Extended Abstracts of the 1992 International Conference on Solid State Devices and Materials, Tsukuba, 1992, pp. 117-119

Nanometer Resolution Measurement of Dielectric Breakdown of Silicon Dioxide Films with AFM/STM

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We investigated local dielectric breakdown voltage for the silicon oxide layer with scanning force/tunneling microscope(AFM/STM) in air. It was manifested that this novel technique can measure dielectric breakdown voltage with nanometer resolution in correlation with the topography. We confirmed that the dielectric breakdown voltage measured with the AFM/STM increased monotonously with increase of the oxide thickness. In addition to the above results, we found that the oxide layer with visible defect had a lower dielectric breakdown voltage.

1. Introduction

Silicon oxide layer is playing an important role in microelectronics devices such as integrated metal-oxide-semiconductor (MOS) devices. In particular, insulating characteristics of the oxide layers are very important for the reliability of the devices. So far, insulating or dielectric breakdown characteristics have been investigated by fabricating MOS capacitor[1]. However, it has been difficult to characterize the local distribution of the dielectric breakdown of the oxide layer with nanometer scale resolution.

In this paper, we first report on a novel technique to measure the nanometer scale distribution of dielectric breakdown voltage of the oxide layer. Further the correlation between the dielectric breakdown voltage and the surface topography of the oxide layer was investigated in air. For this purpose, the scanning force/tunneling microscope (AFM/STM)[2-4] operating under the constant force mode was used.

2. Experimental

The silicon oxide layers used in the present studies were formed on p-type single crystal Si(100) wafers. Wafers were cleaned by the conventional RCA method and thermally oxidized at 950 °C in dry oxygen gas. Resistivity and concentration of oxygen impurity for the wafers were 10-20 Ω·cm and $(13\text{-}15)\times10^{17}cm^{-3}$, respectively. We used two types of oxide layers: One sample was observed without further process (as-grown oxide layer) . The other sample was etch-backed to obtain thinner oxide layer (etch-backed oxide layer). The etching was made with 1 % HF aqueous solution at room temperature. Thickness of the oxide layers was determined with the ellipsometry.

The AFM/STM system used in our experiments is described in detail in a previous paper[2-4]. The sample was mounted on a piezoelectric PZT tube scanner, which moved the sample in X, Y and Z directions. AFM topographic image was obtained by adjusting the sample position Z to maintain a constant repulsive force between the sample and the conductive lever under the strong feedback condition. Force measurement was performed by monitoring the lever deflection with all-fiber interferometer[5]. Local dielectric breakdown voltages were directly obtained by monitoring the dielectric breakdown current I_{BD} flowing between the sample and the conductive lever under the bias voltage V_T. Here, the current I_{BD} was monitored at the back side of the sample. We used a conductive lever with ion-implanted diamond tip sharpened to a radius of curvature of ~1000 Å[6] to simultaneously sense the force and the current I_{BD}. The conductive lever had spring constant $k \fallingdotseq 6N/m$ and mechanical resonant frequency $f_R \fallingdotseq 2kHz$, respectively.

3. Results and discussion

At first, we investigated the dielectric breakdown for the etch-backed oxide layer. The thickness of the oxide layer was

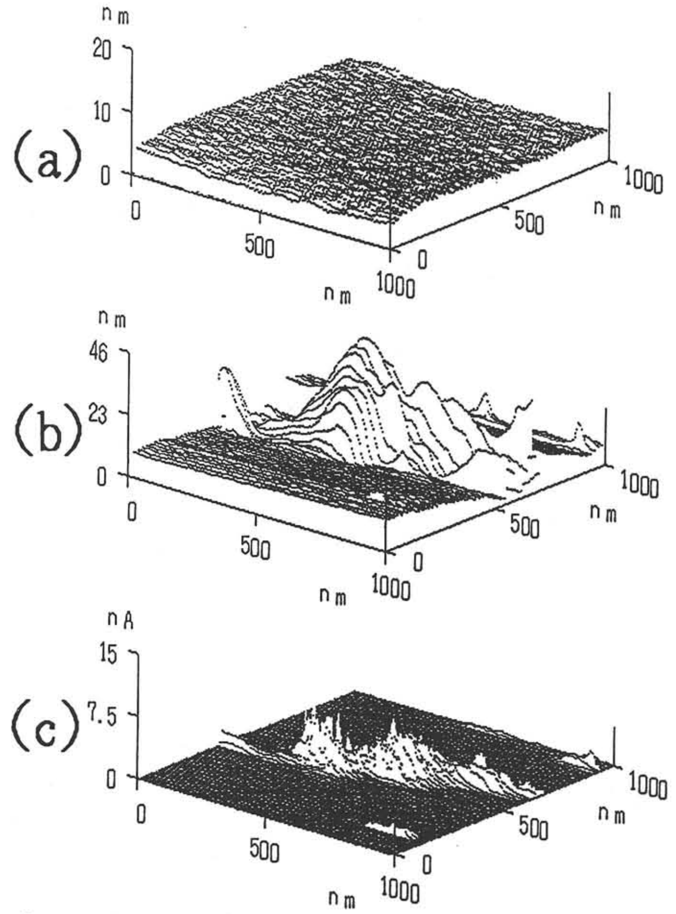

Figure 1 Experimental results of dielectric breakdown for etch-backed oxide layer with flat surface. (a) AFM topographic image measured at V_T=10.0 V, (b) AFM topographic image measured at V_T=12.5 V, (c) STM current image measured simultaneously with (b).

