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High Performance NMOS Devices Using Ultra-Thin VHP Oxynitride

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1. Introduction

With continuing scaling of devices, the direct tunneling gate leakage, boron penetration, and gate dielectric reliability have become increasingly important issues. Although oxynitrides processed in NO or N<sub>2</sub>O ambient [1] may successfully reduce leakage current and boron penetration as a result of nitrogen incorporation at the Si/SiO<sub>2</sub> interface, the nitrogen located at the bottom interface degrades channel carrier mobility [2] and, thus, degrades device performance. In this paper, an alternative technique - NH<sub>3</sub> nitridation followed by high pressure O<sub>2</sub> reoxidation - is presented to achieve an ideally engineered nitrogen profile by effectively growing a thin layer of "pure" SiO<sub>2</sub> underneath the original nitride layer adjacent to the silicon, thereby moving the nitride layer away from the SiO<sub>2</sub>/Si interface [3].

2. Device Fabrication

NMOS transistors were fabricated using 180nm technology. Ultra-thin gate dielectrics were produced by forming a thin nitride layer in an NH<sub>3</sub> ambient at 800-900°C for 30sec followed by O<sub>2</sub> re-oxidation at 25 atm and 850°C for 25 or 50min in a vertical high pressure (VHP) furnace. The equivalent oxide thickness, EOT, was determined from high frequency (100kHz) C-V measurements on 100x100 μm devices considering the quantum-mechanical effect [4].

3. Results and Discussion

The high resolution TEM picture shows that the physical thickness of this nitride + oxide stack is as thin as 25Å, as seen in Fig. 1. From the XPS analysis (Fig. 2), the nitrogen binding energy peak (398.2 eV) is shown to be consistent with the presence of N-(Si)<sub>3</sub>, suggesting that a stoichiometric Si<sub>3</sub>N<sub>4</sub> layer was formed in the film. The SIMS analysis of the sample with NH<sub>3</sub> nitridation at 900°C for 30sec followed by high pressure (25 atm) O<sub>2</sub> re-oxidation in a vertical furnace is illustrated in Fig. 3. The observed features of the VHP oxynitride are described as follows: (1) the peak atomic concentration of nitrogen is as high as 16 at%, which is due to the formation of pure nitride in the film; (2) the nitrogen peak is located within ~20Å of the top interface; (3) a thin layer of "pure" oxide is formed underneath the nitride layer. A comparison of the normalized transconductance (G<sub>m</sub> x

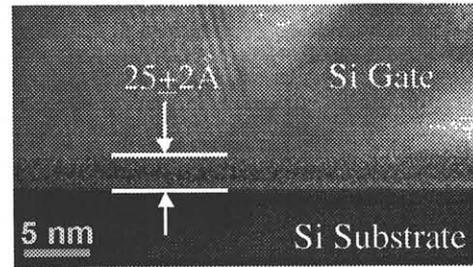


Fig. 1 HRTEM picture of VHP oxynitride (EOT~17Å)

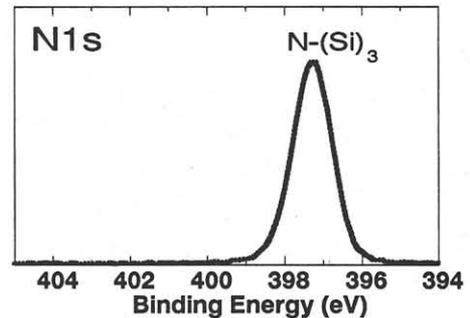


Fig. 2 XPS of VHP oxynitride sample

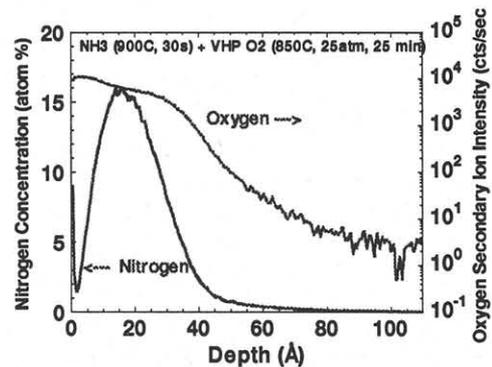


Fig. 3 SIMS analysis of [N] and [O] profiles from VHP oxynitride

Tox) - used as an indicator of carrier mobility in the channel - between the VHP oxynitride and RTO oxide is shown in Fig. 4. Comparable transconductance peaks between the VHP oxynitride and RTO oxide are observed; however, the transconductance of the VHP oxynitride is much higher than that of the RTO oxide in the higher gate voltage regime (i.e.,

