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Temperature-Dependent Soft Breakdown in Ultrathin Gate Oxides

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1. Introduction

The activation energy obtained from the temperature dependence of time-to-breakdown and charge-to-breakdown has been reported[1,2]. The oxide defect generation mechanism has been interpreted in terms of reactions between diffusing monocular hydrogen and Si-H or Si-O bond[2], while transition from stress-induced leakage current(SILC) mode degradation state to soft breakdown(SBD) has been found to occur when the oxide electric field strength reaches a critical value Eoxc regardless oxide thicknesses for 3.5-4.9nm SiO_2[3]. This paper describes a new method for a high-sensitive detection of the critical oxide field Eoxc at which the transition from the SILC degradation state to the SBD occurs. The critical oxide field Eoxc can be detected by the corresponding Fowler-Nordheim(FN) tunnel current J_{SBDC} which is a unique function of Eoxc. Temperature-dependence of the soft breakdown current has been measured and analyzed to reveal the soft breakdown mechanism.

2. Device Fabrication

MOS capacitors were fabricated on p-type or n-type Si(100) substrates with LOCOS structures. Si wafers were cleaned by an $NH_4OH:H_2O_2:H_2O$=0.15:3:7 solution at 80°C for 10 min. Subsequently the surfaces were terminated with hydrogen in a 0.1%HF+1%H_2O_2 solution and simultaneously the surface microroughness was minimized[4]. The gate oxides with thicknesses 2.6 to 3.9nm were grown at 850°C in dry O_2, and phosphorus doped n^+poly-Si gates were formed.

3. Results and Discussion

In order to measure a critical oxide electric field Eoxc at which the direct tunnel current component jumps from the SILC mode degradation state to soft breakdown current, the gate voltage was ramped up and down at a rate of 200mV/sec to a maximum value which was increased by 20mV step for each cycle of voltage scan as shown in Fig. 1. The SBD current is detected when the oxide voltage reaches the maximum value Voxc which induces the soft breakdown current J_{SBDC} at Voxc as illustrated in Fig. 1. However, for gate oxides thinner than 3.0nm, the SBD current can not be easily detected because the hard breakdown(HBD) often occurs during voltage ramping at 20mV step (Fig. 2(a)). In order to make fine control of the gate voltage, the gate current level was changed by 50steps/decade as shown in Fig. 2(b). Thus SBD current can be easily detected because the constant current condition is kept at each cycle of measurements even under the maximum current condition.

The SILC and SBD currents are considered to be controlled by direct tunneling through locally thin oxide in contact with conductive path[3,6,7] as illustrated in Fig. 3 or by trap-assisted tunneling conduction[8] or by variable range hopping via localized states[9]. Takagi et al.[10] have also reported that asymmetric transport properties of the conductive filament which is formed from the substrate toward the gate electrode in SiO_2 can explain the wearout current. The SBD current as observed in Fig. 1 is well reproduced by the calculated direct tunnel current based on a conductive path model[7], in which a conductive filament extends into SiO_2 from the SiO_2/Si(100) interface under stressing.

Temperature dependence of soft-breakdown field Eoxc can be sensitively probed by the corresponding soft breakdown current J_{SBDC} which is measured by the method of Fig. 2(b), as shown in Fig. 4(a) for 2.6nm thick oxides. It is obvious that the oxide wearout is accelerated at higher temperatures. The activation energy of SBD from the SILC mode degradation state is shown in Fig. 4(b), where the change in the activation energy occurs at 150°C. It is shown that the thinner oxide or the substrate injection gives the higher J_{SBDC} and very similar activation energies.

