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# Observation of Scattering Effect on Carrier Mobility of MOSFET with La-incorporated-$HfO_2$ Gate Dielectric

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**Abstract**

**Using cryogenic measurement (from 100K to 300K) we have investigated scattering mechanisms of nMOSFET with La-incorporated-$HfO_2$ dielectric. As the content of La incorporation in the dielectric increases, the more increase of maximum effective mobility has been found at the cryogenic temperature. It is mainly attributed to the reduction of optical phonon scattering due to higher content of La atoms at the interface of dielectric and channel. Though it is relatively small, the existence of La in dielectric reduces Coulomb scattering rate as well.**

## 1. Introduction

As a result of continuous scaling, a traditional silicon oxide-polysilicon gate stack system has been replaced by $HfO_2$-metal gate combination using low temperature replacement gate process [1]. However, some applications like dynamic random access memory (DRAM) still request high temperature process after gate stack formation. In high temperature applications, hafnium based dielectric doped by rare earth metal (La series metals) has been used to control the threshold voltage ($V_t$) of nMOSFET, [2]. This $V_t$ shift has been explained by the formation of Hf-O and La-O dipoles at the $SiO_2$-High-k interface [3]. In the previous report, it was shown that most of La atoms diffused into the interfacial layer and the amount of $V_t$ shift is proportional to the content of La incorporation [4]. Some of the electrical performance such as mobility is limited by scattering processes which generally includes series contribution from coulomb scattering, optical phonon scattering and scattering due to surface roughness. Some claim high phonon scattering caused by high-k atoms can lower the carrier mobility of MOSFETs with high-k dielectric [5]. Even though there are reports of suppressing phonon scattering by forming interface $SiO_2$ layer, but that includes significant compromise of scalability [6]. In this study, we have investigated nMOS transistor performance at cryogenic temperature (100K to 300K) to understand the scattering behavior and mobility degradation in the La incorporated $HfO_2$ gate dielectric MOSFET.

## 2. Experimental

nMOSFETs were fabricated using atomic layer deposition(ALD) $HfO_2$ films of 20Å on Si (100), followed by post deposition annealing at 700 °C in $NH_3$ ambient for 60s. La oxide films of 4Å(La-4A), 7Å, and 12Å-thick were deposited on the $HfO_2$ dielectrics by reactive sputtering. ALD TiN film was used as the gate electrodes and a polysilicon layer was deposited for silicidation. As a control sample(La-0Å), nMOSFETs with a pure $HfO_2$ were fabricated and its electrical properties were compared with the various La-incorporation samples. Drain current-Gate voltage ($I_D$-$V_G$) and Capacitance-Voltage(C-V) were measured at temperatures ranging from 300K to 100K of different devices.

## 3. Results and discussions

The effective mobility ($\mu_{eff}$) extracting from $I_D$ –$V_G$ characteristics for the control device (La-0Å) and La-12Å device is shown in the fig. 1a and 1b, respectively. The increase of $\mu_{eff}$ in the La-12Å sample is observed. The $\mu_{eff}$ decreases with increasing temperature due to the higher phonon scattering energy. The difference of maximum mobility is about 45cm$^2$/Vs for La-0Å and La-12Å sample at 300K.

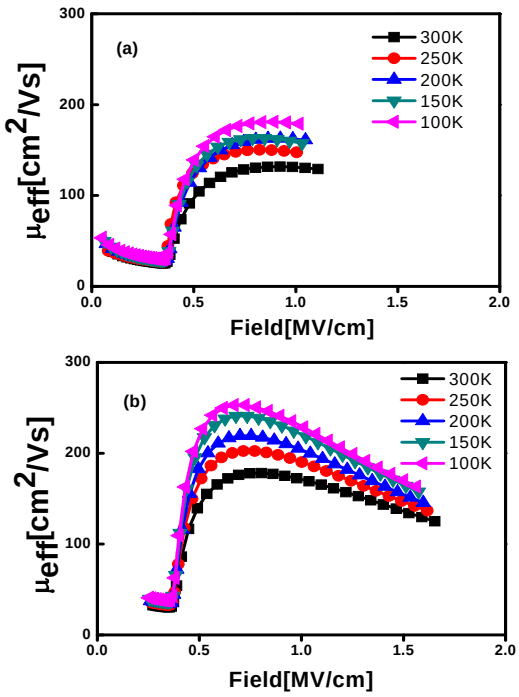


Fig. 1 The $\mu_{eff}$ at different electric field of the La-0Å(a) and the La-12Å sample(b). The La-12Å device showed higher $\mu_{eff}$ than the La-0Å device.

