A Comparative Study of the Effects of Dynamic Stressing on High-field Endurance and Stability of Reoxidized-Nitrided, Fluorinated and Conventional Oxides

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***Abstract*—High field endurance of reoxidized-nitrided oxide (*RNO*), and fluorinated oxide (*FOX*) under dynamic *Fowler-Nordheim* stress were compared with that of conventional oxide. Time-dependent dielectric breakdown (TDDB) of *RNO* and *FOX* is shown to be strongly dependent on frequency, and lifetime under high frequency stress is longer relative to that under DC stress. *RNO* and *FOX* display interface hardness under high field injection at all frequencies. Interface trap generation is not a strong function of frequency in any of the oxides studied. Examination of charge trapping indicates that frequency-dependent hole trapping is responsible for the frequency dependence of TDDB.**

I. INTRODUCTION

Reoxidized-nitrided oxides (*RNOs*) and fluorinated oxides (*FOXs*) have been shown to possess improved high field endurance and hot electron immunity under DC stress as compared with conventional oxides [1]-[4]. In this work, we report the first comparison of high field endurance between these oxides and conventional oxide films (~100 Å) under high field dynamic stress. A unipolar square wave voltage, of frequencies ranging from 50 Hz to 5 MHz, is applied to all the samples and the time to breakdown (t_{BD}) is monitored, along with interface trap generation and bulk charge trapping. Both the *RNO* and *FOX* are shown to have a strongly frequency dependent t_{BD}; this contrasts with the weak dependence of t_{BD} on frequency seen in unipolar-pulse stressed conventional oxides [5]. Verified by charge trapping measurements, a frequency dependent hole trapping model is used to explain this phenomenon.

II. EXPERIMENTS

Devices used in this study were polysilicon-gate, field-isolated MOS capacitors. The substrate material was 10~20 Ω cm <100> n-type Si. The 100-Å oxide was grown at 850°C or 950°C in atmospheric pressure O_2. Sixty minutes of thermal nitridation was performed at 850 or 950°C in 0.1- or 0.01-atm NH_3 [1],[2]. The nitrided oxides were then reoxidized at 850°C in 1-atm O_2 or at 950°C in 0.1-atm O_2 for 180 minutes. The fluorinated oxide was grown by an HF-immersion process [4]. All samples were then annealed in N_2 for 20 minutes and *in-situ* phosphorus doped polysilicon-gate was deposited. A 30-minute forming gas anneal at 450°C completed the process. Process conditions for the gate oxides are listed in Table I. Also listed in Table I are the equivalent oxide thickness and flatband voltage as determined by *C-V* measurements.

A positive square wave voltage with a duty cycle of 50% and rise and fall time of 100 ns was applied to the gate. The breakdown current was monitored by a current probe and a universal counter was used to measure the time until device breakdown. Unless otherwise specified, the gate area used in this work was 10 μm by 10 μm.

III. RESULTS AND DISCUSSION

Fig. 1 shows the effect of stress frequency on time to breakdown, t_{BD}. It can be seen that for both *RNO* and *FOX*, t_{BD} increases with frequency; the lifetime of *RNO(HT)* and *FOX* under 1 MHz stress is increased by 20 and 6 times, respectively, compared with the lifetime under DC stress. Control oxide (*OX*) lifetime does not significantly change with frequency; at high frequencies, *RNO* t_{BD} is about 2 orders of magnitude greater than *OX* t_{BD}, while it is only 3-6 times longer under DC stress [3]. Note that lifetime saturation is observed when the stressing electric field is decreased to 13 MV/cm. A similar phenomenon has been observed for conventional oxide stressed with bipolar waveforms [5], [7].

Table I THE GATE OXIDE DETAILS

Sample	Oxidation Temp.	Nitridation Temp./Time	Nitridation NH3 Pressure	Reoxidation Temp./Time	Reoxidation O2 Pressure	Thickness (Å)	VFB (V)
RNO(LT)	850°C	850°C/60 m	0.1 atm.	850°C/180 m	1 atm.	103	-0.35
RNO(HT)	950°C	950°C/60 m	0.01 atm.	950°C/180 m	0.1 atm.	103	-0.37
FOX	900°C	(Dipped in 50:1 HF for 5 min before oxidation)				95	-0.20
OX, Control	850°C	Control Oxde				99	-0.21

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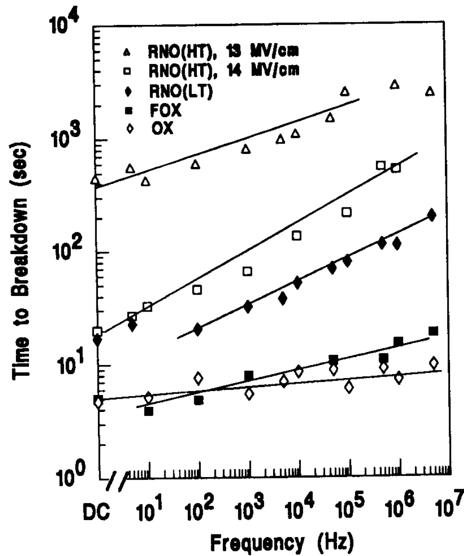

Fig. 1 The frequency depedence of time to breakdown for devices stressed with unipolar square waveform voltage. The stress amplitude is 14 MV/cm unless otherwise noted, and t_{BD} was the product of total injection time before device breakdown and duty cycle of the wave form.

