Mitigation of Intrinsic Vt Variation using Oxygen Inserted (OI) Silicon Channel

Suman Datta

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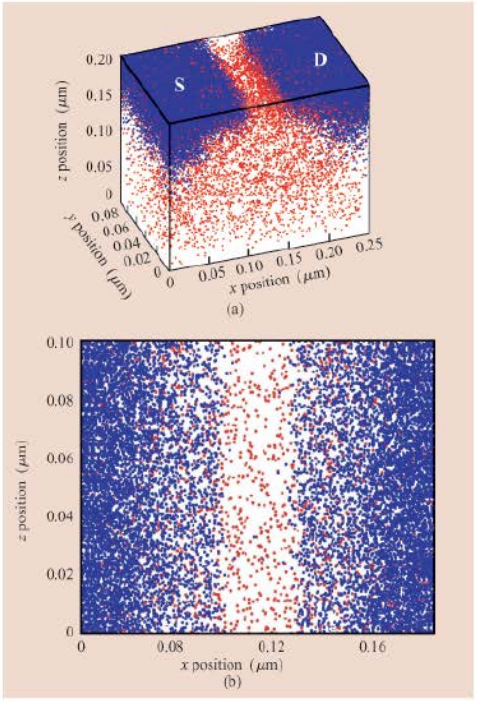
[1]University of Notre Dame, IN, USA; [2]Atomera Inc., Los Gatos, CA, USA

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Outline

- Variation Mitigation Techniques
  - 3D Techniques
    - Alternate doping scheme
    - Effective width increase
  - Planar Techniques
    - Super steep retrograde doping profile
- V_T Variation Improvement with Oxygen Inserted (OI) Channel
- Mobility Enhancement with Oxygen Inserted (OI) Channel
- Future Outlook

Vt Fluctuation



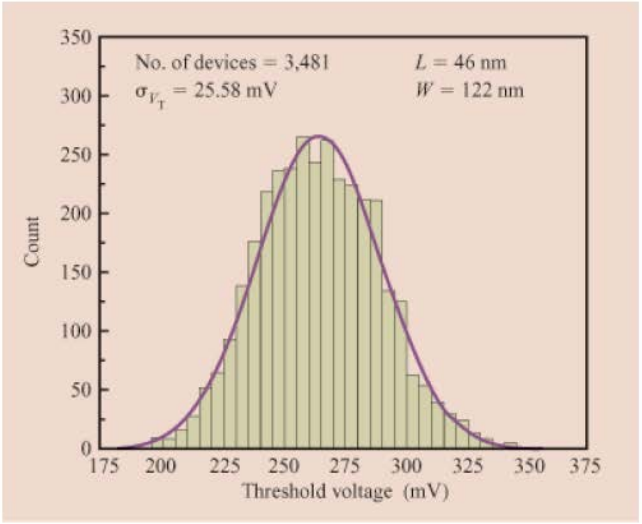


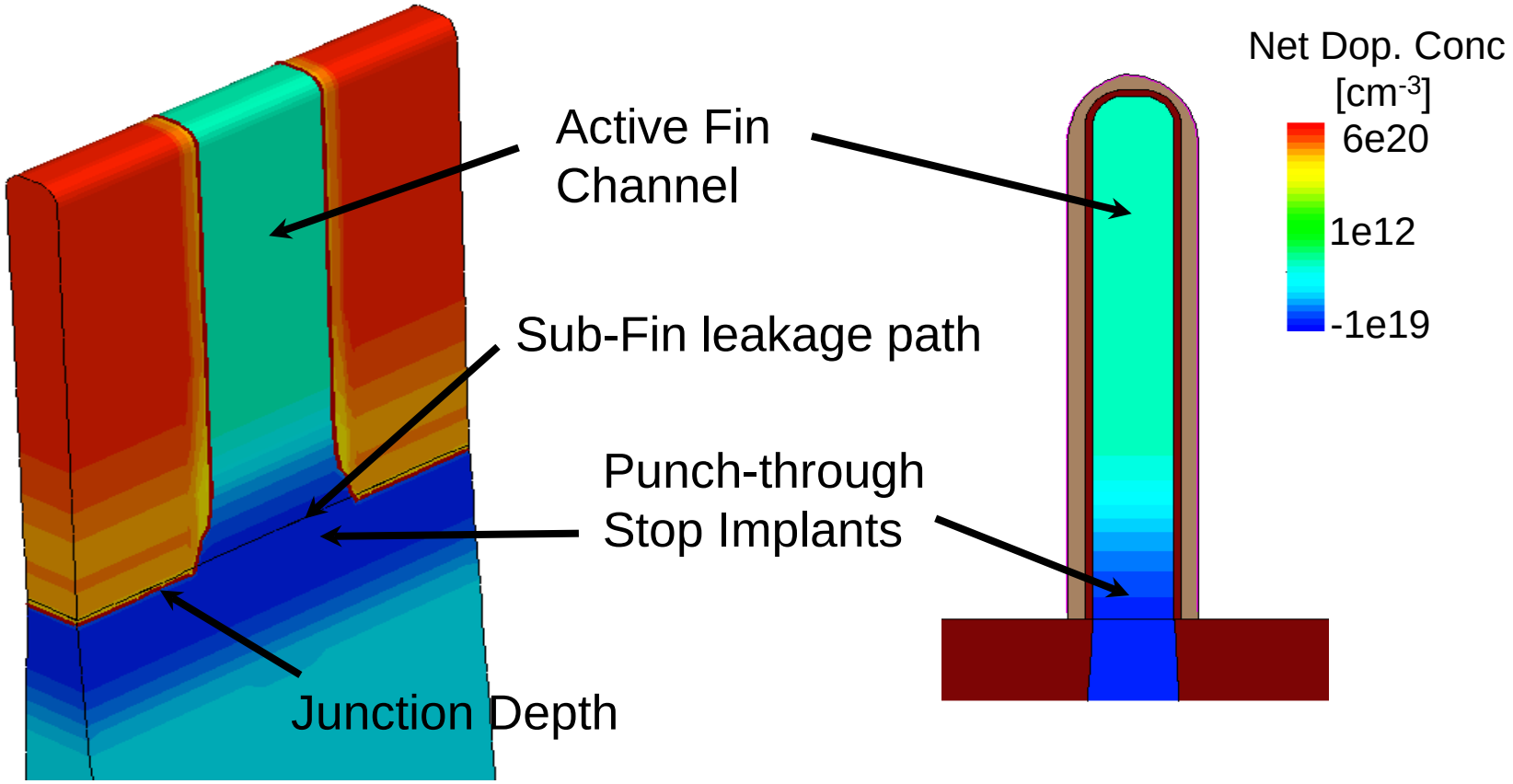
Figure 2

Threshold voltage histogram for FETs in the 90-nm-technology node.

IBM Journal of Res. And Tech. 2003.

- Vt fluctuation is considered a fundamental technology scaling roadmap.

