Peering into Moore's Crystal Ball: Transistor Scaling beyond the 15nm node

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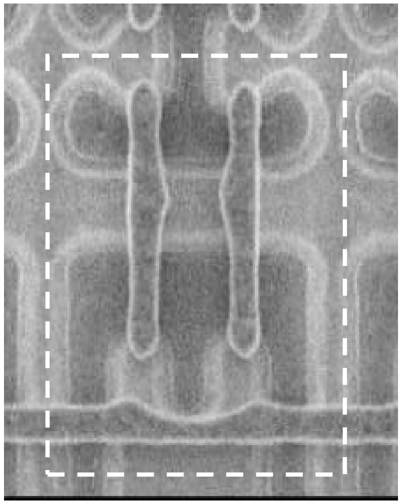
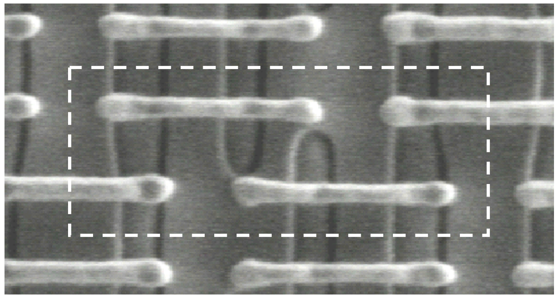
AGENDA

- Scaling
- Gate control
- Mobility
- Resistance
- Capacitance
- Summary

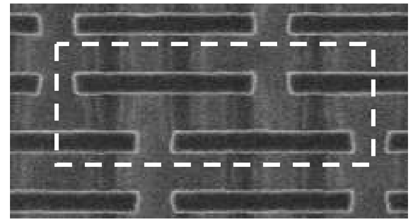
Consistent 2-year scaling



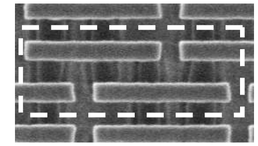
90nm – TALL
1.0 μm²



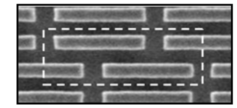
65nm – WIDE - 0.57 μm²



45nm – WIDE
0.346 μm²

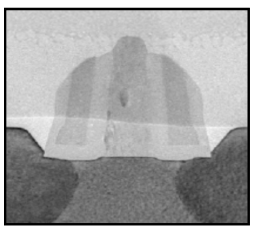
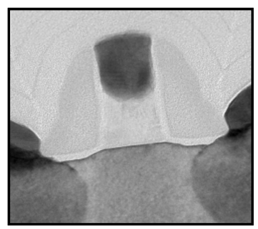
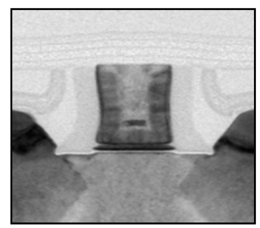
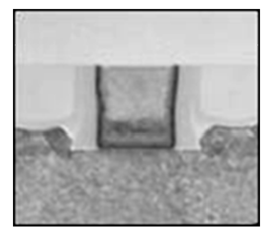


32nm – WIDE
0.171 μm²

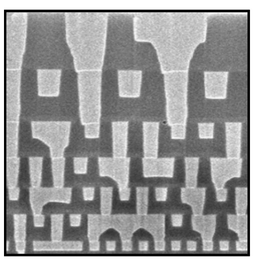
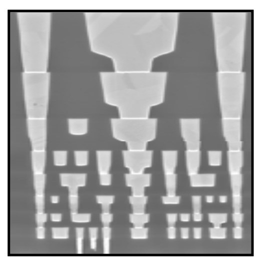


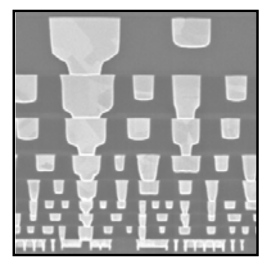
22nm – WIDE
0.092 μm²

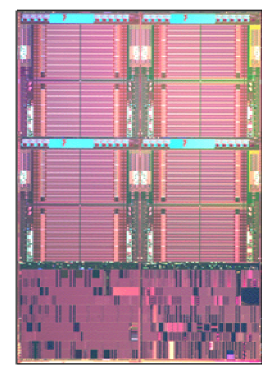
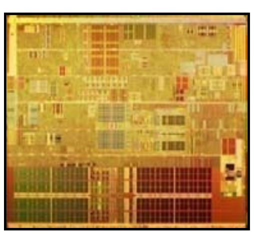
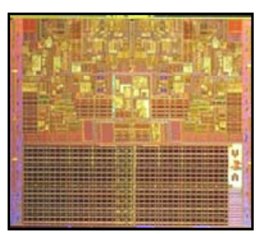
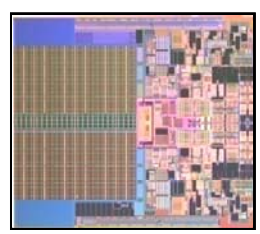
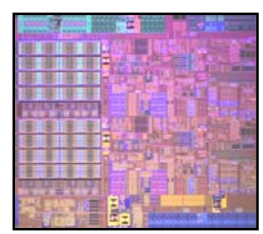
90 nm	65 nm	45 nm	32 nm	22 nm
2003	2005	2007	2009	2011 *projected*

90: 7
65: 8
45: 9
32: 9

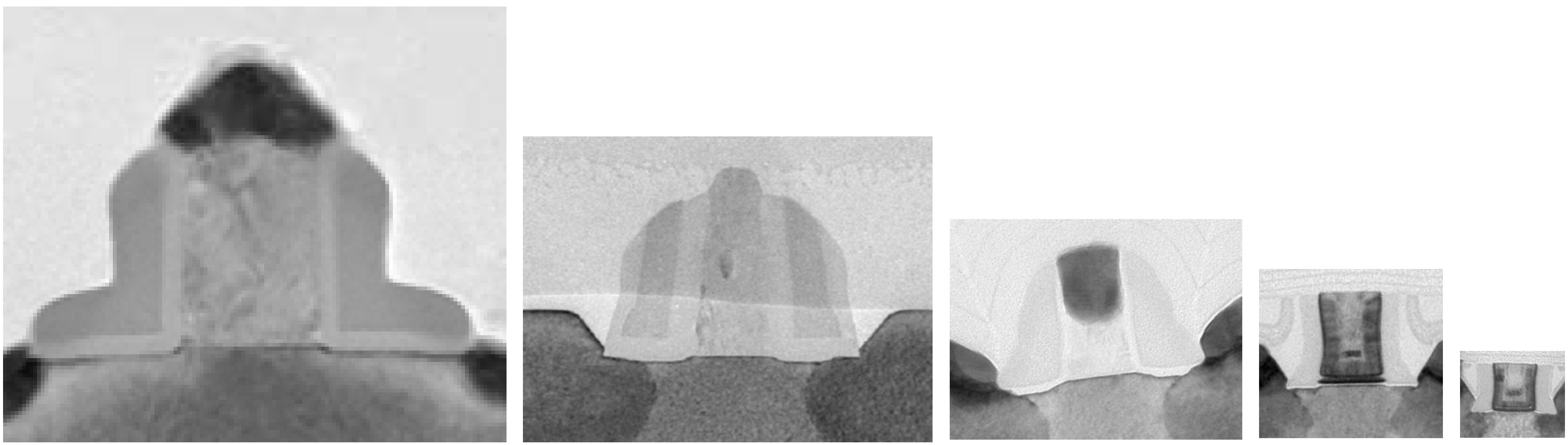





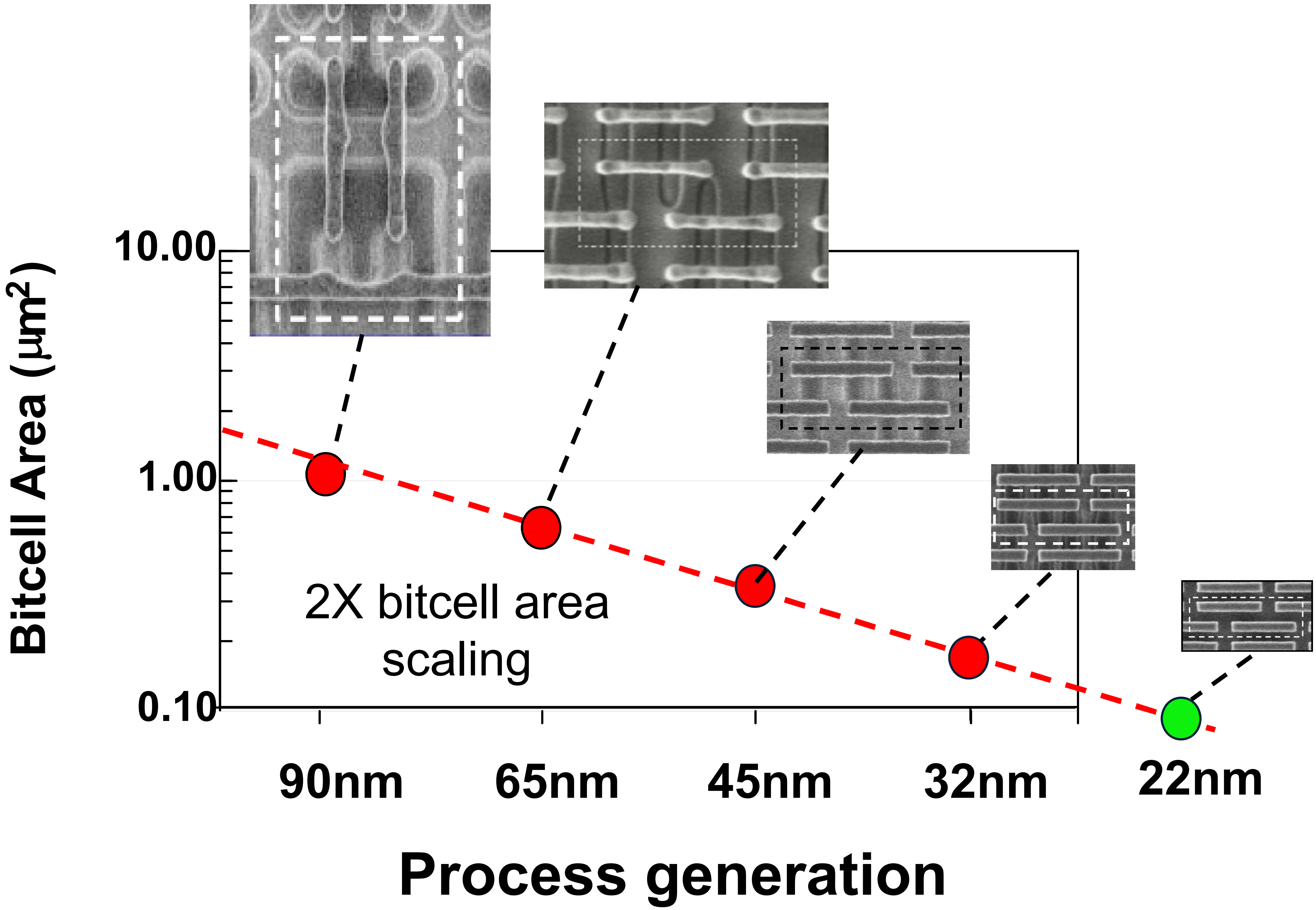
Changes in Scaling

THEN	NOW
• Scaling drove down cost	• Scaling drives down cost
• Scaling drove performance	• Materials drive performance
• Performance constrained	• Power constrained
• Active power dominates	• Standby power dominates
• Independent design-process	• Collaborative design-process



130nm 90nm 65nm 45nm 32nm

Consistent SRAM Density Scaling



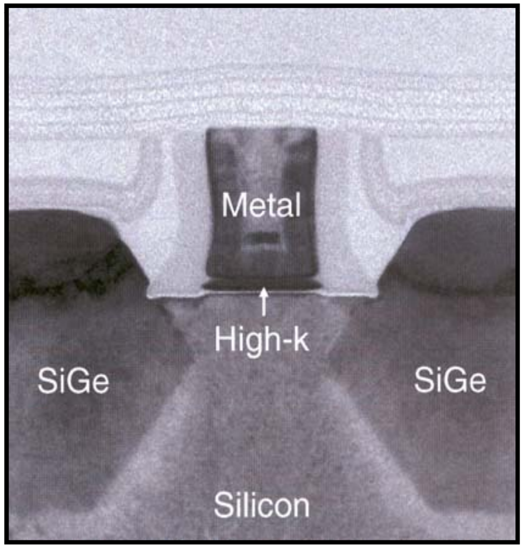
K. Zhang, ISCC, 2009; M. Bohr IDF 2010

AGENDA

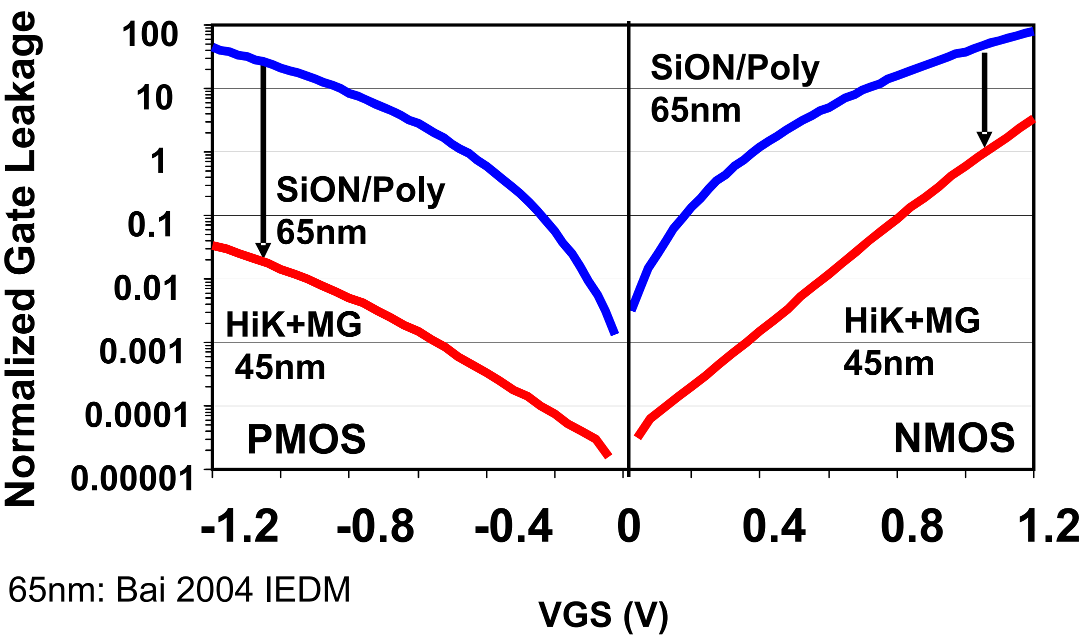
- Scaling
- Gate control
- Mobility
- Resistance
- Capacitance
- Summary

Short Channel Control: HiK-MG

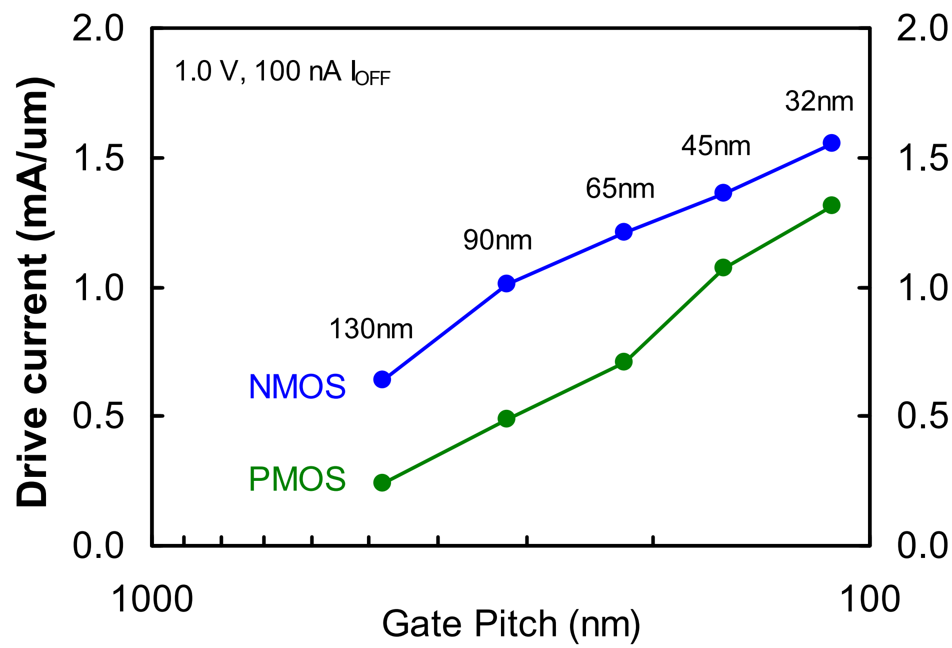
45 nm
HK+MG



High-k/MG enabled 0.7X ToxE scaling while reducing Ig >> 25X for NMOS and 1000X for PMOS

