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Time Evolution of Electrostatic Force Induced by Contact-Electrified Charges on Thin Silicon Oxide Surface

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Time evolution of microscopic contact electrification on thin silicon oxide surface was investigated by an atomic force microscope(AFM). Dissipation of contact-electrified charges after single contact has been successfully imaged by the non-contact DC mode measurement of the induced electrostatic force with the AFM. It was found that the dissipation of the contact-electrified charges had two stages with respect to the time, which was observed remarkably for p-type silicon substrate.

1. Introduction

Contact electrification is one of the physical phenomena which occur everyday around us. However, in the case of metal-insulator or insulator-insulator contact, its mechanism is not well understood.

Recently, Stern et al. and Terris et al. used an atomic force microscope(AFM) as a novel technique for deposition and imaging of localized charges on insulator surfaces[1-3]. Furthermore, Schönenberger and Alvarado achieved finally to image even the single charge[4-5] using an AFM. Thus an AFM seems to be an ultimate microscopic tool for observing and handling charges.

In the present experiment, we investigated the time evolution of the microscopic contact electrification on thin silicon oxide surface using an AFM. We could successfully image the dissipation of contact-electrified charges on the oxide surface. We also investigated the dissipation of contact-electrified charges for the p-type and n-type silicon substrates.

2. Experimental

In the present experiment, we used the AFM combined with the scanning tunneling microscope(STM), namely the scanning force/tunneling microscope(AFM/STM)[6].

Contact electrification and charge detection were performed by the following method. As shown in Fig. 1(a), when the conductive cantilever with the bias voltage V_c was made in contact with thin silicon oxide surface, contact-electrified charges were deposited. The oxide surface was subsequently withdrawn as shown in Fig. 1(b). After contact electrification, deposited charges were imaged as a peak of the electrostatic force induced on the tip of the conductive cantilever with the bias voltage V_s under the non-contact DC mode of the AFM at the distance of $Z \fallingdotseq 500 \sim 700$ Å. Here, the value of the electrostatic force was obtained by multiplying the spring constant by the deflection of conductive cantilever. Deflection of the conductive cantilever was detected with an all-fiber interferometer[7]. As the conductive cantilever, we used a Si_3N_4 microcantilever with a pyramidal Si_3N_4 tip coated with 15 Å thickness Cr film and 500 Å thickness Au film. This cantilever has a spring constant of k=0.16 N/m and a mechanical resonant

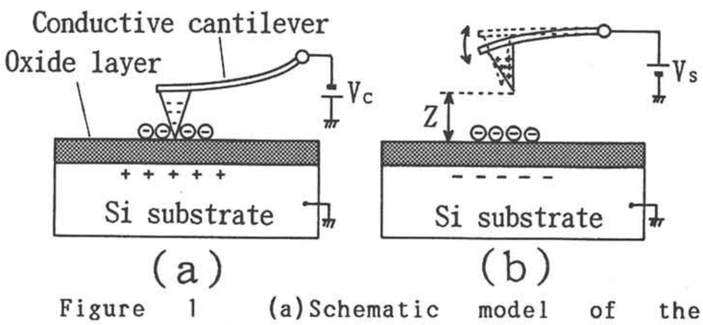

Figure 1 (a) Schematic model of the experimental setup for the contact electrification with the AFM. (b) Schematic model of the experimental setup for the non-contact DC mode measurement of the electrostatic force with the AFM.

frequency of f_R=27 kHz, respectively. The background noise of the interferometer measured under the non-contact mode was ~0.8 $Å_{p-p}$, which corresponds to be ~13 pN_{p-p} evaluated as the force.

The silicon oxide layers used in the present studies were formed on p-type or n-type single crystal Si(100) wafers. Using the ellipsometry, thicknesses of the oxide layers were determined to be 53 ± 12 Å for p-type wafers and 53 ± 3 Å for n-type wafers, respectively.

The experimental conditions were as follows: the bias voltage V_c=-4 V was applied to the conductive cantilever at the contact electrification, the contact duration to deposit the charges was ~20 seconds.