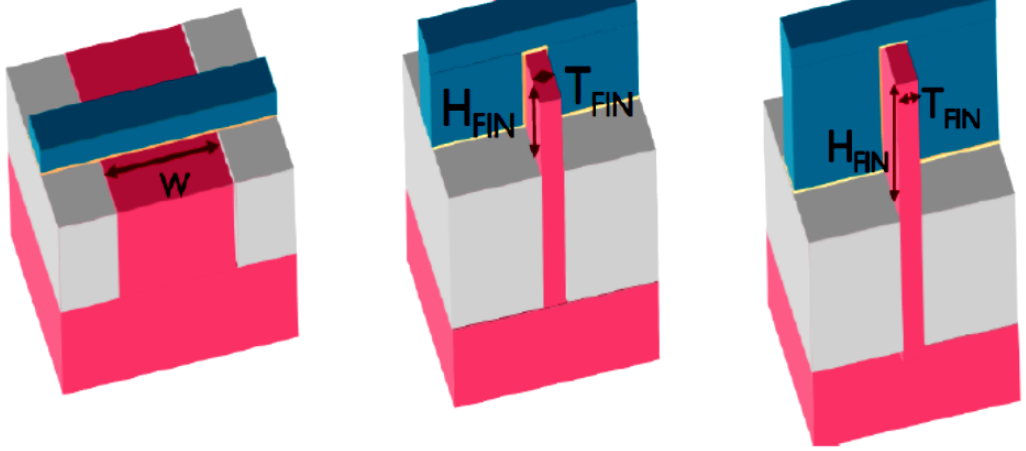
Punch-through Stopper (PTS) Implant

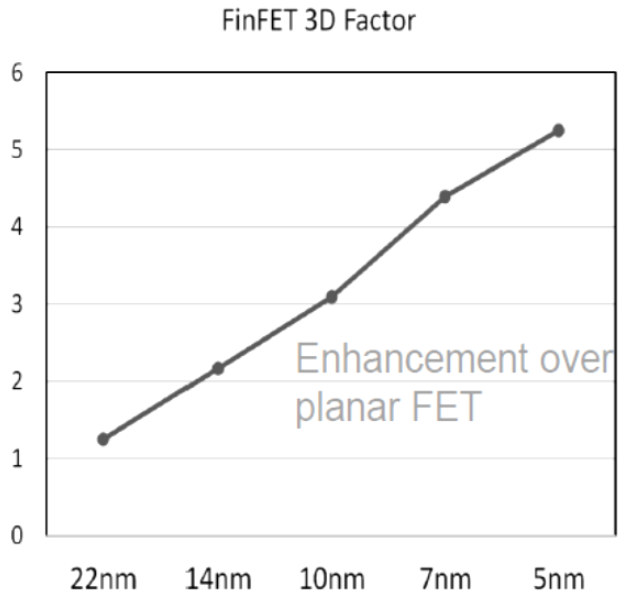


- Punch-through Stop (PTS) implants are required to suppress sub-fin leakage in sub-22nm FinFETs.
- Lower channel doping to improve carrier transport.

[1] S. Natarajan *et al.*, *IEDM Tech Dig.* pp. 71, 2014 [2] C. Auth *et al.*, to appear in *IEDM Tech Dig.*, 2017

Effective Gate Width

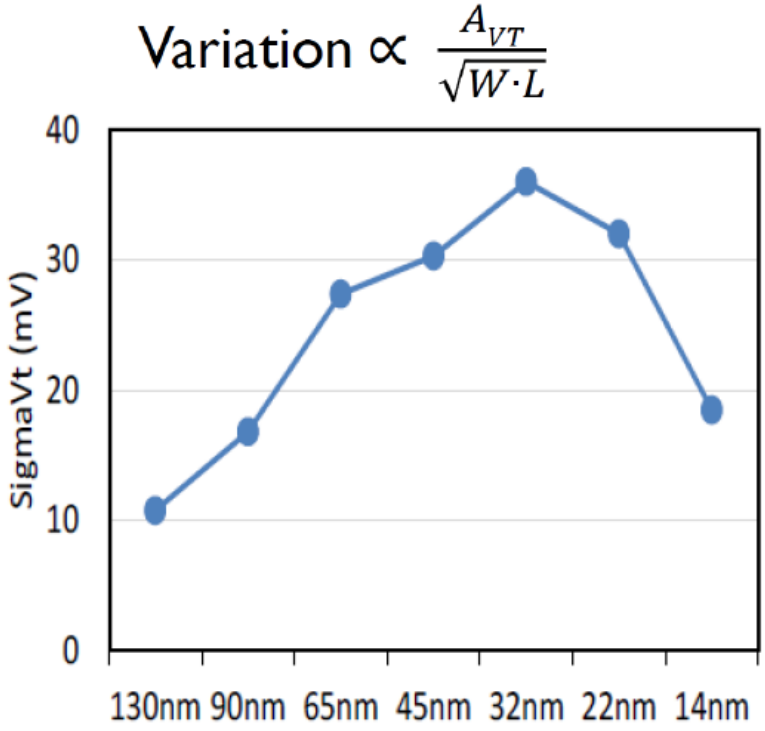




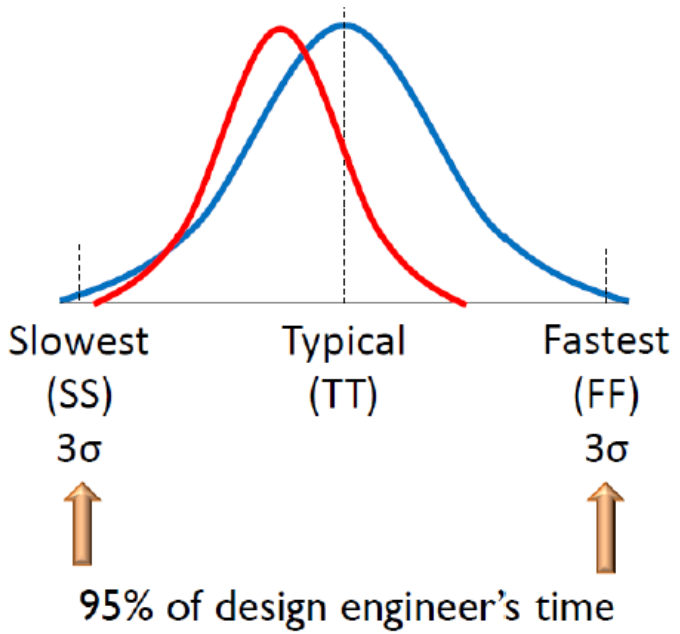
$$\text{3D Factor} = \frac{\text{Total width of FinFET}}{\text{Planar width used}} = \frac{2 \times H_{FIN} + T_{FIN}}{\text{Fin Pitch}}$$

Part of Tri-gate appeal is improved electrostatics
Other part is **folded width**

