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Local Dielectric Breakdown of Thin Silicon Oxide by Dense Contact Electrification

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We achieved microscopic measurement of time dependent dielectric breakdown (TDDB) for a thin silicon oxide using dense contact electrification. By increasing the number of contact-electrified charges, TDDBs of the oxide layer without and with surface roughening were observed. Charge-to-breakdown Q_{BD} in these experiments were estimated to be on the order of 10^{-5} C/cm^2, which is much lower than that obtained in the conventional TDDB measurement using a metal-oxide-semiconductor (MOS) capacitor.

1. Introduction

Silicon oxide layer plays an important role in advanced metal-oxide-semiconductor (MOS) devices.[1] In particular, dielectric breakdown characteristics of the oxide layer greatly affect the reliability of the devices. Hence, for the evaluation of the sub-micron-scale MOS devices, it is necessary to investigate local dielectric breakdown with nanometer-scale resolution.

In this paper, we report the local dielectric breakdown using "dense contact electrification".[2-6] This method enables us to measure time dependent dielectric breakdown (TDDB) with nanometer-scale resolution. Furthermore, we estimated charge-to-breakdown Q_{BD} using simple model. These estimated values were compared with that obtained in the conventional MOS capacitor measurement.

2. Experimental

In the present experiment, we used an atomic force microscope (AFM) equipped with conductive cantilever and external voltage source.[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 imaged as the electrostatic force induced on the tip of the conductive cantilever with the bias voltage V_S (measurement voltage) under the non-contact DC mode as shown in Fig. 1(b).

The silicon oxide layers used in the present study were formed on p-type single crystal Si(100) wafers with resistivity of 10-20 Ω·cm. Using the ellipsometry, the oxide layer thickness was determined to be 54 ± 1 Å.

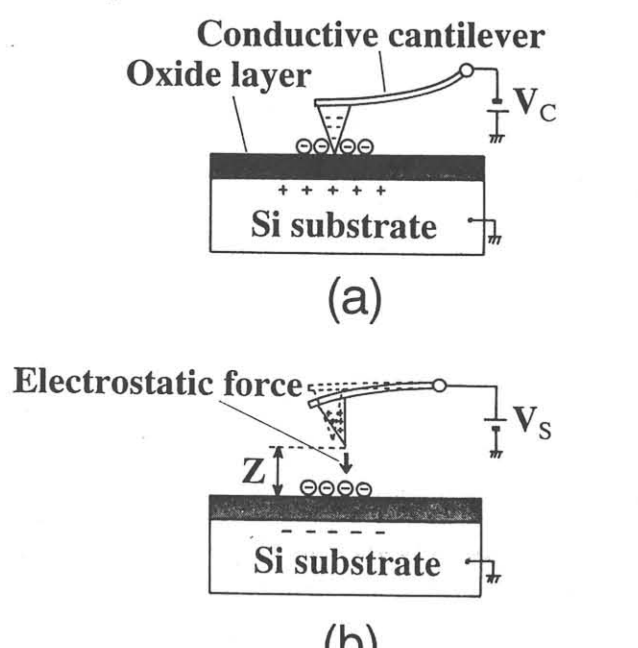

Fig. 1. Schematic models of the experimental setup for the contact electrification with the AFM (a) and electrostatic force measurement with the non-contact DC mode AFM (b).

3. Results and Discussion

3.1 TDDB without oxide surface roughening

Figure 2(a) shows spatial distributions of electrostatic force from 7 s to 12 min 32 s after contact electrification. Here, contact voltage, contact time, measurement voltage and tip-sample distance were V_c=-8 V, t_0=30 s, V_s=-8 V and Z≒620 Å, respectively. In early stage, the electrostatic force decays giving a round peak. However, about 9 minutes after contact electrification a hollow region indicated by the arrow appears in the spatial distribution. This hollow region may indicate that the contact-electrified charges flowed into the oxide layer due to its deterioration. After electrostatic force measurement, surface topography of the oxide layer was observed by the contact mode AFM. As a result, no topographical difference was found between before and after contact electrification. Therefore, TDDB without oxide surface roughening can be achieved under the present contact electrification conditions. Figure 2(b) shows a schematic model of TDDB without oxide surface roughening. Some of contact-electrified charges penetrate into the deteriorated region (the hatched oxide layer), as the solid arrows. After a while, the negative charges seem to dissipate from the hatched region to the silicon substrate via a tunneling process as the broken arrows.