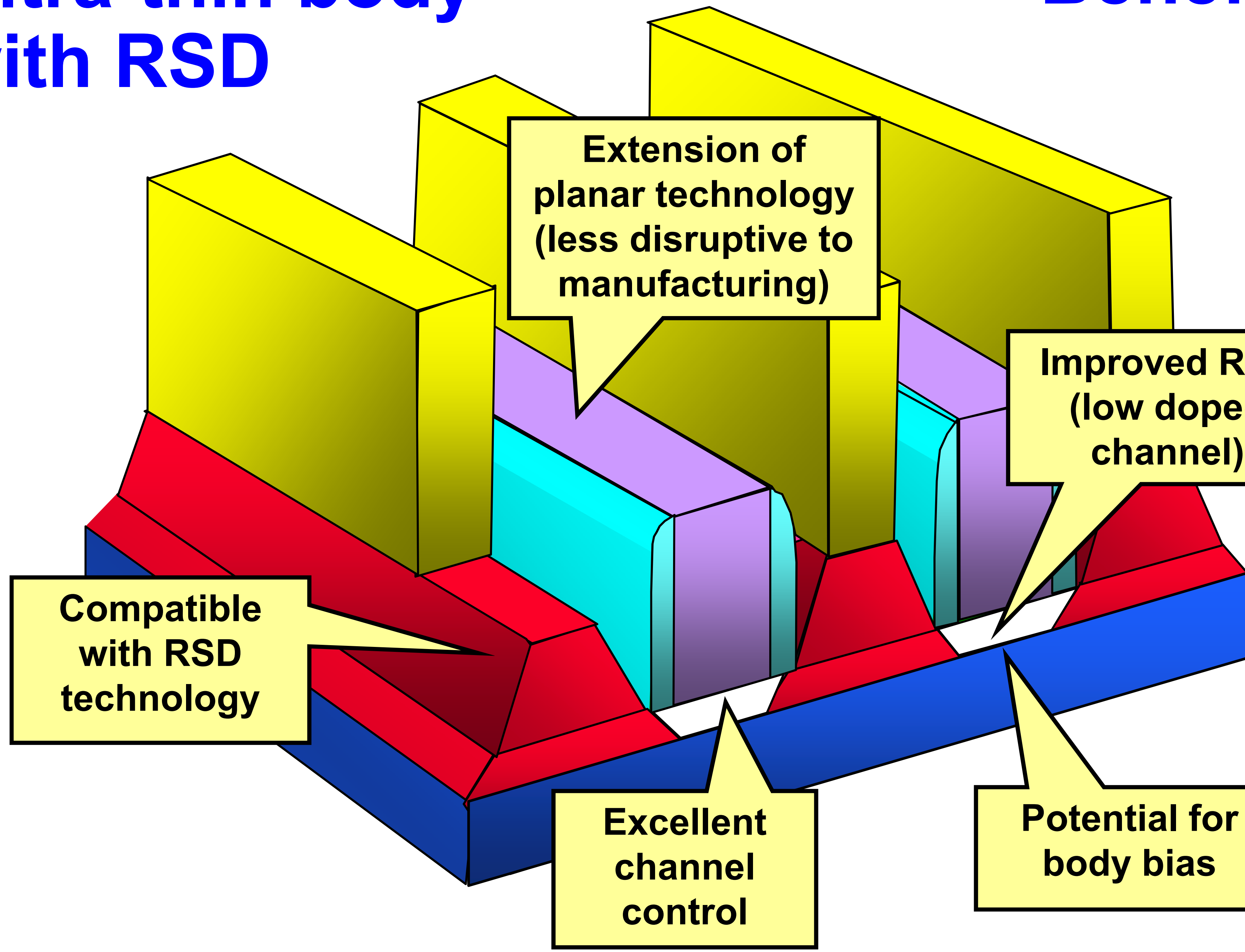


65nm: Bai 2004 IEDM



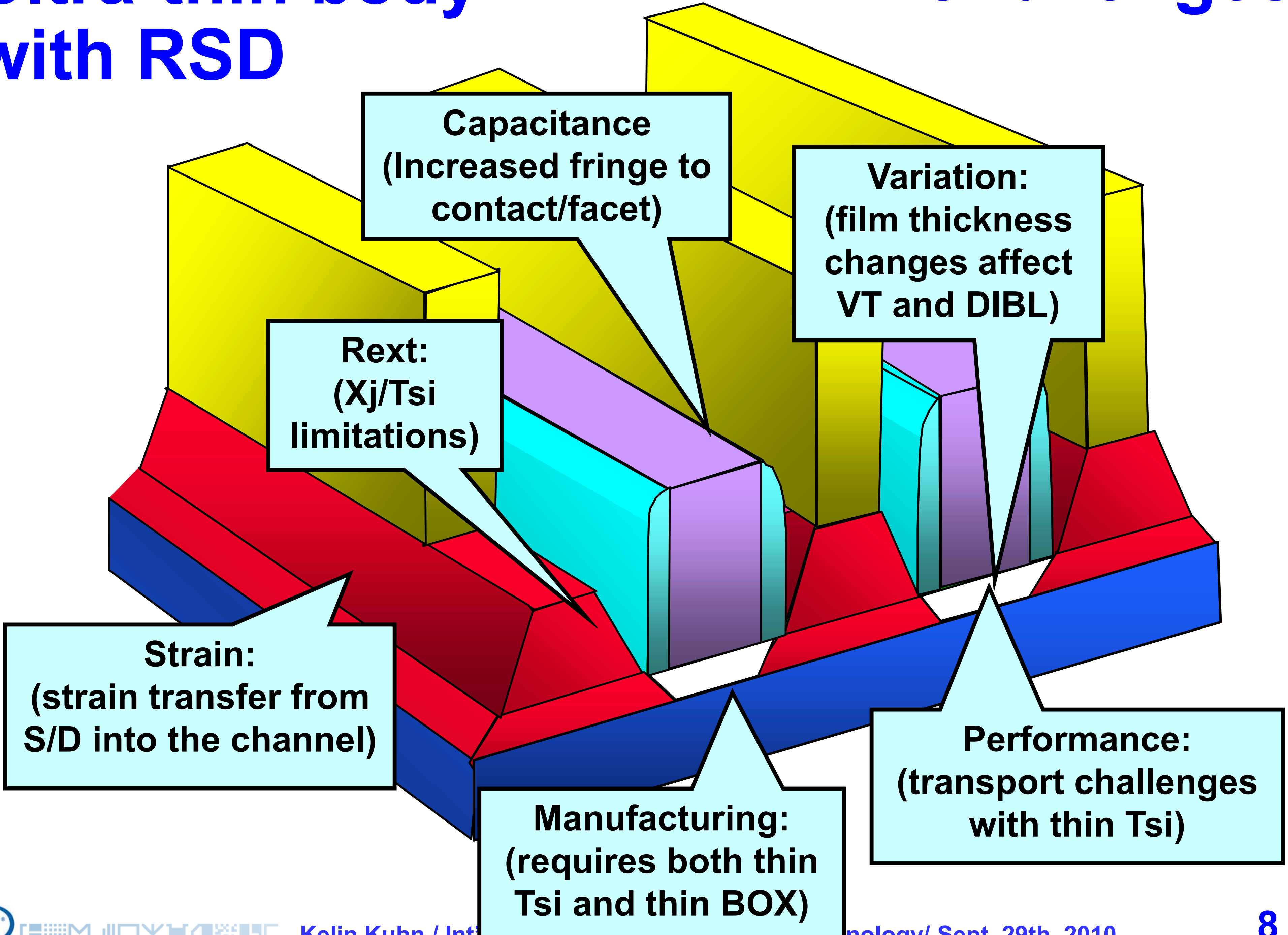
Ultra-thin body with RSD

Benefits



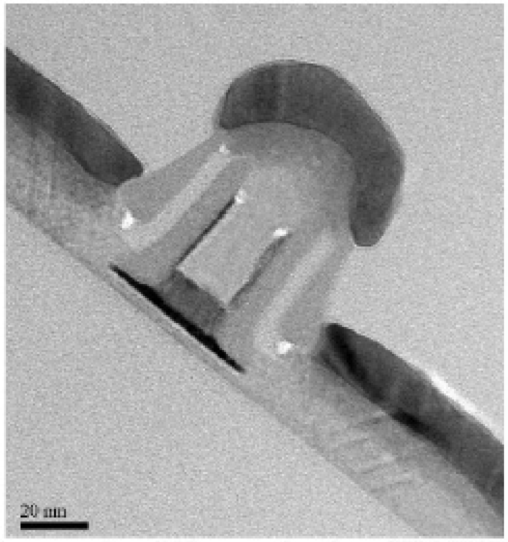
Ultra-thin body with RSD

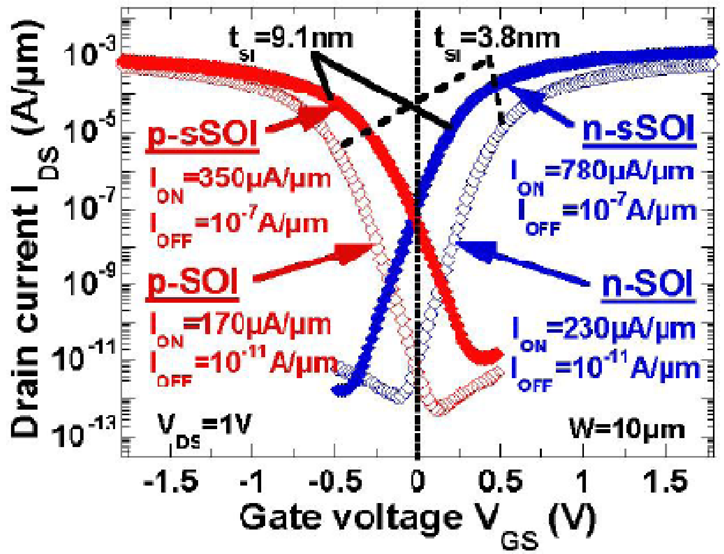
Challenges

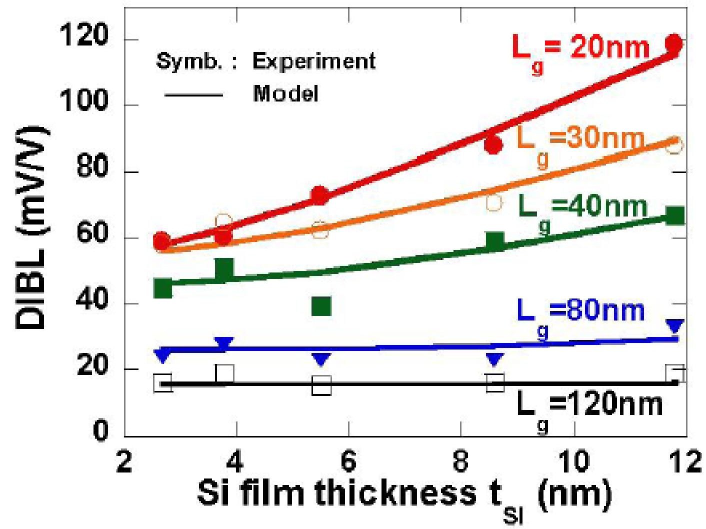


Ultra-thin body

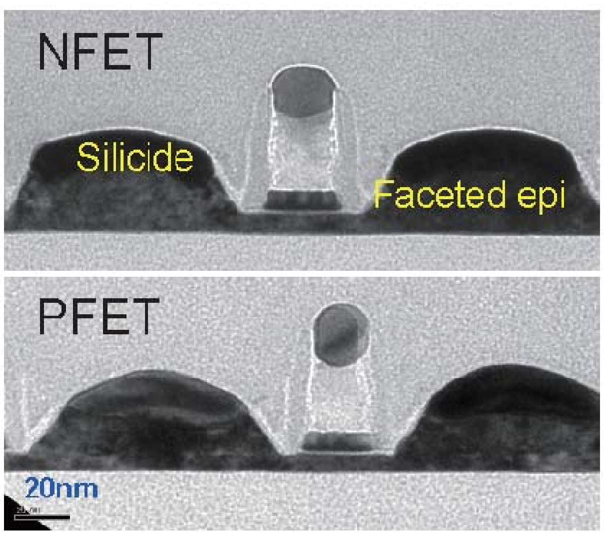
Barral – CEA-LETI / L2MP / SOITEC – IEDM 2007

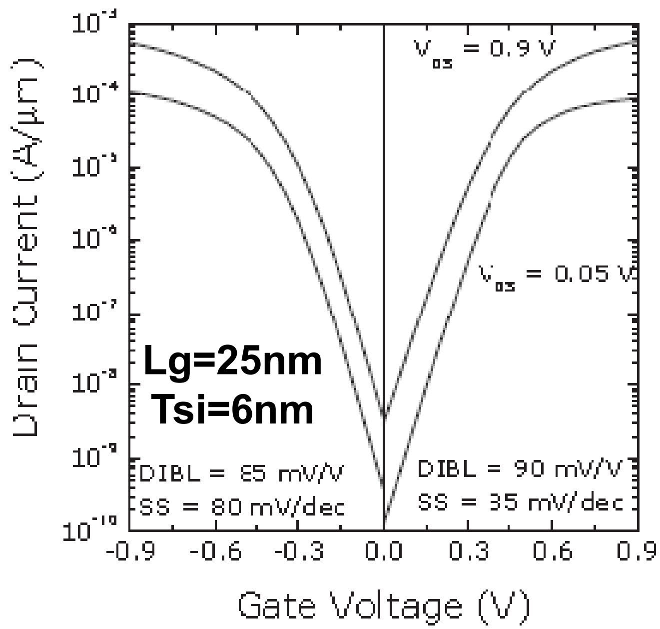


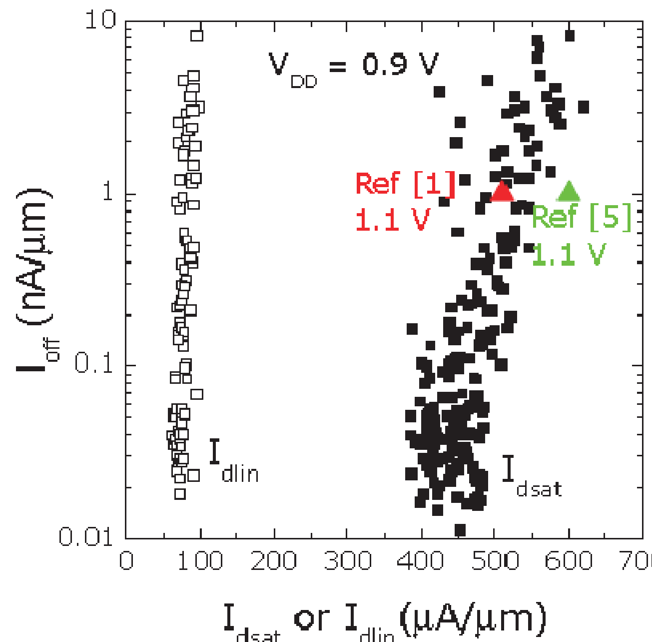




Cheng – IBM – VLSI 2009

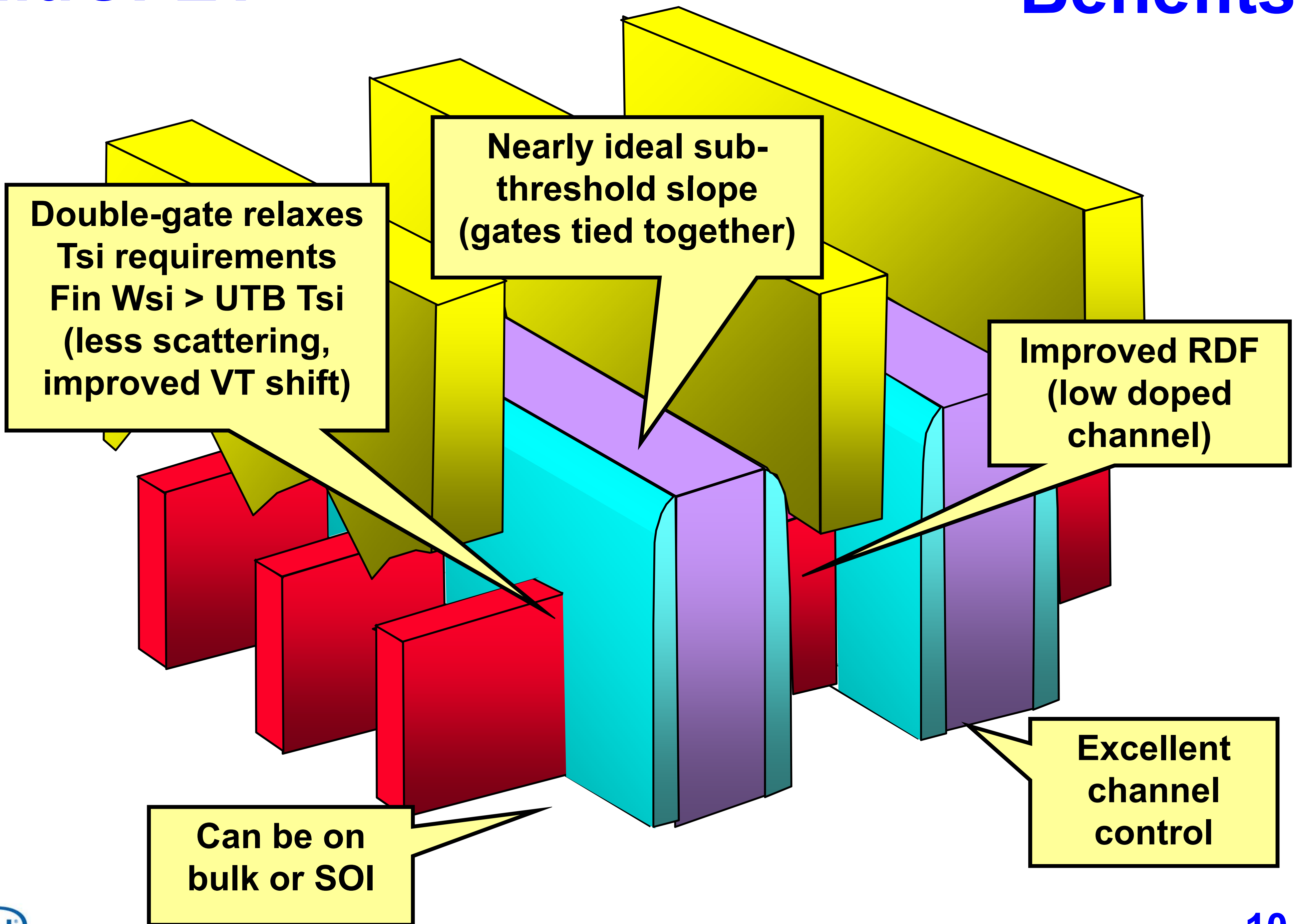






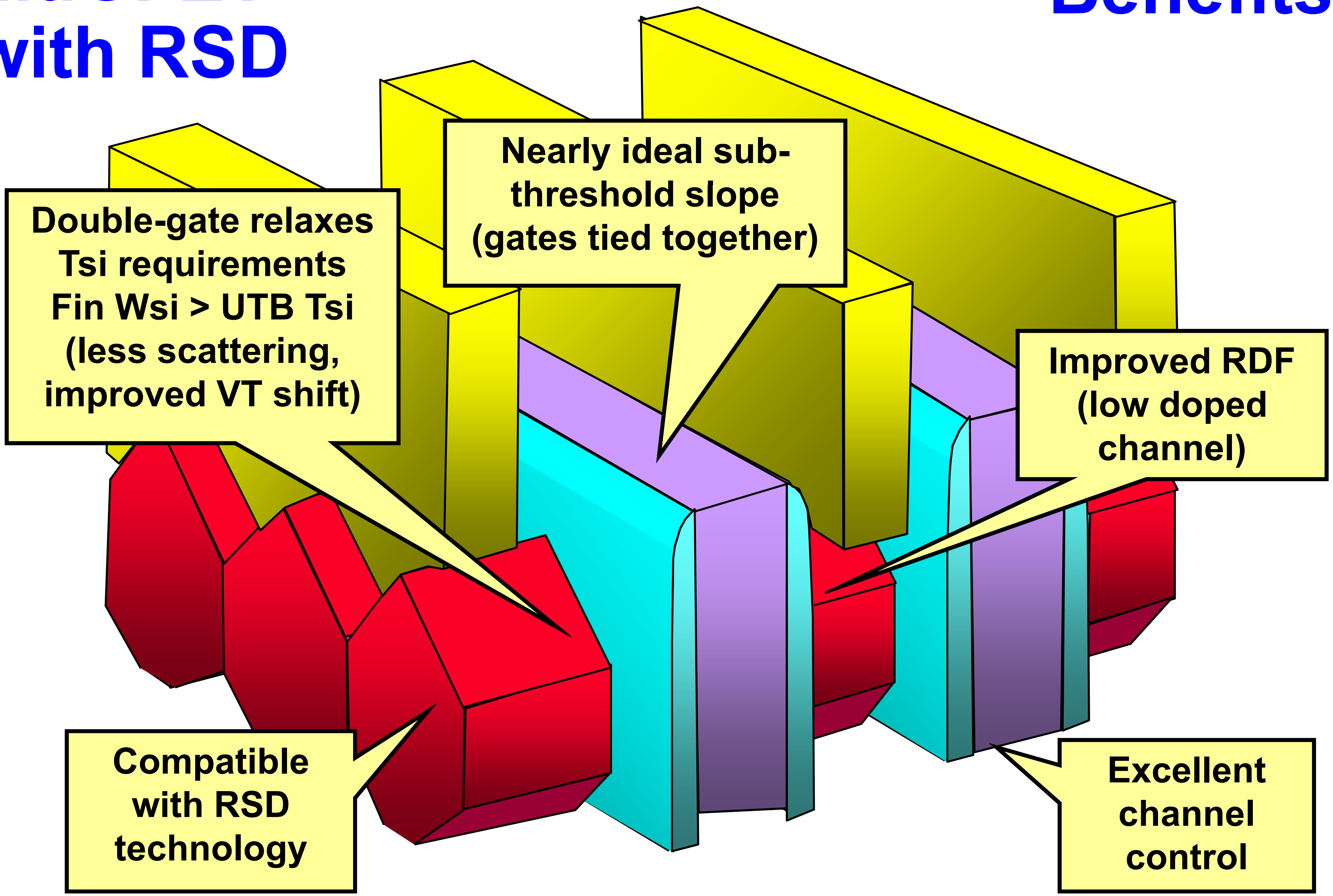
MuGFET

Benefits

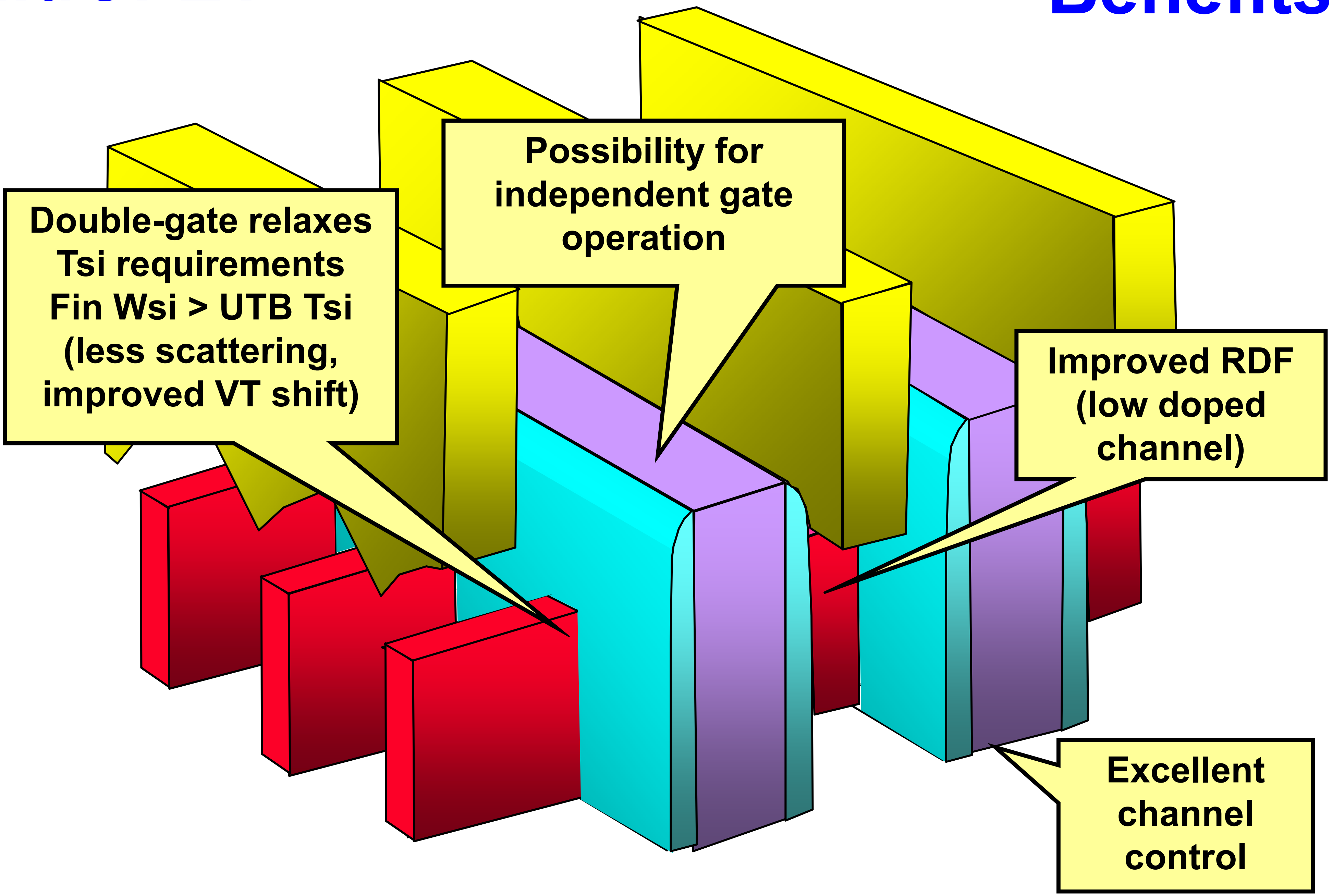


MuGFET with RSD

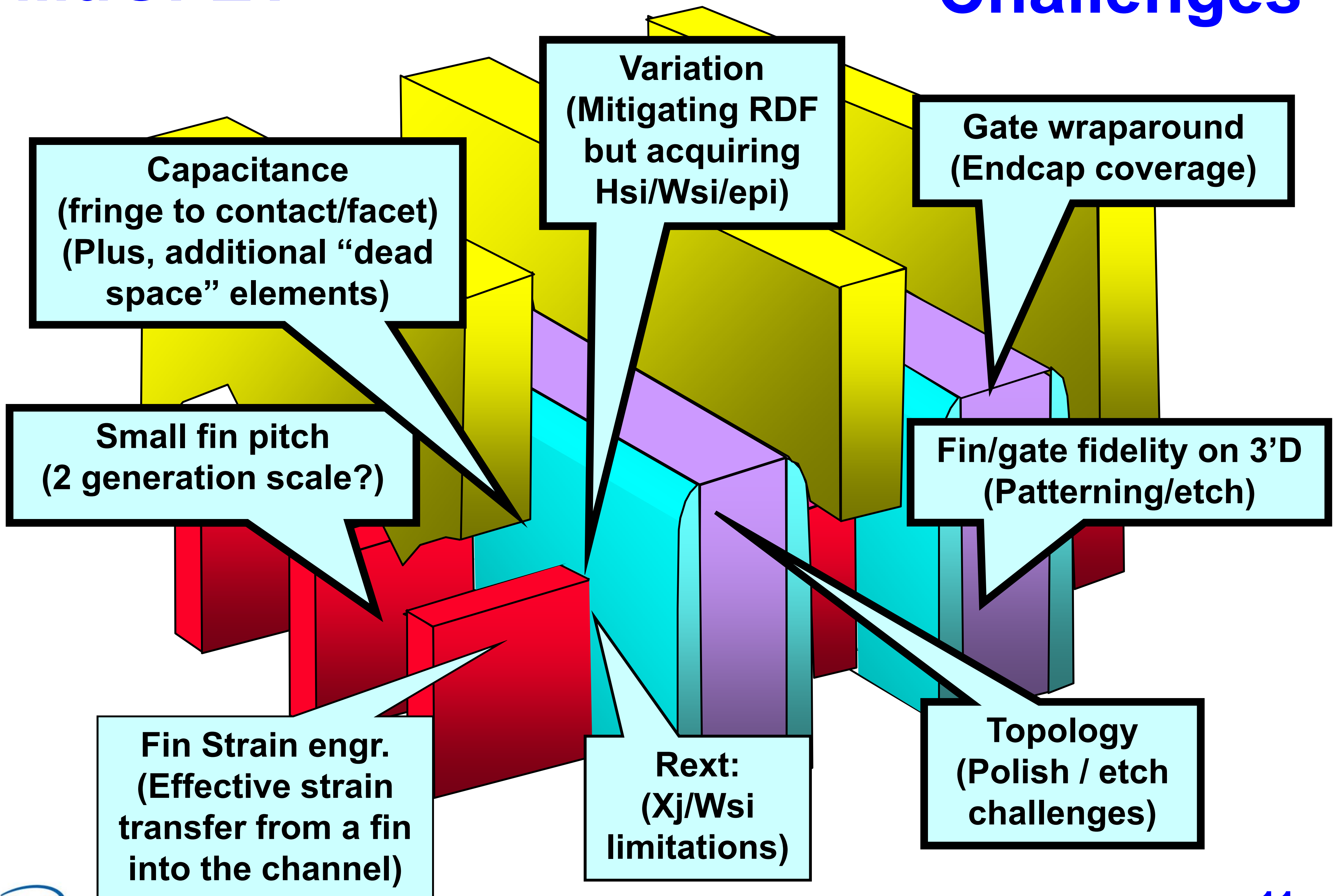
Benefits



MuGFET Benefits

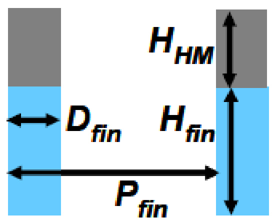


MuGFET Challenges

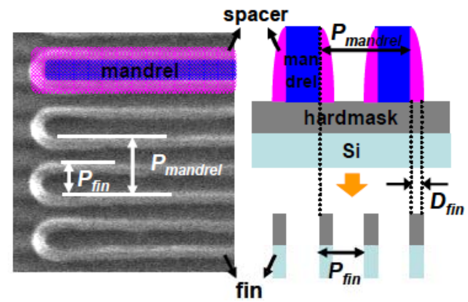


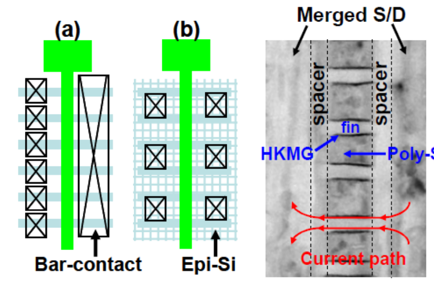
MuGFET

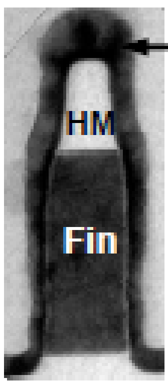
Kawasaki – Toshiba / IBM – IEDM 2009



Year of production	2015	2018	2021
node (nm)	22	16	11
P_{fin} (nm)	40	28	21
D_{fin} (nm)	12	8	6
H_{fin} (nm)	28	20	15
SRAM cell size (μm^2)	0.063	0.03	0.015
L_g at cell (nm)	24	16	12

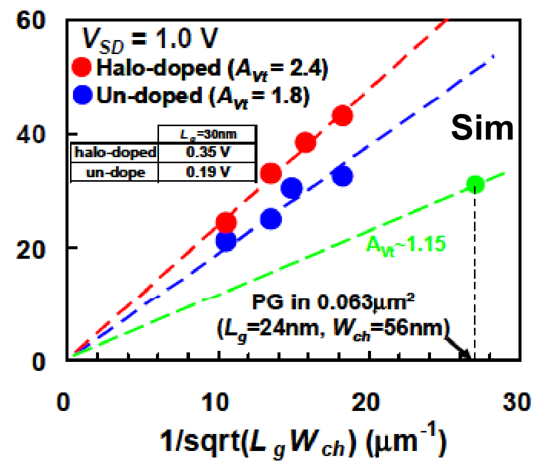


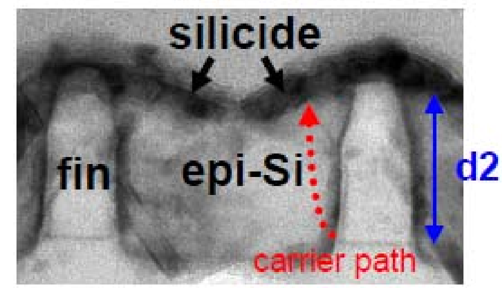




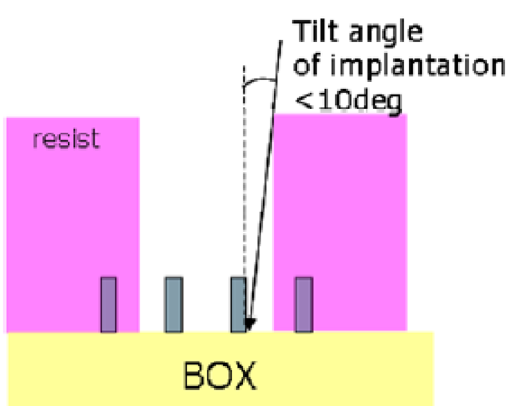
The thickness of HKMG should be uniform along fin height.

