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C-9-2

Stable Observation of the Evolution of Leakage Spots in HfO_2/SiO_2 stacked structures by UHV-C-AFM

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1. Introduction

Several interesting studies by C-AFM (Conductive – Atomic Force Microscopy) [1,2] have been performed so far to investigate the microscopic origin of the degradation phenomena of gate dielectrics in MOSFET. Nevertheless, although the problem of material formation on the surface during the scanning in air and the necessity of doing the experiment in UHV (Ultra High Vacuum) have been addressed already nearly ten years ago [1], to the author's knowledge, any experiment in UHV has yet to be done.

On the other hand, to prepare for the further shrinkage of circuit elements, high-k dielectrics are studied extensively [3]. In this study, we have performed a C-AFM study on HfO_2/SiO_2 stacked structures in UHV atmosphere for the first time and succeeded to observe reproducible images of localized leakage spots.

2. Experiment

The HfO_2 films were deposited on n-type Si(100) wafers by reactive sputtering in O_2/Ar flow, followed by annealing in O_2 or N_2. The annealing condition and the thickness of the samples, determined by Grazing Incidence X-ray Reflectivity and Spectroscopic Ellipsometry, are summarized in Table I. The C-AFM experiment was performed with a Pt coated Si cantilever in a UHV chamber (< 2×10^{-10} torr) and each time the scanning of the whole area (500nm x 500nm) was completed, the bias voltage was increased by 0.1V and the scan of the same area was repeated. When the largest current in the area exceeded 8nA, the tip was moved to a new area and the scanning was resumed starting again from a small bias voltage where no leakage spot was observed.

3. Results and Discussion

Fig.1 shows the current images of sample(1) at positive tip bias. The doughnut-shaped patterns, ~50nm in diameter, start to appear at an imaging bias of 4.2V, Fig.1(a), and it is seen that the number of these doughnut-shaped patterns increases as the bias increases and so does the current at the already existing spots. Only a noise level of current is observed in the background and the leakage is completely local. The local leakage is observed for both polarities for samples (1) and (2). After imaging at a bias of 5.0V, Fig.1(c), the imaging bias is reduced to 3.8V, Fig.1(d), where several leakage spots are observed. Since no leakage spot is observed at this low bias at the beginning for a fresh area, this shows that some irreversible degradation have already taken place in the sample by imaging.

The situation where a tip crosses above a localized leakage spot is schematically shown in Fig.2. Since the shape of the doughnut-shaped pattern in Fig.1 is almost identical, we believe that the size of the leakage path is much smaller than the tip size and consequently what is imaged is the shape of the tip. A doughnut-shaped pattern is obtained if the center of the tip is depleted for some reason and corresponds to one leakage path which is much smaller than the size of the pattern.

Therefore, the image of a single leakage spot depends on the tip shape if the tip is larger than a leakage path. An example is shown in Fig.3, which shows the localized spots observed for sample (3) with a different tip in the case of positive tip bias. Again the shape of each spot is identical (this time, the top of the tip is flat) and this fact strongly supports the image formation mechanism (Fig.2).

Another interesting feature is found in the polarity dependence of the image of a single leakage spot. As can be seen in Fig.1, the size of each leakage spot increases at the beginning but saturates eventually at some bias. Fig.4 shows the saturated image of a single leakage spot of sample(1) for positive and negative tip biases. Although this pattern shows the shape of the same tip, it is seen that the resolution of the image for the positive bias is much sharper and the size of the whole pattern is smaller compared to that for the negative bias. If we assume that the size of the spot in the current image is the sum of the tip size and leakage path size (Fig.2), it can be deduced from the images that the leakage path for negative tip bias is ~15nm larger. Although this could be caused by a difference in trap generation mechanism as explained below, an inversion in the injection direction of carriers could be another possible explanation.

A topography (not shown) was also taken at the same time but no clear relation has been found between the topography and the current image. No topography change has been observed either after taking several current images on the same area, which shows that no material formation took place during the experiment thanks to the UHV environment. Also the fact that the image of the localized spot, which is the shape of the tip, does not change during the experiment means that the tip is also stable during the experiment.

A completely different mode is observed for negative bias of sample (3). Although the leakage observed in Fig.1 is local, the current in Fig.5 is homogeneous, i.e. a finite current is observed all over the surface from ~ –4V. Moreover the current is reversible up to –10V in a sense that when the measurement is repeated at the same area starting again from a small bias, an exactly same result is obtained. This result is in contrast to the local leakage mode where some degradation in the film have already taken place.

Finally, we would like to discuss the results obtained in the local leakage mode. From the current images, the evolution of the leakage spot density and current density of the whole area (500nm x 500nm) as a function of tip bias is obtained for samples (1) and (2) (Fig.6). It is seen that both of them increase exponentially as a function of bias. Although the magnitude of the current density is quite large, we believe that this is caused by a multiple counting of the current at one leakage spot due to a large tip size (Fig.2) and the real current density should be two to three orders of magnitude smaller. By inspecting the band diagram (not shown) assuming that our films are complete dielectrics, it turns out that the results observed for samples (1) and (2) shows the degradation of the interfacial SiO_2 layer only and that the leakage path is created by electrons and holes for positive and negative tip biases, respectively. Therefore, the difference in Fig.4 could imply a big difference in trap generation mechanism by electrons and holes in interfacial SiO_2.

