Extended Abstracts of the 1995 International Conference on Solid State Devices and Materials, Osaka, 1995, pp. 276-278

Correlating Charge-to-Breakdown with Constant-Current Injection to Gate Oxide Lifetime under Constant-Voltage Stress

Koji ERIGUCHI and Yukiharu URAOKA*

Semiconductor Research Center, Matsushita Electric Ind. Co.,Ltd.
**Liquid Crystal Display Development Center, Matsushita Electric Ind. Co.,Ltd.*
3-1-1 Yagumo-nakamachi, Moriguchi, Osaka, Japan

This paper describes the relationship between the charge-to-breakdown with constant current injection (Q_{bd}) and the time-to-breakdown with constant-voltage stress (t_{bd}). The oxide lifetime (t_{bd}) can be predicted from Q_{bd} by evaluating the time dependence of the gate current density J(t) under constant-voltage stress. This relationship is verified for the oxide thickness more than 6 nm and various substrate temperatures in the measurement from 35°C to 150°C.

1. Introduction

The process-induced degradation of thin gate oxide quality becomes a key issue in the development for highly reliable MOSFET devices. Until now, gate oxide reliability is evaluated by FDDB (Field Dependent Dielectric Breakdown) method performed with the ramp-voltage stress, and two kinds of TDDB (Time Dependent Dielectric Breakdown) methods, which are "t_{bd}"(time-to-breakdown) and "Q_{bd}" (charge-to-breakdown) with constant-current injection. The TDDB method under constant-voltage stress (t_{bd}) allows the lifetime prediction of gate oxide. The relationship between FDDB method and t_{bd} method was studied by A. Berman[1)], but that between t_{bd} and Q_{bd} has not ever been clarified . The time dependence of the gate current density J under constant-voltage stress makes it difficult to clarify the relationship, in particular, in the high oxide-field regime (>10 MV/cm).

In order to evaluate the oxide "lifetime" degradation induced by each manufacturing process, the study of the correlation among these techniques is needed. We found experimentally a relationship between Q_{bd} and t_{bd}[2)], using the useful concept in the study of strength and fracture of steel by M. A. Miner in 1945[3)].

In this paper, we clearly show the relationship between Q_{bd} and t_{bd} by Cumulative Damage Law. The Cumulative Damage Law is verified for the thin gate oxide and the high substrate temperature in the measurement.

2. Cumulative Damage Law

M. A. Miner found Cumulative Damage Law by concerning the cyclic "mechanical" stress to the materials (steels)[3)]. We modify this law to the "electrical" stress to the gate oxide lifetime as follows[2].

Under constant-voltage stress, the gate oxide consumes its lifetime by $J(t)\Delta t/Q_{bd}(J)$ at each period(Δt) since Q_{bd} of the gate oxide depends on the injected current density J. The ratio $J\Delta t/Q_{bd}(J)$ corresponds to the effective lifetime expenditure at each increment. The oxide breaks down when the sum of the fraction of the lifetime expenditure at each period ; $J\Delta t/Q_{bd}(J)$, reaches unity, that is,

$$\int_0^{t_{bd}} [J(t)/Q_{bd}(J)]\, dt = 1. \qquad (1)$$

Eq.(1) corresponds to the Cumulative Damage Law to the electrical stress and indicates the relationship between Q_{bd} and t_{bd}.

3. Experimental

MOS capacitors with gate area of $5\mu m^2$ were fabricated on p-type silicon substrate as test samples. After the LOCOS isolation process, gate oxides were formed with thicknesses of 6 and 8 nm in pyrogenic ambient. To verify Eq.(1) for the thinner oxide and the temperature-accelerated measurement, the substrate temperature in the measurement T was controlled from 35°C to 150°C.

The experiment was carried out by the following steps:
1) $Q_{bd}(J,T)$ is measured.
2) Constant-voltage stress is applied to the oxides.
3) Sum of $J\Delta t/Q_{bd}(J,T)$ is calculated for various oxides until the destructive breakdown.

This procedure further gives us information on the dispersion of J(t) data for different samples, which is important for modeling J(t) in the future study.

4. Results and Discussion

4.1. Q_{bd} Measurement

The Weibull distribution of Q_{bd} is shown in Fig.1. The intrinsic breakdown mode can be seen for both 6 and 8 nm oxides. As shown in this figure, Q_{bd} at conventional 50% cumulative failure is used for discussion. Fig.2 shows the dependence of Q_{bd} on the stress current density J for 6 and 8 nm oxides. The substrate temperature was kept to 35°C. The substrate temperature dependence of Q_{bd} is shown in Fig.3 for 8 nm. Arrhenius behavior is evident[4),5)] and the activation energy is calculated as 0.193 eV in this case.

The experimental relationship of $Q_{bd} = K_1 - K_2 \ln(J)$ is adopted[5),6)] for J dependence and the parameters K_1 and K_2 are determined from Figs.2 and 3. They are listed in Table I. Thus, the denominator in Eq.(1), $Q_{bd}(J,T)$ is determined for each oxide and T.

