Two Correlated Mechanisms in Thin SiO₂ Breakdown

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The origin of stressing polarity dependence of Q_{bd} in thin SiO₂ is discussed. It was found for the first time that the temperature dependence of Q_{bd} , which increases with decreasing temperature in the high temperature region and tends to saturate in the low temperature region, is identical irrespective of the stressing polarity and the oxidation condition. It has been proposed that the stress gradient from Si/SiO₂ interface to SiO₂/gate electrode interface determines directly both the Si-H bond density which dominates Q_{bd} in high temperature region and the strained Si-O bond density which dominates Q_{bd} in low temperature region, irrespective of gate polarity and of oxidation condition.

1. INTRODUCTION

The gate oxide integrity has been an important issue to realize highly reliable tunneling oxides. In particular, the stressing polarity dependence of $Q_{bd}^{1)-4}$ will become more serious in future EEPROM devices because Q_{bd} for negative stressing is lowered with decreasing oxide thickness as shown in Fig. 1. In addition, it is well known that the oxidation condition is



Fig. 1 Charge-to-breakdown, Q_{bd} , as a function of oxide thickness for the positive (Gate(+)) and the negative (Gate(-)) stressing polarity. Samples were capacitors except for this work (n channel Tr.). Stressing current density, J_g , was 0.1 A/cm² except for Han (0.2 A/cm²). Measurement temperature was room temperature except for Hasegawa (100 °C). Q_{bd} for Gate(-) is lowered with decreasing oxide thickness, irrespective of sample structure, Jg, and measurement temperature.

also one of the influential factors in Q_{bd} . However, it has not been clarified yet whether the dielectric breakdown mechanism itself is the same for these cases, or not.

In this paper, on the basis of the temperature dependence of Q_{bd} of wet and dry oxides for both

stressing polarities, we will show the origin of Q_{bd} difference by changing the stressing polarity and the oxidation condition.

2. EXPERIMENTAL

The devices used in this work were n-channel MOSFETs with 50 µm channel length and 50 µm channel width. The dry oxides were grown in a dry O₂ atmosphere at 850 °C. The wet oxides were grown at 850 $^{\circ}$ C in a H₂-O₂ (1:2) atmosphere. The oxide thickness ranged from 5.4 to 13.0 nm. Electrons were injected from the inversion layer to the gate oxide for positive gate stressing (denoted by Gate (+)) and from the gate electrode to the gate oxide for negative gate stressing (denoted by Gate (-)). The dielectric breakdown time τ_{bd} was detected by the time when the sharp gate voltage decrease occurred under constantcurrent injection. Q_{bd} is expressed by $J_g \ge \tau_{bd}$, where J_g was set at 0.1 A/cm² for both the substrate injection and gate injection in this study.

3. RESULTS AND DISCUSSION

It has been revealed that the temperature dependence of Q_{bd} can provide the useful information regarding the breakdown mechanism through the activation energy ⁵⁾. Figure 2 shows the temperature dependencies of Q_{bd} for wet and dry oxides using stressing polarity as a parameter. As clearly shown in Fig. 2, Q_{bd} increases with decreasing temperature in the high temperature region, and tends to saturate in the low temperature region for all cases. It is also found in Fig. 2 that the temperature dependence of Q_{bd} seems to be almost the same for the four curves, while the absolute value of Q_{bd} is dependent on the stressing polarity or the oxidation condition. The temperature dependence of Q_{bd} in Fig. 2 can be described by

$$Q_{bd}^{-1}(T) = Q_{bd1}^{-1}(T) + Q_{bd2}^{-1}$$

= {C₁exp($\frac{0.1[eV]}{kT}$)}⁻¹ + C₂⁻¹, (1)

where the first term in the right hand side represents the temperature-dependent part of Q_{bd} with the activation energy E_a of 0.1 eV, which can be dominated by



Fig. 2 Temperature dependence of Q_{bd} of wet and dry oxides for the positive and negative stressing polarity. Each symbol shows the average value of measured five samples. Solid lines indicate the calculated results for each condition by the least square method using Eq. (1) in the text.

hydrogen diffusion from Si-H bonds, and the second term represents the temperature-independent part of Q_{bd} , which can be dominated by the breaking of strained (weak) Si-O bonds. The values of C_1 and C_2 in Eq. (1) were determined by the least square method. The calculated Q_{bd} values were plotted by solid lines



