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Mesoscopic Blockade and Staircase Phenomena of Holes in DNA/Si-MOSFET by Gate Voltage Modulation

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Abstract

Mesoscopic blockade/staircase phenomena of holes in λ-DNA channel bridged between the Si source/drain electrodes, which were fabricated on the SiO_2/Si substrate, were observed at 20 to 200K by applying the gate voltage. It is considered, first, that the DNA/allyl glycidyl ether(AGE), which connects the DNA to the both Si electrodes/Si is the wave function-penetrating-contact, and second, that the potential of the 1-nm-thick AGE dielectric is modulated by the gate voltage. A multi-valued logic circuit by the DNA is expected to perform at liquid nitrogen temperature.

1. Introduction

DNA has a conductive characteristic and forms self-organized nanostructures [1, 2]. 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 one [3]. The DNA FET with Au electrode and the SET with multi-islands utilizing DNA have also been reported [4,5]. We fabricated the DNA transistor, which has Si source, drain and gate electrodes, for the first time, and clarified the drain current control by the gate voltage [6] and the charge retention via guanine base [7,8]. One of purposes of this research is to examine the conduction of the λ-DNA at low temperature.

2. Experimental Method

Figure 1 shows a schematic configuration of the DNA transistor. The distance between the source and drain, which is the channel length, is 120 nm. The width of the source/drain, which is the channel width, is 100 µm. 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). Low-temperature measurements of the I_d-V_g characteristic were pursuit at 20 to 200 K using BCT-4R.

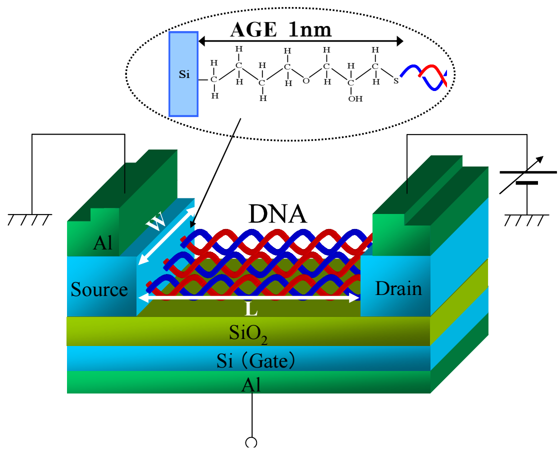


Fig.1 Schematic configuration of the DNA transistor. A 350-nm-thick p-type SOI with a resistivity of 40-60Ωcm was used. The SOI film was thinned to 60 nm and the source/drain electrodes were left by the dry process. The inset shows the connection area of Si electrodes and the DNA molecule. An epoxy function was attached through hydrosilylation of AGE on the Si surface of the source/drain electrodes [9].

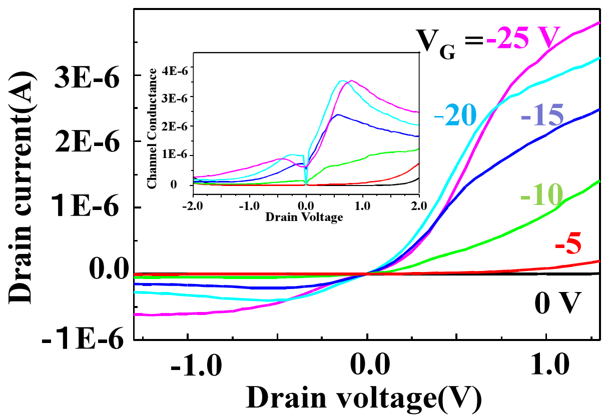
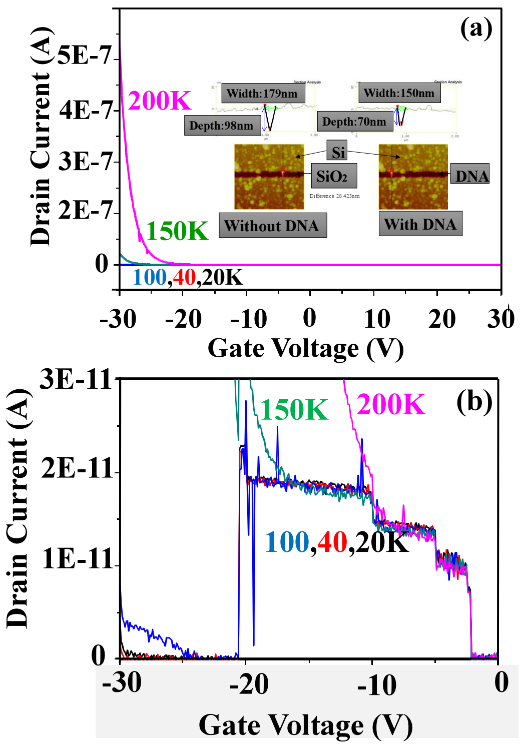


Fig.2 I_d-V_d characteristics of the DNA/Si-MOSFET at V_g of 0 to -25V and at room temperature. Inset is the channel conductance.