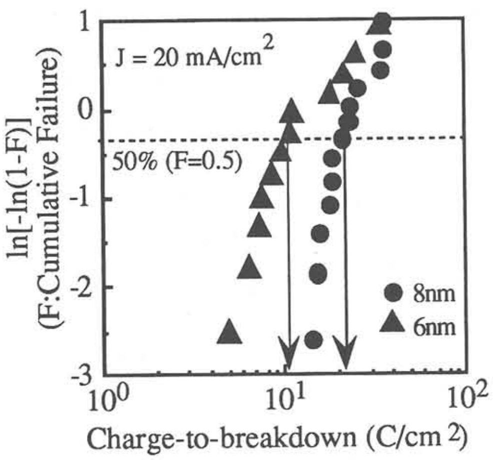

Fig.1. Cumulative failure versus charge-to-breakdown in the Weibull plots. The substrate temperature in the measurement is controlled at 35℃.

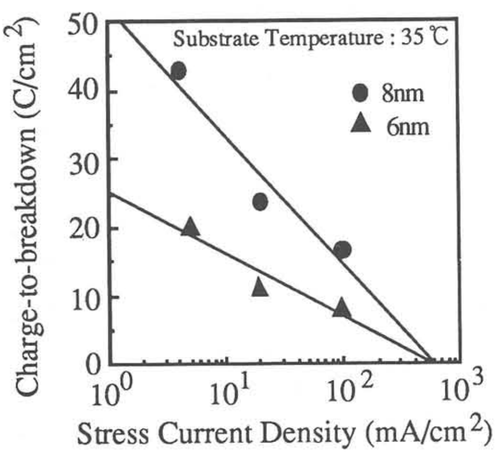

Fig.2. Dependence of charge-to-breakdown at 50% cumulative failure on stress current density.

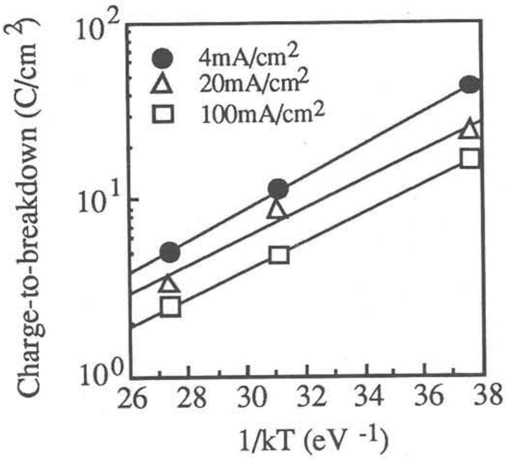

Fig.3. Dependence of Q_{bd} on the substrate temperature in the measurement.

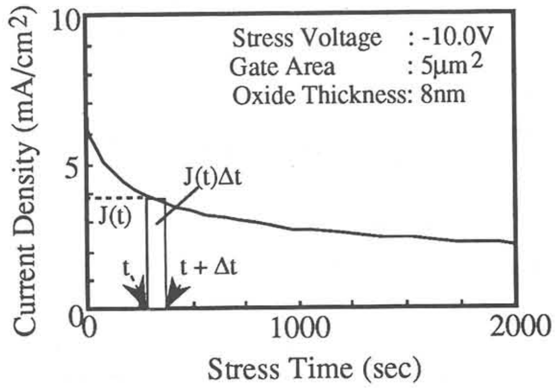

Fig.4. Time evolution of the gate current under constant-voltage stressing. At each increment, the lifetime "$[J\Delta t/Q_{bd}(J,T)]$" is consumed. (T=35℃)

Table I Parameters K_1 and K_2 in $Q_{bd} = K_1 - K_2 \ln J$.

		K_1(C/cm^2)	K_2(C/cm^2)
6 nm	35℃	25.3	4.02
	35℃	52.2	7.95
8 nm	100℃	14.5	2.06
	150℃	6.03	0.795

4.2. t_{bd} Prediction

In the measurement of t_{bd}, the gate current J decreases with time due primarily to the trapped electrons in the oxide[7] as shown in Fig.4. At each increment under stressing, the "effective" oxide lifetime expenditure differs from the magnitude of J(t) since Q_{bd} is a function of the stress current density as shown in Fig.2.

From $Q_{bd}(J,T)$ and J(t), the sum of $J\Delta t / Q_{bd}(J,T)$ is calculated for various oxides in the t_{bd} measurement. Fig.5 shows the relation between $\Sigma[J\Delta t / Q_{bd}(J,T)]$ until the breakdown and the time-to-breakdown for various oxides. Also the dependence of substrate temperature in the measurement T is shown in Fig.6. As seen in these figures, all data fall on a universal curve, indicating that the dispersion of J(t) among the samples is small and negligible. Therefore, any J(t) can be selected as the representative for calculating J(t) by the electron-trapping model[7] or other methods.

