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# Negative Bias Temperature Instability (NBTI) of pMOSFETs with Novel $Hf_xMo_yN_z$ Metal Gate Electrodes

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## 1. Introduction

As the MOSFET devices are scaling down, conventional poly-silicon gate is being replaced by metal gate electrode which is due to its benefits of low gate resistance, eliminate poly-silicon depletion effect and boron penetration issue. To choose an appropriate metal work function ($\Phi_m$) is one of the major considerations for metal gate electrodes. In this work, the modulation of work function for pMOSFETs by $Hf_xMo_yN_z$ metal gate has been demonstrated. However, the pMOSFET performance with $Hf_xMo_yN_z$ metal gate was degraded during negative bias temperature instability (NBTI) stress by increasing nitrogen incorporation. A physical model was proposed to explain the NBTI mechanism.

## 2. Experimental

The pMOSFETs were fabricated on a 4-in n-type Si (100) substrate using conventional self-aligned MOSFET process. The standard RCA cleaning was employed followed by furnace oxidation of $SiO_2$ at 950 $^oC$ for 20 min with 15 nm thickness. The $Hf_xMo_yN_z$ metal gate electrode with different nitrogen ratio (6 %, 10 %, 12 %) were deposited by co-sputtering with pure hafnium (Hf) and molybdenum (Mo) targets in argon (Ar) and nitrogen ($N_2$) mixtures. The sputtering dc power of both target is 250 W. The reactive pressure and the gas flow rate are $2\times10^{-3}$ torr and 50 sccm, respectively. In order to prevent dry etching damage, the $Hf_xMo_yN_z$ gate electrodes were patterned by chemical wet etching. After gate patterning, S/D regions were formed by $B^{11+}$ implantation with a dose of $3\times15$ $cm^{-2}$ at 10 keV. Then, activation annealing was performed in $N_2$ ambient at 950 $^oC$ for 30 sec. All of the samples were finally subjected to backside Al contact and sintering. The device key processes flow is shown in Fig. 1(a). Figure 1(b) shows the bias configuration during NBTI stress. NBTI properties were analyzed by a Keithley 4200 semiconductor characterization analyzer. The NBTI stress parameters of various voltages, temperatures and times are -10 V ~ -15 V, room temperature (RT) ~ 125 $^oC$ and 0 ~ 3200 sec, respectively. Moreover, charge pumping method has also been demonstrated to substantiate the NBTI results.

## 3. Result and Discussion

***$Hf_xMo_yN_z/SiO_2$ pMOSFET device performance***

Figure 2 shows the C-V characteristic of $Hf_xMo_yN_z/SiO_2$ MOS capacitor with different $N_2$ flow ratio. As increasing $N_2$ ratio, a positive flat-band voltage ($V_{fb}$) shift is observed. The $V_{fb}$ shift between the sample with $N_2$ ratio of 0 % and 12 % is about 1V. The inset of Fig. 2 shows the work function ($\Phi_m$) of $Hf_xMo_yN_z$ metal gate as a function of $N_2$ ratio. The work function value of $Hf_xMo_yN_z$ metal gate with different $N_2$ ratio ranged from 4.17 eV (low $N_2$) to 5.16 eV (high $N_2$). The work function is easily to modify by controlling the nitrogen concentration technique, as described in our previous work.[1] Figure 3 shows the typical transfer characteristic ($I_{ds}$-$V_{gs}$) of $Hf_xMo_yN_z/SiO_2$ pMOSFET before and after NBTI stress. After NBTI stress, the negative threshold voltage ($V_{th}$) shift, and the degradations of off leakage current and subthershold slope (S.S.) are observed for the $Hf_xMo_yN_z/SiO_2$ pMOSFET with $N_2$ ratio of 12 %. The device degradation is believed to be due to the increasing of the interface state density and the fixed oxide charge at the Si/$SiO_2$ interface. The output characteristic ($I_{ds}$-$V_{ds}$) for $Hf_xMo_yN_z/SiO_2$ pMOSFET with $N_2$ ratio of 12 % also demonstrates the degradation after NRTI stressing, as shown in Fig. 4.