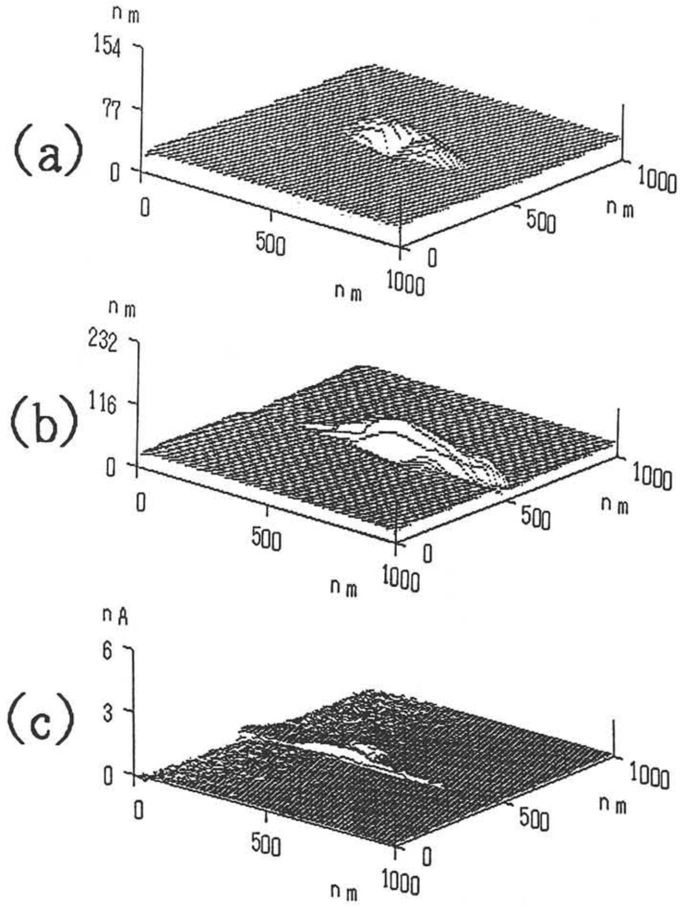

Figure 2 Experimental results of dielectric breakdown for etch-backed oxide layer with visible defect. (a) AFM topographic image measured at V_T=6.0 V, (b) AFM topographic image measured at V_T=8.0 V, (c) STM current image measured simultaneously with (b).

estimated to be 12.5 ± 2.4 nm. Although in most case the surface was uniform and has no visible defect as shown in Fig. 1(a), in special case the surface has defect as shown in Fig. 2(a). This defect may be appeared due to the difference of the etching rate and/or quality for the oxide layer. In the case of the surface without visible defect, with the step increase of 2.5 V of the bias voltage, the current I_{BD} flowed at V_T=12.5 V at last. Here, dielectric breakdown field was roughly estimated to be 12.5 V/12.5 nm =10 MV/cm. From STM current image in Fig. 1(c), we can see that the current I_{BD} flowed locally on the surface. This result may be due to that the thickness of the etch-backed oxide layer is not uniform. On the other hand, in the case of the surface with visible defect, with the step increase of 2.0 V of the bias voltage, the current I_{BD} flowed at V_T=8.0 V. This dielectric breakdown voltage of 8.0 V is 4.5 V lower than that of the oxide layer without visible defect. Dielectric breakdown field was roughly estimated to be 8.0 V/12.5 nm =6.4 MV/cm.

Further, we investigated the dielectric breakdown for the as-grown oxide layer. Figure 3(a) shows AFM topographic image of the as-grown oxide layer with considerably flat surface before dielectric breakdown. The thickness of the oxide layer was estimated to be 10.5 ± 0.7 nm . The bias voltage was V_T=10.0 V. With step increase of 2.5 V of the bias voltage V_T, the dielectric breakdown current I_{BD} flowed at V_T=12.5 V at last. Thus, dielectric breakdown field was roughly estimated to be 12.5 V/10.5 nm =12 MV/cm. Figures 3(b) and 3(c) show AFM topographic and STM current images at V_T=12.5 V after dielectric breakdown. From STM current image in Fig. 3(c), we can see that the current I_{BD} uniformly flowed everywhere on the surface.