Reversal of Intrinsic Variation Trend



S. Natarajan (Intel), IEDM 2014

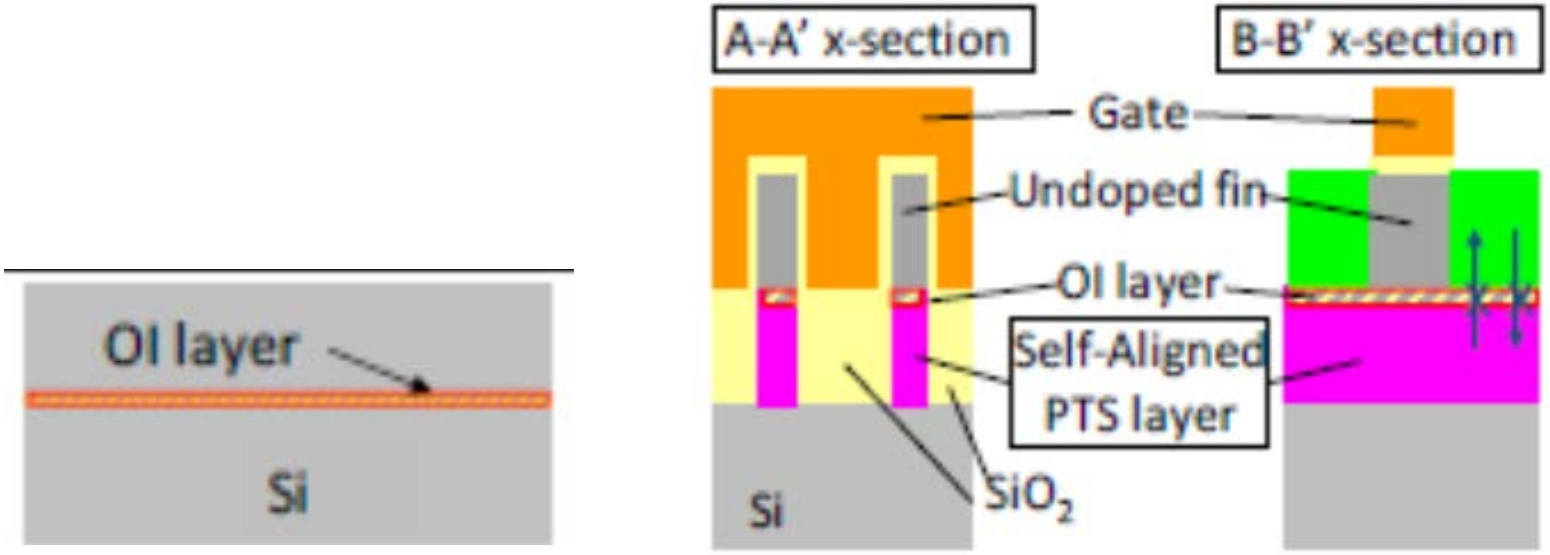


Greg Yeric (ARM), IEDM 2015

Tri-gate was primarily intended for electrostatics

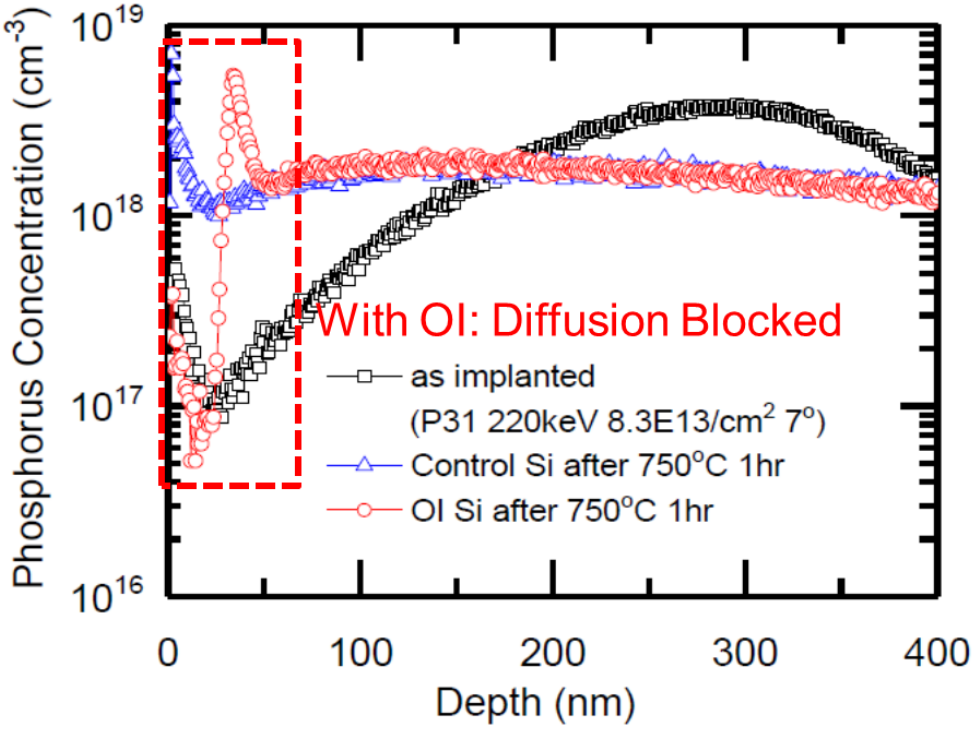
It uses 3D factor to scale effective width to mitigate variation and reduce standard cell foootprint

