Invited

Demands for Submicron MOSFET’s and Nitried Oxide Gate-Dielectrics

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Deep-submicron MOSFET’s require ultrathin (≤10 nm) gate dielectrics satisfying high performance and high stability simultaneously. This paper proposes (reoxidized) nitried oxides prepared by rapid thermal processing (RTP) as a replacement of conventional gate-SiO2 and investigates the physical properties, defect-charge densities, TDDL 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 SiO2. An ultrathin (reoxidized) nitried oxide prepared by RTP is most promising as the gate dielectric of submicron MOSFET’s in place of thermal SiO2.

1. INTRODUCTION

As recent developments of ULSI’s urge further sealing of MOSFET’s dawn to deep submicrons, requirements on the quality of ultrathin (≤10 nm) gate dielectrics become more and more demanding 1 as listed in Table 1. Nitried oxides 2-4), which were nitried in NH3 by furnace annealing (FA), have been reported to show many advantages over thermal SiO2 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 nitried 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 nitried oxides can be eliminated by subsequent rapid reoxidation 8), where RTP was for the first time applied to the full fabrication process of reoxidized nitried oxides.

This paper demonstrates that (reoxidized) nitried 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 SiO2.

Table 1. Demands for submicron MOSFET’s and comparison between thermal SiO2 and nitried SiO2.

<table>
<thead>
<tr>
<th>DEMANDS</th>
<th>Thermal SiO2</th>
<th>Nitried SiO2 reported 24) (by furnace annealing)</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Vt Controllability</td>
<td>Good</td>
<td>High-density Fixed Charges &amp; Interface States (&gt;10^{11} cm^{-2})</td>
</tr>
<tr>
<td>Sharp Turn-on Characteristics</td>
<td></td>
<td>Degraded Peak Mobility (Dry &gt;20-50 %)</td>
</tr>
<tr>
<td>High Mobility</td>
<td>Good</td>
<td>Poor Interface Stability</td>
</tr>
<tr>
<td>High Current Drivability, esp. 5 a high gate-drive</td>
<td>Large Gate-Field-induced Degradation</td>
<td>Improved Interface Stability, but High-density Electron Traps</td>
</tr>
<tr>
<td>High Dielectric Strength</td>
<td>unsatisfactory</td>
<td>Improved Resistance to Impurity Penetration</td>
</tr>
<tr>
<td>High TDD @ High-Field Stability</td>
<td></td>
<td></td>
</tr>
<tr>
<td>High Hot-Carrier Stability</td>
<td></td>
<td>Improved Interface Stability, but High-density Electron Traps</td>
</tr>
<tr>
<td>High Stability to Radiation (incl. Process Damages)</td>
<td>Poor Interface Stability</td>
<td>Improved</td>
</tr>
</tbody>
</table>

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 nitried in NH3. Hereafter, an oxide nitried at 950 °C for 60 s is called NO. These nitried oxides were successively reoxidized in dry O2. 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-SiO2 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 \( [N]_{\text{int}} \) 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 \( D_{\text{lim}} \) 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 \( D_{\text{lim}} \) for (reoxidized) nitrided oxides can be reduced comparable to thermal SiO\(_2\) by optimizing the fabrication condition.

As for TDDB stability, Fig. 4 shows that although nitridation degrades charge-to-breakdown \( Q_{\text{BD}} \), 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 \( \Delta V_{\text{FB}} \) increases monotonically with progress of nitridation, \( \Delta D_{\text{lim}} \) shows a turnaround: it increase at first, reach a maximum at a nitridation time, and then decrease gradually to a lower level than that of SiO\(_2\) 9). Thus it is difficult to make both \( \Delta V_{\text{FB}} \) and \( \Delta D_{\text{lim}} \) 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 \( \Delta V_{\text{FB}} \) and \( \Delta D_{\text{lim}} \) simultaneously (Fig. 5): e.g., the \( \Delta V_{\text{FB}} \) and \( \Delta D_{\text{lim}} \) for ONO are outstandingly reduced.

