Observation of Soft-breakdown in Ultra-thin SiO_2 films under Repetitive Ramped Voltage Stress by Using Conductive Atomic Force Microscopy

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ABSTRACT

In this work the degradation and breakdown characteristics of ultra-thin silicon dioxide (5 nm) was studied by using conductive atomic-force-microscopy (C-AFM). Contrary to what has been reported in the literature, we observed that the threshold voltage (V_{th}) of the I-V characteristics was shifted back and forth along the voltage axis when repetitive ramped voltage stress (RVS) was applied to the oxide. No clear sign of hard breakdown was detected. We attribute this threshold instability behavior to tunneling of injected electrons through traps existed in the ultra-thin oxide, and no physical damage to the oxide during RVS. A model based on trap-assisted tunneling is developed to explain this phenomenon.

Keywords: soft breakdown, ultra-thin oxide, conductive atomic-force-microscopy, ramp voltage stress

1 INTRODUCTION

The degradation and breakdown characteristics of ultra-thin SiO_2 (< 10 nm) films have drawn much attention because it is closely related to the reliability and failure of metal-oxide-semiconductor (MOS) device in modern integrated circuits. It has been well recognized that the oxide breakdown is a highly localized phenomenon [1], typically in a range of several hundred nm^2 [2]. The detection of breakdown characteristics using MOS capacitors can only give an average behavior of the oxide under the gate electrode because the area of MOS capacitors is typically around 10^{-6}~$10^{-3}cm^2$. Therefore, atomic force microscope (AFM)-based tool should be used to monitor the breakdown phenomenon because the AFM tip area is about 10^{-12} ~ $10^{-10}cm^2$. Much previous research work [3-7] has reported the observation of both the hard-breakdown and soft-breakdown in ultra-thin SiO_2 films under repetitive RVS. They found that the threshold voltage (V_{th}) of the I-V characteristics would shift along the voltage axis in one direction under repetitive RVS [6, 7]. They defined a soft-breakdown when the V_{th} shift was not too large and a hard-breakdown if the V_{th} shift became larger. No clear definition was given as to at which V_{th} the hard-breakdown occurred. In this work, we conducted similar experiments to investigate the ultra-thin oxide breakdown by using conductive AFM (C-AFM). Contrary to what has been reported in the literature, only soft breakdown was observed and the V_{th} shifted back and forth along the voltage axis during repetitive RVS. A model based on trap-assisted tunneling [8, 9] has been developed to explain this V_{th} instability behavior.

2 EXPERIMENTAL

A p-type (100) Si wafer with a resistivity of 15 ohm-cm was used as the substrate. After standard RCA clean, a 5 nm ultra-thin oxide was grown on the Si wafer by thermal oxidation at 900℃. Back contact was made by evaporated aluminum onto the Si wafer. The sample was then loaded into the AFM (SEIKO 300HV) chamber at a vacuum of 5×10^{-6} torr to avoid the contamination from the air. Repetitive ramped voltage stress was applied to the sample through a Pt/Ir coated AFM tip in such a way that electrons were injected from Si/SiO_2 interface and the I-V characteristic was monitored after each RVS. The tip is conductive and acts as the metal electrode of MOS structure. Before applying RVS, the root-mean-square surface roughness was determined to be 0.3775 nm by scanning tunneling microscope. In order to avoid the measurement error caused by thermal drift, we set the ramped rate at 3MV/s. The amplification factor of the AFM is 10^{11} and current imaging tunneling spectroscopy (CITS) module was used to monitor the oxide surface before and after RVS. The measured current range was set at 60fA~100pA.

3 RESULTS AND DISCUSSION

Fig. 1 shows the I-V characteristics obtained after the 3rd to the 12th RVS. Clearly, we see that the oxide conducts only when the applied voltage reaches a certain value (the threshold voltage). In this work, we define the V_{th} as the voltage at which the current reaches 1 pA. After the 1st RVS, the V_{th} becomes less and then shifts back and forth as the number of RVS increases. Many current peaks are observed in the measured I-V characteristics. These peaks are believed to be caused by the traping and detraping of electrons at the SiO_2/Si interface. Figure 2 shows the change of the threshold voltage V_{th} as a function of the number of repetitive RVS (up to 45th RVS). As observed, the V_{th} drops from a higher voltage (~ 5.5 V) to lower values those vary between 0.5 and 2 V. The oxide breakdown is confirmed by observing the topographic picture of the oxide surface after RVS using scanning image (contact mode C-AFM) with a bias of 6V. Figures 3 (a), 3(b) and 3(c) depict the current images of the oxide surface after the 1st, the 11th, and the 45th RVS, respectively. Bright spots were observed at the location where the breakdown occurred. The bright spots indicate charge accumulation under the area subjected to RVS resulted in attractive force between the AFM tip and the surface during the scan. We also noted that the breakdown spots propagated laterally as the number of repetitive RVS increased. It is surmised that the oxidation-induced stacking faults or charge trapping enhanced by RVS is the root cause of this breakdown spots propagation. The V_{th} shifts back and forth reflects the fact of soft breakdown of the oxide. To explain the V_{th} shifts under RVS, we developed a theoretical model based on trap-assisted tunneling which is described in the following section.

