IWDTF-11

Rare earth oxide capping effect on La_2O_3 gate dielectrics toward EOT of 0.5nm

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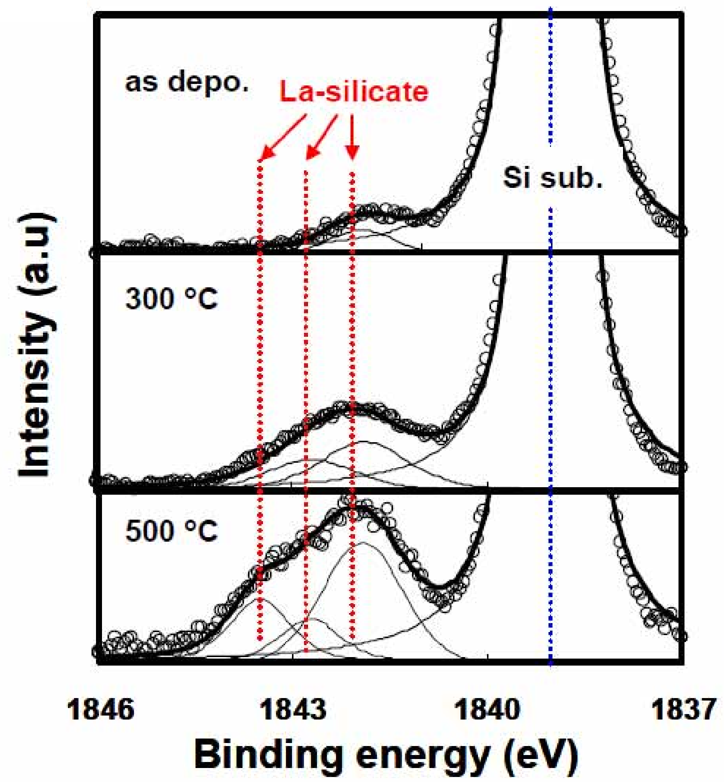
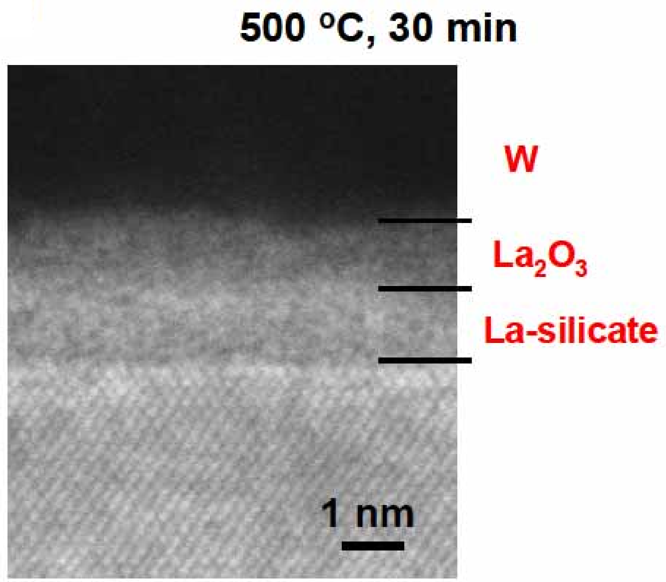
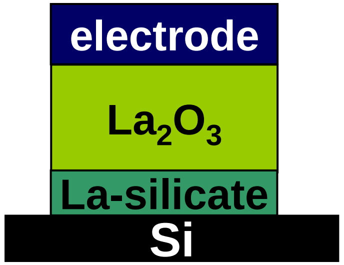
Background ~ La_2O_3 material ~





$La_2O_3 + Si + nO_2$
$\rightarrow$ La_2SiO_5, $La_2Si_2O_7$,
$La_{9.33}Si_6O_{26}$, $La_{10}(SiO_4)_6O_3$, etc.

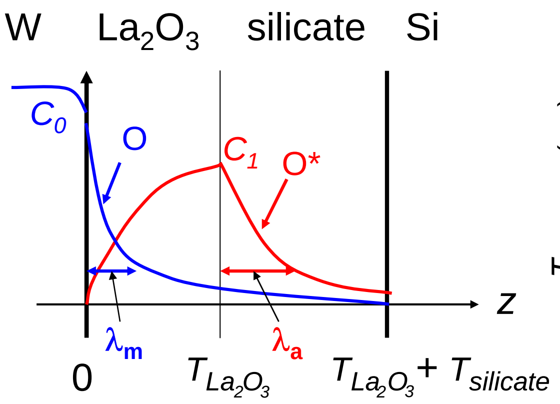


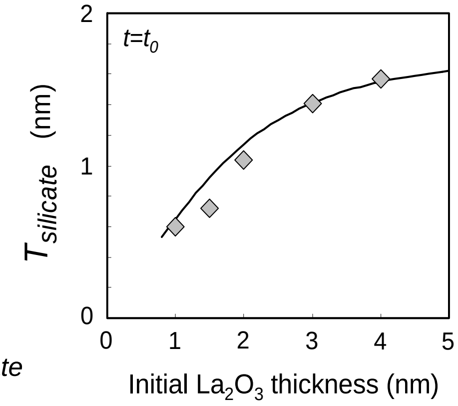
La_2O_3/Si interface : formation of La-silicate

⇨ La-silicate is also high-k material (permittivity ~ 9-12)

⇨ **High-k / Si direct contact is achieved.**

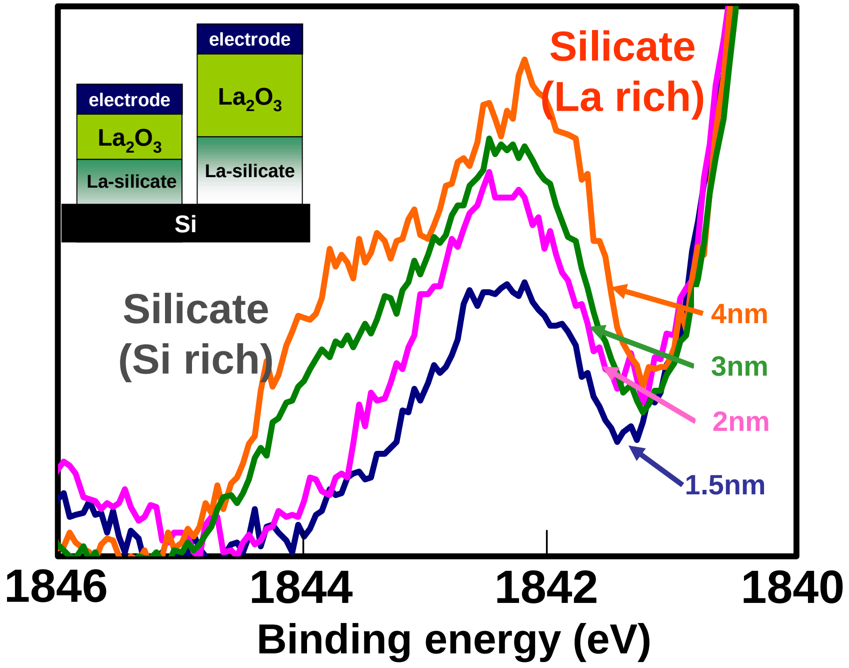
2 Thickness dependent interface reaction





$$C(z) = C_1 \exp\left(-\frac{z - T_{La2O3}}{\lambda_a}\right) \quad (\, z > T_{La2O3} \,)$$

