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Extended TDDB Model Based on Anomalous Gate Area Dependence in Ultra Thin Silicon Dioxides

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An anomalous gate area dependence of lifetime is reported in ultra thin silicon dioxides for the first time. This can be explained only by the four stage model where the dielectric breakdown process consists of the "partial breakdown" and the "complete breakdown". Based on these results, the extended TDDB model is proposed for oxides where the "B mode" stress induced leakage current is observed. Furthermore, it is demonstrated that without considering this model, one cannot predict the accurate lifetime.

1. Introduction

An advanced Si MOS LSI requires the ultra thin gate oxides (<5nm)[1]. We reported the "B mode" stress induced leakage current (B-SILC) and the "B mode shift" in ultra thin silicon dioxides for the first time[2]. Typical behavior of the gate current under constant voltage Fowler - Nordheim (F-N) stress is shown in Fig. 1 for a 4nm-thick oxide film. Several B mode shifts occur before the breakdown and the gate current is composed of a number of single step B mode shifts which originate from unique physical process occurring at different times and different local spots[3]. Furthermore, as the dielectric breakdown process, we proposed the four stage model (FSM)[3] instead of the conventional two stage model (TSM)[4]. In the FSM, one or several B mode shifts occur to lead to the dielectric breakdown at one of such spots.

In this work, an anomalous gate area dependence of lifetime is revealed in the ultra thin oxides for the first time. Furthermore, the conventional time dependent dielectric breakdown (TDDB) model[5,6] is extended from the viewpoint of the gate area dependence.

2. Sample Preparation

MOS capacitors with 4nm-thick gate oxides and n^+ polycrystalline silicon gate electrodes were fabricated on CZ-p type Si (100) substrates.

3. Extended TDDB Model

The gate area dependence of the lifetime, TTF (Time To Failure), is shown in Fig. 2 for various electric fields, Eox. (accumulation mode of substrate silicon) The conventional TDDB model[5] assumes; (i) uniform distribution of latent defects which do not cause oxide breakdowns until a given stress time, and (ii) the number of latent defects is proportional to the gate area, S. Namely, a linear relationship between TTF and S in logarithmic scale is expected from following equation[5];

$$Q(\ln t) = \frac{1}{1 + \frac{1}{S \cdot D(\ln t)}} \qquad (1),$$

where Q(ln t) is the cumulative breakdown rate and D(ln t) is the density of latent defect for breakdown. In Fig. 2, dotted lines show the predicted TTF values using Eq. (1) with measured TTF at $S \geq 10^4 \mu m^2$. It is clear that measured TTF at $S \leq 10^3 \mu m^2$ is smaller than predicted TTF and that the

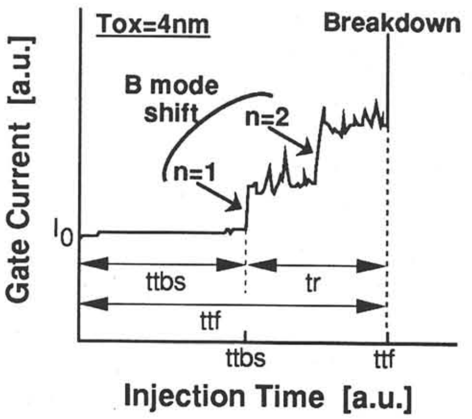

Fig. 1 Typical behavior of the gate current of a 4nm-thick oxide film under constant-voltage Fowler-Nordheim stress. The number of B mode shift is indicated by n.

