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Local Leakage Current of HfO_2 Thin Films Characterized by Conducting Atomic Force Microscopy

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1. Introduction

Recently, many high-k materials replacing SiO_2 have been investigated to achieve low leakage current for next generation gate dielectric films in metal-oxide-semiconductor field-effect transistors (MOSFETs) [1]. HfO_2 films are very attractive as a promising candidate for the gate dielectric materials because of its high dielectric constant (~25), good thermal stability in direct contact with Si, relatively large band gap, and reasonable barrier height for carrier injection into the oxide film [2].

We have studied the relationship between the electrical and crystallographic properties of HfO_2 thin films and found that the leakage current and the hysteresis in capacitance-voltage characteristics are strongly dependent upon local bonding structures such as grain boundaries and orientation of the grain [3]. In this work, we investigated the local leakage characteristics of HfO_2 thin films, using conducting atomic force microscopy (C-AFM) and discussed the relationship between the morphological structure and the local leakage current microscopically.

2. Experimental

HfO_2 films were deposited by electron beam evaporation in an ultra-high vacuum (UHV) chamber at 700°C with a HfO_2 target on p-type Si(100) substrates. The base pressure of the UHV chamber was $5x10^{-10}$ torr and the O_2 pressure during the deposition was about $2x10^{-7}$ torr. The deposited HfO_2 film thickness was 3.1 nm evaluated from cross-sectional transmission electron microscopy (TEM). The surface morphology and the local electrical properties were measured by C-AFM at room temperature.

3. Results and Discussion

Figure 1 shows (a) surface morphology and (b) current images of a HfO_2 film on a Si(100) substrate. Both the images were simultaneously obtained at the same area. It is found that preferential conductive regions in the current image coincide with morphological protrusions on the HfO_2 surface, as shown by white circles in the images.

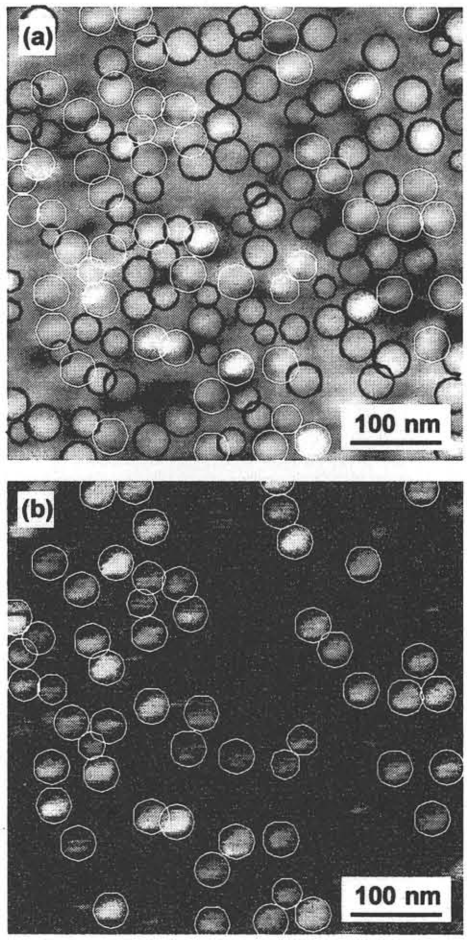

Fig. 1 (a) Surface morphology and (b) current images of a HfO_2 film on a Si(100) substrate deposited at 700°C, measured by C-AFM.

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This fact indicates that the local leakage region is observed at a thicker region in HfO_2 film thickness. Hence, we can deduce that the leakage site of the HfO_2 film is governed by a crystallographic origin.