3.2 TDDB with oxide surface roughening

We performed contact electrification with higher contact voltage V_c. Figure 3(a) shows the spatial distributions of the electrostatic forces from 7 s to 12 min 32 s after contact electrification. Here, V_c=-10 V, t_0=30 s, V_s=10 V and Z≒620 Å, respectively. A hollow region appears clearly even in the spatial distribution at 7 s after contact electrification and increases with time. We confirmed that surface topography of the oxide layer became rough after electrostatic force measurement. This surface roughening of the oxide layer seems to be caused by Joule heating with high density current flowing directly through the deteriorated oxide layer (the hatched oxide layer) as shown in Fig. 3(b). Therefore, TDDB measurement with oxide surface roughening seems to be applicable under the present conditions.

3.3 Comparison with dense contact electrification and MOS capacitor

We estimated the charge-to-breakdown Q_{BD} in our experiment and compared it with

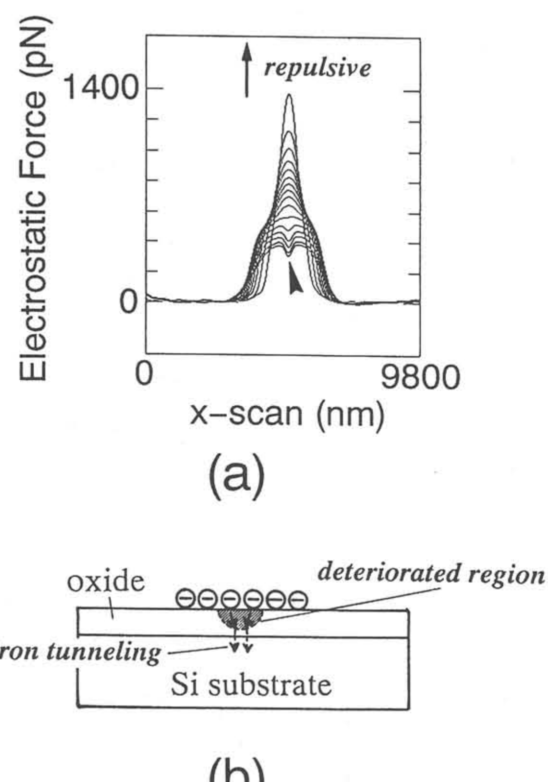

Fig. 2. (a) Spatial distributions of the electrostatic force form 7 s to 12 min 32 s after dense contact electrification. (b) Schematic model of TDDB without oxide surface roughening.

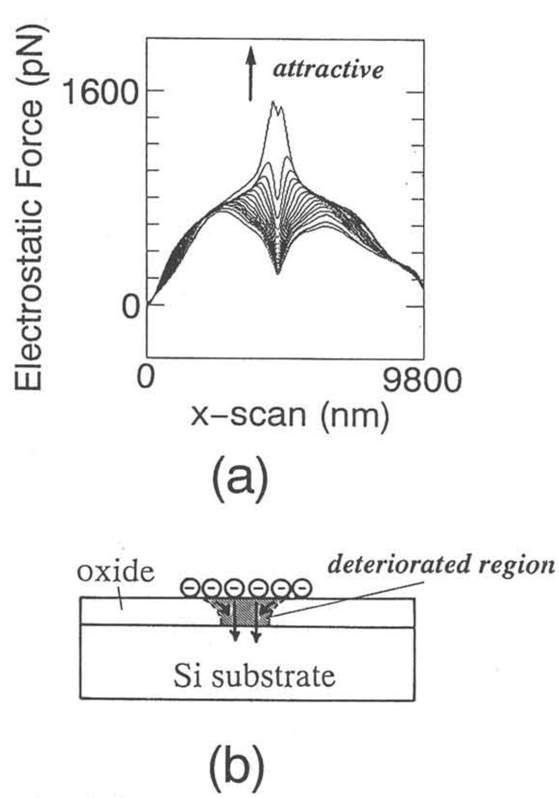

Fig. 3. (a) Spatial distributions of the electrostatic force form 7 s to 12 min 32 s after dense contact electrification. (b) Schematic model of TDDB with oxide surface roughening.