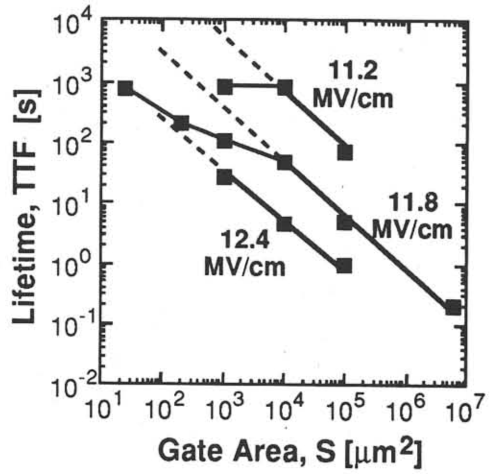

Fig. 2 Gate area dependence of lifetime, TTF, of 4nm-thick oxide film for various electric fields. Dotted lines show the predicted TTF values based on the conventional TDDB model.

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difference between both TTF values becomes larger as the decrease of the electric field. This anomalous gate area dependence cannot be explained by the conventional TDDB model based on the TSM.

In the FSM[3], the dielectric breakdown process consists of following two individual processes; (i) the B mode shift ("partial breakdown") at one or several local spots at different times, and (ii) the "complete breakdown" at one of such B mode shifted spots. Therefore, the lifetime, ttf, can be divided into; (i) time to the B mode shift (ttbs), and (ii) residual time to breakdown from the B mode shift (tr) as shown in Fig. 1. (ttf=ttbs+tr) Using the Weibull plots of ttf, ttbs and tr of each capacitor measured under constant voltage F-N stress, TTF, TTBS and TR were obtained as 50% level of cumulative events, respectively.

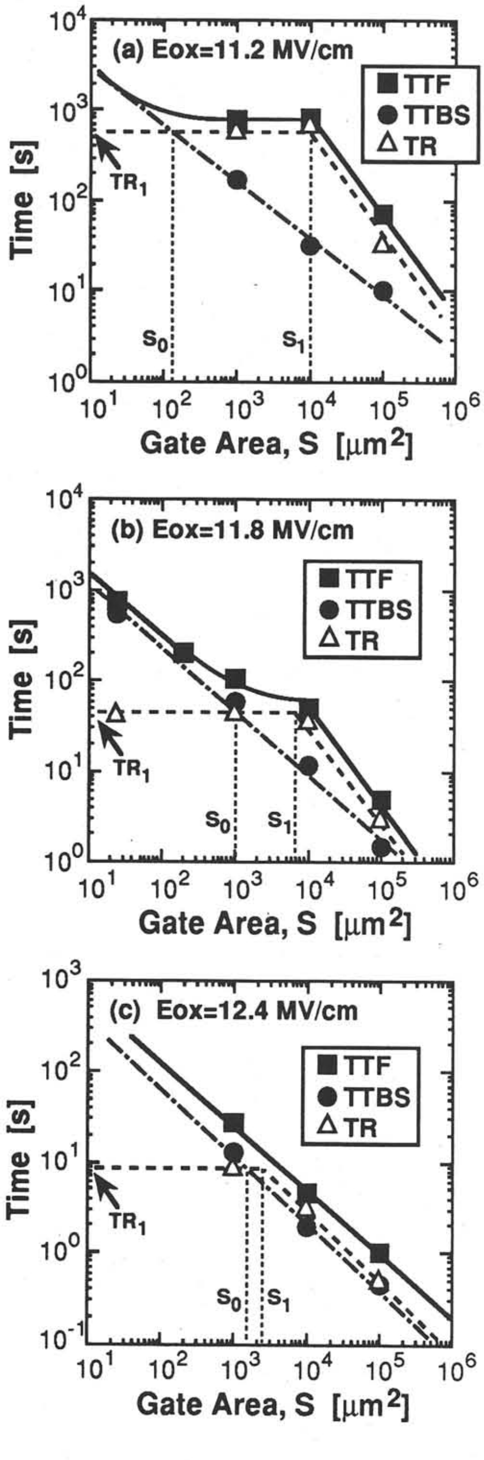

Fig. 3 Gate area dependence of TTF(■), TTBS(●) and TR(△) for electric fields of (a) 11.2, (b) 11.8 and (c) 12.4 MV/cm measured at room temperature.