Quantity of radical oxygen atoms depended on film material and thickness



Increasing La_2O_3 thickness

⇩

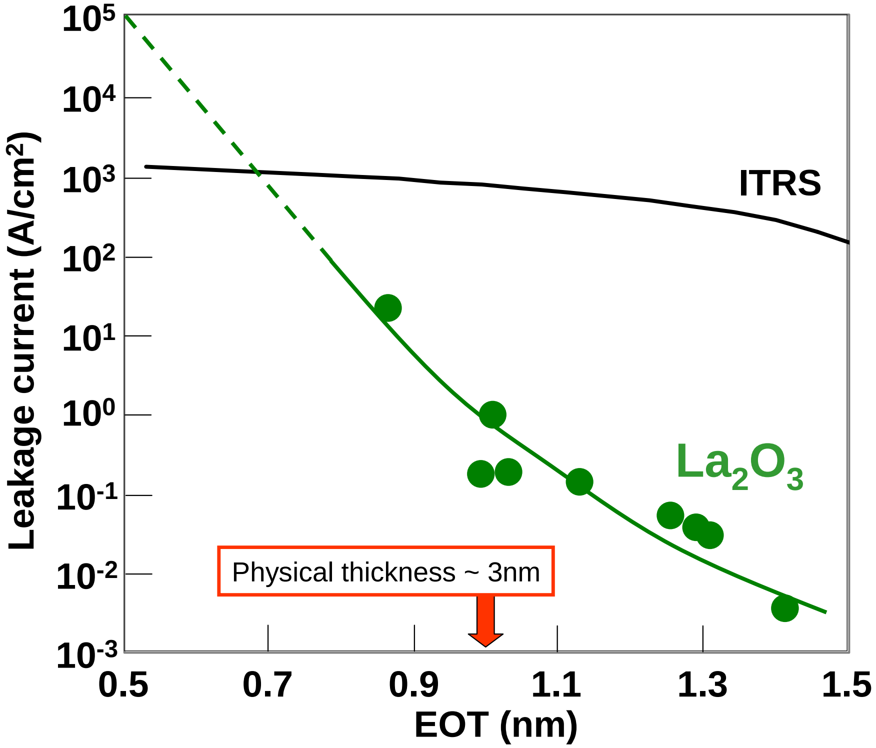
Radical oxygen atoms in La_2O_3 film increase

⇩

Generation of Silicate become large

3

Issues of La_2O_3 for EOT scaling



Process or material that can suppresses formation of Si-rich silicate are necessary even if the physical thickness is more than 3 nm (leakage current can be suppressed)

Process

- **high temperature and spike anneal**

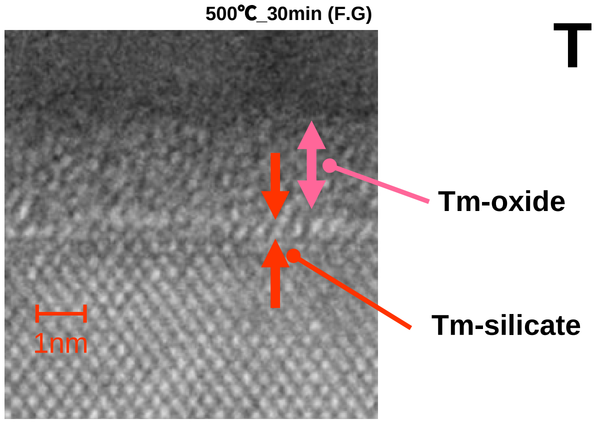
[D.Kitayama, et. al., ECS Transactions, 33 (3) 527-535 (2010)]

Material

- **Rare-earth oxide capping?**

Difference in the formation of radical oxygen atoms

W/Tm-oxide/Si

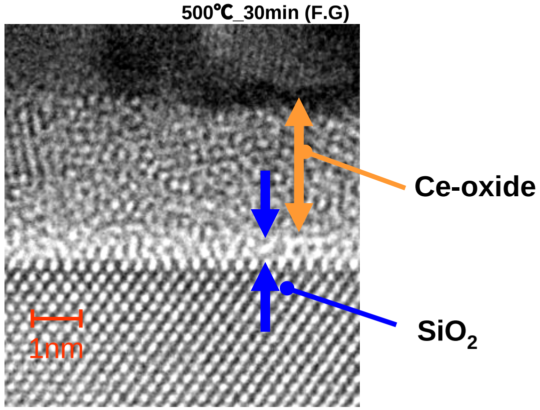


Thin silicate layer formed at interface

Reactivity with Si : Low

Generation of radical oxygen atoms : not easy

W/Ce-oxide/Si



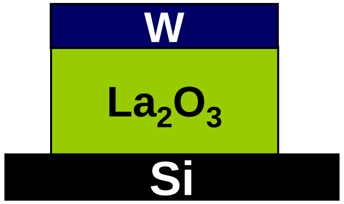
SiO_2 layer formed at interface

Reactivity with Si : high

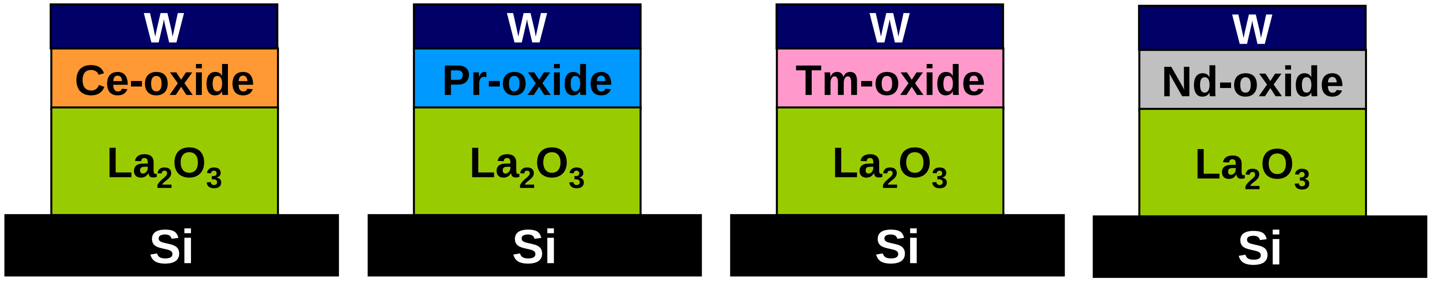
Generation of radical oxygen atoms : easy

Capping with RE-oxides may change the interface reaction

Samples prepared in this study



We fabricated RE-earth oxide capped on La_2O_3 film and confirmed their capping effects



CeO_X, PrO_X, TmO_X, NdO_X capped on La_2O_3 gate dielectric

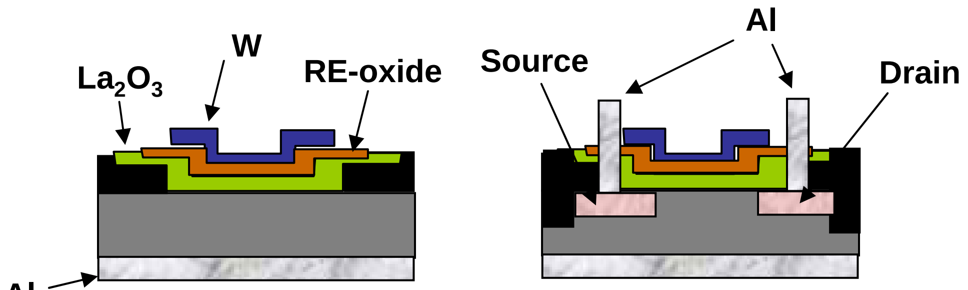
Best capping material on La_2O_3 was examined

Device fabrication

- **n-type Si substrate (MOS capacitor)**
  p-type Si substrate (MOSFET)
- **SPM, HF last treatment**
- **High-k and capping materials deposition by EB deposited**
- **Tungsten (W) metal gate electrode deposition by RF sputtering**

