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Invited

Demands for Submicron MOSFET's and Nitrided Oxide Gate-Dielectrics

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Deep-submicron MOSFET's require ultrathin (≦10nm) gate dielectrics satisfying high performance and high stability simultaneously. This paper proposes (reoxidized) nitrided oxides prepared by rapid thermal processing (RTP) as a replacement of conventional gate-SiO_2 and investigates the physical properties, defect-charge densities, TDDB stability, MOSFET performance, and hot-carrier stability. In contrast with popularly heavy nitridations, light nitridation combined with the subsequent reoxidation improves reliability significantly, while achieving device performance comparable or superior to that of SiO_2. An ultrathin (reoxidized) nitrided oxide prepared by RTP is most promising as the gate dielectric of submicron MOSFET's in place of thermal SiO_2.

1. INTRODUCTION

As recent developments of ULSI's urge further scaling of MOSFET's down to deep submicrons, requirements on the quality of ultrathin (≦10 nm) gate dielectrics become more and more demanding [1] as listed in Table 1. Nitrided oxides [2)-4)], which were nitrided in NH_3 by furnace annealing (FA), have been reported to show many advantages over thermal SiO_2 such as improved interface stability, while showing some disadvantages (Table 1). Recently, the author has revealed [5)-13)] that the disadvantages of degraded device performance reported for FA-prepared heavily nitrided oxides can be minimized by optimizing the fabrication condition using rapid thermal processing (RTP) thanks to the RTP's merits [5)] such as short-time and cold-wall processing. Furthermore, the author has reported that the disadvantage of high-density electron traps in nitrided oxides can be eliminated by subsequent rapid reoxidation [8)], where RTP was for the first time applied to the full fabrication process of reoxidized nitrided oxides.

This paper demonstrates that (reoxidized) nitrided oxides prepared by RTP can satisfy both the performance and reliability demands in Table 1 at the same time and so they are most promising as the gate dielectric of submicron MOSFET's in place of conventional SiO_2.

Table 1. Demands for submicron MOSFET's and comparison between thermal SiO_2 and nitrided SiO_2.

DEMANDS	Thermal SiO_2	Nitrided SiO_2 reported [2)-4)] (by furnace annealing)
High V_T Controllability	Good	*High-density* Fixed Charges & Interface States (> 10^{11} cm^{-2})
Sharp Turn-on Characteristics		
High Mobility	Good	*Degraded* Peak Mobility (by >20-50 %)
High Current Drivability, *esp.* @ a high gate-drive	*Large* Gate-Field-Induced Degradation	(*unknown*)
High Dielectric Strength	*unsatisfactory*	*e.g.*, Improved Resistance to Impurity Penatration
High TDDB (High-Field) Stability	*Poor* Interface Stability	Improved Interface Stability, but *High-density* Electron Traps
High Hot-Carrier Stability		
High Stability to Radiative (*incl.* Process) Damages		Improved

2. EXPERIMENTAL

The MOS transistors and capacitors studied were fabricated by using the conventional polysilicon-gate MOS process [12)]. 7.7-nm-thick oxides were nitrided in NH_3. Hereafter, an oxide nitrided at 950 °C for 60 s is called *NO*. These nitrided oxides were successively reoxidized in dry O_2. *NO* reoxidized at 1150 °C for 60 s is called *ONO*.

3. RESULTS and DISCUSSION

3-1. Physical Properties

Fig. 1 shows how AES depth profiles are changed by nitridation [7)]. Nitrogen piles up very rapidly at both the Si-SiO_2 interface and the outer surface. While dielectric constant is increased [7] by nitrogen incorporation, no film thickness increase occurs. Subsequent reoxidation hardly changes nitrogen concentration near the interface $[N]_{int}$, while increasing film thickness slightly [10), 12)]. Fig. 2 shows that nitridation increases hydrogen concentration $[H]$ significantly [9], which results from the decomposition of NH_3. In contrast, subsequent reoxidation reduces $[H]$ to a low level comparable to that of thermal SiO_2.

3-2. Defect Charges and TDDB Stability

As for defect charges, Fig. 3 shows that both N_f and D_{it_m} vary similarly as nitridation proceeds [7]: both increase at first, reach respective maxima at a nitridation time, and then decrease gradually showing turnarounds to low levels comparable to those of SiO_2. While thermal annealing of heavily nitrided oxides results in undesirably large N_f increase, that of lightly nitrided ones decreases it monotonically [12]. Thus N_f and D_{it_m} for (reoxidized) nitrided oxides can be reduced comparable to thermal SiO_2 by optimizing the fabrication condition.

