**Understanding Mobility Mechanisms in Extremely Scaled HfO2 (EOT 0.42 nm) Using Remote Interfacial Layer Scavenging Technique and Vt-tuning Dipoles with Gate-First Process**

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**Abstract**  were capped with Poly-Si followed by a conventional self-aligned process using 1000°C rapid thermal annealing. Mobility

We demonstrate a novel “remote interfacial layer (IL) scavenging” technique yielding a record-setting equivalent oxide thickness (EOT) of 0.42 nm using a HfO2-based MOSFET high-κ gate dielectric. Intrinsic effects of IL scaling on carrier mobility are clarified using this method. We reveal that the mobility degradation observed for La-containing high-κ is not due to the La dipole but due to the intrinsic IL scaling effect, whereas an Al dipole brings about

characterization was carried out on 10×10μm2 nMOSFETs with a substrate doping concentration of 1×1017 cm-3 using IV and split-CV

method at Vds = 50 mV and f = 1 MHz in the wafer temperature range of 45-300K. TEM, EELS, and SIMS were performed for

physical characterization of the HK/MG stacks.

**Results and Discussions**

additional mobility degradation. This unique nature of the La dipole

enables aggressive EOT scaling in conjunction with IL scaling for the 16 nm technology node without extrinsic mobility degradation.

*A. Direct and Remote IL Scavenging*

The concept of the remote IL scavenging is illustrated in Fig. 2 in

**Introduction**  contrast with other published IL scavenging schemes (2-6). Fig. 3

demonstrates aggressive EOT scaling of HfO2 down to 0.54 nm

Improvement of CMOS performance by gate length (Lg) scaling has been reported for a gate-first high-κ/metal gate (HK/MG) process (1).

(fitted by (9)) when the Gibbs free energy change at 1000K (ΔG°1000 ) of the following reaction (1) has a large positive value.

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| Continued Lg scaling beyond the 22 nm node requires EOT < 0.6 nm | *S* | + | 2 | *M* | *O* |  | → | 2 | *x* | *M* | + | *SiO* | (1) |
| to suppress short-channel effects. EOT scaling with a gate-first |  |  | *y* |  | *x* | *y* |  | *y* | |  |  | 2 |  |

process is hampered by IL growth during high-temperature processes. Several approaches to circumvent this issue have been reported (2-6); however, they require direct modifications of high-κ and the adverse effects of scavenging metals in high-κ are not fully understood. In this paper, we introduce a new concept of remote IL scavenging and its advantages over a direct IL scavenging are shown. Then, we discuss the impact of intrinsic IL scaling and La and Al dipoles on electron mobility and propose physical models. Although many studies have been performed on the impact of La addition (7, 8), interpretation of La-induced mobility degradation is still controversial and a unified model consistently explaining all results is highly

where M is the doped element in TiN. The order of the ΔG°1000 (M1 < 0 < M2 << M3) is in agreement with the EOT scaling trend, indicating that oxidation of M3 is the driving force of the reaction. The EOT scaling can be controlled by changing the amount of M3 as shown in Fig. 4. TEM reveals that the EOT change was brought about via IL scaling down to zero (Fig. 5). The EELS profile of M3 (Fig. 6) and the SIMS profile of O (Fig. 7) clearly support the concept of the remote IL scavenging. As seen in Fig. 8, the remote IL scavenging has 10× lower Jg compared to the direct IL scavenging. As a result, a competitive EOT value (0.54 nm) meeting ITRS requirement for the 16 nm node has been obtained while

anticipated. maintaining the Jg (Vg = Vfb-1V) at 0.86 A/cm 2. The flat Vt-EOT

trend in Fig. 9 also indicates that no fixed charge/dipole is generated

**Experimental**  by the remote IL scavenging. These trends can be understood by

the reaction model depicted in Fig 10, in which oxygen vacancies

nMOSFETs with HK/MG stacks were fabricated using a gate-first process as shown in Fig. 1. After HfO2 and cap layers (La, Al) deposition, TiN films were deposited as metal electrodes and then scavenging elements (M1, M2, and M3) were doped in the TiN while maintaining an undoped high-κ/TiN interface. In the control samples, TiN-M3 and TaN-M3 alloy films were deposited to let M3 elements directly contact high-κ layers. Then, the MG/HK stacks

(Vo) in HfO2 act as media for a cascade reaction of oxygen transfer from the IL to the M3 atoms in the TiN and thus [Vo] in HfO2 is maintained constant. Fig. 11 shows mobility benefits of the remote

IL scavenging over the direct IL scavenging. The Vfb-EOT trends in Fig. 12 indicate that the EOT scaling by the remote IL scavenging

and the effective work function (EWF) tuning by the La- and Al-

dipole are additive, which makes this technique a viable option for

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CMOS integration.