In situ

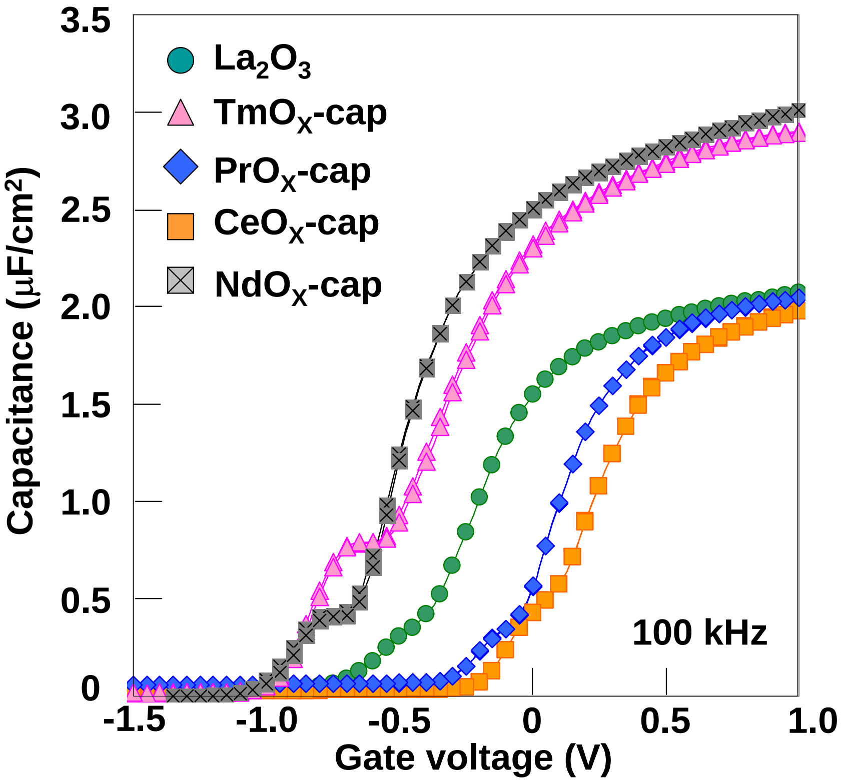
- **PMA (Post Metallization Annealing) 500℃ 30min (FG:3%H_2)**
- **Source, Drain Al interconnection**
- **Bottom electrode Al deposition**



MOS capacitor **MOSFET**

CV characteristics after 500°C annealing

- La_2O_3(4nm)
- RE-oxide(1nm) capping on La_2O_3(3nm)



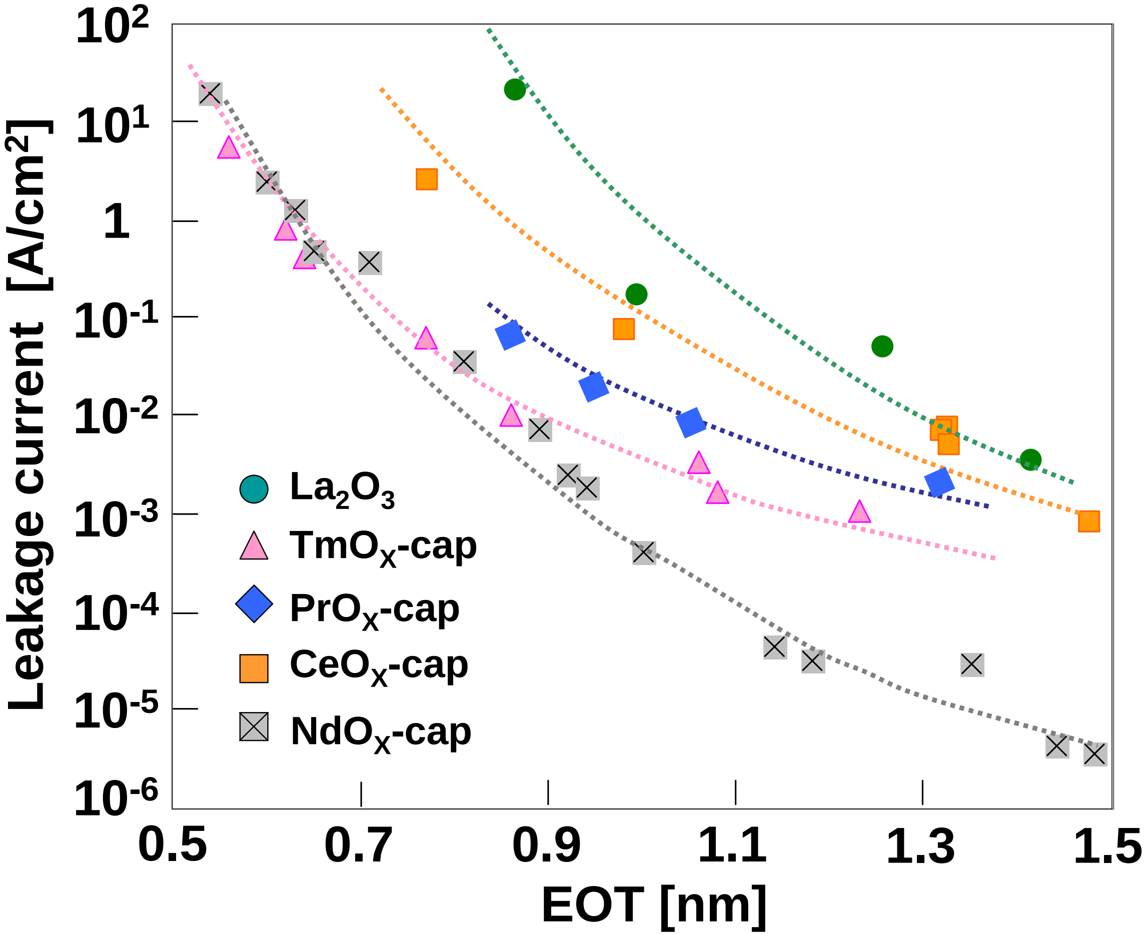
Capping material	EOT (nm)
without	1.32
Ce-oxide	1.30
Pr-oxide	1.25
Tm-oxide	0.89
Nd-oxide	0.86

