1.2nm HfSiON/SiON stacked gate insulators for 65nm-node MISFETs
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Abstract
We realized the Hf-based gate stack with an EOT of 1.2 nm that has a high mobility (N/P:87/96% of that of SiO2 gate) as well as a low leakage current (a factor of 1/1000). With reducing EOT, the interfacial trap density (Dit) increases by the diffusion of Hf atoms through underlayer SiO2 and degrades the mobility. SiON (N:3%) underlayer is effective to suppress Hf diffusion, which leads the reduction of the Dit and high mobility. Nitridation of the HfSiO film is also effective to maintain the leakage current reduction ratio down to the equivalent oxide thickness (EOT) of 1.2 nm. These processes realize high mobility and lower leakage in our 1.2nm-EOT gate stack.

1. Introduction
High-k gate insulator is required for low power device operation. Recently, high-performance, low-power circuit operation was achieved in 90nm node devices by using a HfSiO/SiO2 (EOT=1.6nm) gate insulator [1,2]. It is difficult, however, to maintain a high Imax and a low leakage current with a thinner gate insulator (EOT=1.2nm), which would be required for 65nm node devices. We have thus investigated the reasons for the degradation in leakage current and FET performance caused by the reduction in the gate insulator thickness. In this report, we present a gate insulator structure suitable for 65nm node devices.

2. Experiment
MISFETs with a gate insulator film consisting of HfSiO and HfSiON were fabricated. 2nm-thick of MOCVD HfSO films were grown on the various thickness of SiO2 or SiON ([N]=3%) underlayer (thickness of 0.5-2nm). HfSiON films were then formed by NH3 annealing. 150nm-thick Si gate electrodes were deposited by LPCVD using SiH4 at 500°C and 620°C. To activate arsenic and boron in gate electrode, source, and drain region, 10 seconds of rapid thermal annealing was performed at 1000°C.

3. Results and Discussion
i) Leakage current
Fig. 1 shows the leakage currents of HfSiO/SiO2 or HfSiON/SiO2 MISFETs as a function of EOT varied by reducing the thickness of underlayer. As thinning the EOT, the leakage current reduction ratio of HfSiO/SiO2 against SiO2 decreases. On the other hand, HfSiON/SiO2 leakage current reduction ratio is almost 1/1000 against SiO2 even with thinner gate insulator thickness. Through this experiment, it is also found that the HfSiON/SiO2 leakage current increases and EOT decreases with increasing nitridation temperature against HfSiO/SiO2, which physical thickness is as same as HfSiON/SiO2 (Fig.2).

Fig. 3 shows the leakage current with and without nitridation of the HfSiO film. From TEM observations, we confirmed that the thicknesses of HfSiO and HfSiON were exactly the same. A leakage current density increase and strong temperature dependence were observed for HfSiON. The Poole-Frenkel type of leakage current appeared as a result of the nitridation. From this temperature dependence, it was found that a 140mV electron conduction state was generated by nitridation.

Fig. 4 shows EELS (Electron Energy Loss Spectroscopy) data for HfSiO and HfSiON. The results suggest that a band gap narrowing from 5.4eV to 4.3eV was also caused by nitridation (Fig. 5). From these results, it is found that the leakage current increase in Fig. 2 and 3 is due to the band gap narrowing by nitridation of HfSiO. Still the HfSiON film exhibited a lower leakage current (a factor of 1/1000) at a thinner EOT down to 1.2nm (Fig. 1). This is caused by the increase of dielectric constant of HfSiO film. Nitridation increases the dielectric constant from K=12 to K=20 [3], as high as that of HfO2, and reduces EOT of HfSiO film as shown in Fig.2. Though nitridation increases the leakage current of HfSiO film, it reduces EOT. As a result, the leakage current reduction ratio is maintained with thin EOT as shown in Fig.1.

ii) FET performance as a function of film structure
The mobilities of NFET with HfSiO/SiO2 and HfSiON/SiO2 are compared in Fig. 6. The trapped and fixed charge density of HfSiO/SiO2 and HfSiON/SiO2 MISFET is suppressed not to affect the mobility degradation [1]. Both HfSiO/SiO2 and HfSiON/SiO2 shows high mobility (90% compared to SiO2) at EOT=1.8nm. Mobility is improved by the nitridation in the region of EOT less than 1.5nm. This is caused by the suppression of Hf atoms segregation, which occurs by crystallization [4]. But the problem still remains that mobility degrades by reducing EOT even with amorphous HfSiON/SiO2.

