dV_D is observed is as follows. The captured electrons in the guanine-base are detrapped by the electric field in the channel. By recombination of the electrons and holes, the excess holes are emitted to the channel from the n^+Si according to the mass action law. Figure 3 shows the

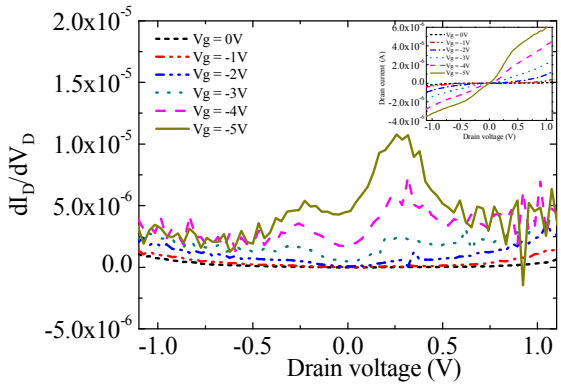

Fig.2 Relationship between dI_D/dV_D and the drain voltage.

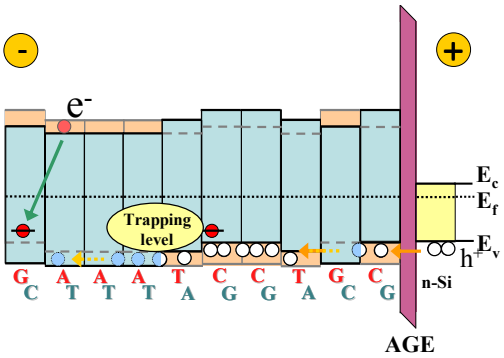

Fig.3 Schematic representation of conduction and memory mechanisms in the DNA.

schematic representation of the conduction and memory mechanisms via guanine-base. The hole carriers which are generated in the guanine-base or emitted to the channel from the Si electrode by direct-tunneling through the AGE film flow the DNA channel by the drift mechanism. The electrons which are generated in the thymine (T) or adenine (A)-base are either captured at the energy level in the guanine-base or recombined with the holes. Therefore, the electron currents are not observed in the present DNA FET. The trapping levels in the guanine-base serve as the origin of the memory phenomenon.

Figure 4 shows the dependence of the drain current on the refresh voltage which is applied to the gate electrode. Although the increase of the drain current is gradually suppressed from -5 to -20V for refresh voltage, the decrease of the drain current is observed from -30 to -50V for the refresh voltages. The reason of this phenomenon is thought to be that the captured electrons in the DNA are detrapped by applying the refresh voltage larger than -30V and therefore the amplification of the field effect is suppressed. This result indicates that the density of the trapping level in the DNA is large.

Figure 5 shows the dependence of the drain current increase, ΔI_D, on the repetition number with and without refresh. The refresh voltages of -20 and -50V are applied to the gate for 30s before each measurement. The drain current increase is small for -20V and the drain current decreases for -50V of refresh voltage. It is found that the refresh process of the DNA Memory FET is influenced by both the voltage applied to the gate and the duration for the refresh process. The number of the detrapped electrons

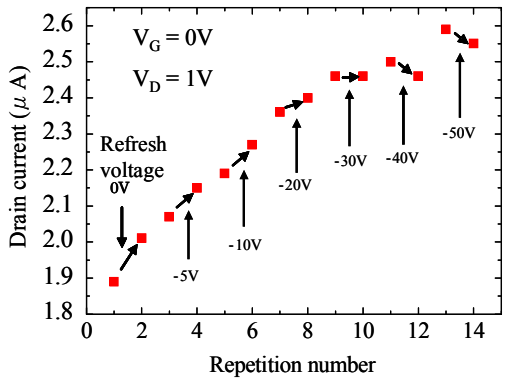

Fig.4 Dependence of I_D on refresh voltage.

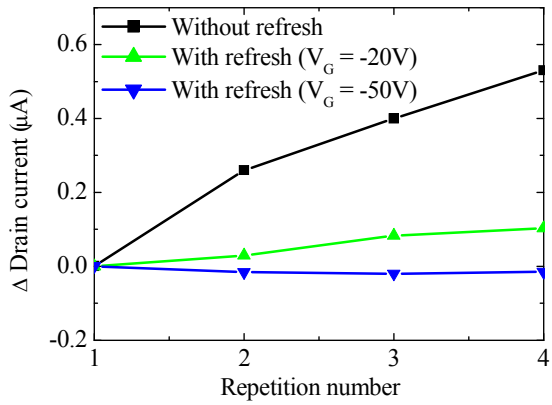

Fig.5 Dependence of ΔI_D on repetition number with and without refresh.

increases as the refresh voltage or the duration increases. The duration of the refresh process affects the retention property for V_G of -20V and not affect it for V_G of -50V.

4. Conclusions

The charge retention mechanism of the DNA was examined using the DNA channel/SiO_2/Si gate structure. The followings were clarified. 1) The dI_D/dV_D characteristics indicate that the trapping level in guanine-base is closely related with the charge retention. 2) The refresh process of the DNA Memory FET is influenced by both the voltage applied to the gate and the duration for the refresh process. The number of the detrapped electrons increases as the refresh voltage increases. 3) The captured energy level of electron is near the valence band edge in the band gap of guanine-base and its density is large.

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