*B. Impact of Intrinsic IL Scaling and Dipoles on Mobility*

The electron mobility as a function of EOT is compared in Fig. 13 and the Id-Vg characteristics are shown in Fig. 14. The change of Id as a function of sensing time delay reveals that the measurement error due to charge trapping is negligibly small even for the scavenged IL stack (not shown). The trend for the remote IL scavenging is considered as the intrinsic IL scaling effect because of

cancelled out and long and low density net dipoles may be formed. Since the dipole strength (length × density) remains the same, a sufficient Vt shift is still attainable while the mobility degradation by RCS is minimized. The previously mentioned models for high and middle Eeff mobility are summarized in Fig. 20. Finally, aggressive EOT scaling was performed by combining the remote IL scavenging and the La dipole. As shown in Fig. 21, a record-setting EOT (0.42 nm) for HfO2-based high-κ was achieved with an EWF close to nFET band-edge. Moreover, Fig. 22 demonstrates no extrinsic mobility degradation by the La dipole, as predicted by our model.

no extrinsic fixed charge/dipole (Fig. 9) and no interface degradation,   
as indicated by a good subthreshold slope (Fig. 14). It is interesting **Conclusion** to note that the mobility-EOT slope for the La addition is identical to

that of the intrinsic IL scaling, whereas addition of the Al degrades

mobility at both Eeff regimes. Then, the temperature dependence of mobility was studied (Fig. 15(a)-(d)) to clarify the physical origin of

the mobility-EOT trends. The surface roughness scattering limited

mobility (µSRS) for each sample was extracted by extrapolating the mobility at 45K and Eeff 1MV/cm, where the temperature dependence disappeared. The µSRS-EOT trends at 45K are shown in Fig. 16(a). After subtracting µSRS from the total mobility (µtot) at 300K using Matthiessens’s rule, both the remote IL scavenging and

the La addition show no degradation, as seen in Fig. 16(b).

Considering the good interface properties and the EOT scaling for

these samples, the mobility degradation is attributable to remote SRS

(r-SRS) enhanced by IL thickness (TIL) scaling (10).On the other hand,the mobility degradation without EOT scaling for the Al

addition suggests r-SRS enhanced by increase of amplitude of roughness (ΔTIL). Next, the electron mobility is plotted as a function of temperature (Fig. 17) to understand the middle Eeff mobility trend. The temperature dependence (T-0.81) for the

The remote IL scavenging technique enables ultimate scaling of HfO2 down to EOT 0.42 nm with a gate-first process. For the first time, we experimentally separate the intrinsic IL scaling effect on mobility from the La and Al dipole effects and clarify the physical origins behind the mobility-EOT trends. Based on these understandings, feasibility of extreme EOT scaling by the remote IL scavenging combined with EWF tuning by the La dipole is demonstrated with no extrinsic mobility degradation, which makes this technology a promising candidate for the 16 nm node.

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Watson Research Center, where the devices were fabricated.

HfO2/TiN stack indicates soft optical phonon response of HfO2 (11). **References**

A slightly weaker sensitivity for the remote IL scavenging sample is

explained by enhanced remote phonon scattering (RPS). Fig. 18 summarizes the mobility trend as a function of IL thickness in comparison to the estimation from the RPS theory (12). The IL

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the corresponding EOT values. The trendline for the remote IL scavenging can be interpreted as a combined effect of RPS and remote Coulomb scattering (RCS) from HfO2 because the slope is steeper than that of the RPS theory alone. It should be noted that the RCS by the La dipole was not observed, in contrast to a clear degradation by the Al dipole. We attribute the difference to the silicate forming nature of La, as evidenced by the Z-contrast image and EELS profiles obtained by Cs-corrected STEM with a spacial