Fig. 3 Relationship between calculated C_2 and C_1 in Eq. (1) in the text for various conditions. Note that C_2 is proportional to C_1 for all measurement conditions.

in Fig. 2. Figure 3 shows the correlation between C_1 and C_2 for wet and dry oxides under the positive and the negative stressing. It should be noted that the linear relationship between C_1 and C_2 holds irrespective of the stressing polarity and the oxidation condition. Thus, Eq. (1) can be expressed below;

$$Q_{bd}(T) = \alpha(T)C_2, \tag{2}$$

$$\alpha(T) = \frac{1}{\gamma \exp(-\frac{0.1[eV]}{kT}) + 1},$$
(3)

$$\gamma = \frac{C_2}{C_1}.$$
 (4)

Hence, γ is independent of the oxidation condition and the stressing polarity.

In order to quantitatively confirm Eq. (2), Q_{bd}/C_2 was plotted as a function of reciprocal temperature in Fig. 4.



Fig. 4 Normalized charge to breakdown Q_{bd}/C_2 as a function of reciprocal temperature. The C_2 is calculated result by least square method using Eq. (1). Temperature dependence of Q_{bd}/C_2 is identical, irrespective of stressing polarity and oxidation condition.

It was confirmed that Q_{bd}/C_2 can be represented by single curve indicated by solid line. This result dominates that the temperature dependent breakdown term and, consequently, the temperature dependent breakdown mechanism are closely correlated with the temperature independent ones, suggesting that a common physical parameter would determine both dielectric mechanisms.

We think that the strain existing in SiO_2 network will be responsible for dielectric breakdown of SiO_2 . It is well known that the stress due to lattice mismatch between Si substrate and SiO_2 arises at Si/SiO_2 interface, and that this stress decreases towards $SiO_2/gate$ electrode interface. As a result, the strain in SiO_2 network has the gradient from Si/SiO_2 interface to $SiO_2/gate$ electrode interface. We consider that the amount of strain caused by stress dominates both the density of strained (weak) Si-O bond, [strained Si-O], and that of Si-H bond, [Si-H]. Figure 5 shows the schematic diagram of our model for [strained Si-O] and [Si-H]. It is inferred that [strained Si-O] and [Si-H] are directly related to macroscopic strain in SiO_2 . Figure 6 indicates the peak wave number of absorption band due



Fig. 5 Schematic diagram of density distributions of Si-H bond, [Si-H], and of strained Si-O bond, [strained Si-O], in our model. We infer that both the density of Si-H bond and that of strained Si-O bond are high at Si/SiO₂ interface, and that they have density gradient vertically toward SiO₂/gate electrode interface.



Fig. 6 Peak wave number of absorption band due to Si-O-Si stretching vibration measured by FT-IR versus oxide thickness for wet and dry oxides. Thick oxides were etched back to the required thickness.

to Si-O-Si stretching vibration measured by Fouriertransform Infrared (FT-IR) spectroscopy as a function of gate oxide thickness. Actually, as shown in Fig. 6, it was confirmed that the wet oxide, whose Qbd is larger than Qbd of the dry oxide, has a smaller strain in the depth profile of the peak wave number of absorption band due to Si-O-Si stretching vibration measured by The Qbd difference between positive and FT-IR. negative stressing can be explained consistently by considering the strain gradient in SiO2. Since the strain becomes larger at Si/SiO2 interface than that at SiO₂/gate electrode interface, it is considered that the densities of strained Si-O and Si-H bonds becomes larger at the Si/SiO₂ interface. As a result, the negative gate stressing, which generates hot electrons at the Si/SiO2 interface, exhibits lower Qbd, due to the bond breaking of strained Si-O and Si-H at the Si/SiO2 interface.

4. CONCLUSION

On the basis of temperature dependence of Q_{bd} , it was found that the dielectric breakdown mechanism of ultrathin SiO₂ is the same, irrespective of the stressing polarity and the oxidation condition. We have proposed that the strain gradient in SiO₂ determines both the amount of Si-H bond, which dominates Q_{bd} at high temperatures, and that of strained Si-O bond, which dominates Q_{bd} at low temperatures.

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