As illustrated in Fig. 5, if the thermochemical E model[5] is assumed to explain the activation energy for thermal bond breakage ΔEa for SBD, then one obtains :

$$\Delta Ea = Ea - p \cdot Eloc. \qquad (1)$$

Here, Ea is the activation energy of SBD from the SILC mode degradation state, p is the dipole moment of strained Si-O-Si bond and Eloc is the local oxide field given by Voxc/tox(see the model in Fig. 3(a)). The oxygen vacancy results in a Si-Si bond replacing the strained Si-O-Si bond under oxide field stressing[5]. The conductive path model assumes that Si-Si bonds is formed from strained Si-O-Si bonds, in consistency with the thermochemical E model.

As illustrated in Fig. 3, the conductive path is formed in oxide at SILC mode degradation and also at SBD state. The remaining oxide thickness tox above the conductive path and the corresponding area S_T for SILC and S_L for SBD(S_T>>S_L) are obtained by quantitative analysis of SILC and SBD current measured at different temperatures as seen in Fig. 6(a) and (b). For the SILC state, the length of conductive region Tox-tox(see Fig. 3(a)) is obtained by the remaining oxide thickness tox. Also, the total area S_T of such conductive region ranges from 0.5% to 1.2% of the total gate area below 120°C, while above 150°C, S_T is larger. On the other hand, it is interesting to note that in the SBD state both tox and S_L do not depend on temperature. This indicates that the SBD current is controlled by tunneling through the remaining oxide. The local oxide field Eloc of Eq. (1) is evaluated by Eloc=Vox/tox, where tox is the remaining oxide thickness at SILC mode degradation state(see Fig. 6 (a)). Increase in the activation energy of SBD from the SILC mode degradation state above 150°C can be associated with the decrease of Eloc as shown in Fig. 7.

4. Summary

It is shown that SBD current is controlled by tunneling through the remaining oxide above the localized conductive path. The activation energy for the transition from SILC mode degradation to SBD can be explained by temperature dependence of local oxide field.

Acknowledgment

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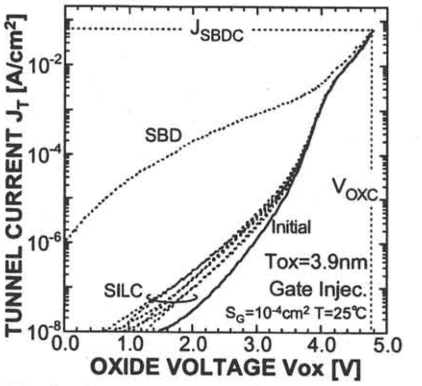

Fig. 1. Current-voltage characteristics for a capacitor with Tox=3.9nm.

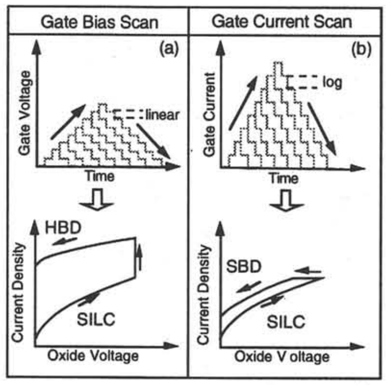

Fig. 2. Measurement method of the transition from SILC mode to SBD for Tox<3nm.

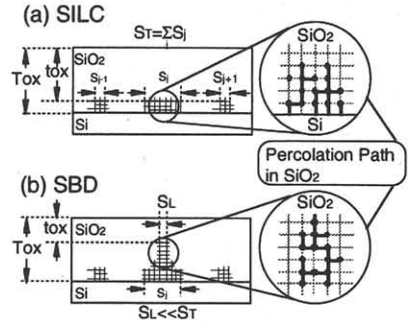

Fig. 3. Schematic illustration to explain formation of the conductive region Sj which induces SILC(a) and formation of the conductive path S_L which leads to soft breakdown(b). tox is the oxide thickness remaining above the conductive path.