Oxygen Incorporated (OI) Channel



Oxygen Incorporated (OI) Channel by Atomera for Improved Intrinsic Vt Variation

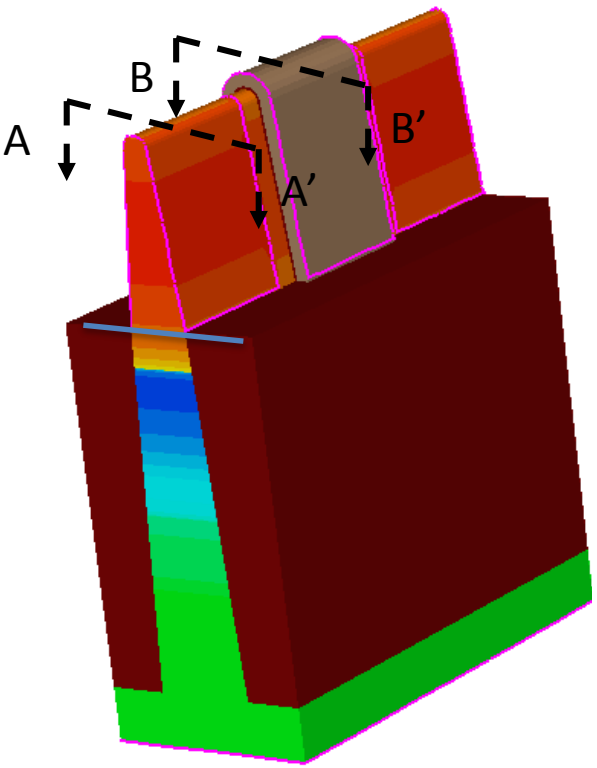
OI Silicon Channel for TED Blocking

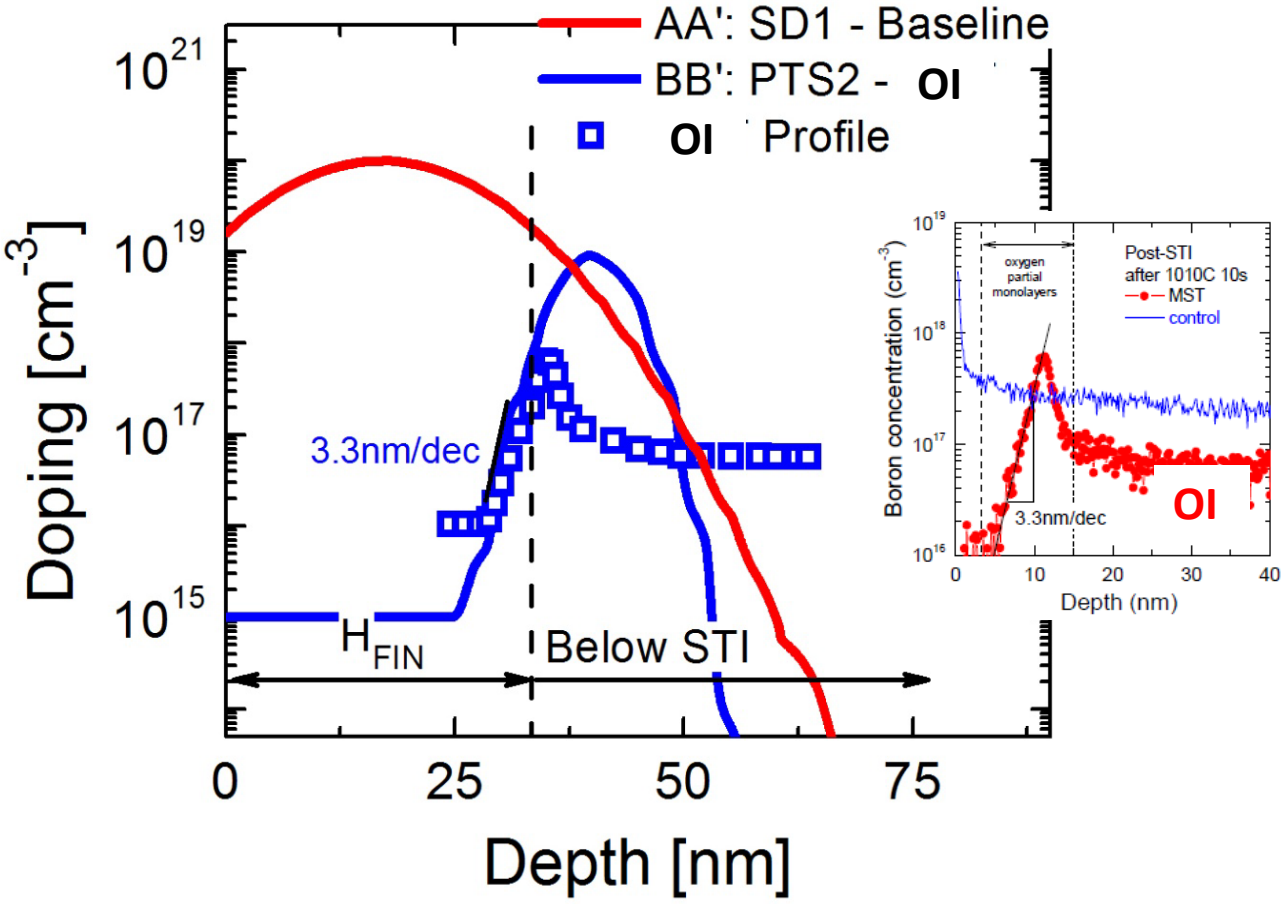


- Transient enhanced diffusion (TED) causes Boron/Phosphorus to diffuse upward toward surface during annealing
- OI layer blocks TED and allows targeting of lower surface concentration to improve RDF-induced V_T variation.

- [3] H. Takeuchi *et al.,* "Punch-Through Stop Doping Profile Control via Interstitial Trapping by Oxygen-Insertion Silicon Channel", JEDS-2017