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| **IL preparation** | | | | | | | | | | | | **Ta(Ti)N-alloy** | | | | | |  |  |  |  | | --- | --- | --- | --- | | **Type** | **Direct** | | **Remote** | | **Scavenging element (M)** | **Within or in contact with High-**κ | | **Isolated from High-**κ | | **Schematics** | **Metal Gate**  **High-k**  **M**  **SiO2**  **O** | **TaN-M alloy**  **M**  **High-k**  **M**  **SiO2**  **O** | **TiN**  **M**  **High-k**  **SiO2**  **O** | | **Ref.** | **(2-5)** | **Previous work (6)** | **This work** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | **Capacitance Density (**μ**F/cm2)** | | | | **4** | | | **TiN (Ref.)** | | | | | | | | | |
| **TiN+M1 dope** | | | | | | | | | | | | |
| **HfO2 deposition** | | | | | | | | | | | | **3** | | | **TiN+M2 dope**  **TiN+M3 dope** | | | | | | | | | |
| **(Cap layer deposition)** | | | | | | | | | | | | **EOT 0.54nm** | | | | | | | | | | | | |
| **TiN deposition** | | | | | | | | | | | | **2** | | **M1-3 dope** | | | | | | | | | | |
| **(Scavenging metal dope)** | | | | | | | | | | | | **1.0X** | | | | | | | | | | | | |
| **deposition** | | | | |
| **1** | | **TiN** | | | | | **EOT 0.96nm** | | | | | |
| **Poly-Si deposition** | | | | | | | | | | | | **HfO2** | | | | |
| **SiO2** | | | | |
| **Gate-First process flow** | | | | | | | | | | | | **0** **-0.4 -0.2 0.0** | | | | | | **0.2 0.4** | | | | **0.6** | **0.8** | **1.0** |
| **S/D RTA 1000oC, 5sec** | | | | | | | | | | | |
| **Silicidation + FGA** | | | | | | | | | | | |
| **Gate Voltage (V)** | | | | | | | | | | | | |
| **EOT (nm)** | | Fig. 1: Process flow. | | | | | | | | **0.8** | | | **1.0** | | Fig. 2: Schematics of direct and remote IL scavenging. | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | Fig. 3: Accumulation CV curves for | | | | | | | | | | | | | | | | |
| The scavenging metal is isolated from high-κ in the remote case. | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | TiN with various doping metals. | | | | | | | | | | | | | | | | |
| **1.1** | | | | | | | |
| **(a) M3: 0.5X** | | | | **(b) M3: 1.0X** | | | | | | | | | | ***after 1000oC*** | | | | | | | | | | | | | | | | | | **SIMS Intensity (counts)** | | | **103** | | **0** | **TiN +** | | | | | | **HfO2/IL** | | | **16O** | |
| **1.0** | | | | | | | |
| **TiN+M3 dope** | | | | | | | | | | | | | | | | | | | | | | **HfO2** | | | | | | | | | | **M dope** | | | | | |
| **0.9** | | | | | | | | **TiN + M3 dope** | | | | | | | | | **Intensity (a.u.)** | | | | | | | **Ti** | | | | | | | | | | | | | | | |
| **0.8** | | | | | | | | **HfO2** | | | | | | | | | **102** | | ***after*** | | | | | | **M = M2 1.0X** | | | **300** | |
| **0.7** | **M3 dope** | | | | | | |
| **0.6** | **0-1.0X**  **TiN** | | | | | | |
| **SiO2** | | | | | | | | |
| **0.5** | **HfO2**  **SiO2** | | | | | | |
| **101** | |
| **Si** | | | | | | | | **Hf**  **M3** | | | | | | | | | | | | | | | | | | | | | | | | **M = M3 0.5X** | | |
| ***1000oC*** | | | | | |
| **M = M3 1.0X** | | |
| **0.4** | **0.0** | | **0.2** | | **0.4** | **0.6** | |
| **100** | | | | | | **200** | | |
| **Normalized M3 Dope Amount** | | | | | | | | | | | | | | | **Electron Beam Position** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | **Erosion Time (s)** | | | | | | | | | | | | | | | | |
| Fig. 4: EOT as function of normalized | | | | | | | | | | | | | | | Fig. 5: TEM images of TiN/HfO2 stacks | | | | | | | | | | | | | | Fig. 6: Depths profiles of Ti, Hf, M3 | | | | | | | | | | | | | | | | | | | | Fig. 7: 16O SIMS profiles for TiN | | | | | | | | | | | | | | |
