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Local Current Leakage Characterization in La_2O_3-Al_2O_3 Composite Films by Conductive Atomic Force Microscopy

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1. Introduction

Reliability of high-k gate dielectric films has been vigorously examined for the purpose of applying practically to metal-oxide-semiconductor (MOS) transistors. Since high-k films generally have complicated structures consisting of a few kinds of elements, not only the macroscopic device performance measurement but also the microscopic analysis for local electric properties is important to clarify the current leakage and degradation mechanisms in the films. Conductive atomic force microscopy (C-AFM) is a powerful tool to analyze the local morphological and electrical properties in gate dielectric films[1,2]. We have elucidated thus far local current leakage and degradation processes in stressed SiO_2 films using C-AFM[3-7].

Recently, we have synthesized La_2O_3-Al_2O_3 composite films which are expected as one of promising high-k gate films[8]. Our previous study revealed that post-deposition annealing (PDA) at high temperatures for the La_2O_3-Al_2O_3 composite films dramatically improves their capacitance equivalent oxide thickness but leads to the degradation of current leakage property. In this work, we focus on the phenomena associated with the local current leakage in the La_2O_3-Al_2O_3 composite films grown under various conditions. C-AFM analysis is demonstrated to detect current leakage spots and investigate the leakage properties depending on the sample voltage. The effect of local leakage current on the macroscopic device properties is also discussed.

2. Experiment

Samples were grown by a pulsed laser deposition (PLD) method with La_2O_3 and Al_2O_3 targets. La_2O_3-Al_2O_3 composite films with a thickness of 4.2 nm were formed by stacking alternately ultra-thin Al_2O_3 and La_2O_3 layers on HF-treated n-type Si (100) substrates[8]. The Al_2O_3 content in the film was set to be 33%. The substrate temperature and ambient oxygen pressure during PLD were 400°C and 20 Pa, respectively. After the deposition, PDA was performed at 1000°C for 15 s in a N_2 ambient. Macroscopic device properties were evaluated by measuring current-voltage (*I-V*) characteristics using a MOS capacitor made with the synthesized composite film which has a Pt gate electrode with a gate area of 3×10^{-4} cm^2. Microscopic local current leakage properties were observed by C-AFM with a Pt-coated Si conductive tip. Surface topography and current images with a current noise level of 50 fA were simultaneously obtained under a vacuum condition of ~0.1 Pa. All current leakage properties were measured under the accumulation condition. In this experiment, for better correspondence between the characteristics obtained from the device measurements and the C-AFM observations, we employed the oxide voltage which was calculated both from the flatband and gate voltages of the MOS capacitor and the substrate voltage used in the C-AFM observation.

3. Results and Discussion

Figure 1 shows *I-V* characteristics obtained from the MOS capacitor and average current density measured from C-AFM current images taken at various oxide voltages. An effective contact area of a C-AFM tip is assumed to be 2×10^{-12} cm^2 [3]. The voltage dependence of current densities measured from the C-AFM agrees well with the *I-V* characteristic obtained from the MOS capacitor. A dotted line shown at the high voltage region is the *I-V* curve calculated assuming the Fowler-Nordheim (F-N) tunneling conduction[6] with an electron barrier height of 1.75 eV.

Figures 2(a) and 2(b) show a current image at an oxide voltage of 2.3 V and a corresponding surface topography image, respectively. Several current leakage spots with currents more than one digit larger than the average current are observed in the current image. Root-mean-square of surface roughness in the topography image was measured to be 0.12 nm. There is no remarkable correspondence between the sites of observed current spots and the surface morphology, indicating that the leakage spot is not merely attributed to the surface roughness. The size of the leakage spot is approximately equal to that of the tip contact area. When the leakage spot was identified as the site where the current exceeded a threshold value which is defined as a value larger than the average current by an amount of three times standard deviation of currents, a sum of current from all leakage spots can be estimated. As a result, the leakage current from the spots accounts for 12% of total current from the scanned area. This means that the region other than the spots mainly contributes to the current observed in the *I-V* characteristic of the MOS capacitor shown in Fig. 1.

Next, we examine the origin of the leakage spots. A current image taken at an oxide voltage of 1.8 V, which is lower than the case in Fig. 2, is shown in Fig. 3(a). For the observed leakage spots circled by (1) to (5), each current density depending on the oxide voltage was measured and resultant *I-V* characteristics are shown in Fig. 3(b) for the spots (1) to (3) and Fig. 3(c) for the spots (4) and (5) as well as measured average current densities from the scanned area. The dotted line shown in the figures is the same as that in Fig. 1. The leakage currents from the spots (1)-(3) have large values compared with the average currents at lower voltages and these currents do not increase very much at higher voltages. This phenomenon suggests current conduction via defects existing in the film. On the other hand, the leakage currents from the spots (4) and (5) drastically increase with increasing the oxide voltage. The *I-V* characteristic at the high voltage region can be seen as a F-N tunneling conduction with a shift to the low voltage, as shown in Fig. 3(c). At least two possibilities might explain the voltage shift: electric field enhancement due to positive charges and lowering of electron barrier height in the film. Since, at the low voltage region, the spot leakage currents are observed to be much larger than the average current, the shift is probably caused by the low electron barrier height at the leakage spot sites. A dashed line in Fig. 3(c) shows F-N tunneling conduction curve with an electron barrier height of 1.55 eV and fits well the I-V characteristics at the high voltage region. This barrier lowering is attributable to local structural changes such as compositional fluctuation in the film.

