

Past and Future of Mirco/Nano-Electronics

January 7, 2011

**@Muthayammal Engineering
College
Rasipuram, Tamilnadu, India**

**Hiroshi Iwai,
Tokyo Institute of Technology**



Tokyo Institute of Technology
Founded in 1881, Promoted to Univ. 1929

Institute Overview



Established in 1881 → 130th anniversary in 2011

3 undergraduate schools

School of Science, School of Engineering, School of Bioscience and Biotechnology

Einstein Visit

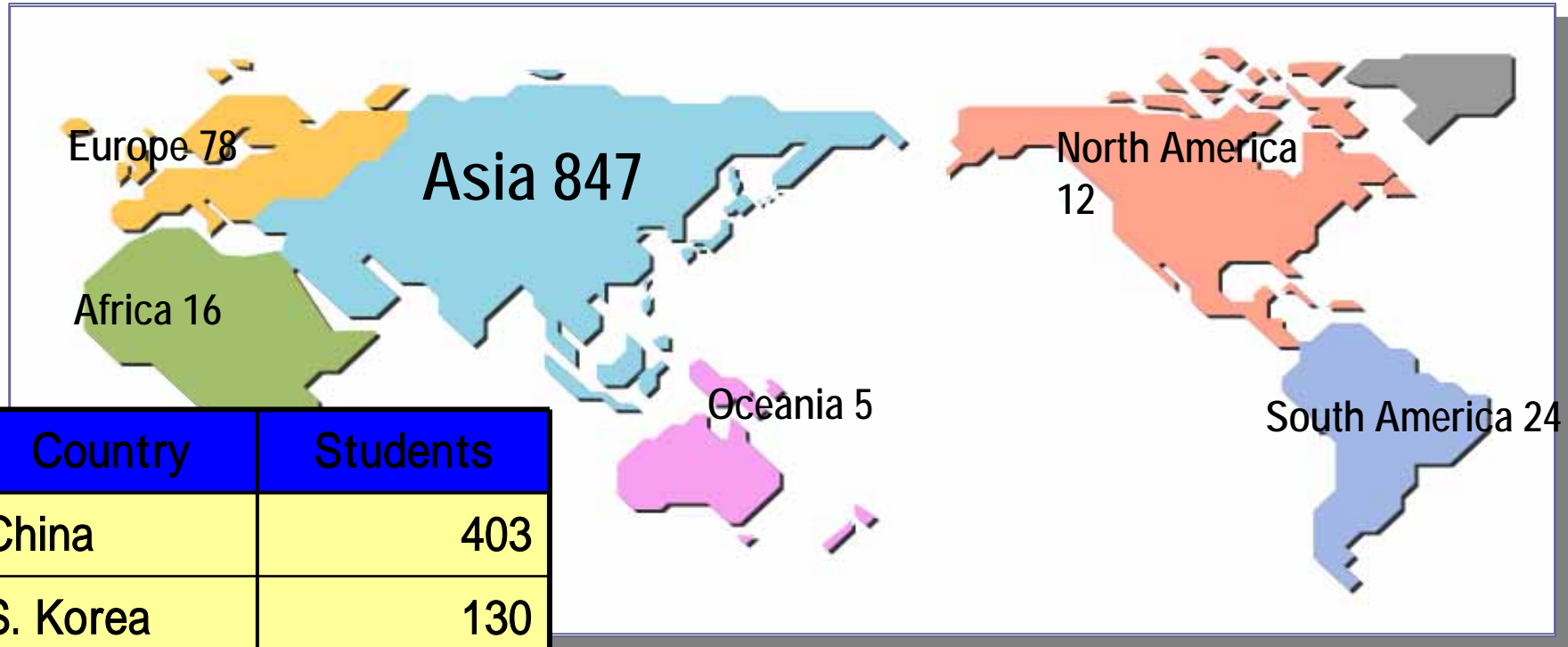
7 graduate schools

Science and Engineering Science, Science and Engineering Technology,
Bioscience and Biotechnology, Interdisciplinary Graduate School of Science and Engineering,
Information Science and Engineering, Decision Science and Technology, Innovation Management

Total Number of Students

	Undergraduate	Graduate	Master's	Doctoral	Teaching Staff	Student/Instructor	Staff
Tokyo Inst.	5,000	5,000	3,500	1,500	1,200	8.3	550
Per Year	1,200		1,800	500			

International Students



Country	Students
China	403
S. Korea	130
Indonesia	64
Thailand	55
Vietnam	60
Malaysia	28

Total 982
(As of May. 1, 2005)

(2010年10月1日現在)



物理電子システム創成専攻
教授 西井 洋
Emergent and Analog Physics
Professor
Hiroshi Nishino



物理電子システム創成専攻
教授 西井 洋
Emergent and Analog Physics
Professor
Hiroshi Nishino



物理電子システム創成専攻
准教授 大月 俊一郎
Emergent and Analog Physics
Associate Professor
Shunji Otsuki



フロンティア研究機構
特任准教授
アハメト パールハット
Frontier Research Center
Associate Professor
Ahmet Parlaktas

教員
(10人)



Simon Min Sze
(客員教授)



岡村 博志
(客員教授)



名取 洋一
(特任教授)



杉井 慎之
(連携教授)



西山 彰
(連携教授)



舟橋 邦之
(助教)

技術員
(1人)



辻岡 大

博士
研究員
(1人)



Man Kumar Gera

博士
学生
(19人)



佐々木 謙一
(D3)



林 憲一
(D3)



川崎 高橋
(D3)



佐藤 謙志
(D3)



高橋
(D3)



高田 謙治
(D3)



下村 浩
(D3)



Mahmoud El-Metwally
(D3)



Abulhasim Abulhasan
(D3)



鈴木 誠
(D3)



藤田 伸也
(D2)



李 映前
(D2)



谷野 貴洋
(D2)



藤原 成
(D2)



藤原 康
(D2)



高橋 康夫
(D1)



Yoshihiro Nakayama
(D1)



Mohammad Shohby Had
(D1)



石塚 健士
(D1)



修士
学生
(26人)



小澤 友美
(M2)



小澤 雅夫
(M2)



神田 志志
(M2)



渡辺 謙伸
(M2)



高橋 寛重
(M2)



西井 弘典
(M2)



眞研
(M2)



Dou Chunming
(M2)



石川 純平
(M2)



木村 謙一郎
(M2)



佐藤 謙志
(M2)



田中 正典
(M2)



青藤 勇
(M2)



東山 大祐
(M1)



小山 秀夫
(M1)



藤井 隆典
(M1)



中島 一裕
(M1)



金田 誠
(M1)



鈴木 邦也
(M1)



Li Wei
(M1)



大西 健人
(M1)



吉村 啓彦
(M1)



神野 浩介
(M1)



高田 謙治
(M1)



夏目 真介
(M1)



金原 謙
(M1)



学部
生
(3人)



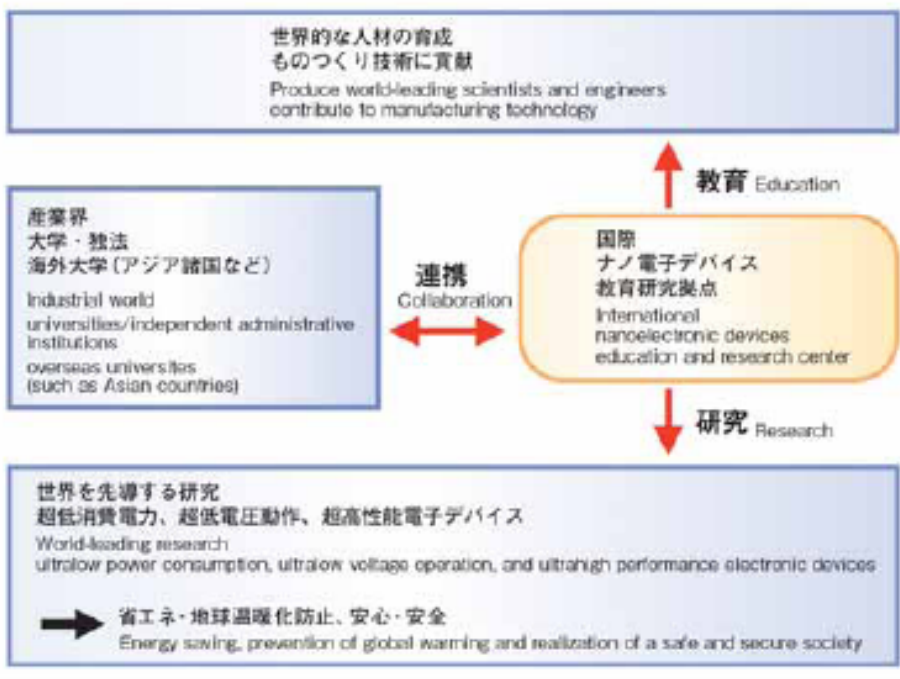
藤原 士
(B4)



久保 昌彦
(B4)



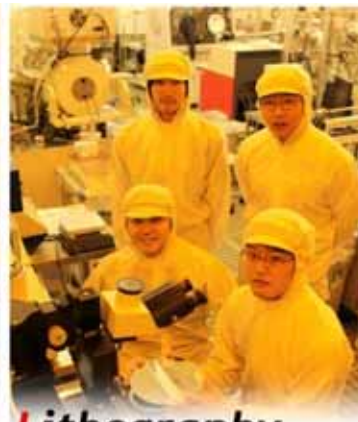
山口 成幸
(B4)



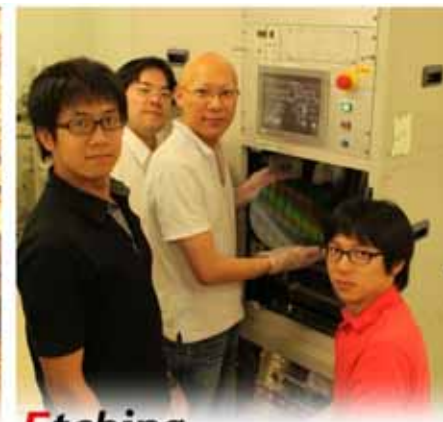
研究風景



Deposition



Lithography



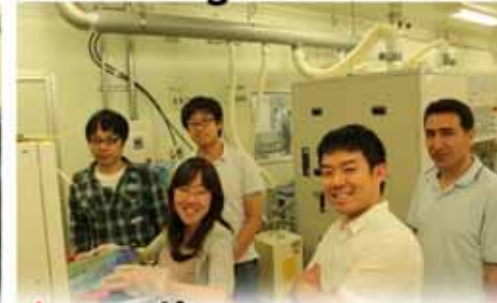
Etching



Analysis



Measurement



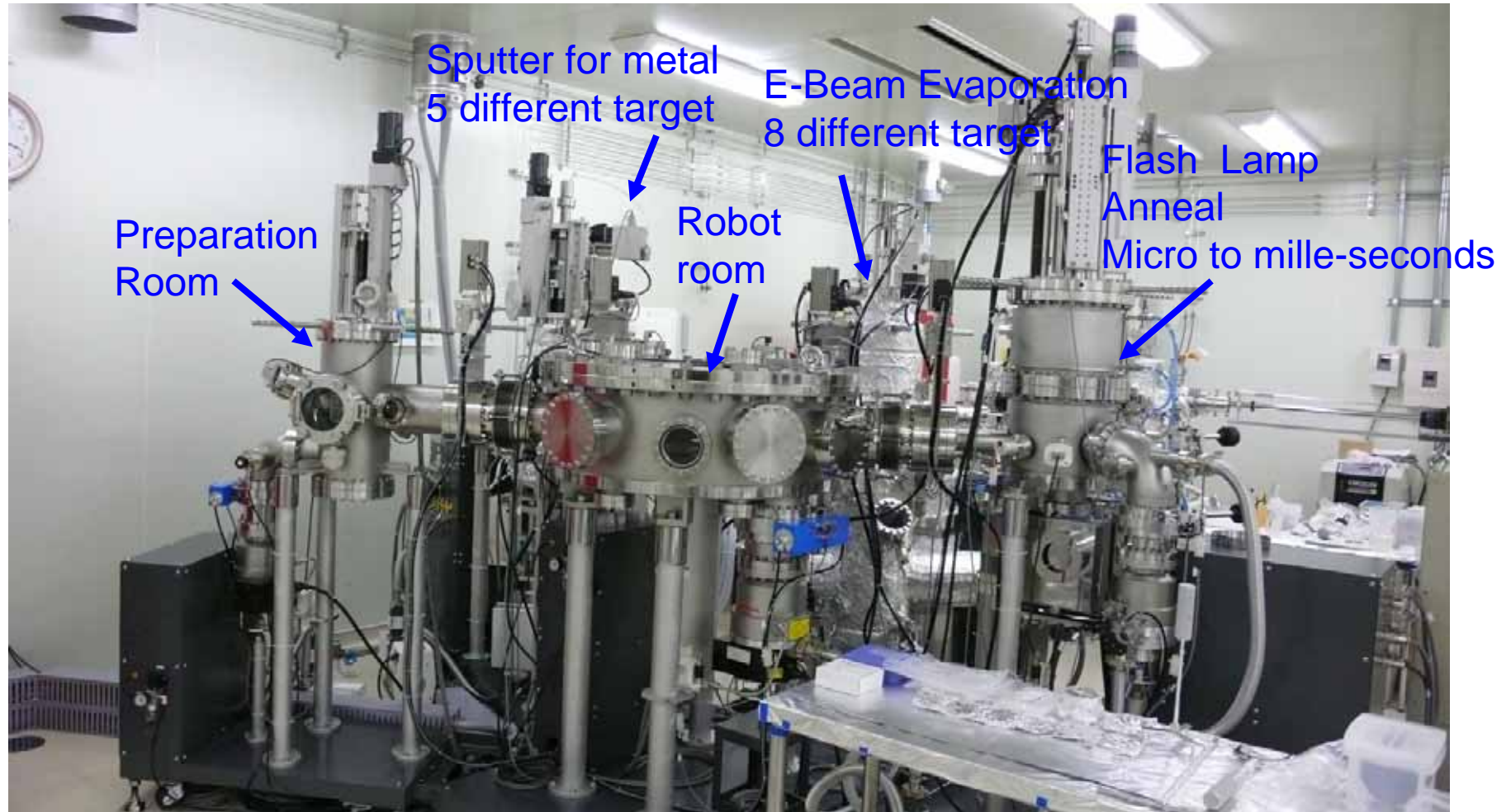
Annealing



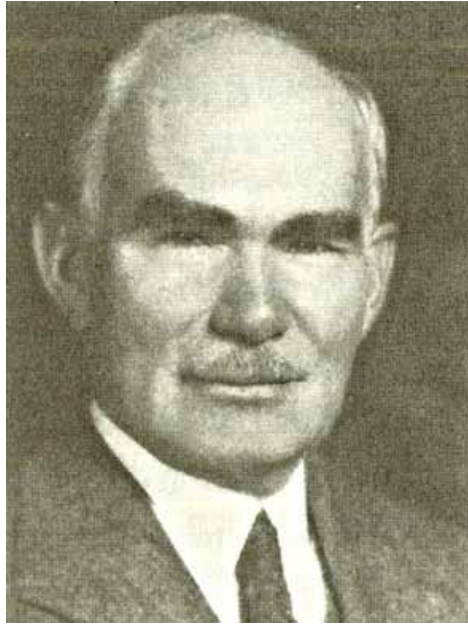
Office



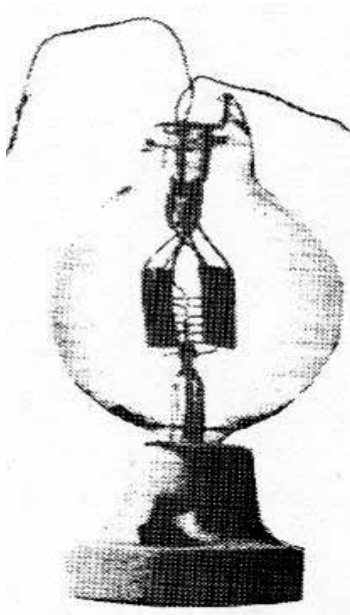
Cluster tool for high-k thin film deposition



- There were many inventions in the 20th century:
Airplane, Nuclear Power generation, Computer,
Space aircraft, etc
- However, everything has to be controlled by
electronics
- Electronics
Most important invention in the 20th century
- What is Electronics: To use electrons,
Electronic Circuits

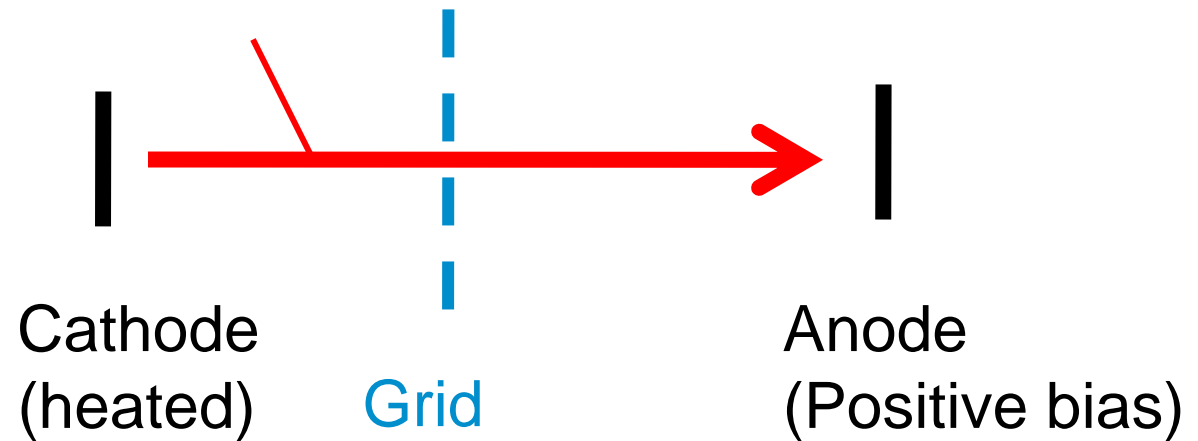


Lee De Forest



Electronic Circuits started by the invention of vacuum tube (Triode) in 1906

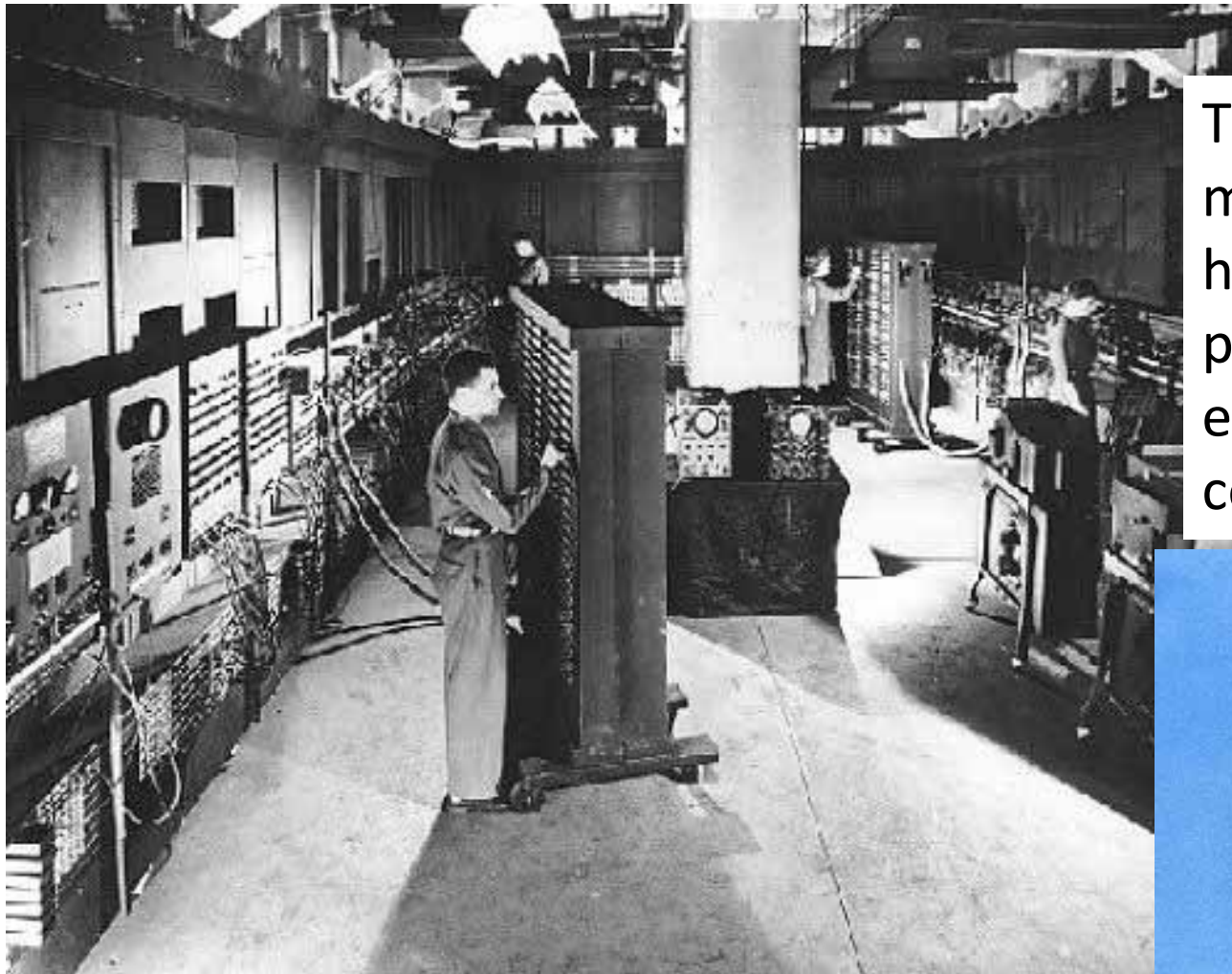
Thermal electrons from cathode controlled by grid bias



Same mechanism as that of transistor

First Computer Eniac: made of huge number of vacuum tubes 1946
Big size, huge power, short life time filament

→ dreamed of replacing vacuum tube with solid-state device



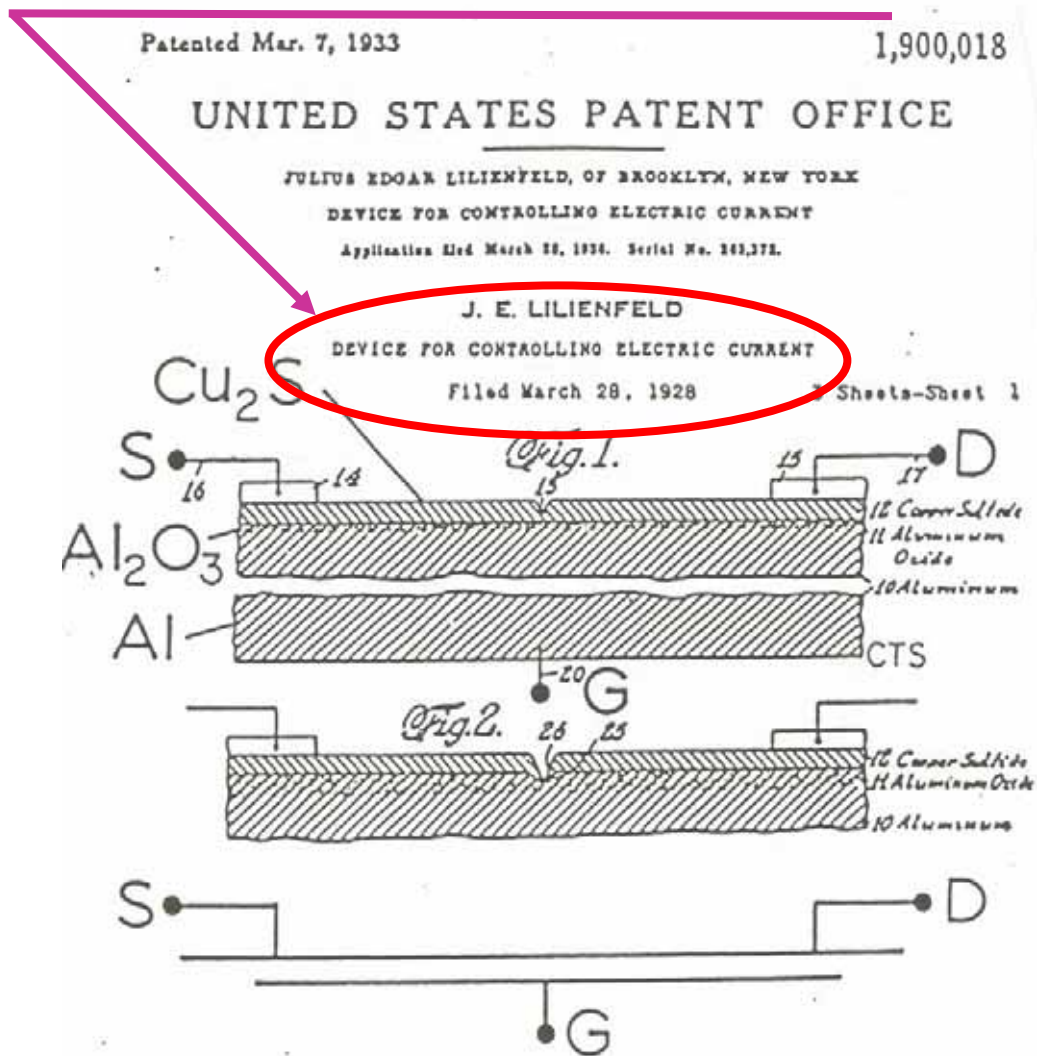
Today's pocket PC
made of semiconductor
has much higher
performance with
extremely low power
consumption



