Large Leakage Current Reduction of Silicon Oxide and High-K Oxides Using the Phonon-Energy-Coupling Enhancement Effect

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Since discovery of RTP-induced phonon-energy-coupling enhancement (PECE) effect for reducing leakage current of SiO_2 and HfSiON [1-4], many people have been suspecting its authenticity. This is because there are many puzzling issues regarding the PECE effect. For example, in our early publications [1-4] we did not present both the I-V and C-V curves of the same sample. Also, the mechanism for generation of the PECE effect was not clear at that time. In this abstract, we will present, for the first time, a TEM image of a RTP-processed SiO_2 sample to confirm the authenticity of the PECE effect. We will show the key factor that generates the PECE effect and study the leakage current reduction of HfSiON.

Fig. 1a shows I-V curves of SiO_2 samples before and after RTP, where there are 3 orders of magnitude leakage current reduction. The TEM image in Fig. 1b demonstrates that the leakage current reduction is not due to the oxide thickness increase. All these results suggest that the observed leakage current reduction is true and reproducible. Fig. 2 shows that a little amount of oxygen is the key factor for leakage reduction. Thin oxide processed in RTP in pure N_2 or He exhibits very high leakage current. After introducing a little amount of O_2, leakage current is reduced by 100 times. RTP not only creates necessary structure change for the PECE effect but also meanwhile generates defects for high leakage current. The O_2 is necessary for repairing the defects. This repairing also causes slight regrowth of oxide (1-2Å). Once this thin repairing layer (1-2Å) is lost, the PECE effect disappears. Any chemicals attacking oxide may cause losing of the PECE effect. Therefore, even if one accidentally generates this effect, it may be lost in the followed fabrication processes.

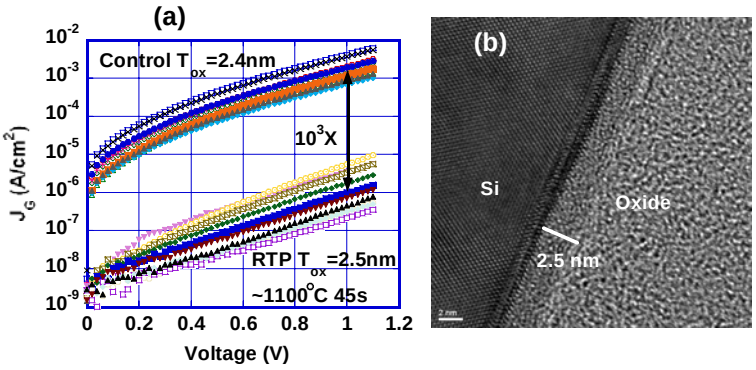

Figure 1 (a) Gate leakage current of control SiO_2 on n-type Si without RTP treatment and that with RTP-induced PECE effect. The V_{FB} is 0 V for the Al/SiO_2/n-Si MOS capacitors. (b) Cross sectional TEM of the same RTP-processed sample shown in (a). TEM was carried out by M. J. Kim and R. M. Wallace of Univ. of Texas at Dallas.

The PECE effect is caused by phonon energy coupling from Si-O bonds to Si-Si bonds. Therefore, as long as there are Si-O bonds in an insulator on a Si substrate, the PECE effect should occur. For Hf/(Hf+Si)=50%, the leakage current reduction is 1.5 orders of magnitude (See Fig. 3). When Hf/(Hf+Si) is increased to 65%, the leakage current reduction is reduced to 1 order of magnitude (See Fig. 4). The results in Fig. 1 can be considered as Hf/(Hf+Si)=0%. Using these results, we can construct a curve, orders of magnitude reduction vs. Si/(Si+Hf) or concentration of Si-O bonds, as shown in Fig. 5. It is amazing that we obtained a linear relation. The straight line also passes the origin, which represents HfO_2. This clearly suggests that the leakage reduction correlates with concentration of Si-O bonds. Fig. 6 shows the leakage current of HfSiON with EOT of 1nm after the PECE effect is added. The optimum Hf concentration is ~50-60%. Fig. 7 shows the scalability of HfSiON and SiON with the PECE effect applied. HfSiON's EOT can be scaled down to below 3Å .