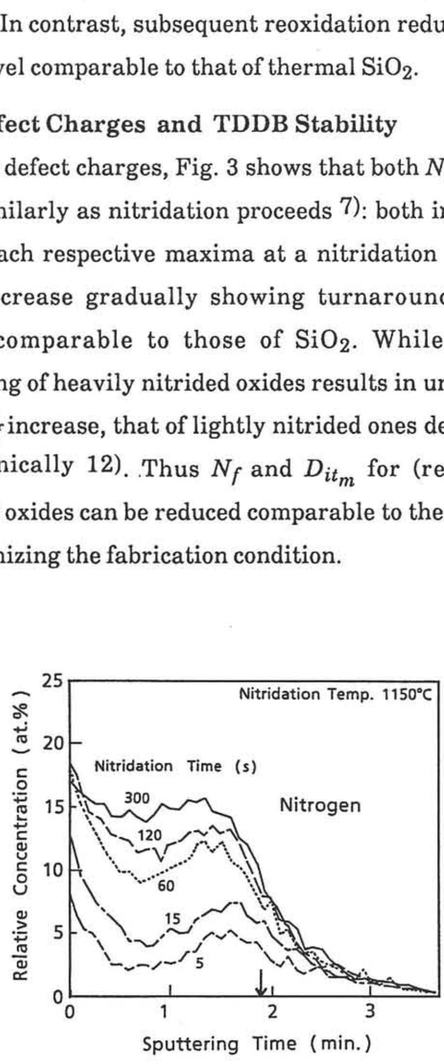

Fig. 1. Nitrogen AES depth profiles of oxides nitrided for various nitridation times at 1150 °C. An arrow indicates the position of the Si-SiO_2 interface.

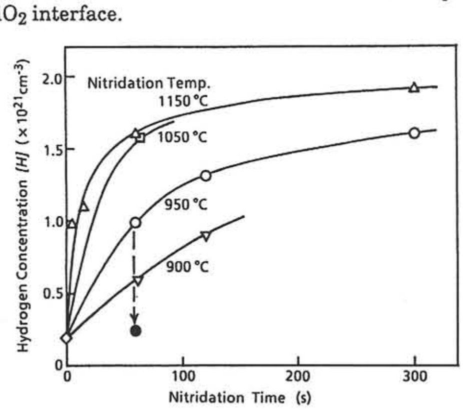

Fig. 2. Hydrogen concentration $[H]$ measured by SIMS versus nitridation time. A dashed arrow and ● indicate the effect of reoxidation of NO at 1150 °C for 60 s.

As for TDDB stability, Fig. 4 shows that although nitridation degrades charge-to-breakdown Q_{BD}, additional reoxidation improves it outstandingly [8] to a level larger by ~16 times than that of SiO_2. As for high-field-induced degradation (Fig. 5), while ΔV_{FB} increases monotonically with progress of nitridation, ΔD_{it_m} shows a turnaround: it increase at first, reach a maximum at a nitridation time, and then decrease gradually to a level lower than that of SiO_2 [9]. Thus it is difficult to make both ΔV_{FB} and ΔD_{it_m} of a nitrided oxide small at the same time, because light nitridation suffers from degraded interface stability and heavy one induces huge electron trapping. This dilemma can be solved by additional reoxidation [8], which can reduce both ΔV_{FB} and ΔD_{it_m} simultaneously (Fig. 5): *e.g.*, the ΔV_{FB} and ΔD_{it_m} for *ONO* are outstandingly reduced