Figs.3 I_d-V_g characteristics (a) and the mesoscopic blockade/staircase (b) at temperatures from 20 to 200 K of the DNA/Si-MOSFET. Inset is the AFM images w/wo DNA.

3. Results and discussion

Figure 2 shows the relationship between the drain current I_d and drain voltage V_d of the DNA/Si-MOSFET. I_d was controlled by the gate voltage (V_g) application and the hole carriers dominate the channel conduction. The channel conductance dI_d/dV_d shows the maximum value at V_d of approximately 0.7 V. The guanine (G)-base generates the hole carriers frequently, because the ionic potential of it is the smallest of the other DNA base [10,11]. By capturing electrons in the guanine-base, the generated holes dominate the conduction of the DNA. The slope of $I_d(V_d)$ is equal to $1/(R_{DNA}+2R_C)$, where R_{DNA} and R_C are the resistances of the DNA channel and the contact, respectively. V_g changes the R_{DNA} via the Fermi energy E_f modulation. Figures 3(a) and 3(b) show I_d-V_g characteristics and the mesoscopic blockade/staircase of the DNA/Si-MOSFET. The thermal activated component decreases as the temperature decreases. The blockade phenomenon disappears at V_g of -2.5V. This voltage corresponds to the threshold gate voltage. The staircases consist of three plateau areas of -2.5~-5V, -5~-10V and -10~-20V. As V_g increases, the applied voltage to the AGE connecting to both sides of the DNA increases. The reason why the sudden jump in $I_d(V_g)$ is observed with increasing V_g is the join of a new energy state shown by eq. (1).

$$\int_0^{Ef} eD(E)dE = Q_{DNA} , \qquad (1)$$

where $D(E)$ and Q_{DNA} are the state density of the DNA and the charge in the DNA. The channel conductance is smaller than quantum conductance $2e^2/h$ due to the elastic scattering in the DNA channel. It is thought that the wave func

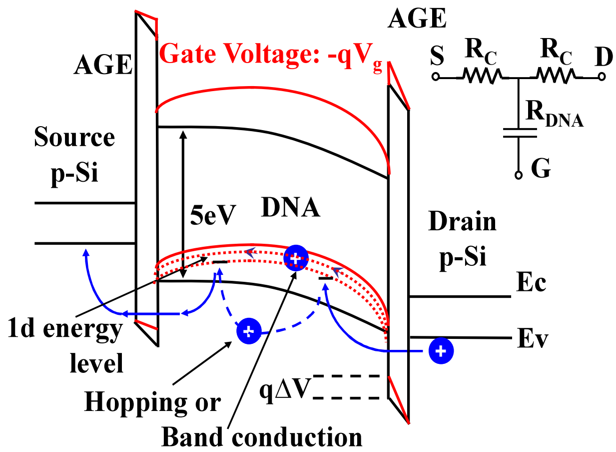


Fig. 4 Potential diagram at non-gate voltage application and at $-qV_g$(red line) and the equivalent circuit of DNA/Si-MOSFET.

tion in the DNA penetrates into the p-Si, because $I_d(V_d)$ shows the linear characteristic in small drain voltages and $I_d(V_g)$ shows the staircase characteristics [12]. Figure 4 shows the potential diagram at non-gate voltage and at $-qV_g$ and the equivalent circuit. It is thought that holes emitted to the DNA are captured at the one-dimensional (1D) energy level and take the hopping motion between 1D energy levels or ballistic motion according to the 1D-wire band, because the DNA is a quantum wire with the 2 nm diameter. The duration τ of the hole in the DNA is identified by $\tau=h/\Delta E$ with the uncertainty ΔE of the 1D energy level. These experimental results indicate the feasibility of the multi-valued logic circuit constructed by the DNA performed at liquid nitrogen temperature.

4. Conclusions

Mesoscopic blockade and staircase phenomena of holes in λ-DNA channel were observed at 20 to 200K by modulating the gate voltage. These phenomena are due to the wave function-penetrating-contact and the potential modulation of the AGE dielectric. The feasibility of the multi-valued logic circuit constructed by the DNA performed at liquid nitrogen temperature was shown.

Acknowledgements

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