4 THE MODEL FOR THRESHOLD VOLTAGE INSTABILITY

It has been reported that the I-V characteristic of ultra-thin oxide without stress follows the Fowler-Nordheim (FN) tunneling mechanism [6, 10]. However, the I-V characteristics did not the FN tunneling after several times of RVS. Since the contact area between the sample and AFM tip is only about ~ 10^{-11} cm^2, for a well grown silicon dioxide only a few traps can be existed in the area subjected to RVS. Figure 4 shows the energy-band diagram of the proposed trap-assisted tunneling model. Two isolated traps are assumed to be located in the oxide, one is near the SiO_2/Si interface (0.3 ~ 1.0 nm), and the other is a little bit farther (1.5 ~ 2.0 nm) from the interface. During RVS, in addition to direct tunneling through the oxide, electrons injected from the SiO_2/Si interface would first tunnel to the nearer trap, then to the farther trap, and finally out of the oxide. The current densities for tunneling from interface to the nearer trap, from nearer trap to the farther trap, and from the farther trap to the AFM tip can be respectively expressed as

$$J_R = P_R(1-f_a)$$
$$J_T = P_T(f_a - f_b)$$
$$J_L = P_L(f_b)$$

where f_a and f_b are the trap occupying factor, and P_L, P_T, and P_R the tunneling probability. The tunneling probabilities can be either FN tunneling or direct tunneling. The trap-assisted tunneling occurred when

$$J_L = J_T = J_R$$

and the total trap-assisted tunneling current density can be written as

$$J_{TAT} = \frac{P_L P_T P_R}{P_L P_T + P_R P_T + P_L P_R}$$

Since direct tunneling would occur at the same time if no trap generated under the AFM tip, the total current density is

$$J_{Total} = N_T \times J_{TAT} + (1 - N_T) \times J_{DT}$$

where N_T is the ratio of the trap-assisted tunneling area to the contact area between the sample and AFM tip. In our case $N_T = 10^{-2}$. Based on the model, the I-V characteristics can be calculated. Figure 5 shows the theoretical I-V characteristics demonstrating the effect of tunneling distance of the nearer trap, in which the farther trap is set 1.5 nm and the tunneling distance of the nearer trap is chosen to be 0.45 nm, 0.6nm and 0.75 nm, respectively. As observed, obvious difference in the shape of I-V characteristics can be obtained but the V_{th} is nearly the same for different tunneling distances of the nearer trap. Figure 6 depicts the theoretical I-V characteristics demonstrating the effect of tunneling distance of the farther trap, in which the nearer trap is set 0.45 nm and the tunneling distance of the nearer trap is chosen to be 1.5 nm, 1.8 nm and 2.1 nm, respectively. Apparently, the theoretical I-V characteristics exhibit V_{th} shift along the gate voltage axis as the tunneling distances of the farther trap are different. The farther the farther trap is away from the SiO_2/Si interface, the further the V_{th} shifts to the left along the voltage axis. Figure 7 illustrates the measured I-V characteristics of the ultra-thin oxide after the 6th, 8th, and 9th RVS. The theoretical I-V characteristics are also shown in the figure. Excellent fit is obtained between the measured and the theoretical data. Therefore, the back and forth shifts of V_{th} is believed to be caused by the generation of farther traps during RVS. For I-V characteristics not obeying FN tunneling mechanism after repetitive RVS is due to the generation of both of the nearer traps and farther traps in the oxide. Since the population of these traps in the ultra-thin oxide is not too large, only soft breakdown is observed during repetitive RVS.

5 CONCLUSION

In this work, we investigated the degradation and breakdown characteristics of ultra-thin silicon dioxide by using C-AFM. Different from those have been reported in the literature, we noticed that V_{th} shifted back and forth when repetitive RVS was applied. This instability in threshold voltage is associated with the traps generation in the oxide during stress. A trap-assisted tunneling in accompanied with direct tunneling was used to model the I-V characteristics and excellent fit is obtained with the measured data. We found that the V_{th} shift during RVS is mainly due to the generation of farther traps, and the generation of nearer traps in the oxide affects the shape of I-V characteristics.

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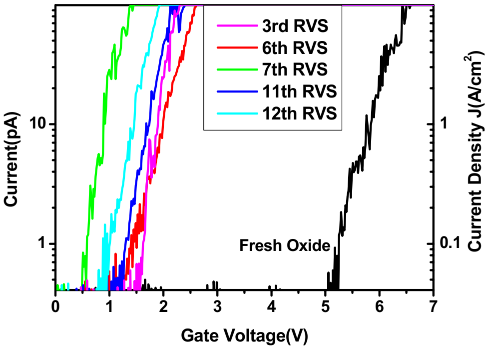

Figure 1: I-V characteristics after the 3rd, 6th, 7th,11th,and 12th RVS.

