A study of dielectric breakdown mechanism through the statistical analysis of post-breakdown resistance of thin SiO$_2$ films

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Abstract

A post-breakdown resistance of SiO$_2$ has been studied as a quantitative monitor to describe the dielectric breakdown characteristics. First, a clear difference between dry and wet oxides is shown in terms of the post-breakdown resistance of SiO$_2$ as well as the charge-to-breakdown. Then, a boundary between hard- and soft-breakdown in sub-10 nm SiO$_2$ is discussed from the viewpoint of a time constant for the energy dissipation in MOS closed circuit, through the statistical analysis of the post-breakdown resistance. The idea becomes more important in modeling and assessment of scaled-down CMOS device reliability. © 2000 Elsevier Science Ltd. All rights reserved.

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1. Introduction

The gate oxide thickness of CMOS devices is aggressively reduced to a nanometer region, and its long-term reliability is a key concern in the Silicon Technology Roadmap [1]. However, even the dielectric breakdown mechanism of gate oxides has not been clarified yet. A difference between wet and dry oxides is still an open question, though these oxides have been used for actual silicon devices for 40 years. On the other hand, in a thin oxide region, characteristic phenomena such as the soft breakdown (SBD) [2], which does not cause a significant jump of conductance and is in contrast with the usual hard breakdown (HBD), or the stress-induced leakage current (SILC) [3], which is a leakage current observed after a strong electrical stress, are observed. The understanding and the control of these degradation phenomena are very tough challenges in the area of the device reliability in the current and future Si LSIs (large-scale integration).

In this paper, we statistically discuss a post-breakdown resistance, $R_{bd}$, as well as $Q_{bd}$, as a quantitative monitor to characterize the dielectric breakdown ($Q_{bd}$ denotes the charge-to-breakdown). Although it was reported that the post-breakdown electrical properties of SiO$_2$ films included much information on the dielectric breakdown mechanism [4], a statistical analysis of the post-breakdown properties may be the first challenge to understanding the oxide dielectric breakdown. Through this analysis, we experimentally demonstrate a clear difference between dry and wet oxides as well as a polarity effect of the stressing field on the breakdown. On the other hand, several models have been proposed concerning SBD or SILC, and most of them have discussed conduction mechanisms by measuring specific samples. The reliability, however, should be investigated in terms of the statistics, because the reliability indices behave intrinsically in a statistical sense. In fact, the charge-to-breakdown, $Q_{bd}$, or the time-to-breakdown, $\tau_{bd}$, has been generally described by a statistical function such as Weibull or Lognormal distribution function. Since both HBD and SBD coexist on a same wafer with a thin gate oxide, it is necessary that a difference between HBD and SBD is also treated as a stochastic process. In fact, a new aspect of the boundary between HBD and SBD is pointed out through the $R_{bd}$ distribution analysis.

2. Post-breakdown characteristics of SiO$_2$

The devices used in this study were MOS capacitors or MOSFETs with n$^+$poly-Si gate electrodes. The gate oxides were grown in dry or wet ambient at 850°C. Fig. 1 shows typical current–voltage characteristics of SiO$_2$ in pre- and post-breakdown conditions. There are two modes of
dielectric breakdown in thin oxides (typically thinner than 10 nm), which are called as soft- and hard-breakdowns. There is a big current level difference between them.

Since the dielectric breakdown is an irreversible and transient process, it is rather difficult to characterize what actually happens inside SiO2. Furthermore, as far as the SiO2 reliability is concerned, there remains a number of controversial issues. The stress field polarity or the oxide growth ambient effects on the lifetime of SiO2 are typical examples. To acquire a new set of information on these issues in the SiO2 reliability, we have defined the post-breakdown resistance, \( R_{bd} \), as \( R_{bd}^{-1} = I_g [A \text{ at } V_g = 0.5 \text{ V}] / 0.5 \text{ [V]} \), and have analyzed the \( R_{bd} \) statistics of SiO2 [5]. Since a strong non-linear conduction is observed in the SBD case as shown in Fig. 1, \( R_{bd} \) defined above is not necessarily adequate for describing the resistance. However, it will be shown in the following section that the \( R_{bd} \) statistics give a clear and quantitative distinction for characterizing each of them.

### 3. Polarity and oxide growth ambient effects on dielectric breakdown

The devices were mainly stressed under a constant current condition, changing the stressing polarity. We measured \( V_{g_{fin}}^m \) and \( V_{g_{fim}}^m \) (initial and final stress voltages to maintain a constant current), and \( R_{bd} \) as well as \( Q_{bd} \). The results were analyzed statistically in the Weibull distribution function. Fig. 2 shows Weibull plots of \( Q_{bd} \) and \( R_{bd} \) of 8.6 nm dry oxides for both stress polarities [5], where \( F \) and \( P \) mean the cumulative failure probability of dielectric breakdown and the percent of resistance distribution of post-breakdown SiO2, respectively. Note that a smaller \( Q_{bd} \) case (negative gate bias) statistically corresponds to a larger \( R_{bd} \). Since we think the dielectric breakdown is induced by the conductive spot connection through SiO2 [5,6], the post-breakdown resistance (\( R_{bd} \)) is considered as a measure of breakdown spot size. In order to directly observe the conducting filament radius after breakdown, we measured the rupture portions of SiO2 for both stressing polarities by using XTEM. It was confirmed that the width of the breakdown portion for \( V_g(1) \) was larger than that for \( V_g(2) \) [7]. This fact strongly suggests that the lateral growth of conductive defects prior to the breakdown is associated with \( R_{bd} \) in the polarity dependence experiment, and that the spread of defects in \( V_g(1) \) stressed oxides is wider than that in \( V_g(2) \) stressed oxides before dielectric breakdown.