Tm-oxide and Nd-oxide capping device : large reduction of EOT value

→ Both capping material can EOT scaling

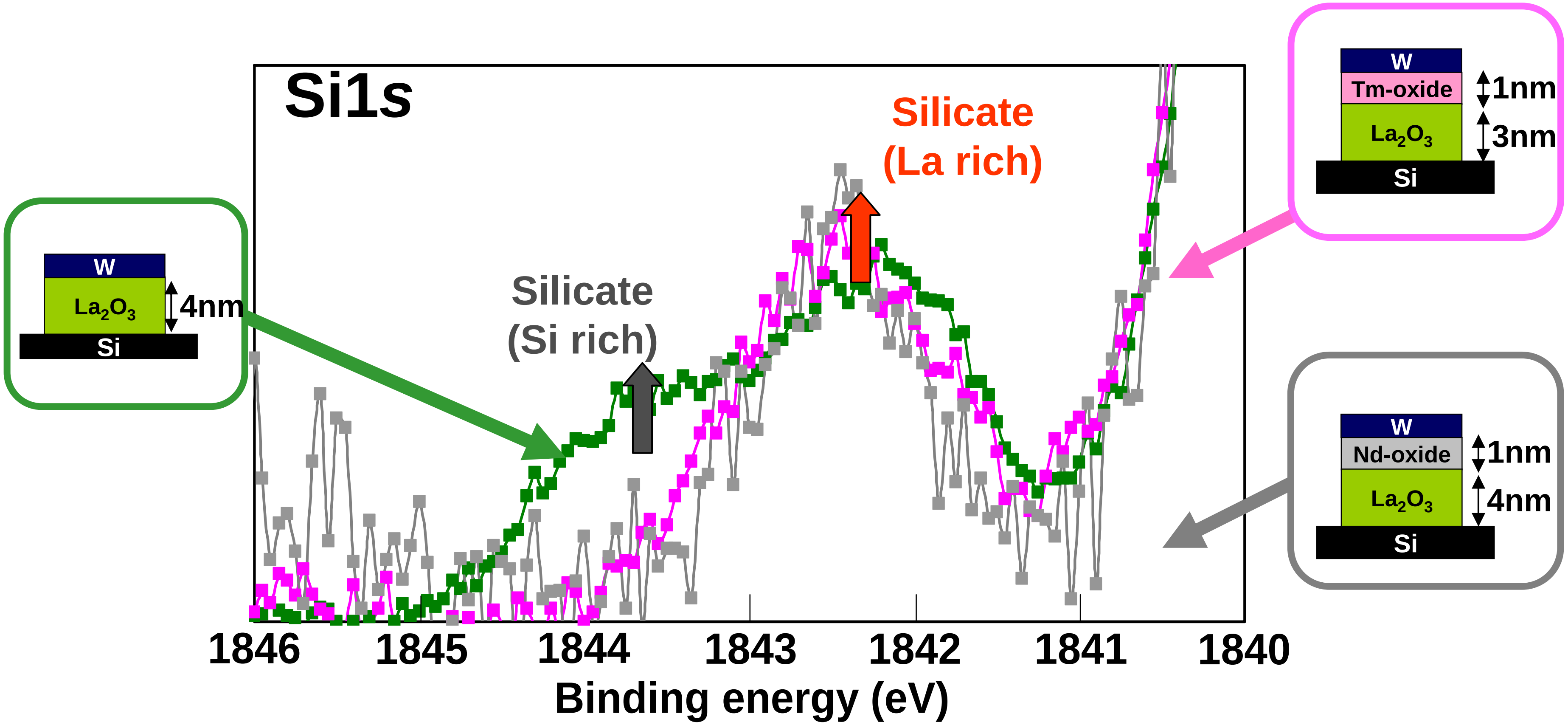
leakage current - EOT

La_2O_3(2.5~4.5 nm)
RE-oxide (1nm) capping on La_2O_3 (1~5 nm)



Tm- and Nd-oxide exhibit large leakage current suppression

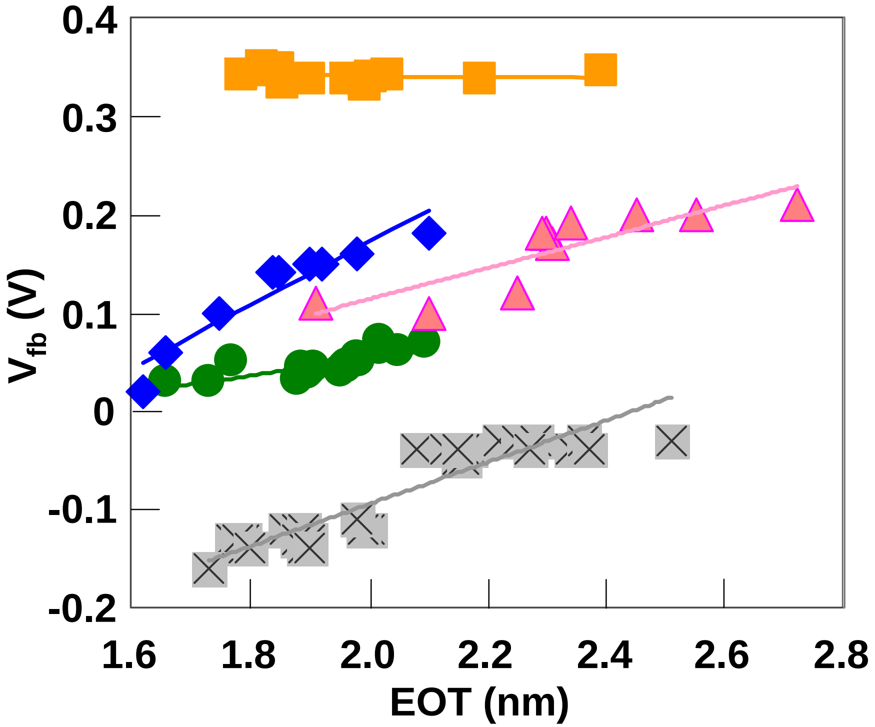
XPS Si 1*s* spectra of Tm- and Nd-oxide capping

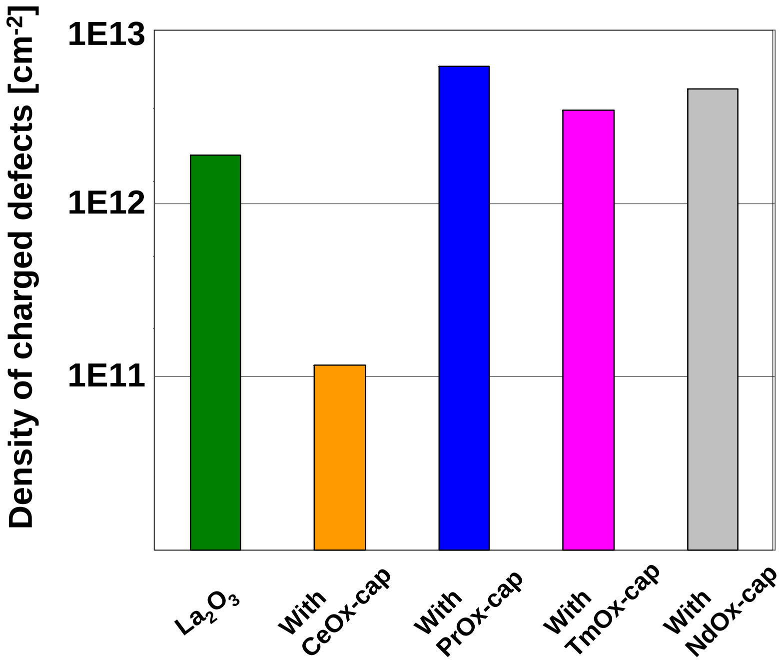


Both Tm- and Nd-oxide capping on La_2O_3 can suppress the formation of Si-rich silicate

Suppression of radical oxygen atom generation is the key to suppress the Si-rich silicate phase