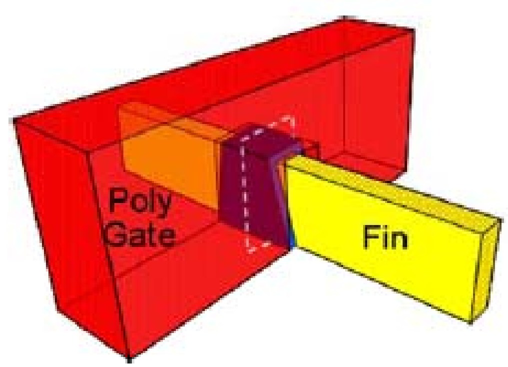
source of σV_t	origin
T_{ox} variation	non-uniform thickness of HK
ε_{ox} variation	non-uniform composition of HK
WF avriation	non-uniformity of MG
	grain size variation
	multi-surface oritations
charges	traps and states

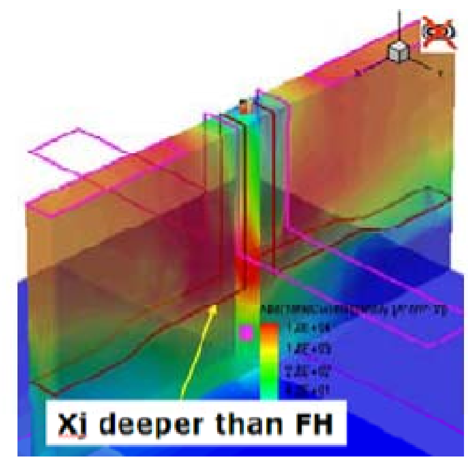




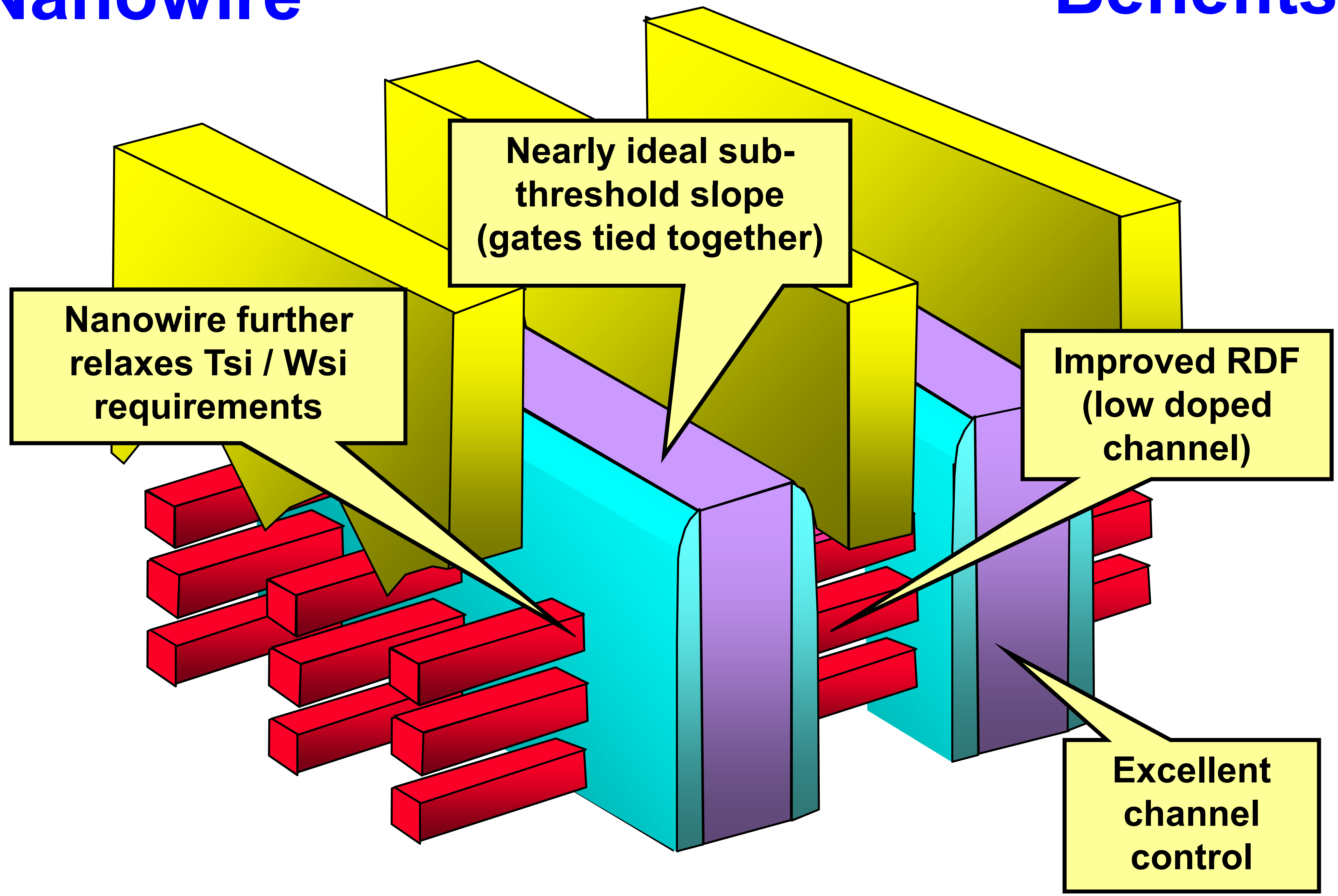
Jurczak – IMEC - SOI 2009



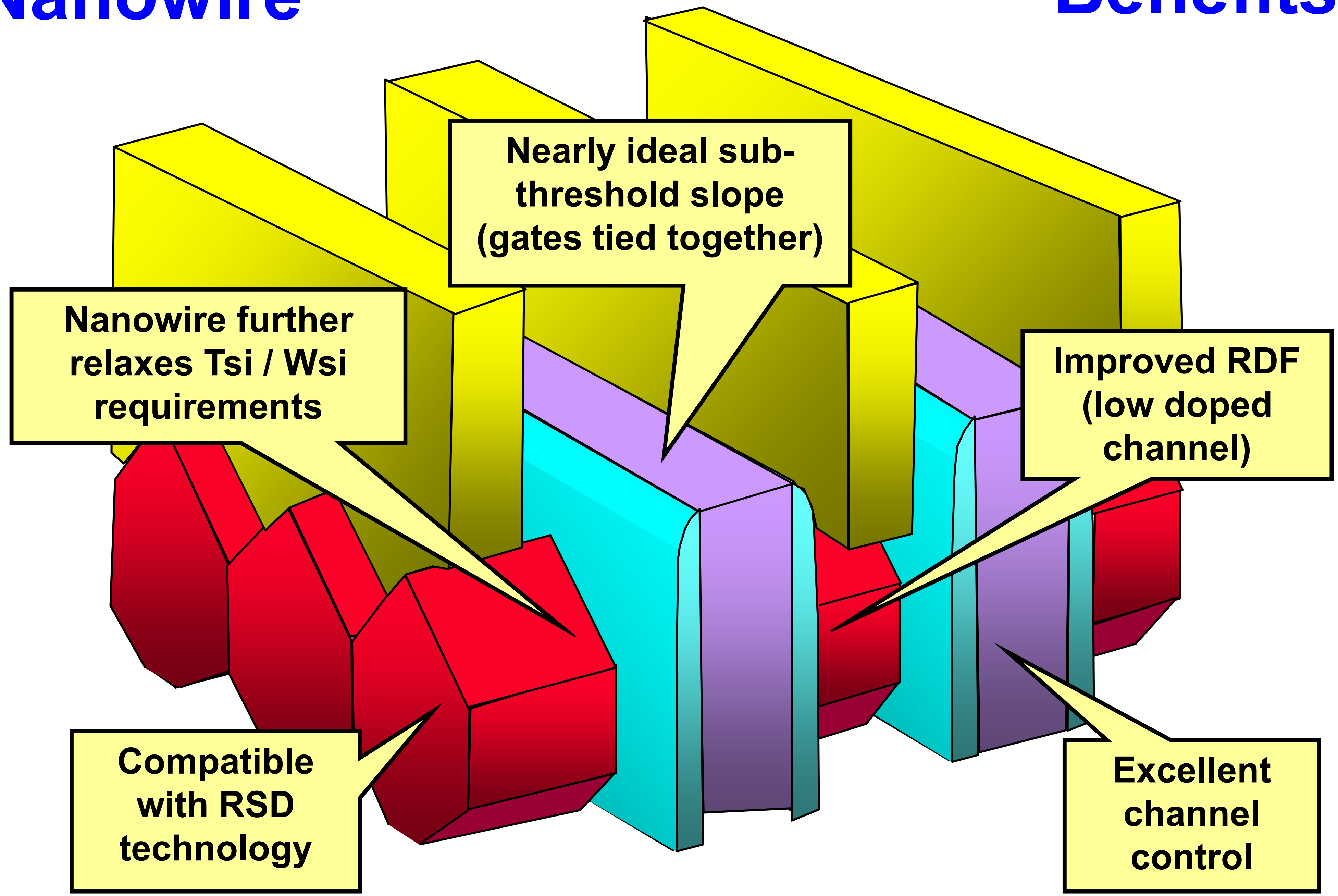




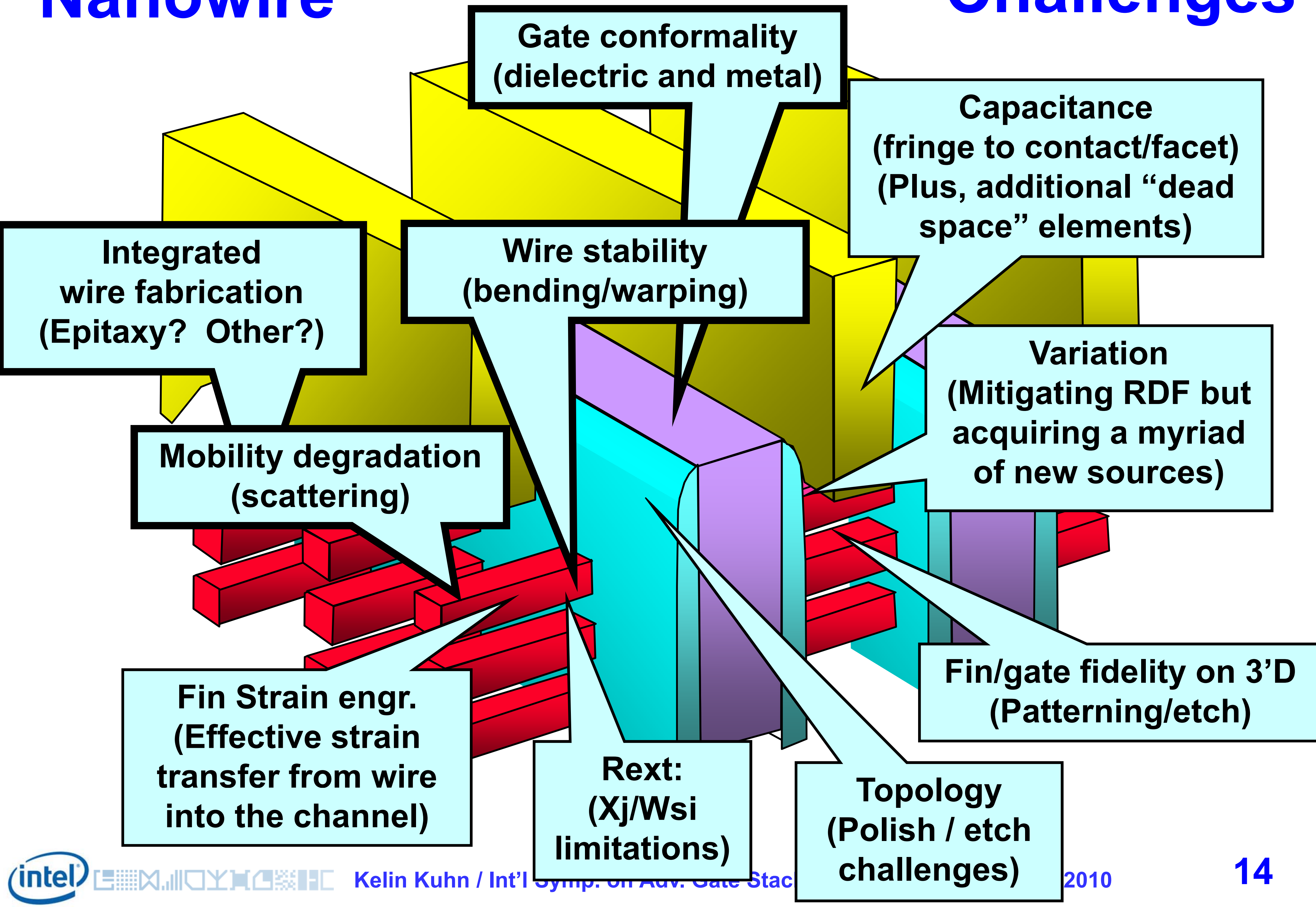
Nanowire Benefits



Nanowire Benefits

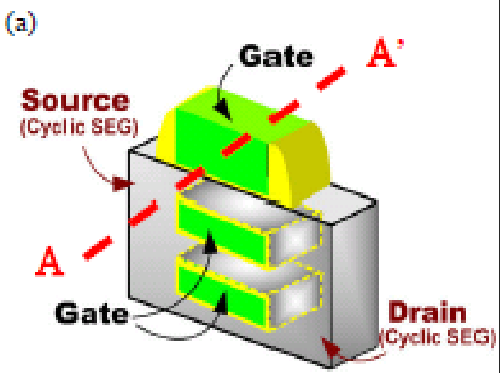


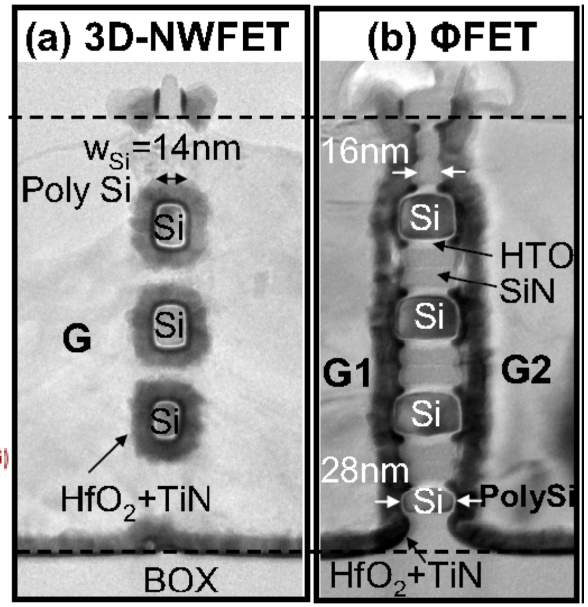
Nanowire Challenges

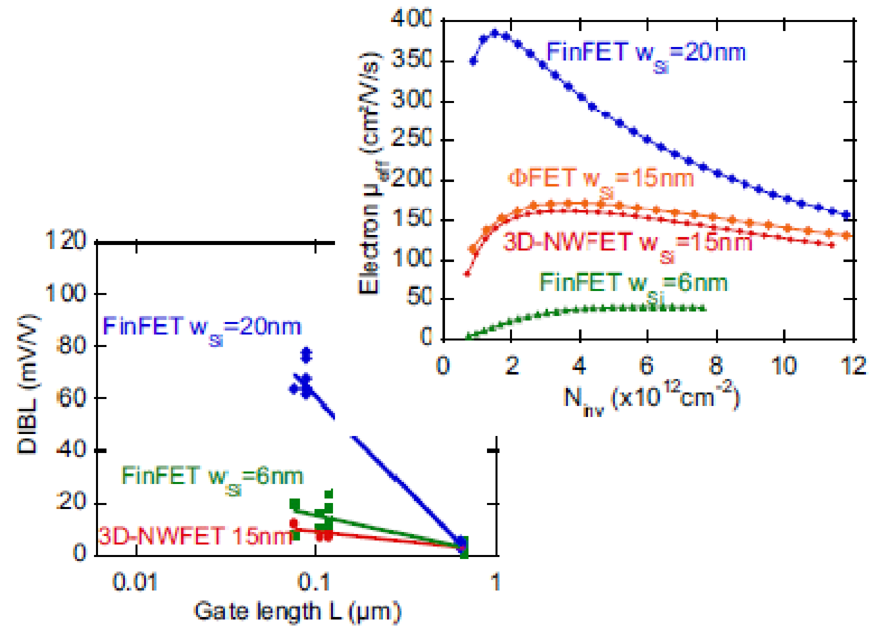


Nanowire FETs

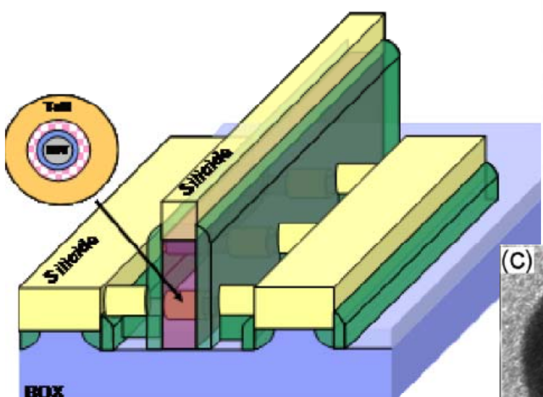
Dupre – CEA-LETI – IEDM 2008

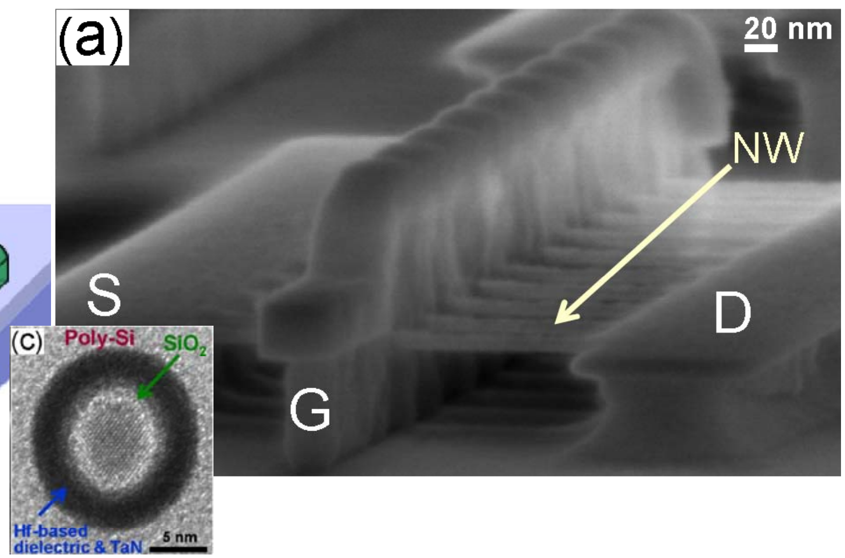


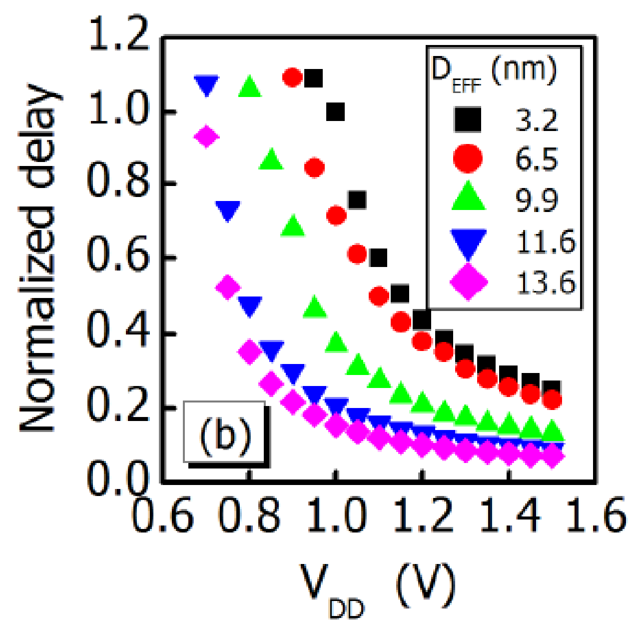




Bangsaruntip – IBM – IEDM 2009

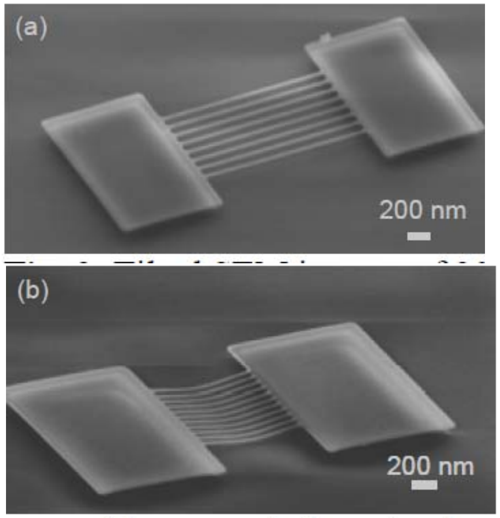


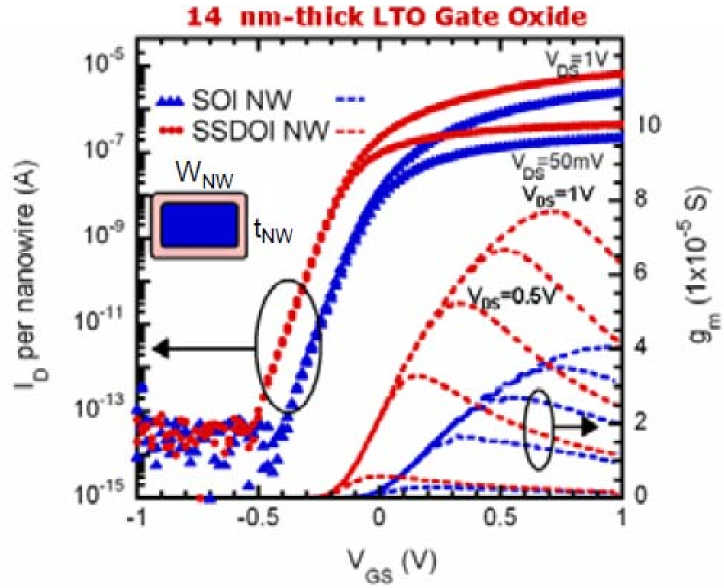


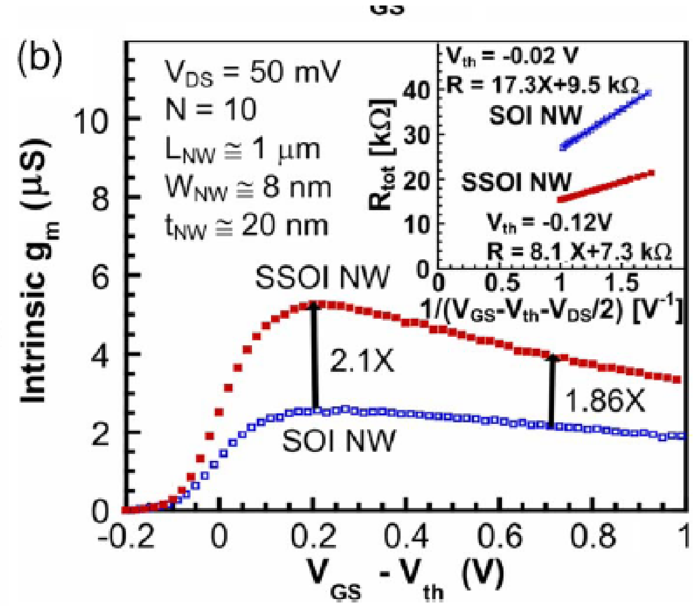


Nanowire FETs

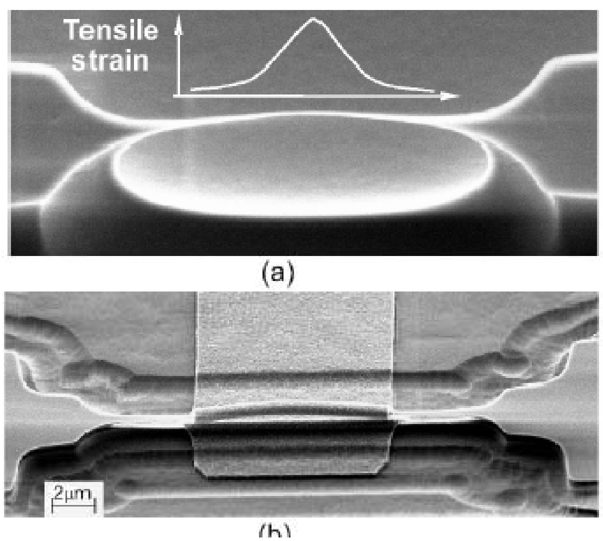
Hashemi/Hoyt – MIT
IEDM 2008 EDL/ESSDRC 2009