***NBTI characterization of $Hf_xMo_yN_z/SiO_2$ pMOSFET***

Figure 5 shows the threshold voltage shift (-$\triangle V_{th}$) dependence on stress time for $Hf_xMo_yN_z/SiO_2$ pMOSFET with $N_2$ ratio of 12 %. The -$\triangle V_{th}$ is found to be shifted slightly as a function of the stress time, stress voltage ($V_{stress}$) and stress temperature. Jeppson and Svensson are the first authors who proposed a physical model of NBTI, which is related to the diffusion and reaction process. [2]-[3] From the power law analysis ($\Delta V_{th} = \alpha \times t^{\beta}$), an exponent value of β was extracted about 0.24 ~ 0.27. It is suggested that the NBTI degradation mechanism is similar to the chemical reacting species model.[3] In this study, the NBTI degradation mechanism is explained by physical model and energy band diagram. Figure 6 shows the S.S. reduction during stress for $Hf_xMo_yN_z/SiO_2$ pMOSFET with $N_2$ ratio of 6 %, 10 % and 12 %. The higher $N_2$ ratio, the larger S.S. degradation are observed under the same stress condition. It is implied that the NBTI degradation is more serious for the devices of higher nitrogen concentration within the metal gate. Figure 7 shows dependence of the $V_{th}$ shift on the stress temperature for $Hf_xMo_yN_z/SiO_2$ pMOSFET with $N_2$ flow ratio of 12 %. The $V_{th}$ shift is sensitive to the stress temperature. The activation energy of NBTI in $Hf_xMo_yN_z/SiO_2$ pMOSFET with different $N_2$ ratio was evaluated as shown in Fig. 8. Activation energy of the $Hf_xMo_yN_z/SiO_2$ pMOSFET with $N_2$ ratio of 6 %, 10 % and 12 % are 0.01~0.15 eV, 0.06~0.078 eV and 0.12~0.125 eV, respectively. Compare to the each sample, the $Hf_xMo_yN_z/SiO_2$ pMOSFET with 12 % $N_2$ ratio has higher activation energy, which means it is more sensitive to the stress temperature. According to the reference [3], higher stress temperature enhances NBTI degradation. As mentioned above, the $Hf_xMo_yN_z/SiO_2$ pMOSFET with 12 % $N_2$ ratio has higher NBTI degradation than the $Hf_xMo_yN_z/SiO_2$ pMOSFET with 6 % $N_2$ ratio.

***Physical models for the NBTI of $Hf_xMo_yN_z/SiO_2$ pMOSFETs***

A physical model is proposed to explain why does NBTI degradation increased with increasing $N_2$ flow ratio. Figure 9 shows the physical model for the nitrogen diffused into the $SiO_2$ during the deposition of metal nitride gate. For the sample with 12 % $N_2$ ratio (Fig. 9 (b)), more nitrogen diffused into either bulk $SiO_2$ or $SiO_2$/Si interface than the sample with 6 % $N_2$ ratio (Fig. 9 (a)). Ushio et al., [4] reported that the NBTI degradation was enhanced by nitrogen incorporation into the $SiO_2$ due to the low reaction energy at the $SiO_xN_y$/Si interface. Charge pumping method has also been demonstrated to substantiate the NBTI results, as shown in Fig. 10(a) and (b). Figure 10(b) shows charge pumping current ($I_{cp}$) increases significantly after NBTI stress, and the interface state density ($\triangle N_{it}$) of the device with 12 % $N_2$ ratio is higher than 6 % $N_2$ ratio. After NBTI stress, a slight negative $I_{cp}$ shift can be observed due to the high donor type interface trap concentration.[5] Furthermore, the dependence of the $\triangle$Icp on the stress time for $Hf_xMo_yN_z/SiO_2$ pMOSFET with $N_2$ ratio of 6 % and 12 % are shown in Fig. 11. Figure 12 shows the energy band diagram of the $Hf_xMo_yN_z/SiO_2$ pMOSFET during NBTI stress. During NBTI stress, the nitrogen at the $SiO_2$/Si interface and being weakly bonded to the Si atoms, react with the holes and dissociate from the Si atom to form interface state and fixed oxide charge. The released nitrogen species from the interface diffuse into $SiO_2$ and react with O forming ON group. Finally, the generation of interface state and fixed oxide charge during NBTI stress contribute to the performance degradation of the $Hf_xMo_yN_z/SiO_2$ pMOSFET.

## 4. Conclusion

The NBTI of novel $Hf_xMo_yN_z$ metal gate pMOSFET has been studied in this paper for the first time. The threshold voltage ($V_{th}$) shift, and the degradations of drive current ($I_{ds}$) and subthershold slope (S.S.) are found during NBTI stress. The device performance degradation is caused by nitrogen diffusion into $SiO_2$ during the deposition of metal nitride gate. Moreover, a physical model and a novel energy band diagram have been proposed to explain the NBTI mechanism.