Density of charged defects



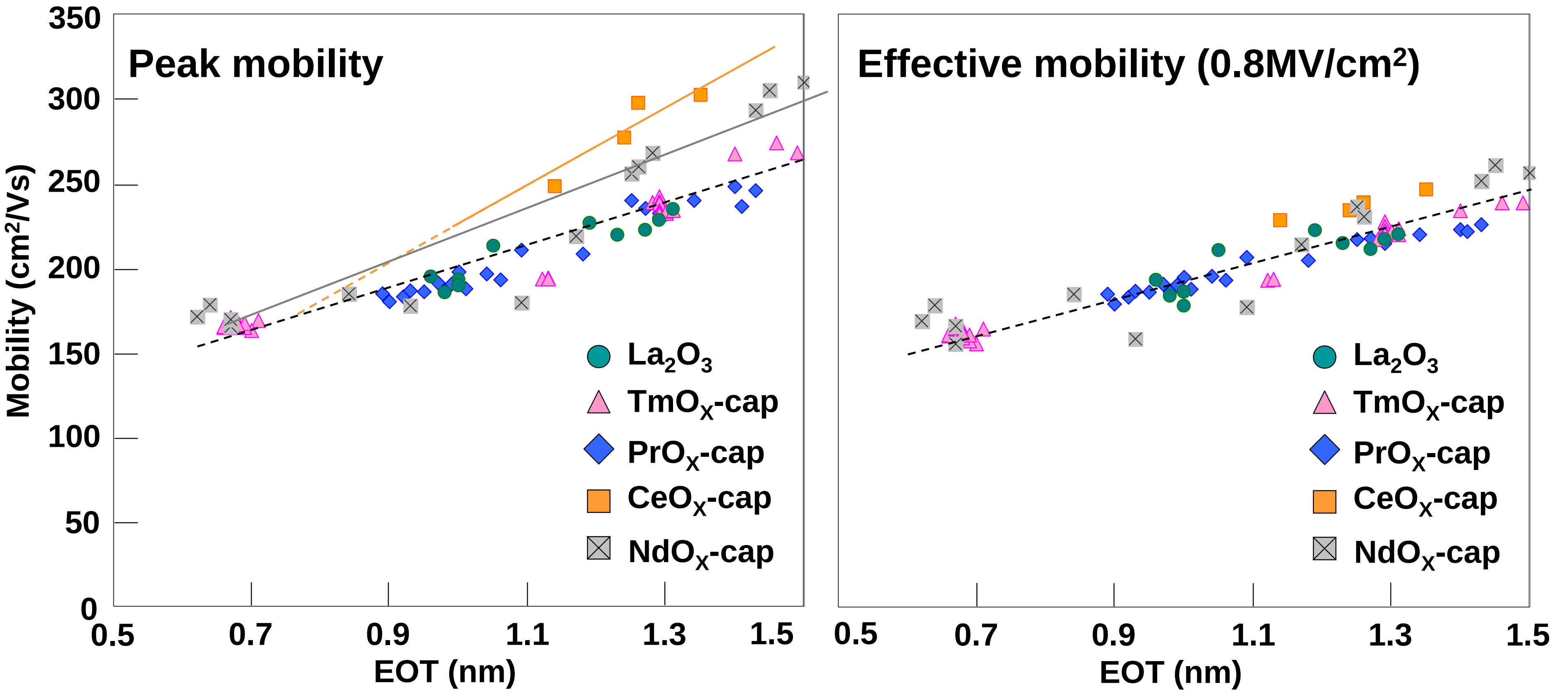


Witout capping, Tm- and Nd-oxide capping ~ 10^{12} (cm^{-2})

↓

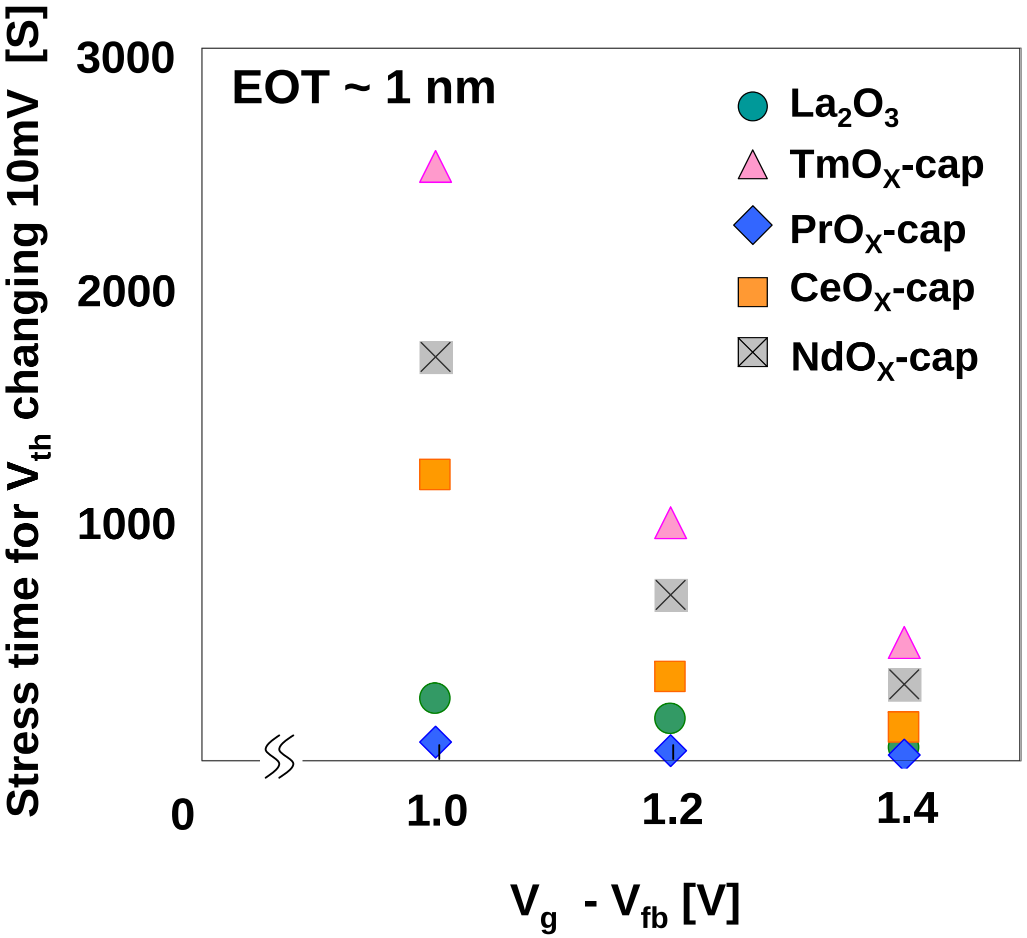
A comparable fixed charge density with Tm- and Nd-oxide cappings.

Mobility



Mobility values with and without capping device are almost the same

Reliability measurement with RE-oxide capping



better

Tm-oxide capping

Nd-oxide capping

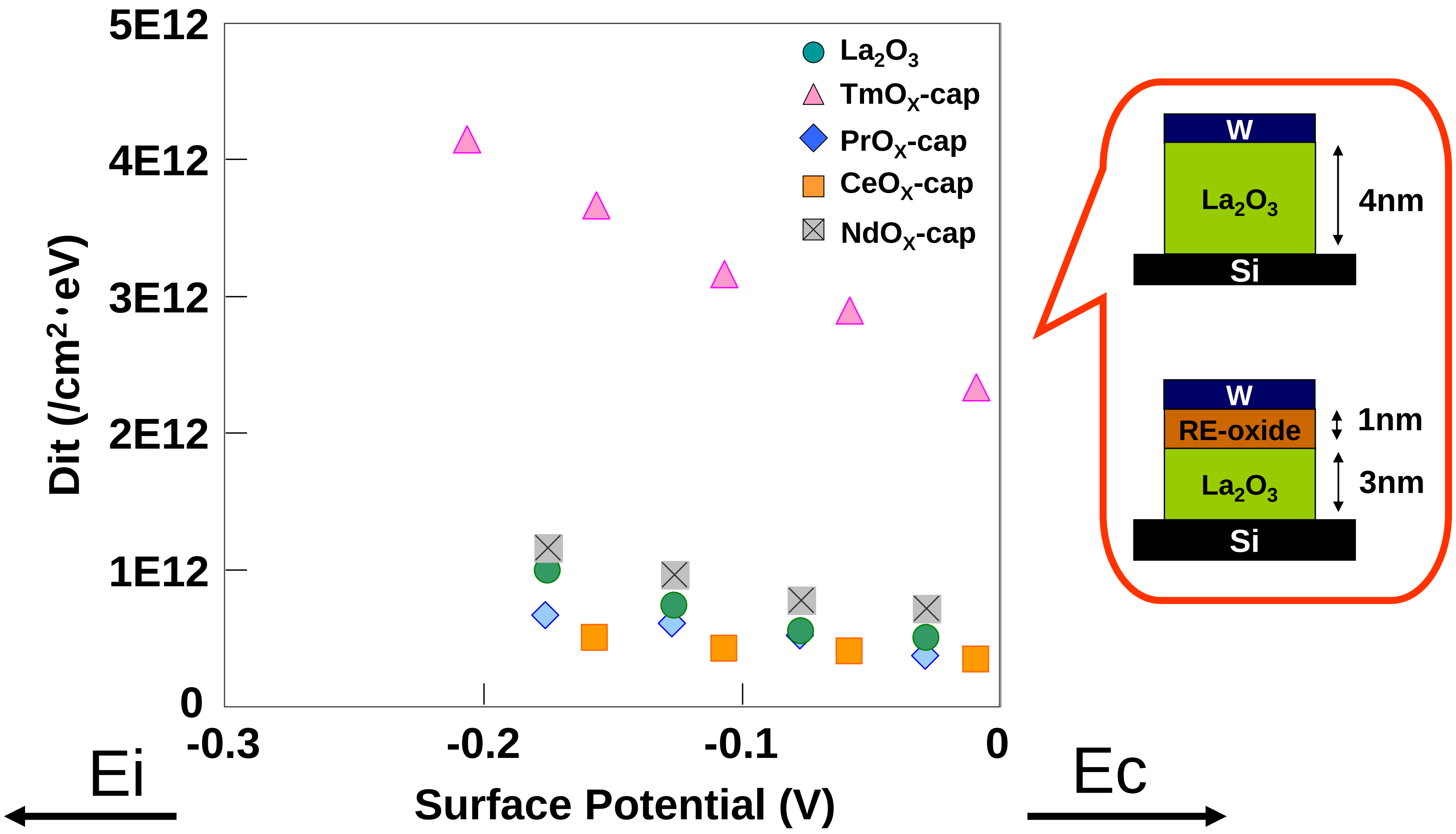
Ce-oxide capping

Without capping

Pr-oxide capping

Tm- and Nd-oxide capping exhibit better reliability

Interfacial state



Tm-oxide cap : high degradation (more than single-digit)