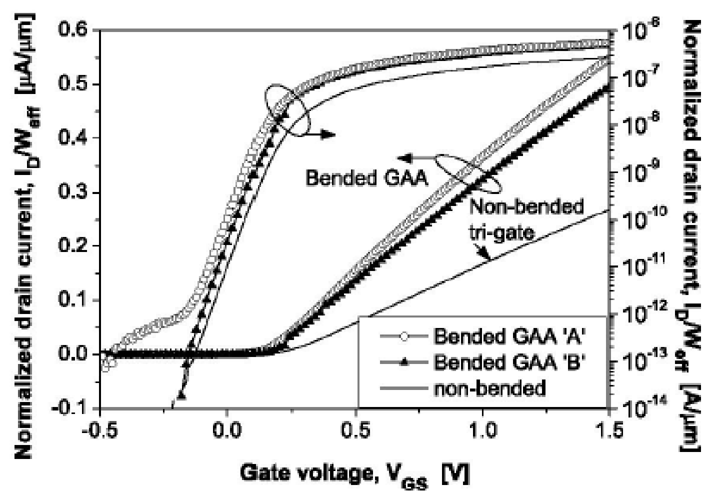


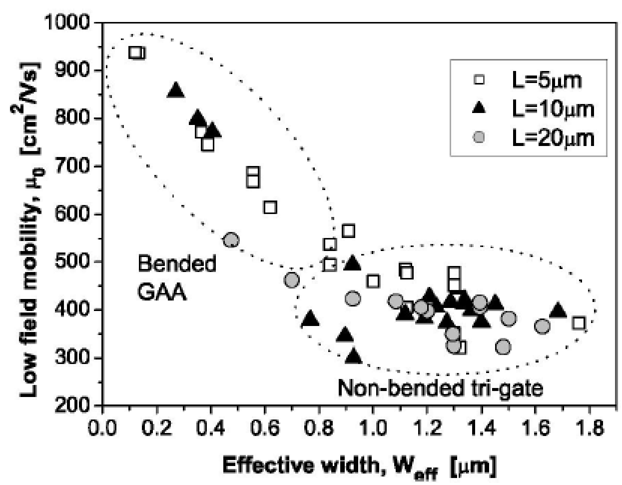




Moselund – Ecole Polytechnique, Switzerland
IEDM 2007

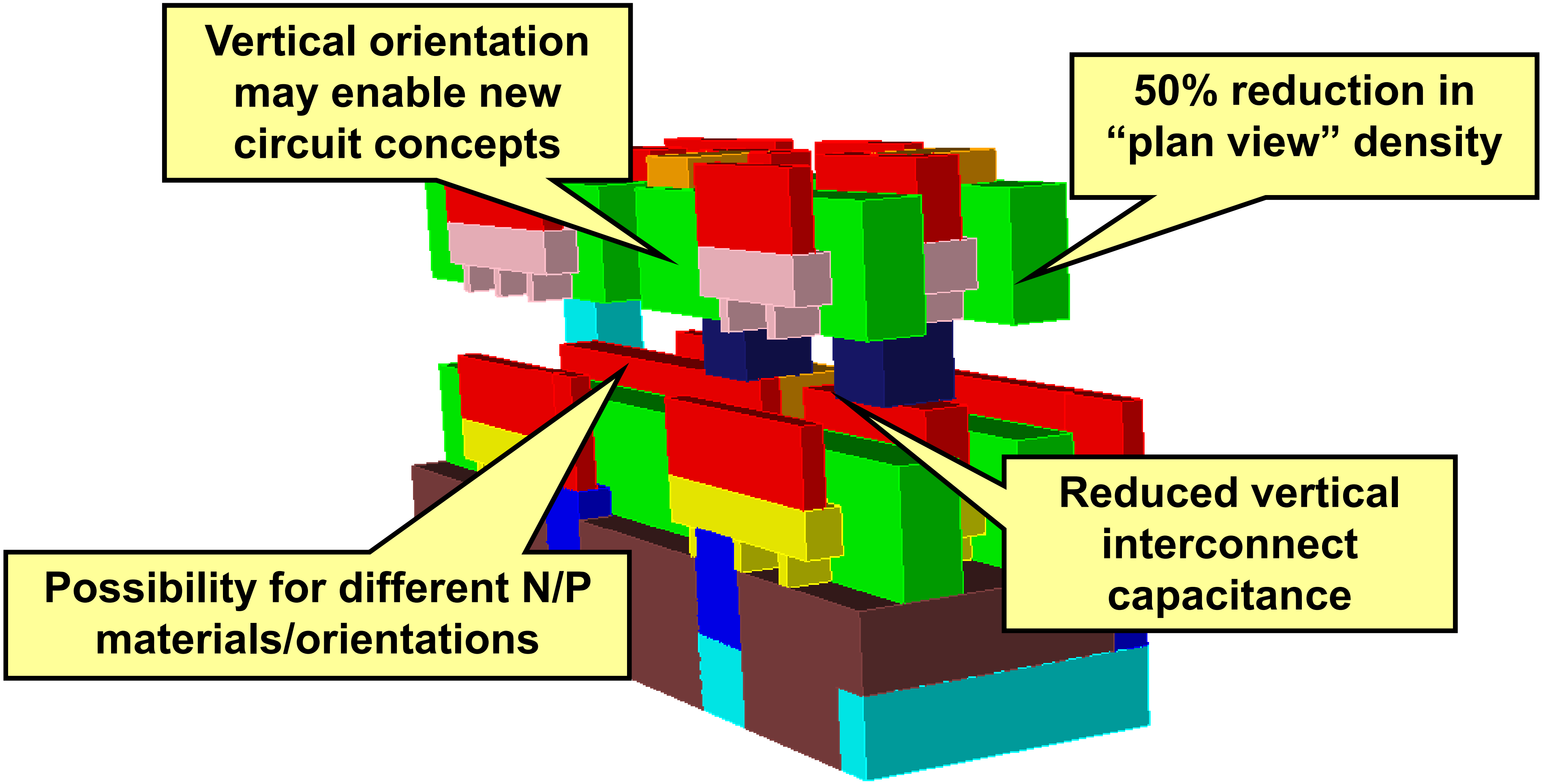






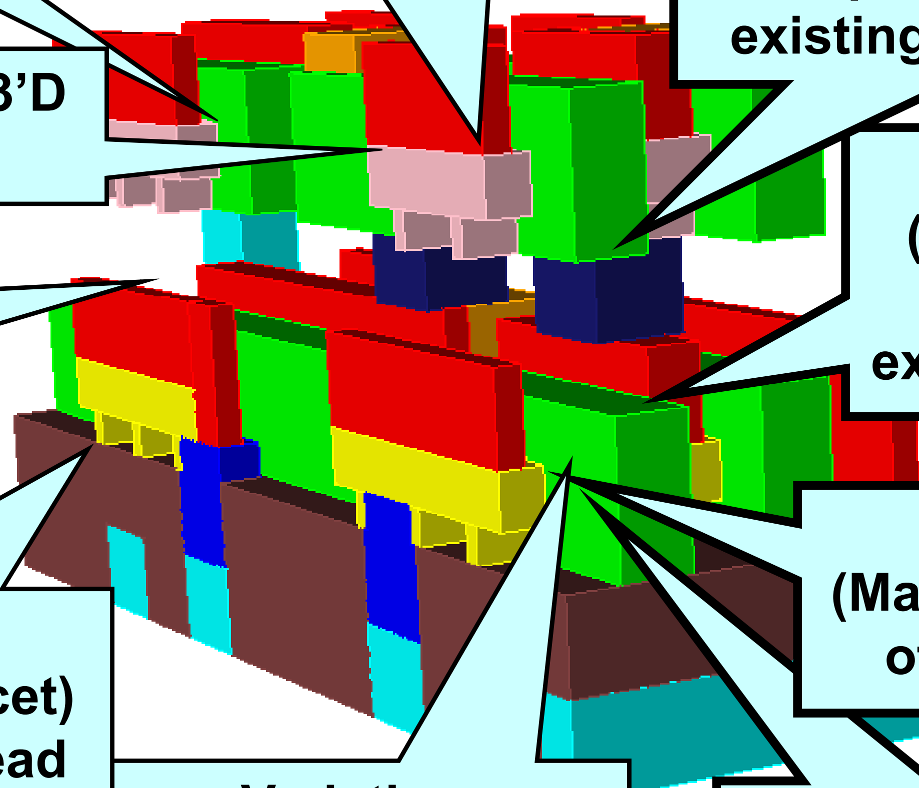
Vertical Architectures

Benefits



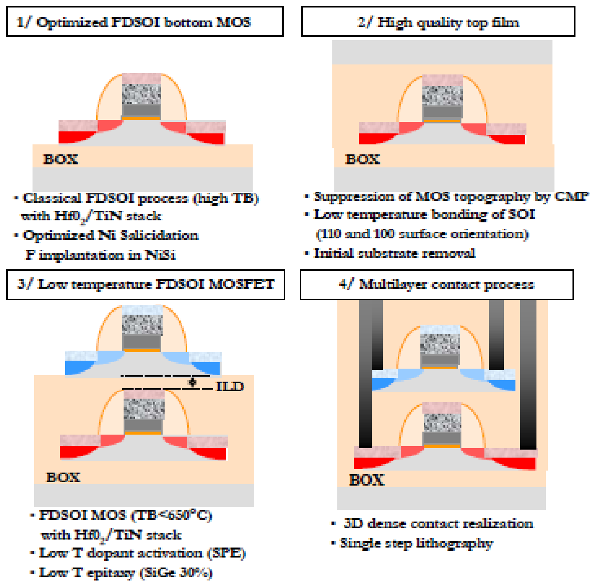
Vertical Architectures

Challenges



Vertical

Batude – CEA LETI - IEDM 2009 – stacked 110/100



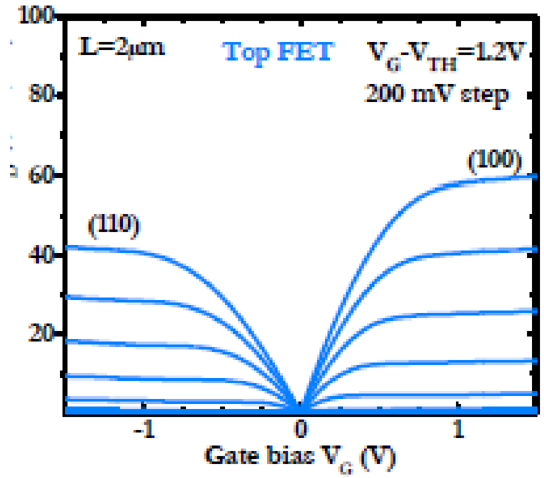


Fig.15: I_D-V_D characteristics of top FET

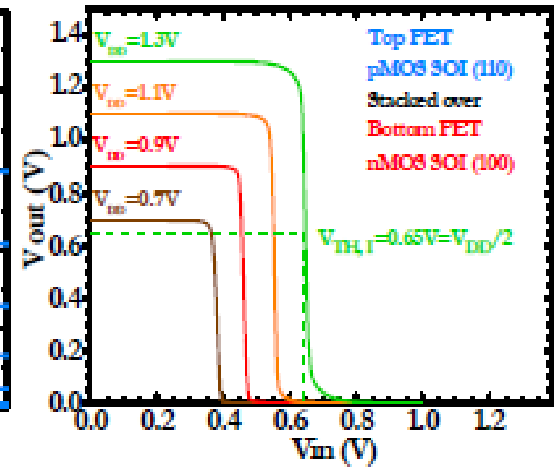
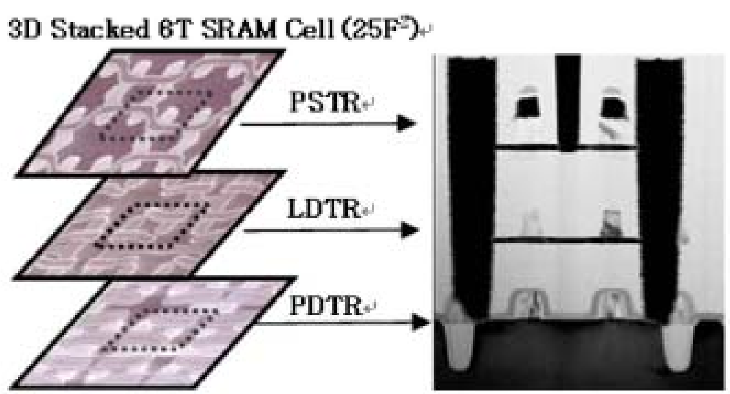
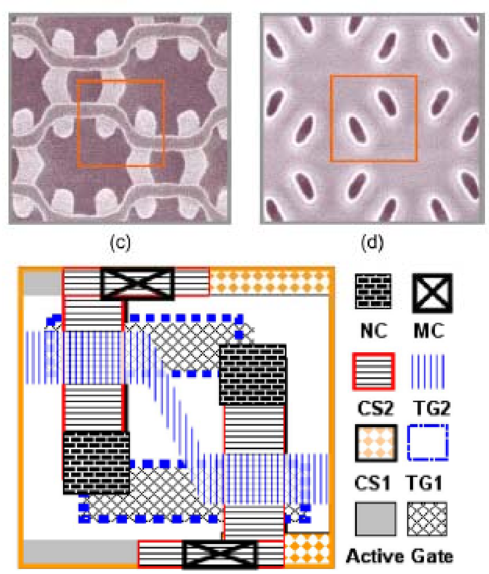
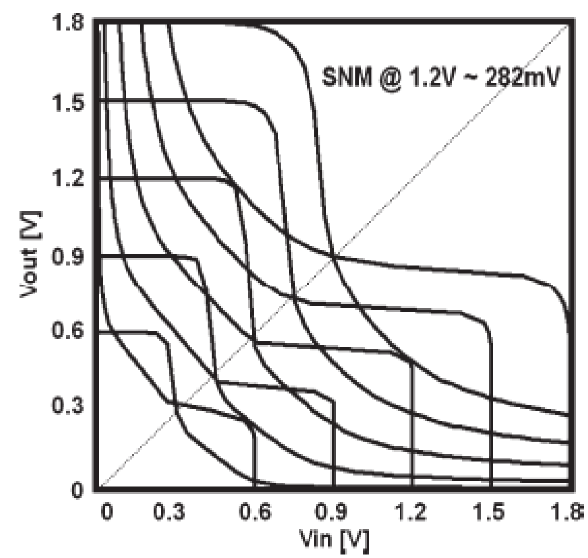


Fig.16:Transfer Voltage characteristic of an inverter: top SOI (110) pFET and bottom SOI (100) nFET

Jung – Samsung - IEEE TED 2010 – 3'D stacked 6T







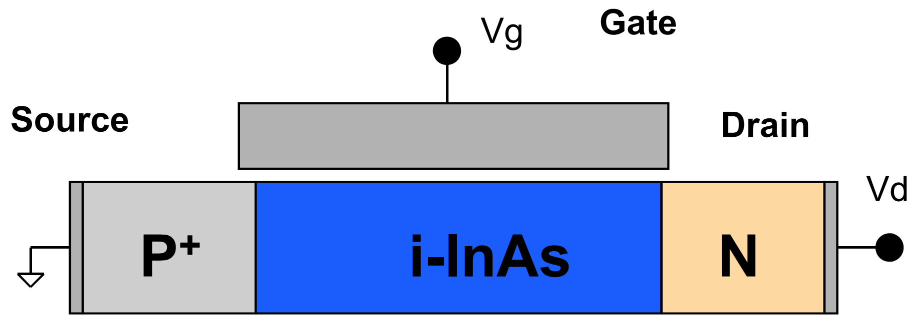
TFET (Tunneling Field-Effect Transistor)

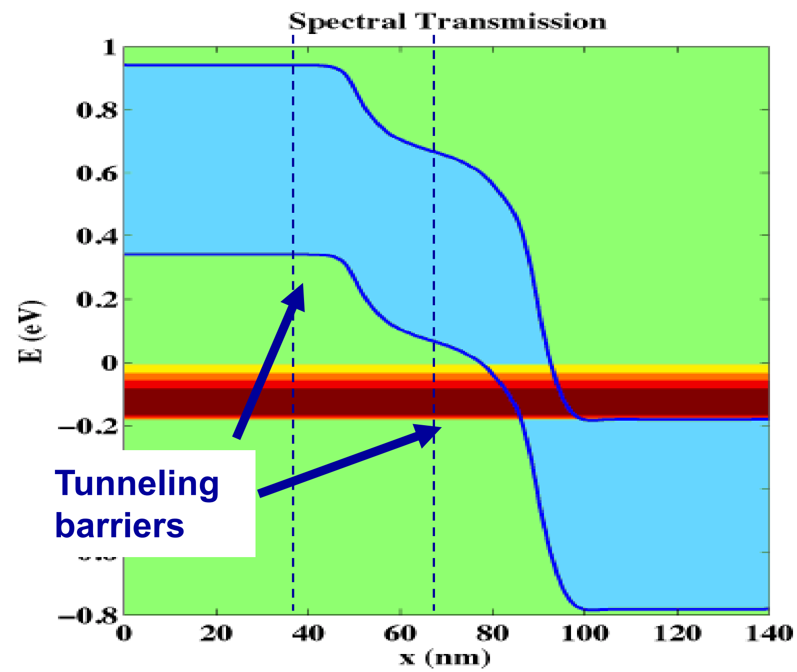
Principle of operation
- Band-to-band- tunneling through source barrier, modulated by gate field

Advantages
- Steep (< 60 mV/dec) sub-threshold slope
- Large Ion/Ioff ratio

Disadvantages
- Low drive currents
- Ambipolar conduction
- Unidirectional conduction
- Potentially high hot-e^- effects

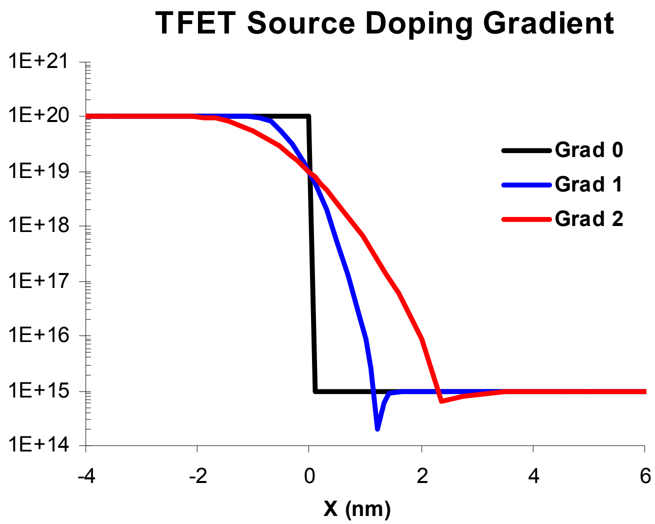
Technology Intercept
- Unlikely candidate for Si, Ge, or $Si_{1-x}Ge_x$ systems (drive currents too low)
- Probably needs III-V band-gap engineering, perhaps with “broken-gap”

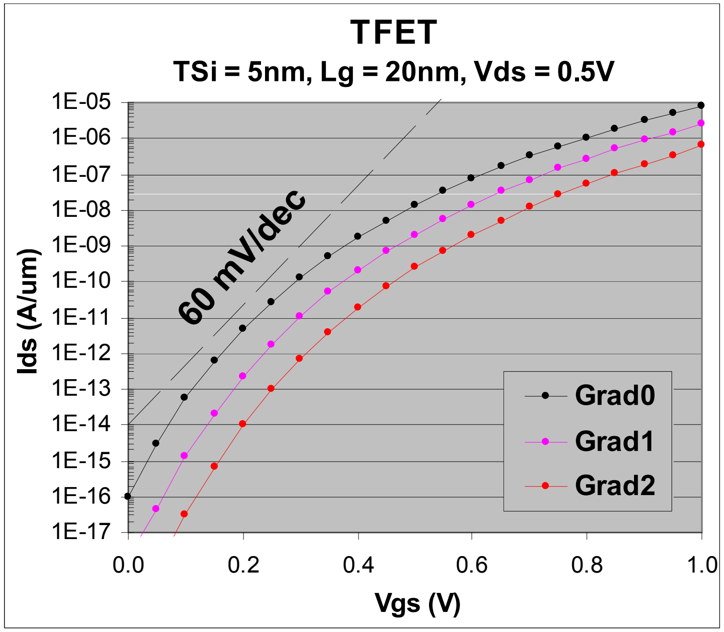




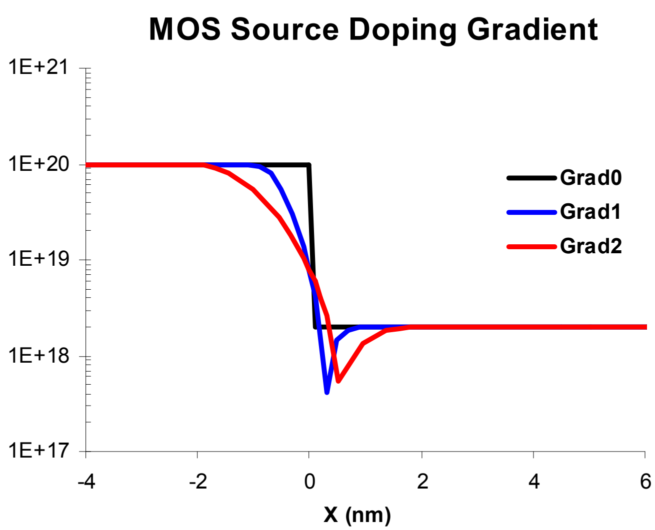
Courtsey M. Luisier (Purdue)
M. Luisier and G. Klimeck, EDL, 2009