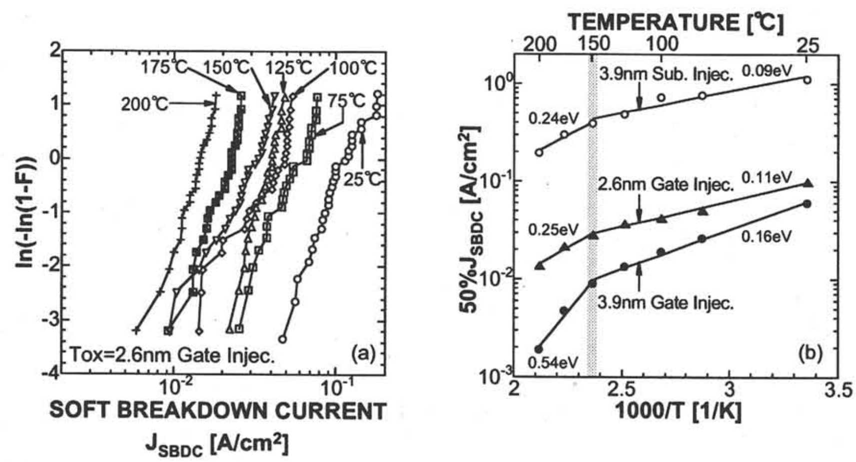

Fig. 4. Weibull plots as a function of the critical soft breakdown current J_{SBDC} for capacitors with Tox=2.6nm under gate injection(a). Temperature dependence of 50%J_{SBDC} for capacitors with 2.6 and 3.9nm oxides(b).

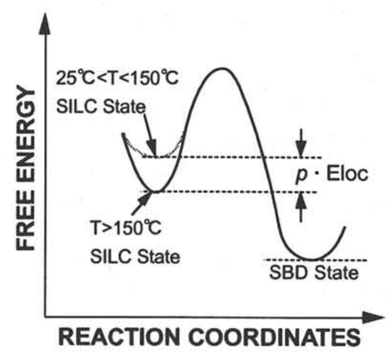

Fig. 5. Free energy versus reaction coordinates to explain transition from SILC degradation state to SBD state.

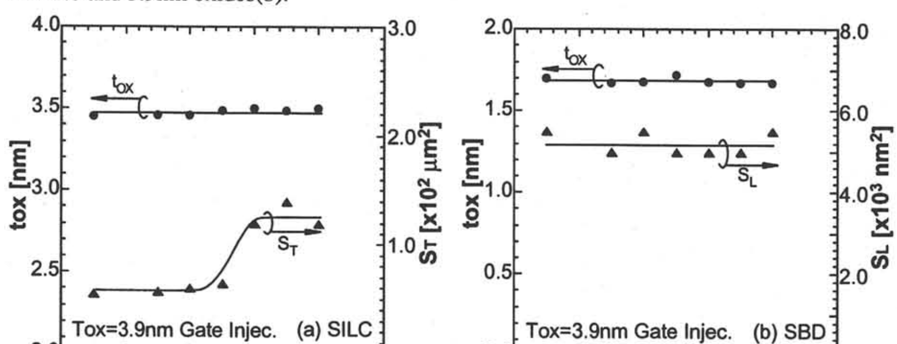

Fig. 6. The remaining oxide thickness tox existing above the localized conducting region obtained from measured I-V curves for SILC (a) and SBD (b) plotted as a function of temperature. S_T and S_L were also calculated from the measured SILC and SBD current.

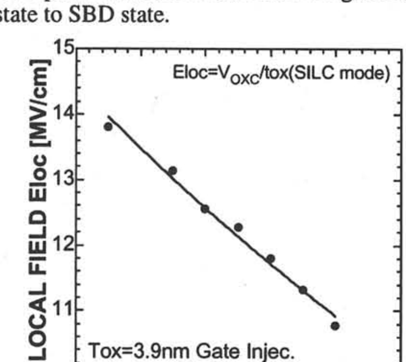

Fig. 7. Temperature dependence of the local oxide field Eloc=Voxc/tox obtained from the analysis for capacitors with Tox=3.9nm.