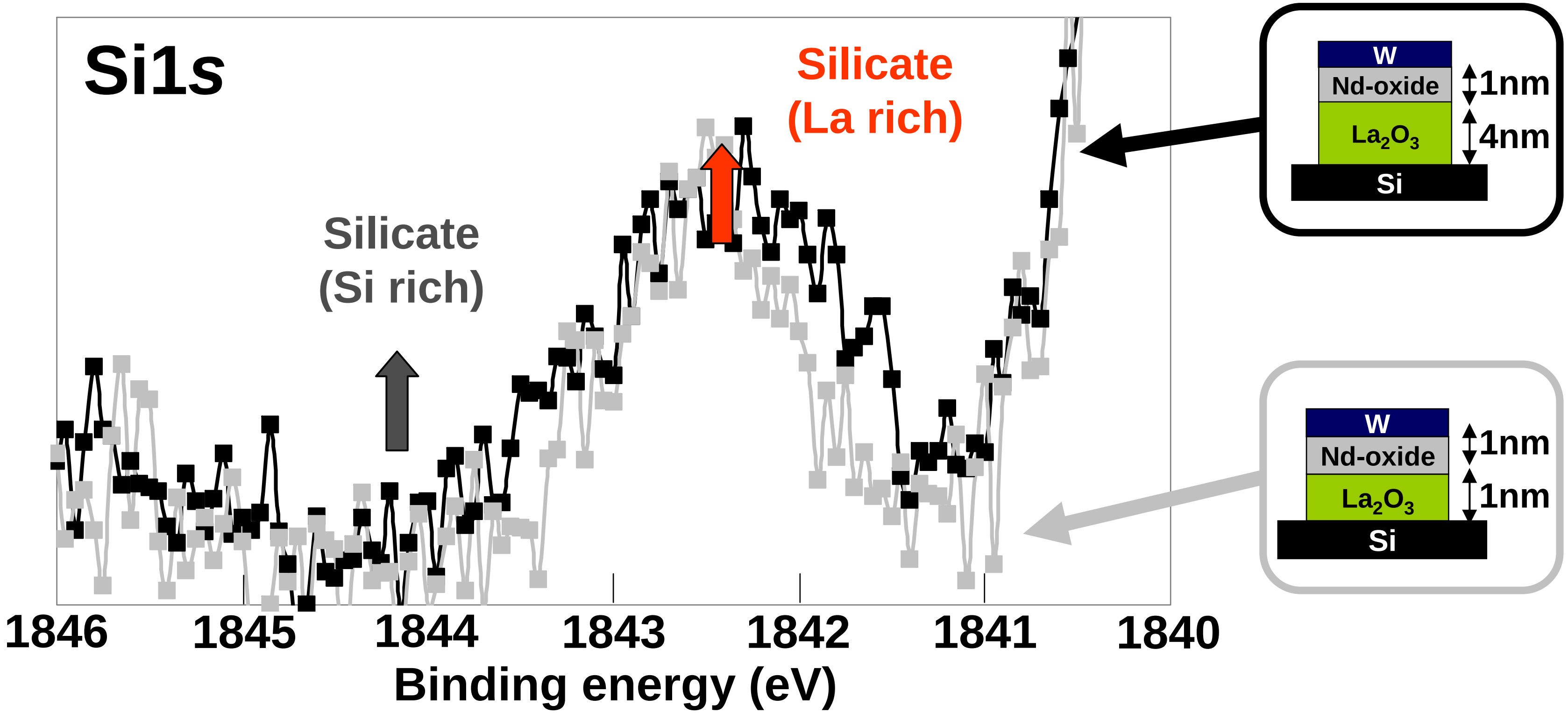
other cap : stay at the same state

Effects of capping materials

Capping material	scaling	J_g suppression	Defects reduction	mobility	reliability	Dit
Ce-oxide	×	○	◎	○	○	○
Pr-oxide	△	○	△	△	×	○
Tm-oxide	◎	○	△	△	◎	×
Nd-oxide	◎	◎	△	○	○	△

Nd-oxide cap is the best among those materials

Oxide thickness scaling with NdOx capping



Identical interface reaction with La_2O_3 scaling can be obtained with Nd-oxide capping

→advantage for EOT scaling

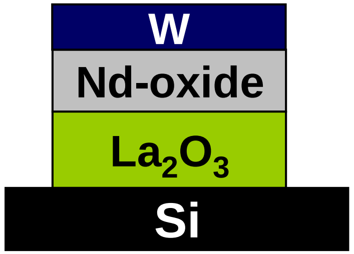
Conclusion

We confirmed the effects of RE-earth oxide capped on La_2O_3 film

- Tm- and Nd-oxide capping on La_2O_3 can suppress the formation of Si-rich silicate
  （EOT~0.5 nm can be achieved)
- Identical interface reaction with La_2O_3 scaling can be obtained with Nd-oxide capping