TTBS is considered to follow the conventional TDDB model because TTBS depends on the number of latent defects for the B mode shift in entire gate area. At a given stress condition, on the other hand, TR depends only on the number of B mode shifted spots, n, taking place before the breakdown, because the residual time is observed only after the B mode shift takes place. Although the number n becomes smaller as the decrease of S, it should be noted that the minimum value of the number n is only one (single step B mode shift). Therefore, the number n merely depends on S when S is smaller than a threshold value S_1. After all, TTF is expressed as follows depending on S;

$$TTF(S) = \begin{cases} TTBS(S) + TR_1 & \text{when } S \le S_1 \\ TTBS(S) + TR(n(S)) & \text{when } S > S_1 \end{cases} \quad (2),$$

where TR_1 is given at $n(S \le S_1) \approx 1$. Note that the conventional TDDB model based on the TSM is considered to be a case where $TR \rightarrow 0$.

Measured gate area dependence of TTBS, TR and TTF are shown in Fig. 3(a)~(c) for various electric fields. As the decrease of S, TR increases at $S>S_1$ and is almost constant value TR_1 at $S \le S_1$. In contrast, TTBS increases monotonously following the conventional TDDB model and becomes larger than TR_1 at $S=S_0$. As shown in Fig. 3, S_1 is large enough to be observed. It is shown that TTF, TTBS and TR follow the extended TDDB model and, hence, the FSM is strongly supported. This extended TDDB model can be adopted not only for the ultra thin oxides but also for thicker oxides where the B-SILC takes place.

4. Effect on Lifetime Prediction

As the decrease of the electric field, S_0 decreases and S_1 increases monotonously as shown in Fig. 3(a)~(c). This electric field dependence can be explained by the change of the ratio of TR/TTBS as shown in Fig. 4, because TTF is just a sum of TTBS and TR. The ratio TR/TTBS is shown in Fig. 5 as a function of quasi-Q_{BD} ($S=10^4\mu m^2$) for various

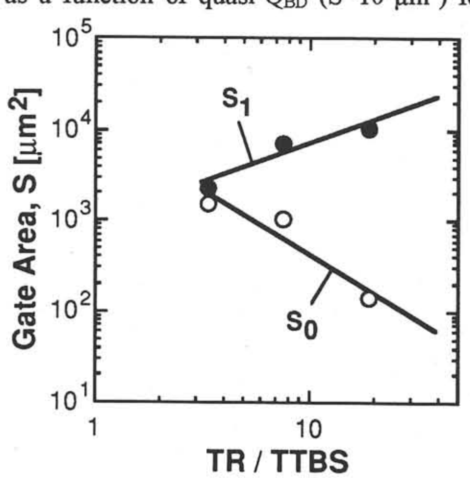

Fig. 4 Relationship between the gate area S_0, S_1 and the ratio TR/TTBS taken from data shown in Fig.3(a)~(c). TR_1 and TTBS($S=10^4\mu m^2$) were used as TR and TTBS, respectively.

electric fields and temperatures, where quasi-Q_{BD} is defined as $I_0 \times$ TTF. It is shown that TR/TTBS can be universally expressed with quasi-Q_{BD} for any electric fields and temperatures. Taking into account that the oxide film is subjected to soft stressing with large quasi-Q_{BD} under the typical device-operating condition, it is clear that TR/TTBS becomes much larger and, hence, S_0 becomes much smaller and S_1 becomes much larger.