J. E. LILIENFELD

DEVICES FOR CONTROLLED ELECTRIC CURRENT

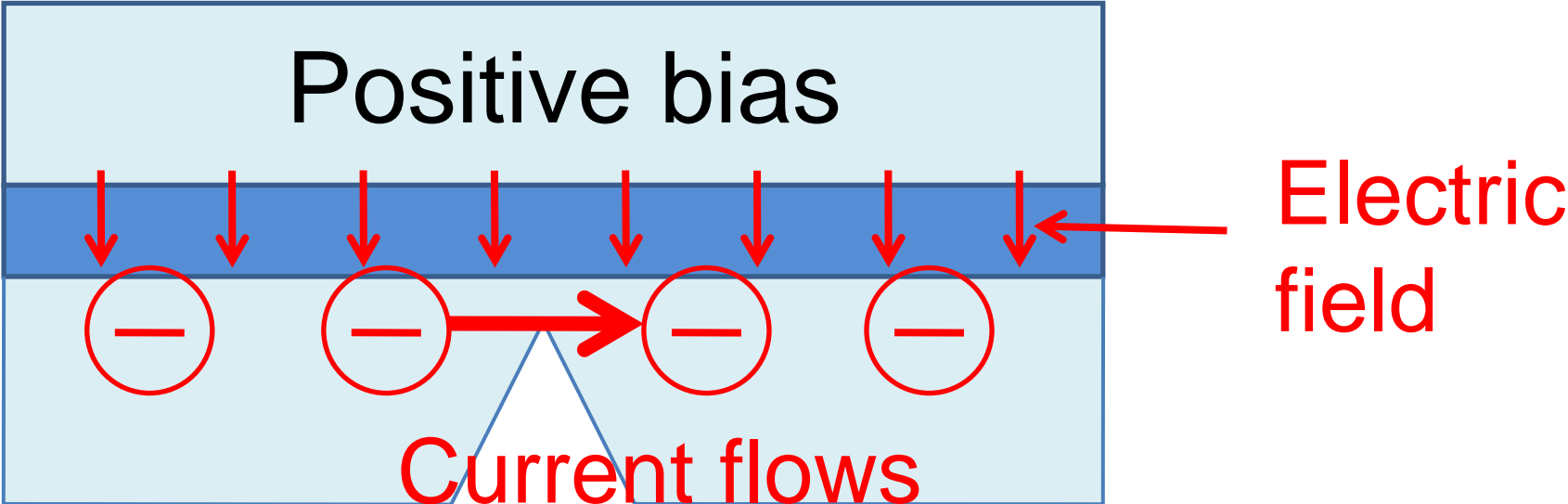
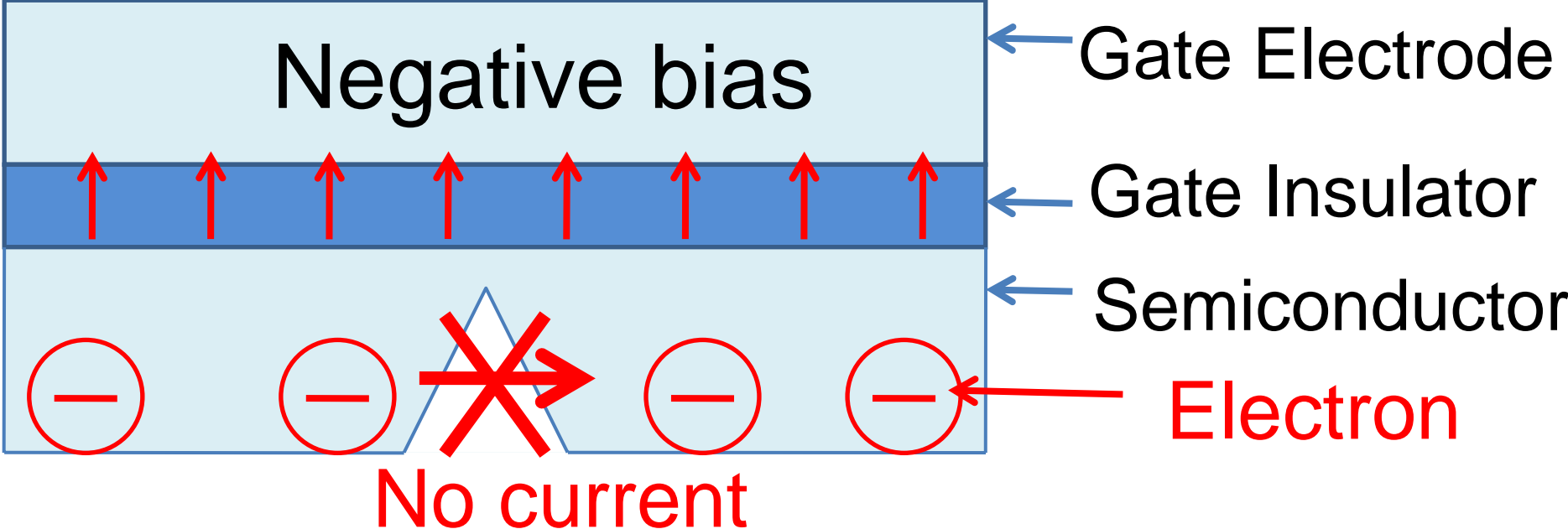
Filed March 28, 1928

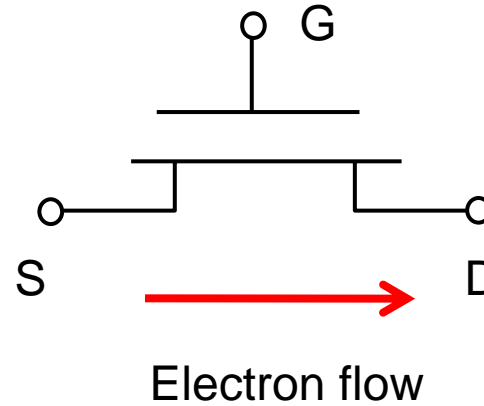
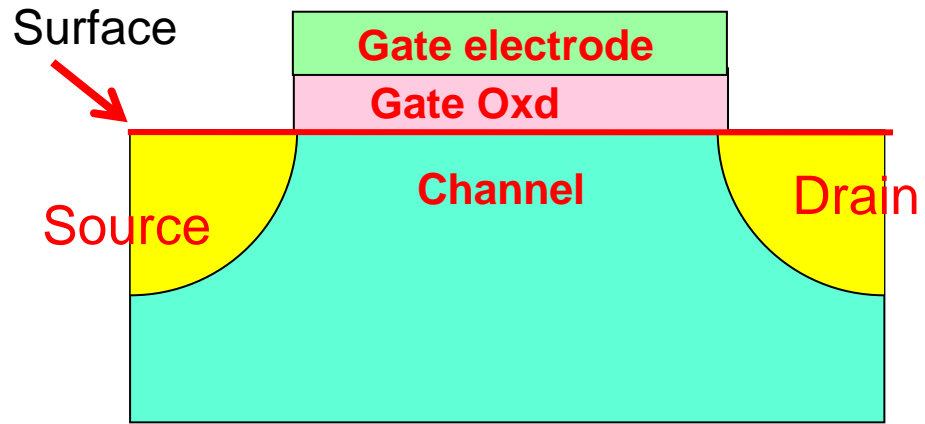


J.E.LILIENFELD



Capacitor structure with notch

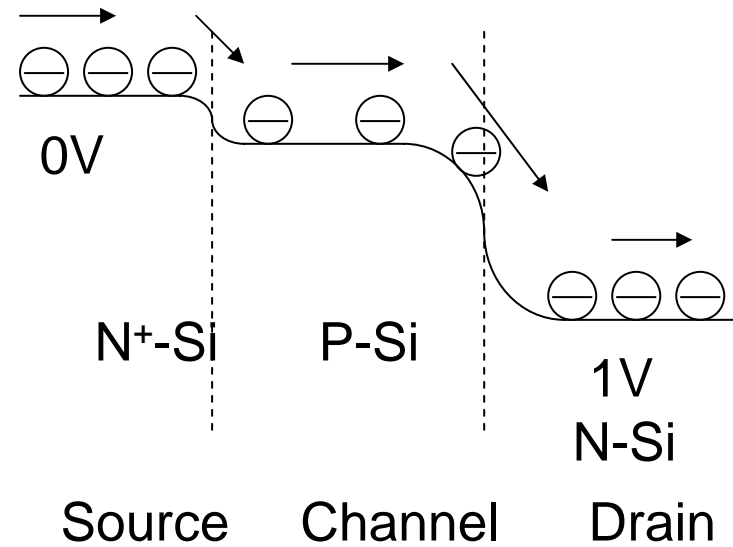
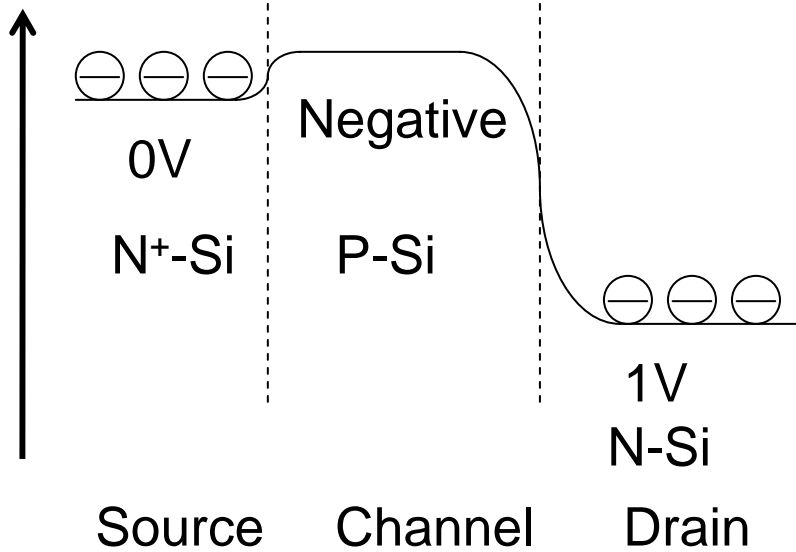




0 bias for gate

Positive bias for gate

Surface Potential (Negative direction)

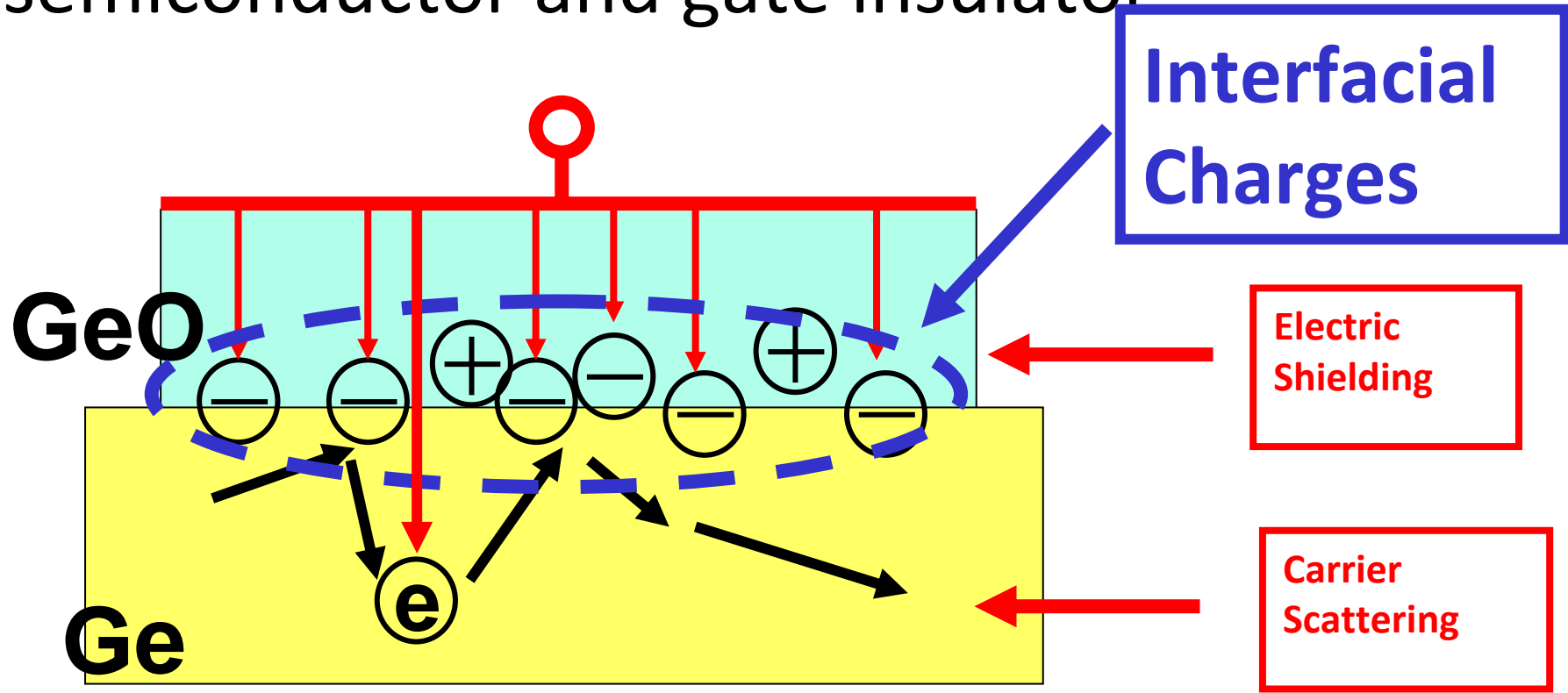


However, no one could realize MOSFET operation for more than 30 years.

Because of very bad interface property between the semiconductor and gate insulator

Even Shockley!

Very bad interface property between the semiconductor and gate insulator



Drain Current was several orders of magnitude smaller than expected

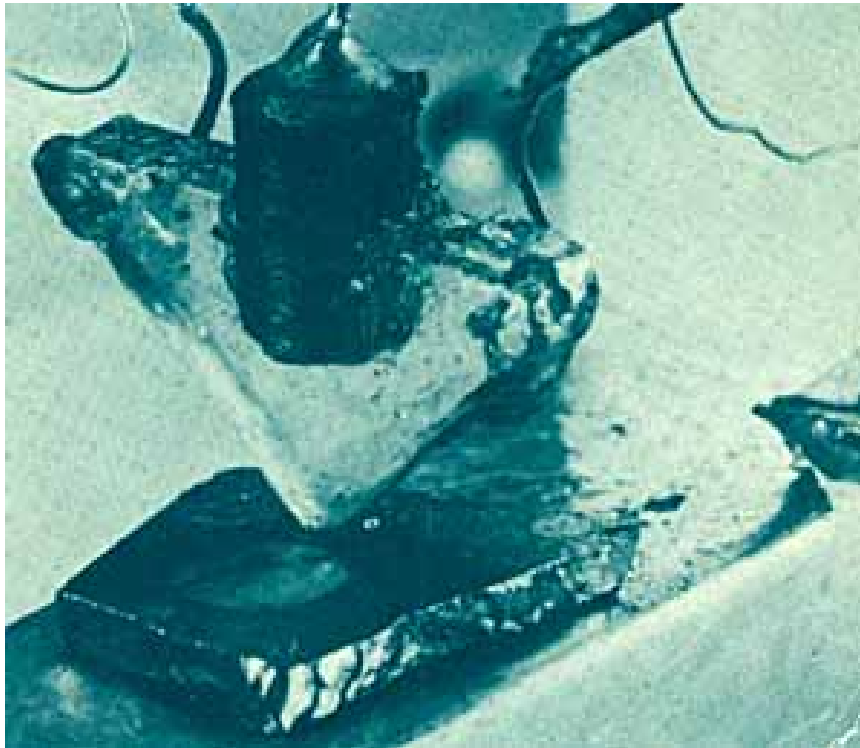
Even Shockley!

However, they found amplification phenomenon when investigating Ge surface when putting needles.

This is the 1st Transistor:

**Not Field Effect Transistor,
But Bipolar Transistor (another mechanism)**

1947: 1st transistor



Bipolar using Ge

J. Bardeen

W. Bratten,

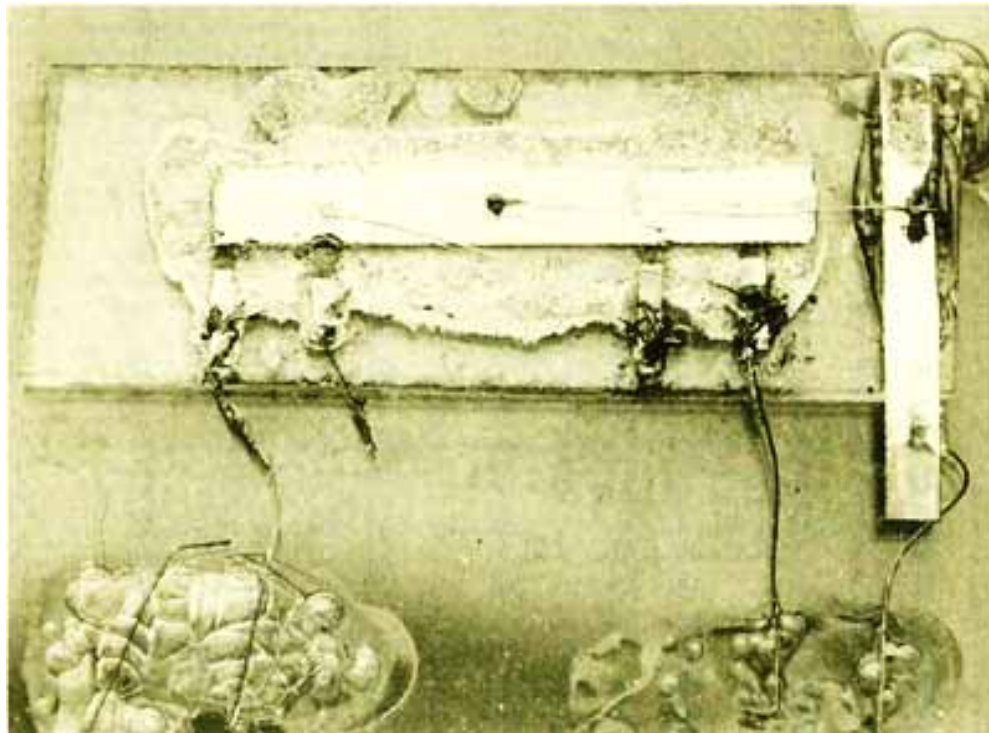


W. Shockley

1958: 1st Integrated Circuit

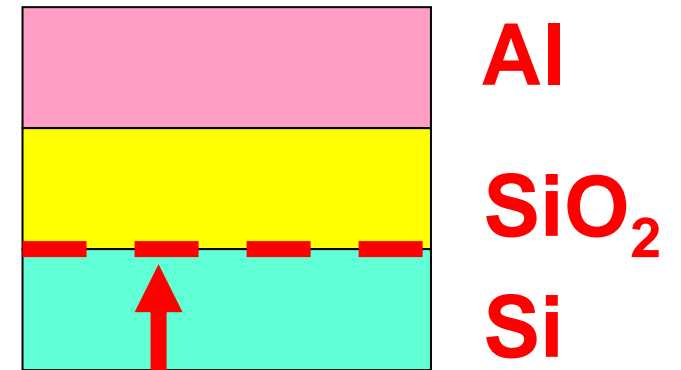
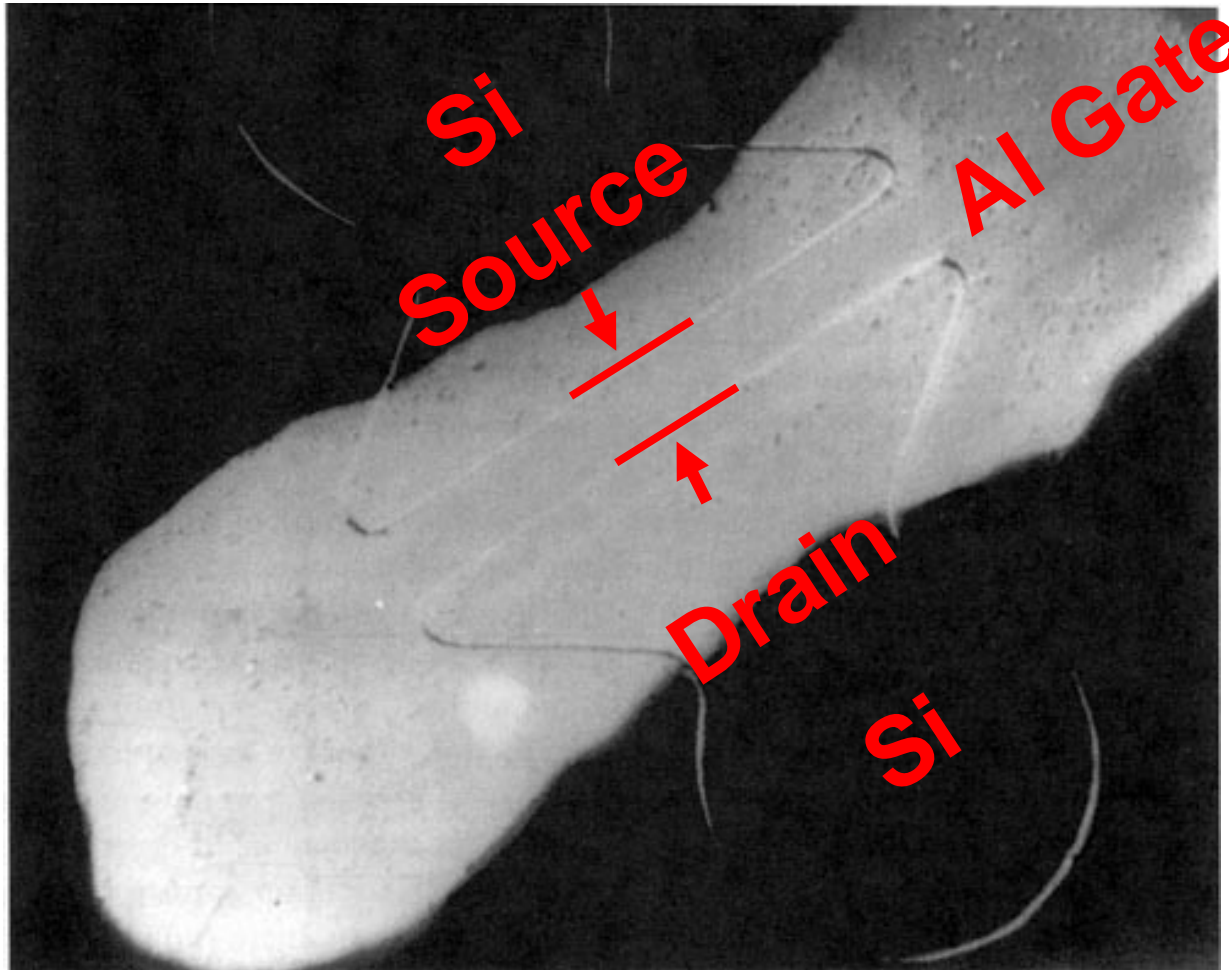
Jack S. Kilby

Connect 2 bipolar transistors in the Same substrate by bonding wire.