Fig. 7 shows the results of the charge pumping current Ip (proportional to interface trap density: Dit) of NFET with HfSiO/SiO2. Increase of Dit is observed with reducing the underlayer SiO2 thickness. Dit increase is presumably due to the Hf diffusion through underlayer SiO2. Fig. 8 shows the mobility of HfSiON with different thickness of underlayer SiO2, showing large mobility degradation with reducing the underlayer SiO2 thickness. Dit of HfSiO/SiO2 is 50% against SiO2 as a function of Dit. It is clearly found that the Dit is main limitation factor for the mobility degradation. Fig. 10 shows the Dit of SiO2, HfSiO/SiO2, and HfSiON/SiO2 for NFET with underlayer SiO2 are higher than Dit of SiO2. In the case of underlayer SiON (N:3%) structure, however, Dit is almost the same level as Dit of SiO2. The underlayer SiON film is thus effective for the suppression of Dit generation by preventing the Hf diffusion. Fig. 12 shows that N/PFET mobility of HfSiON/SiON (N:3%) is higher than that of HfSiO/SiO2. It has been reported that underlayer SiON degrades mobility of NFET [5]. With the low nitrogen concentration SiON (N:3%) underlayer, however, high mobility of N/PFET were achieved. Finally, the HfSiON/SiON MISFET characteristics are confirmed in table 1. Mobility of N/PFET is 87% / 96% at 1MV/cm against SiO2 gate film, respectively. Good S factor, lower leakage current, low hysteresis were also demonstrated.

Conclusion
By applying a thermal nitridation process, ultra-thin HfSiON gate dielectrics with an EOT of 1.2nm and a gate leakage current reduction ratio on the order of 3 were fabricated and utilized for 65nm CMOS technology. The fabricated devices also exhibited notably high mobility (N/P: 87%/96%), due to the suppression of interface trap generation by the SiON underlayer.

References
Electron Mobility (cm$^2$/V sec)

HfSiO

HfSiON

EOT (nm)

Vg (V)

Fig. 1  $I_g$ dependence on EOT of HfSiO and HfSiON

HfSiON maintained an $I_g$ reduction ratio on the order of 3 down to EOT = 1.2 nm.

Fig. 2 EOT and $I_g$ of HfSiO/SiO$_2$ under various nitridation condition

Fig. 3 P-F plot of HfSiO/SiO$_2$ and HfSiON/SiO$_2$ leakage current

Through nitridation, leakage current increases and temperature dependence appears.

Fig. 4 Band gap measured by EELS spectra

Fig. 5 Band diagram of HfSiO and HfSiON

Though nitridation improves the mobility, mobility of HfSiON also degrades by reducing EOT.

Fig. 6 Mobility dependence on SiO$_2$ thickness

Mobility also degrades by reducing SiO$_2$ underlayer thickness.

Fig. 7 Charge Pumping Current of HfSiON with various thickness of interfacial SiO$_2$ layer

$D_{it}$ increases with reduction of SiO$_2$ underlayer thickness.

Fig. 8 Mobility dependence on interfacial SiO$_2$ thickness

Mobility also degrades by reducing SiO$_2$ underlayer thickness.

Fig. 9 Relation between mobility and $D_{it}$ in HfSiO/SiO$_2$ NFET at low $E_{eff}$

Mobility at carrier density=10$^{12}$cm$^{-2}$ ($E_{eff}$ is around 0.65MV/cm) is shown.

$D_{it}$ reduction is effective to improve mobility.

Table 1  FET characteristics of our HfSiON stack

<table>
<thead>
<tr>
<th>EOT (nm)</th>
<th>HfSiO/SiO$_2$</th>
<th>HfSiON/SiO$_2$</th>
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<tbody>
<tr>
<td>1.2</td>
<td>3.2E-02</td>
<td>2.3E-03</td>
</tr>
<tr>
<td>1.6</td>
<td>87% 96%</td>
<td></td>
</tr>
<tr>
<td>S (mV/dec)</td>
<td>72 75</td>
<td></td>
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<tr>
<td>Dit (cm$^{-2}$)</td>
<td>2.3E+10 2.7E+10</td>
<td></td>
</tr>
<tr>
<td>Vth Shift (V)</td>
<td>0.11 -0.59</td>
<td></td>
</tr>
<tr>
<td>Hysteresis (mV)</td>
<td>0.3 -0.3</td>
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