Extended Abstracts of the 18th (1986 International) Conference on Solid State Devices and Materials, Tokyo, 1986, pp. 463-466

Breakdown Characteristics of Ultra Thin Silicon Oxide

Takahisa Kusaka, Yuzuru Ohji, and Kiichiro Mukai

Central Research Laboratory, Hitachi Ltd.

Kokubunji, Tokyo 185, Japan

To evaluate the reliability of thin thermally grown oxide films, we examined their intrinsic breakdown characteristics and investigated oxide defects in them, using ultra-thin oxides (3-10nm). It is demonstrated that the breakdown-time of oxide films becomes longer as the film thickness is decreased, which can be explained by a trap generation model. Furthermore, we were able to determine that, with decreasing film thickness, the defect density of the weak spot mode decreases.

INTRODUCTION

With the scaling down of device dimensions, the use of thin SiO_2 films with thickness of less than 10 nm will soon become common in MOS technology. It is very important to understand the properties of thin SiO_2 films subjected to high electric fields, especially high field dielectric breakdown. Recently it was reported that the intrinsic breakdown-time of thin oxide became longer with oxide film thinning [1][2] and this could be explained by trap generation [3], but the quantitative relation between the breakdown characteristics and the trap generation rate was not clear. Furthermore, when thin oxide films are applied in practical devices, the presence of oxide defects will be a serious problem, but it has not yet been precisely determined just how serious it will be in films less than 10 nm thick.

This paper describes intrinsic breakdown characteristics quantitatively based on electron trap generation, using ultra-thin oxides (3-10nm), and predicts the lifetime under low current or field stress conditions. Oxide defects, which may affect film reliability, are also examined to evaluate the prospects for further oxide scaling.

EXPERIMENTAL

In this work, MOS structures with various film thicknesses, including thick field oxide film structures, were fabricated on (100) oriented 10 ohm-cm N-type silicon wafers. Gate oxides were thermally grown in a 1000°C dry (O_2+N_2) ambient. The film thickness was measured with an ellipsometer. After oxidation, a 310 nm thick poly-Si layer was deposited in a LPCVD system and diffused with phosphorus. The poly-Si was etched by the plasma method to form 100 μm^2 and 7.3 mm^2 gate electrodes. The small MOS capacitors were used to clarify the intrinsic breakdown characteristics of the films by means of a constant current stress test, and the large ones were used to examine oxide defects by TDDB (time dependent dielectric breakdown) measurement.

RESULT AND DISCUSSION

Figure1 illustrates the dependence of breakdown-time (t_{BD}) on injection current density (J). For each value of J, the changes in voltage measured across the devices were monitored until destructive breakdown (a sudden decrease of voltage across the device) was observed. It was observed that t_{BD} decreases with oxide thickness, and breakdown charge (Q_{BD}), ($Q_{BD}=t_{BD}xJ$), decreases with the injection current density [4] and with oxide thickness. This phenomenon may be an indication of more efficient trapping in the film and also generation of new trap sites at higher current density or thicker film thickness. Therefore, we attempted to determine the electron trap generation rate precisely.

Under constant current stress, gate voltage (Vg) rise does not saturate, but goes up linearly with time. This can be explained by the presence of trap generation at a finite and constant rate [5]. Thus, we calculated oxide trap generation rate in the form of dVg/dF, where Vg increases linearly with F, the latter being tunneling fluence (F=Q/q). It was found that the generation rate increases with the injection current density and with oxide thickness, and there was a strong relation between Q_{BD} and dVg/dF. This relation is shown in Fig. 2. It was observed that log(dVg/dF) decreases linearly with $\log Q_{BD}$ and the slope is -1. This demonstrates empirically that dVg/dF is inversely proportional to Q_{BD}. We attempted to consider the physical meaning of this relation. Under constant current stress, the rise of gate voltage (ΔVg) is mainly caused by trap generation and electron capturing, and the following equation is generally formed.

$$Q_{BD} \cdot \frac{dV_g}{dF} = q \cdot \Delta V_g \qquad (1)$$

From the experimental results described above, $(\Delta Vg)_{BD}$ is constant, meaning that oxide breakdown occurs when the increase in the internal electric field comes up to a certain level due to electron capturing in the film.

Next, the generation rate was examined. In case of F-N tunneling, electrons gain energy while traveling in the oxide conduction band, and electron-oxide interactions increase with the distance that electrons travel in the oxide conduction band. From this concept, the generation rate of thin oxide has been proposed [3].

$$\frac{dV_g}{dF} = C\exp\left[-\frac{U}{q\lambda E_{ox}\{1-\exp(-s/\lambda)\}}\right] \qquad (2)$$

where U is critical energy for trap generation, λ is mean-free-path and s is the distance that electrons travel in the conduction band, respectively. It was found that all the trap generation rate data in Fig. 2 fit this equation. Combining Eqs. (1)-(2), we could deduce the relation between J and t_{BD}.

$$J \cdot t_{BD} = \frac{A}{\exp\left[-\frac{U}{q\lambda E_{ox}\{1-\exp(-s/\lambda)\}}\right]} \qquad (3)$$

