Extended Abstracts of the 2005 International Conference on Solid State Devices and Materials, Kobe, 2005, pp.236-237

A-4-1 (Invited)

Nanoscale Observations for Degradation Phenomena in SiO_2 and High-k Gate Insulators Using Conductive-Atomic Force Microscopy

Shigeaki Zaima, Akiyoshi Seko, Yukihiko Watanabe[1], Toshifumi Sago, Mitsuo Sakashita, Hiroki Kondo, Akira Sakai, and Masaki Ogawa[2]

Graduate School of Engineering, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8603, Japan
Phone: +81-52-789-2762 E-mail: zaima@alice.xtal.nagoya-u.ac.jp
[1]Toyota Central R&D Labs., Inc.
[2]Center for Cooperative Research in Advanced Science & Technology, Nagoya University

1. Introduction

Improvement in ULSI performance has been achieved by miniaturization and integration of metal-oxide-semiconductor (MOS) devices. The MOS device has already been scaled down to a nanometer size and the gate insulator has become thinner and thinner. Thus the fluctuation of various electrical properties in respective devices severely influences the total performance of ULSIs and hence understandings of local phenomena occurring in devices are essential. From this point of view, characterization of gate insulators using conductive-atomic force microscopy (C-AFM) has been attracting much attention [1-3]. C-AFM is a powerful tool to study localized current conduction phenomena in gate insulators, because it can simultaneously detect surface topography and current distribution. Recently, we have developed a C-AFM observation technique to analyze degradation phenomena of gate SiO_2 films, in which the electrical stress was applied in the form of a MOS capacitor [4]. In this paper, we review the recent results using C-AFM which clarify the local current leakage and the degradation process until the electric breakdown in gate SiO_2 and high-k insulators. We evaluate quantitatively the observed localized phenomena in comparison with electrical properties of usual MOS devices.

2. Derivation of C-AFM tip contact area

Figure 1 shows current-voltage (*I-V*) characteristics of nonstressed SiO_2 films with an ellipsometrical thickness of 11.3 nm. *I-V* data obtained from the MOS capacitor clearly obey the Fowler-Nordheim (FN) tunneling conduction mechanism, as shown by a dotted curve. *I-V* characteristics were also measured by the C-AFM detection at fixed positions and the data can be well fitted to the FN curve assuming that an effective contact area of a C-AFM tip was 2×10^{-12} cm^2. This derivation of the tip contact area allows us to link quantitatively the C-AFM data to the macroscopic electrical properties obtained from the device such as MOS capacitors.

3. Origin of local current leakage in stressed gate SiO_2 films

Gate SiO_2 films were stressed by applying the FN stress from the gate electrode of MOS capacitors. Existence of holes trapped in the stressed SiO_2 film was confirmed from a negative voltage shift of the MOS capacitance-voltage (*C-V*) curve. The film was then thinned from 11.3 nm to 4.7 nm by chemical etching just before the C-AFM observation. Figures 2 (a) and (b) show a surface topography and a current image, respectively. A number of current leakage spots are clearly observed in the current image. There is no marked correspondence between the surface morphology and the leakage spot sites. Furthermore, the facts that nonstressed SiO_2 films exhibited no such leakage spots in the C-AFM image and there observed no negative voltage shift in the *C-V* curves strongly suggest that the leakage spots in Fig. 2(a) are attributed to the trapped holes caused by the FN stress [4,5]. Figure 3 shows three *I-V* characteristics measured from the leakage spot and background region of the stressed SiO_2 film and from the nonstressed SiO_2 film. The *I-V* curve of nonstressed SiO_2 films is clearly fitted to the FN curve. Those of stressed SiO_2 films can also be fitted to the FN curves with some voltage shifts, indicating the existence of the trapped holes at not only the leakage spot sites but also the background region [6]. Dependence of these voltage shifts on thinned SiO_2 film thicknesses revealed the location of charge centroid and the amount of trapped holes. As a result, it is clarified that the trapped holes exist at a position away from the Si/SiO_2 interface by ~1 nm and the trapped hole density at the leakage spot is approximately two times larger than that at the background region. We have also confirmed that the total amount of the trapped holes estimated from this method was almost equivalent to that measured by the *C-V* characteristics of MOS capacitors.