**Acknowledgment**
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**Reference**

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(a)

| Key | Process |
|---|---|
| Gate | $Hf_xMo_yN_z$, 100nm (6%, 10%, 12%) |
| Dielectric | $SiO_2$, 15nm |
| Implant | $B^{11+}$, 10keV, 3E15 |
| Activation | 950°C, 30sec |

(b)

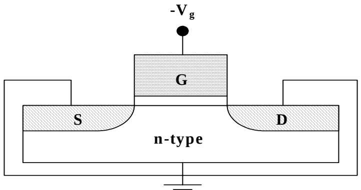


Fig.1 (a) The key process flow of $Hf_xMo_yN_z$ metal gate pMOSFET device. (b) Bias configuration during NBTI stress.

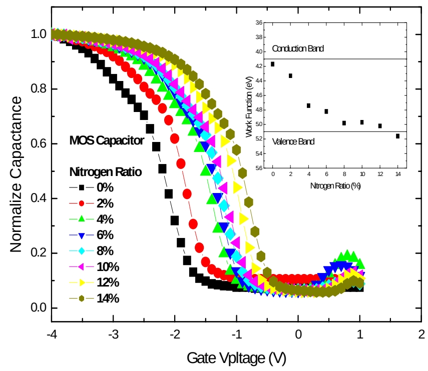


Fig.2 C-V characteristic of $Hf_xMo_yN_z/SiO_2$ capacitor. The $Hf_xMo_yN_z$ gate electrode work function increased with increasing $N_2$ ratio.

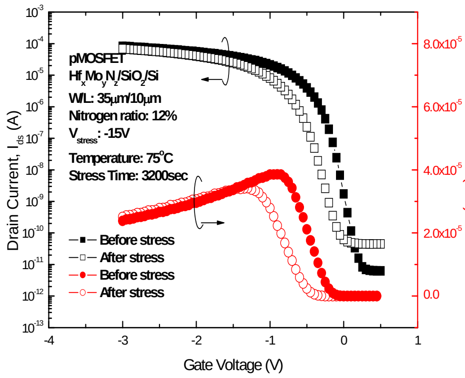


Fig.3 Typical transfer characteristic (Ids-Vgs) of $Hf_xMo_yN_z/SiO_2$ pMOSFET with $N_2$ flow ratio of 12%.

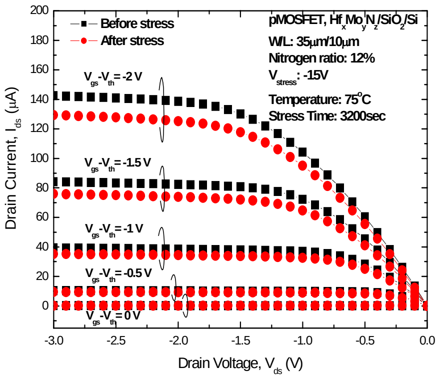


Fig.4 The output characteristic (Ids-Vds) of $Hf_xMo_yN_z/SiO_2$ pMOSFET with $N_2$ flow ratio of 12%.

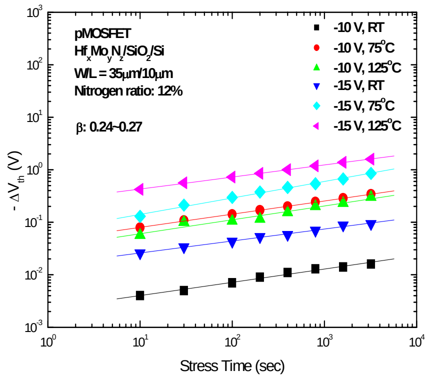


Fig. 5 NBTI stress time dependence of $-\triangle V_{th}$ for $Hf_xMo_yN_z/SiO_2$ pMOSFET with $N_2$ flow ratio of 12%.

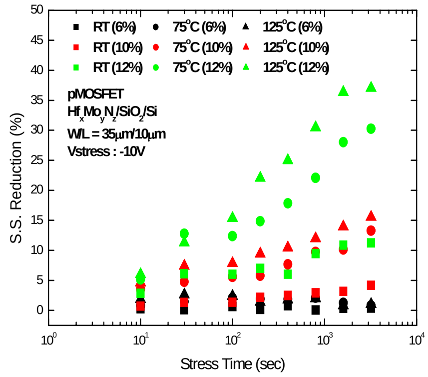


Fig. 6 NBTI stress time dependence of S.S. reduction for $Hf_xMo_yN_z/SiO_2$ pMOSFET with $N_2$ flow ratio of 12%.