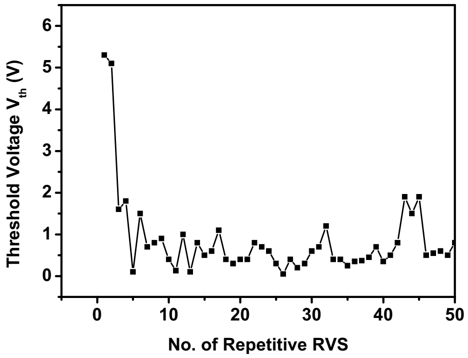

Figure 2: Threshold voltage change during repetitive RVS stress.

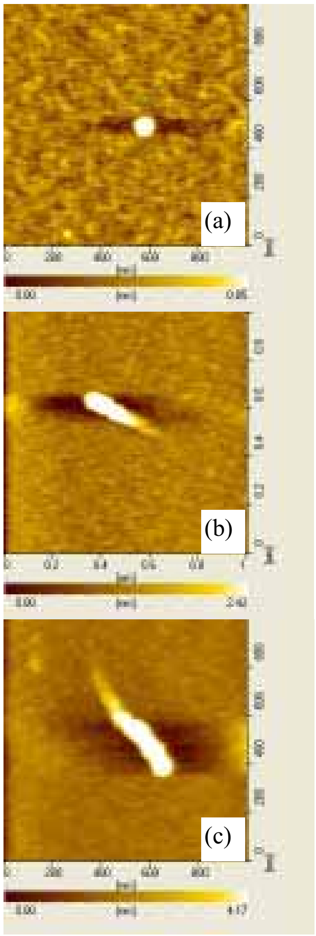

Figure 3: Topography pictures for ultra-thin oxides after (a) the 1st, (b) the 11th, and (c) the 45th RVS.

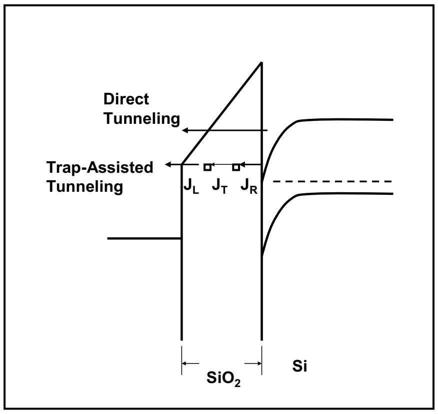

Figure 4: Energy-band diagram of the proposed trap-assisted tunneling model. .

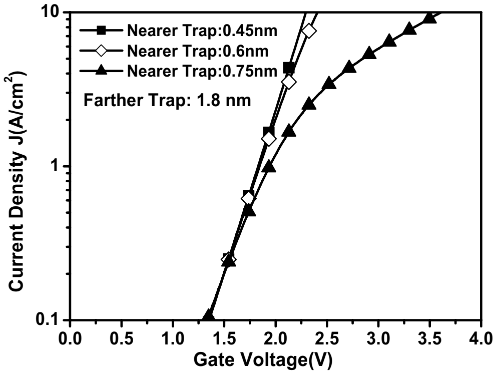

Figure 5: Theoretical I-V characteristics demonstrating the effect of tunneling distance of the nearer trap

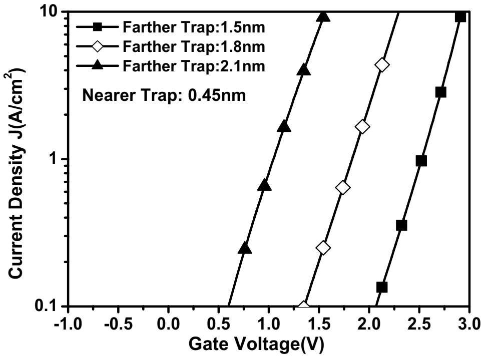

Figure 6: Theoretical I-V characteristics demonstrating the effect of tunneling distance of the farther trap

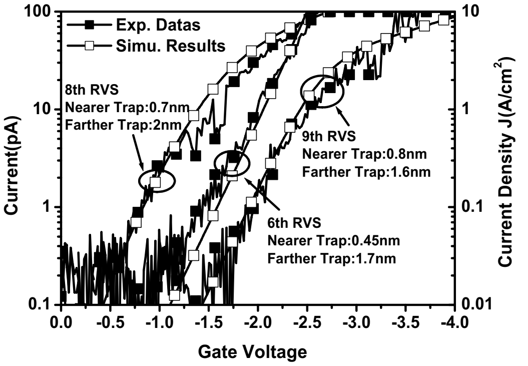

Figure 7: Measured and theoretical I-V characteristics of the ultra-thin oxide after the 6th, 8th, and 9th RVS.