4. Breakdown in stressed and nonstressed gate SiO_2 films [7]

Figures 4 (a) and (b) show current images of stressed and nonstressed SiO_2 films obtained by repeating the C-AFM scan at the same area with a constant substrate voltage of -5.5 V and -7 V, respectively. In case of the stressed SiO_2 film with trapped holes, the brightness of leakage spots gradually increased until the third scan and then, the breakdown occurred at one of the leakage spots at the fourth scan, as shown in Fig. 4 (a). This degradation process until the breakdown at the leakage spot seems to be a positive feedback process. In the nonstressed SiO_2 film, on the other hand, no leakage spots were observed until the fifth scan and the breakdown suddenly occurred at the sixth scan. Figure 5 shows the time dependent behavior of current leakage until the breakdown in the stressed and nonstressed SiO_2 films. The leakage current at the breakdown sites in nonstressed SiO_2 films decreases with the time, contrary to the case of stressed SiO_2 films. On the other hand, the difference between the observed times until the breakdown in both films suggests a similar amount of charges injected into the films. This result indicates that the modulation of the internal electric field caused by the trapped charges mainly affects the degradation process leading to the breakdown.

5. Analysis of current leakage in the gate high-k films

A La_2O_3-Al_2O_3 composite film is one of promising candidates for next generation high-k gate insulators [8]. Figure 6 shows the *I-V* characteristics of La_2O_3-Al_2O_3 composite films with a thickness of 4.2 nm, obtained from a MOS capacitor and an average current density of C-AFM images. Since these *I-V* characteristics exhibit good agreement, the leakage current obtained from C-AFM measurements is completely reflected in that of MOS capacitors. A dotted line at the high voltage region in Fig. 6 is the *I-V* curve calculated using an equation of the FN tunneling conduction to fit the experimental data, assuming a barrier height of 1.75 eV for electrons. These results mean that local fluctuation of electronic structures in the gate high-k insulator can be characterized by analyzing the local leakage current which is measured by C-AFM.

6. Conclusion

We have demonstrated that the C-AFM observation reveals local current leakage behavior and degradation phenomena in SiO_2 and high-k gate insulators. Quantitative analysis of local leakage current in the gate insulator allows us to compare the nanometer-scale electrical properties and macro-scale ones ordinarily measured in MOS capacitors. C-AFM has a great potential not only to observe spatial distributions of current leakage sites but also to clarify the local electronic properties in gate insulators.

References

[1] A. Ando, R. Hasunuma, T. Maeda, K. Sakamoto, K. Miki, Y. Nishioka, T. Sakamoto: Appl. Surf. Sci. 162-163 (2000) 401.

[2] H. Ikeda, N. Kurumado, K. Ohmori, M. Sakashita, A. Sakai, S. Zaima and Y. Yasuda: Surf. Sci. 493 (2001) 653.

[3] M. Porti, M. Nafría and X. Aymerich: Microelec. Reliability **43** (2003) 1501.

[4] Y. Watanabe, A. Seko, H. Kondo, A. Sakai, S. Zaima and Y. Yasuda: Jpn. J. Appl. Phys. **43** (2004) L144.

[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) 4683.

[7] A. Seko, Y. Watanabe, H. Kondo, A. Sakai, S. Zaima and Y. Yasuda: Jpn. J. Appl. Phys. in press.

[8] R. Fujitsuka, M. Sakashita, A. Sakai, M. Ogawa, S. Zaima and Y. Yasuda: Jpn. J. Appl. Phys. 44 (2005) 2428.