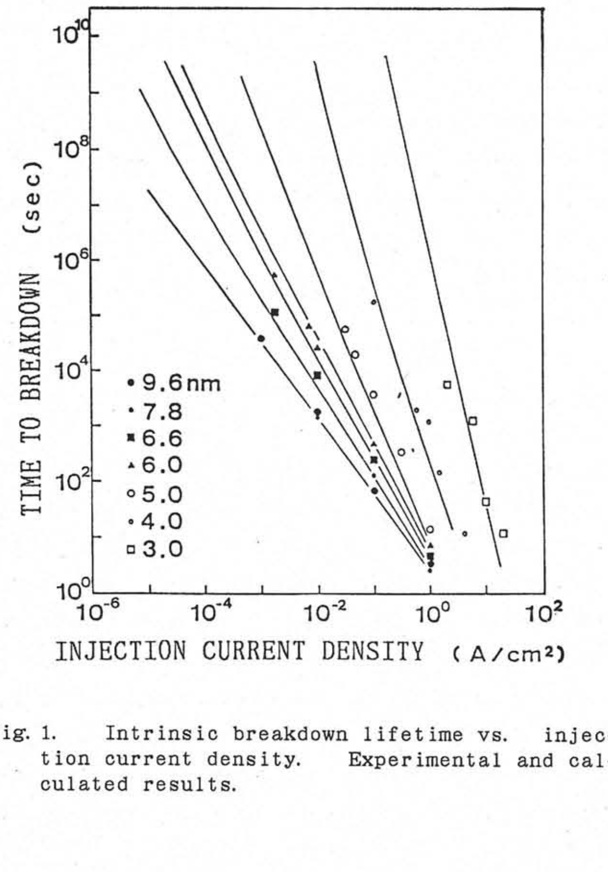

Fig. 1. Intrinsic breakdown lifetime vs. injection current density. Experimental and calculated results.

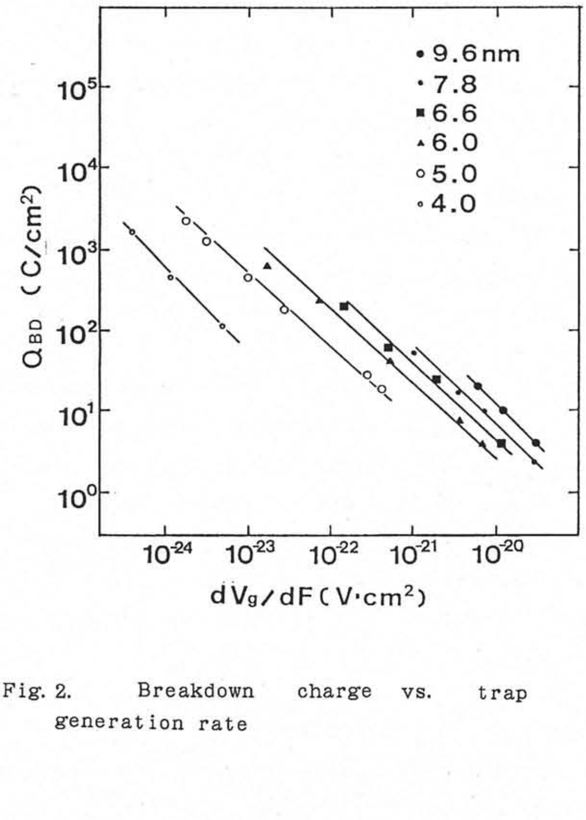

Fig. 2. Breakdown charge vs. trap generation rate

In Fig. 1, the solid lines are the results of Eq(3) and the dots are experimental results. Using Eq(3), we can predict the breakdown-time of thin oxide films under low field conditions.

It is clarified that the intrinsic breakdown characteristics of oxide films subjected to electron current injection improve with decreasing film thickness, but when very thin films are applied in practical devices, not only the intrinsic breakdown characteristics but also breakdowns related to oxide defects will be a serious problem. It is therefore necessary to consider the effects of oxide defects.

It is well known that there are two oxide defect modes, initial short mode (A mode) and weak spot mode (B mode), and that B mode defects reduce film lifetime [6][7]. Thus, we undertook a precise examination of these two modes.

Figure3 illustrates the oxide thickness dependence of A and B mode defect density calculated from TDDB experimental results, using 108 capacitors ($7.3 mm^2$) for each oxide thickness. Though it is difficult to separate the weak spot breakdown mode from the intrinsic breakdown mode (no oxide defects), we assume that the small capacitors have no defects and long lifetimes and that the capacitors which have shorter lifetimes are B mode capacitors. It was found that the A mode defect density increases and the B mode defect density decreases with oxide thinning, even if thickness is less than 10 nm. Two possible models are proposed for this phenomenon. First, it has been reported that oxygen microprecipitates and metallic contamination in Si substrates are major sources of B mode defects and that B mode defects increase with oxide thickness of more than 20 nm [6][7]. Another possible model is that electron-oxide interactions increase with s (the distance that electrons travel in the conduction band of oxide). When oxide thickness becomes less than 10 nm, s becomes shorter and shorter, and weak spots in thin oxide films have less effect upon trap generation or breakdown characteristics. The oxide thickness dependence of the B mode defects can be explained by these, and possibly other, reasons.