1960: First MOSFET
by D. Kahng and M. Atalla

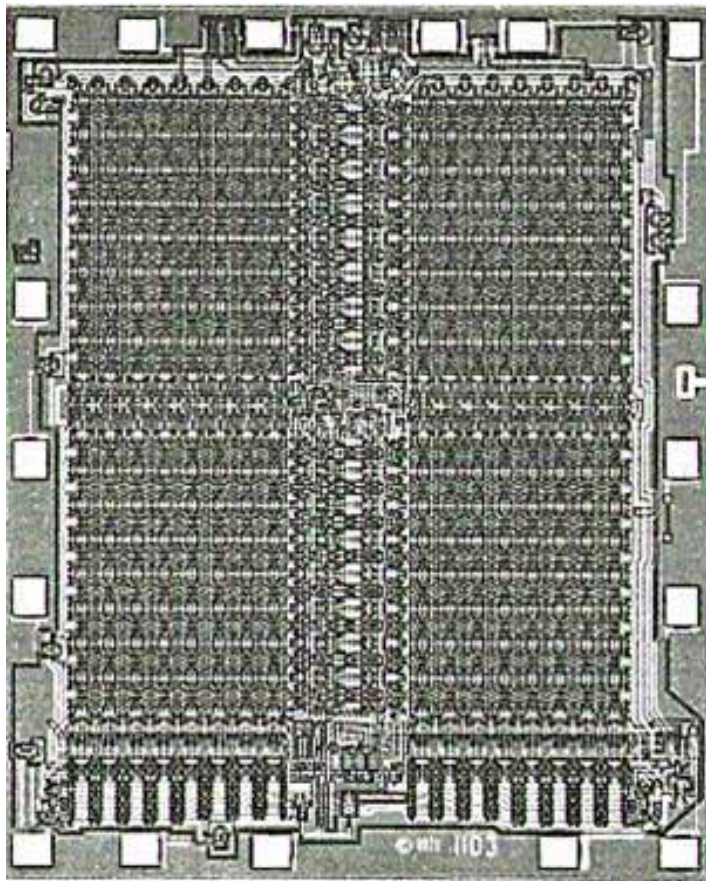
Top View



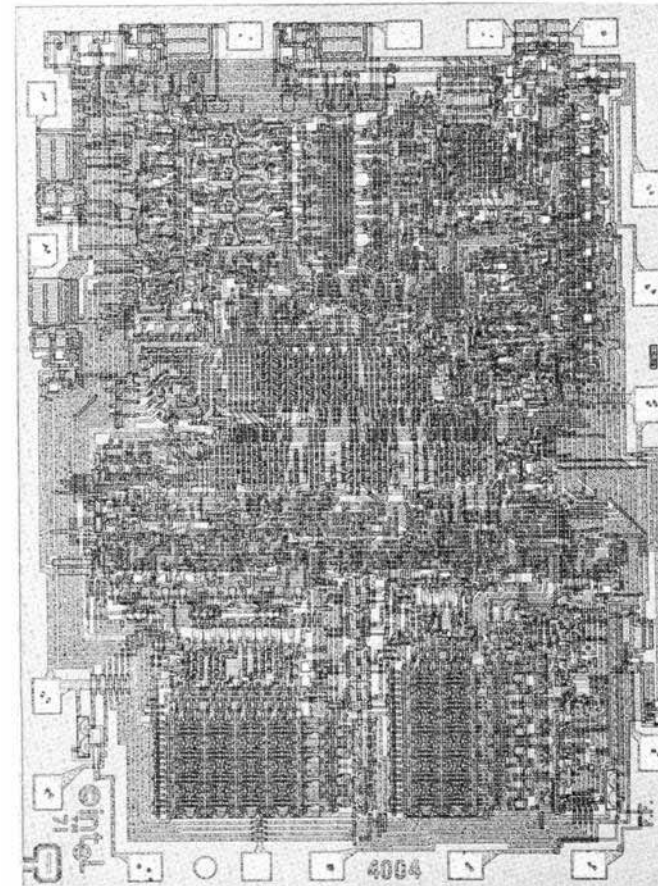
Si/SiO₂ Interface is
extraordinarily good

1970,71: 1st generation of LSIs

DRAM Intel 1103



MPU Intel 4004



MOS LSI experienced continuous progress for many years

	Name of Integrated Circuits	Number of Transistors
1960s	IC (Integrated Circuits)	~ 10
1970s	LSI (Large Scale Integrated Circuit)	~1,000
1980s	VLSI (Very Large Scale IC)	~10,000
1990s	ULSI (Ultra Large Scale IC)	~1,000,000
2000s	?LSI (? Large Scale IC)	~1000,000,000

Gate Electrode
Poly Si

Gate Insulator
SiO₂

Substrate
Si

MOSFET: Metal Oxide Semiconductor
Field Effect Transistor

Use Gate Field Effect for switching

Gate Electrode
Poly Si

Gate Insulator
SiO₂

Source

n-Si



n-Si

Drain

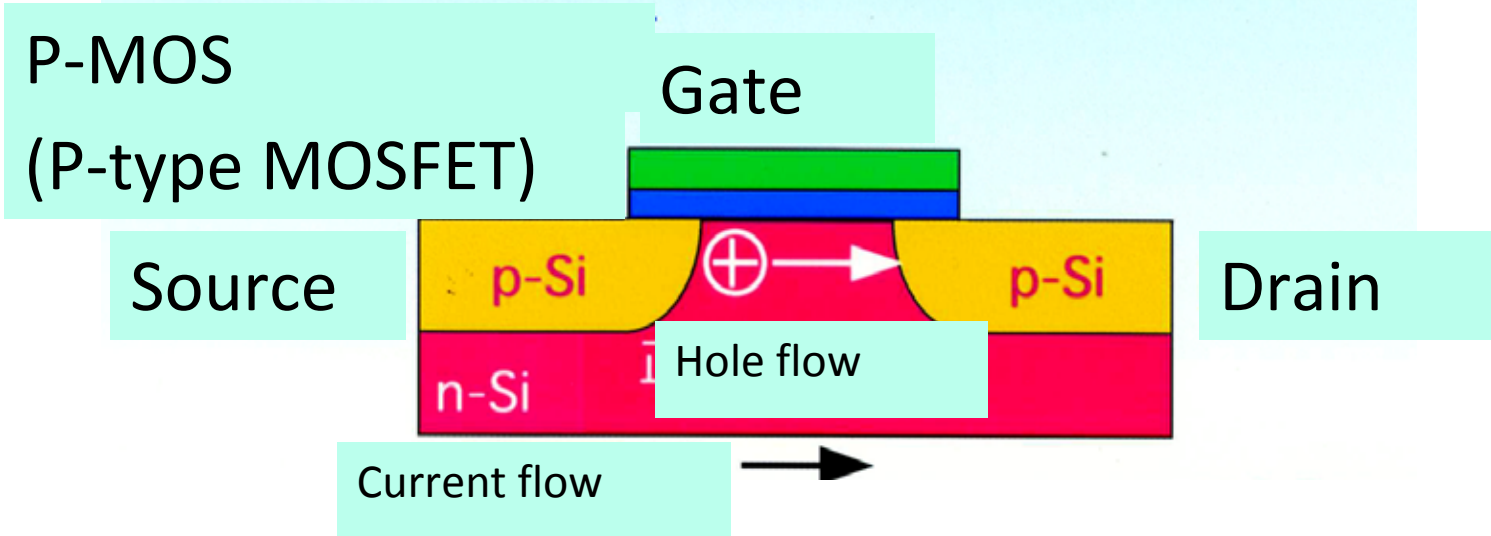
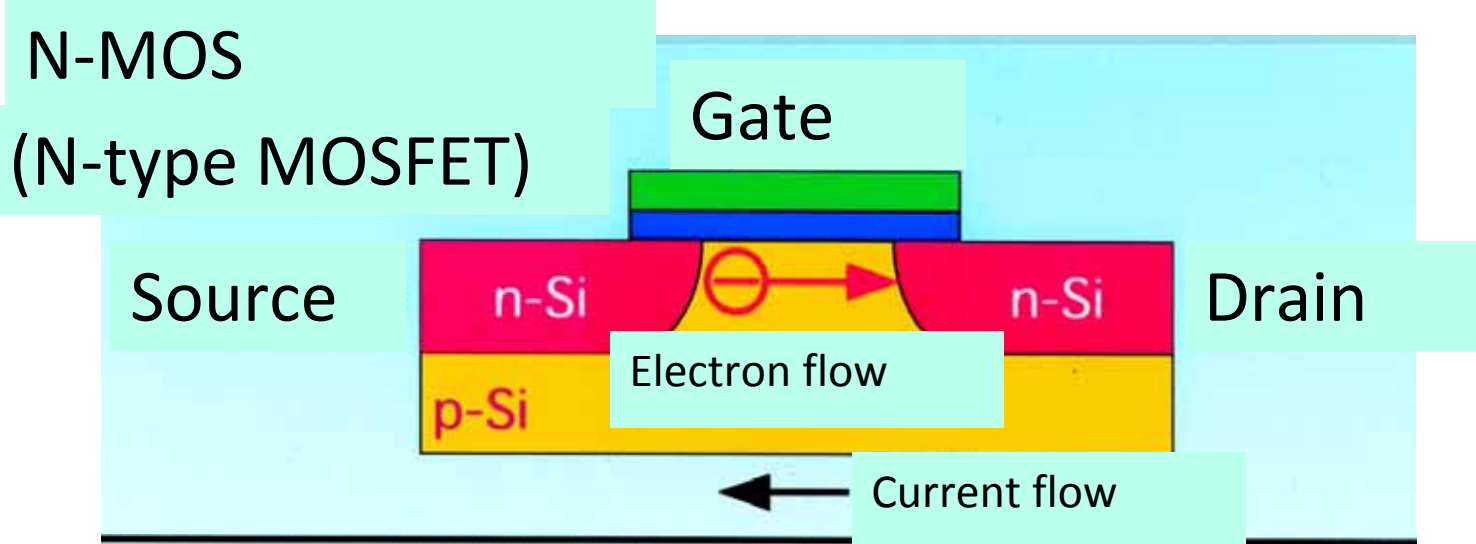
p-Si

Si

Substrate

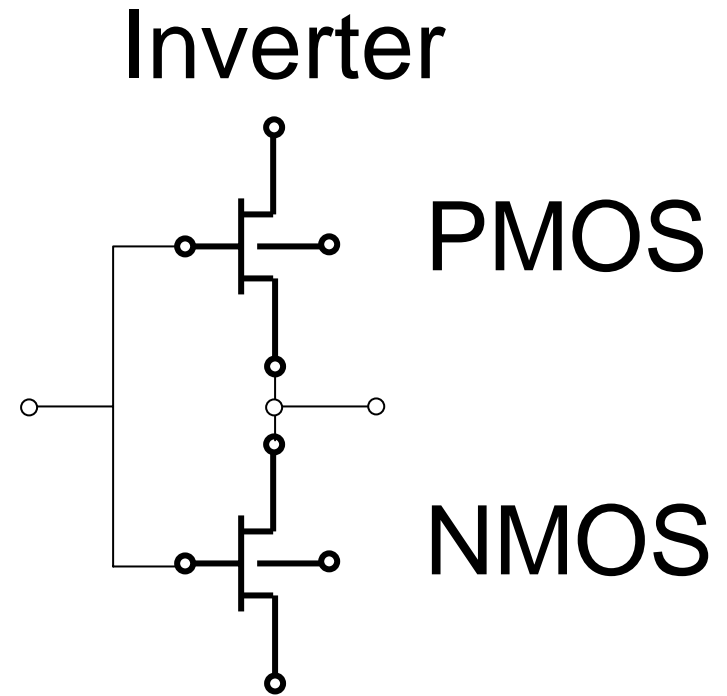
Channel

N-MOS (N-type MOSFET)



CMOS

Complimentary MOS



When NMOS is ON, PMOS is OFF

When PMOS is ON, NMOS is OFF

Needless to say, but....

CMOS Technology:

Indispensable for our human society

All the human activities are controlled by CMOS

living, production, financing, telecommunication,
transportation, medical care, education,
entertainment, etc.

Without CMOS:

There is no computer in banks, and
world economical activities immediately stop.

Cellarer phone dose not exists

Downsizing of the components has been the driving force for circuit evolution



1900	1950	1960	1970	2000
Vacuum Tube	Transistor	IC	LSI	ULSI
10 cm	cm	mm	10 μm	100 nm
10^{-1}m	10^{-2}m	10^{-3}m	10^{-5}m	10^{-7}m

In 100 years, the size reduced by one million times. There have been many devices from stone age. **We have never experienced such a tremendous reduction of devices in human history.**

Downsizing

1. Reduce Capacitance

→ Reduce switching time of MOSFETs

→ Increase clock frequency

→ Increase circuit operation speed

2. Increase number of Transistors

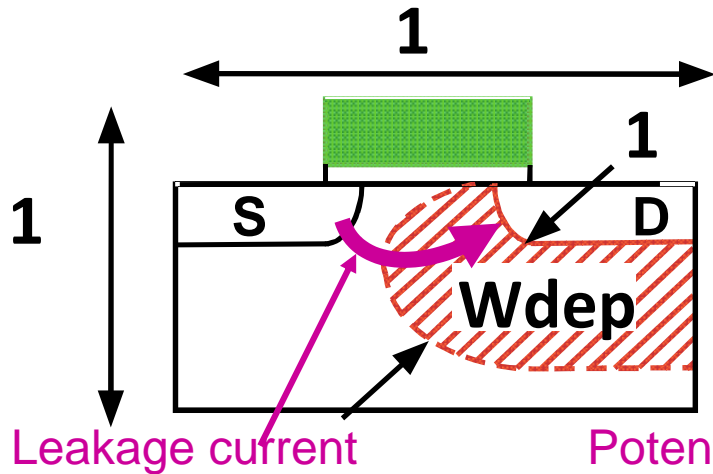
→ Parallel processing

→ Increase circuit operation speed

Downsizing contribute to the performance increase in double ways

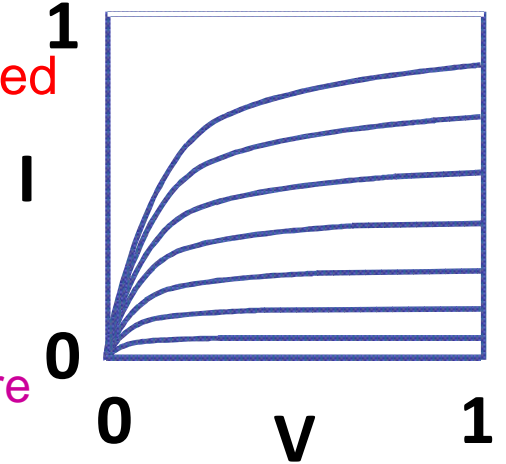
Thus, downsizing of Si devices is the most important and critical issue.²⁶

Scaling Method: by R. Dennard in 1974



W_{dep} : Space Charge Region (or Depletion Region) Width

W_{dep} has to be suppressed
Otherwise, large leakage
between S and D



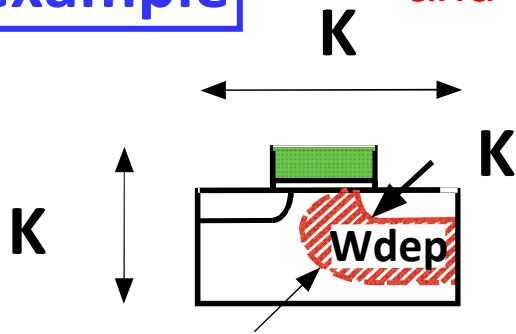
Potential in space charge region is high, and thus, electrons in source are attracted to the space charge region.

$K=0.7$
for
example

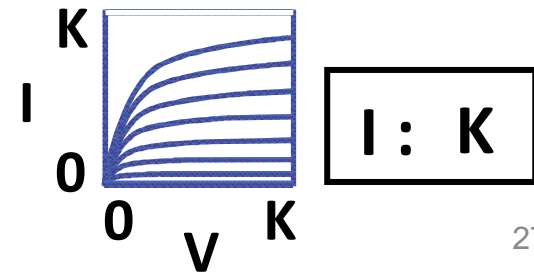
$X, Y, Z : K, \quad V : K, \quad N_a : 1/K$

By the scaling, W_{dep} is suppressed in proportion,
and thus, leakage can be suppressed.

→ Good scaled I-V characteristics



$W_{dep} \propto \sqrt{V/N_a}$
: K



$I : K$

Downscaling merit: Beautiful!

Geometry & Supply voltage	L_g, W_g T_{ox}, V_{dd}	K	Scaling K : K=0.7 for example
Drive current in saturation	I_d	K	$I_d = v_{sat} W_g C_o (V_g - V_{th})$ C_o : gate C per unit area $\rightarrow W_g (t_{ox}^{-1})(V_g - V_{th}) = W_g t_{ox}^{-1}(V_g - V_{th}) = KK^{-1}K = K$
I_d per unit W_g	$I_d/\mu m$	1	I_d per unit $W_g = I_d / W_g = 1$
Gate capacitance	C_g	K	$C_g = \epsilon_o \epsilon_{ox} L_g W_g / t_{ox} \rightarrow KK/K = K$
Switching speed	τ	K	$\tau = C_g V_{dd} / I_d \rightarrow KK/K = K$
Clock frequency	f	1/K	$f = 1/\tau = 1/K$
Chip area	A_{chip}	α	α: Scaling factor \rightarrow In the past, $\alpha > 1$ for most cases
Integration (# of Tr)	N	α/K^2	$N \rightarrow \alpha/K^2 = 1/K^2$, when $\alpha=1$
Power per chip	P	α	$fNCV^2/2 \rightarrow K^{-1}(\alpha K^{-2})K(K^1)^2 = \alpha = 1$, when $\alpha=1$

$k = 0.7$ and $\alpha = 1$

Single MOFET

$V_{dd} \rightarrow 0.7$

$L_g \rightarrow 0.7$

$I_d \rightarrow 0.7$

$C_g \rightarrow 0.7$

P (Power)/Clock

$\rightarrow 0.7^3 = 0.34$

τ (Switching time) $\rightarrow 0.7$

$k = 0.7^2 = 0.5$ and $\alpha = 1$

$V_{dd} \rightarrow 0.5$

$L_g \rightarrow 0.5$

$I_d \rightarrow 0.5$

$C_g \rightarrow 0.5$

P (Power)/Clock

$\rightarrow 0.5^3 = 0.125$

τ (Switching time) $\rightarrow 0.5$

Chip

N (# of Tr) $\rightarrow 1/0.7^2 = 2$

f (Clock) $\rightarrow 1/0.7 = 1.4$

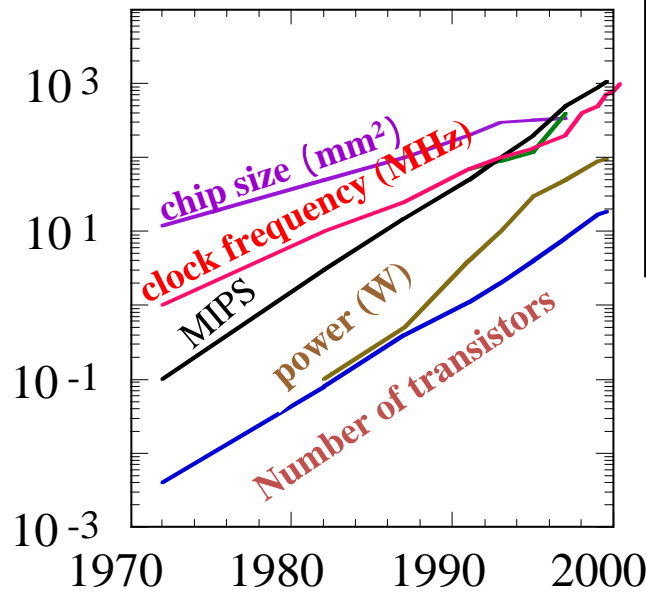
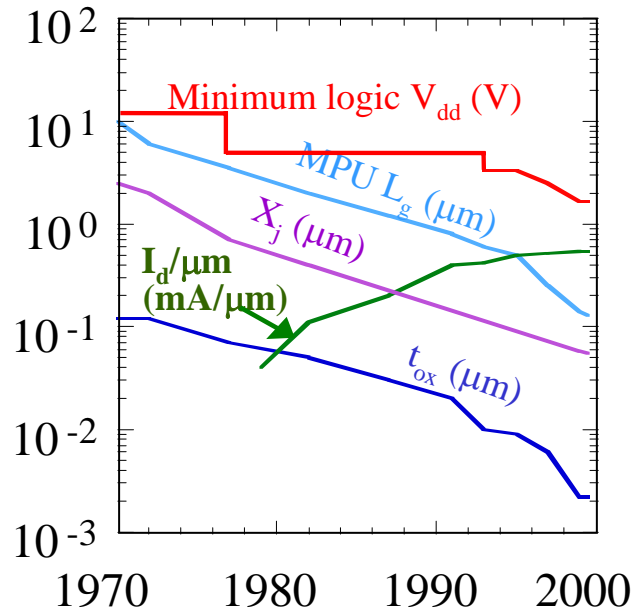
P (Power) $\rightarrow 1$

N (# of Tr) $\rightarrow 1/0.5^2 = 4$

f (Clock) $\rightarrow 1/0.5 = 2$

P (Power) $\rightarrow 1$

Actual past downscaling trend until year 2000



Past 30 years scaling
 Merit: N, f increase
 Demerit: P increase

V_{dd} scaling insufficient
 ↓
 Additional significant increase in I_d, f, P

Source: Iwai and S. Ohmi, Microelectronics Reliability 42 (2002), pp.1251-1268

Change in 30 years

	Ideal scaling	Real Change		Ideal scaling	Real Change		Ideal scaling	Real Change
L_g	K	10^{-2}	I_d	K (10^{-2})	10^{-1}	f	$1/K(10^2)$	10^3
t_{ox}	K(10^{-2})	10^{-2}	$I_d/\mu m$	1	10^1	P	$\alpha(10^1)$	10^5
V_{dd}	K(10^{-2})	10^{-1}	N	$\alpha/K^2(10^5)$	10^4	= $f\alpha NCV^2$		
A_{chip}	α	10^1						

V_d scaling insufficient, α increased → N, I_d , f, P increased significantly

Many people wanted to say about the limit. Past predictions were not correct!!

Period	Expected limit(size)	Cause
Late 1970's	1 μ m:	SCE
Early 1980's	0.5 μ m:	S/D resistance
Early 1980's	0.25 μ m:	Direct-tunneling of gate SiO ₂
Late 1980's	0.1 μ m:	'0.1 μ m brick wall'(various)
2000	50nm:	'Red brick wall' (various)
2000	10nm:	Fundamental?

Historically, many predictions of the limit of downsizing.

VLSI text book written 1979 predict that 0.25 micrometer would be the limit because of direct-tunneling current through the very thin-gate oxide.

INTRODUCTION TO **VLSI** SYSTEMS

CARVER MEAD • LYNN CONWAY





C. Mead

L. Conway

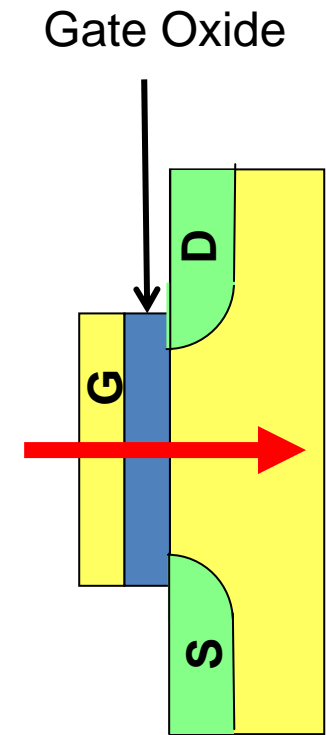
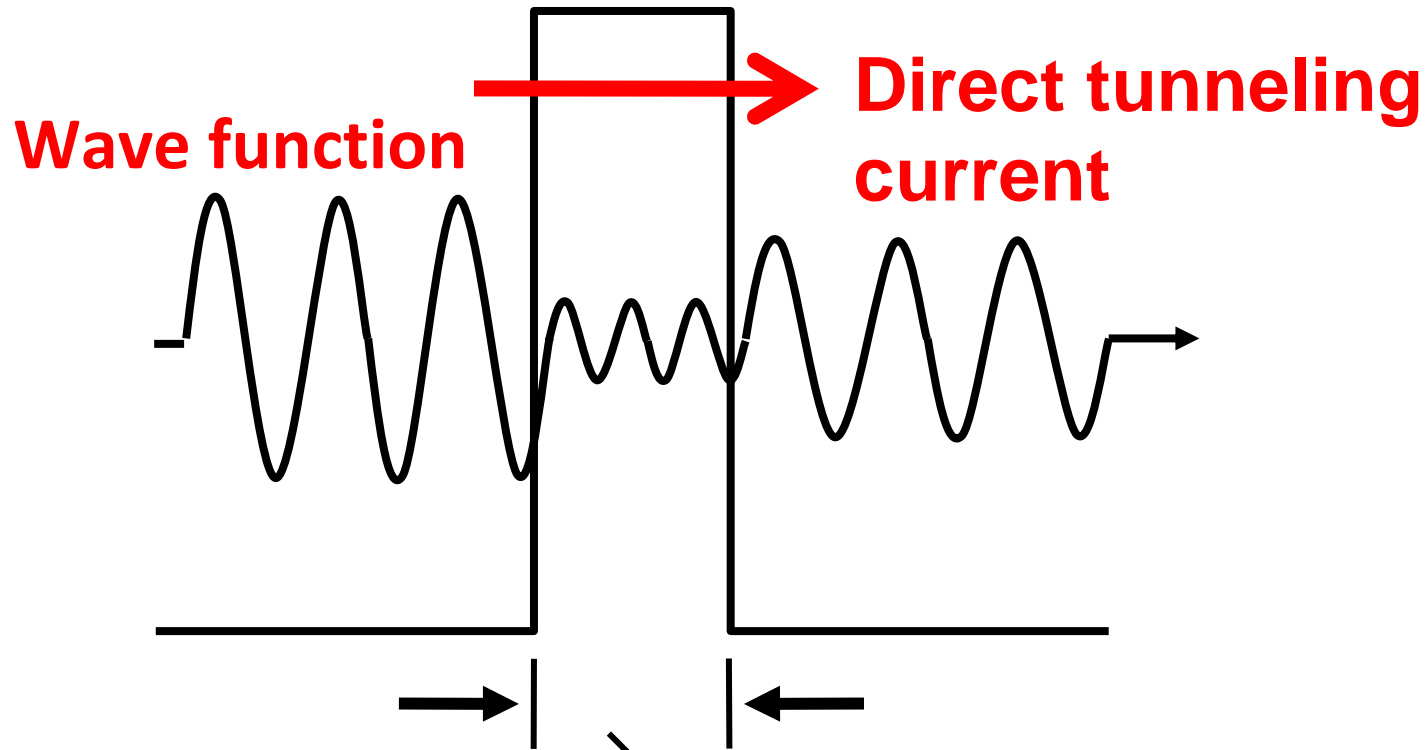
VLSI textbook

Finally, there appears to be a fundamental limit ¹⁰ of approximately quarter micron channel length, where certain physical effects such as the **tunneling through the gate oxide begin to make the devices of smaller dimension unworkable.**

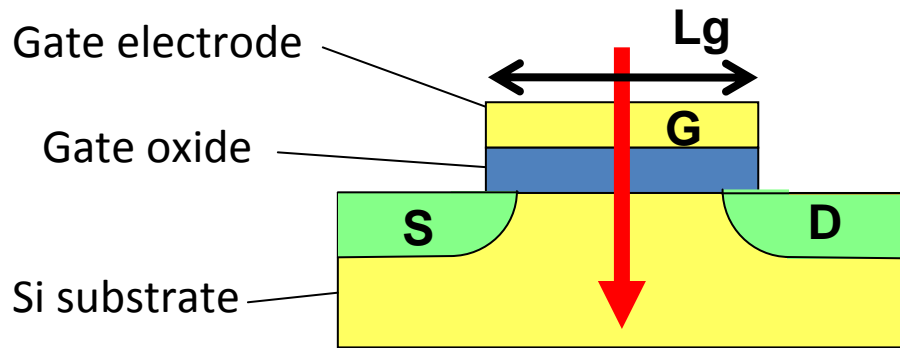
Direct-tunneling effect

Gate Electrode Gate Oxide Si Substrate

Potential Barrier



Direct tunneling leakage current start to flow when the thickness is 3 nm.