3. Results and Discussion

At first, we investigated the dissipation of the contact-electrified charges on the thin silicon oxide formed on p-type silicon substrate. Figure 2 shows the time evolution of the contact-electrified charges. Here, contact-electrified charges were detected as the spatial change of the electrostatic force for the one dimensional scan. The upward and downward directions of Z-axis correspond to the increase of the repulsive and attractive forces, respectively.

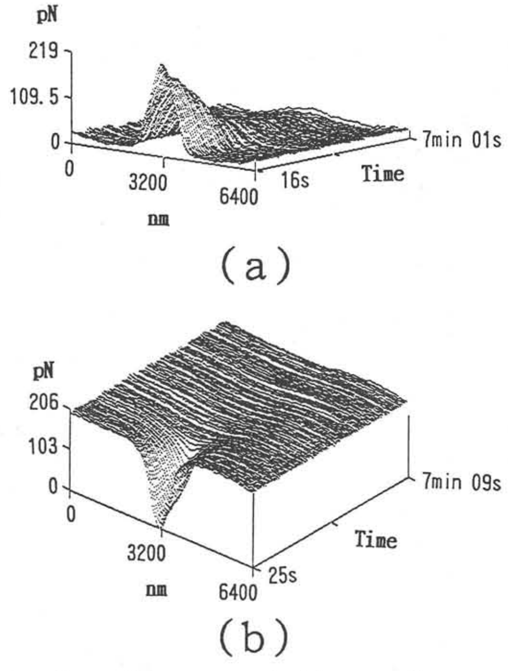

Figure 2 Time evolution of contact-electrified charges measured under (a) V_s=-4 V and (b) V_s=4 V. Those charges were deposited under V_c=-4 V. Thin silicon oxide was formed on p-type silicon substrate. The distance Z changed from Z≒779 Å to Z≒808 Å for(a) and from Z≒771 Å to Z≒789 Å for (b) during the measurement.

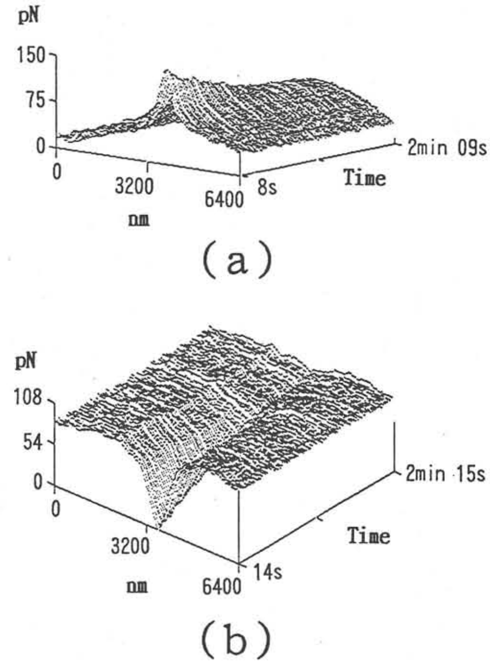

Figure 3 Time evolution of contact-electrified charges measured under (a) V_s=-4 V and (b) V_s=4 V. Those charges were deposited under V_c=-4 V. Thin silicon oxide was formed on n-type silicon substrate. The distance Z changed from Z≒520 Å to Z≒502 Å for (a) and from Z≒520 Å to Z≒484 Å for (b) during the measurement.

Figures 2(a) and 2(b) were obtained under the bias voltage V_s=-4 V and V_s=4 V, respectively. We can see that the electrostatic forces were observed as repulsive force under V_s=-4 V and attractive force under V_s=4 V, respectively. These results indicate that the sign of the contact-electrified charges was negative.

Figure 3 shows the time evolution of the contact-electrified charges on the oxide surface formed on n-type silicon substrate. These images were obtained under the bias voltage of V_s=-4 V and V_s=4 V, respectively. We can see that the electrostatic forces were observed as repulsive force under V_s=-4 V and attractive force under V_s=4 V, respectively. These results also indicate that the sign of the contact-electrified charges was negative.