Nd-oxide is the best material as capped on La_2O_3 for EOT scaling

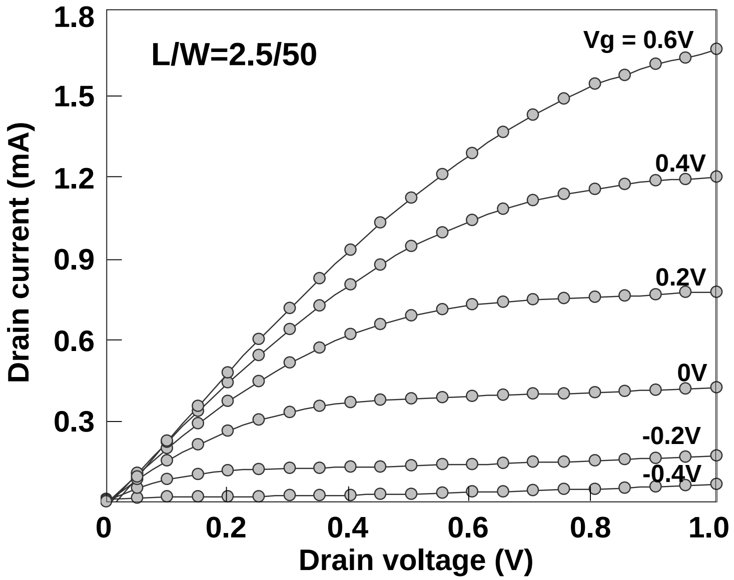
W/Nd-oxide/La_2O_3/Si MOSFET

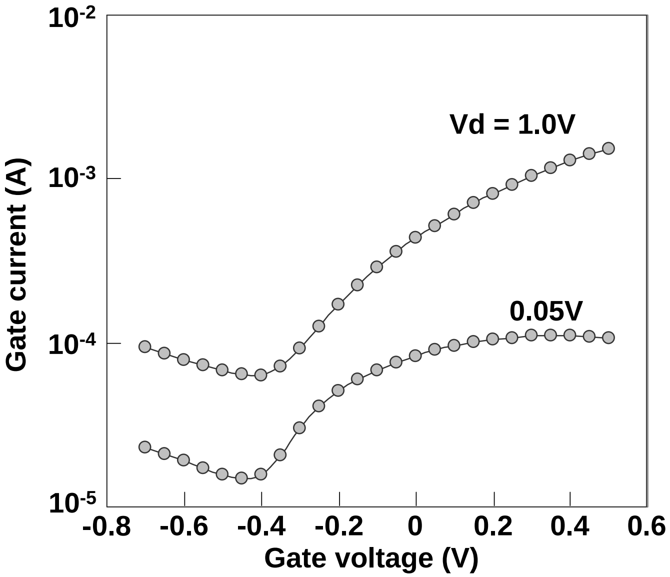


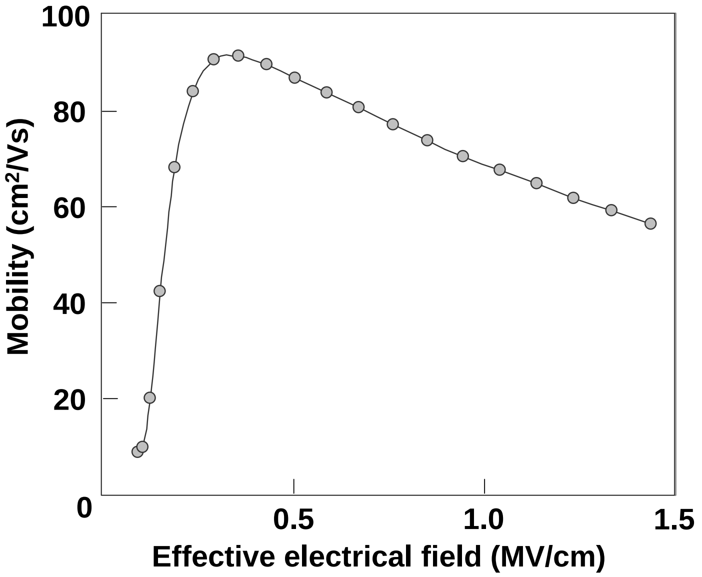
EOT= 0.45 nm

V_{th} = -0.39 V (Vd=0.05 V)

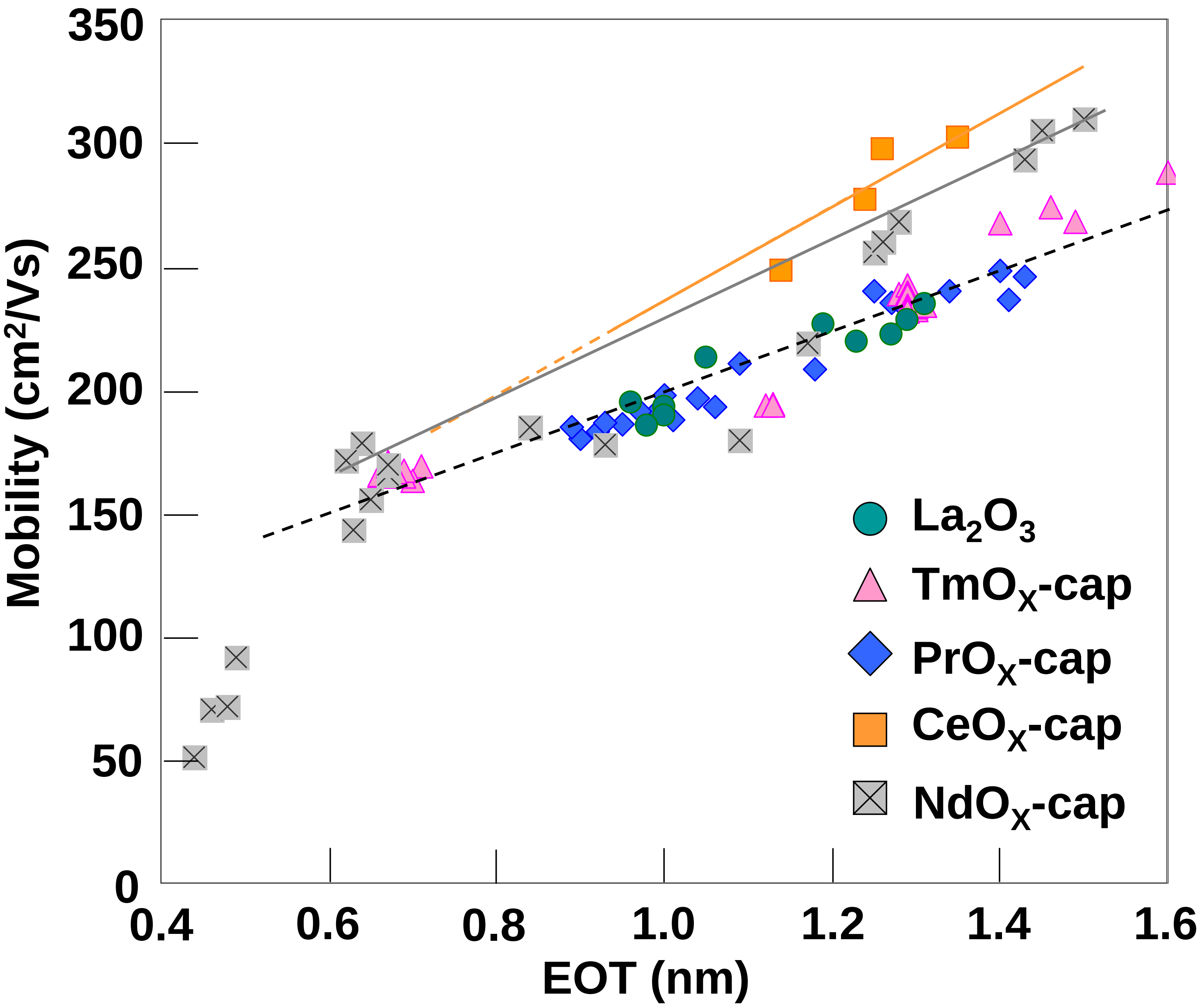
S.S = 127 mV/dec





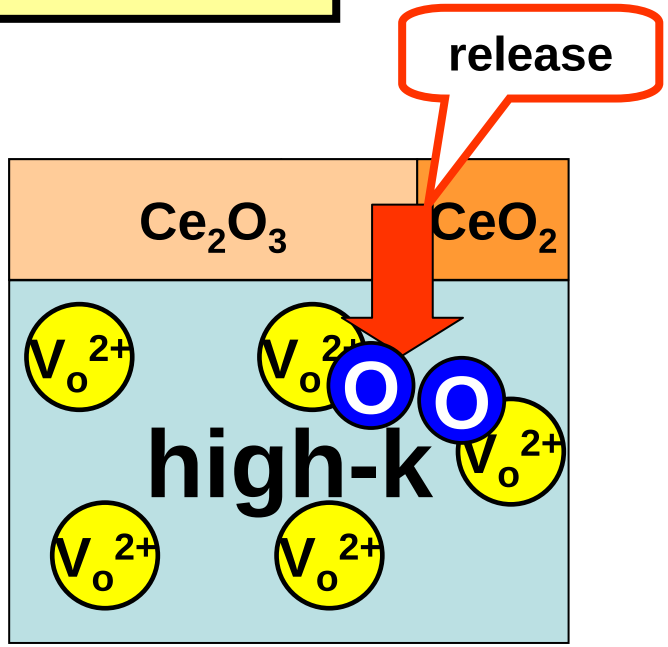


Mobility


Mobility (cm²/Vs)
350
300
250
200
150
100
50
0
0.4
0.6
0.8
1.0
1.2
1.4
1.6
EOT (nm)
La₂O₃
TmOₓ-cap
PrOₓ-cap
CeOₓ-cap
NdOₓ-cap