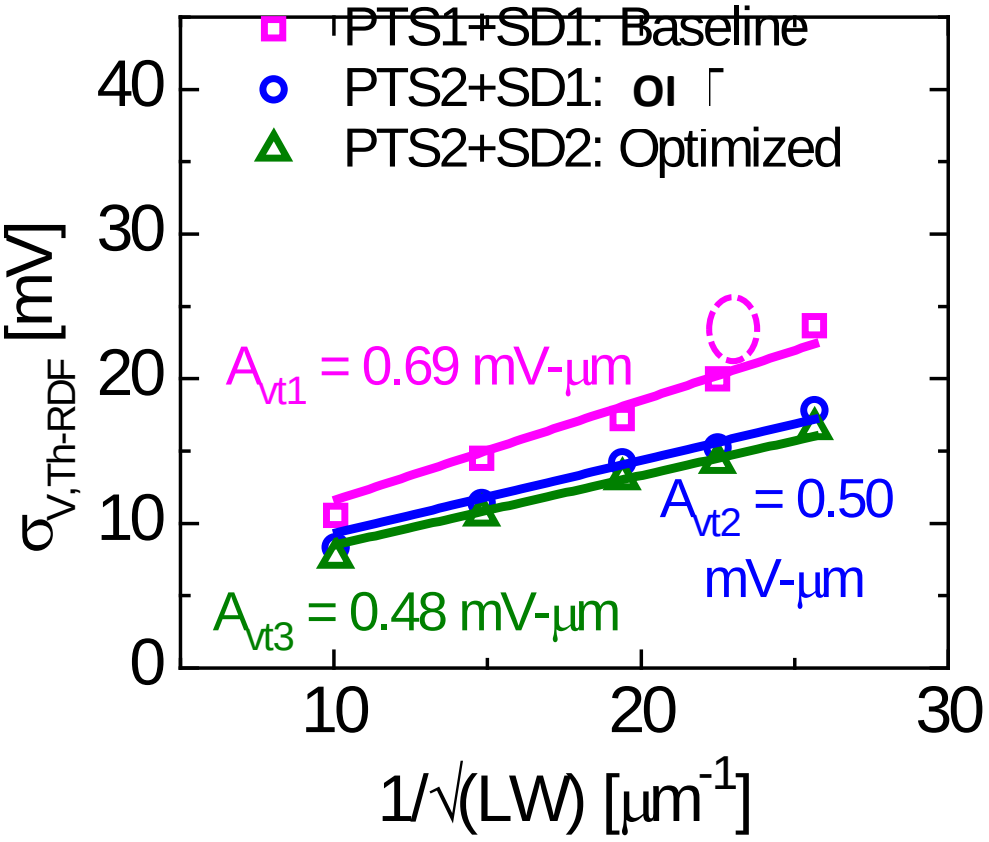
PTS Optimization with OI silicon





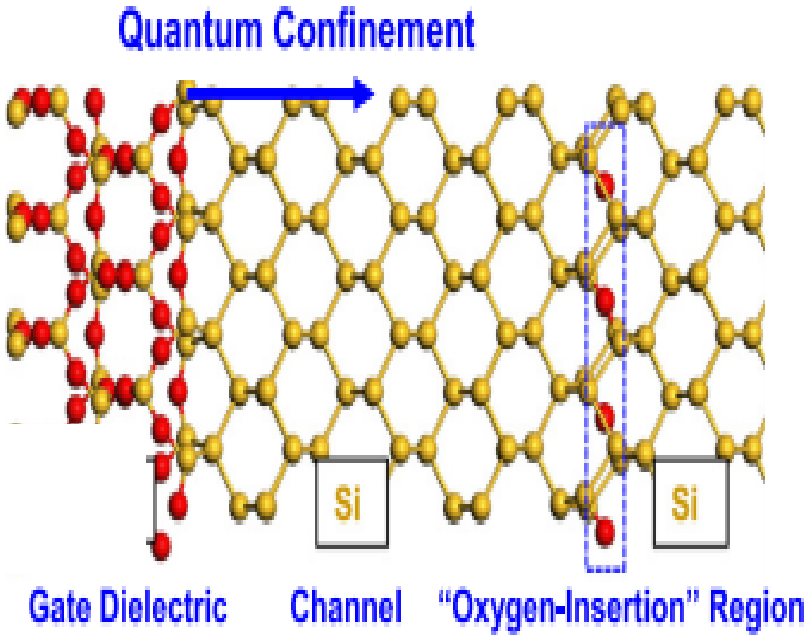
- Punch through stopper (PST) dopant profile optimization using OI silicon:
  - S/D profile (SD1: baseline)
  - PST profile (PST2: OI Si)

FinFET A_{vt} : RDF only

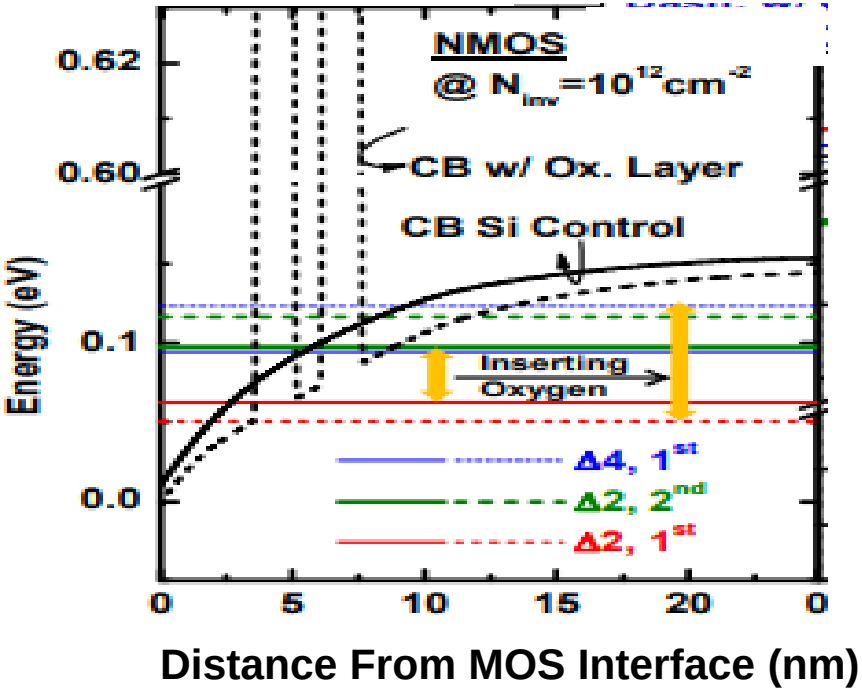


- Considering only RDF fluctuation, OI Si FinFET shows **30%** improvement in $\sigma_{V,Th-RDF}$ and $A_{vt\ (RDF)}$ over baseline FinFET

OI Silicon channel for Mobility Enhancement



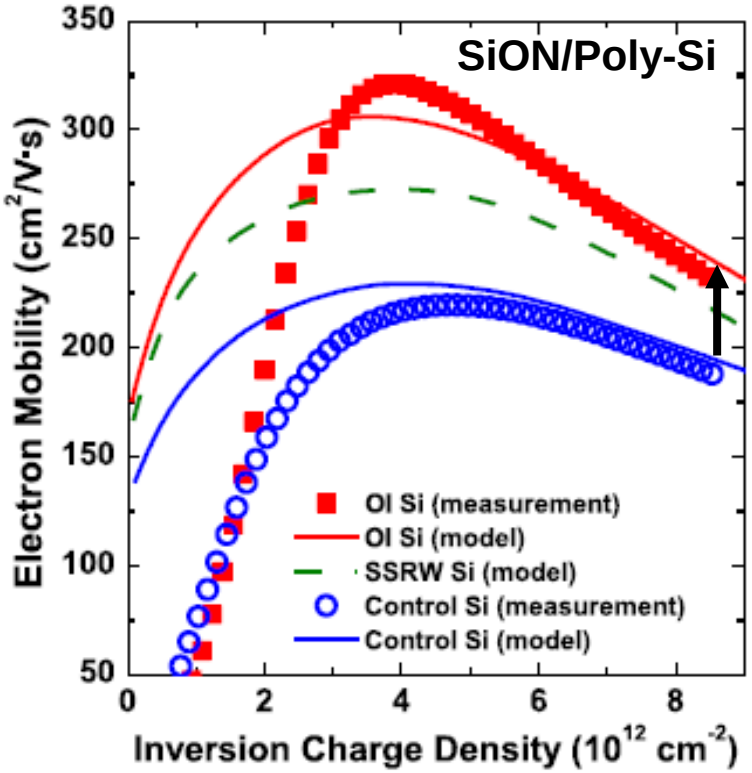
Dash: OI Si Channel Solid: Control Si



- Oxygen Insertion creates pseudo-energy barrier in Si MOSFET channel that:
  - 1. Splits Δ-2 valley sub-band levels, further lowering transport effective mass.
  - 2. Results in electron mobility improvement over a control Silicon MOSFET

- [4] N. Xu et al., "MOSFET Performance and Scalability Enhancement by Insertion of Oxygen Layers," IEDM 2012, pp. 127 [5] N. Xu et al., "Electron mobility enhancement in (100) oxygen-inserted silicon channel ," APL 107, 123502 (2015)