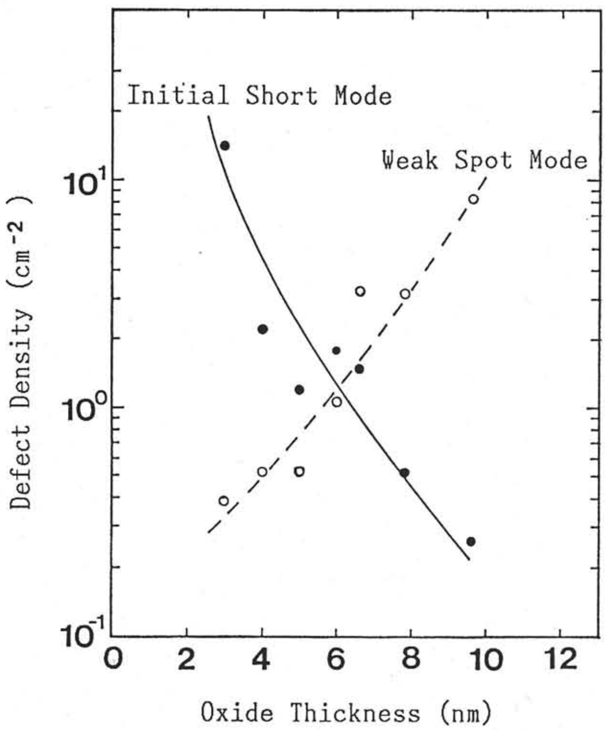

Fig. 3. Oxide defect density vs. oxide thickness.

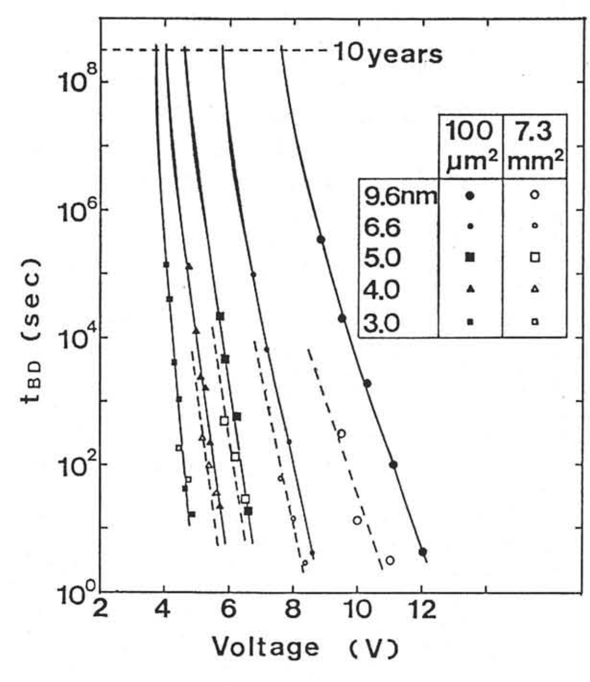

Fig. 4. The time to 50% failure (TDDB) of $7.3\ mm^2$ capacitors and the intrinsic breakdown lifetime of $100\ \mu m^2$ capacitors vs. gate voltage.

Figure4 shows the time to 50% failure in TDDB of 7.3 mm^2 capacitors and the time to breakdown of 100 μm^2 capacitors vs. applied gate voltage. The solid lines represent calculated results using Eq. (3). It is clear that the difference in the lifetime of the two modes decreases with oxide thinning, which can be explained by a decrease in weak spot defects. In practical applications, even oxide films 4 nm thick have lifetimes in excess of 10 years under 2.5V operation.

SUMMARY

Thinner oxide films have longer lifetimes. We used an electron trap generation model to explain this phenomenon and to estimate the lifetime under low electric field or low current conditions. Furthermore, we were able to determine that weak spot mode defect density of films increased with film thickness. From these results, it can be conducted that thin oxide films less than 10 nm in thickness will be of great practical use if their initial short mode defect density can be minimized.

ACKNOWLEDGEMENT

The authors wish to express thanks to Prof. Takuo Sugano and Dr. Kunihiro Asada of the University of Tokyo for their helpful discussions and to Mr. Masami Ozawa for careful sample preparation.

REFERENCES

[1] C. Hu, Technical Digest of 1985 IEDM, p. 368

[2] Y. Hokari, T. Baba, and N. Kawamura, Proc. Int. Reliability Symp., 1982 p. 46

[3] M. S. Liang, J. Y. Choi, P. K. Ko and C. Hu, Technical Digest of 1984 IEDM, p. 152

[4] M. M. Moslehi and K. C. Saraswat, Technical Digest of 1984 IEDM, p. 157

[5] M. S. Liang and C. Hu, Technical Digest of 1981 IEDM, p. 396

[6] K. Yamabe, K. Taniguchi and Y. Matsushita, Proc. Int. Reliability Symp., 1983 p. 184

[7] K. Yamabe and K. Taniguchi, IEEE Trans. Electron Devices, vol. ED-32, 1985, p. 423