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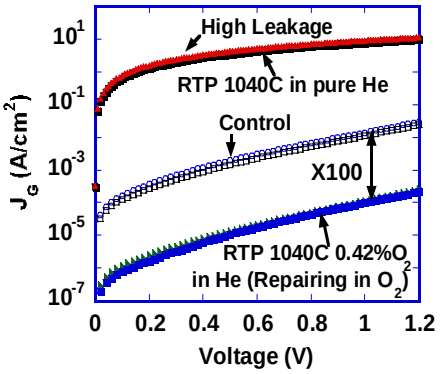

Figure 2 RTP treatment of SiO_2 (2.2 nm) in pure He leads to high leakage current while RTP treatment in He with 0.42% O_2 leads to reduced leakage current. T_{ox} is 2.3nm after RTP.

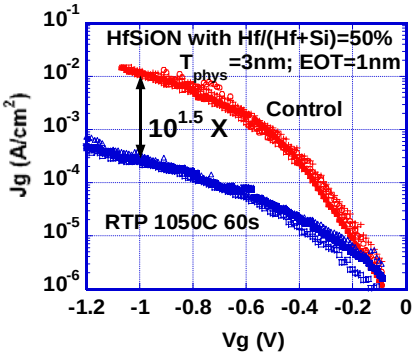

Fig. 3 Gate leakage current of HfSiON with Hf/(Hf+Si)=50% which is reduced by 1.5 orders of magnitude, after RTP.

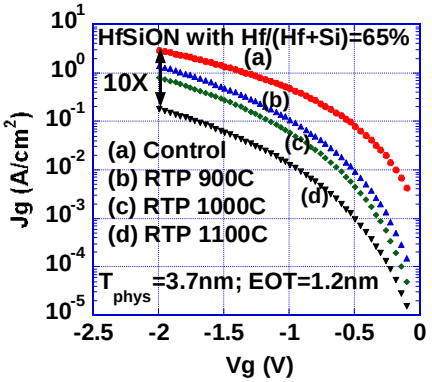

Fig. 4 Gate leakage current of HfSiON with Hf/(Hf+Si)=65% which is reduced by 1 orders of magnitude after RTP.

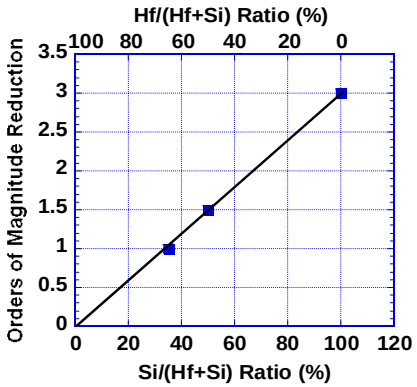

Fig. 5 Orders of magnitude reduction vs Si concentration. It is amazing that it is linearly related to concentration of Si-O bonds. This is an evidence of PECE effect.

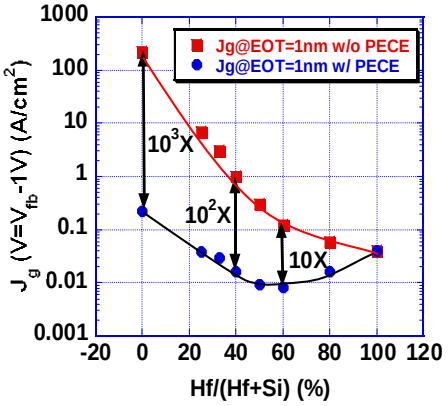

Fig. 6 Leakage current of HfSiON vs Hf concentration for EOT= 1nm. Data (w/o PECE) are from Fig. 14 for 0%, Koyama et al. [8] for 20%-40%, Seikine et al. [6] for 50%, Koike et al. [7] for 60% & 80%, and Tsai et al [9] for 100%..

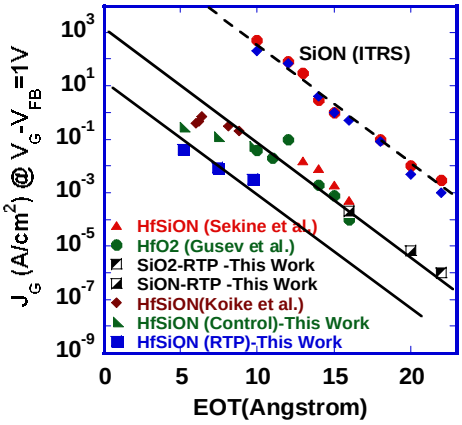

Fig. 7 Gate leakage current vs EOT for various oxides and high-k oxides. With help of the PECE effect, high-k oxides can be scaled down to <0.3 Å. Some data are from ITRS, Sekine et al. [6], Gusev et al. [5], and Koike et al. [7].