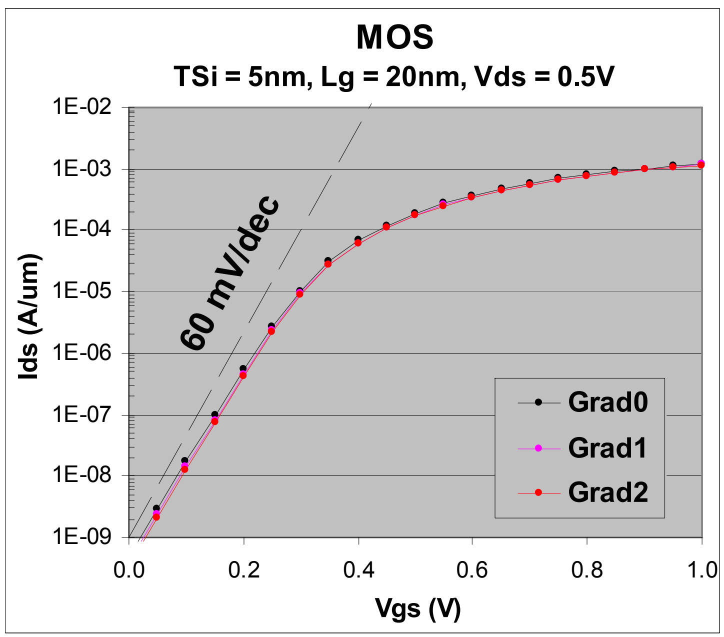
Sensitivity to Source Doping Variation





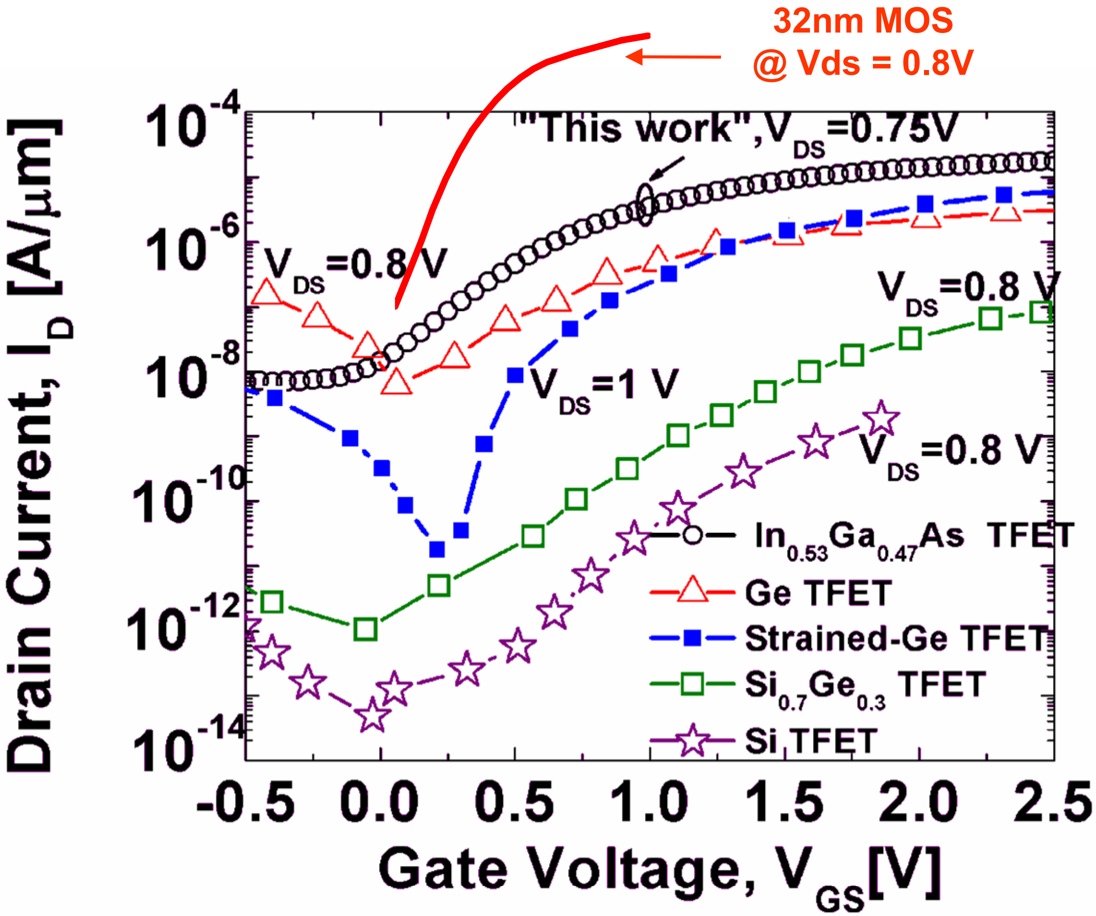
TFET behavior is very sensitive to the source doping "shape"





MOS behavior has little sensitive to the source doping "shape"

Best Demonstrated TFETs



S. Mookerjea et al., IEDM '09

- Still MUCH lower drive currents than conventional MOS
- Require band-gap engineering with hetero-junction δ layers
- Sub-threshold slope still poor

	Ref. [2]	Ref. [3]	Ref. [4]	[1]
SS (mV/dec)	52.8	42	~300	46
I_{ON} (μA/μm)	12.1	0.01	1E-4	1.2
I_{ON}/I_{OFF}	1E4	1E4	1E2	7E7

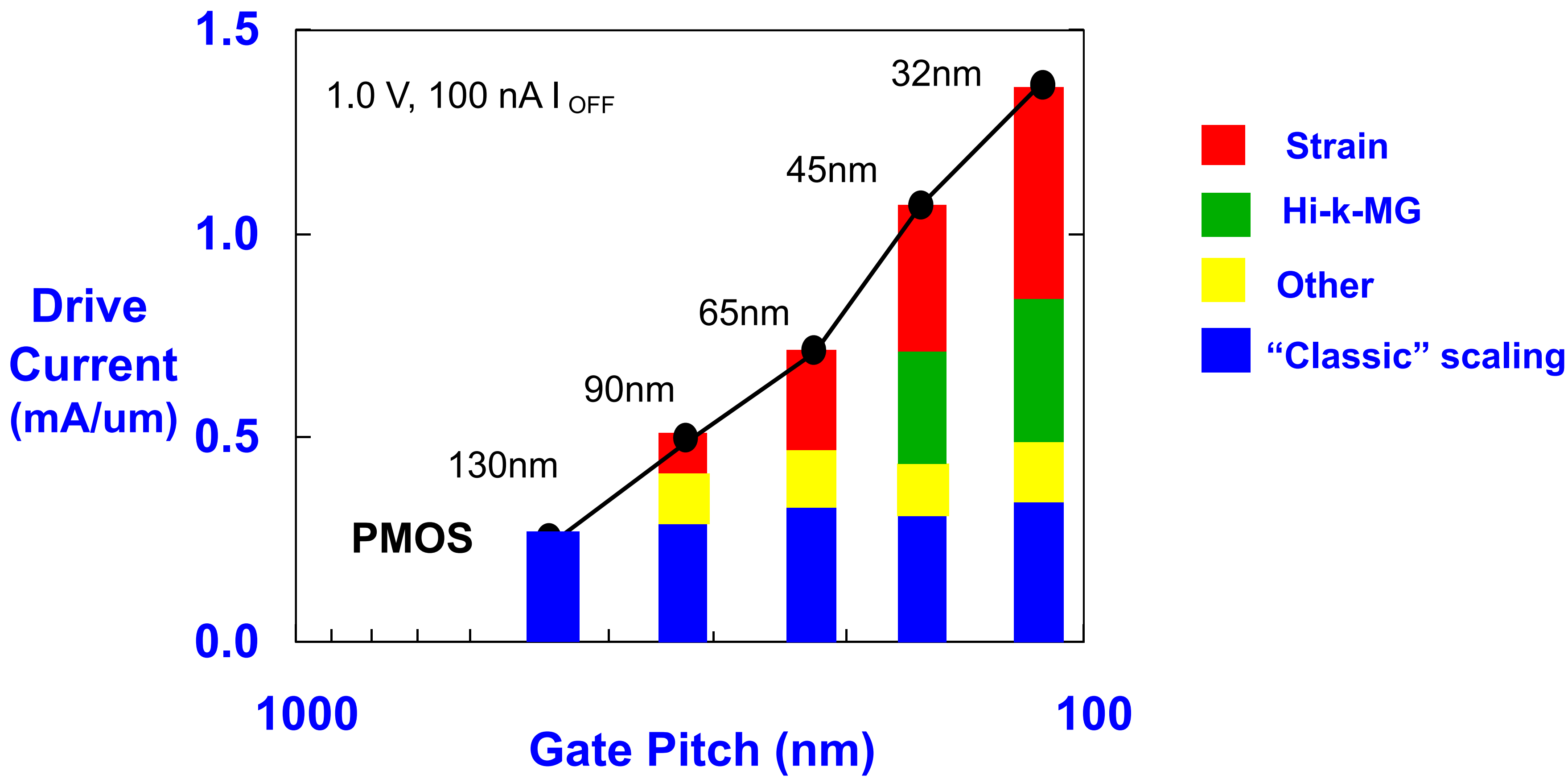
Table. I. Comparison to reported silicon TFETs. ($V_{DS}=V_{GS}-V_{BTBT}=1.0V$)

[1] K. Jeon, et al., VLSI (11.4.1.-1) 2010
[2] W. Choi et al., IEEE-EDL vol.28, no.8, p.743 (2007)
[3] F. Mayer et al., IEDM Tech Dig., p.163 (2008)
[4] T. Krishnamohan et al., IEDM Tech Dig., p.947 (2008)

AGENDA

- Scaling
- Gate control
- Mobility
- Resistance
- Capacitance
- Summary

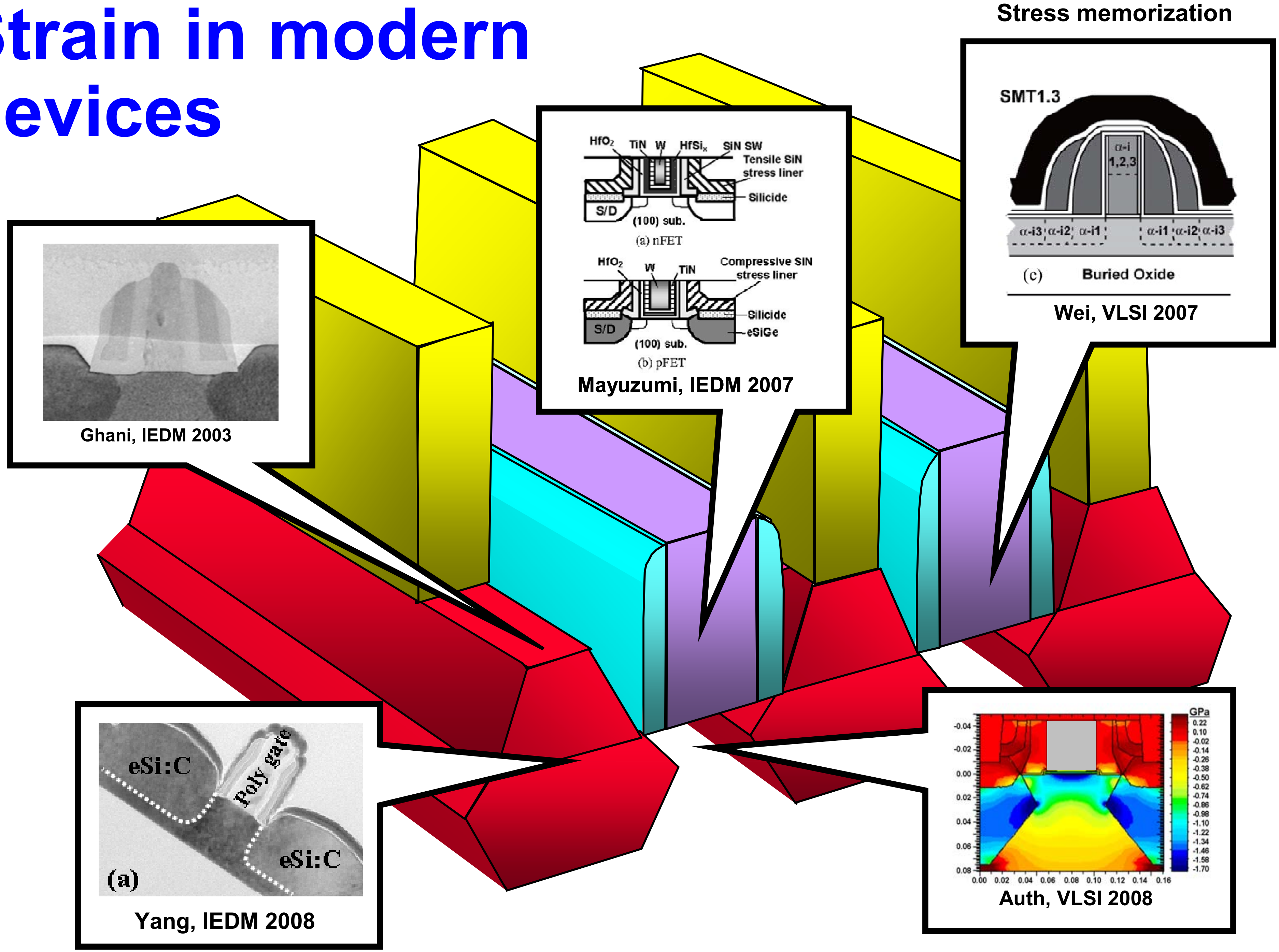
Transistor Performance Trend



Strain is a critical ingredient in modern transistor scaling

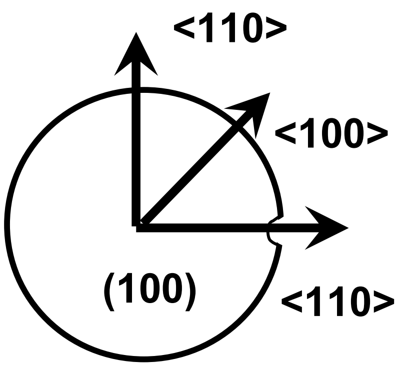
Strain was first introduced at 90nm, and its contribution has increased in each subsequent generation

Strain in modern devices



ORIENTATION

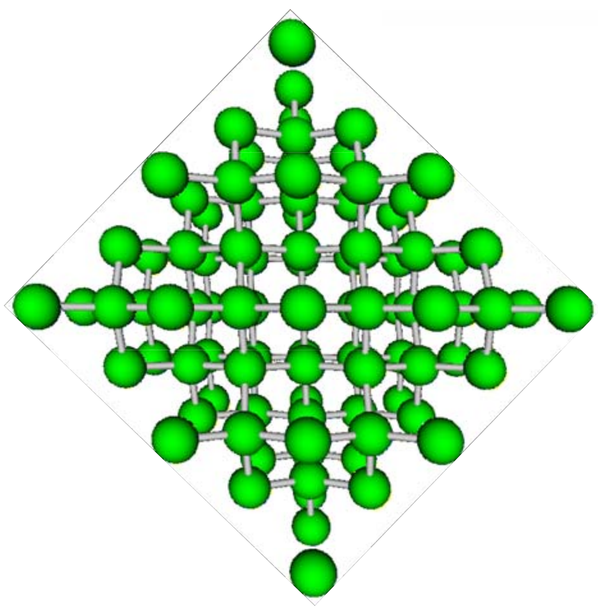
(100) surface – top down



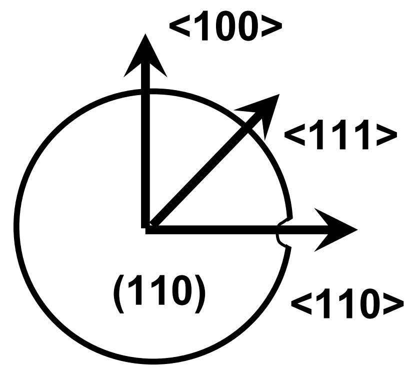
Standard wafer / direction
(100) Surface / <110> channel

(100) Surface / <100>
(a "45 degree" wafer)

Both <110> directions are the same.



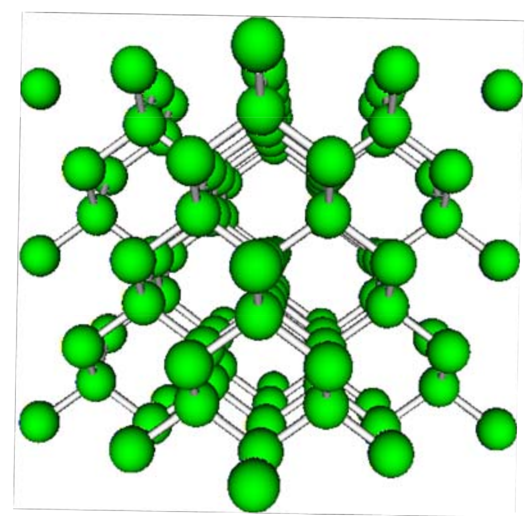
(110) surface – top down



Non-standard

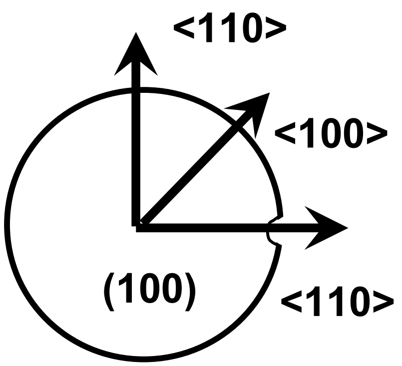
(110) Surface

Three possible channel directions
<110> <111> and <100>



ORIENTATION

(100) surface – top down

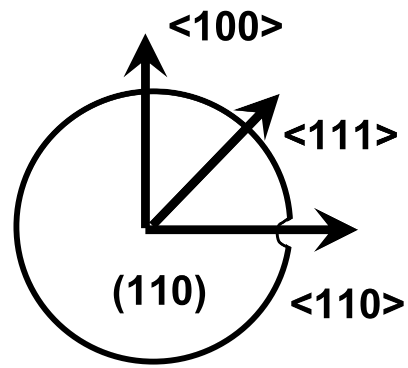


Standard wafer / direction
(100) Surface / <110> channel

(100) Surface / <100>
(a "45 degree" wafer)

Both <110> directions are the same.

(110) surface – top down

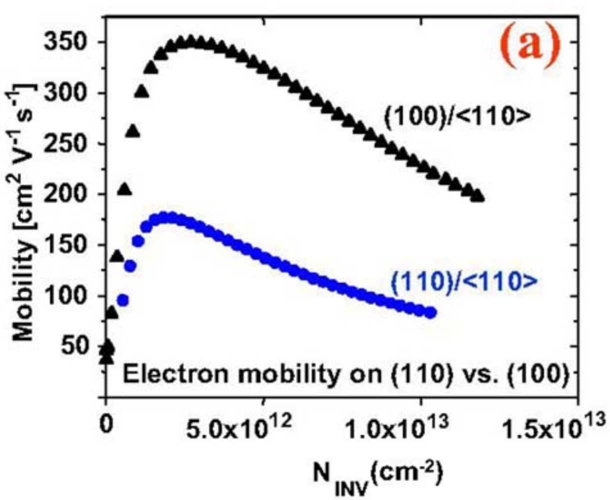


Non-standard

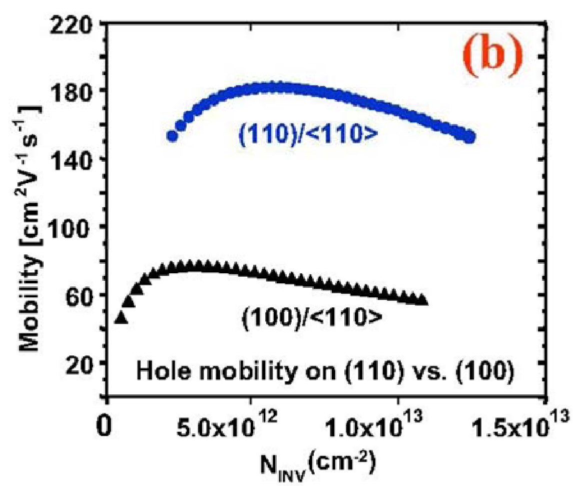
(110) Surface

Three possible channel directions
<110> <111> and <100>

(100) BEST NMOS



(110) <110> BEST PMOS

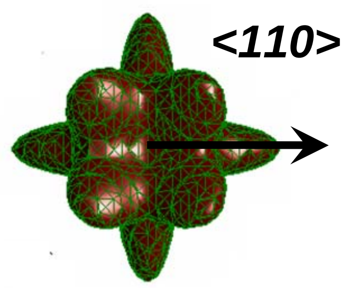


Yang
AMD/IBM
EDST 2007

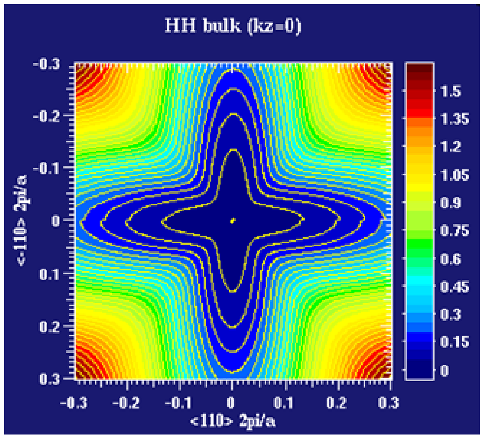
Orientation and Strain: More complex for non-(100) orientations

(100)

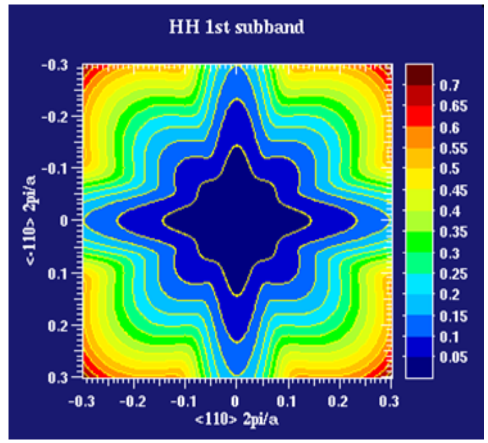
<110>



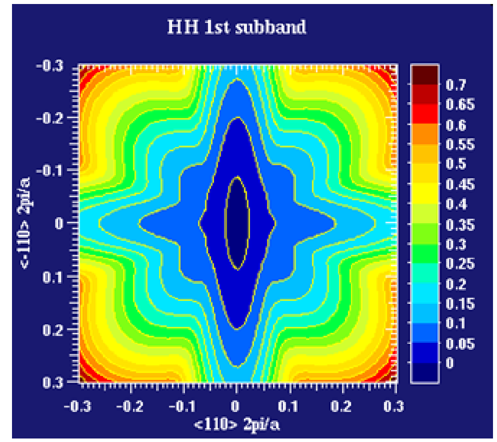
(001) Surface (k⊥=0)



(001) Surface Vg=-1V

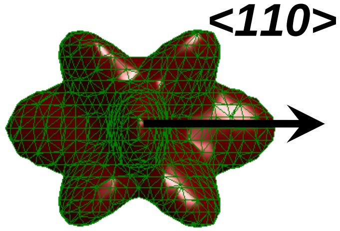


(001) Surface
Vg=-1V, Sxx=-1GPa

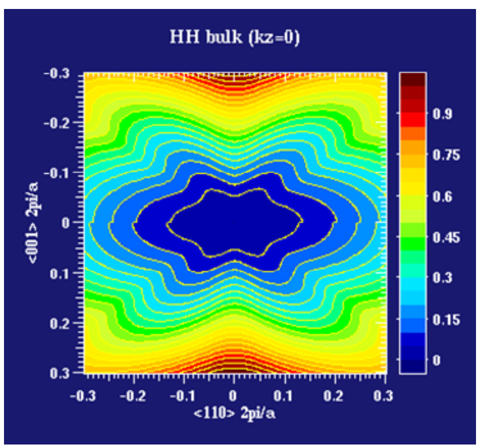


(110)

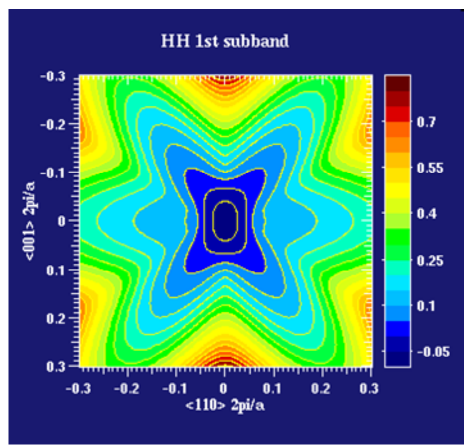
<110>



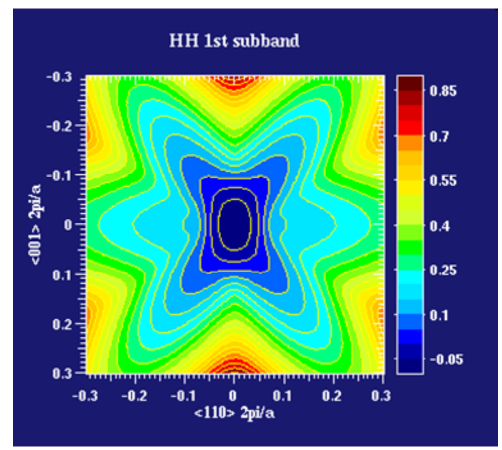
(110) Surface (k⊥=0)



