Interfaces of High-k Gate Insulator in Carbon Nanotube FETs

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1. Introduction
Carbon nanotubes are one of promising materials for CMOS devices because of their high carrier mobility for both of electrons and holes. For CMOS applications, it is necessary to control the polarity of conduction carriers. In the previous study, we have realized air-stable, high-performance, Si-process compatible, n-type carbon nanotube field-effect transistors (CNFETs) and CMOS inverters, utilizing fixed charges in the high-k gate insulator deposited by atomic layer deposition (ALD) [1, 2]. However, we have not fully understood the location and origin of the fixed charges, nor their effect on the device property.

In this study, we have studied the electrostatic property of the interfaces of the gate insulator layer by Kelvin probe force microscopy (KFM). Charge distributions are measured for the interfaces between HfO₂ and a Au contact and between HfO₂ and a SiO₂/Si substrate. In addition, the formation of interface dipole is investigated for a-few-monolayer HfO₂ layer.

2. Experimental
Figure 1(a) and (b) show the schematic structures of the samples used in this study to measure the interface charges by KFM. These structures respectively imitate the gate insulator on the source (drain) contact electrodes, and the gate insulator on the SiO₂/Si substrate in CNFETs. The HfO₂ was deposited on a Au electrode or on a 10-nm-thick-SiO₂/Si substrate by ALD technique at 250°C, followed by post-deposition annealing at 300°C in vacuum. Then, the HfO₂ layer was partially removed by reactive ion etching.

The circuit configuration for KFM measurement is also schematically shown in Fig. 1. In the KFM measurement, $V_{DC}$ is adjusted so that the electrostatic force between the tip and sample becomes zero, thus the contact potential difference ($V_{CPD}$) is measured as $-V_{DC}$. The $V_{CPD}$ was measured at room temperature in vacuum with a Au-coated conductive tip.

3. Results and discussion
First, we studied the interface between the contact electrode and the gate insulator with the sample shown in Fig. 1(a). Figure 2 shows the line profile of $V_{CPD}$ measured by KFM for the thickness of HfO₂ of 6 nm. The surface potential of the HfO₂ layer ($V_s$), which is given by the difference between $V_{CPD}$’s measured on the HfO₂ surface and on the Au surface, was about 0.9 V. The surface potential of HfO₂ increased with the thickness of the HfO₂ layer ($t$), and saturated at about 10 nm as shown in Fig. 3. The maximum surface potential was about 1 V. The space charge ($N(t)$) in the HfO₂ layer was evaluated from the thickness dependence by

$$N(t) = \varepsilon_0 \varepsilon_r \frac{\Delta V_s}{q t},$$

where $\varepsilon_0 \varepsilon_r$ is the dielectric constant and $q$ is elementary charge. Figure 4 shows the space charge distribution in the HfO₂ layer. This result indicates that most of the positive charges distribute within 10 nm from the interface. The integrated sheet charge density was $4.5 \times 10^{13}$ cm².

We also studied the interface between the HfO₂ gate insulator and a SiO₂/Si substrate. Figure 5 and 6 shows the surface potential of the HfO₂ layer on the SiO₂/Si substrate, and the space charge distribution in the HfO₂ layer, respectively. The integrated sheet charge density was $6.1 \times 10^{13}$ cm². In addition, we found that a one-monolayer deposition of HfO₂ built up the surface potential by $\Delta \sim 0.4$ V. This suggests an existence of the interface dipole layer between the SiO₂ and HfO₂.

Figure 7 summarizes the schematic energy diagrams suggested from this study for (a) the HfO₂/Au structure and (b) the HfO₂/SiO₂/Si structure. The positive charges distributing near the interface build up the potential in the HfO₂ layer. In the case of HfO₂/SiO₂ interface, the potential varies abruptly at the interface due to the interface dipole.

4. Conclusions
We have studied the interfaces of HfO₂ gate insulator for CNFETs by KFM. The results show the positive charges distribute near the interfaces between the HfO₂ and Au contact and between the HfO₂ and the SiO₂/Si substrate. In addition, it was suggested that there existed an interface dipole between the HfO₂ and SiO₂/Si substrate.

Acknowledgements
This work was partially supported by NEDO Grant ’08, ALCA of JST, and a Grant-in-Aid for Scientific Research on Priority Areas from the Ministry of Education, Culture, Sports, Science and Technology.
References

Fig. 1 Schematics of samples measured by KFM for (a) the interface between HfO$_2$ and Au and (b) the interface between HfO$_2$ and SiO$_2$/Si substrate.

Fig. 2 Line profile of the $V_{CPD}$ measured by KFM for the thickness of HfO$_2$ of 6 nm.

Fig. 3 Thickness dependence of the surface potential of HfO$_2$ layer on Au contact.

Fig. 4 Charge distribution in HfO$_2$ layer on Au contact evaluated from the thickness dependence of the surface potential.

Fig. 5 Thickness dependence of surface potential of HfO$_2$ layer on SiO$_2$/Si Substrate.

Fig. 6 Charge distribution in HfO$_2$ layer on SiO$_2$/Si substrate.

Fig. 7 Schematic energy diagrams of (a) the HfO$_2$/Au structure and (b) the HfO$_2$/SiO$_2$/Si structure.