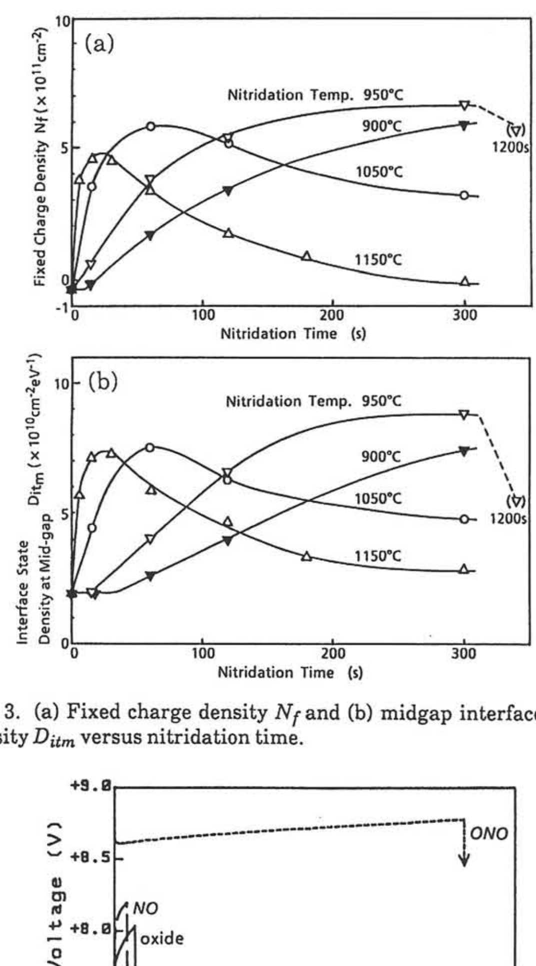

Fig. 3. (a) Fixed charge density N_f and (b) midgap interface state density D_{itm} versus nitridation time.

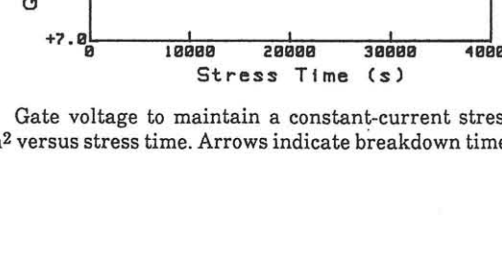

Fig. 4. Gate voltage to maintain a constant-current stress at 10 mA/cm^2 versus stress time. Arrows indicate breakdown times.

by >100 times from those of thermal SiO_2. The ΔV_{FB} behaviors are explained by a model 7), 12) that electron traps originate from hydrogen (Fig. 6(a)). The ΔD_{it_m} behaviors are explained by a two-factor model 7), 12) that one factor *[H]* degrades ΔD_{it_m} while the other factor $[N]_{int}$ improves it (Fig. 6(b)). Thus, smaller *[H]* and larger $[N]_{int}$ by nitridation and successful *[H]* reduction by reoxidation are crucial to obtain reliable dielectrics.

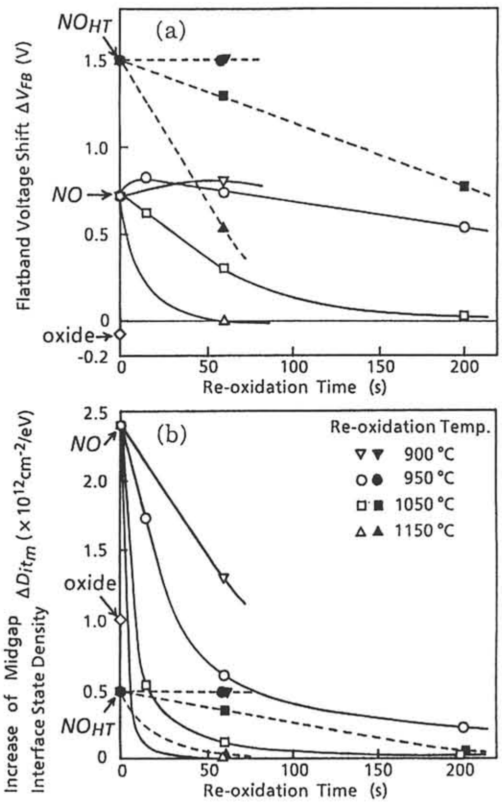

Fig. 5. (a) Flatband voltage shift ΔV_{FB} and (b) increase of midgap interface state density ΔD_{itm} induced by 0.1-C/cm^2 electron injection versus reoxidation time. The starting nitrided oxides are *NO* (lightly nitrided at 950 °C for 60 s) and NO_{HT} (heavily nitrided at 1150 °C for 60 s).