3. Conclusions

We have studied local current leakage property in PDA-treated La_2O_3-Al_2O_3 composite films using C-AFM. The quantitative comparison of current leakage was achieved between the C-AFM observation and the macroscopic measurement for the MOS capacitor. Current leakage spots were observed in the current images at all voltage regions. We confirmed two types of current conduction at the leakage spot sites, which can be categorized by the mediation of either the defects in the film or the low electron barrier height of the film.

References

[1] K. Honda, A. Sakai, M. Sakashita, H. Ikeda, S. Zaima and Y. Yasuda: Jpn. J. Appl. Phys. **43**, (2004) 1571.
[2] H. Ikeda, T. Goto, M. Sakashita, A. Sakai, S. Zaima and Y. Yasuda: Jpn. J. Appl. Phys. **42**, (2003) 1949.
[3] Y. Watanabe, A. Seko, H. Kondo, A. Sakai, S. Zaima and Y. Yasuda: Jpn. J. Appl. Phys. **43**, (2004) L144.
[4] Y. Watanabe, A. Seko, H. Kondo, A. Sakai, S. Zaima and Y. Yasuda: Jpn. J. Appl. Phys. **43**, (2004) 1843.
[5] Y. Watanabe, A. Seko, H. Kondo, A. Sakai, S. Zaima and Y. Yasuda: Jpn. J. Appl. Phys. **43**, (2004) 4679.
[6] A. Seko, Y. Watanabe, H. Kondo, A. Sakai, S. Zaima and Y. Yasuda: Jpn. J. Appl. Phys. **43**, (2004) 6483.
[7] A. Seko, Y. Watanabe, H. Kondo, A. Sakai, S. Zaima and Y. Yasuda: Jpn. J. Appl. Phys., submitted.
[8] R. Fujitsuka, M. Sakashita, A. Sakai, M. Ogawa, S. Zaima and Y. Yasuda: Jpn. J. Appl. Phys. **44**, (2005) 2428.

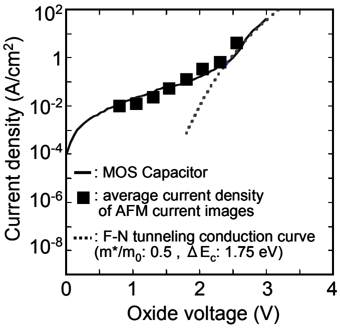

Fig. 1. *I-V* characteristics obtained from a MOS capacitor and average current densities of C-AFM current images.

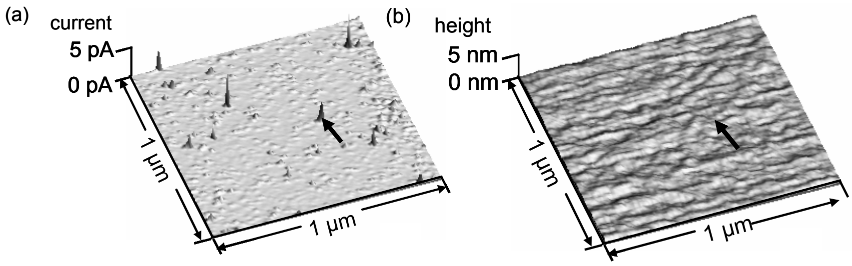

Fig. 2. (a) Current image at an oxide voltage of 2.3 V and (b) surface topography image. An arrow indicates exactly the same positions on each image.

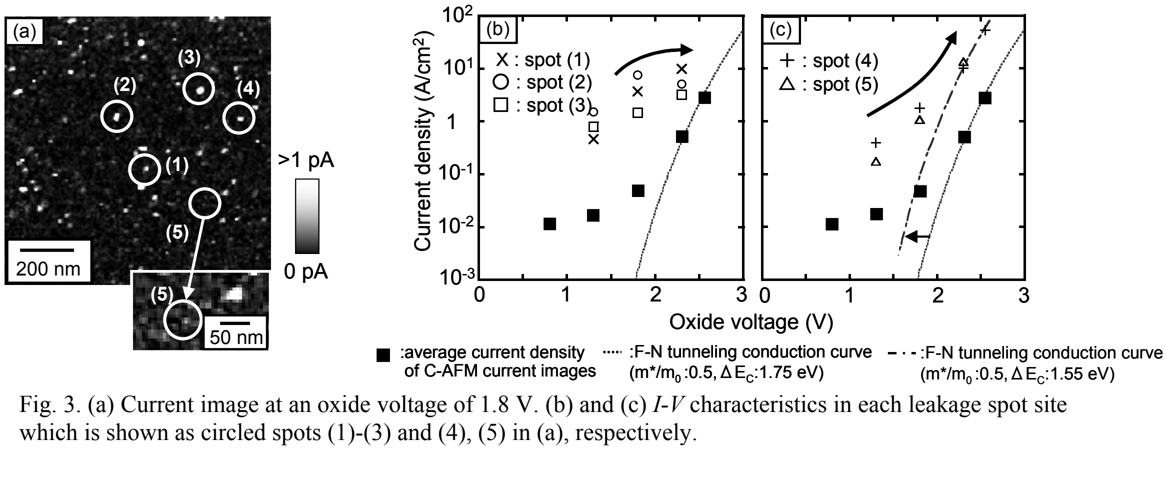

Fig. 3. (a) Current image at an oxide voltage of 1.8 V. (b) and (c) *I-V* characteristics in each leakage spot site which is shown as circled spots (1)-(3) and (4), (5) in (a), respectively.