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Observation of Positively Charged Trap Site in Silicon Oxide Layer with an Atomic Force Microscope

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We investigated contact-electrified charges on a thin silicon oxide surface by an atomic force microscope (AFM) with a conductive cantilever. As a result, we successfully observed the electrostatic force related to positively charged trap site in silicon oxide layer in addition to the electrostatic force induced by densely contact-electrified charges on the oxide surface. From estimation of trap site density, the estimated value roughly agrees with the typical value obtained from the C-V measurement in the MOS capacitor.

1. Introduction

Electrical properties related to charge behavior on or in a thin silicon oxide layer are greatly important for performance and reliability of metal-oxide-semiconductor (MOS) devices. For example, trapped charges in the oxide layer affect seriously the device performance and reliability.[1] Hence, for the development of the deep sub-half micron scale MOS devices, it is very important to investigate distribution of the trapped charges in the oxide layer with nanometer-scale resolution.

In the present experiment, we investigated the trap site in the oxide layer using reproducible and controllable contact electrification.[2-6] Furthermore, we estimated trap site density Q_{ss} from the experimental result.

2. Experimental

An AFM equipped with a conductive cantilever and external bias voltage source was used to deposit and observe the contact-electrified charges.[7] Deposition and observation of contact-electrified charges are described in elsewhere.[2-6] Briefly, deposition of charges is performed by single contact between the conductive cantilever with the bias voltage V_c (contact voltage) and a thin silicon oxide surface for a certain time t_0 (contact time) as shown in Fig. 1(a). After contact electrification, deposited charges were observed as electrostatic force induced on the tip of the conductive cantilever with bias voltage V_s (measurement voltage) under non-contact DC mode as shown in Fig. 1(b). In particular, measurement voltage was set to V_s=0 V for the observation of trap site. Here, the electrostatic force is proportional to the square of the electric charges.[8]

The silicon oxide layers used were formed on p-type single crystal Si(100)

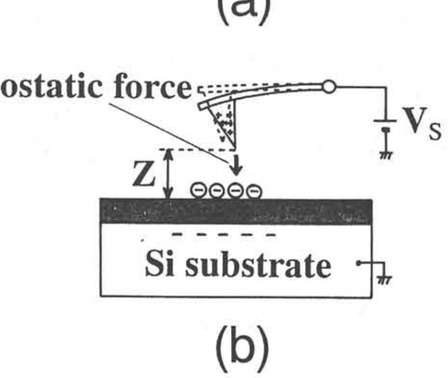

Fig. 1. Schematic models of experimental set up for contact electrification with AFM (a) and electrostatic force measurement with non-contact DC mode AFM (b).

wafers with resistivity of 10-20 Ω·cm. The oxide thickness was estimated to be 54 Å ± 1 Å by ellipsometry.

3. Results and Discussion

Figure 2 shows two dimensional spatial distribution of the electrostatic force due to trapped charges at ~30 s after contact electrification. Here, contact electrification was performed under contact voltage of $V_c=-6$ V and contact time of 30 s and electrostatic force was observed under the measurement voltage $V_s=0$ V and tip-sample distance $Z \fallingdotseq 110$ Å. Contrast from bright to dark in Fig. 2 corresponds to variation from weak to strong attractive electrostatic force. We can see that spatial distribution of the electrostatic force has dark, bright and gray regions concentrically. Maximum variation of the electrostatic force in the dark region was ~180 pN.

Figure 3(a) shows one dimensional spatial distribution of the electrostatic force and its time evolution. Each spatial distribution indicated by '1','2','3' and '4' was observed at 21 s, 2 min 46 s, 5 min 11 s and 7 min 35 s after contact electrification, respectively. Here, contact voltage, contact time, measurement voltage and tip-sample distance were $V_c=-6$ V, 20 s, $V_s=0$ V and $Z \fallingdotseq 150$ Å, respectively. We can see that a valley at the center disappear with time evolution. In addition, protrusions at neighbor of the valley also disappear. We compared the electrostatic forces at point 'A' (bottom of valley) and 'B' (top of protrusion) measured from the broken line. First, the electrostatic force at point 'A' decreases with time evolution ('1'→'2'→'3'). In particular, in the spatial distribution at '3', the electrostatic force at point 'A' become nearly zero. However, it begins to increase again in the later stage ('3'→'4') and tends to be closer to solid line (f_0).