Mobility Improvement with OI Channel with Poly Si-SiON



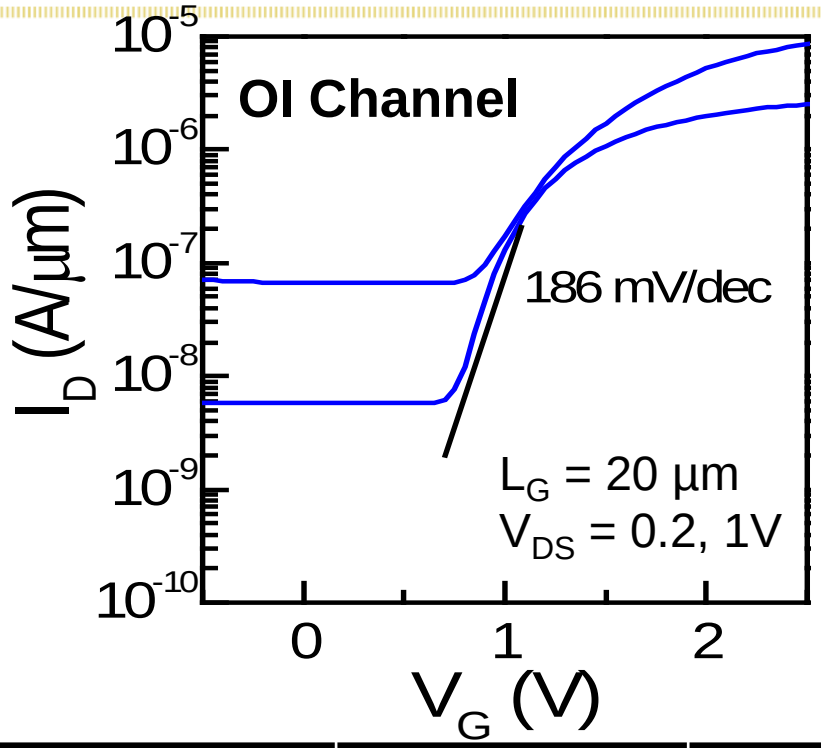
25%

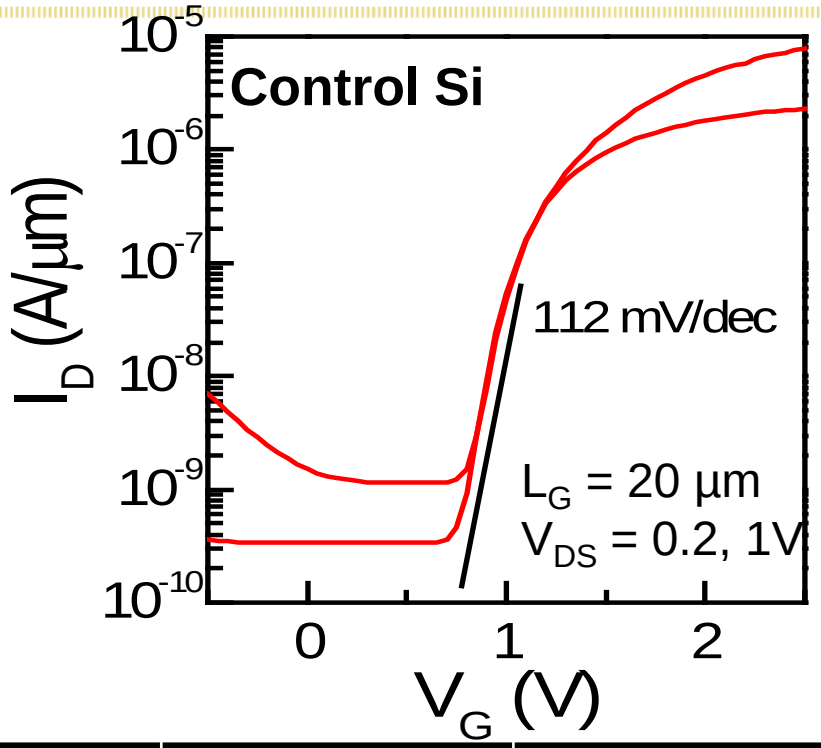
T. J. King (Berkeley)

- 25% electron mobility improvement (n_s = 8x10^{12} cm^{-2}) is observed with OI channel and SiON/Poly gate stack.
- Is this OI-induced mobility enhancement retained with HfO_2/TiN gate stack?

- [4] N. Xu et al., "Electron mobility enhancement in (100) oxygen-inserted silicon channel ," APL 107, 123502 (2015)

High-k / metal gate FETs with OI Si channel

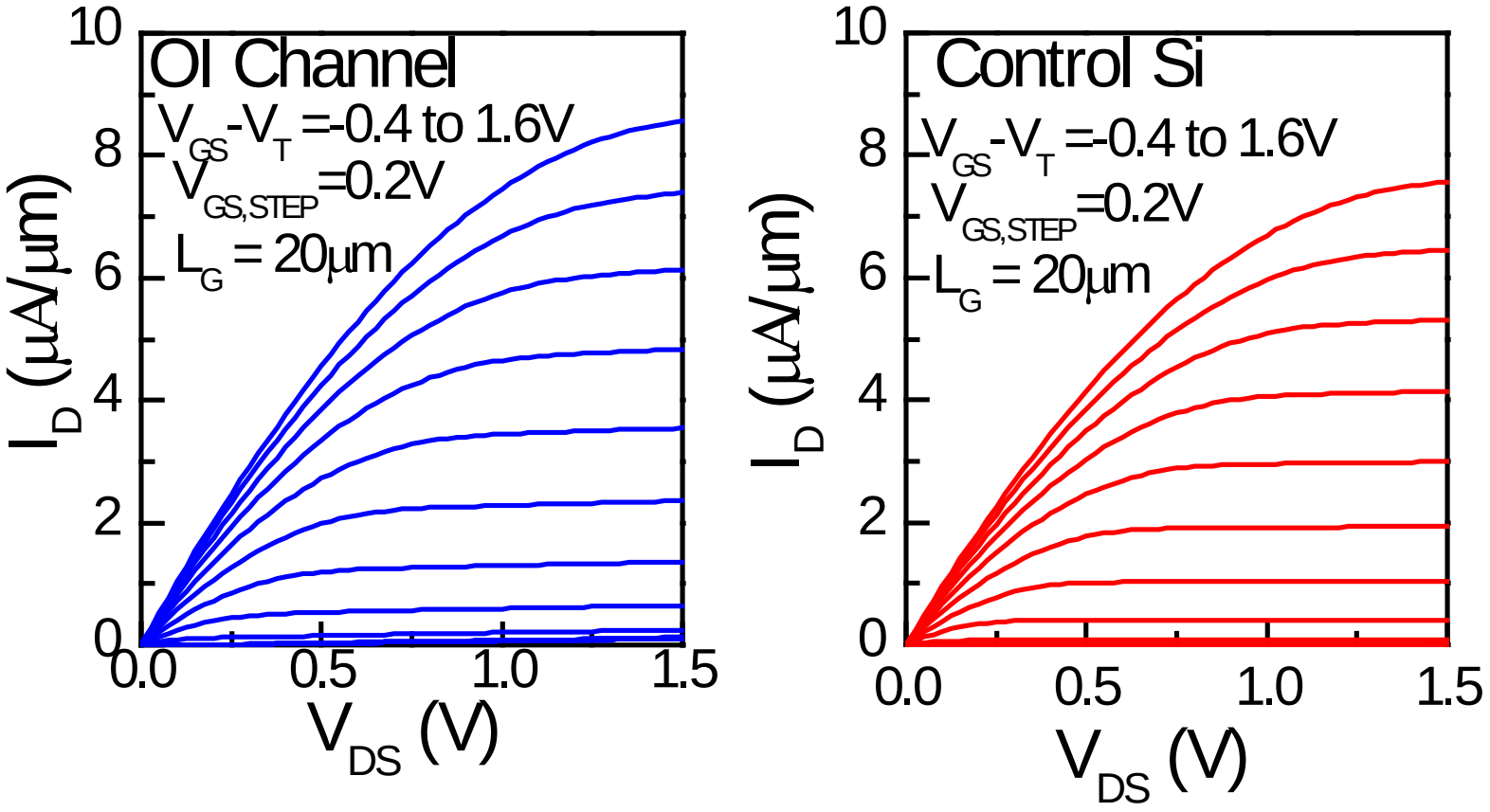




Substrate	SS_{LIN} (mV/dec)	$V_{T,LIN}$ (mV)	$I_{D,LIN}$ (µA/µm) V_G-V_T =1V	$I_{D,SAT}$ (µA/µm) V_G-V_T =1V
OI Channel	186	854	1.94	5.05
Control	112	962	1.69	4.38

