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Behavior of Local Charge Trapping Sites in La_2O_3-Al_2O_3 Composite Films under Constant Voltage Stress

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1. Introduction

It is well known that high-k gate dielectric films generically have a higher number of intrinsic defects which readily trap charges, compared with conventional gate SiO_2 films. Since the trapped charges are harmful in device performance, leading to threshold voltage shift, carrier mobility degradation, and dielectric current leakage [1-3], clarifying creation mechanisms of trapping sites and behaviors of the trapped charge is essential to improve the device reliability. In general, the trapping site is attributed to structural defects with an atomically-scaled size in the film. Therefore, not only the macroscopic measurement of electrical properties using conventional devices but also the microscopic one is thoroughly required.

We have focused on conductive atomic force microscopy (C-AFM) which can detect a microscopic distribution of local current leakage sites in gate dielectric films [4-6]. Recently, local current leakage and their origins in La_2O_3-Al_2O_3 composite films [7] have also been studied by C-AFM [8]. In this work, we investigate the performance of charge trapping sites in the La_2O_3-Al_2O_3 composite film by observing local current leakage spots under constant voltage stress applied during C-AFM observation.

2. Experiment

La_2O_3-Al_2O_3 composite films with a thickness of 4.2 nm were synthesized on HF-treated n-type Si (001) substrates by a pulsed laser deposition (PLD). A composition ratio was set to be La_2O_3:Al_2O_3 = 67:33. After the deposition, post deposition annealing (PDA) was performed at 1000°C for 15 s in nitrogen ambient. We have confirmed that these samples have homogeneous and amorphous structure by cross-sectional high-resolution transmission electron microscopy [7]. Capacitance equivalent oxide thickness of the samples was 1.4 nm. For the macroscopic measurements, current-voltage (*I-V*), current-time (*I-t*) and capacitance-voltage (*C-V*) characteristics were measured by using MOS capacitors which have Pt top electrodes with a gate area of 3×10^{-4} cm^2 and an Al back electrode. On the other hand, for the microscopic observation, current and topographic images with a scanning area of 1 μm^2 were observed by C-AFM with a Pt-coated Si conductive tip. In order to obtain the current density, an effective C-AFM tip contact area of 2×10^{-12} cm^2 was employed [8]. In this C-AFM system, we can obtain a current noise level of approximately 50 fA [8]. The current leakage measurements using MOS capacitors and C-AFM were performed under the accumulation condition in which Si substrate becomes cathode electrode.

3. Results and Discussion

Figure 1 shows *I-t* characteristics obtained from the MOS capacitor at constant gate voltages of 3.2 V and 3.4 V. In these gate voltage cases where the Fowler-Nordheim (F-N) current becomes dominant [8], the leakage current density increases with time. This tendency strongly suggests that holes are trapped in the film during the constant voltage stress and enhanced electric field caused by the trapped holes results in the current increase.

Figures 2(a)-(d) show current images of an identical area taken under continuous scanning at a substrate voltage of -3.25 V. In this measurement, we scanned the area several times at a substrate voltage of 0 V between the seventh and the eighth scans. Several current leakage spots were observed in all the current images whereas a topography image obtained simultaneously exhibited a very flat surface (not shown). Most of the leakage spots appearing in the early stage of scanning frequency are caused by increased current at the intrinsic defects sites and/or the sites with the structural fluctuation of the film [8]. It is observed that the number of leakage spots gradually increases with scanning frequency until the seventh scan. Figures 3(a) and 3(b) shows a series of close-up current images revealing the time evolution of the spots circled (1) and (2) in Fig. 2(b), respectively. As shown in Fig. 3(a), new leakage spots are prone to be created around the pre-existing leakage spots. On the other hand, it is also observed in Fig. 3(b) that pre-existing leakage spots were simply grown during the constant voltage stress.

It should be noticed in Fig. 2(c) that the leakage spots drastically decrease due to the 0 V scanning and increase again after the eighth scan. In order to examine this phenomenon in more detail, we have analyzed the current images microscopically. Average current densities (ACD) estimated from all observed area and the background region in the current images, and the area ratio of the leakage spots are shown in Figs. 4 and 5, respectively. They are plotted against the scanning frequency. Here, the background region is defined by the area other than the leakage spot sites. It is observed that both ACD for all the area and the area ratio of the leakage spots increase with the scanning frequency until the seventh scan. This means that the leakage spot current dominates all the detected current. The drastic reduction of leakage spots observed in Fig. 2(c) can be seen as a sudden drop of the ACD and the area ratio between the seventh and the eighth scans. On the contrary, the current density at the background region exhibits no drastic changes but gradual decrease with the scanning frequency.