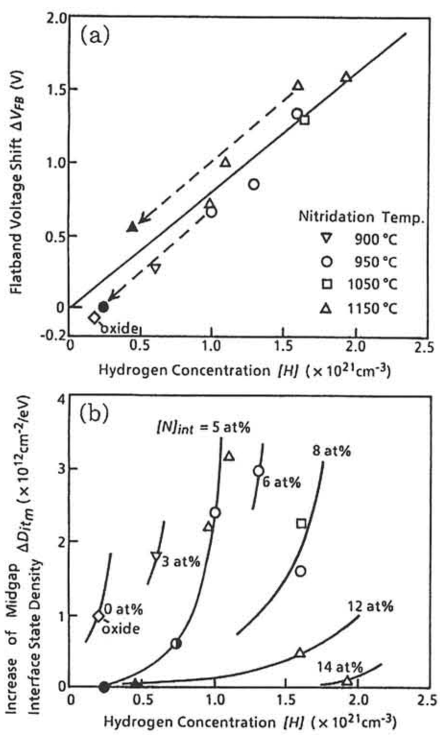

Fig. 6. (a) ΔV_{FB} and (b) ΔD_{itm} induced by 0.1-C/cm^2 electron injection versus hydrogen concentration *[H]*. ◑ and ● (▲ and ▲) in these figures are the data for *NO* (NO_{HT}) reoxidized for 60 s at 1050 and 1150 °C, respectively.

3-3. MOSFET Performance and Hot-Carrier Stability

Fig. 7 shows that *NO* and *ONO* MOSFET's exhibit excellent device performance comparable to that for an oxide one 11), 13): *e.g.*, for *ONO*, the subthreshold swing is almost the same, and the V_T and peak mobility are smaller only by 0.07 V and 9 % than those for SiO_2, respectively. Furthermore, an important observation to be made in Fig. 7 is that V_G-induced mobility degradation for *NO* and *ONO* is markedly reduced from that of thermal SiO_2 13), resulting in the larger normalized drivability (I_D/C_i) at high V_G. This means that one of the major scaling limitations 1) can be significantly reduced.

From Fig. 8, reoxidation of a nitrided oxide is found to achieve remarkable improvement of hot-carrier stability 11): *e.g.*, lifetimes reaching 30-mV V_T shift and 10-% g_{mmax} degradation for *ONO* are significantly improved by 3 and 1.5 orders of magnitude over thermal SiO_2, respectively. Fig. 9 shows that nitridation reduces V_T shift

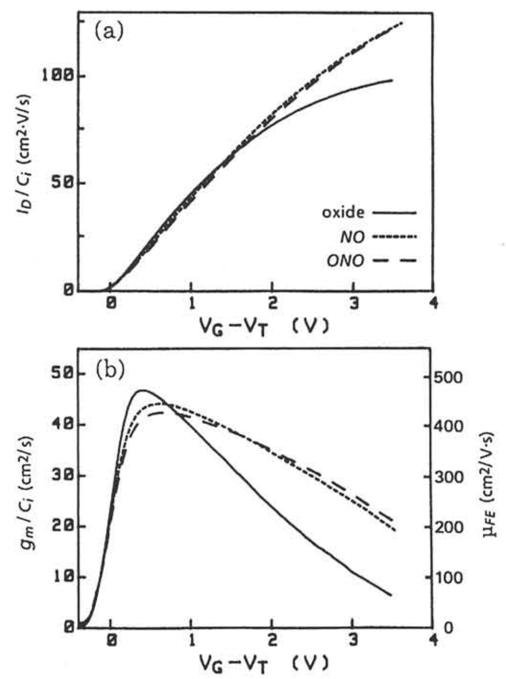

Fig. 7. (a) Drain current I_D and (b) transconductance g_m normalized by insulator capacitance C_i versus gate drive V_G-V_T for large-geometry MOSFET's with SiO_2, *NO*, and *ONO*. Field-effect mobility μ_{FE} is also shown in Fig. (b). The measured V_D was 0.1 V.

significantly but does g_{mmax} degradation only slightly. On the other hand, as subsequent reoxidation proceeds, g_{mmax} degradation as well as V_T shift is reduced very rapidly and then saturated to respective values, which are smaller as the starting nitridation is heavier. Thus reoxidation is inevitably required also for hot-carrier hardening.