Process induced oxygen defects compensation

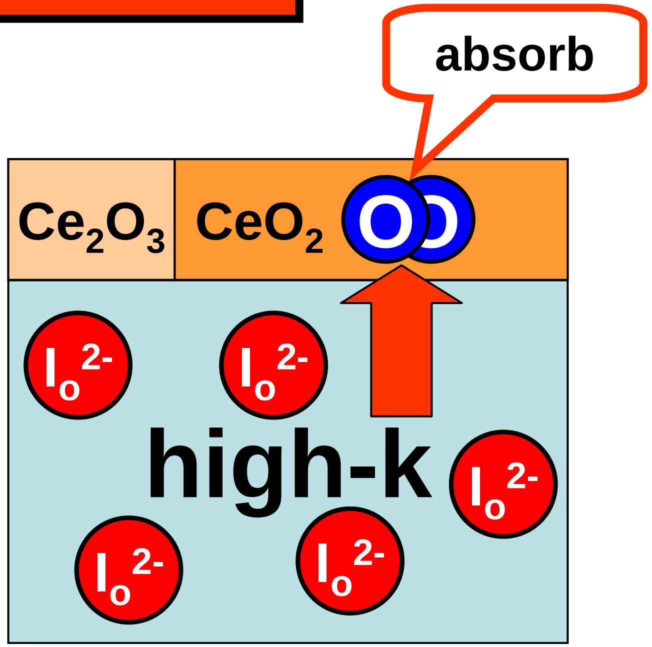
Reduction



$CeO_2 \rightarrow Ce_2O_3 + O$

$2e^- + V_O^{2-} + O$

Oxidation

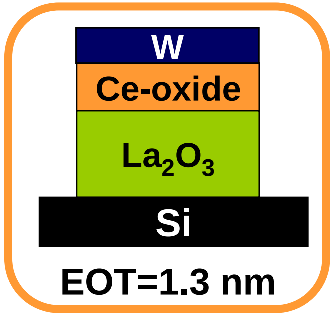


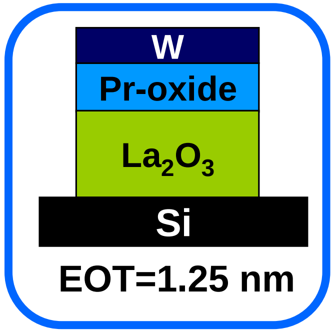
$Ce_2O_3 + O \rightarrow CeO_2$

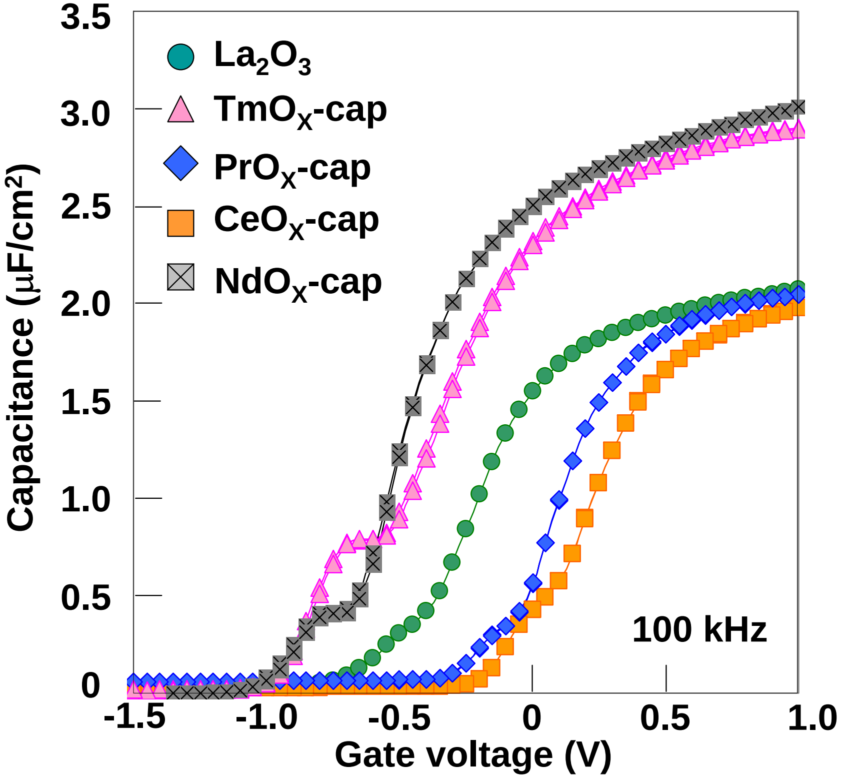
$I_O^{2-} - 2e^- \rightarrow O$

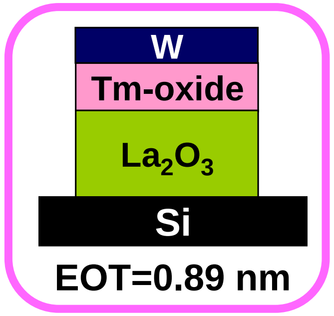
1 Device fabrication

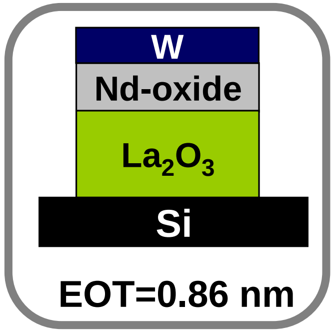
Physical thickness = 4nm (La_2O_3 : EOT=1.32nm)











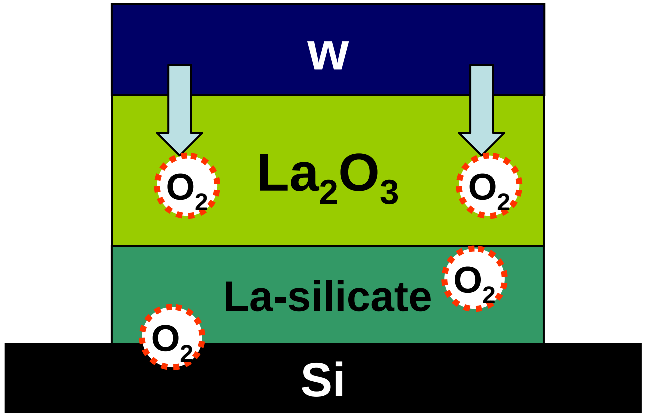
Tm-oxide and Nd-oxide capping device : EOT scaling is achieved

Tm-oxide and Nd-oxide cap have a suppressing effect of La-silicate formation

Formation of La-silicate

$La_2O_3 + Si + nO_2 \rightarrow La_2SiO_5, La_2Si_2O_7, La_{9.33}Si_6O_{26}, La_{10}(SiO_4)_6O_3$, etc

Without cap



O_2 keep coming from W and reactive with La_2O_3

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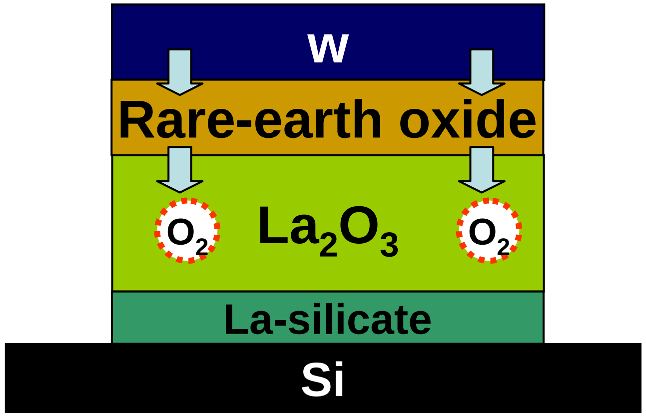
Thickness of La-silicate: increase

Capped on La_2O_3



O_2 supply was limited by rare-earth oxide

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Thickness of La-silicate: unchanged