In order to evaluate quantitatively the dissipation of the contact-electrified charges in Figs. 2 and 3, we estimated the peak value of the electrostatic force by subtracting the background. Figure 4 shows the peak value of the electrostatic force as a function of the time. Here, the closed circles(●) and the open circles(○) correspond to the peak values of repulsive forces in Fig. 2(a) and attractive forces in Fig. 2(b), respectively. On the other hand, the closed triangles(▲) and the open triangles(△) correspond to the peak values of repulsive forces in Fig. 3(a) and attractive forces in Fig. 3(b), respectively. Here, the error bars indicate the variance due to the background subtraction. The decay of the electrostatic forces correspond to the dissipation of the contact-electrified charges. The electrostatic forces at the start of the measurement for p-type silicon substrate were estimated to be ~200pN for both the repulsive and attractive forces. On the other hand, the electrostatic forces at the start of the measurement for n-type silicon substrate were estimate to be ~110pN for the repulsive force and ~100pN for the attractive forces, respectively. We can see that the peak values of the electrostatic forces for p-type silicon substrate were roughly twice as large as those for n-type silicon substrate. This result may indicate that the contact-electrified charges on the thin silicon oxide surface are easily deposited on p-type silicon substrate than n-type silicon substrate. Furthermore, we can see that the dissipation of the contact-electrified charges had two stages with respect to the time t. In the case of p-type silicon substrate, during the first stage (time t<100 s), there is not remarkable difference of the dissipation of the charges between the attractive force and the repulsive force measurement. On the contrary, during the second stage (time t>100 s), the dissipation of the charges under the attractive force measurement was much faster than that under the repulsive force measurement. In the case of n-type silicon substrate, although the dissipation of the charges seems to have the same tendency as the case of p-type silicon substrate for the first (time t<50 s) and the second stage (time t>50 s), there is uncertainty due to the large variance of the electrostatic force. We evaluated the time constant τ_{CE} of the electrostatic forces. Here, we assumed that the electrostatic forces F(t) could be expressed as

$$F(t)=F_0 \exp(-t/\tau_{CE}), \quad (1)$$

where F_0 denoted the value of the electrostatic force at start point of the first or second stage. The time constant τ_{CE} were estimated by extrapolation. In the case of p-type silicon substrate, τ_{CE} is estimated to be ~170 s (t<100 s), ~70 s (t>100 s) for the repulsive forces and ~130 s (t<100 s), ~20 s (t>100 s) for the attractive forces, respectively. On the other hand, in the case of n-type silicon substrate, τ_{CE} is estimated to be ~ 80 s through the whole measurement for the repulsive forces and ~80 s (t<50 s), ~60 s (t>50 s) for the attractive forces, respectively. We can see that, in the case of p-type silicon substrate, the time constant τ_{CE} changed remarkably between the first and second stage. However, these mechanism of the dissipation of the charges is now under investigation.

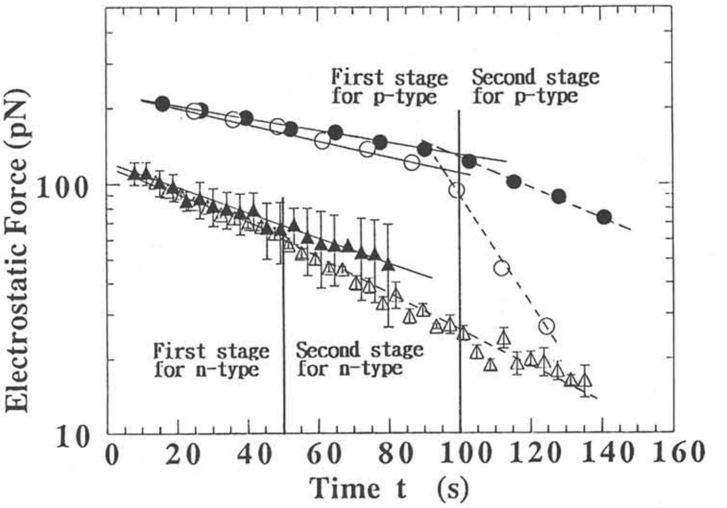

Figure 4 The peak value of the electrostatic force as a function of the time. The solid and dashed lines are guide to the eyes.

4. Conclusion

We investigated the time evolution of the contact-electrified charges for p-type and n-type silicon substrates. As a result, we could successfully image the dissipation of the contact-electrified charges after single contact. Also, we found that the dissipation of the charges had two stages with respect to the time.

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