Fig. 3 shows a comparison between dry and wet oxides in terms of \( Q_{bd} \) and \( R_{bd} \) of 10 nm oxides. Note that wet oxides with a larger \( Q_{bd} \) show a larger \( R_{bd} \), which is in contrast with the results in Fig. 2. Namely, a longer lifetime does not always mean a smaller \( R_{bd} \). This implies that the conductive spot formation just before breakdown in wet oxides is qualitatively different from that in dry oxides, and that the spread of defect formation in wet oxides is narrower and more anisotropic than that of dry oxides. It is inferred that the difference should be related to the robustness against the
local bond breaking of OH terminated SiO₂ tetrahedron in the wet oxide. These findings should be taken into consideration in the theoretical analysis of the time dependent dielectric breakdown. In other words, the results shown here may provide a number of information on the microscopic dielectric breakdown mechanism that are difficult to infer from the simple $Q_{bd}$ or $\tau_{bd}$ analysis.

4. Stored energy consideration — HBD and SBD

It will be worth while to discuss a boundary between HBD and SBD from the viewpoint of the $R_{bd}$ statistics. We note that the ratio of SBD with HBD statistically varies under different measurement conditions. Namely, SBD is more frequently observed in weaker fields, smaller areas, as shown in Fig. 4, as well as in thinner oxides. All of these results seem to imply that SBD is associated with a smaller energy stored in a MOS capacitor before breakdown.

In order to describe better the dielectric breakdown quantitatively, we also introduce a discharging energy, which is defined as a difference of the energy stored in the capacitor between pre- and post-breakdown, as $\epsilon_{\text{disch}} = S_{\text{ch}} \times C_{\text{ox}} \times ((V_{g}^{\text{ini}})^2 - (V_{g}^{\text{final}})^2)/2$, from the simple capacitor consideration, where $S_{\text{ch}}$ is the capacitor area and $C_{\text{ox}}$ is the capacitance value [5].

Fig. 5(a) and (b) show the relationship between $R_{bd}$ and $\epsilon_{\text{disch}}$ as a parameter of the stress current density and the area, respectively. In the case of HBD, $R_{bd}$ of devices with a same area is universally described as a function of the discharging energy, even when the stress current density is changed, as shown in Fig. 5(a). On the other hand, in the different device area, $R_{bd}$ is not simply determined by $\epsilon_{\text{disch}}$ as shown in Fig. 5(b). This fact implies that not all of the energy stored in the capacitor is dissipated, but a part of the energy stored in the local area of the capacitor surrounding a conductive spot linkage path is used for creating a conductive path in HBD. On the other hand, the discharging energy in the case of SBD has little to do with $R_{bd}$ as shown in both Fig. 5(a) and (b). If a single conductive filament is formed by the defect connection and the number of the conductive filaments is determined stochastically in the case of SBD, it is reasonable that $R_{bd}$ distribution for a given discharging energy is very broad. This is a striking contrast to the HBD case. A schematic comparison between SBD

Fig. 3. Comparison of (a) $Q_{bd}$ and (b) $R_{bd}$ between dry and wet oxides in the Weibull plot. This is in contrast to the polarity dependence as shown in Fig. 2.

Fig. 4. Weibull plots of $R_{bd}$: (a) as a parameter of the stress current density $S = 100 \times 100 \mu m^2$ and $T_{ox} = 4.2 \text{nm}$, and (b) as a parameter of the device area, where all of the samples measured show SBD in case of $4 \times 2 \mu m^2$ ($T_{ox} = 4.2 \text{nm}$ and $I_g = +0.1 \text{A/cm}^2$).
and HBD inferred from those consideration is shown in Fig. 6, where the conductive spot linkage path and the locally melted conductive path by a large energy injection describe the characteristic features of SBD and HBD, respectively. Since $Q_{bd}$ statistics in the SBD case is described by the same Weibull distribution as that in the HBD one, the mechanism triggering the dielectric breakdown is the same for both BD, but the mechanism forming the final conductive path through SiO$_2$ is different from each other. It is worthy of note that not all of the energy stored in the capacitor is used for the breakdown process. So, it is interesting to consider what determines the energy available for dielectric breakdown, and what characterizes the boundary between SBD and HBD.