As shown in Fig. 2, the field dependence of TDDB is independent of frequency. It is known that the slope of the plot log (t_{BD}) *vs.* $1/E$ gives the sum of the impact ionization coefficient, H, and the *F-N* tunneling coefficient, B [6]. Since the values of B for all the dielectrics used in this study are comparable [3], Fig.2 indicates that *RNO* has the same frequency invariant value of H as does conventional oxide. This observation confirms an earlier report [3]. Therefore, it is unlikely that the improved lifetime for *RNO* under high frequency dynamic stressing is due to a decrease of the impact ionization rate.

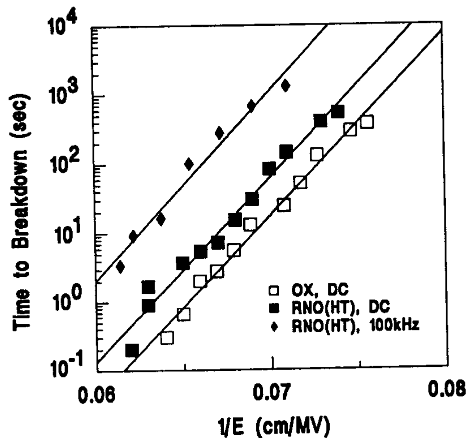

Fig. 2 Comparison of electric field (E) dependence of t_{BD} under DC and 100 kHz stress. The markers are experimental data, the lines are the best fits to the experimental data based on $t_{BD}=\tau_0 \exp[(B+H)/E]$, where H is the impact ionization coefficient, B is the *Fowler-Nordheim* tunneling coefficient.

The effects of dynamic stress on the interface trap density are evaluated by comparing the quasi-static *C-V* curves presented in Fig. 3. The distortion of these *C-V* curves, hence the interface trap density D_{it}, is not a strong function of stress frequency for the devices studied. Consequently, the previously known relative immunity of *RNOs* and *FOXs* to interface trap generation under DC stress is conserved under unipolar dynamic stress. This observation indicates that the resistance of the *RNO* and *FOX* to interface trap generation is not the cause of their frequency dependent TDDB and, therefore, probably not the cause of their greater t_{BD}'s than con-

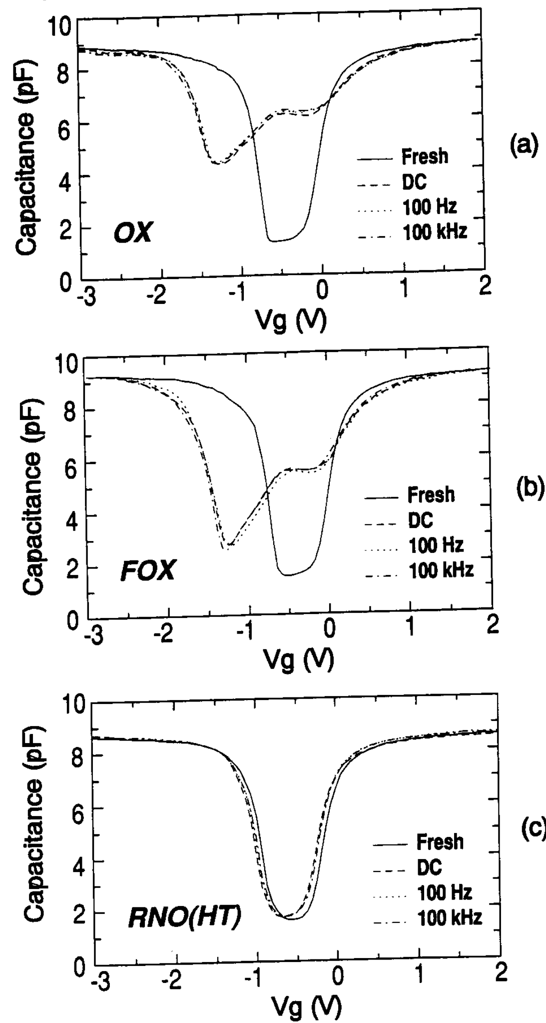

Fig. 3 Quasistatic *C-V* curves for (a) control oxide, (b) *FOX*, and (c) *RNO(HT)* before and after DC and dynamic stressing at 100 Hz and 100 kHz. The stress field is 13 MV/cm and stressing time is 1 second for DC stress and 2 second for dynamic stress. The gate area is 50 μm by 50 μm.

ventional oxides. In fact, it has been observed that conventional oxide has much longer lifetime under bipolar dynamic stress than under DC stress, although the bipolar stress induces a greater interface-trap generation rate than DC stress [7].