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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 \( \bullet \) indicate the effect of reoxidation of NO at 1150 °C for 80 s.

Fig. 3. (a) Fixed charge density \( N_f \) and (b) midgap interface state density \( D_{\text{lim}} \) 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 SiO₂. The ΔV₉ FB behaviors are explained by a model [7], [12] that electron traps originate from hydrogen (Fig. 6(a)). The ΔDₜₐₗₚ behaviors are explained by a two-factor model [7], [12] that one factor [H] degrades ΔDₜₐₗₚ while the other factor [N]ₜₐₜ improves it (Fig. 6(b)). Thus, smaller [H] and larger [N]ₜₐₜ by nitridation and successful [H] reduction by reoxidation are crucial to obtain reliable dielectrics.

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 V₇ and peak mobility are smaller only by 0.07 V and 9 % than those for SiO₂, respectively. Furthermore, an important observation to be made in Fig. 7 is that V₉-induced mobility degradation for NO and ONO is markedly reduced from that of thermal SiO₂ [13], resulting in the larger normalized drivability (Ip/Cₜ) at high V₉. 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 V₉ shift and 10-% gₜₐₘₐₜ degradation for ONO are significantly improved by 3 and 1.5 orders of magnitude over thermal SiO₂, respectively. Fig. 9 shows that nitridation reduces V₇-shift.
significantly but does $g_{\text{max}}$ degradation only slightly. On the other hand, as subsequent reoxidation proceeds, $g_{\text{max}}$ 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.

![Graph](image)

**Fig. 8.** (a) Threshold voltage shift $\Delta V_T$ shift and (b) degradation of maximum transconductance $-\Delta g_{\text{max}}/g_{\text{max}}$ as a function of stress time for 0.8-μm MOSFET's with SiO₂, NO, and ONO. The stress condition was $V_D/V_G=6$ V/2 V.

![Graph](image)

**Fig. 9.** (a) $V_T$ shift and (b) $g_{\text{max}}$ degradation after fixed products (substrate current x 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.

<table>
<thead>
<tr>
<th>Insulator Capacitance $C_i$</th>
<th>Heavy Nitridation $\sim$ 5 at%</th>
<th>Light Nitridation $\sim$ 3 at%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Defect-Charge $N_{\text{D}}$, $N_{\text{L}}$</td>
<td>comparable</td>
<td>comparable</td>
</tr>
<tr>
<td>Turn-on chara. $V_T$, S</td>
<td>slightly decreased</td>
<td>comparable</td>
</tr>
<tr>
<td>Mobility &amp; Drivability $f_{\text{peak}}/C_i$</td>
<td>comparable</td>
<td>worse</td>
</tr>
<tr>
<td>Threshold voltage $\Delta V_T$</td>
<td>better</td>
<td>worse</td>
</tr>
<tr>
<td>High-FIELD (P-N) Stability $\Delta V_{\text{FWHM}}$</td>
<td>much better</td>
<td>worse</td>
</tr>
<tr>
<td>TDDB Stability $Q_{\text{DTDB}}$</td>
<td>much better</td>
<td>comparable</td>
</tr>
<tr>
<td>Interfacial Nitrogen $D_{\text{N}}$</td>
<td>much better</td>
<td>comparable</td>
</tr>
<tr>
<td>Reoxidized Lightly-NO</td>
<td>comparable</td>
<td>Published by the IEEE 2009. 195</td>
</tr>
</tbody>
</table>

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 SiO₂. An ultrathin (reoxidized) nitrided oxide prepared by RTP is most promising as the gate dielectric of submicron MOSFET’s in place of thermal SiO₂.

ACKNOWLEDGMENT

The author wishes to thank Dr. H. Iwasaki, Prof. H. Matsunami with Kyoto University, and Dr. T. Takemoto.

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