(110) Surface Vg=-1V



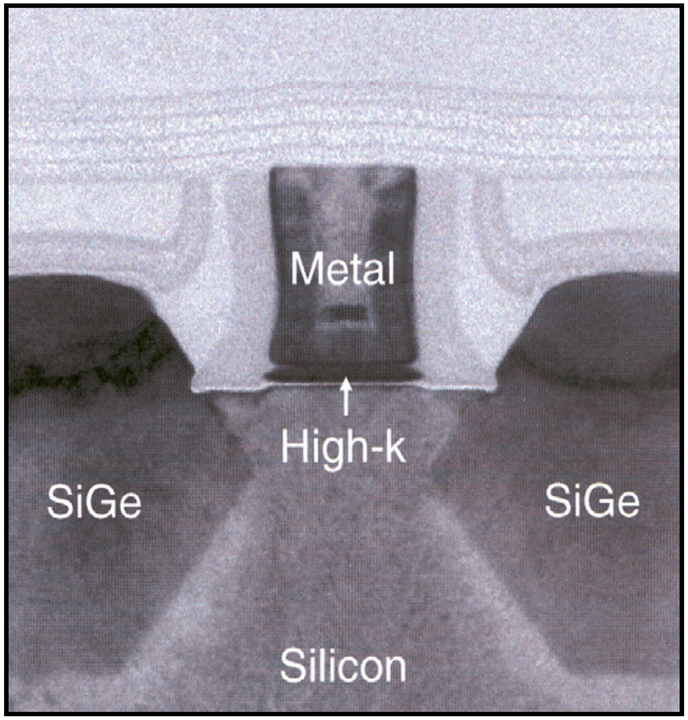
(110) Surface
Vg=-1V, Sxx=-1GPa



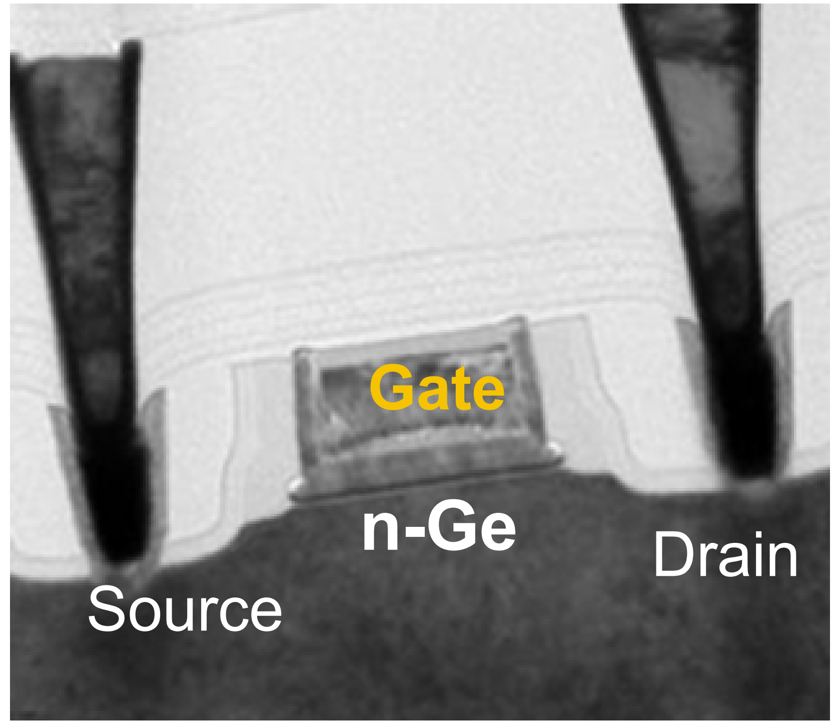
BULK | **1'D CONFINED** | **1'D CONFINED STRAINED**

Kuhn/Packan, Intel, IEDM 2008

Si vs Ge MOSFETs



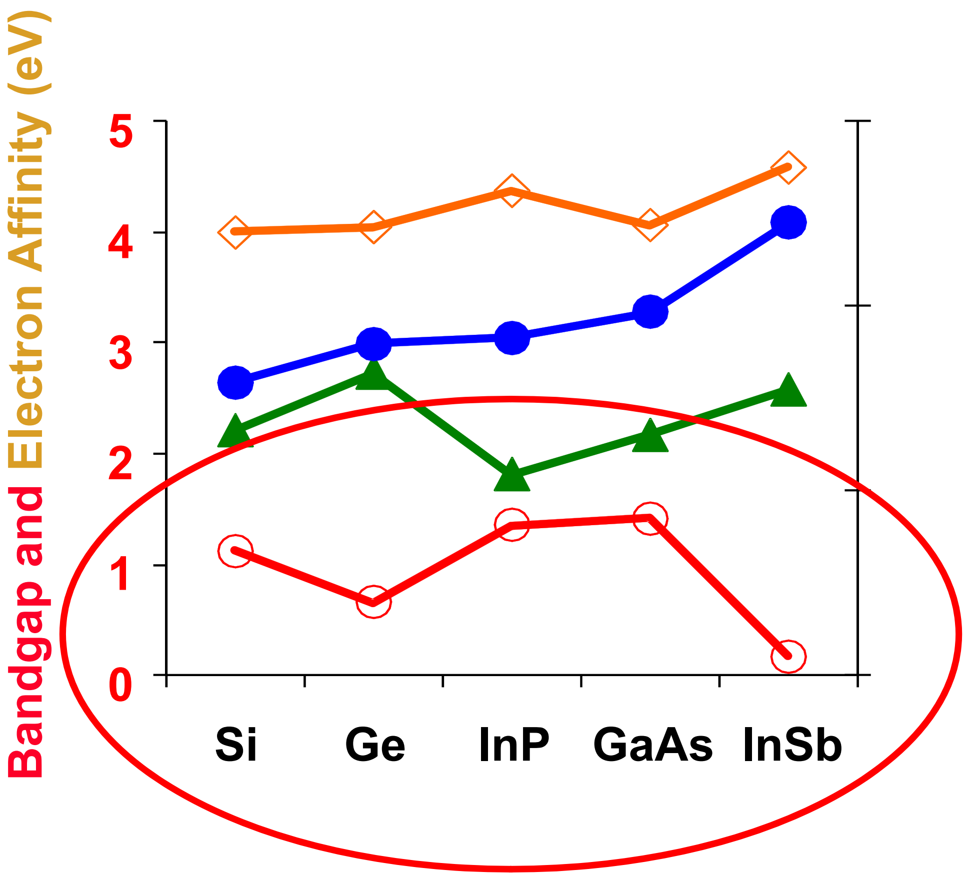
Intel 45nm HiK-MG Si device [43]



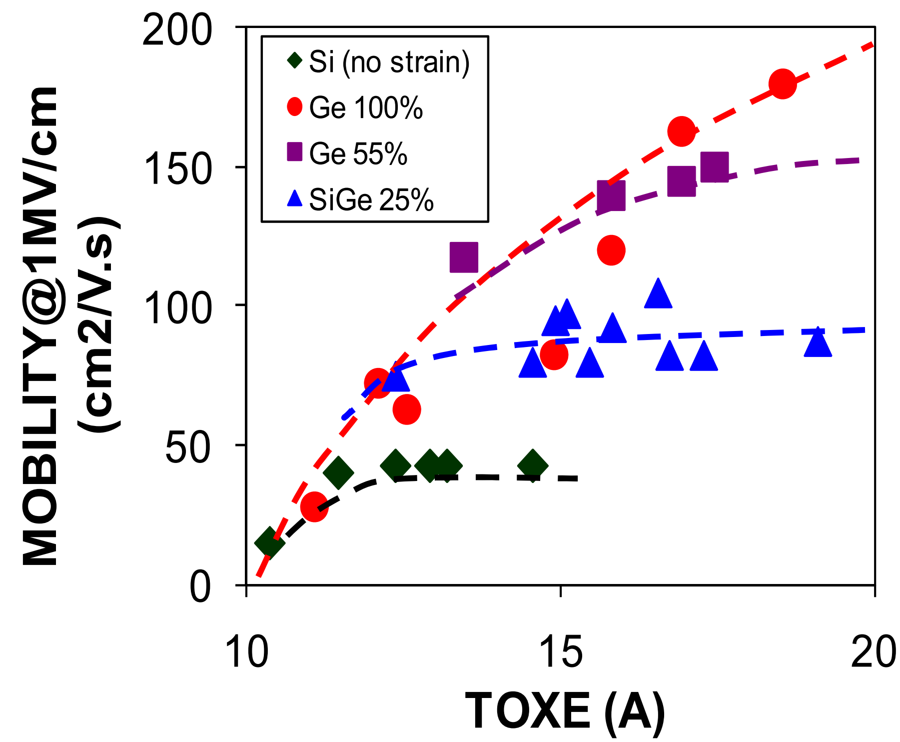
Intel HiK-MG Ge device

The introduction of manufacturable HiK-MG transistors has led to the reconsideration of Ge channels

Ge Historical Issues:
Still critical today

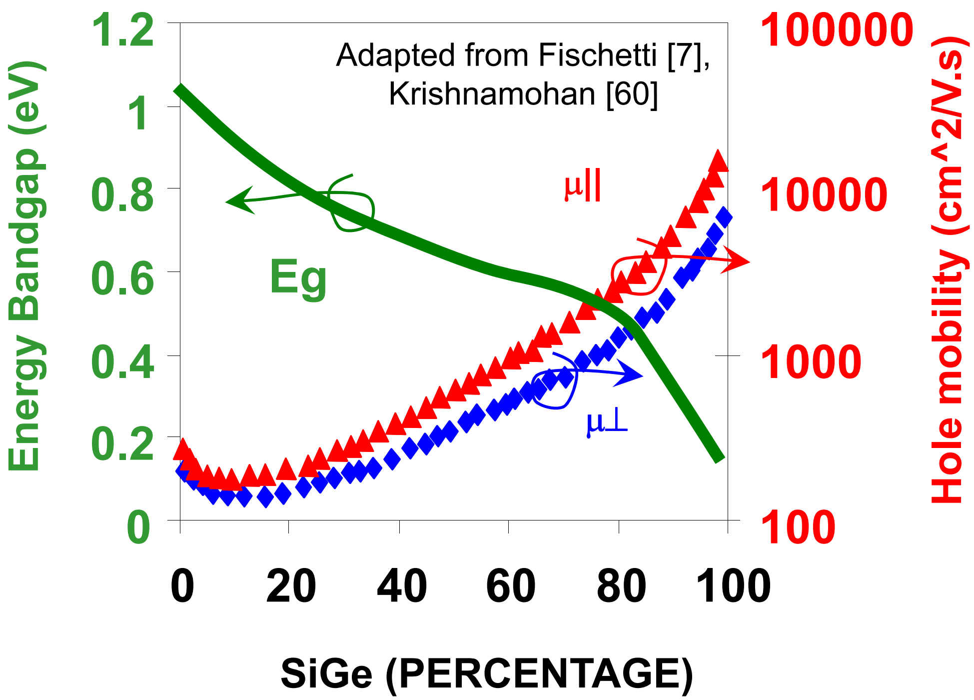


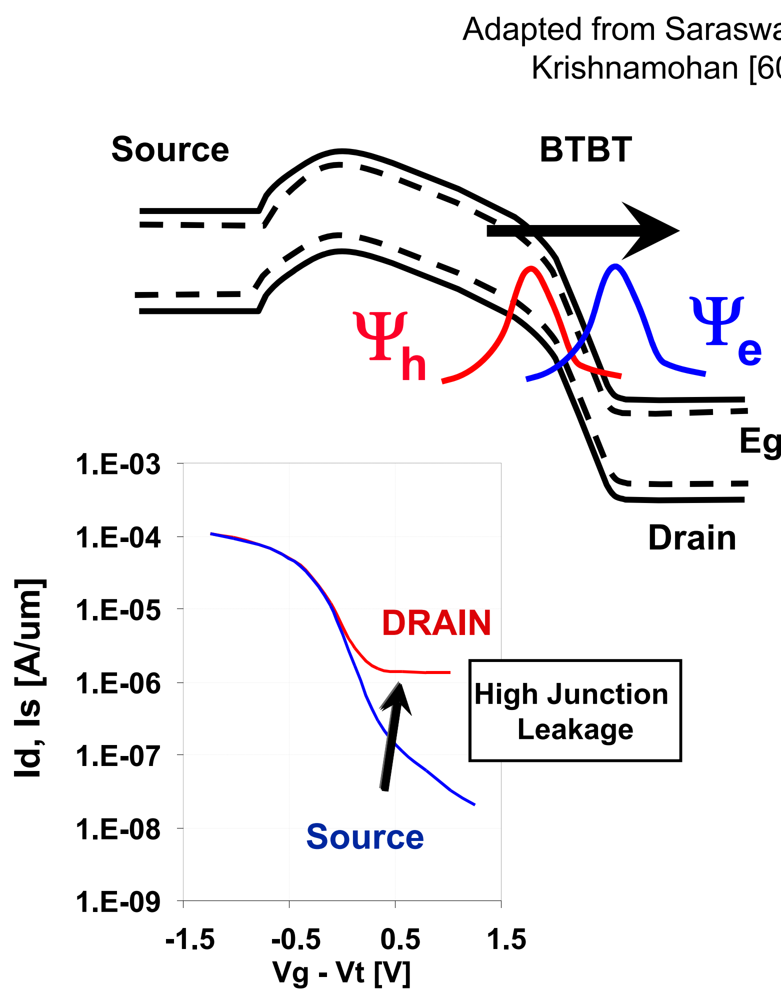
Narrow Bandgap



Poor Quality Dielectric

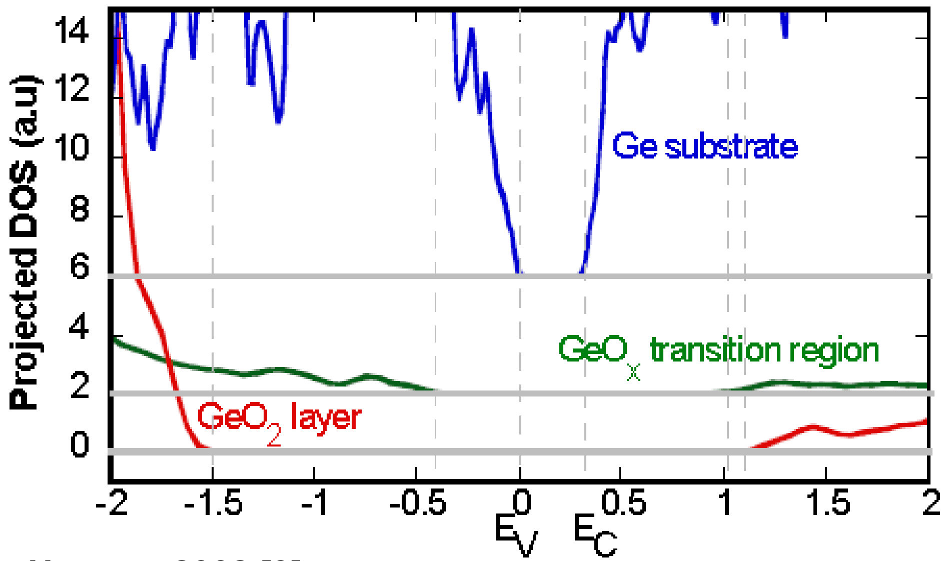
Narrow Bandgap



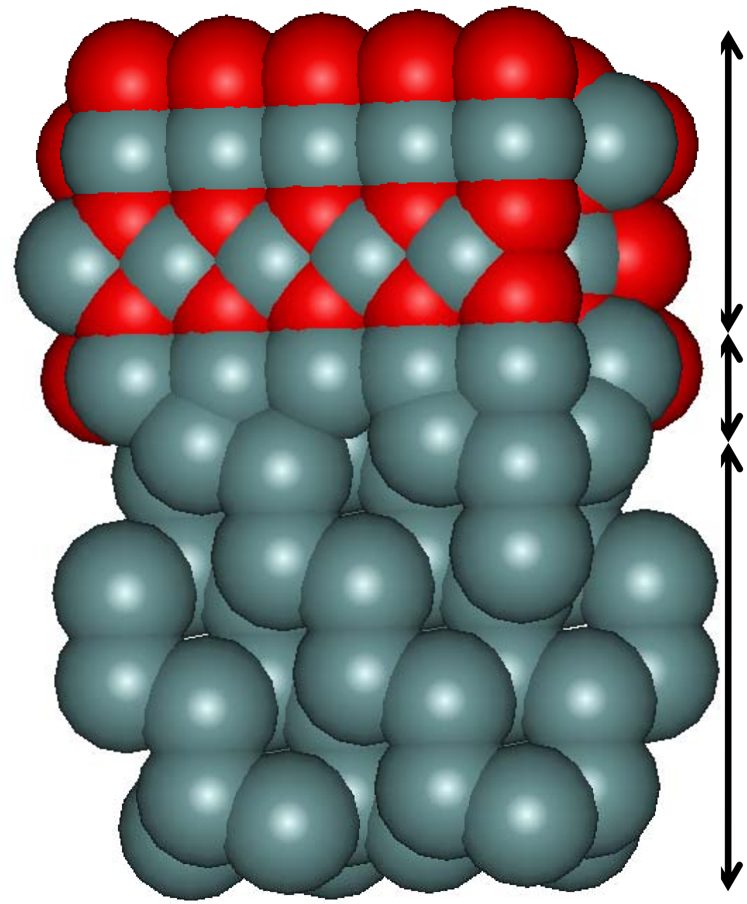


Band-to-band tunneling: challenge for low Eg materials

Dielectric Quality



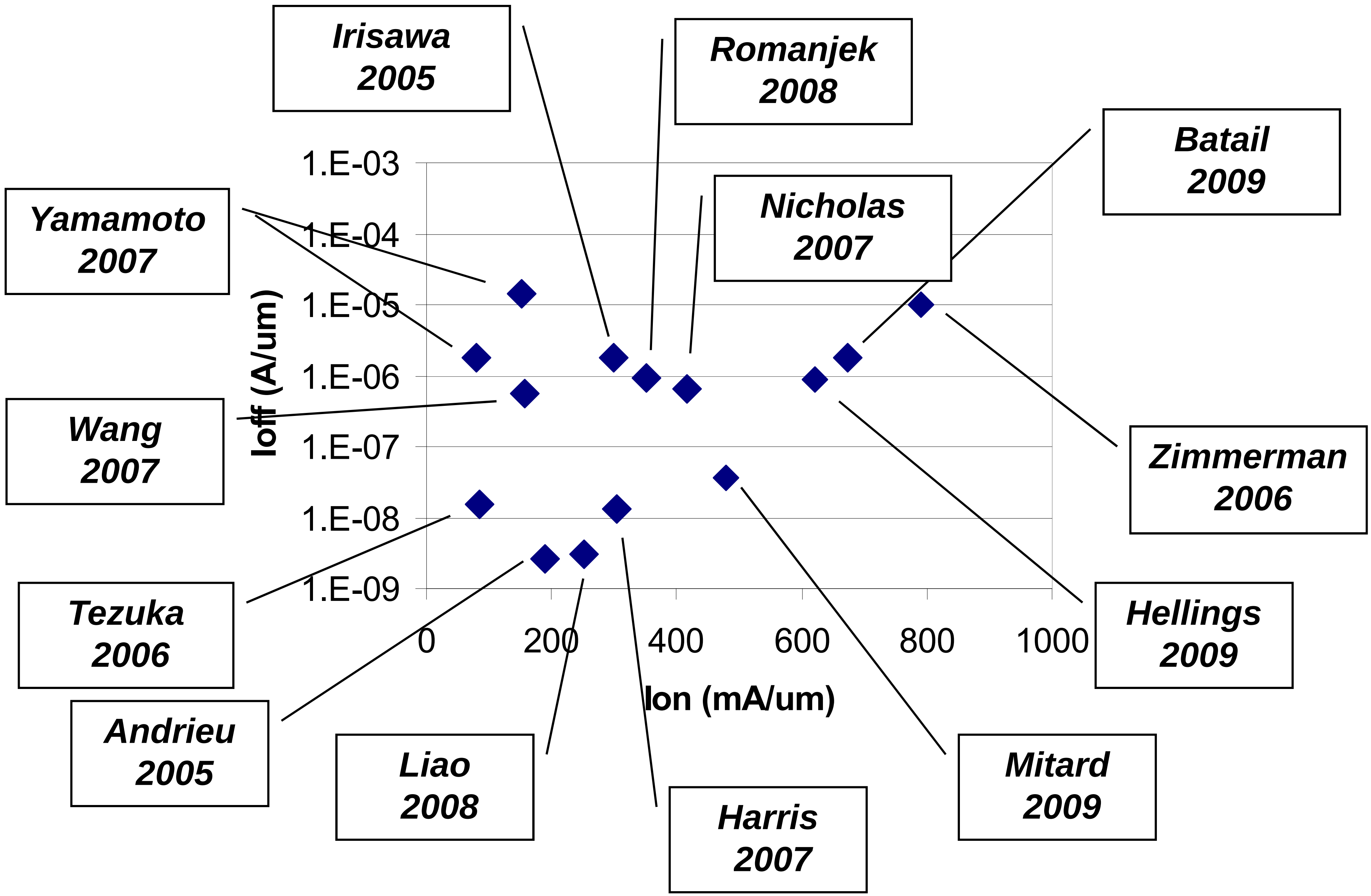
Heynes, 2008 [9]



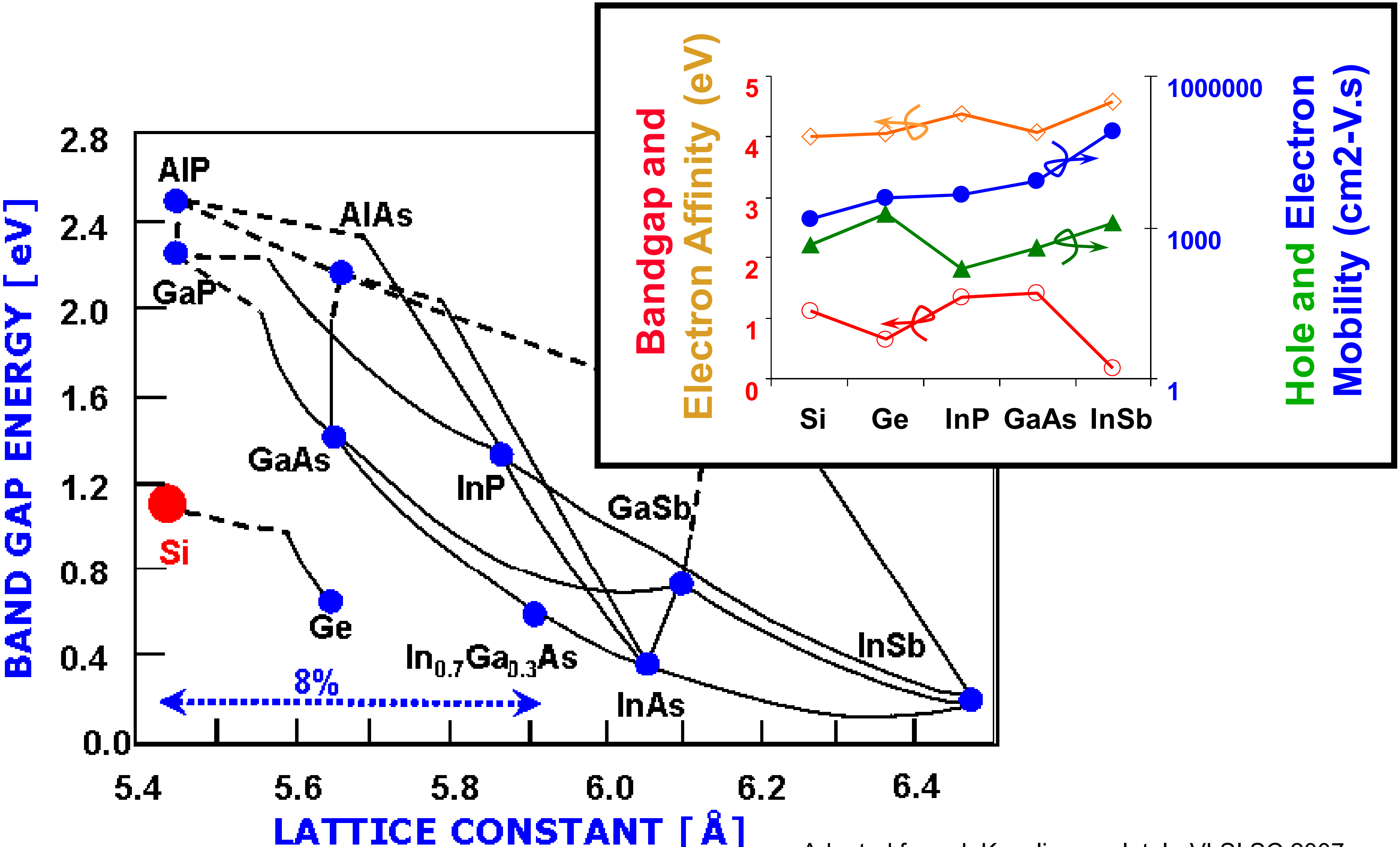
Since HiK-MG dielectrics typically form with a bilayer (the HiK + an interface layer) the challenge of germanium oxide still exists.