To examine charge trapping, both positive ($+V_g$) *I-V* and negative ($-V_g$) *I-V* curves were measured before and after stress as illustrated in Fig. 4 and Fig. 5. For sample *RNO(HT)*, the positive *I-V* curves shift negatively after stress, indicating positive charge trapping (Fig. 4a). Interestingly, the positive charge build-up is frequency dependent. No such dependence can be seen in the *OX* sample as shown in Fig. 5a. The presence or absence of the frequency dependence of hole trapping correlates with the frequency dependence of t_{BD}. Since hole trapping is believed to be a necessary step in oxide breakdown [8], we postulate that the frequency dependence of hole trapping is responsible for the frequency dependence of *RNO* and *FOX* time to breakdown. For negative *I-V*, as shown in Fig. 4b and Fig. 5b, one can also see positive charge trapping at the lower fields ($|V_g| \sim 9$-9.5 V) where hole detrapping is not favorable. However, unlike the *+I-V* where the shift of *I-V* curves decreases with stress frequency, the low voltage shift of *-I-V* is less sensitive to stress frequency. Yet, control oxide has a much higher leakage current at the lower fields than *RNO*.

To further examine the frequency dependence of charge trapping, high frequency *C-V* curves are measured before and after stressing. The flatband voltage shifts, ΔV_{FB}, are extracted from these *C-V* curves and shown in Fig. 6 as a function of stress frequency. For *RNO*, the magnitude of (negative) ΔV_{FB} decreases with stress frequency, indicating reduced hole trapping. This is in agreement with the *I-V* characteristics. For control oxide and fluorinated oxide, the positive ΔV_{FB} decreases with stress frequency, suggesting that net electron trapping decreases. Although a decrease in electron trapping under dynamic stress has been suggested as the cause of lifetime increase [9], we did not see evidence to support this

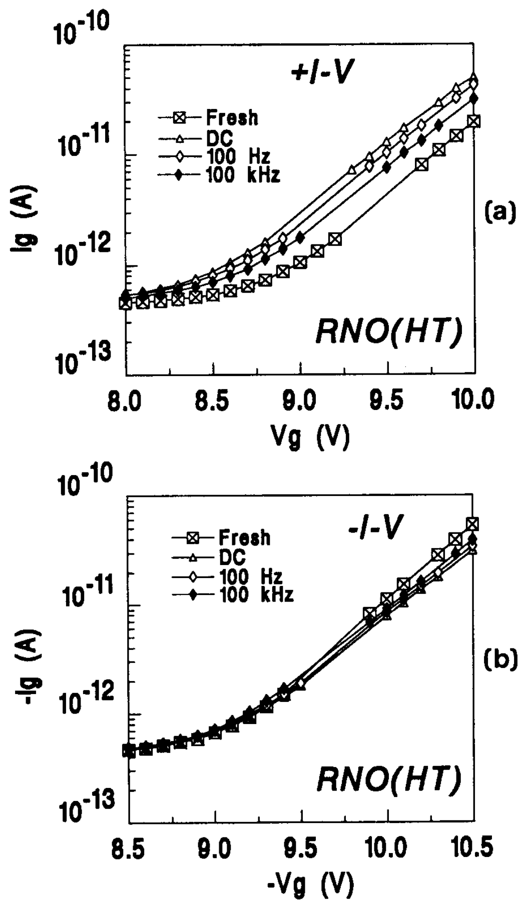

Fig. 4 *I-V* curves for sample *RNO(HT)* before and after stressing for (a) positive gate voltage, (b) negative voltage. The injection field is 13 MV/cm and injection time for DC and unipolar stressing is 1 and 2 second, respectively.