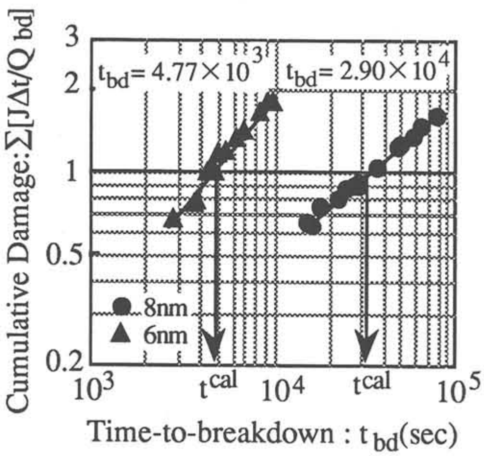

Fig.5. Distribution of the sum :$\Sigma[J\Delta t/Q_{bd}]$ for different gate oxide thicknesses. t_{bd} at 50% cumulative failure is also shown.

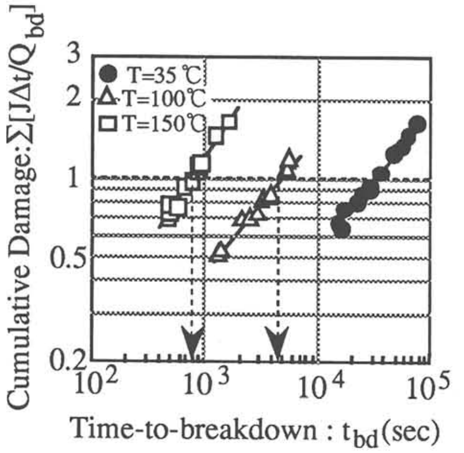

Fig.6. Distribution of the sum :$\Sigma[J\Delta t/Q_{bd}]$ for different substrate temperatures in the measurement. t_{bd} at 50% cumulative failure is also determined for each T.

From these figures, t_{bd} at 50% cumulative failure can be predicted from the intersection between $\Sigma[J\Delta t/Q_{bd}(J,T)]=1$ and the data. Fig.7 represents a comparison between t_{bd} experimentally determined from 50% cumulative failure and t^{cal} derived from the method above. As seen in this figure, t_{bd} and t^{cal} agree well with each other for various gate oxide thicknesses and substrate temperatures in the measurement, supporting the validity of Eq.(1). These results indicate that t_{bd} or the process-induced lifetime degradation of oxide is quantitatively estimated from Q_{bd} (a good monitor for the process-induced damage to the oxide) by modeling J(t) and using Eq.(1) without measuring t_{bd}. Moreover, the time required for measuring t_{bd} is shortened by the method. Also Eq.(1) can be applied to the thin gate oxide thickness and to the temperature-accelerated measurement.

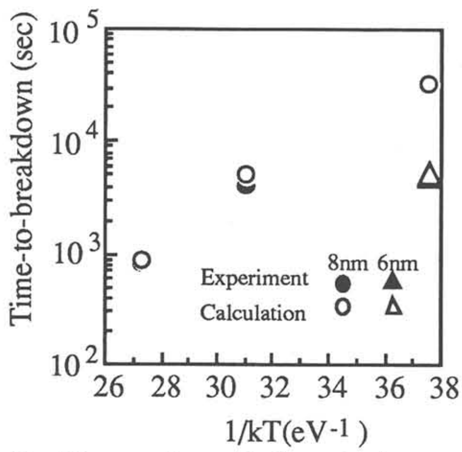

Fig.7. The experimentally determined t_{bd} and the calculated t^{cal} for various oxide thicknesses and substrate temperatures in the measurement.

5. Conclusion

The relationship between t_{bd} and Q_{bd} is clarified by Cumulative Damage Law. This law is successfully applied to the thin oxide evaluation and to the temperature-accelerated testing, and also gives the evaluation method of oxide lifetime degradation induced by each manufacturing process by Q_{bd}.

Acknowledgments

The authors would like to thank Dr. K. Hatada and Dr. T. Takemoto for their encouragement and Dr. S. Odanaka for his helpful discussion. Also the authors acknowledge T. Yamada and H. Nakagawa for their supports.

References

1) A. Berman, IEEE *Reliability Physics Symp.*, (1981) 204.
2) K. Eriguchi et al., IEEE **EDL-16** (1995) 187.
3) M. A. Miner, J. Appl. Mechanics **12** (1945) A-159.
4) M. M. Moslehi et al., in *Tech. Dig.* IEDM (1984) 157.
5) K. Eriguchi et al., Jpn. J. Appl. Phys. **33** (1994) 83.
6) M. -S. Liang et al., in *Tech. Dig.* IEDM (1984) 152.
7) I.-C.Chen et al., IEEE **ED-32** (1985) 413.