Direct tunneling leakage was found to be OK! In 1994!

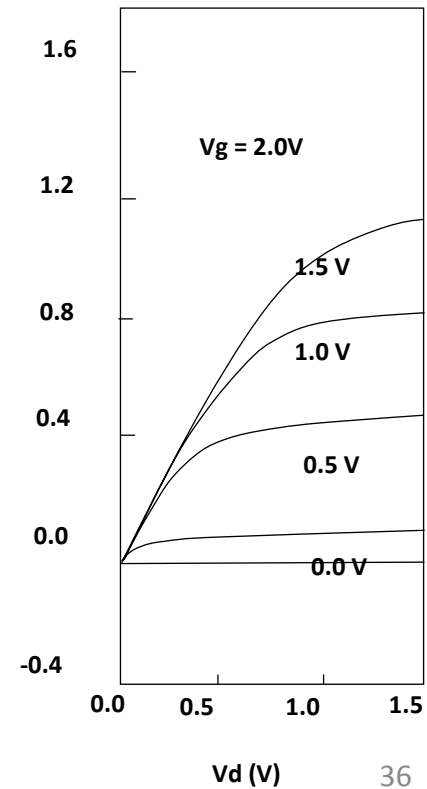
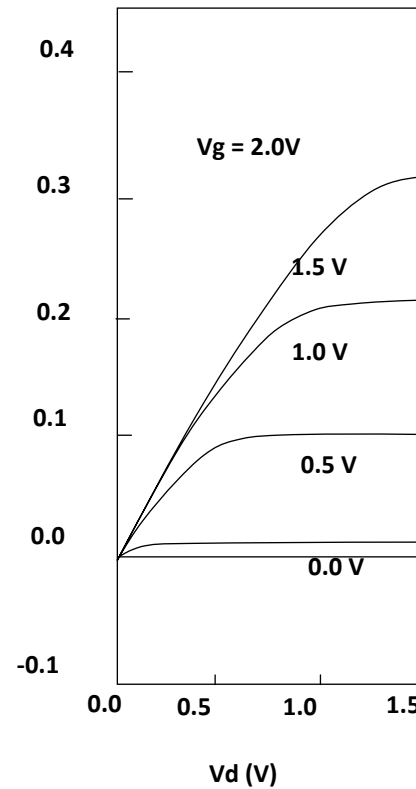
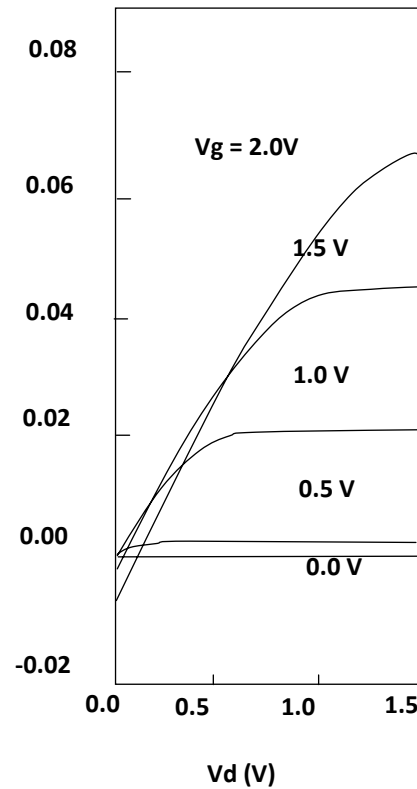
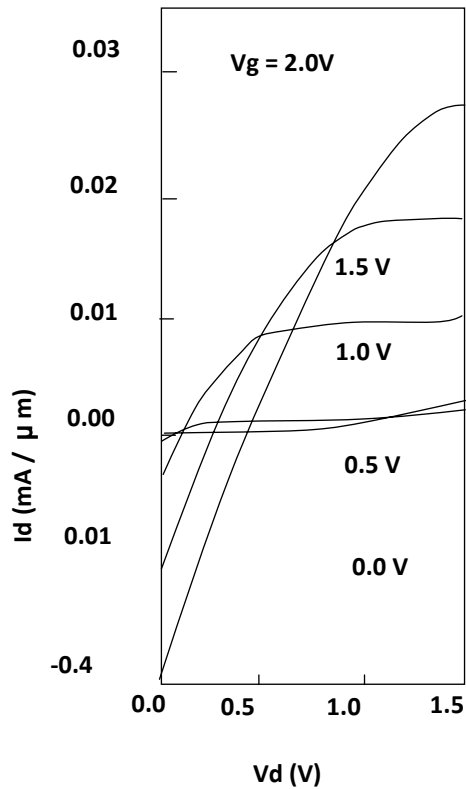
MOSFETs with 1.5 nm gate oxide

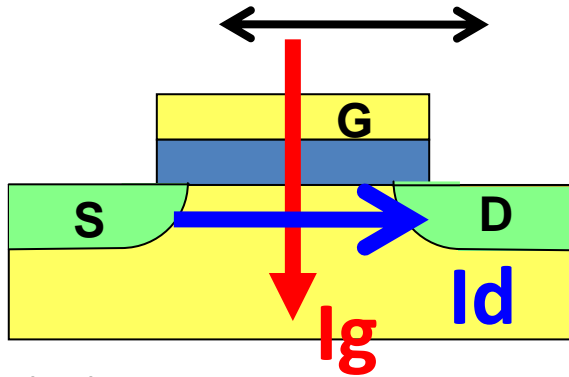
$L_g = 10 \mu\text{m}$

$L_g = 5 \mu\text{m}$

$L_g = 1.0 \mu\text{m}$

$L_g = 0.1 \mu\text{m}$





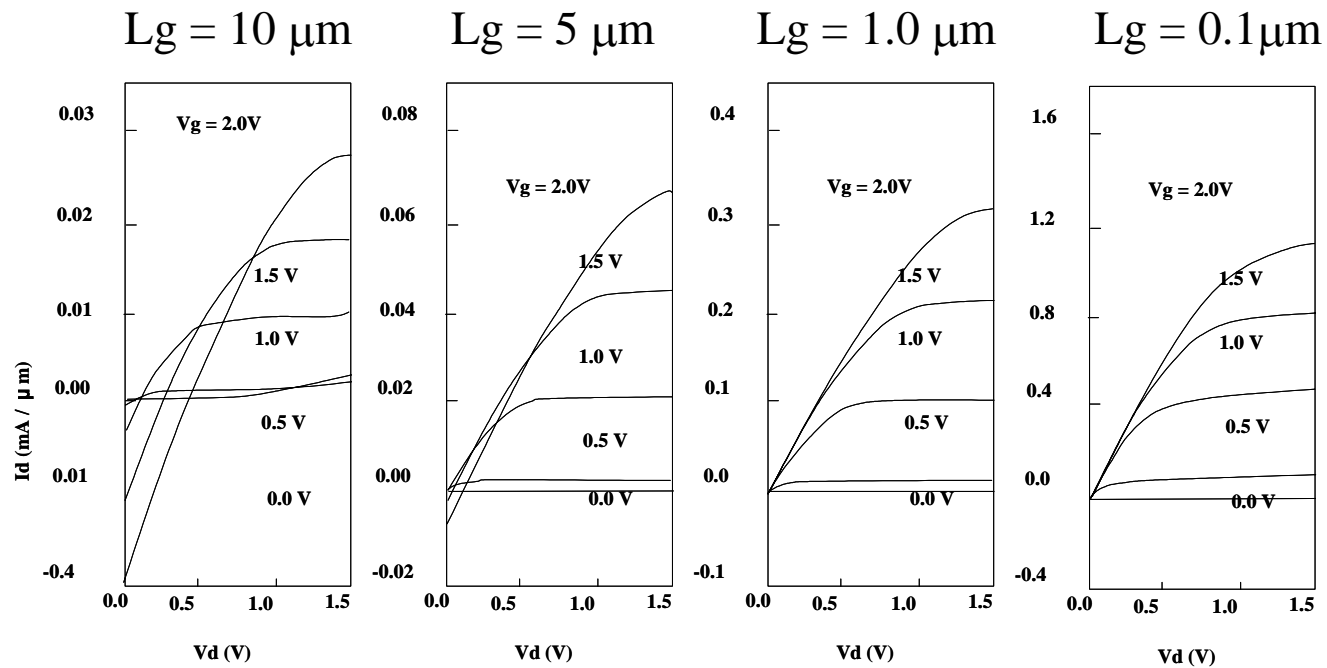
Gate leakage: $I_g \propto \text{Gate Area} \propto \text{Gate length (L}_g)$

Drain current: $I_d \propto 1/\text{Gate length (L}_g)$

$L_g \rightarrow$ small,

Then, $I_g \rightarrow$ small, $I_d \rightarrow$ large, Thus, $I_g/I_d \rightarrow$ very small

I_d
→



Do not believe a text book statement, blindly!

Never Give Up!

No one knows future!

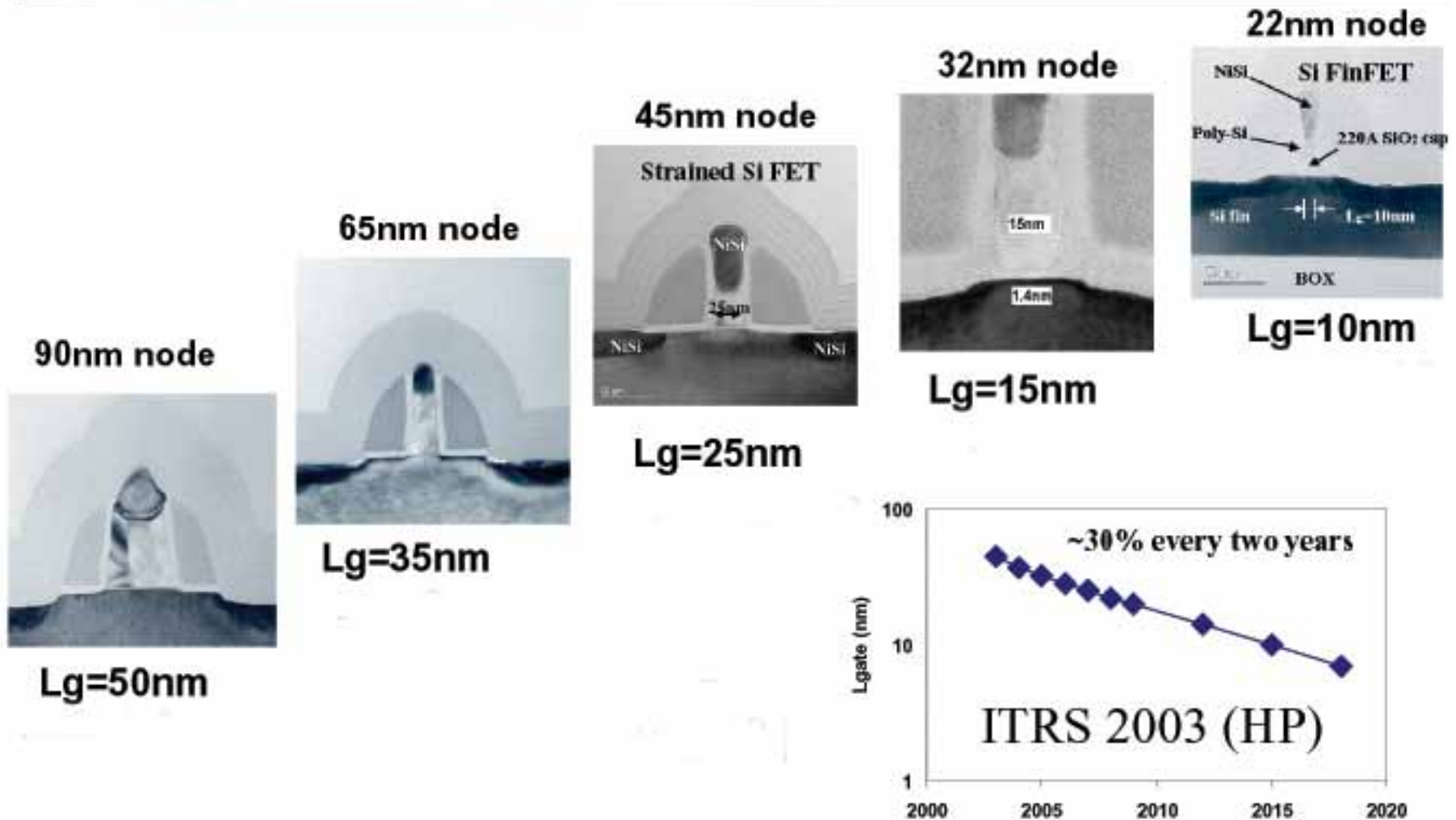
There would be a solution!

Think, Think, and Think!

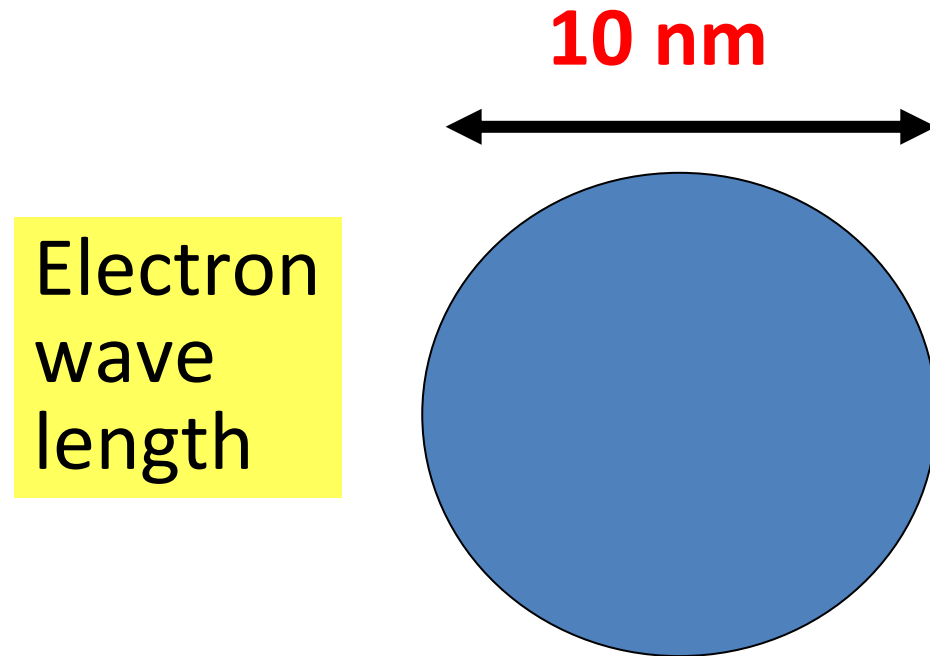
Or, Wait the time!

Some one will think for you

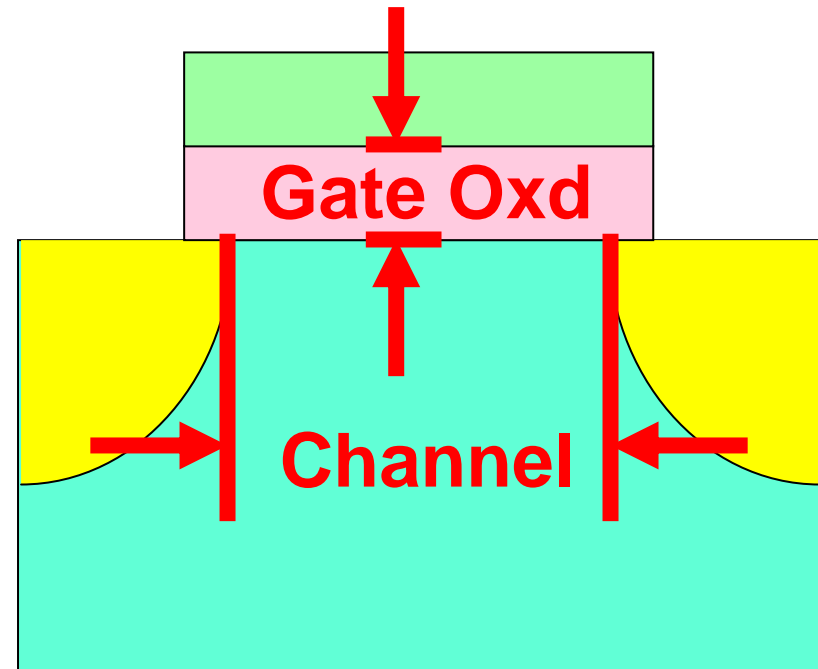
Transistor Scaling Continues



Downsizing limit?

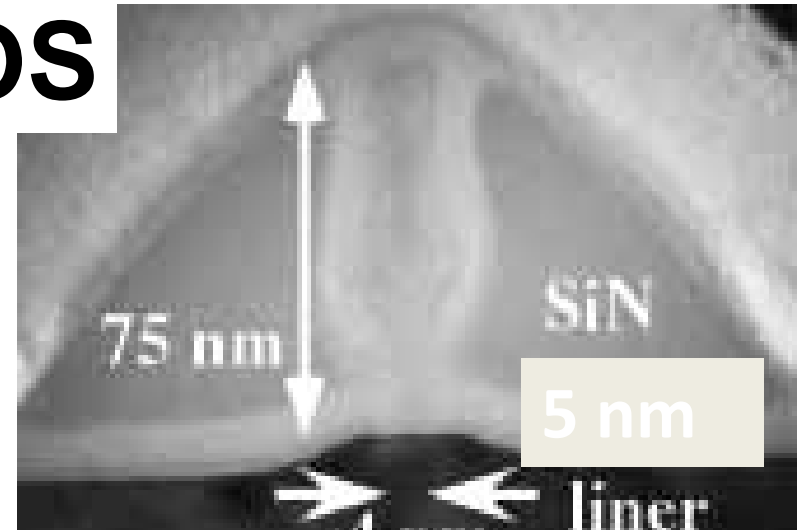


Channel length?

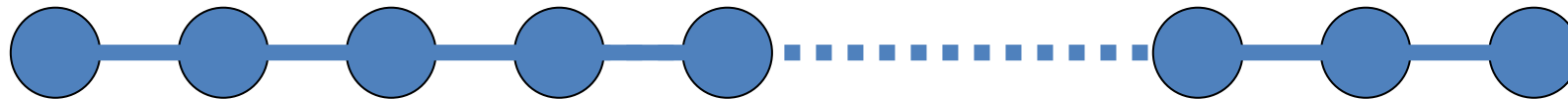


5 nm gate length CMOS

Is a Real Nano Device!!

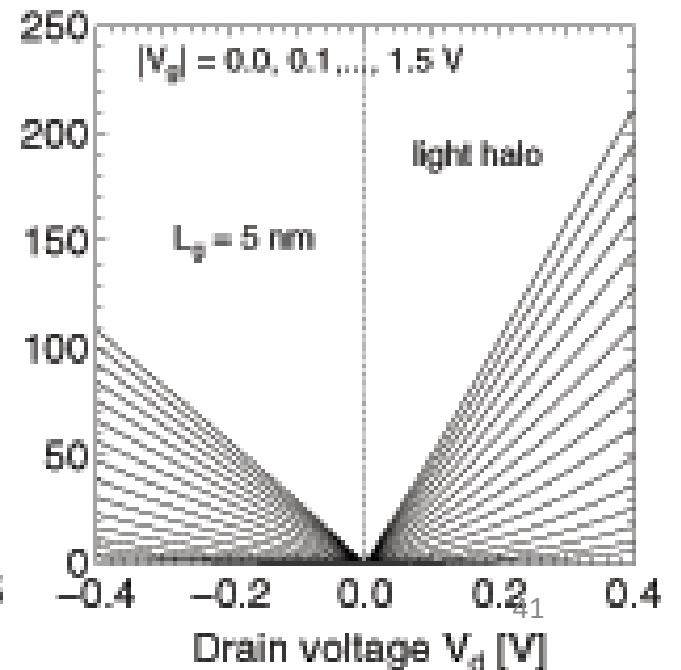
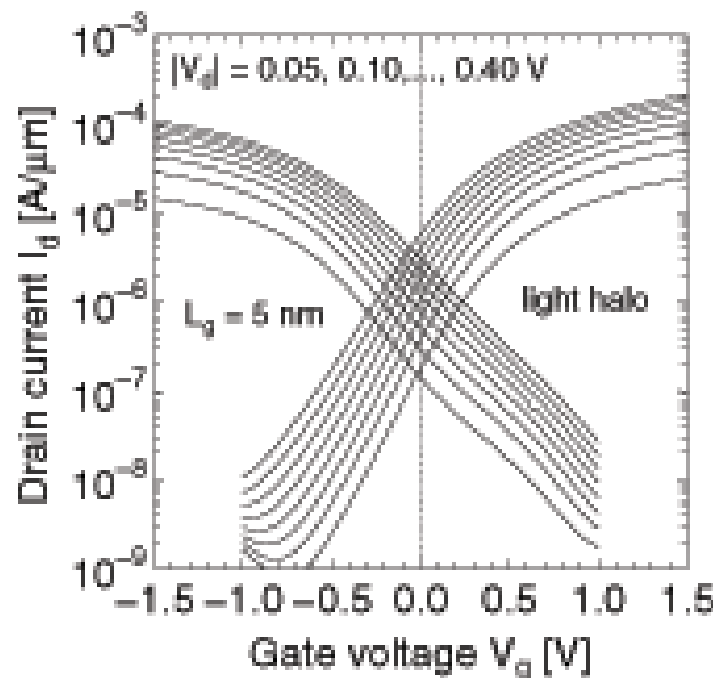


Length of 18 Si atoms



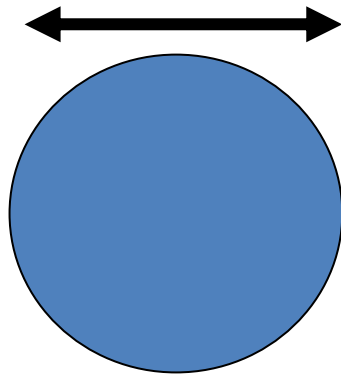
H. Wakabayashi
et.al, NEC

IEDM, 2003



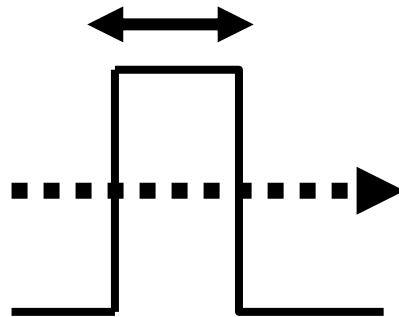
Electron
wave
length

10 nm



Tunneling
distance

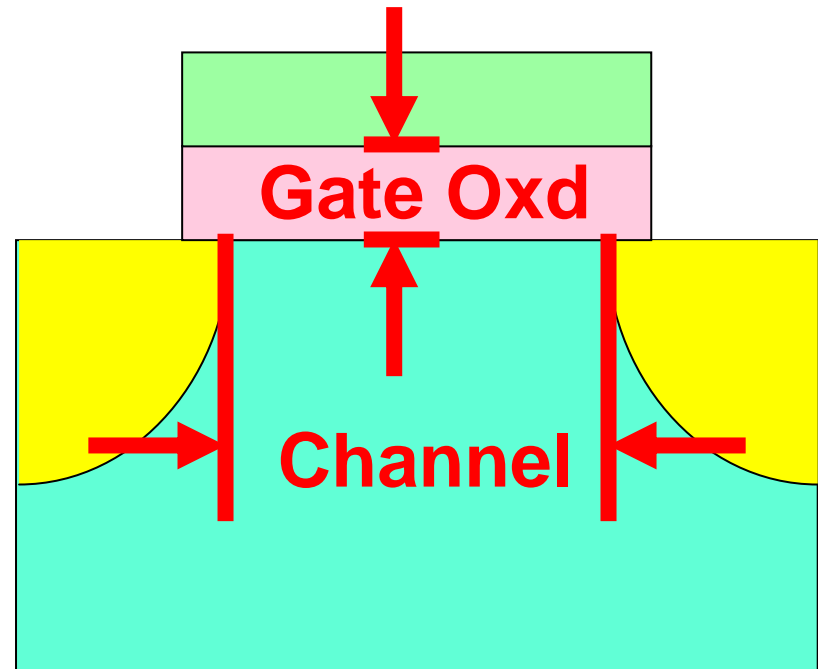
3 nm



Downsizing limit!