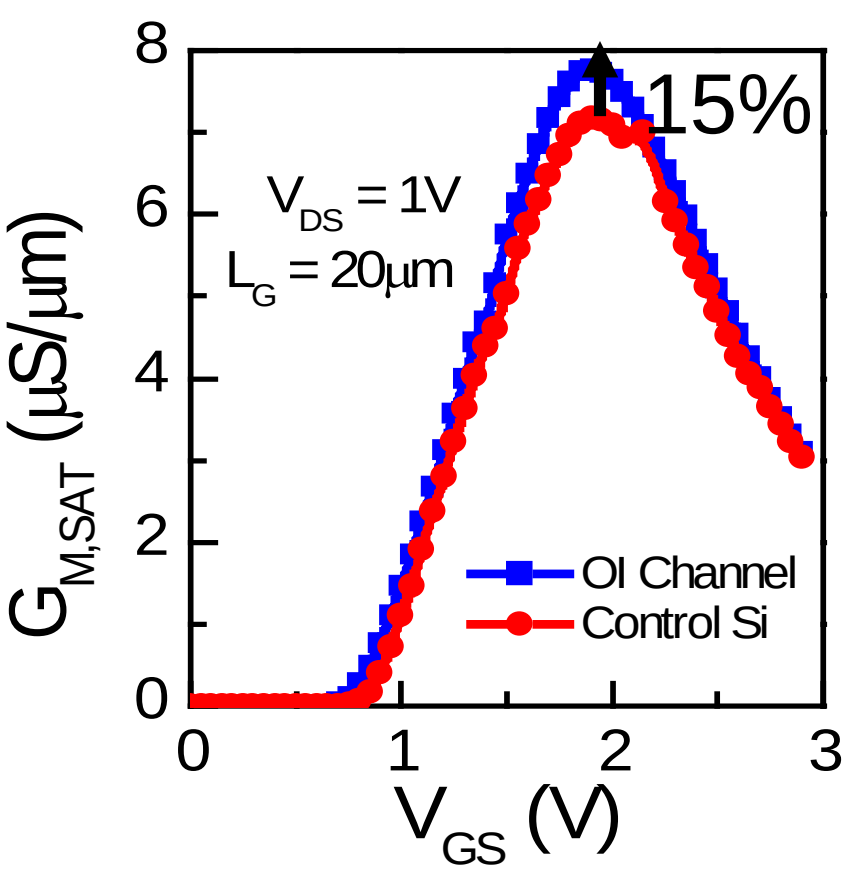
- OI channel FET shows 15% higher $I_{D,LIN}$ and $I_{D,SAT}$ over Control FET at matched overdrive.

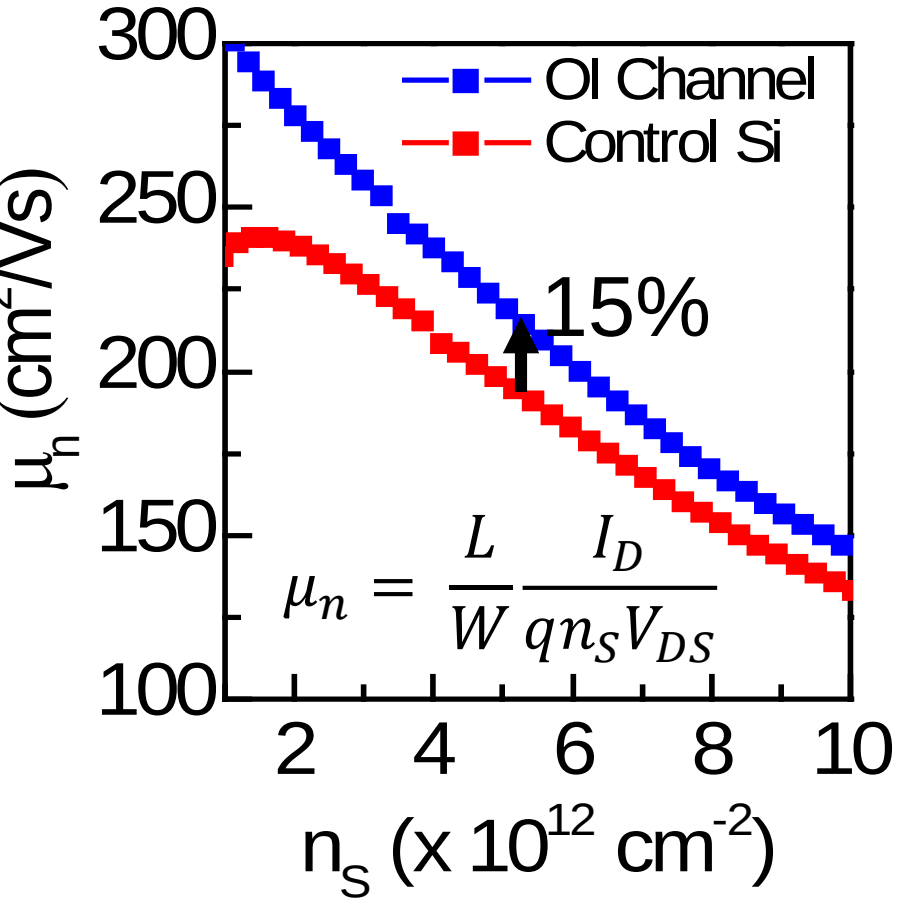
Output Characteristics



- At fixed $V_G - V_T$, OI channel shows 15% higher $I_{D,SAT}$ than Control Si.