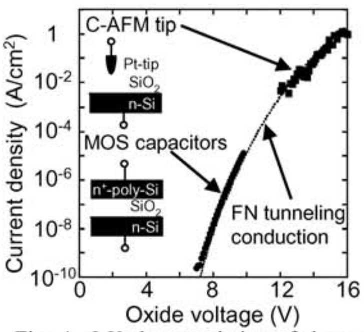

Fig. 1. *I-V* characteristics of the gate SiO_2 film with a thickness of 11.3 nm obtained from a MOS capacitor and a C-AFM measurement.

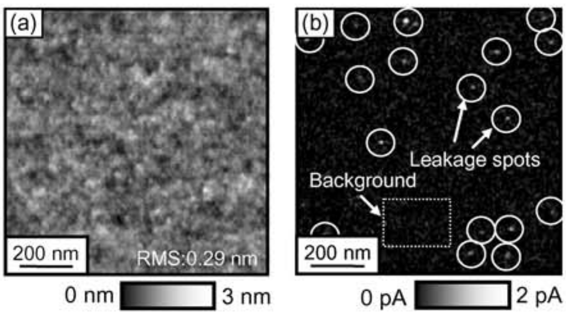

Fig. 2. C-AFM images of (a) surface topography and (b) a corresponding current image of the stressed SiO_2 film taken at a substrate voltage of -5 V.

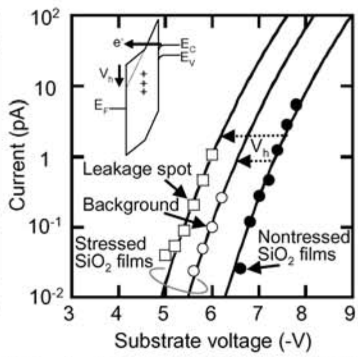

Fig. 3. *I-V* characteristics of the leakage spot and the background region in stressed SiO_2 films and an average current of the current image in nonstressed SiO_2 films.

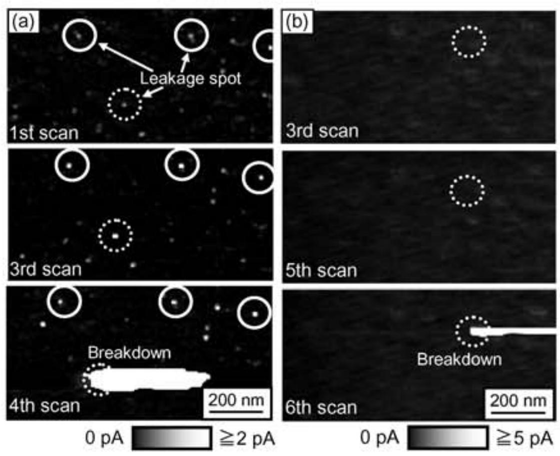

Fig. 4. Current images of (a) stressed and (b) nonstressed SiO_2 films with a thickness of 4.7 nm obtained by repeating the scan at the same area with a substrate voltage of -5.5 V and -7 V, respectively.

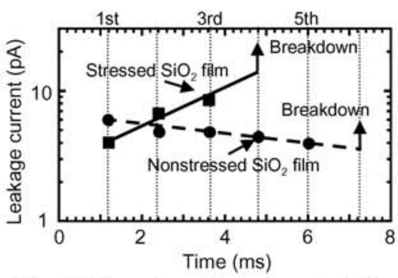

Fig. 5. Time-dependent characteristics of leakage current at the sites where the breakdown conclusively occurred.

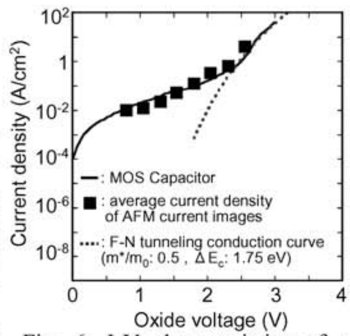

Fig. 6. I-V characteristics of a La_2O_3-Al_2O_3 composite film obtained from a MOS capacitor and the average current densities of C-AFM current images.