Dramatic Enhancement of Phonon Energy Coupling at the SiO_2/Si Interface Due to Rapid Thermal Processing of the Gate Oxide

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In 1996, Lyding, Hess, and Kizilyalli [1] discovered the isotope effect of hot-electron degradation of MOS transistors, i.e. the lifetime of MOS transistors treated in deuterium (D) is ~50 times longer than the transistors treated in hydrogen (H). It was suggested theoretically that the isotope effect is originated from the energy coupling from the Si-D bond to the Si-Si TO phonon mode, which significantly strengthens the Si-D bonds [2]. Later, we observed the direct experimental evidence of energy coupling from Si-D bonds to the Si-Si TO mode and the Si-O mode using Fourier transform infrared (FTIR) spectroscopy [3].

In this paper, we report a surprising discovery that the phonon energy coupling is dramatically enhanced by direct rapid thermal process (RTP) of the SiO_2. Fig. 1 shows the vibrational modes of an as-grown SiO_2/Si sample, a SiO_2/Si sample treated in RTP only, and that treated in RTP plus D_2 anneal. When the SiO_2 is subjected to RTP process only, the Si-Si TO phonon mode, Si-O TO rocking mode, and the Si-Si LO mode are dramatically enhanced. The enhancement for the Si-Si TO mode is about 50% which is much larger than that for the deuterium anneal only (~25% [3]). When the SiO_2 is subjected to RTP plus D_2 anneal, the Si-Si TO phonon mode, Si-O TO rocking mode, and Si-D wagging mode are all dramatically enhanced. The enhancement for the Si-Si TO mode is about 73% that is about three times larger than that for deuterium anneal only (~25% [3]). We also observed that there is no phonon-energy-coupling enhancement if the oxide is thicker than 800 Å (not shown here). It is expected that the reliability of the MOS transistors will be dramatically enhanced if the gate oxides of the MOS transistors are subjected to RTP process directly and then to do deuterium anneal.

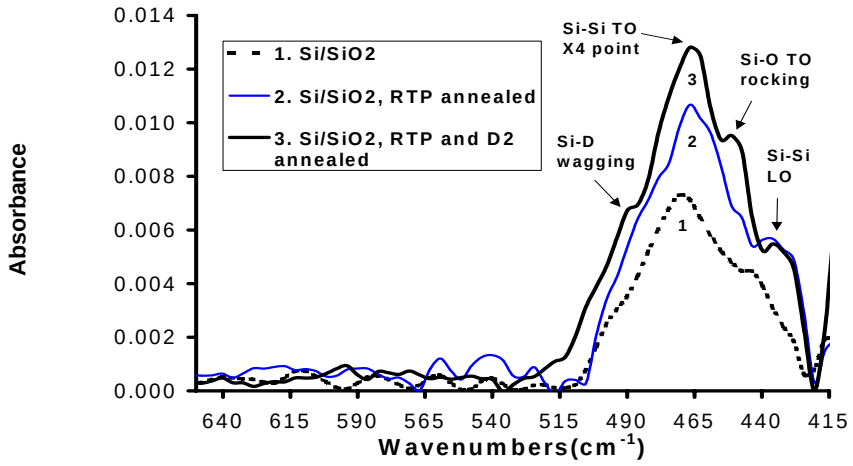
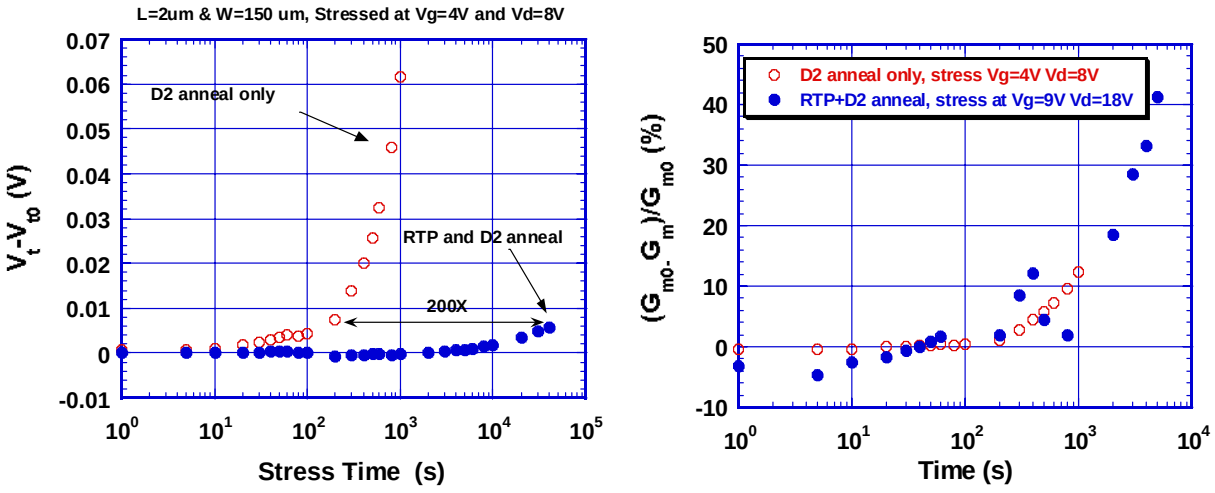


