

High-Frequency Time-Dependent Breakdown of SiO₂

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Abstract—Time-dependent dielectric breakdown (TDDB) of thin oxides (8.6–11 nm) is compared under dc, pulse, and bipolar pulse conditions for frequencies up to 4 MHz. Lifetime under unipolar pulse conditions does not deviate largely from that under dc conditions; however, lifetime under bipolar stress conditions increases by a factor of 40 to 100 at frequencies above 10 kHz. The field acceleration of breakdown time is similar for dc and pulse stressing.

I. INTRODUCTION

A GREAT DEAL of effort has been spent studying time-dependent dielectric breakdown (TDDB) of SiO₂ under constant voltage conditions (see, for example, [1]–[4]), but there has been no study of TDDB under ac conditions at frequencies above 10 kHz [5], [6]. This paper presents results of unipolar and bipolar pulse testing up to 4 MHz.

II. EXPERIMENT

N-MOSFET's were used to compare the results of unipolar and bipolar stressing. We used transistors rather than capacitors so that the substrate would be certain to go into inversion rather than deep depletion when positive V_g was applied. Unipolar stressing of capacitors ($-V_g$ polarity) was performed for comparison. We saw no evidence for early breakdown at the source/drain edge of the MOSFET structures. This is an expected characteristic of a well-developed technology.

The devices were fabricated on (100) oriented p-type substrate with resistivity of 10–30 $\Omega \cdot \text{cm}$. LOCOS isolation was used. The gate oxide was grown in dry O₂ at 900°C followed by a 20-min N₂ anneal. The capacitor gate oxide thickness was 10 nm; transistors were fabricated with oxide thicknesses of 11 and 8.6 nm. *In-situ* phosphorus-doped polysilicon was deposited at 650°C to form the gate electrode. A N₂ anneal at 900°C for 20 min followed. This was the final step for capacitor fabrication. The transistors were completed using conventional NMOS technology. After metallization, the wafers were sintered in forming gas at 400°C for 20 min.

All experiments were controlled via an HP 9836 computer. An HP 4140 picoammeter/voltage source was used for the constant voltage trials. AC waveforms were generated by an HP 8115A pulse generator. A Tektronix current probe and

AM503 amplifier was used to detect breakdown during the ac trials. An HP 5316A counter was used to monitor the time between the activation of the pulse generator and the device breakdown. A digital oscilloscope was used to monitor signal levels.

III. UNIPOLAR STRESSING

Capacitors of 100 μm^2 were stressed at two different fields and frequencies ranging from 0 to 4 MHz. The signal polarity was chosen for electron injection from the gate. As the data in Fig. 1 show, there is not a substantial difference between the dc and high-frequency values of time to breakdown (t_{BD}). t_{BD} is defined as the cumulative amount of time the rectangular voltage is at its maximum ON value. Each data point is the average of several measurements. Due to the expected scatter in constant voltage TDDB data [3], it is difficult to conclude whether the data in Fig. 1 show a small increase in t_{BD} with increasing frequency or just the usual t_{BD} scatter. However, a previous study [5] did conclude that in the dc to 10-kHz range there was a small ($\times 2$ – $\times 4$) increase in t_{BD} with increasing frequency. Our data indicate that at high frequencies this factor does not increase further. The data in Fig. 1 indicate that one may project ac lifetime from dc measurements simply by considering the duty factor. The lifetime derived in this manner will be, at worst, overly conservative. Presumably, if there were significant voltage overshoot at the signal transitions, this statement might not be true, and, in fact, one could see degradation of t_{BD} at high frequencies [7].

IV. BIPOLAR STRESSING

N-channel transistors ($T_{OX} = 11$ nm) were used for the bipolar stressing experiment. Before starting ac stressing, transistors were dc stressed in both polarities to find positive and negative gate voltages which gave approximately equal values of t_{BD} (a value of V_g about 1 V larger needs to be used in the negative polarity direction because of band bending). Experimental results are presented in Fig. 2(a). The data clearly show an increase in lifetime for devices that are subject to high-frequency bipolar stress. Data taken on 8.6-nm MOSFET structures exhibited the same behavior except that the ratio of 1-MHz t_{BD} to dc t_{BD} is somewhat larger than for the thicker oxide transistors (100 versus 40).

The values of $+V_g$ and $-V_g$ used during the ac tests were the same as those used during the dc tests; this was checked with the oscilloscope. The frequency range of this experiment was limited to that for which we could obtain clean waveforms. As shown in Fig. 2(b), we were able to generate

Manuscript received December 28, 1990; revised March 11, 1991. This work was supported by SRC, Sandia Laboratories, AMD, MICRO, and ISTO/SDIO through ONR under Contract N00014-85-K-0603.

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IEEE Log Number 9100358.