Channel length

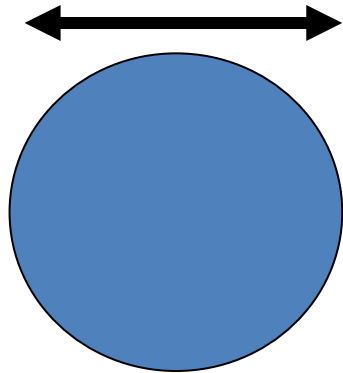
Gate oxide thickness



Prediction now!

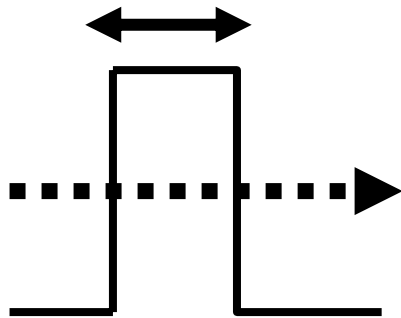
Electron wave length

10 nm



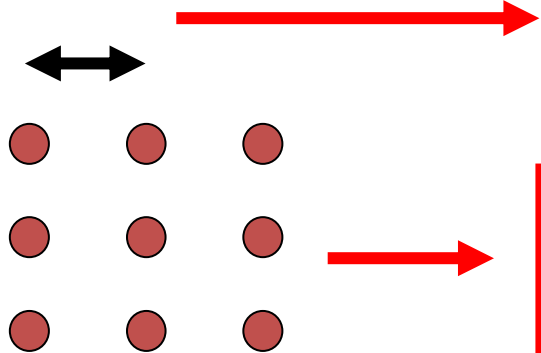
Tunneling distance

3 nm



Atom distance

0.3 nm

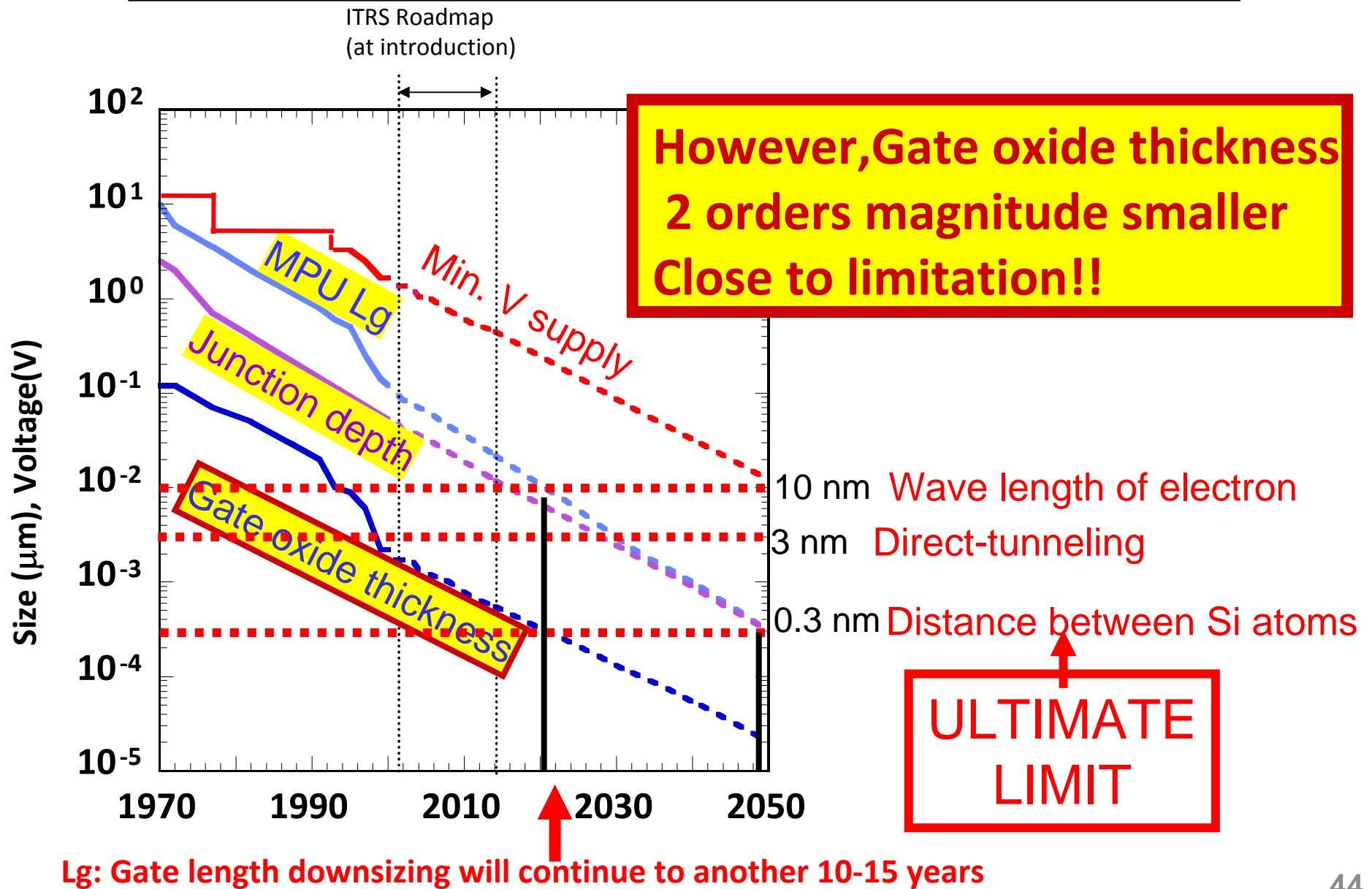


MOSFET operation

$L_g = 2 \sim 1.5 \text{ nm?}$

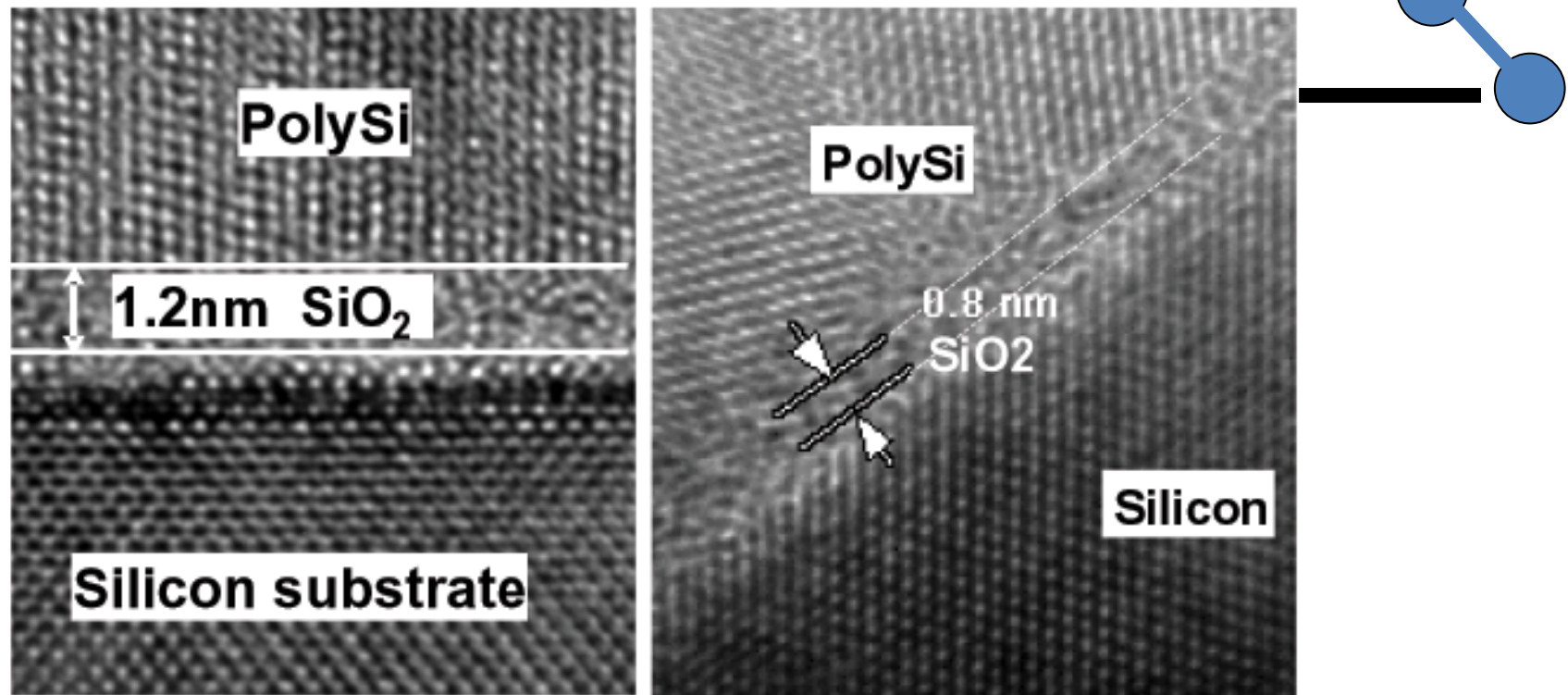
Below this,
no one knows future!

Ultimate limitation



0.8 nm Gate Oxide Thickness MOSFETs operates!!

0.8 nm: Distance of 3 Si atoms!!



- 1.2nm physical SiO₂ in production (90nm logic node)
- 0.8nm physical SiO₂ in research transistors

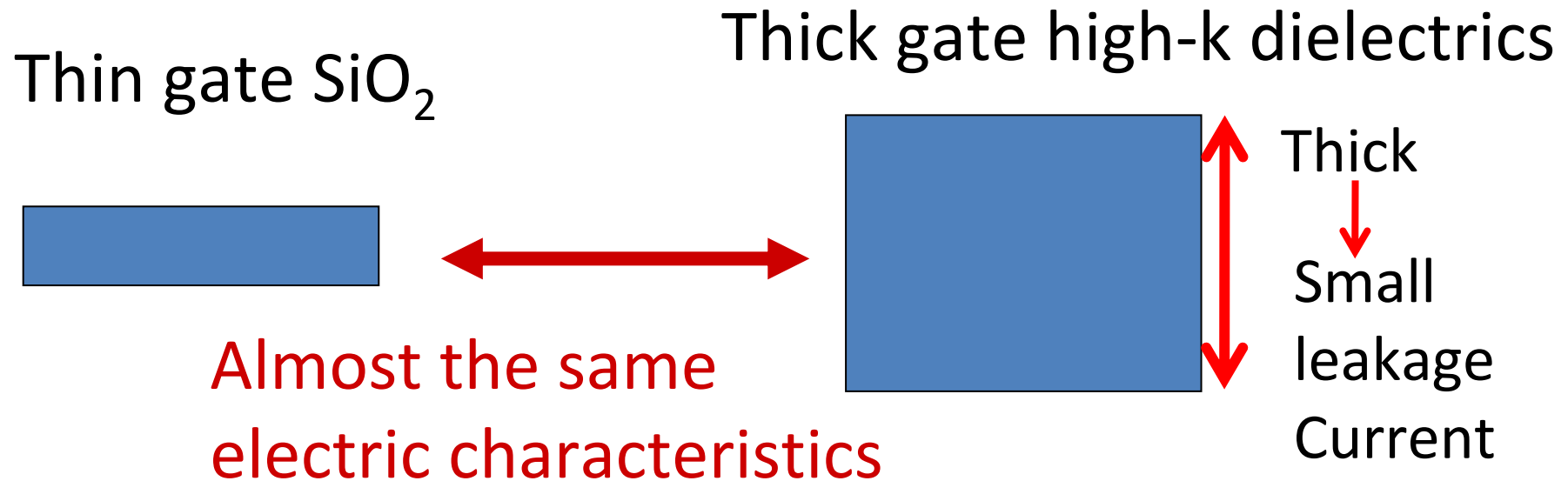
By Robert Chau, IWGI 2003

So, we are now in the limitation
of downsizing?

Do you believe this or do not?

There is a solution! **K: Dielectric Constant**

To use high-k dielectrics



However, very difficult and big challenge!

Remember MOSFET had not been realized without Si/SiO_2 !

Choice of High-k elements for oxide

Candidates														Gas or liquid at 1000 K							
Unstable at Si interface														Radio active							
H														He							
Li	Be													B	C	N	O	F	Ne		
Na	Mg													Al	Si	P	S	Cl	Ar		
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr				
Rh	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rb	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe				
Cs	Ba		Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn				
Fr	Ra		Rf	Ha	Sg	Ns	Hs	Mt													
		La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu					
		Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr					

HfO₂ based dielectrics are selected as the first generation materials, because of their merit in

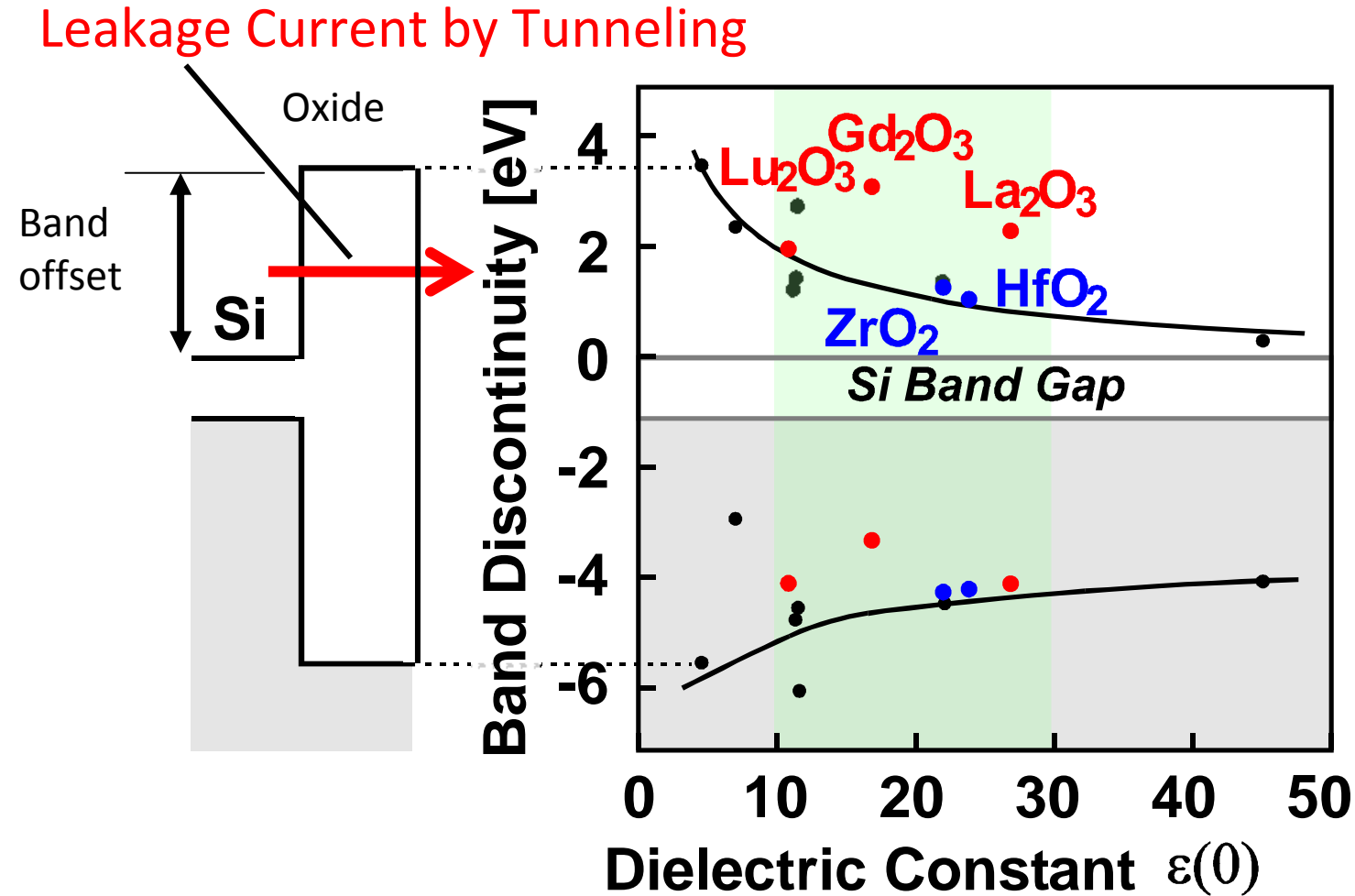
- 1) band-offset,
- 2) dielectric constant
- 3) thermal stability

La₂O₃ based dielectrics are thought to be the next generation materials, which may not need a thicker interfacial layer

R. Hauser, IEDM Short Course, 1999

Hubbard and Schlom, J Mater Res 11 2757 (1996)

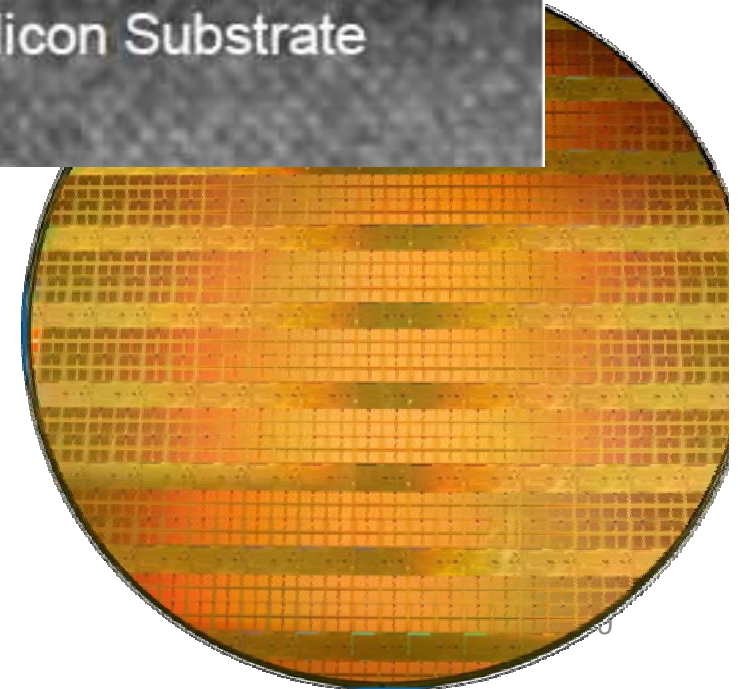
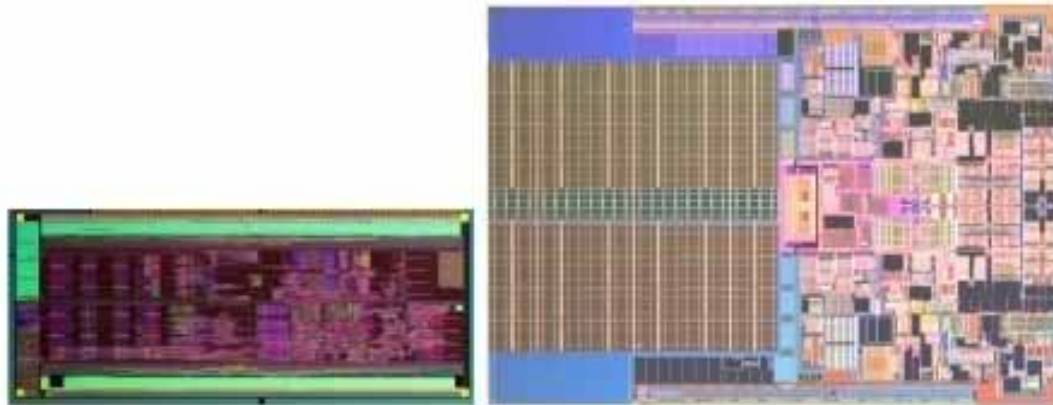
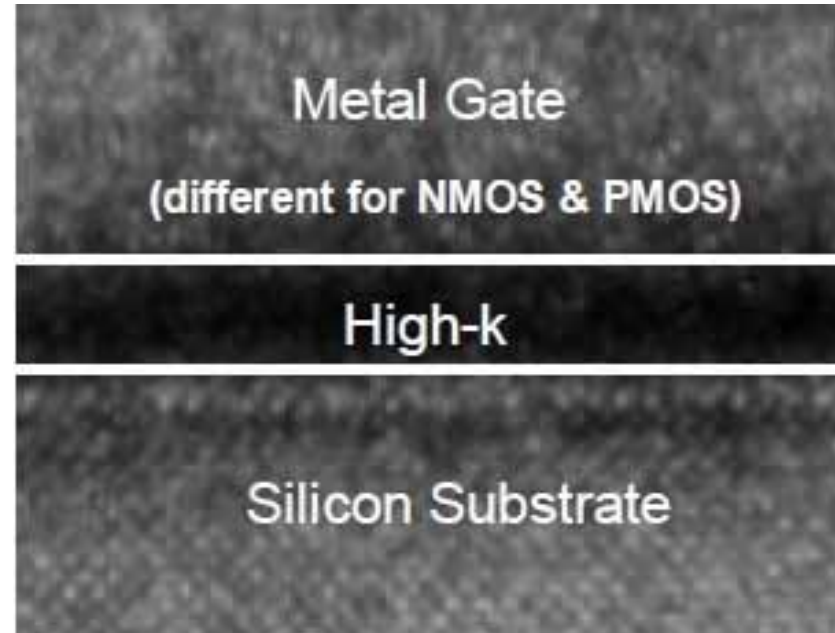
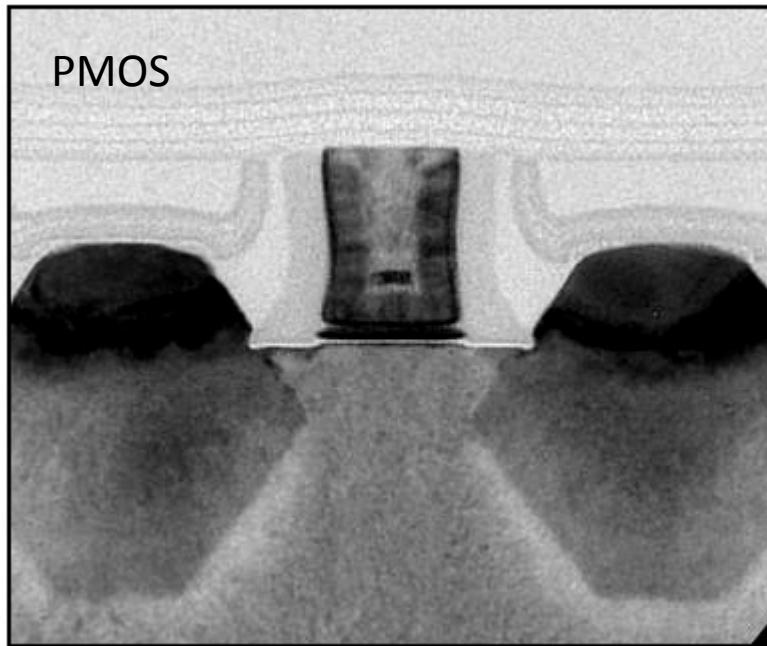
Conduction band offset vs. Dielectric Constant