4. Conclusions

The C-AFM in UHV has been used for the first time for HfO_2/SiO_2 stacked gate dielectrics to spatially resolve the occurrence of leakage current on a nanometer scale and reproducible images of localized leakage spots are observed successfully.

Acknowledgements

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References

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Table I Specification of the samples.

Sample	Annealing Condition	d_{HfO2}(nm)	d_{SiO2}(nm)
(1)	N_2 , 600C , 30sec	6.3	3.4
(2)	O_2 , 600C , 30sec	6.3	3.7
(3)	O_2 , 500C , 30sec	4.5	2.1

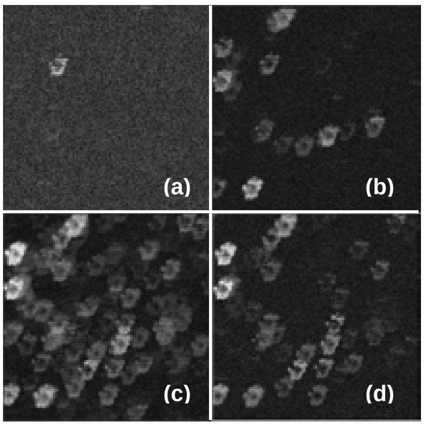

Fig.1 Current images of sample(1) at positive tip bias (500nm x 500nm). The tip biases are (a) 4.2V, (b) 4.6V, (c) 5.0V and (d) 3.8V.

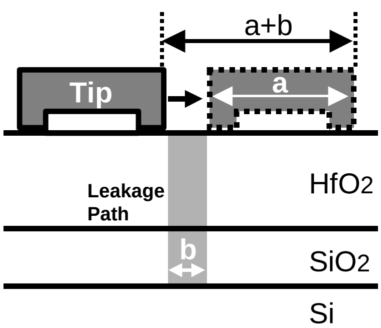

Fig.2 The process where a conductive tip moves above the leakage path is shown schematically. The width of the current image will be the total of the tip width, a, and leakage path, b.

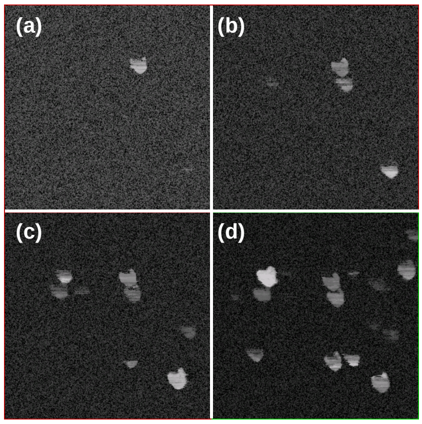

Fig.3 Current images of sample(3) at positive tip bias (500nm x 500nm). The tip biases are (a) 3.0V, (b) 3.1V, (c) 3.2V and (d) 3.3V.

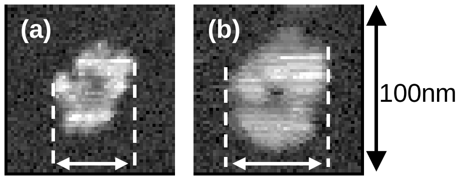

Fig.4 Current images of a single leakage path of sample(1) for (a) positive (4.6V) and (b) negative tip bias (–6.5V). The size difference is ~15nm for both horizontal (indicated by white arrows) and vertical directions.

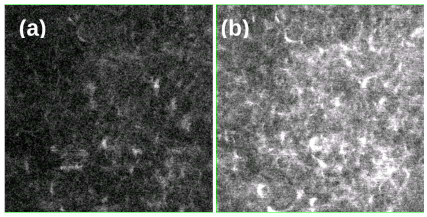

Fig.5 Current images of sample(3) at negative tip bias (500nm x 500nm). The tip biases are (a) –9.5V and (b) –10.0V.

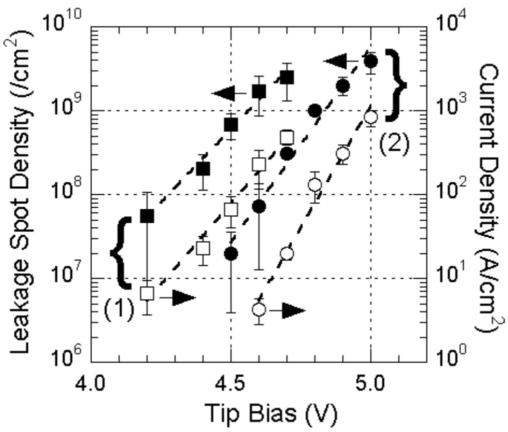

Fig.6 Tip bias dependence of the leakage spot density and current density of samples (1) and (2) for positive tip bias.