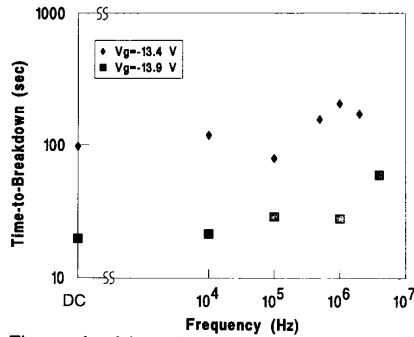
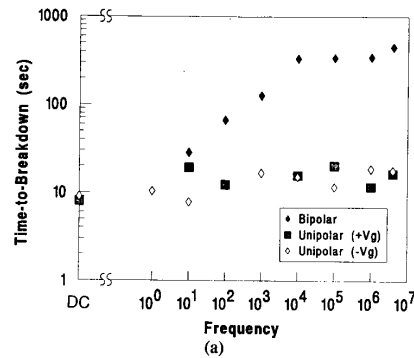


Fig. 1. Time to breakdown (t_{BD}) of 10-nm gate oxide capacitors in accumulation from dc to 4 MHz. t_{BD} is equal to the experiment duration multiplied by the signal duty cycle. Lifetime is not degraded at high frequencies and may even be enhanced.



5 V/div 200 ns/div

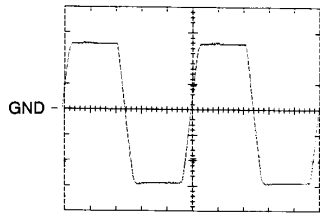


Fig. 2. (a) t_{BD} as a function of frequency for 11-nm gate oxide transistors under unipolar and bipolar stress. Unipolar t_{BD} shows similar frequency dependence for both gate voltage polarities. Bipolar t_{BD} is enhanced over that for the unipolar and dc cases. (b) Clean waveforms were obtained at all frequencies used. This figure shows an oscilloscope trace of the waveform used for 1-MHz bipolar stressing.

signals with a minimum of ringing up to the low megahertz range. Identical signal transition times were used for the unipolar and bipolar signals to ensure that any ringing which occurred would be worse on the bipolar signal. This, presumably, would lead to more severe stressing for the devices subjected to the bipolar waveform. Therefore, the longer t_{BD} from bipolar stressing is all the more conclusive.

The data in Fig. 2(a) confirm that unipolar stress lifetime is slightly longer than dc lifetime. Furthermore, t_{BD} from both positive and negative pulse stress tests shows similar frequency dependence.

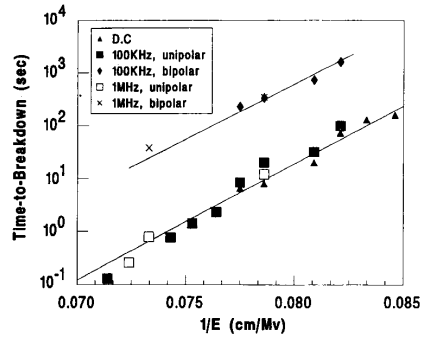


Fig. 3. DC, unipolar, and bipolar t_{BD} all have similar field dependences. The data shown here are for positive V_g .

Bipolar stress lifetime in the megahertz range is 10 times higher than that at 10 Hz and 40 times higher than the dc lifetime at the same applied voltage. We believe that the increase in t_{BD} at high frequency is due to a net decrease in the amount of trapped positive charge in the oxide. Reference [6] showed that the amount of trapped positive charge is reduced under bipolar conditions at frequencies as low as 200 Hz. Above 10 kHz, the bipolar and unipolar lifetimes are fairly constant and a time constant of about 0.2 ms appears to be associated with this saturation phenomenon, at least at the electric field used during this experiment. The appearance of a time constant suggests that under ac conditions the hole concentration cannot reach its steady-state dc value [5]. Our results show that field reversal is even more effective than just turning the signal OFF in extending t_{BD} . At this time, the reason is not clear. One possibility is that electron injection from both electrodes can neutralize trapped holes near both electrodes more effectively, thus prolonging the oxide lifetime.

Fig. 3 shows that t_{BD} under bipolar conditions increases linearly with $1/E$; this field dependence is a familiar result of dc TDDB studies. The slopes of the bipolar and dc curves are similar. Therefore, one may predict bipolar t_{BD} using the same acceleration factors as for dc t_{BD} after one has determined the ratio of bipolar to dc t_{BD} for the frequency and oxide thickness of interest.

V. CONCLUSIONS

Oxide time to breakdown under unipolar and bipolar pulse stress has been shown to be greater than that under dc conditions. The values of dc and unipolar t_{BD} are sufficiently close to make reasonable projections of unipolar t_{BD} from dc measurements. Although bipolar t_{BD} can be as much as 100 times larger than dc t_{BD} at 1 MHz, the similar field dependences of bipolar and dc t_{BD} allows one to make bipolar lifetime projections after a minimum of bipolar TDDB testing.

ACKNOWLEDGMENT

The authors would like to thank Dr. Y. Fong of SunDisk, Inc. for his useful suggestions regarding the experimental setup.

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