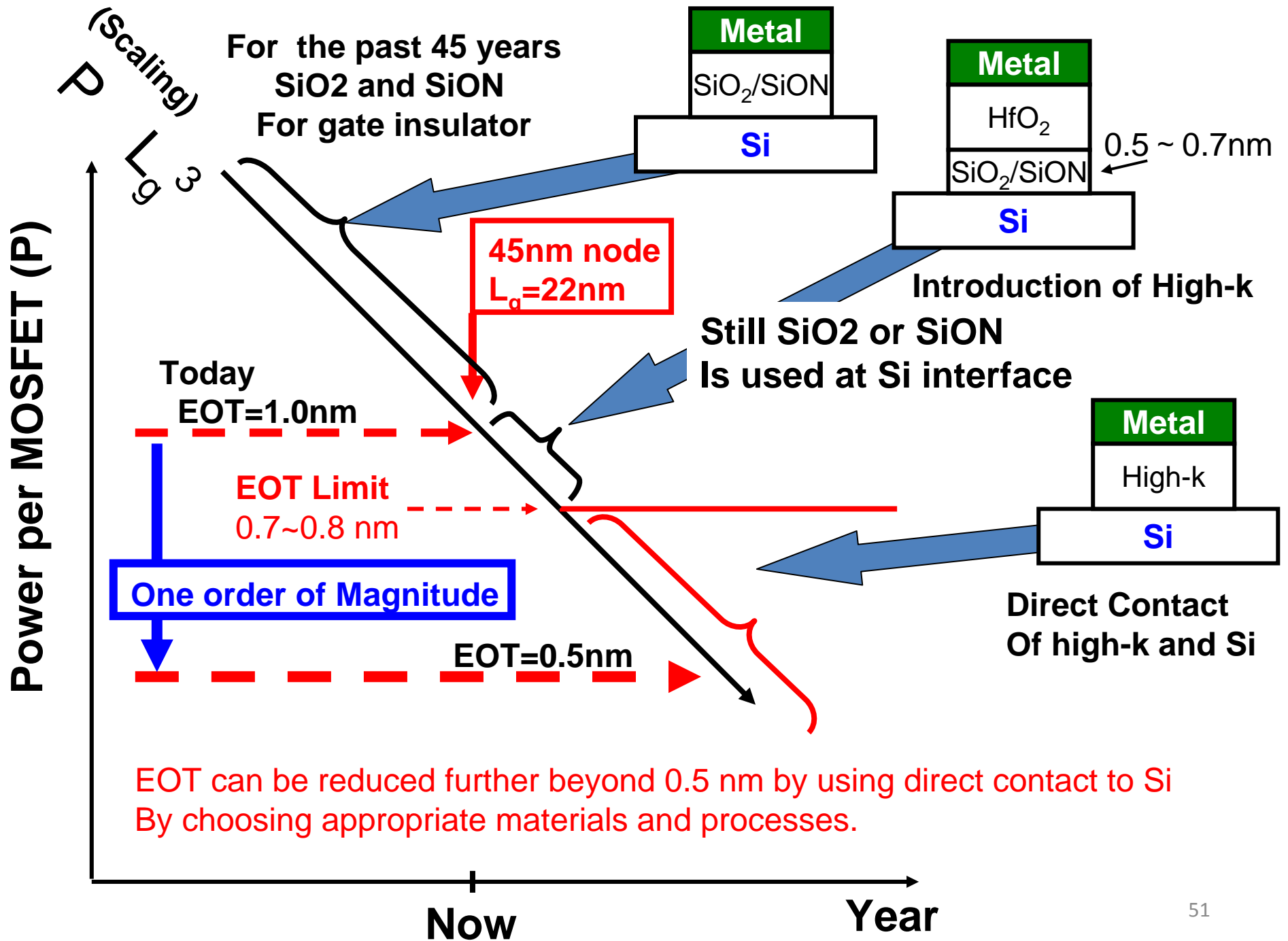


XPS measurement by Prof. T. Hattori, INFOS 2003

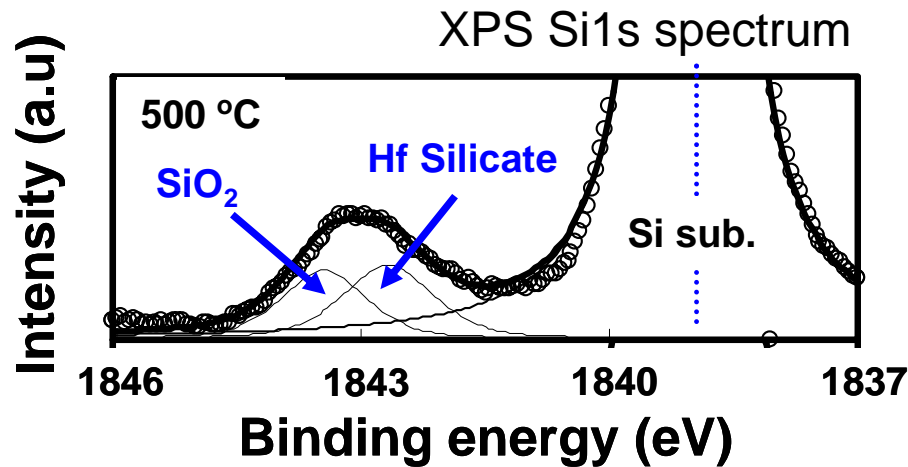
High-k gate insulator MOSFETs for Intel: EOT=1nm

EOT: Equivalent Oxide Thickness

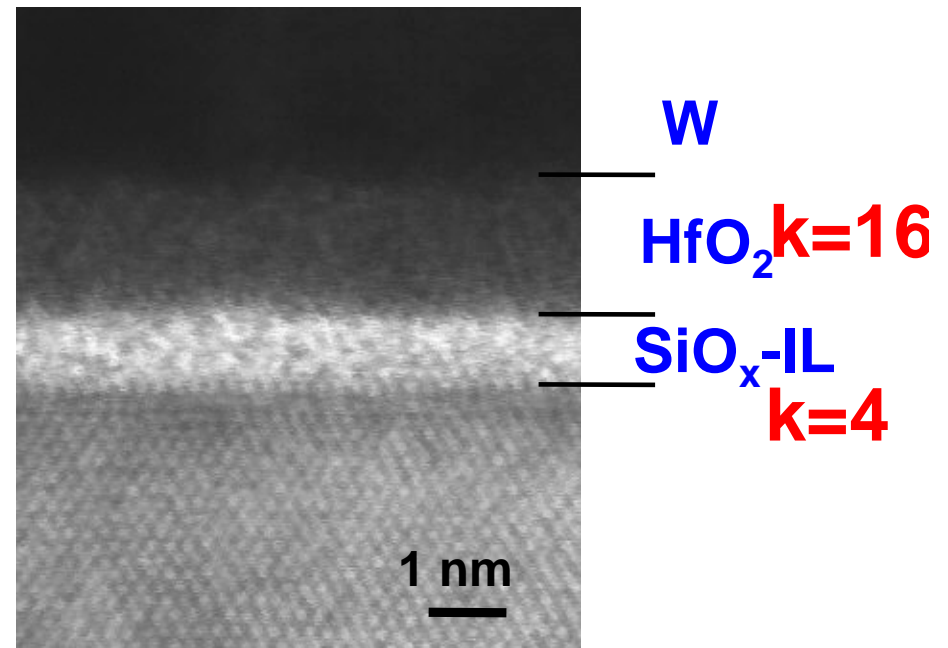




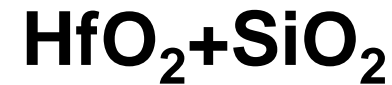
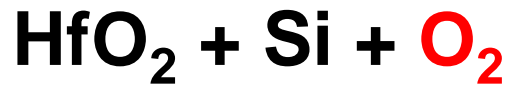
SiO_x-IL growth at HfO₂/Si Interface



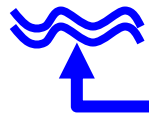
TEM image 500 °C 30min



Phase separator



H. Shimizu, JJAP, 44, pp. 6131



Oxygen supplied from W gate electrode

D.J.Lichtenwalner, Tans. ECS 11, 319

SiO_x-IL is formed after annealing

Oxygen control is required for optimizing the reaction

Choice of High-k elements for oxide

Candidates 														Gas or liquid at 1000 K											
Unstable at Si interface														Radio active											
H																				He					
Li	Be																			B	C	N	O	F	Ne
Na	Mg																			Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fc	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr								
Rh	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rb	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe								
Cs	Ba		Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn								
Fr	Ra			Rf	Ha	Sg	Ns	Hs	Mt																
		La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu									
		Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr									

HfO₂ based dielectrics are selected as the first generation materials, because of their merit in

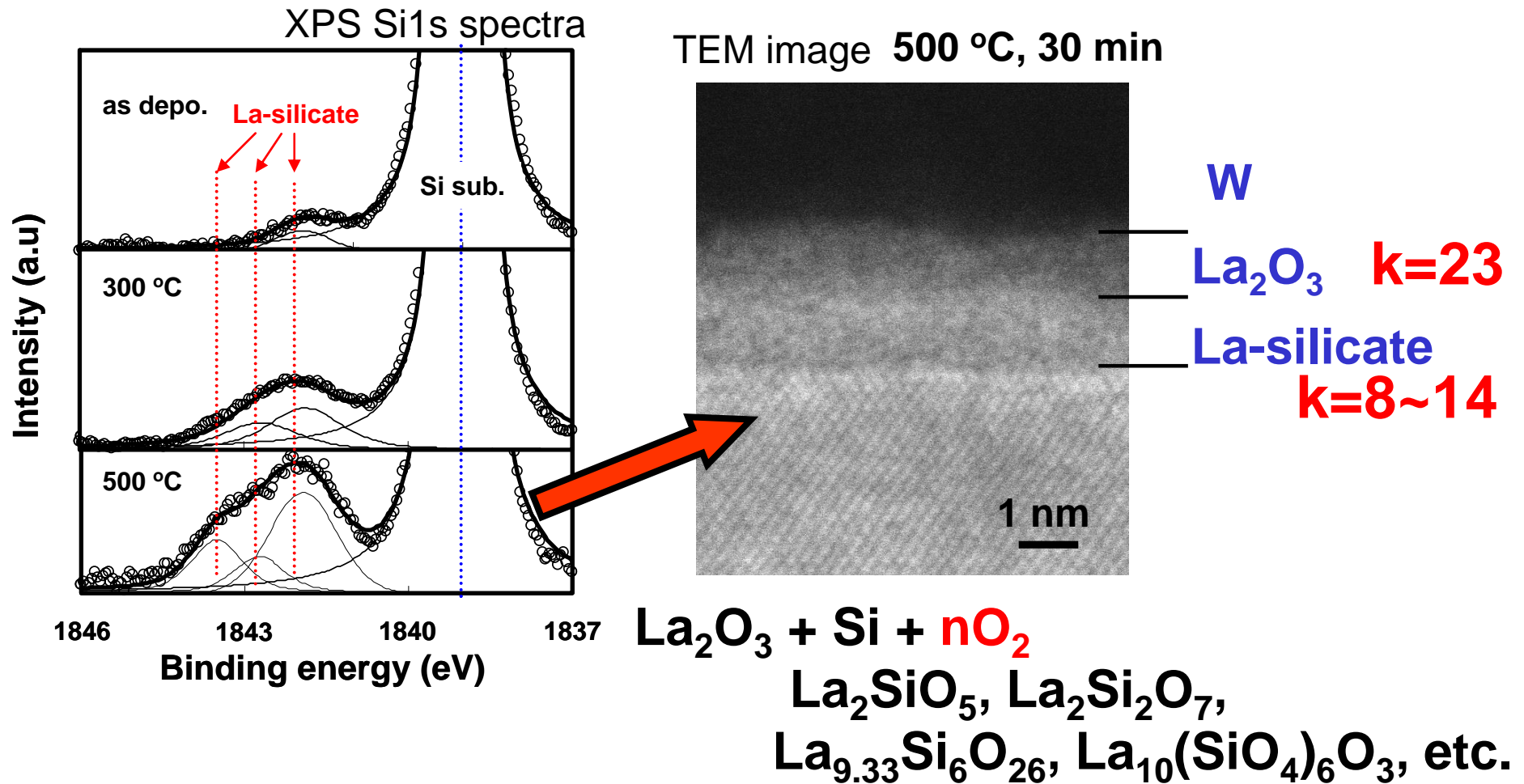
- 1) band-offset,
- 2) dielectric constant
- 3) thermal stability

La₂O₃ based dielectrics are thought to be the next generation materials, which may not need a thicker interfacial layer

R. Hauser, IEDM Short Course, 1999
Hubbard and Schlom, J Mater Res 11 2757 (1996)

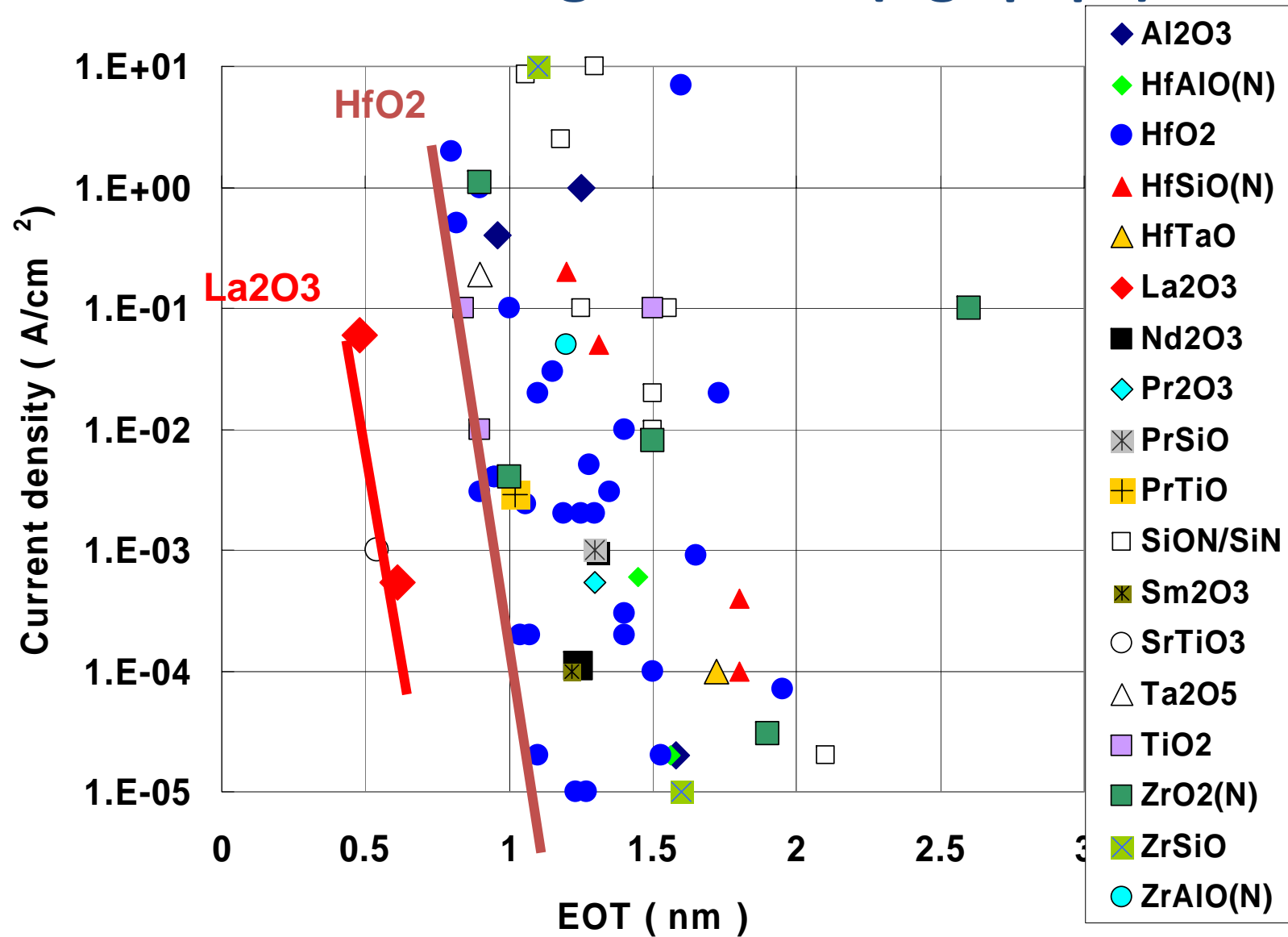
La-Silicate Reaction at $\text{La}_2\text{O}_3/\text{Si}$

Direct contact high-k/Si is possible



La_2O_3 can achieve direct contact of high-k/Si

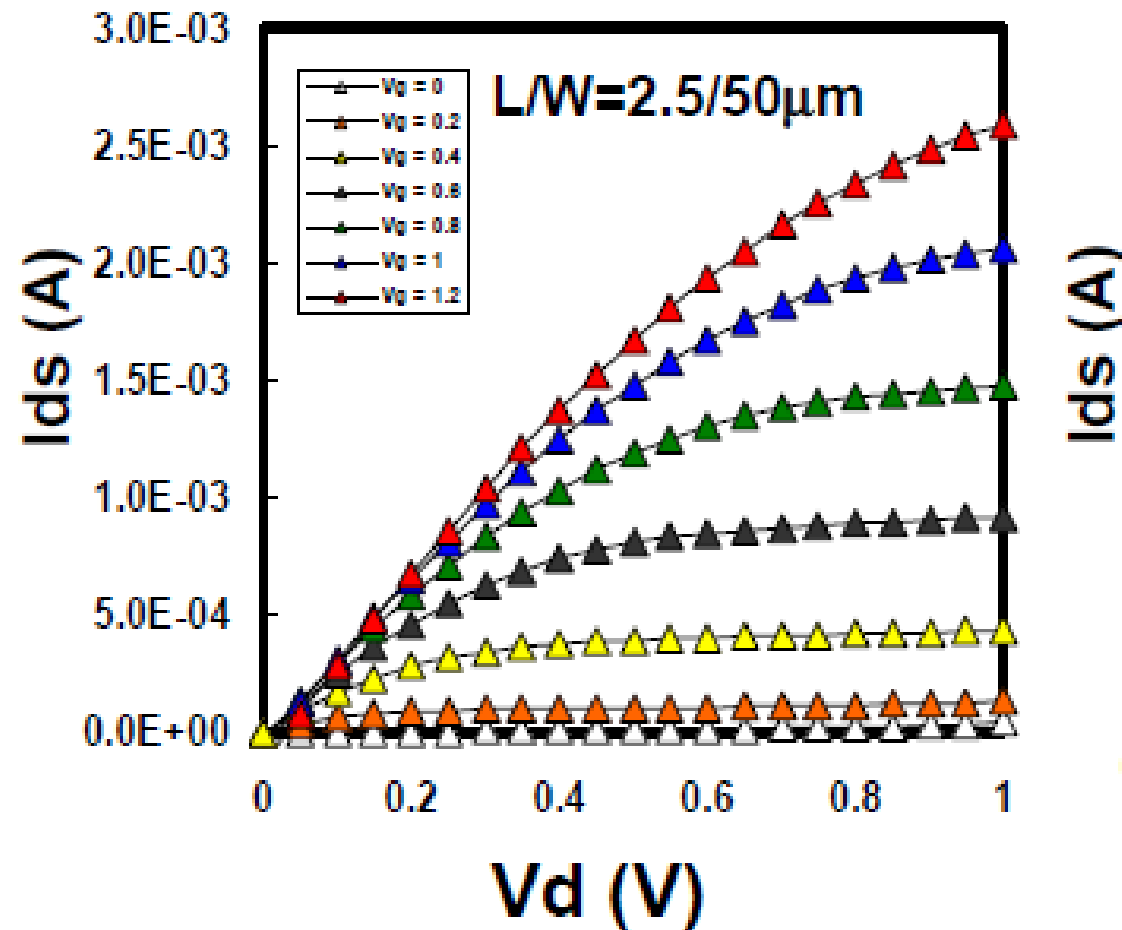
Gate Leakage vs EOT, ($V_g = |1|V$)