Figure 3(b) shows a schematic model of spatial distributions of electrostatic force in Fig. 3(a). A valley, protrusion and plateau in the spatial distribution of the electrostatic force correspond to attractive force due to the densely contact-electrified electrons ($Q_s<0$) and electrically neutralized region ($Q_s=0$) and positively charged trap site in the oxide layer ($Q_s>0$),

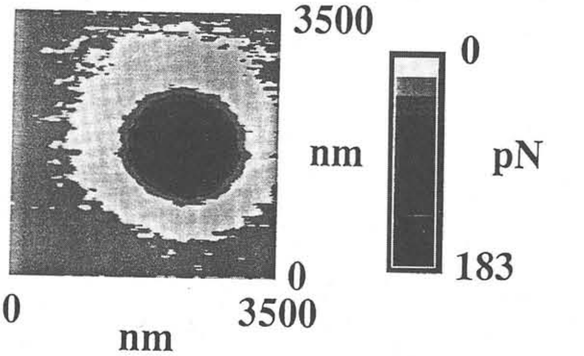

Fig. 2. Two dimensional spasial distribution of the electrostatic force. Here, contact voltage, contact time, measurement voltage and tip-sample distance were $V_c=-6$ V, $t_0=30$ s $V_s=0$ V and $Z \fallingdotseq 110$ Å, respectively.

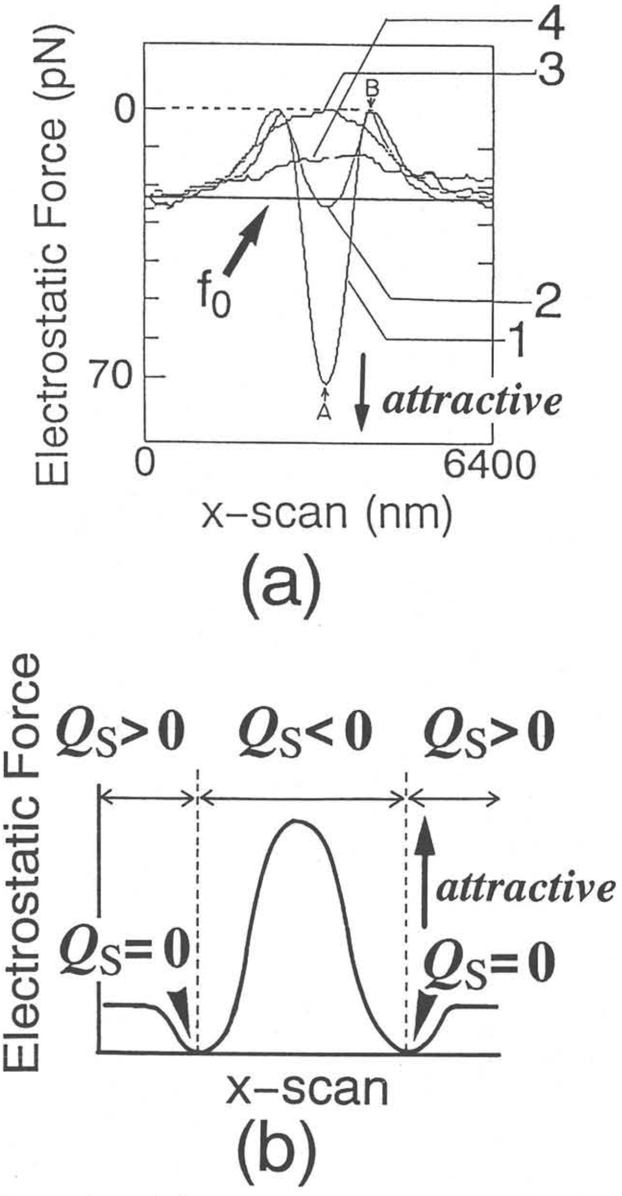

Fig. 3. (a) One dimensional spatial distribution of the electrostatic force and its time evolution. Here, $V_c=-6$ V, $t_0=20$ s, $V_s=0$ V and $Z \fallingdotseq 150$ Å, respectively. (b) Schematic model of the spatial distribution of the electrostatic force in (a).