| M3 dope amount in TiN. | | | | | | | | | | | | | | | with different M3 dope (0.5X and 1.0X). | | | | | | | | | | | | | | by EELS after full process flow. | | | | | | | | | | | | | | | | | | with various doping metals. | | | | | | | | | | | | | | | | |
| **Jg (A/cm2)at Vfb-1V** | **104** | | | | | | | | | | | | | **Vt(V)** | | **0.9 0.6** | **1.0** | **Tinv (nm)**  **1.1**  **1.2**  **1.3** | | | | | | **1.4** | | **1.5** | **TiN** | | | | | **Oo** | **Oxidation of M** | | | | | | | | | | | | | | | **Mobility (cm2/Vs)** | | **10**   |  |  | | --- | --- | |  |  | | | | | | | | | | | | | | |
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| **Electron Mobility (cm2/Vs)** | **1000 900** | μ**SRS** | | | | **(a)** | **1000**  **900** | | **45K** | | | μ**SRS** | **(b)** | **1000**  **900** | | | **Tinv 0.98nm** | **(c)** | | | **1000**  **900**  **800**  **700** | | | **(d) Tinv 1.55nm** | | | | | | | | **2000** | | | | | | **Ninv=5x1012 cm-2** | | | | | | | | | | |
| **800** | **800** | | **800** | | | **Electron Mobility (cm2/Vs)**   **1000**  **800**  **600**  **400**  **200** | | | | | |
| **462xEeff-1.20** | | | |
| **700** | **700** | | **700** | | | μ**SRS** | | | |
| **600** | | | | | | **Electron Mobility (cm2/Vs)** | **600 500**  **400**  **300**  **200** | **270xEeff-0.72** | | **Electron Mobility (cm2/Vs)** | **600**  **500**  **400**  **300**  **200** | | **Electron Mobility (cm2/Vs)** | **600** | | μ**SRS** | | | | | | | | **T-0.81** | | | | | | | | | | |
| **219xEeff-0.69** | | | |
| **500** | | | | | | **500** | |
| **400** | | **45K** | | | | **400** | |
| **277xEeff-0.83** | | | | | | | |
| **300** | **60K**  **100K** | | | | |
| **300** | | μ**=(1/**μ**tot-1/**μ**SRS)-1** | | | | | | | | | | |
| **45K** | | | |
| **45K** | | | | | | | |
| **200** | | | | | | **200** | |
| **Ref: HfO2/TiN** | | | | | | | | | | |
| **300K** | | | | | | **60K 100K** | | | **60K** | | | | **60K** | | | | | | | |
| **100K** | | | | **100K** | | | | | | | | **Remote IL scavenging:** | | | | | | | | | | |
| **100**   **0.1** | | | **Tinv 1.35nm**  **1** | | | **100**   **0.1** | | **150K** | | | **Tinv 1.10nm** | | **100**   **0.1** | | | **150K** | | | | **150K** | | | | | | | | | | | **100** | | | | | | **HfO2/TiN+M3 dope** | | | | | | | | | | |
| **300K** | | | **300K** | | | | **100**   **0.1** | | | | **300K** | | | **1** | | | |
| **1** | | **1** | | | | **100** | | | | | | | **200** | | | **300** |
| **Effective Field (MV/cm)** | | | | | | | | **Effective Field (MV/cm)** | | | | | | | | **Effective Field (MV/cm)** | | | | | | | | **Effective Field (MV/cm)** | | | | | | | | **Temperature (K)** | | | | | | | | | | | | | | | | |
| Fig. 15: Electron mobility as function of Eeff obtained at various wafer temperatures (45-300K) for | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | Fig. 17: Temperature dependence of | | | | | | | | | | | | | | | | |
| (a) HfO2/TiN, (b) HfO2/TiN+M3 dope, (c) HfO2/La-cap/TiN, and (d) HfO2/Al-cap/TiN. μSRS was | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | electron mobility at Ninv = 5x1012cm-2. The | | | | | | | | | | | | | | | | |
| extrapolated from the mobility regions where the temperature dependence disappears in high Eeff. | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | temperature dependence (~T-0.81) indicates | | | | | | | | | | | | | | | | |
| **Tinv (nm)**  **Tinv (nm)**  **0.9 1.0 1.1 1.2 1.3 1.4 1.5 1.6 1.7**  **0.9 1.0 1.1 1.2 1.3 1.4 1.5 1.6 1.7**  **500**  **500**  **200**  **100**  **0**   |  |  |  |  |  |  |  |  | | --- | --- | --- | --- | --- | --- | --- | --- | |  |  |  |  |  |  |  |  | | | | | | | | | | | | | | | | | | | | |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
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