5. Power consideration — breakdown transient

Finally, we discuss the energy dissipation dynamics just at the breakdown. It is inferred that the boundary between HBD and SBD might be very sensitive to the injection power as well as the total discharging energy, because a part of the injected energy is lost through the thermal conduction. Namely, it takes a finite time to discharge a given energy in a closed circuit, which will significantly affect the transition from HBD to SBD. So, it will be worthy of consideration of a circuit time constant in the reliability test system including the sample itself. We have actually defined two kinds of time constants in the dielectric breakdown transient in the MOS system. One is the time for discharging the energy stored in the capacitor into the infant conductive spot linkage, $\tau_{disch}$, which is strongly dependent on MOS closed circuit including the measurement system. The other one is the time for rupturing the conductive filament to HBD, $\tau_{rupt}$, which is related to the surrounding thermal conduction property [6]. It is noted that these experiments such as changing the oxide thickness or the device area can modify both the discharging energy, $\epsilon_{disch}$, and the circuit time constant, $\tau_{disch}$, by changing the actual capacitance of the sample itself.

![Fig. 5. $R_{bd}$ as a function of discharging energy, $\epsilon_{disch}$, as a parameter of: (a) stress current density, $J_g$ and (b) device area, $S$. Note that $\epsilon_{disch}$ in HBD is not described by the total area but by an unit area of the capacitor, as shown in (b).](image)

![Fig. 6. Schematic models representing both: (a) SBD and (b) HBD modes. They look similar, but a quantitative difference of discharging power leads to the qualitative difference of conduction scheme between two breakdown modes.](image)
In order to differentiate between $\tau_{\text{disch}}$ and $E_{\text{disch}}$ effects, we performed an experiment in which the time constant in the MOS closed circuit just at the breakdown was only modified without any influence on the gate oxide lifetime, by connecting an external inductor to the MOS system in series [6–8]. It was performed under a constant current stress condition as shown in Fig. 7(a). This experimental setup can intentionally modulate only $t_{\text{disch}}$ in the MOS closed circuit just at the breakdown. The resistance of inductor was very small (several ohms) and was negligible in terms of the DC reliability stress condition. We examined the ratio of SBD with HBD of 4.2 nm SiO$_2$ film for three kinds of external inductance values from 0 to 1 H [8]. Fig. 7(b) shows a distinct variation of the statistical distribution between HBD and SBD of the same oxide capacitor by inserting a several-ohm inductor. This is a clear evidence of the dynamic characteristics of the dielectric breakdown, because the external inductance significantly reduces the effect of transient injection of large energy on account of a longer characteristic time constant of the circuit. It should be mentioned that there was no difference of TDDB results irrespective of the insertion of the external inductance.

It has been clearly demonstrated that the dielectric breakdown depends neither only on the oxide thickness ($T_{\text{ox}}$), nor on the oxide voltage ($V_{\text{ox}}$), but also on the channel area ($S_{\text{ch}}$) or the system impedance ($Z$) including the sample itself. A small difference of the peak power in the energy emission through a balance of $\tau_{\text{disch}}$ with $\tau_{\text{rupt}}$ can lead to the difference between HBD and SBD, and both a critical energy and a balance of two time constants determine the boundary between them. In HBD, the energy stored in the capacitor is injected into the linkage of conductive defects to result in the conductive pipe with a wide radius, while in SBD it is not enough to form the wide conductive path. Thus, in the case that $\tau_{\text{disch}}/\tau_{\text{rupt}}$ is large, a large part of the injected energy is lost to the surroundings and SBD is observed. To our knowledge, this is the first experimental demonstration of the dynamic aspects of dielectric breakdown that have been observed systematically by using the statistical distribution analysis [8]. Note that both the stored energy and the system impedance at the breakdown are modified, when the size or the oxide thickness of MOS capacitor is changed [9]. In addition, the results of the external inductance experiment indicate that the thin oxide reliability analysis is very sensitive to the stress conditions such as not only voltage or current, but also external impedance including the power source output, as previously reported [10].

6. Conclusions

The polarity dependence and a clear difference between dry and wet oxides in the dielectric breakdown have been discussed through the statistical analysis of the post-breakdown SiO$_2$ resistance. In particular, it has been inferred that the wet oxide has more robust network structure than the dry oxide from the relationship between $R_{\text{bd}}$ and $Q_{\text{bd}}$ statistics. Furthermore, it has been pointed out that both the discharging energy and the time constant of MOS system are strongly related to the thin SiO$_2$ dielectric breakdown. Above all, a balance of two time constants significantly affects the boundary between HBD and SBD.

In thinner oxides, the reliability analysis is very sensitive to the stressing conditions such as not only voltage or current, but also the system impedance including the sample itself. Thus, it is emphasized that the stress conditions should be more carefully considered in the reliability research of the gate dielectrics. In fact, it is concluded that the transistor level reliability in a LSI chip depends on where a transistor is in a chip. Nonetheless, more accurate treatment of the dielectric breakdown from the theoretical point of view will be possible by employing an advanced percolation analysis that...
takes account of the breakdown transient dynamics discussed in this paper. The statistical analysis of the post-breakdown resistance will also facilitate a further understanding of the dielectric breakdown mechanism of SiO₂ by providing a new set of information.

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