Fig. 1 FTIR spectra of (1) an as grown Si/SiO2 wafer (N^+), (2) a Si/SiO_2 wafer after RTP annealing (1050°C in nitrogen for 4 minutes), and (3) a Si/SiO_2 wafer after RTP (1050°C in nitrogen for 4 minutes) plus deuterium annealing. The oxide thickness is 23 nm. The spectral resolution is 8 cm^{-1} with 128 scans and 65 degree grazing angle.

MOS devices were fabricated using conventional processes. In addition to the conventional process, the unique process is to do rapid thermal process (RTP) at 1050°C in N_2 for 1 minute directly on the gate oxide right after the oxide growth and before deposition of the gate metal or the polysilicon gate. In semiconductor industry, the rapid thermal annealing (RTA) is carried out after the polysilicon gate formation. In the FTIR experiments, we observed that there is no phonon-energy-coupling-enhancement effect when the gate oxide is thicker than 800 Å. Therefore, if the polysilicon (~1000 Å) is put on top of the oxide, there should be no phonon-energy coupling enhancement even if the oxide itself is very thin. After metallization, the deuterium anneal was carried

out at 450°C for 30 min in 100% D_2. From Fig. 2a, it can be seen that the threshold voltage V_t shift of the transistor processed in RTP plus the D_2 anneal is dramatically suppressed. The lifetime of the MOS transistor processed in RTP plus D_2 anneal is improved by 200 times over those annealed in D_2 only for ~1% shift. In order to fully appreciate the effect, we increased the stress voltage of the transistor processed in RTP plus D_2 anneal so that its degradation was the same as that of the transistors processed in D_2 only as shown in Fig. 2b. It can be seen that the transistor that was processed in RTP plus D_2 anneal and stressed at a drain voltage of 18 V exhibits the same degradation as that processed in D_2 only and stressed at a drain voltage of 8V. The drain voltage has been increased more than twice. This will allow chip designers to use much higher operating voltages, leading to much higher transistor speed.



(a) (b)

Fig. 2 (a) The threshold voltage shift of a MOS transistor processed in deuterium only and that processed in RTP plus deuterium anneal. The devices (L=2 μm, W=150 μm, and T_{ox}=32 nm) were stressed at V_g= 4 V and V_d= 8 V. For ~1% shift, the transistor processed in RTP plus deuterium anneal lasts 200 times longer than that processed in deuterium only. (b) Comparison of the threshold voltage shift of a MOS transistor processed in deuterium only and stressed at V_g= 4 V and V_d= 8 V with that processed in RTP plus deuterium anneal and stressed at V_g= 9 V and V_d= 18 V. The transistor processed in RTP plus deuterium anneal can withstand as twice of the gate and drain voltages as that processed in deuterium only.

In summary, we discovered a new effect for the SiO_2/Si system, *phonon-energy-coupling-enhancement effect*, i.e. the vibrational modes of the Si-Si and Si-O bonds exhibit enhanced coupling when RTP is applied to the SiO_2/Si system. With combination of the RTP and deuterium (D) anneal, the strongest coupling is observed among the Si-D, Si-Si, and Si-O bonds. When applying this effect to the MOS transistors, we observed dramatic improvement of MOS devices. The hot-electron related lifetime of MOS transistors has been improved by 200 times over the deuterium-annealed transistors. Because there is 50 times' improvement for deuterium annealed transistors over the traditional hydrogen annealed devices, the total improvement for transistors processed in RTP plus deuterium anneal may reach 10,000 times over the conventional hydrogen-processed transistors.

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1 J. W. Lyding, K. Hess, and I. C. Kizilyalli, "Reduction of hot electron degradation in MOS transistors by deuterium processing," *Appl. Phys. Lett.*, vol. 68, pp. 2526-2528, 1996.

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3. Z. Chen, J. Guo, and P. Ong, "Evidence for Energy Coupling from the Si-D Vibration Mode to the Si-Si and Si-O Vibration Modes at the SiO_2/Si Interface," *Appl. Phys. Lett.* vol. 83, pp. 2151-2153, 2003.