EOT = 0.48 nm

Our results

Transistor with La₂O₃ gate insulator



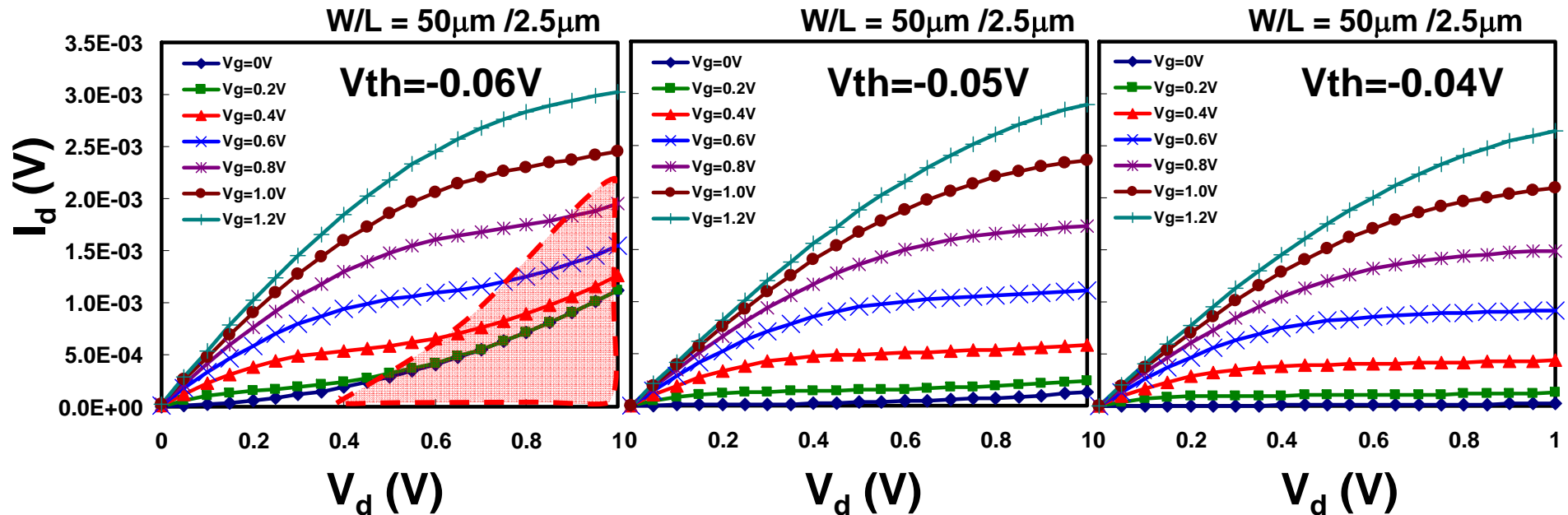
EOT=0.37nm

La2O3

EOT=0.37nm

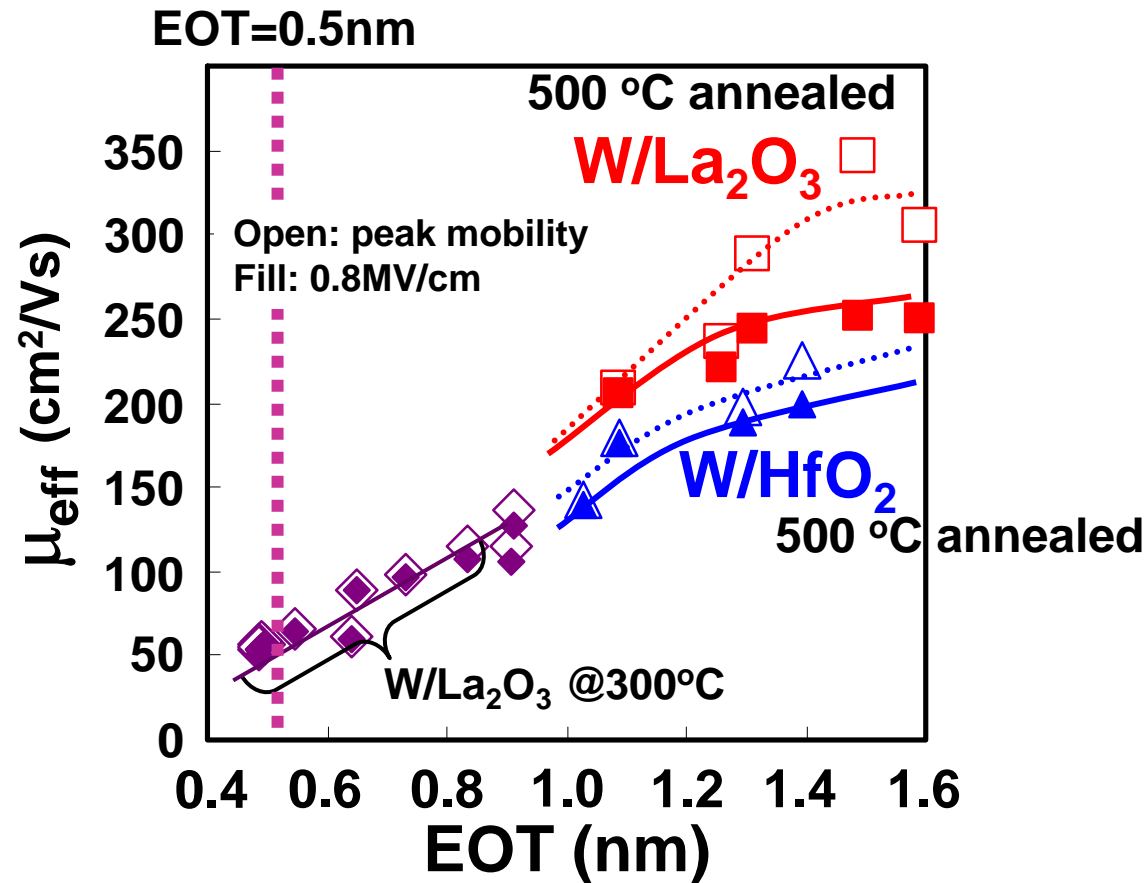
EOT=0.40nm

EOT=0.48nm



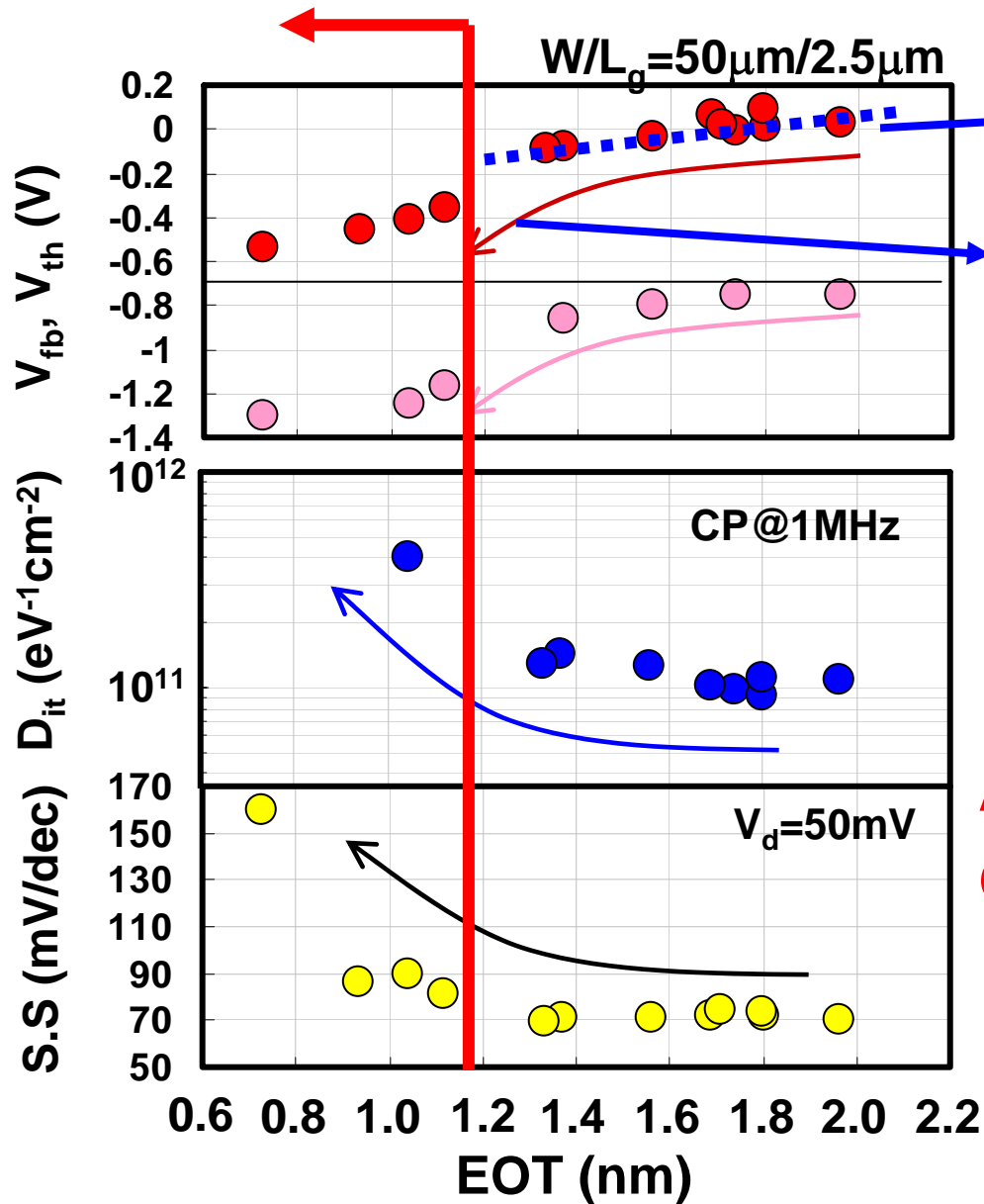
0.48 \rightarrow 0.37nm Increase of I_d at 30%

μ_{eff} of W/La₂O₃ and W/HfO₂ nFET on EOT



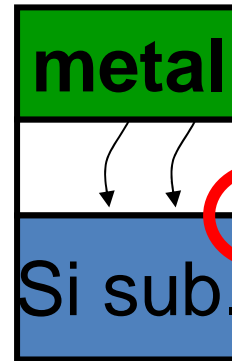
- W/La₂O₃ exhibits higher μ_{eff} than W/HfO₂
- μ_{eff} start degrades below EOT=1.4nm

FET characteristics of W/La₂O₃ on EOT



$N_{fix} = 7 \times 10^{12} \text{ cm}^{-2}$

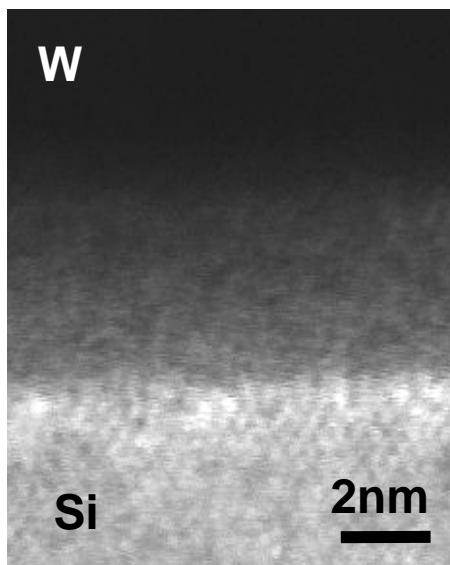
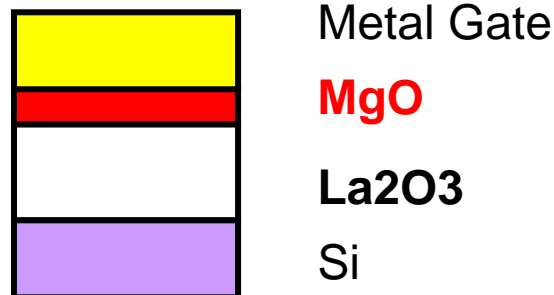
Aggressive N_{fix} generation at EOT < 1.2nm



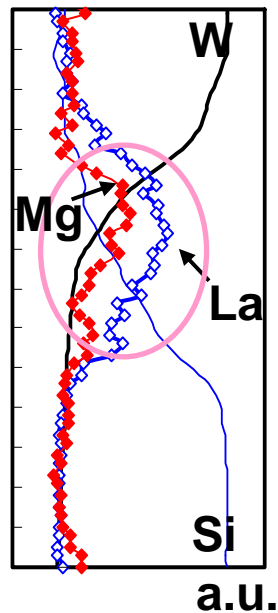
N_{fix} and D_{it}

All characteristics start to degrade or shift below EOT = 1.4nm

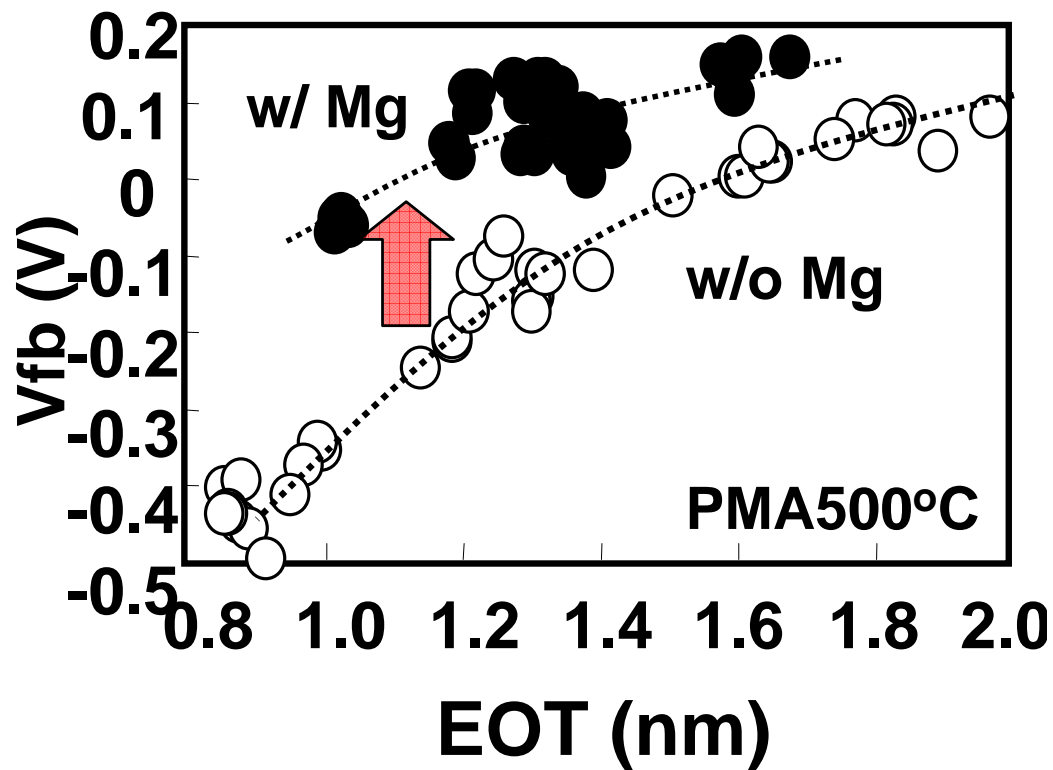
Gate Metal Induced Defects Compensation



TEM

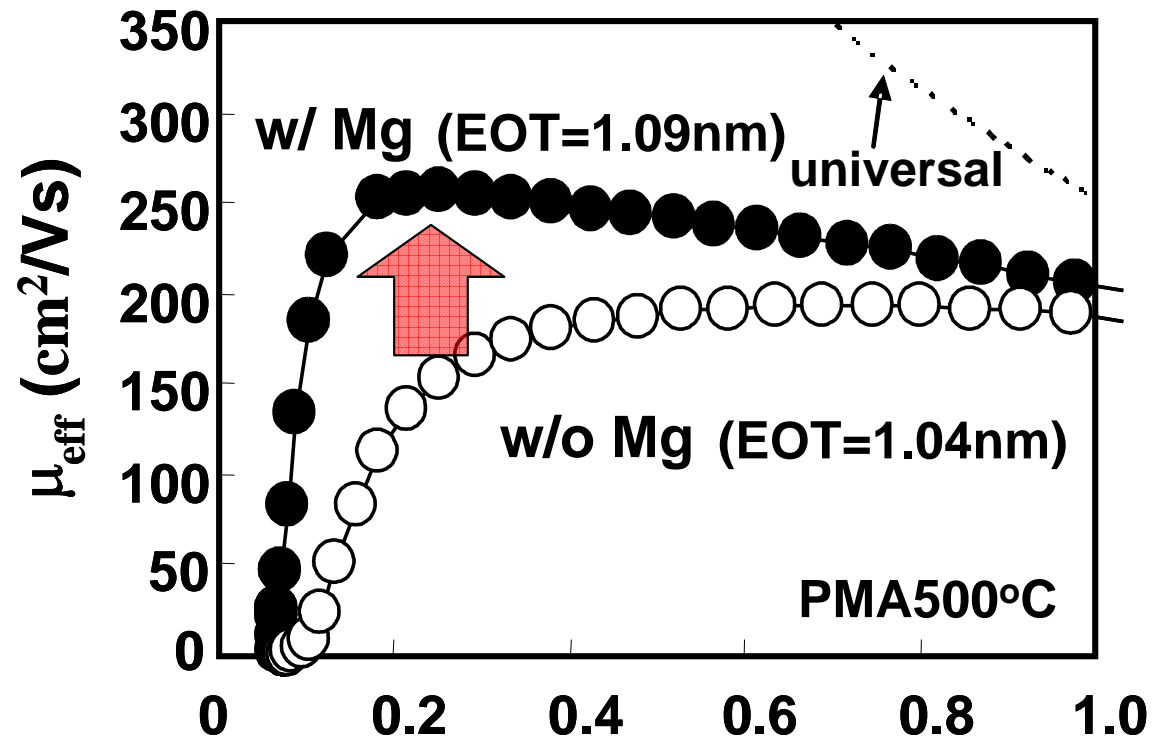


EDX



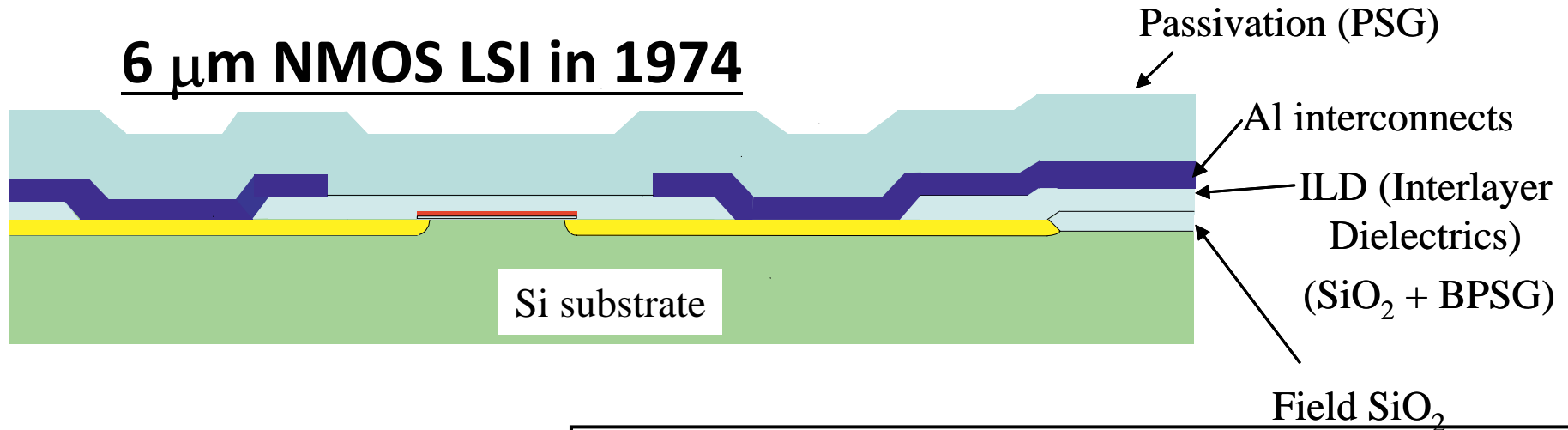
Suppression of aggressive shift in V_{fb}

Mobility Improvement with Mg Incorporation

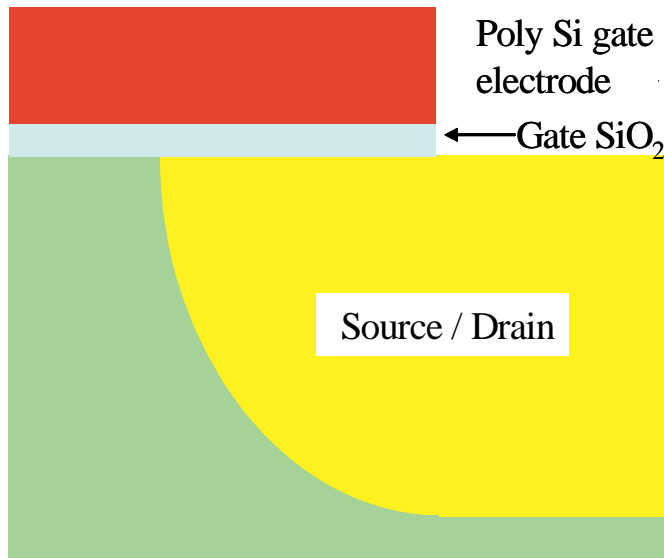


Recovery of μ_{eff} mainly at low E_{eff}

6 μm NMOS LSI in 1974



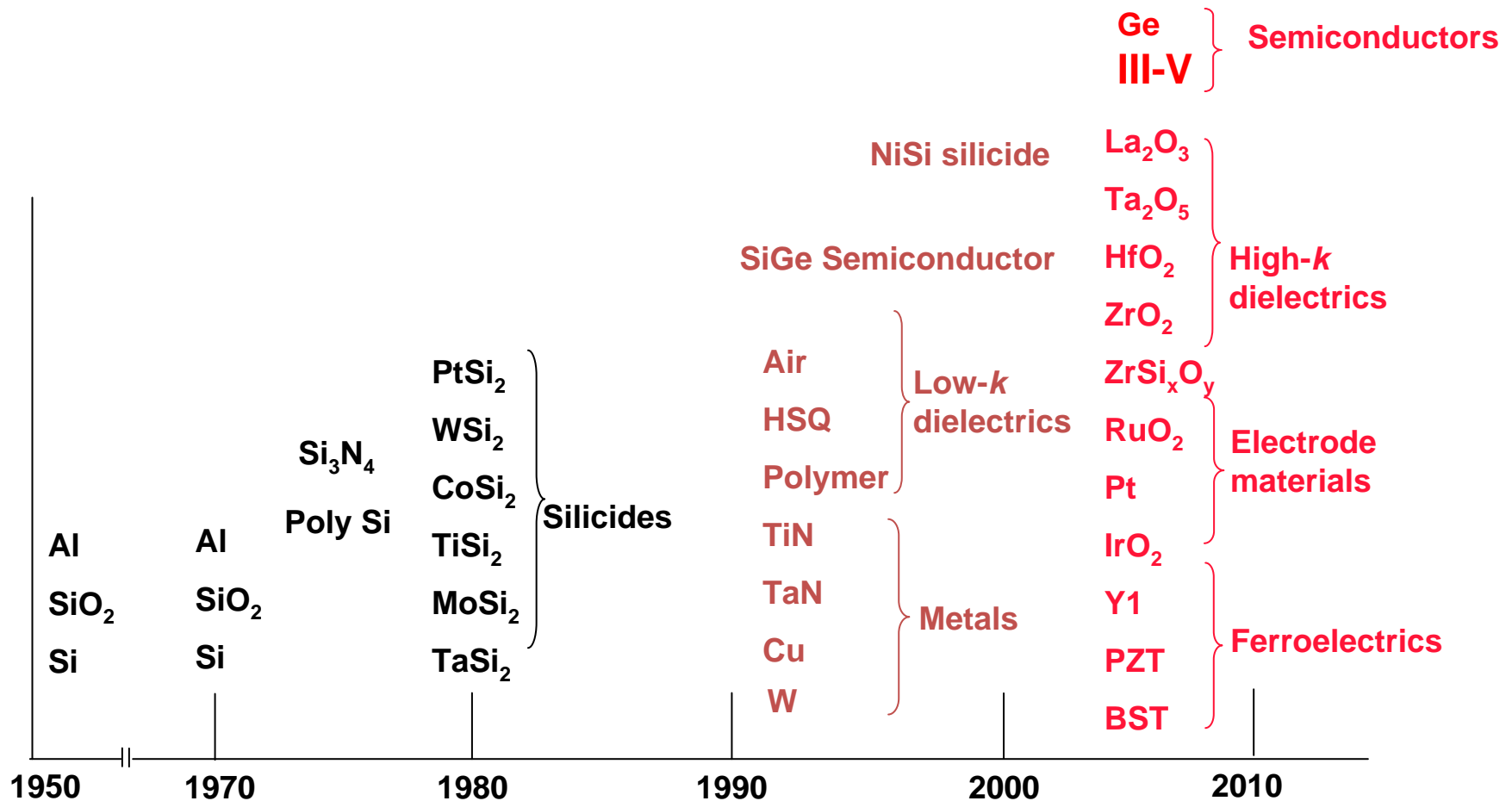
magnification
↓



<u>Layers</u>	<u>Materials</u>	<u>Atoms</u>
1. Si substrate	1. Si	1. Si
2. Field oxide	2. SiO ₂	2. O
3. Gate oxide	3. BPSG	3. P
4. Poly Si	4. Al	4. B
5. S/D	5. PSG	5. Al
6. Interlayer		(H, N, Cl)
7. Aluminum		
8. Passivation		

New materials

Just examples!
Many other candidates



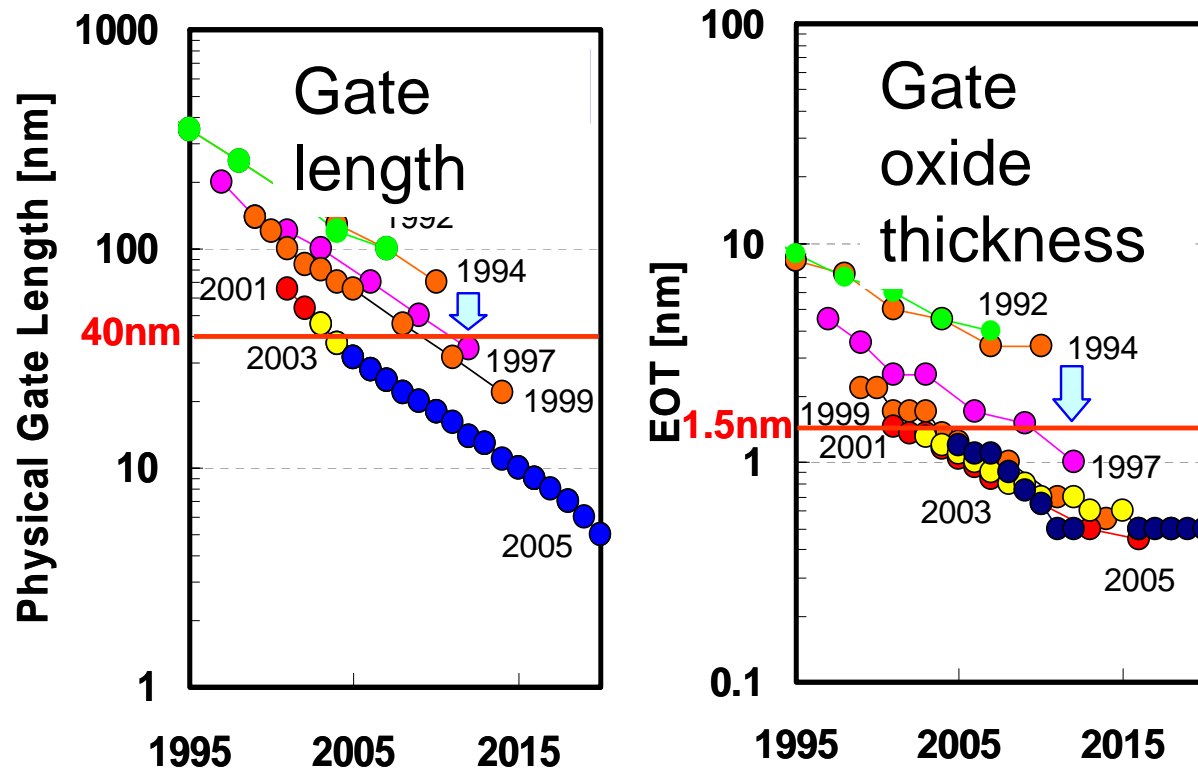
Y. Nishi, Si Nano Workshop, 2006,

(S. Sze, Based on invited talk at Stanford Univ., Aug. 1999)

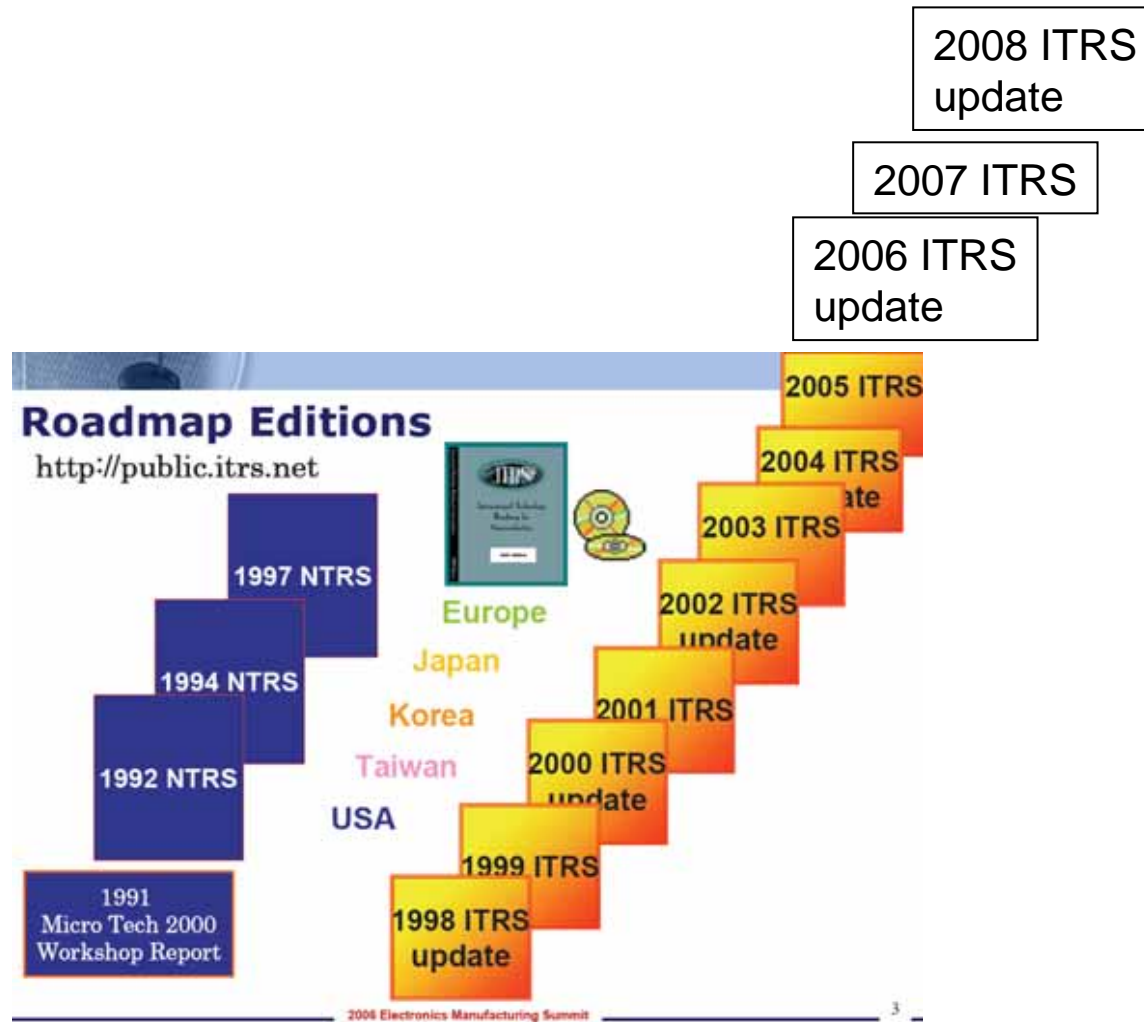
What is a roadmap? What is ITRS?