In addition, it should be noticed in Fig. 1 that there are also protrusions indicating no significant current conduction, as shown by black circles in the morphological image. This means there are two kinds of protrusions with different crystallographic structures. A cross-sectional TEM image of the same HfO_2 sample is shown in Fig. 2. This image clearly reveals the fact that the HfO_2 film is polycrystallized and has a columnar structure basically (denoted by A in the figure). Moreover, stacked polycrystalline grains are also observed in the film (denoted by B). The coverage of the stacked grains on the surface was roughly estimated to be about 8% from the expanded cross-sectional TEM image. From Fig. 1, on the other hand, the coverage of the conductive protrusion region is about 6%, which is in good agreement with the stacked-grain coverage. It can be concluded that the conductive protrusion consists of a stacked polycrystalline grains.

Figure 3 shows current-voltage (I-V) characteristics of a conductive region (white circle in Fig. 1) and a background region on the HfO_2 film for negative sample biases (inversion condition), measured by C-AFM. For the background, the I-V curve has an elbow-shaped bend at about –3.6 V. At the lower current region, the I-V curve consists of direct tunneling current of electrons from the Si inversion layer to the Pt cantilever. At the higher current region, Fowler-Nordheim (F-N) tunneling current of the inversion electrons is dominant. From the band diagram, in fact, the conduction band edge of Si at the HfO_2/Si interface agrees with that of HfO_2 at the Pt/HfO_2 interface under a sample bias of –3.63 V. This fact supports the change from direct tunneling to F-N tunneling current at –3.6 V and suggests that the HfO_2 film as thin as 3.1 nm has an ideal band structure.

On the other hand, the I-V curve for the conductive region is also dominated by direct tunneling current below –2.4 V. However, the current is larger by a factor of 10^2 than that for the background. This fact can be explained by assuming that effective thickness for the electron tunneling is reduced to 2.3 nm, which is evaluated from the slope of I-V characteristics. Consequently, it can be deduced that the grain boundary at the stacked polycrystalline grains has an effect of reduction in the electron-tunneling thickness, resulting in conductive region.

4. Conclusions

We have investigated the relationship between the morphological structure and the local leakage current of HfO_2 thin films microscopically, using C-AFM. It is clarified that the stacked polycrystalline grains act as a leakage site due to reduction in the effective thickness for the electron tunneling.

Acknowledgements

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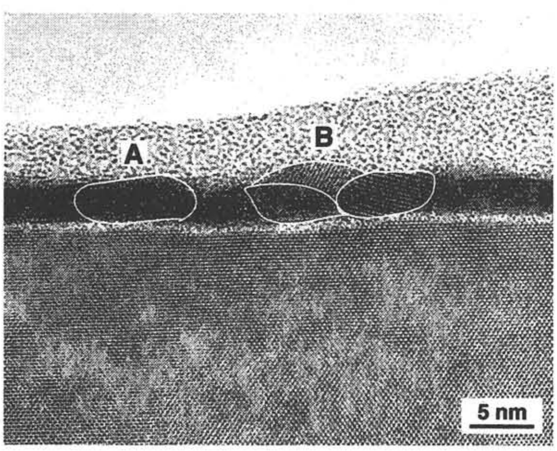

Fig. 2 Cross-sectional TEM image of a HfO_2 film on a Si(100) substrate deposited at 700°C.

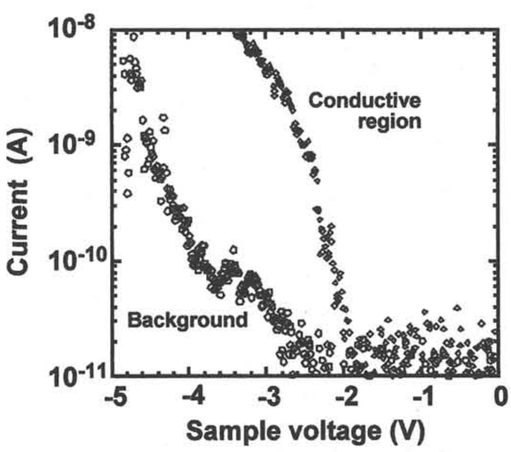

Fig. 3 Current-voltage characteristics of a conductive region and a background region, measured by C-AFM.