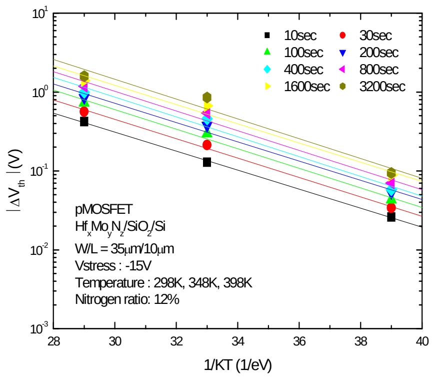


Fig. 7 Dependence of the $V_{th}$ shift on the stress temperature for $Hf_xMo_yN_z/SiO_2$ pMOSFET with $N_2$ flow ratio of 12%

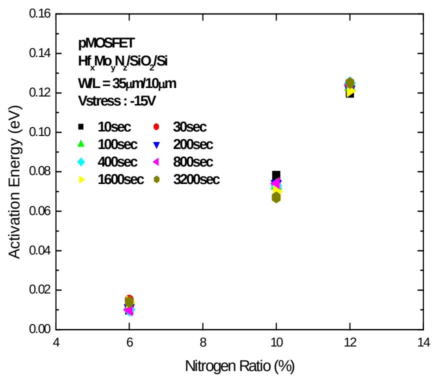


Fig. 8 Activation energy dependence of nitrogen ratio for $Hf_xMo_yN_z/SiO_2$ pMOSFET with -15 V, 3200 sec stress.

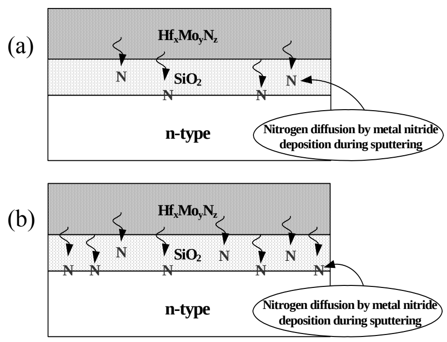


Fig. 9 Physical model for nitrogen atom distribution. The nitrogen diffuse into the $SiO_2$ during metal gate deposition.(a) 6% and (b) 12% nitrogen ratio.

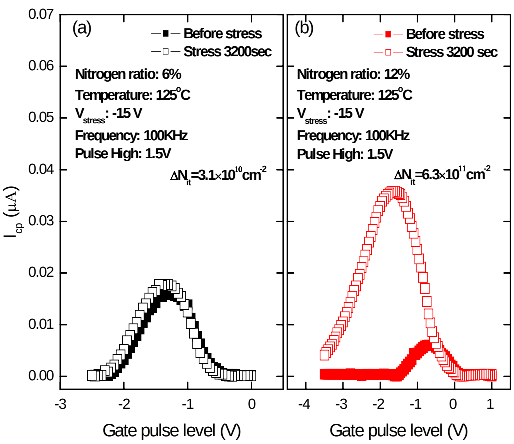


Fig. 10 Charge pumping current characteristic of $Hf_xMo_yN_z/SiO_2$ pMOSFET with $N_2$ ratio of 12%.

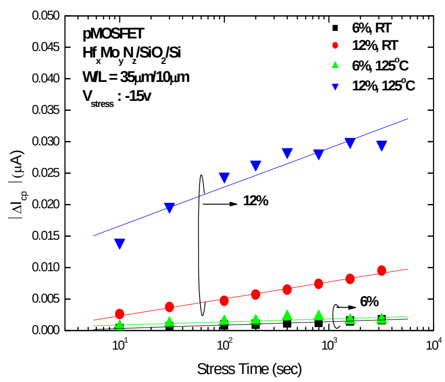


Fig. 11 Dependence of the $\triangle$Icp on the stress time for $Hf_xMo_yN_z/SiO_2$ pMOSFET with $N_2$ ratio of 6% and 12%.

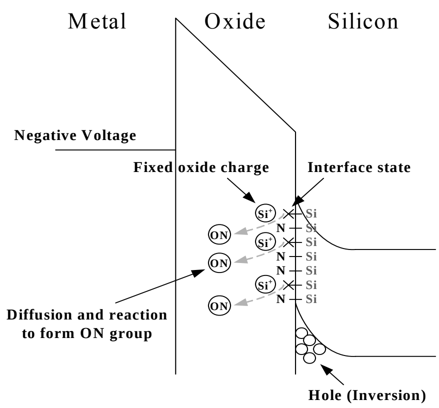


Fig. 12 Energy band diagram of the $Hf_xMo_yN_z/SiO_2$ pMOSFET during NBTI stress.