Germanium oxide exists in several morphologies, unfortunately, most are hydroscopic and/or volatile.

Ge Benchmarking



III-V: The Lure of High Mobility



Adapted from J. Kavalieros – Intel - VLSI SC 2007
K. Kuhn – ECS 2010

III-V MOSFETs: "Density-of-states bottleneck"

From R. Kim

- **On-current of a MOSFET**

$$I = Q\upsilon$$

- **Velocity υ**
  - Diffusive : mobility μ, $\upsilon = \mu \mathscr{E}$
  - Ballistic: injection velocity υ_{inj}
  - Light $m^* \rightarrow$ high μ, high υ_{inj}

- **Charge Q**
  - MOS limit ($C_Q \gg C_{ox}$), $C \approx C_{ox}$
  - Light $m^* \rightarrow$ less D (C_Q), less C, less Q
  - More important for thin oxide (large C_{ox}),

  "DOS bottleneck"

$$Q = C\left(V_G - V_{th}\right)$$

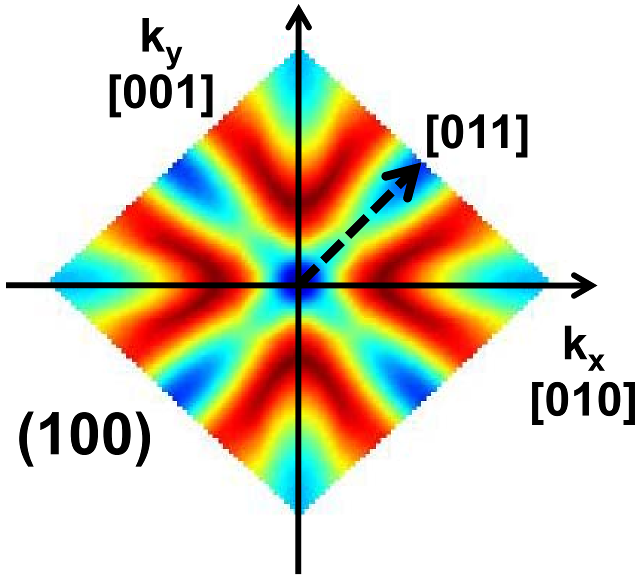
$$\frac{1}{C} = \frac{1}{C_{ox}} + \frac{1}{C_Q}$$

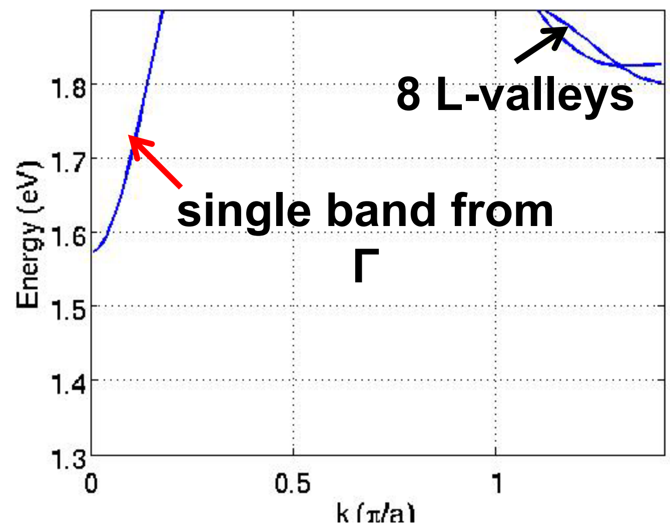
$$C_Q = q^2 D$$

Use of L-valleys: GaAs

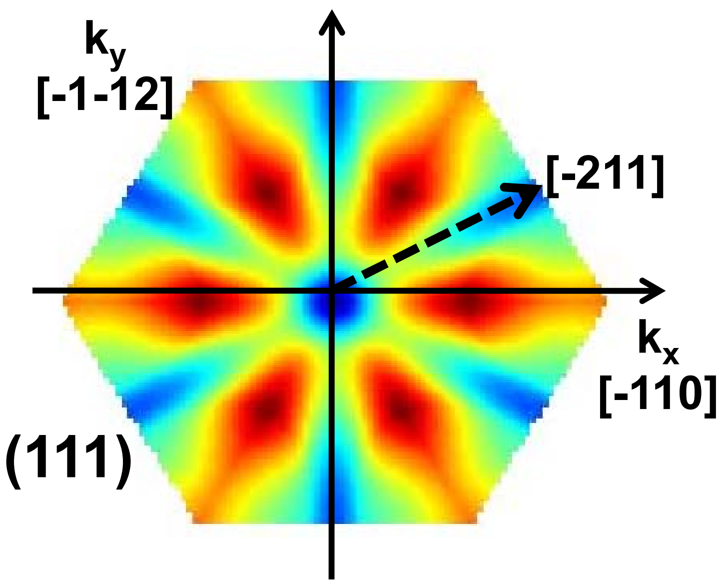
From R. Kim

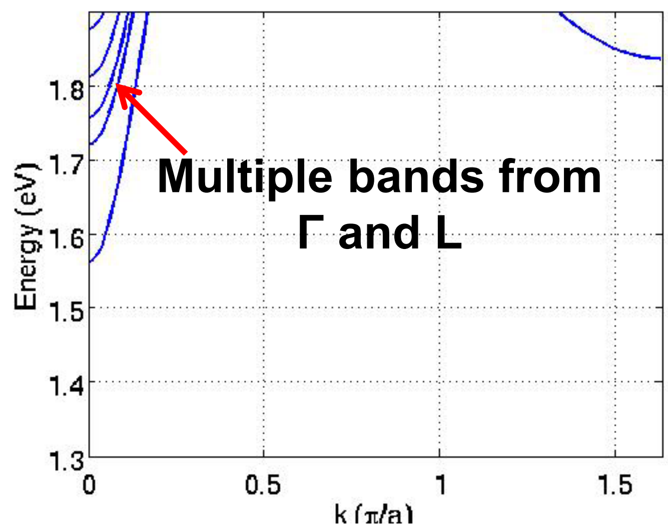
- GaAs 4 nm





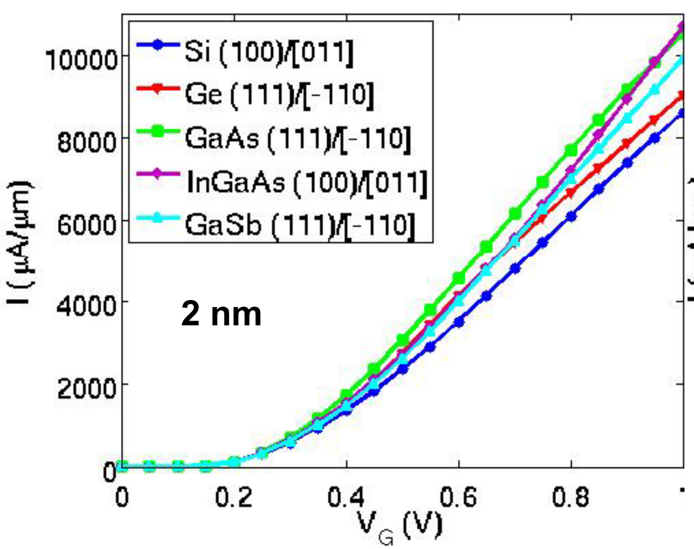
Small DOS with high v_{inj}
High DOS with low v_{inj}



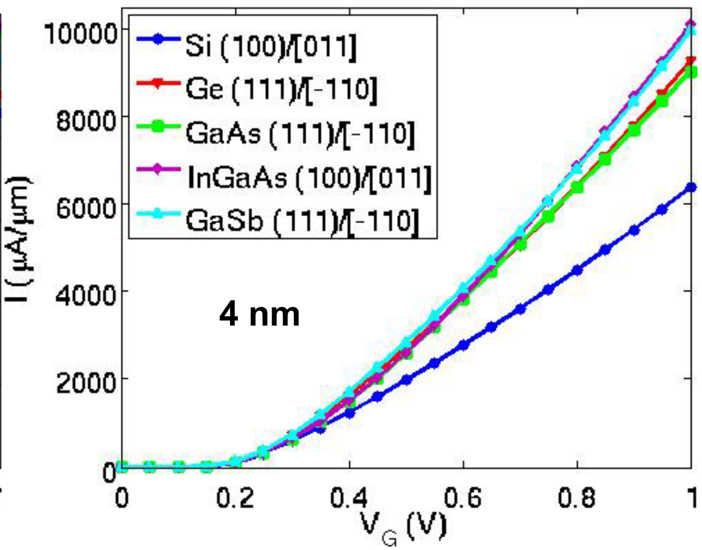


More DOS with high v_{inj}

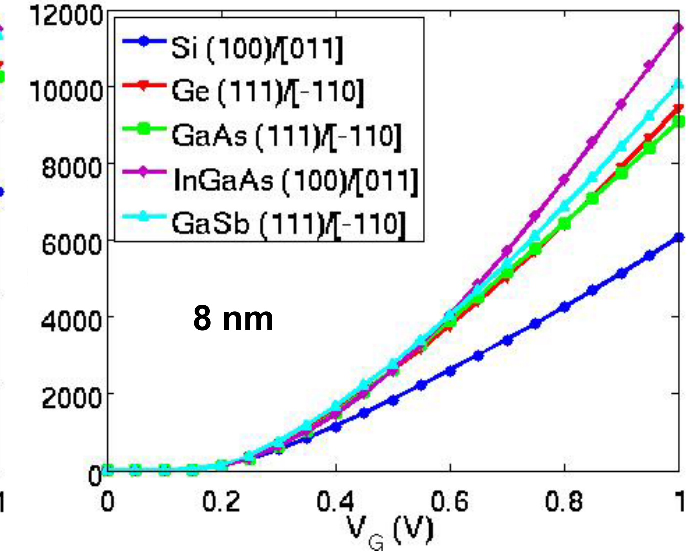
Different body thicknesses (EOT=1.0 nm)



GaAs>InGaAs>GaSb>Ge>Si

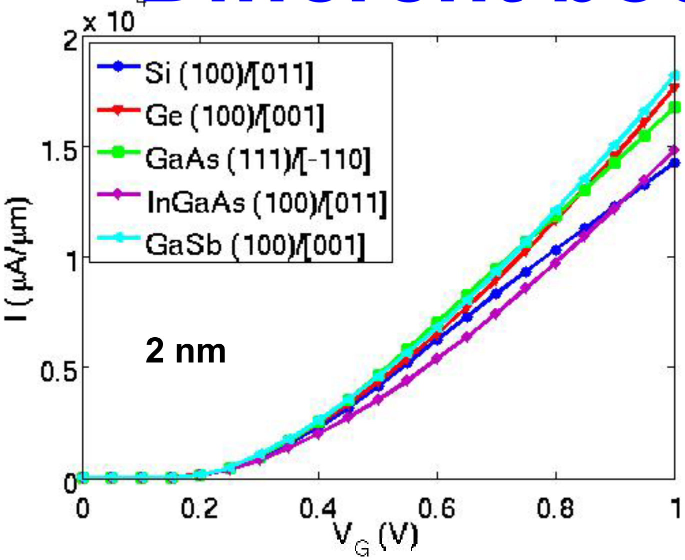


GaSb,InGaAs>Ge,GaAs>Si

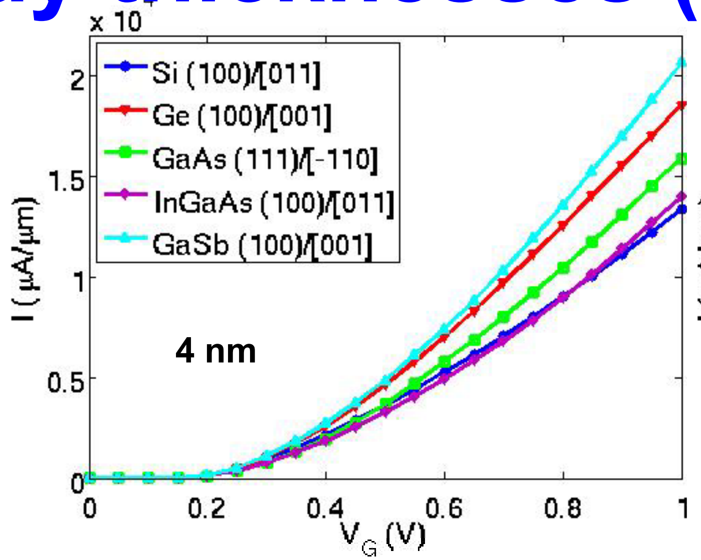


InGaAs>GaSb>Ge,GaAs>Si

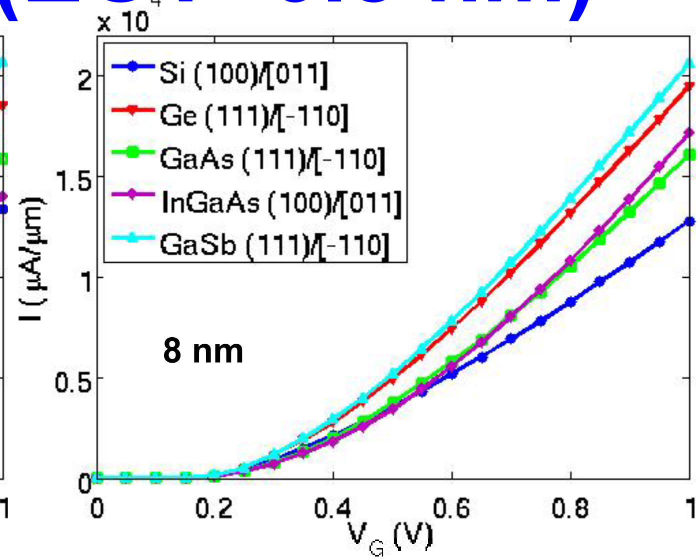
Different body thicknesses (EOT=0.5 nm)