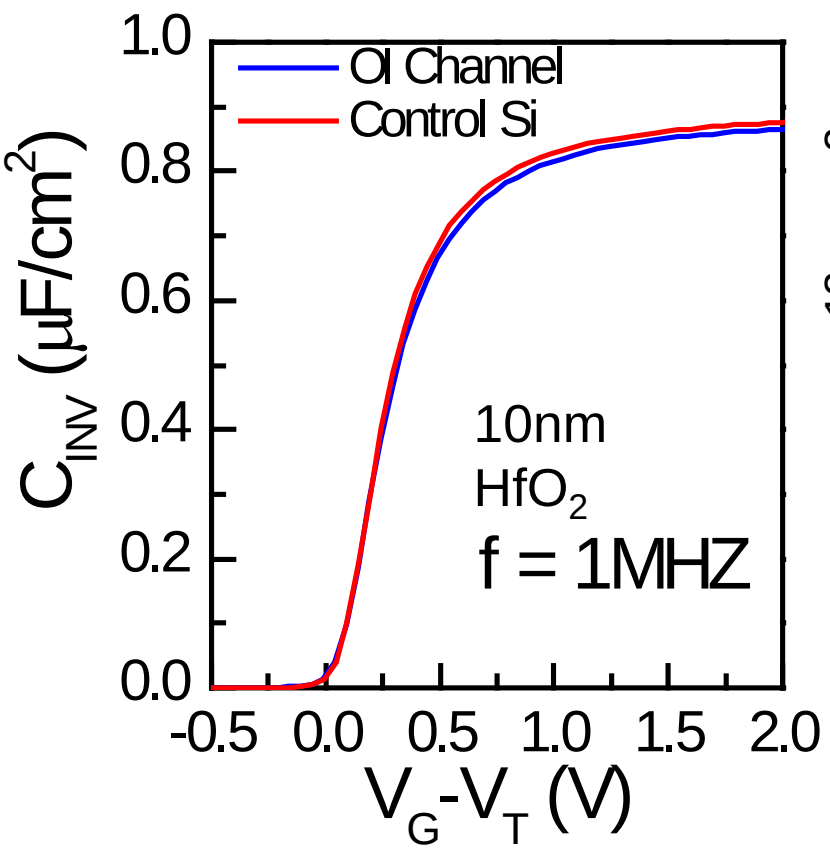
G_M and Electron Mobility

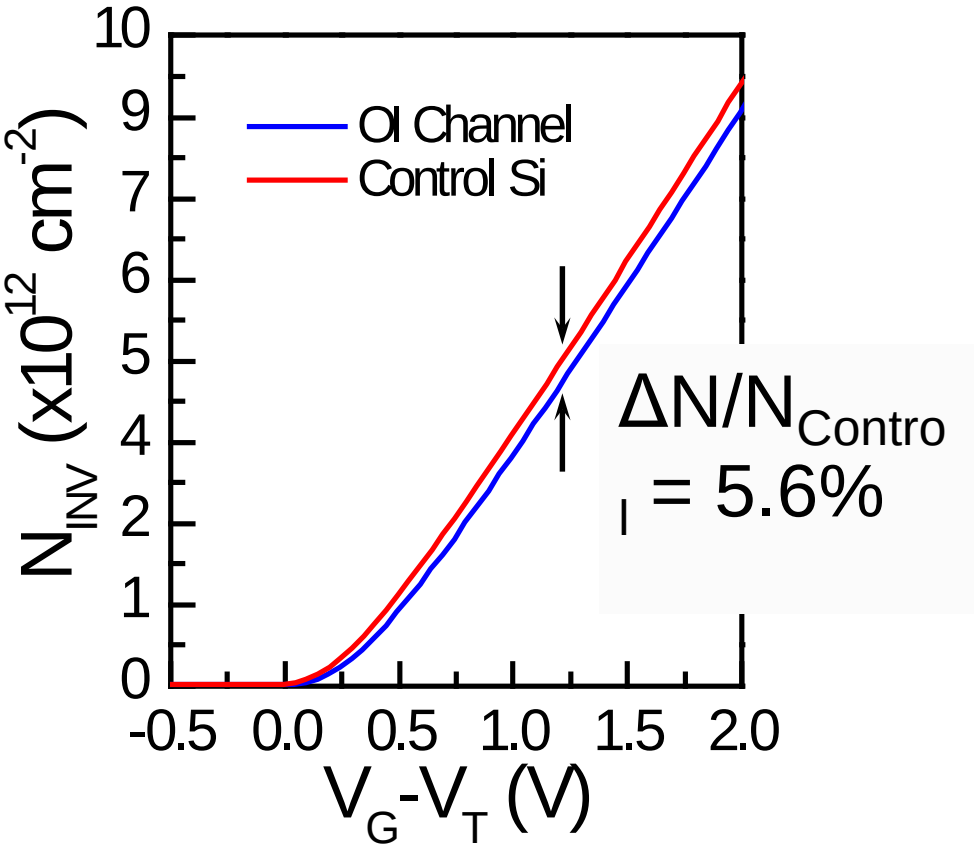




- At matched N_{INV} = 5x 10^{12} cm^{-2} , OI channel device shows 15% higher transconductance and electron mobility over Control Si.

Split-CV Characterization





- OI Channel shows 5.6% lower N_{INV} at fixed $V_G - V_T$.

Future Outlook

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- Oxygen Inserted (OI) Silicon channel provides a CMOS-compatible method to simultaneously reduce V_T variation and improve transistor drive currents.

- 30% improvement in Vt variation potentially with OI channel in FinFET configuration

- In both SiON/Poly-Si and HfO_2/TiN gate stack, Oxygen Inserted (OI) Silicon channel provides 15% low field electron mobility enhancement.

- Future work to focus on BTI benefit of OI channel in high-k/metal gate planar FETs

Thank You

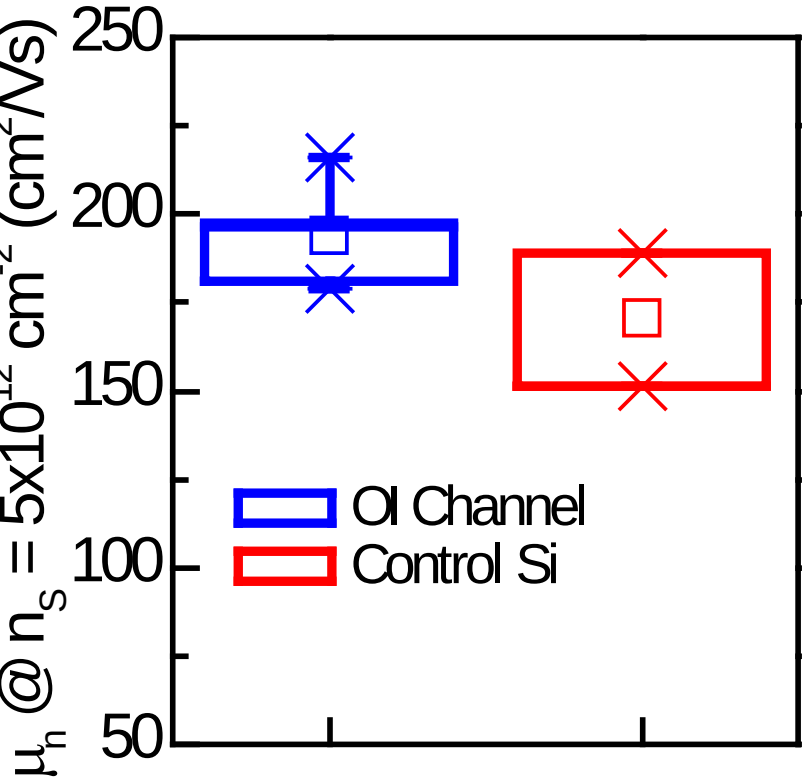
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BACK-UP

Statistical Mobility Analysis



Substrate	Mean μ_n (cm^2/Vs)	$\sigma(\mu_n)$ (cm^2/Vs)
OI Channel	194	16
Control Si	170	26

- Mean electron mobility is 14% higher in OI Channel FETs than Control Si FETs.
- Indicative that mobility gain is expected with OI layer with scaled HK/MG stack.