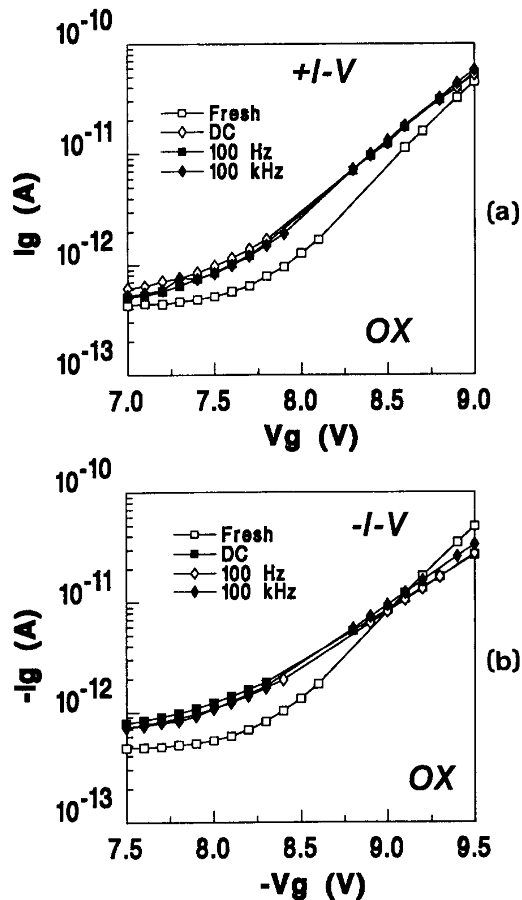

Fig. 5 *I-V* curves for sample *OX* before and after stressing for (a) positive gate voltage, (b) negative voltage. The injection field is 13 MV/cm and injection time for DC and unipolar stressing is 1 and 2 second, respectively.

for sample *OX* or *FOX*. In fact, electron trapping in *OX* is a stronger function of frequency than in *FOX* (Fig. 6) while *FOX* t_{BD} is a much stronger function of frequency than *OX* t_{BD} (Fig. 1). We observe negative ΔV_{FB} in *RNO,* in contrast to positive ΔV_{FB} in *FOX* and *OX,* due to a much lower electron trap generation rate in *RNO* [3], [10].

It has been shown that compared with thermal oxide, *RNO* possesses shallower hole traps which are more easily detrapped, even under floating gate condition [10], [11]. Evidence for this is seen in the *-I-V* characteristics. As lower fields *-I-V* curve shifts and slope changes are less in *RNO* than in control oxide, indicating less localized hole accumulation at the injection anode. If impact generated holes do not move far enough from the anode during the high V_g half cycle, they may detrap during the zero V_g half cycle.

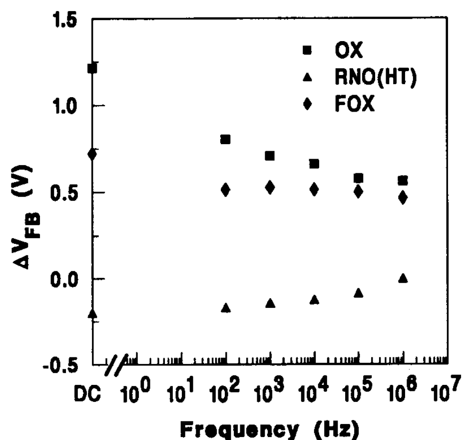

Fig. 6 The effects of injection frequency on flatband voltage shift, ΔV_{FB}. 50 μm by 50 μm capacitors and an electric field of 13 MV/cm were used.. The injection time for DC and unipolar stressing is 1 and 2 second, respectively.
V_{FB}

IV. Summary

A strongly frequency dependent TDDB has been observed in reoxidized-nitrided oxides and in fluorinated oxides, although the field acceleration factor is similar to that under static stress. Under the condition of positive V_g dynamic stress, neither the interface trap generation nor the electron trapping is correlated with the observed frequency dependence of TDDB. It is believed that a decrease in hole trapping under high frequency stress is responsible for the increase in lifetime.

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References

[1] W. Yang, R. Jayaraman, and C.G. Sodini, *IEEE Trans. Electron Devices*, ED-35, p.935, 1988.

[2] B.J. Gross, K.S. Krisch, and C.G. Sodini, *IEEE Trans. Electron Devices*, ED-38, p.2036, 1991.

[3] Z.H. Liu, *et al, in Extended Abstracts of the 23rd (1991) International Conference on Solid State Devices and Materials*, p. 26, Japan, 1991.

[4] Y. Nishioka, E.F. Da Silva, Jr., Y. Wang, and T.P. Ma, *IEEE Electron Device Lett.*, EDL-9, p.38, 1988.

[5] E. Rosenbaum and C. Hu, *IEEE Electron Device Lett.*, EDL-12, p.267, 1991

[6] I.C. Chen and C. Hu, *IEEE Electron Device Lett.*, EDL-8, p.140, 1987.

[7] E. Rosenbaum, Z.H. Liu, and C. Hu, to be presented at *International Electron Devices Meeting*, 1991.

[8] I.C. Chen, S.E. Holland, and C. Hu, *IEEE Trans. Electron Devices*, ED-32, p.413, 1985.

[9] S. Haddad and M.S. Liang, *IEEE Electron Device Lett.*, EDL-8, p.524, 1987.

[10] D.J. DiMaria and J.H. Stathis, *J. Appl. Phys.*, vol. 70, p.1500, 1991.

[11] K.S. Krisch, B.J. Gross, and C.G. Sodini, *J. Appl. Phys.*, vol. 70, p. 2185, 1991.