GaSb>GaAs>Ge>Si>InGaAs



GaSb>Ge>GaAs>Si,InGaAs



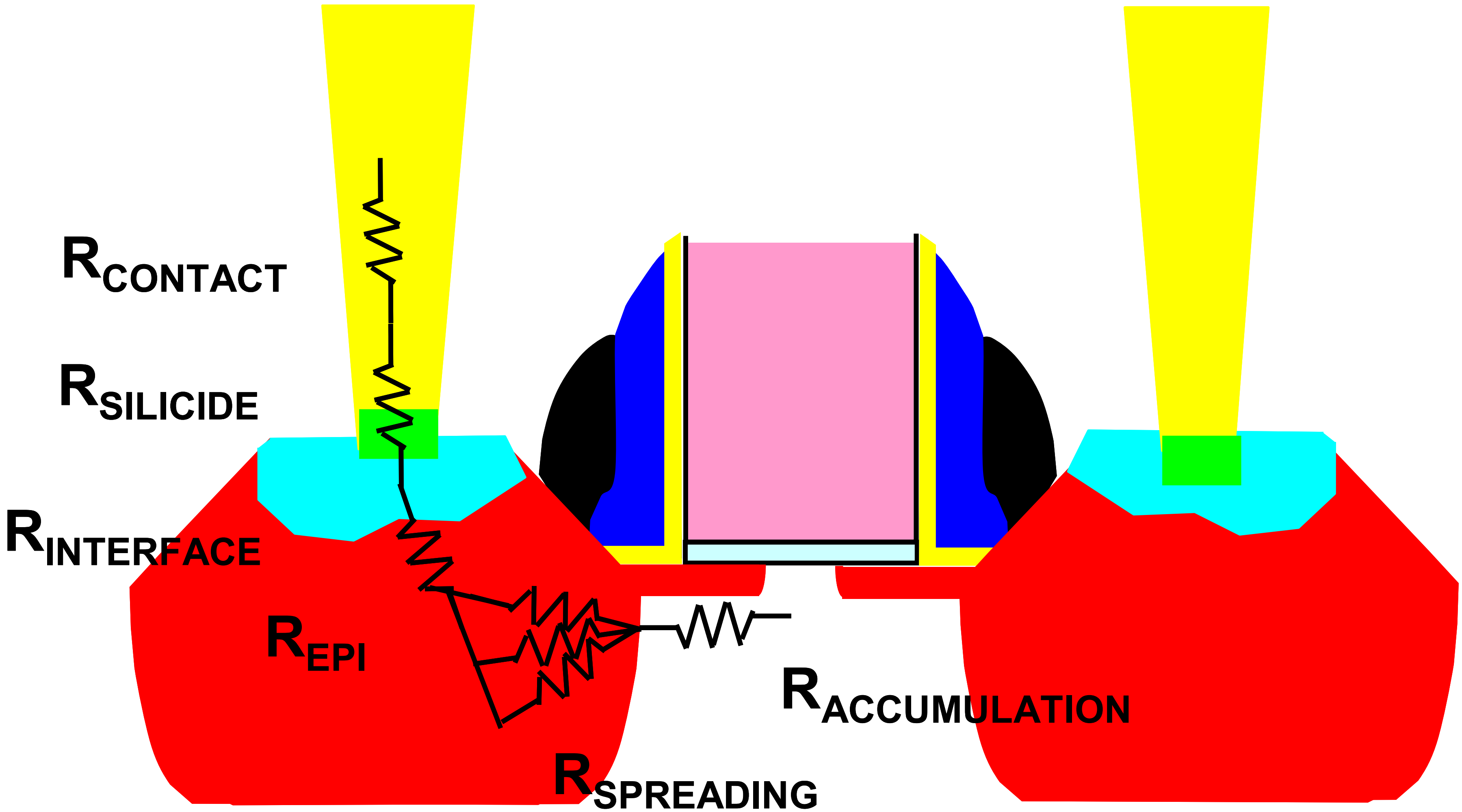
GaSb>Ge>GaAs, InGaAs>Si

From R. Kim

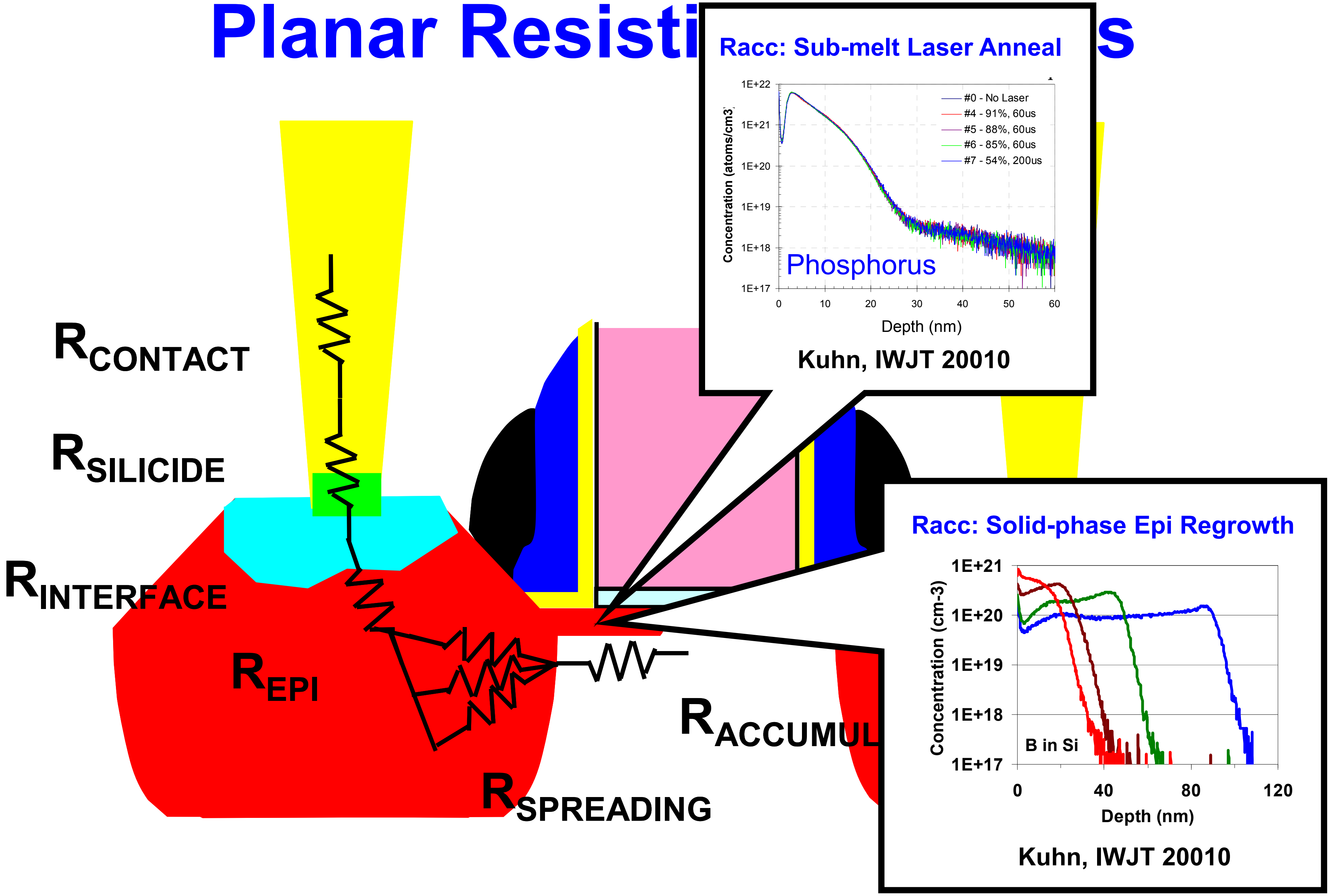
AGENDA

- Scaling
- Gate control
- Mobility
- Resistance
- Capacitance
- Summary

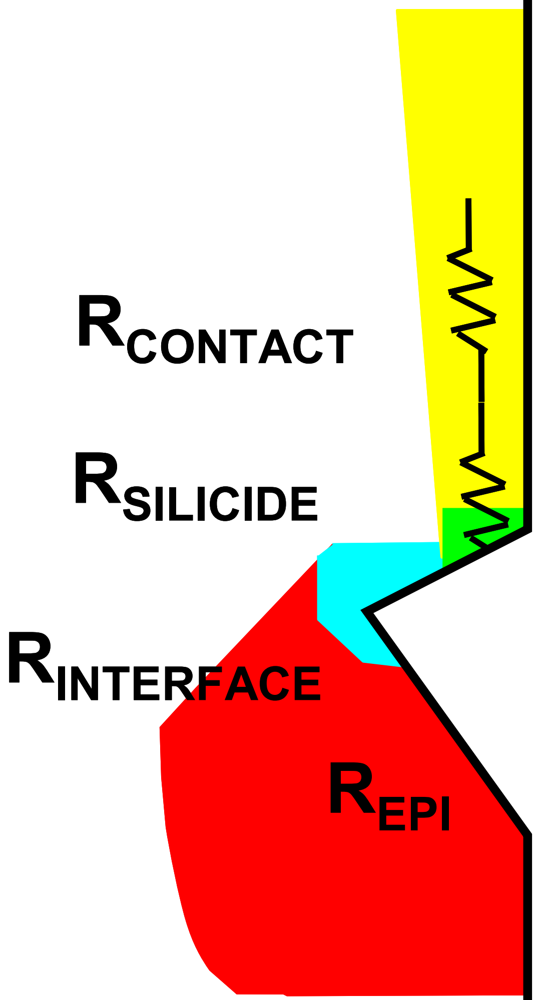
Planar Resistive Elements



Planar Resisti s

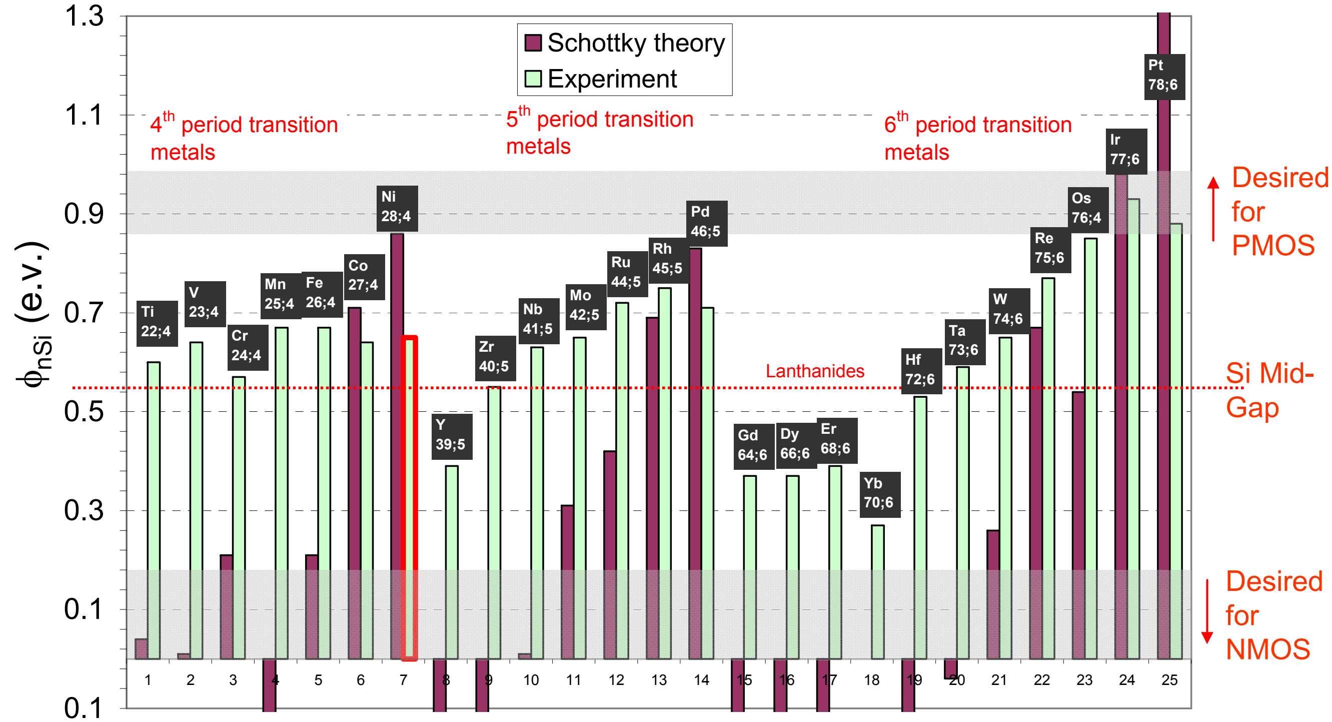


Plan



Rinterface: Reduction in Schottky Barrier Height

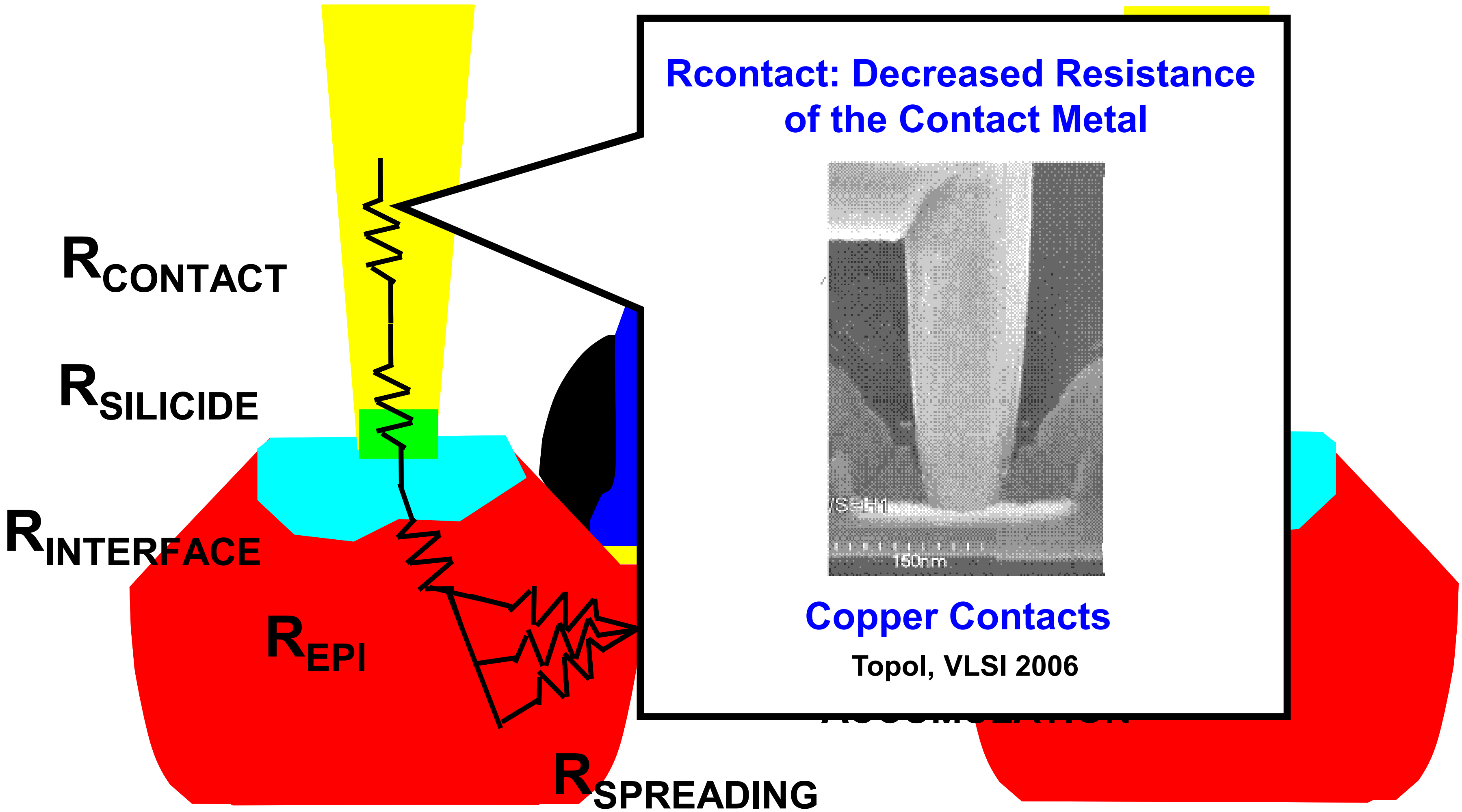
$$R_{\text{interface}} \propto \exp\left(\frac{q\phi_B}{\sqrt{N_D}}\right)$$



Schottky Barrier Height Reduction is a critical area for development. Techniques under investigation include exotic alloys, implants, and Fermi-unpinning layers

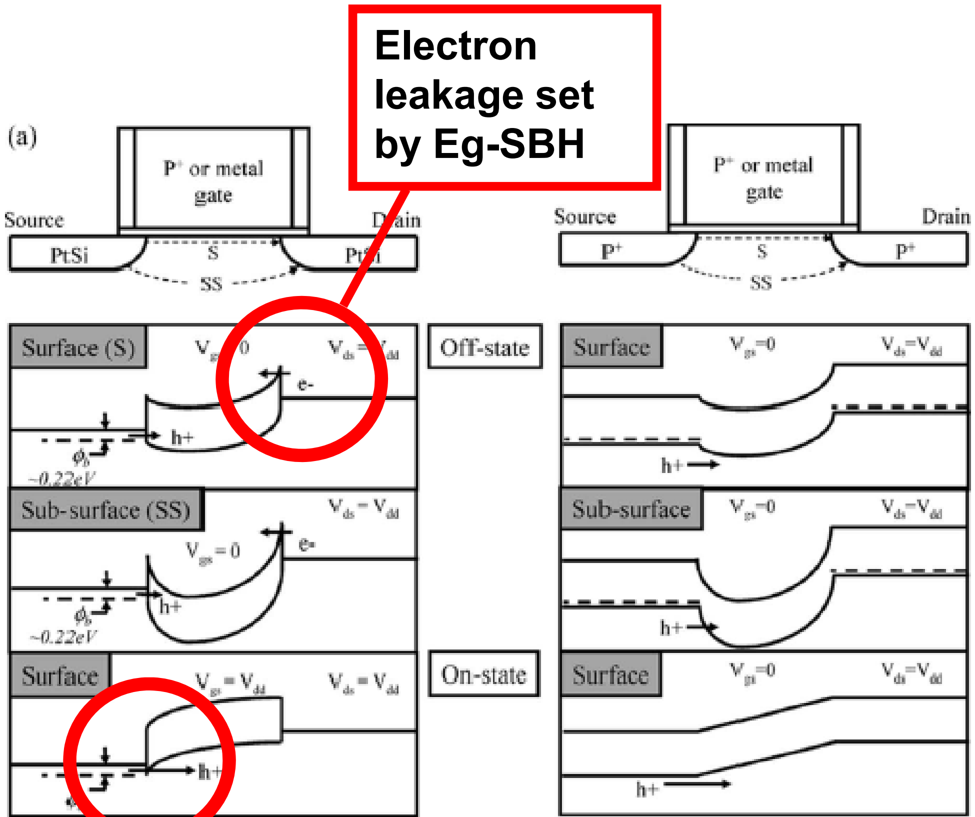
Kuhn, IWJT 20010

Planar Resistive Elements



Kuhn, IWJT 20010

Schottky barrier S/D – an option?



Metallic SD ***Conventional***

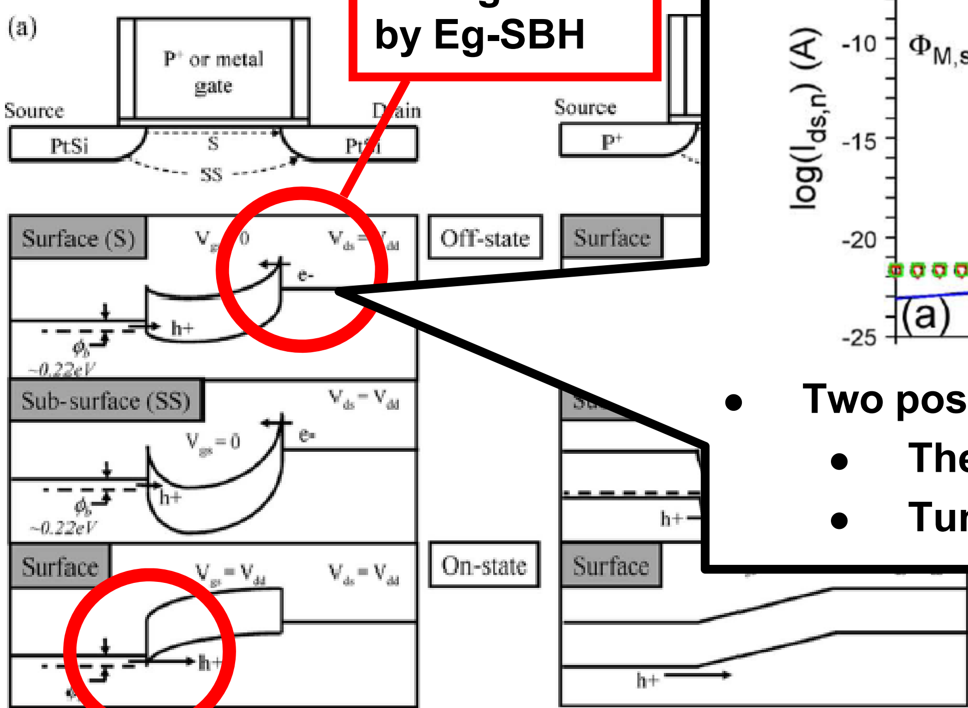
Larson – Spinnaker TED 2006

Hole barrier set by SBH

- In a metal SB-MOS, S/D forms an atomically abrupt Schottky-barrier having the height ϕb.
- The extreme limit for metal in the S/D regions (with associated improvements in Rext)
- Unconventional operation (field emission device in the ON state)
- Needs complementary devices (midgap silicide or two silicides)

Schottky barrier S/D – an option?

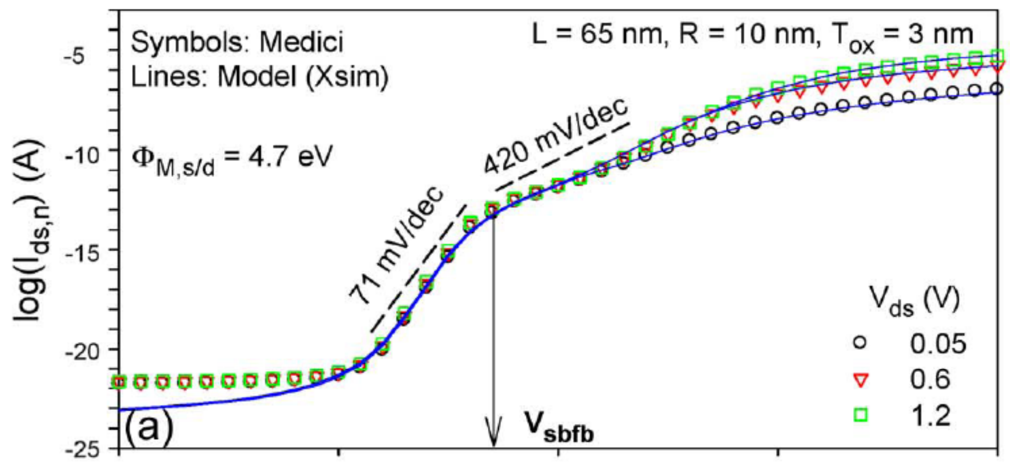
Electron leakage set by Eg-SBH



Metallic SD

Conventional

Zhu IEEE TED May 2009



- **Two possible conduction paths:**
  - **Thermionic – over the barrier – good SS slope**
  - **Tunneling – through the barrier – poor SS slope**

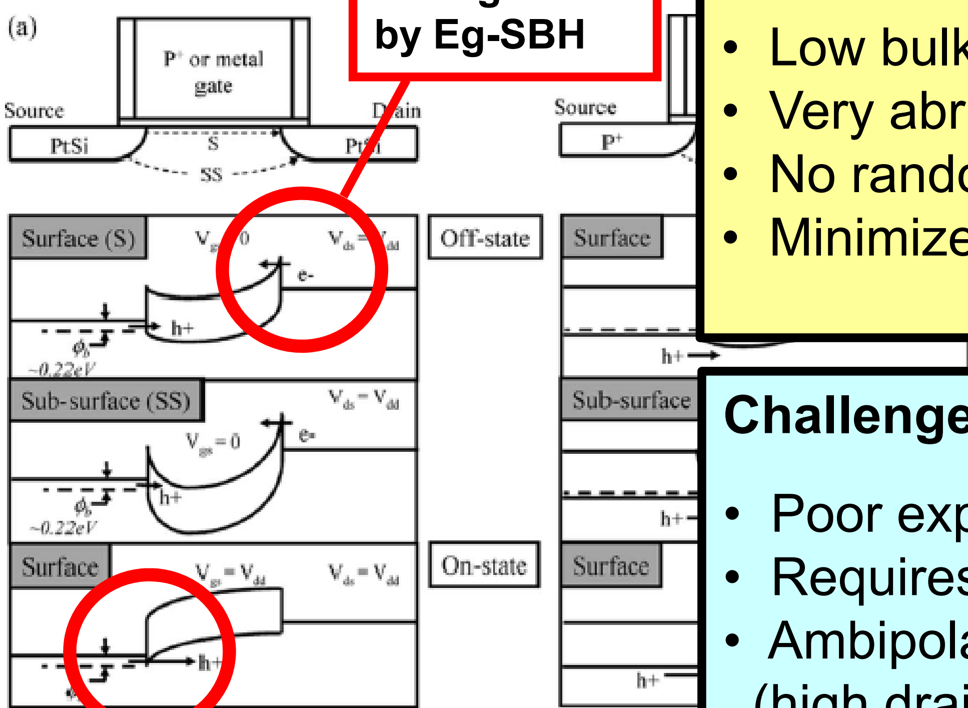
Hole barrier set by SBH

Larson – Spinnaker TED 2006

- Unconventional operation (field emission device in the ON state)
- Needs complementary devices (midgap silicide or two silicides)

Schottky barrier S/D – an option?

Electron leakage set by Eg-SBH



Metallic SD

Conv

Hole barrier set by SBH

Larson – Spinnak
TED 2006

Benefits

- Low bulk resistance contacts to the channel
- Very abrupt junctions
- No random s/d dopant fluctuation effects
- Minimize s/d carrier-carrier scattering effects

Challenges

- Poor experimental drive currents
- Requires bandedge Schottky barriers
- Ambipolar conduction (high drain-body leakage for bulk devices)
- Early contact formation limits midsection process temperatures
- Need alternative approach for s/d stressors

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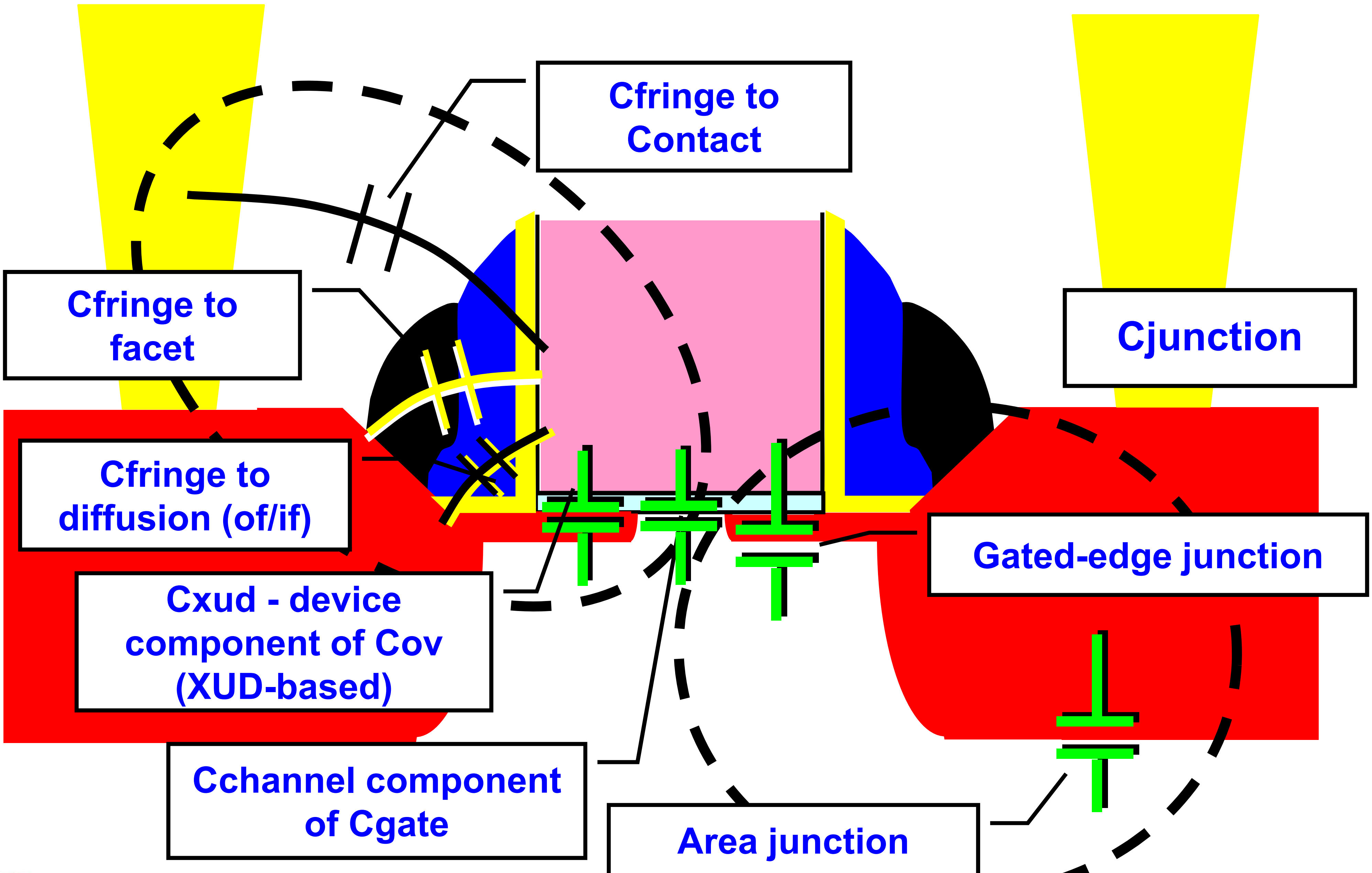
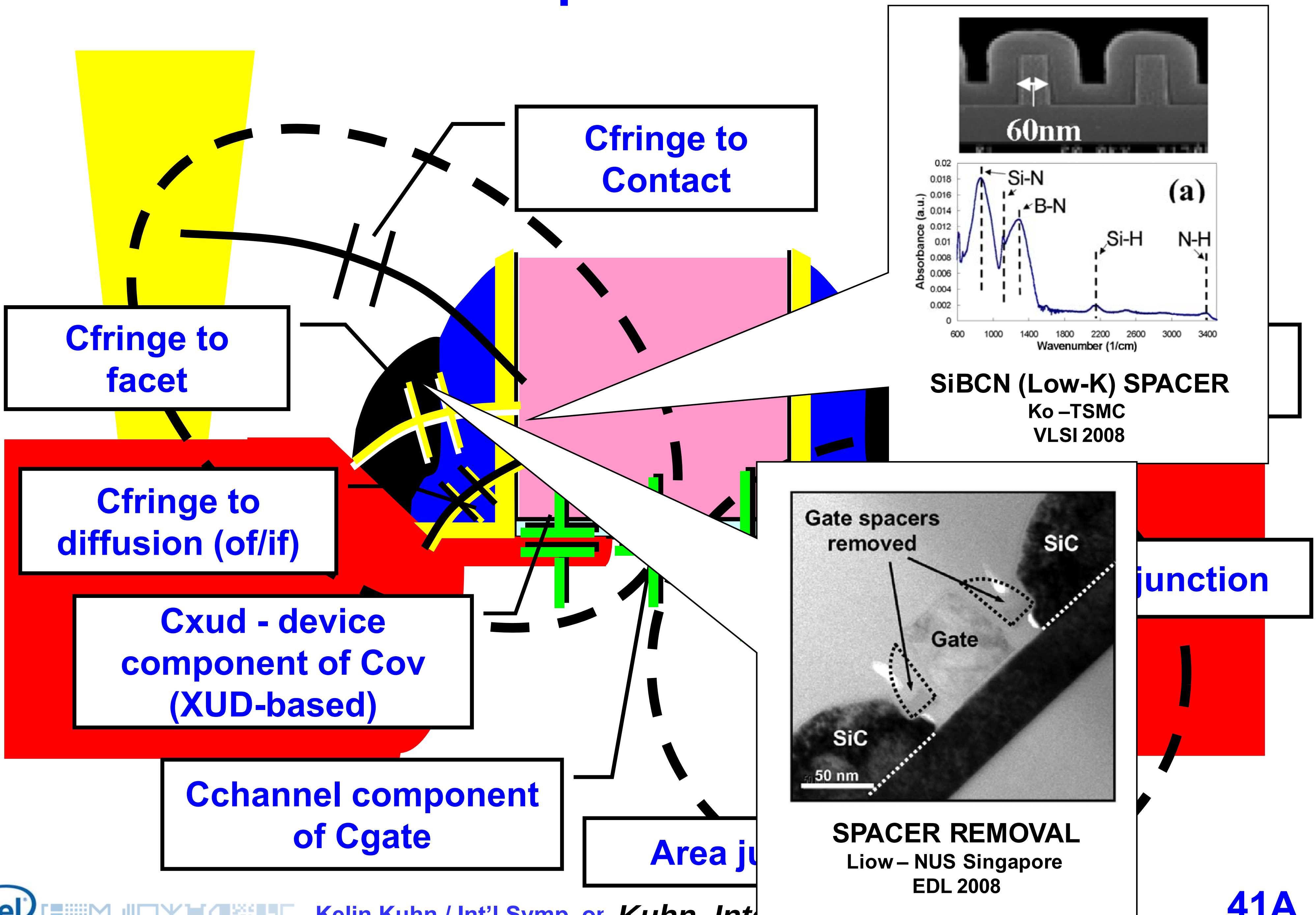
Planar Capacitive Elements



Planar Capacitive Elements



AGENDA

- Scaling
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Looking Forward

Low risk Enhancements in strain technology Enhancements in HiK/MG technology
Medium Risk Optimized substrate and channel orientation Reduction in MOS parasitic resistance Reduction in MOS parasitic capacitance
High risk UTB devices / MuGFETS Nanowires 3'D Stacked Devices Advanced materials (Ge/III-V)

Q&A