Schematic illustration of TTBS, TR and TTF at lower electric fields estimated based on above results is shown in Fig. 6. It is strongly required to predict the lifetime under typical-operating condition based on the extended TDDB model. Therefore, the procedure for lifetime prediction must also be extended based on this model. The key point of this "extended procedure" is to predict TTBS and TR separately and to calculate the lifetime using Eq. (2). By the "conventional procedure" without considering the extended TDDB model, however, one cannot obtain the accurate lifetime. Depending on the accelerated test condition including the electric field, temperature and the gate area, one obtains underestimated or overestimated lifetimes. For example, when one applies a test condition where TTBS»TR, the lifetime extrapolated to the typical device-operating condition will not correspond to TTF but most likely to TTBS. In such a case, the conventional procedure underestimates the lifetime and the difference between the lifetimes predicted by both procedures can be expressed by TTF/TTBS. TTF/TTBS becomes larger as the decrease of the electric field as shown in Fig. 7. In this case, the lifetime is underestimated 3~4 orders even at 9 MV/cm.

5. Conclusion

An anomalous gate area dependence of lifetime is reported in the ultra thin gate oxides for the first time. This can be explained only by the four stage dielectric breakdown process model(FSM) and, hence, the FSM is strongly supported. Based on these results, the extended TDDB model is proposed for oxide films where the B-SILC can be observed. Furthermore, it is demonstrated that without using the "extended procedure" for the lifetime prediction, one cannot obtain the accurate lifetime.

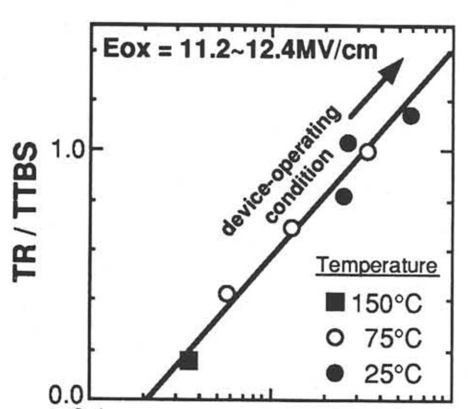

Fig. 5 Relationship between quasi-Q_{BD} and the ratio of TR/TTBS for various electric fields and temperatures. ($S=10^4\mu m^2$)

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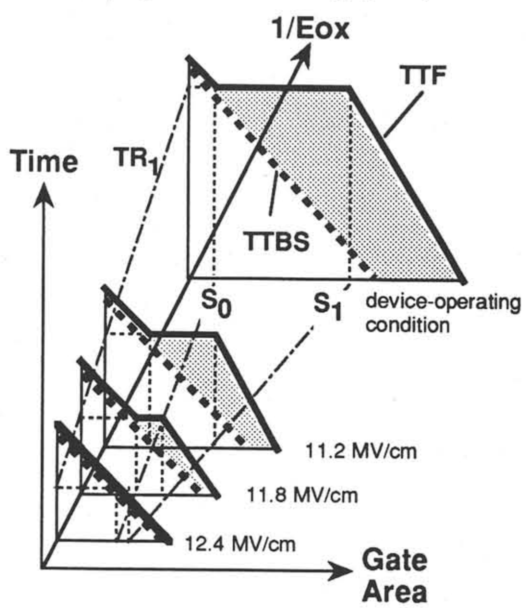

Fig. 6 Schematic illustration of lifetimes based on the extended TDDB model.

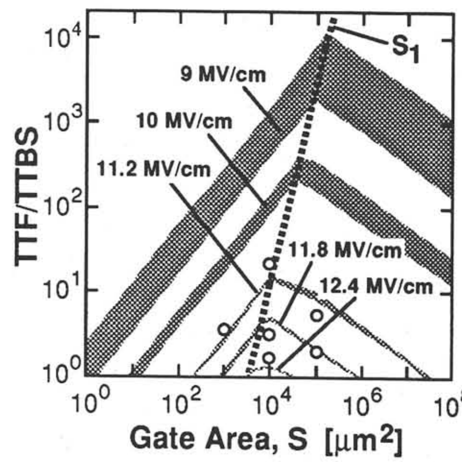

Fig. 7 The gate area dependence of simulated TTF/TTBS which shows the ratio of lifetimes predicted by the "extended procedure" and the "conventional procedure" for various electric fields. Open marks show the measured values shown in Fig.3.