that obtained in the conventional TDDB measurement using a MOS capacitor. First, we calculated contact-electrified charges Q_s in dense contact electrification by means of point-charge approximation, taking into account the effect of image charge in a silicon substrate. Here, we used the following equation to evaluate Q_s,

$$F(t) \fallingdotseq Q_s(t) C V_s / 4\pi\varepsilon_0 (Z+R)^2 - Q_s(t) C V_s / 4\pi\varepsilon_0 (Z+R+2h)^2. \quad (1)$$

Here, R,Z and h denote radius of curvature of the tip, tip-sample distance and oxide thickness, respectively. C denotes capacitance between the tip and sample, which are treated as a sphere-plane model. Using R=250 Å, Z=620 Å and h=54 Å, Q_s is estimated to be $\sim 2\times10^{-16}$ C for dense contact electrification of negative charges in Figs. 2 and 3. Assuming that the effective diameter for electrostatic force sensing on the tip is 500 Å (=2R), charge-to-breakdown $Q_{BD}=Q_s/\pi R^2$ is estimated to be $\sim 1\times10^{-5}$ C/cm^2.

On the other hand, in the conventional TDDB measurement using the MOS capacitor, it is reported that charge-to-breakdown Q_{BD} at 50% cumulative failure is $\sim 5\times10^{-1}$ C/cm^2 ($t_{ox} \fallingdotseq 50$ Å).[8] Assuming the electrode area of nm^2, Q_{BD} in the conventional TDDB measurement is estimated to be $\sim 5\times10^{-15}$ C/nm^2, which corresponds to the number of injected charges of $\sim 3\times10^4$ per nm^2, or $\sim 5\times10^2$ per atom. Thus, Q_{BD} in the conventional TDDB measurement seems to be unreasonably large. In case of TDDB measurement using contact electrification, the number of injected charges is estimated to be $\sim 7\times10^{-1}$ per nm^2, or $\sim 1\times10^{-2}$ per atom. The difference of Q_{BD} between contact electrification and MOS capacitor measurement may be attributed to the difference of the measurement procedure. That is, while deposition and observation of contact-electrified charges were conducted independently in contact electrification, observation and charge injection were performed simultaneously in MOS capacitor measurement.

4. Conclusion

We achieved microscopic measurement of TDDB for a thin silicon oxide layer by dense contact electrification. As a result, TDDB of the oxide layer without oxide surface roughening was observed, then TDDB of the oxide layer with oxide surface roughening was observed. Furthermore, charge-to-breakdown in dense contact electrification was estimated to be on the order of 10^{-5} C/cm^2. This estimatd value is much smaller than the value obtained in the conventional TDDB measurement using a MOS capacitor. From the estimation of the number of injected charges per atom, TDDB measurement using dense contact electrification is expected to provide a more quantitative evaluation of charge-to-breakdown of the silicon oxide layer than the conventional TDDB measurement using a MOS capacitor.

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References

1) S.M.Sze: Physics of Semeconductor Devices 2nd ed. (John Wiley & Sons, Canada, 1981)
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.Sugwara and Y.Fukano: Jpn.J.Appl.Phys. **32** (1993) 2983.
8) E.Hasegawa, K.Akimoto, M.Tsukiji, T.Kubota and A.Ishitani: Ext.Abstr. 1993 Intn'l. Conf. Solid State Devices and Materials, Chiba, 1993 (Business Center for Academic Societies Japan, Tokyo, 1993) p.86.