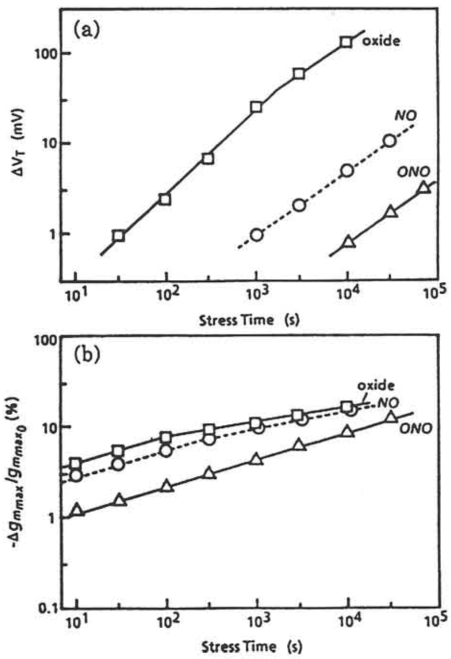

Fig. 8. (a) Threshold voltage shift ΔV_T shift and (b) degradation of maximum transconductance $-\Delta g_{mmax}/g_{mmax0}$ as a function of stress time for 0.8-μm MOSFET's with SiO_2, *NO*, and *ONO*. The stress condition was $V_D/V_G = 6$ V/2 V.

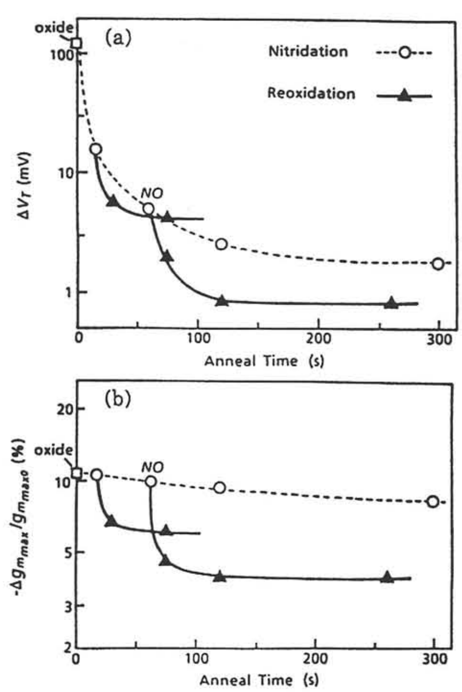

Fig. 9. (a) V_T shift and (b) g_{mmax} degradation after fixed products (substrate current × stress time) of 1 and 0.1 C, respectively, as a function of anneal time for nitridations at 950 °C and subsequent reoxidations at 1150 °C.

Table 2. Summary of the investigated characteristics for light and heavy nitridations with respect to the demands listed in Table 1.

	Characteristic		SiO_2 → + Nitridation → + Reoxidation	Reoxidized Lightly-NO	Reoxidized Heavily-NO
	Interfacial Nitrogen $[N]_{int}$			Heavy Nitridation (> 10 at%) / Light Nitridation (~5 at%)	
	Hydrogen $[H]$			comparable	*too much*
PERFORMANCE	Insulator Capacitance C_I			*slightly decreased*	comparable
PERFORMANCE	Defect-Charge N_f, D_{it} / Turn-on chara. V_T, S			comparable	*worse*
PERFORMANCE	Mobility & Drivability	μ_{peak}		comparable	*worse*
PERFORMANCE	Mobility & Drivability	I_D/C_I		better	*worse*
STABILITY	TDDB Stability Q_{BD}			much better	comparable
STABILITY	High-Field (F-N) Stability	ΔV_{FB}		much better	*worse*
STABILITY	High-Field (F-N) Stability	ΔD_{it}		much better	better
STABILITY	Hot-Carrier Stability	ΔV_T		much better	much better
STABILITY	Hot-Carrier Stability	Δg_m		much better	better

4. CONCLUSION

Table 2 summarizes how nitridation and subsequent reoxidation satisfy the demands for scaled MOSFET's. Heavy nitridation is unfavorable mainly because too much hydrogen is introduced and this can be hardly reduced by reoxidation. In contrast, reoxidation of lightly nitrided oxides significantly improves reliability, while achieving device performance comparable or superior to that of thermal SiO_2. An ultrathin (reoxidized) nitrided oxide prepared by RTP is most promising as the gate dielectric of submicron MOSFET's in place of thermal SiO_2.

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