$V_g > 1.0V$ ). From the  $I_d$ - $V_d$  characteristics illustrated in Fig. 5, the VHP oxynitride shows much higher drain current than the RTO oxide. Enhanced channel mobility as a result of the combined effects of the nitrogen profile moving away from the bottom interface, due to the high pressure reoxidation, and a lower vertical electric field due to the larger physical thickness may account for the improved drain current driveability. In Fig. 6, it is shown that VHP oxynitride exhibits comparable switching on-off characteristics to that of an RTO oxide in terms of the sub-threshold slopes ( $\sim 70$  mV/dec.), indicating that the high pressure  $O_2$  re-oxidation effectively moves the nitride layer away from the Si substrate and forms an excellent  $SiO_2/Si$  interface. The threshold voltage ( $V_t$ ) shift observed between VHP oxynitride and RTO oxide (i.e., the VHP oxynitride has a smaller  $V_t$ ) may be attributed to the  $NH_3$  nitridation step, which generates a certain amount of positive oxide charge in the film. In addition, the gate-induced drain leakage (GIDL) of VHP oxynitride is nearly one order of magnitude lower than that of RTO oxide and this phenomenon is believed to be attributed to the larger physical thickness of the VHP oxynitride. Gate leakage currents ( $J_g$ ) at  $V_g = -1.5V$  vs. EOT is shown in Fig. 7. The gate leakage current of VHP oxynitrides at  $V_g = -1.5V$  are more than 10 times lower than those of RTO oxides at different thicknesses (EOT), primarily because the  $NH_3$  nitridation step increases the absolute value of the flat-band voltage (i.e., more negative  $V_{FB}$ ) and the nitrogen incorporation in the film increases the dielectric constant and allows a larger physical thickness for VHP oxynitride to achieve the same EOT.

#### 4. Conclusions

We have demonstrated a technique - high pressure  $O_2$  re-oxidation on a nitride layer, formed by  $NH_3$  nitridation of a silicon substrate - to achieve an engineered nitrogen distribution. The VHP technique can be employed to fabricate ultra-thin (EOT= $17\text{\AA}$ ) oxynitrides with an ideally engineered nitrogen distribution. In addition, the VHP oxynitride also shows more than 10 times lower leakage current, higher drain current, and higher normalized transconductance ( $V_g > 1.0V$ ) compared to the RTO oxide.

#### References

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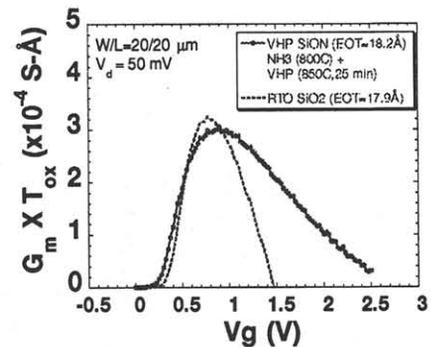


Fig. 4 Normalized transconductance comparison

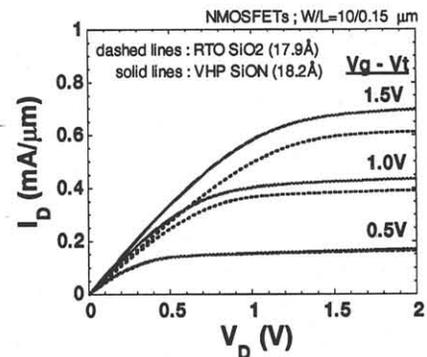


Fig. 5  $I_d$ - $V_d$  comparison between VHP oxynitride and RTO oxide (EOT $\sim 18\text{\AA}$ )

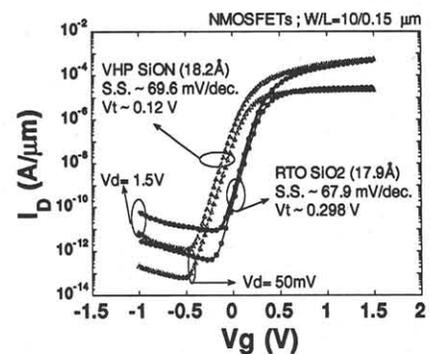


Fig. 6 Log  $I_d$ - $V_d$  comparison between VHP oxynitride and RTO oxide (EOT $\sim 18\text{\AA}$ )

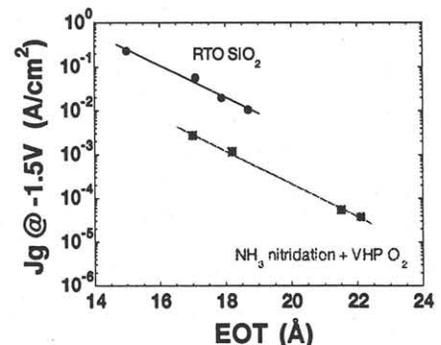


Fig. 7 Gate leakage current comparison between VHP oxynitride and RTO oxide as a function of EOT.