From AFM topographic images such as Fig. 1 ~ 3, we confirmed that the topography of the oxide surface was reproducible before the dielectric breakdown. However, it changed to be rough surface after the dielectric breakdown. This roughening

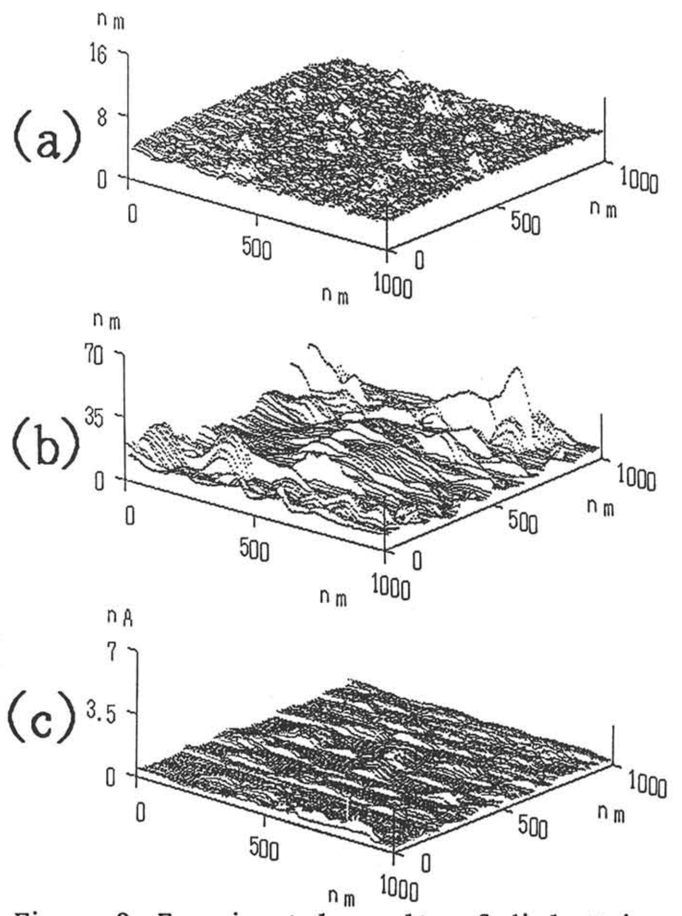

Figure 3 Experimental results of dielectric breakdown for as-grown oxide layer with flat surface. (a) AFM topographic image measured at V_T=10.0 V, (b) AFM topographic image measured at V_T=12.5 V, (c) STM current image measured simultaneously with (b).

phenomena are now under investigation.

Fig. 4 shows typical experimental values for the dielectric breakdown voltage as a function of the oxide layer thickness. Here, open-triangles, open-circles, and closed-triangles correspond to etch-backed oxide layer with flat surface, as-grown oxide layer with flat surface and etch-backed oxide layer with visible defect, respectively. Lower and upper bound of dielectric breakdown voltages correspond to where the dielectric breakdown current began to flow locally on the surface and flowed everywhere on the surface, respectively. Horizontal bars correspond to the scattring of oxide layer thickness measured by the ellipsometry. From Fig. 4, we confirmed that, for the as-grown and etch-backed oxide layers with flat surface, the dielectric breakdown voltage measured by the AFM/STM increase monotonously with increase of the oxide layer thickness. However, for the etch-backed oxide layer with visible defect, the breakdown voltage becomes lower.

In order to investigate the dielectric breakdown voltage of MOS capacitor in the larger area, the AFM/STM should be combined with the optical microscope with a coarse X-Y stage which enables us to assign the place measured by the AFM/STM.

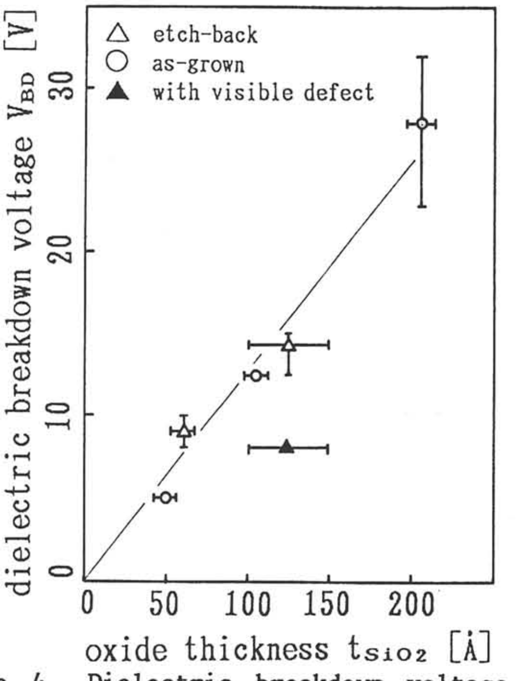

Figure 4 Dielectric breakdown voltage of the oxide layer as a function of the oxide layer thickness.

4. Conclusion

We first applied the AFM/STM to measure local dielectric breakdown voltage in air with nanometer resolution in correlation with the topography. We confirmed that the dielectric breakdown voltage measured with the AFM/STM increased monotonously with increase of the oxide thickness. Further, we found that the oxide layer with visible defect had a lower dielectric breakdown voltage.

Acknowledgment

We would like to thank Dr. Takao Okada, Mr. Syuzo Mishima and Mr. Syuichi Ito of Olympus Optical Co. Ltd for the construction of the AFM/STM unit.

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