respectively. The decrease of the electrostatic force during '1'→'2'→'3' indicates dissipation of the densely contact-electrified electrons. The nearly zero electrostatic force at '3' means that a part of the contact-electrified electrons were soaked into the oxide layer and captured by positively charged trap site. Thus, electrostatic forces due to the contact-electrified electrons and positively charged trap site were cancelled out. The increase of the electrostatic force during '3'→'4' indicates that the contact-electrified electrons got away from positively charged trap site and went into silicon substrate via tunneling process. Thus, attractive force due to positively charged trap site appears during '3'→'4' at point 'A'. On the other hand, the electrostatic force at point 'B' is nearly zero at initial stage ('1'→'2') , then increases with time evolution ('2'→'3'→'4'). Finally, the electrostatic force at point 'B' also tends to be closer to solid line. The nearly zero electrostatic force during '1'→'2' and the following increase of the electrostatic force '2'→'3'→'4' indicate the similar charge behavior during '3'→'4' at point 'A'. Being closer to solid line both at point 'A' and 'B' indicate that the positively charged trap site in the oxide layer are observed as the residual electrostatic force, i.e., $f_0 \fallingdotseq 20$ pN.

We calculated the trap site density in the oxide layer Q_{ss} as Q_{ox}/S_{eff}. Q_{ox} and S_{eff} denote charge quantity of positively charged trap site in the oxide layer and effective area for detection of the electrostatic force, respectively. Q_{ox} was estimated from the electrostatic force. Here, the tip and sample were approximated by sphere-plane model including an effect of image charge and silicon substrate was regarded as conductor. From Fig. 3(a), using the attractive force $f_0 \fallingdotseq 20$ pN due to the positively charged trap site, Q_{ox} is estimated $(6.9\pm4.8)\times10^{-18}$ C. On the other hand, effective area for detection of the electrostatic force is given by $S_{eff}=\pi R^2$, where a radius of effective area is assumed to equal the radius of curvature of the tip, i.e., R=250 Å. Thus, the trapped charge density $Q_{ss}=Q_{ox}/\pi R^2$ is estimated $(3.5\pm2.4)\times10^{-7}$ C/cm^2. This estimated value roughly agrees with typical value obtained from the C-V measurement in the MOS capacitor with p-type silicon substrate. Therefore, the AFM can evaluate the trapped charge density semi-quantitatively through electrostatic force measurement.

4. Conclusion

We investigated contact-electrified charges on or in a thin silicon oxide surface by an AFM with a conductive cantilever. As a result, we successfully observed the electrostatic force related to positively charged trap site in silicon oxide layer in addition to the electrostatic force induced by densely contact-electrified charges on the oxide surface. From the calculation by sphere-plane model, trapped charge density is estimated $(3.5\pm2.4)\times10^{-7}$ C/cm^2. This estimated value roughly agrees with the typical value obtained from the C-V measurement in the MOS capacitor with p-type silicon substrate.

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References

1)E.H.Nicollian and J.R.Brews: MOS (Metal-Oxide-Semiconductor) Physics and Technology (Wiley, Canada, 1982)
2)S.Morita,Y.Fukano,T.Uchihashi,Y.Sugawara, Y.Yamanishi and T.Oasa: Appl.Surf.Sci. 75 (1994) 151.
3)S.Morita,Y.Fukano,T.Uchihashi,T.Okusako, Y.Sugawara,Y.Yamanishi and T.Oasa: Jpn.J.Appl.Phys. 32 (1993) L1701.
4)S.Morita,Y.Sugawara,Y.Fukano,T.Uchihashi, T.Okusako,A.Chayahara,Y.Yamanishi and T.Oasa: Jpn.J.Appl.Phys. 32 (1993) L1852.
5)Y.Sugawara,S.Morita,Y.Fukano,T.Uchihashi, T.Okusako,A.Chayahara,Y.Yamanishi and T.Oasa: Jpn.J.Appl.Phys. 33 (1994) L70.
6)Y.Sugawara,S.Morita,Y.Fukano,T.Uchihashi, T.Okusako,A.Chayahara,Y.Yamanishi and T.Oasa: Jpn.J.Appl.Phys. 33 (1994) L74.
7)S.Morita,Y.Sugawara and Y.Fukano : Jpn.J.Appl.Phys., 32 (1993) 2983.
8)Y.Fukano,T.Uchihashi,T.Okusako,K.Hontani, A.Chayahara,Y.Sugawara,Y.Yamanishi,T.Oasa, T.Okada and S.Morita: Proceedings of Intn'l. Conf. on Advanced Microelectronic Devices and Processing (Tohoku University, Sendai, 1994) p.365.