The increase of maximum $\mu_{eff}$ with La thickness at cryogenic temperature (Fig. 2) and the diffusion of La at the interface [3] indicates that the interface with La atoms could reduce the scattering.

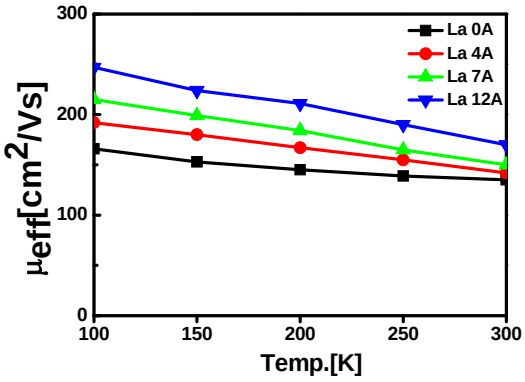


Fig. 2 The maximum $\mu_{eff}$ with La incorporation.

Effect of surface roughness on the effective mobility can be neglected at moderate field, the $\mu_{eff}$ is related with the Coulomb mobility ($\mu_{coul}$) and optical phonon mobility ($\mu_{ph}$) by the Matthiessen's rule:

$$\frac{1}{\mu_{eff}} = \frac{1}{\mu_{ph}} + \frac{1}{\mu_{coul}} + \frac{1}{\mu_{sr}}$$

While the $\mu_{coul}$ is extracted using the linear fitting the $\mu_{eff}$ at low field region, the $\mu_{ph}$ is calculated using equation (1). Scattering rate is also estimated by S.R.=(q/(μ·m*)) with m* is effective mass of electron in silicon.

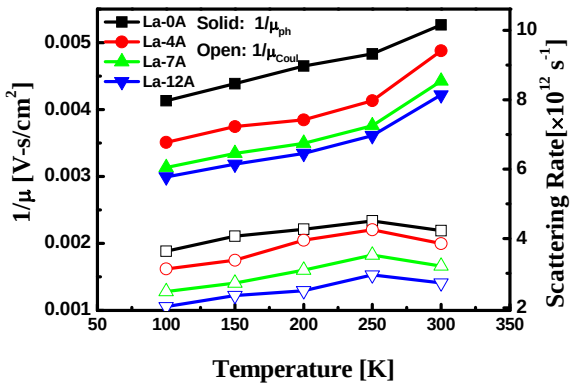


Fig.3 Scattering rate due to optical phonons and coulomb.

Shown in the fig. 3, the optical phonon scattering rate is significantly higher than the Coulomb scattering rate, which means the phonon scattering is the main factor governing the effective mobility at low field region. The existence of La in dielectric reduces not only optical phonon scattering rate but also Coulomb scattering rate. It is powerful evidence to conclude that the La atoms bond with the O ions forming the dipoles at the interface, reducing the sub-threshold swing (Fig. 4). As a result, thicker La layer reduces the trap density - sub-threshold swing - corresponding to Coulomb scattering (Fig. 3) and soft optical phonon scattering in $HfO_2$.

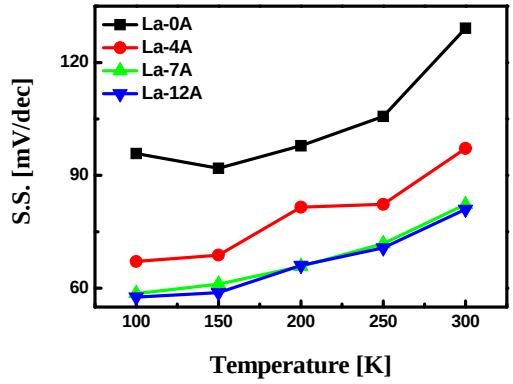


Fig.4 Temperature dependence of sub-threshold swing for all samples.

## 3. Conclusions

The phonon scattering effect of La incorporated high-k metal-gate nMOSFET has been studied at cryogenic temperature. The increase of effective mobility with La-incorporated $HfO_2$ is mainly governed by the reduction of optical phonon scattering. The formation of dipoles with the participation of La atoms reduces the oxygen ions and then the Coulomb scattering.


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