The observed difference in time evolution of the current density at the leakage spot and the background region can be explained by charge trapping and detrapping mechanisms at defect sites in the film. To begin with, we consider the intrinsic defect which acts as a hole trapping site. At the area with trapped holes, leakage current locally increases due to the enhancement of electric field caused by the holes. Since the increased current newly creates hole trapping sites, the density of trapped holes increases further. By this positive feedback process, prominent increase in the leakage current probably occurs with increasing the scanning frequency. The fact that the leakage spot current is drastically reduced after the 0 V scanning possibly reflects that these trapping sites readily detrap the holes. On the other hand, the current at the background region gradually decreases with the scanning frequency even after the 0 V scanning, as shown in Fig. 4. This suggests that electron trapping dominates over the hole trapping at the background region and the trapped electrons are hardly detrapped from the sites.

4. Conclusions

We have studied the behavior of local current leakage sites in La_2O_3-Al_2O_3 composite films using C-AFM. Time evolution of the leakage spots during the constant voltage stage was observed. A remarkable difference of the time dependence was also detected between the leakage spots and the background regions of the film. Current increase in the leakage spot can be explained by the progressive hole trapping mechanism via positive feedback process. On the other hand, the current density at the background region monotonically decreases with time, being attributed to the electron trapping in the film. The detrapped behavior was found to be quite different between the hole and the electron: the hole was more easily detrapped than the electron.

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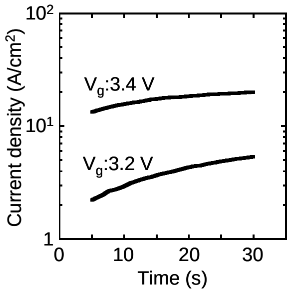

Fig. 1. *I-t* characteristics obtained from the MOS capacitor at constant gate voltages.of 3.2 V and 3.4 V.

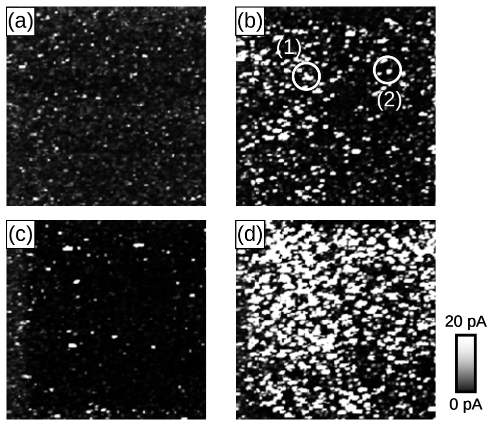

Fig. 2. Current images of an identical area taken under continuous scanning at a substrate voltage of -3.25 V: (a) first, (b) seventh, (c) eighth and (d) fourteenth scans. Scanning area is set to be 1 μm^2.

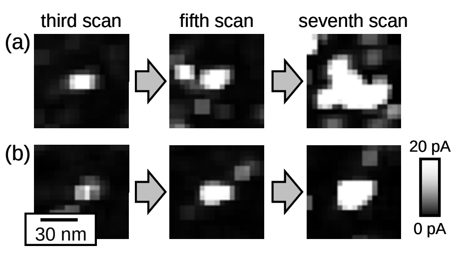

Fig. 3. Close-up current images at the third, fifth and seventh scans of (a) the leakage spot circled (1) and (b) that circled (2) in Fig. 2(b).

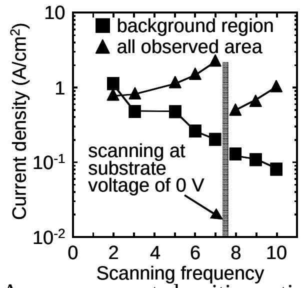

Fig. 4. Average current densities estimated from all observed area and the background region in the current images at a substrate voltage of -3.25 V as a function of scanning frequency.

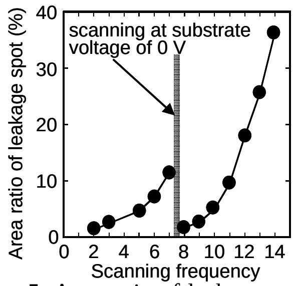

Fig. 5. Area ratio of leakage spots at a substrate voltage of -3.25 V as a function of scanning frequency.