Roadmap: Prediction of future technologies

ITRS: International Technology Roadmap for Semiconductors
made by SIA (Semiconductor Industry Association with
Collaboration with Japan, Europe, Korea and Taiwan)



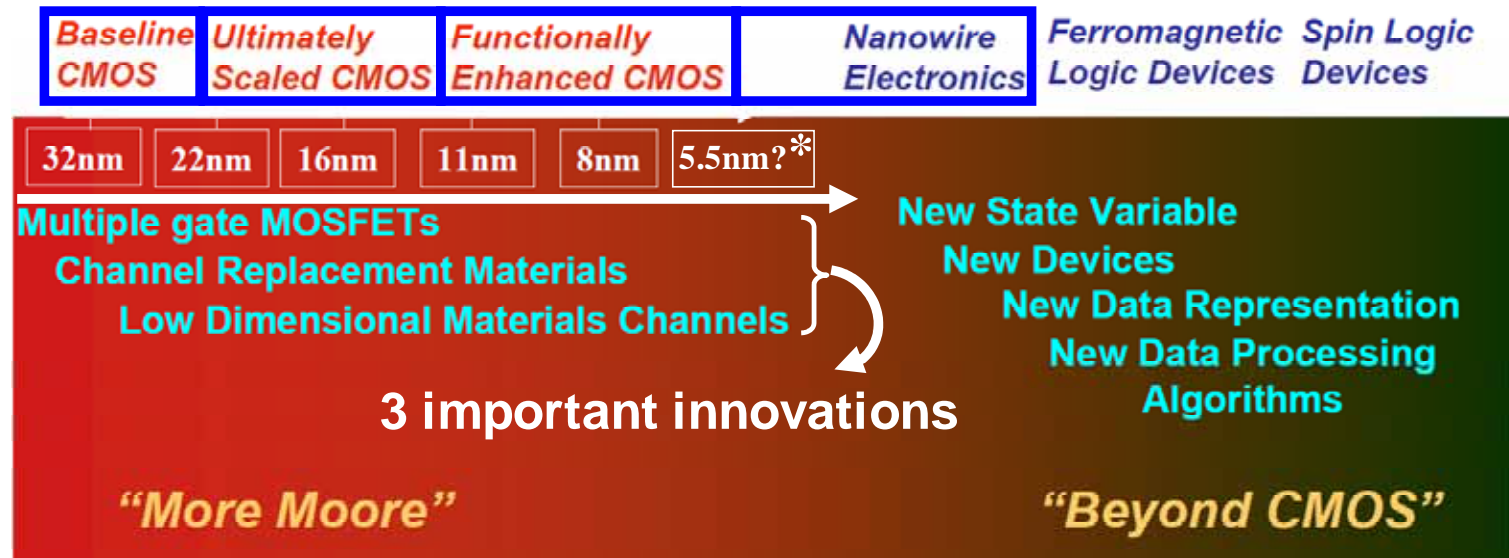
1992 -1997:NTRS (National Technology Roadmap)
1998 - : ITRS (International Technology Roadmap)



Question:

How far we can go
with downscaling?

- There will be still 4~6 cycles (or technology generations) left until we reach 11 ~ 5.5 nm technologies, at which we will reach down-scaling limit, in some year between 2020-30 (H. Iwai, IWJT2008).
- Even After reaching the down-scaling limit, we could still continue R & D, seeking sufficiently higher I_{d-sat} under low V_{dd} .
- Two candidates have emerged for R & D
 1. Nanowire/tube MOSFETs
 2. Alternative channel MOSFETs (III-V, Ge)
- Other Beyond CMOS devices are still in the cloud.



ITRS figure edited by Iwai

How far can we go?

Past

0.7 times per 3 years In 40 years: 15 generations,
Size 1/200, Area 1/40,000

1973年



8 μ m → 6 μ m → 4 μ m → 3 μ m → 2 μ m → 1.2 μ m → 0.8 μ m → 0.5 μ m

→ 0.35 μ m → 0.25 μ m → 180nm → 130nm → 90nm → 65nm → 45nm

Now

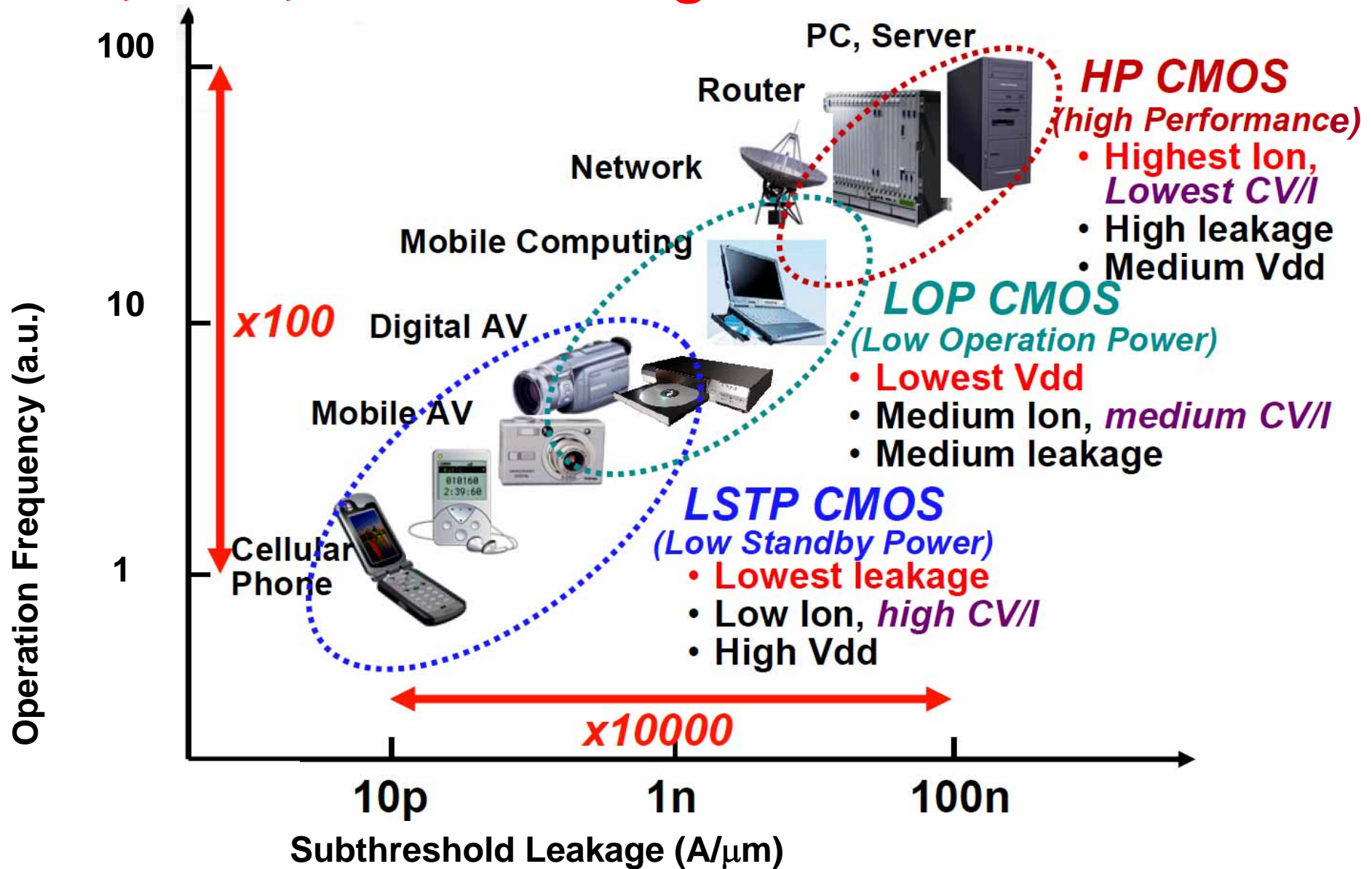


Future

→ 32nm → 22nm → 16nm → 11.5 nm → 8nm → 5.5nm? → 4nm? → 2.9 nm?

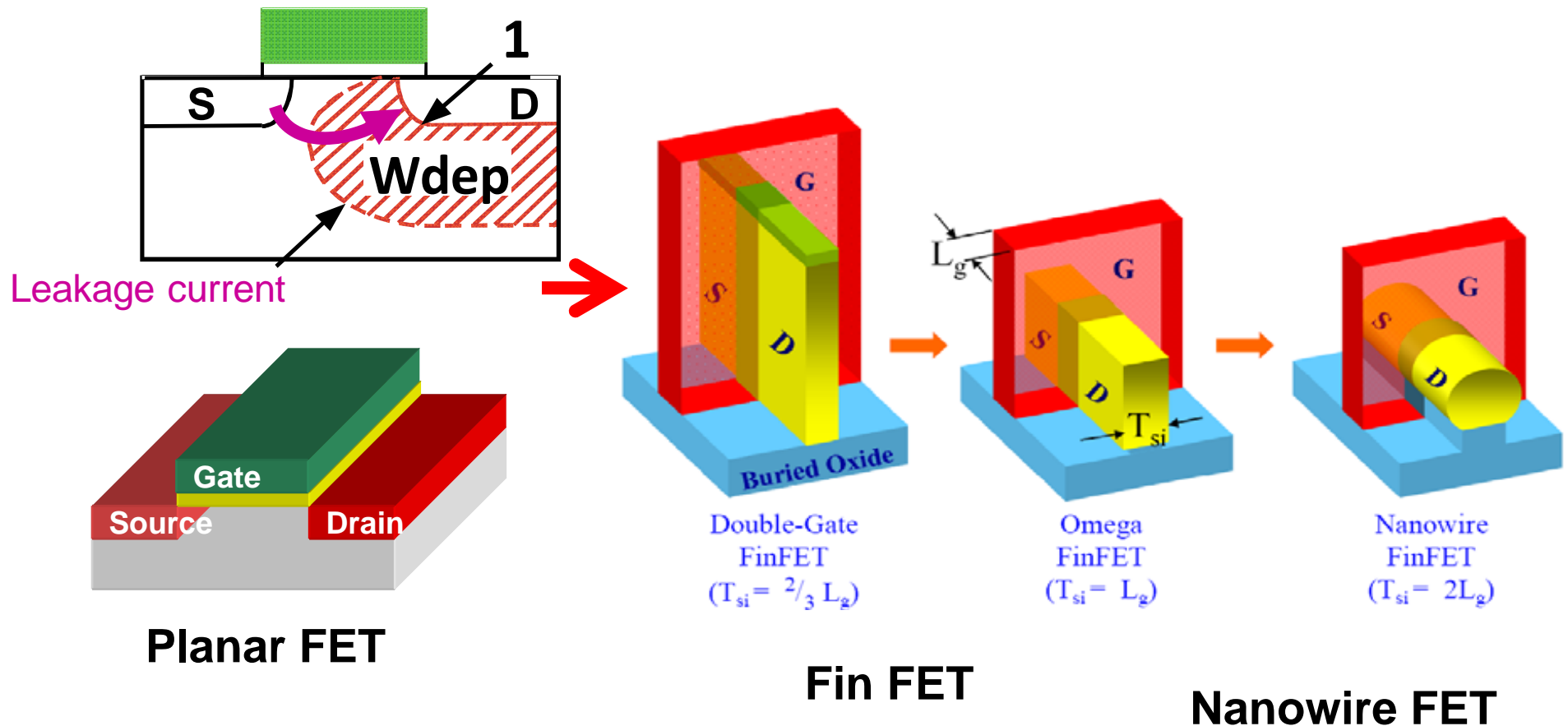
- At least 5,6 generations, for 15 ~ 20 years
- Hopefully 8 generations, for 30 years

HP, LOP, LSTP for Logic CMOS

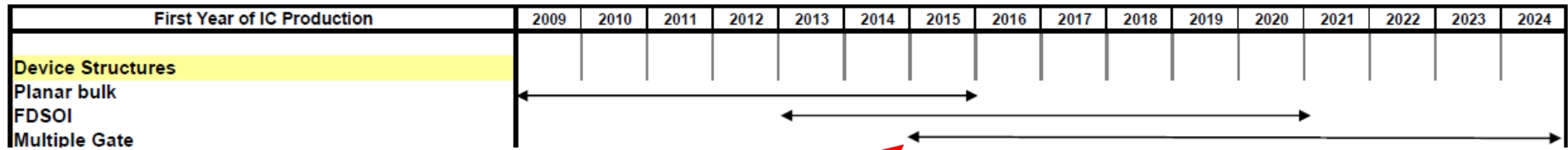


Because of off-leakage control,

Planar \rightarrow Fin \rightarrow Nanowire

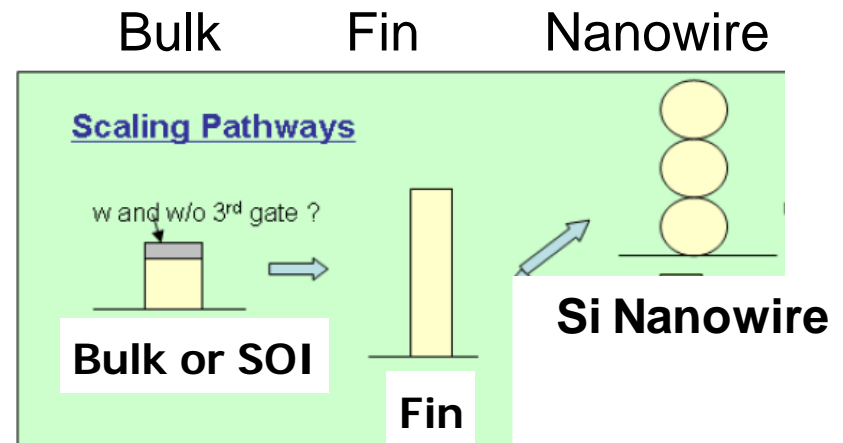


Nanowire FET



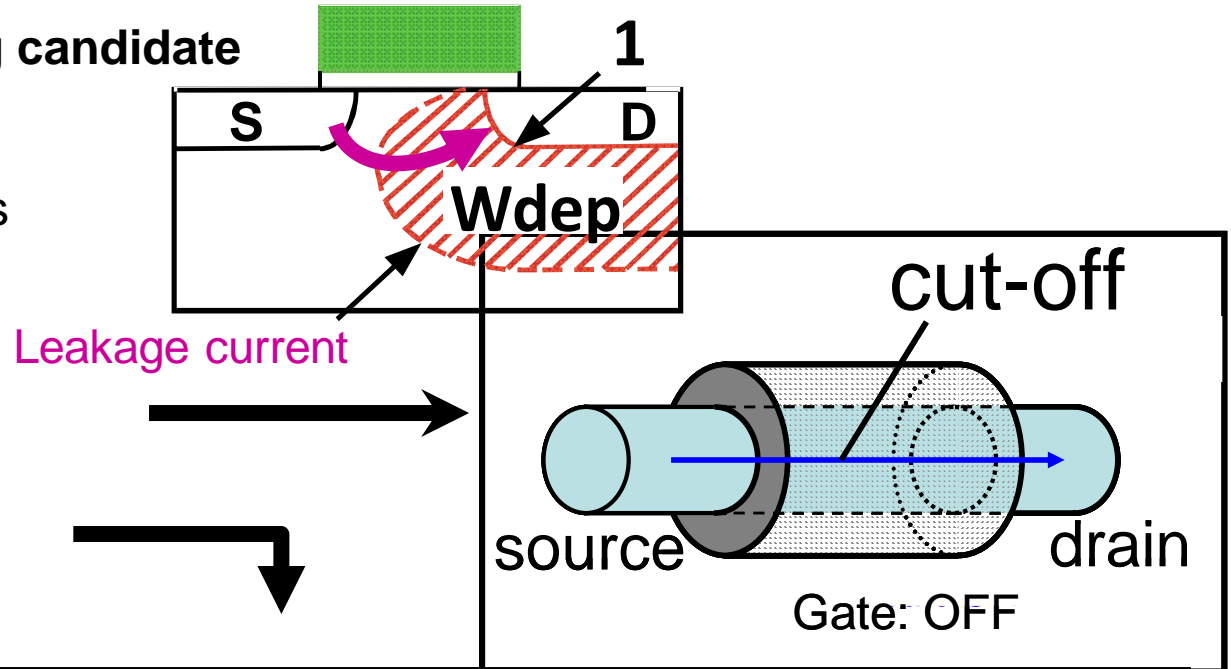
Multiple Gate (Fin)FET

ITRS 2009



Si nanowire FET as a strong candidate

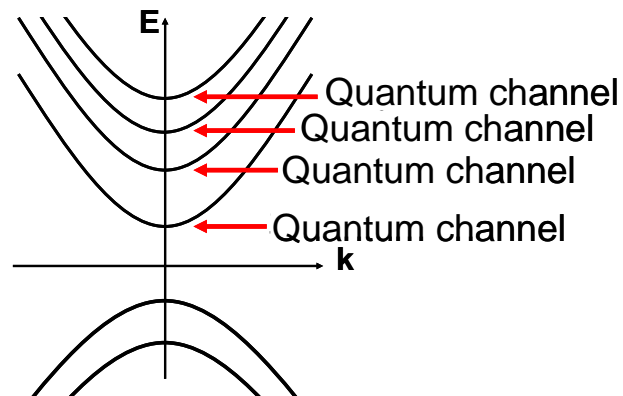
1. Compatibility with current CMOS process
2. Good controllability of I_{OFF}
3. High drive current



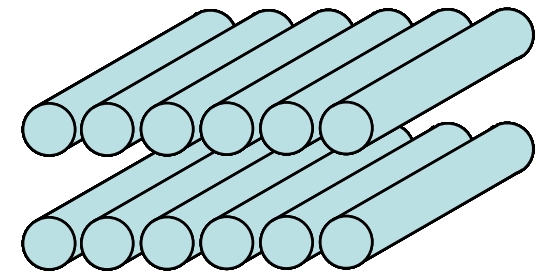
1D ballistic conduction

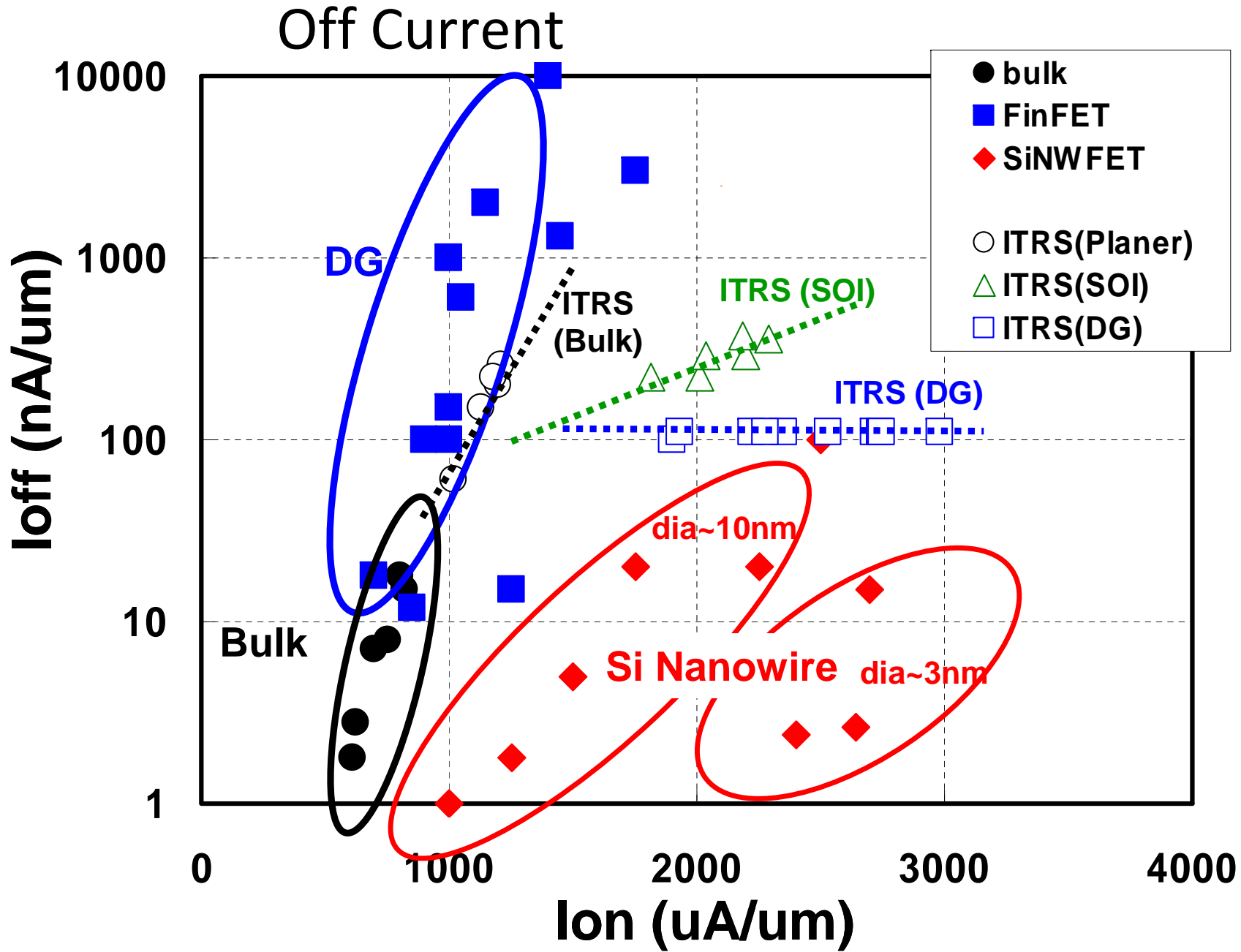


Multi quantum Channel



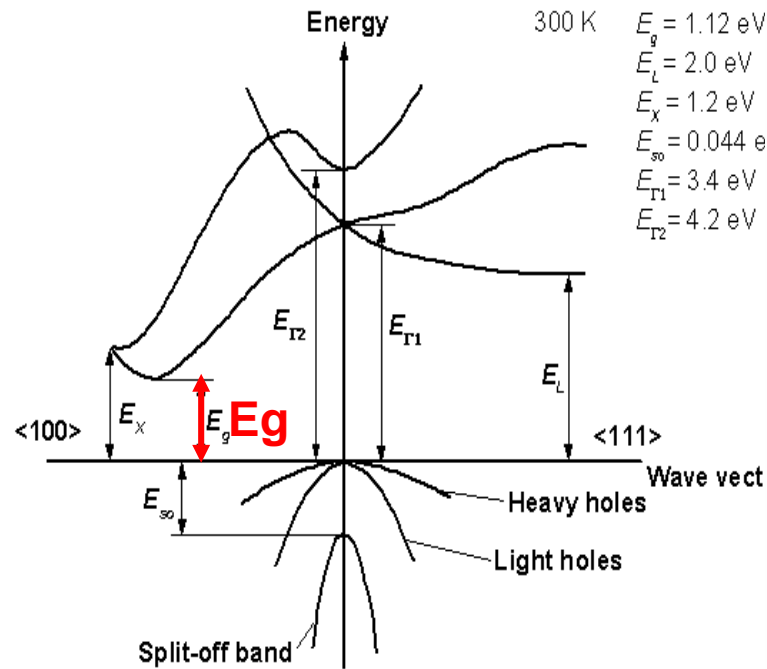
High integration of wires



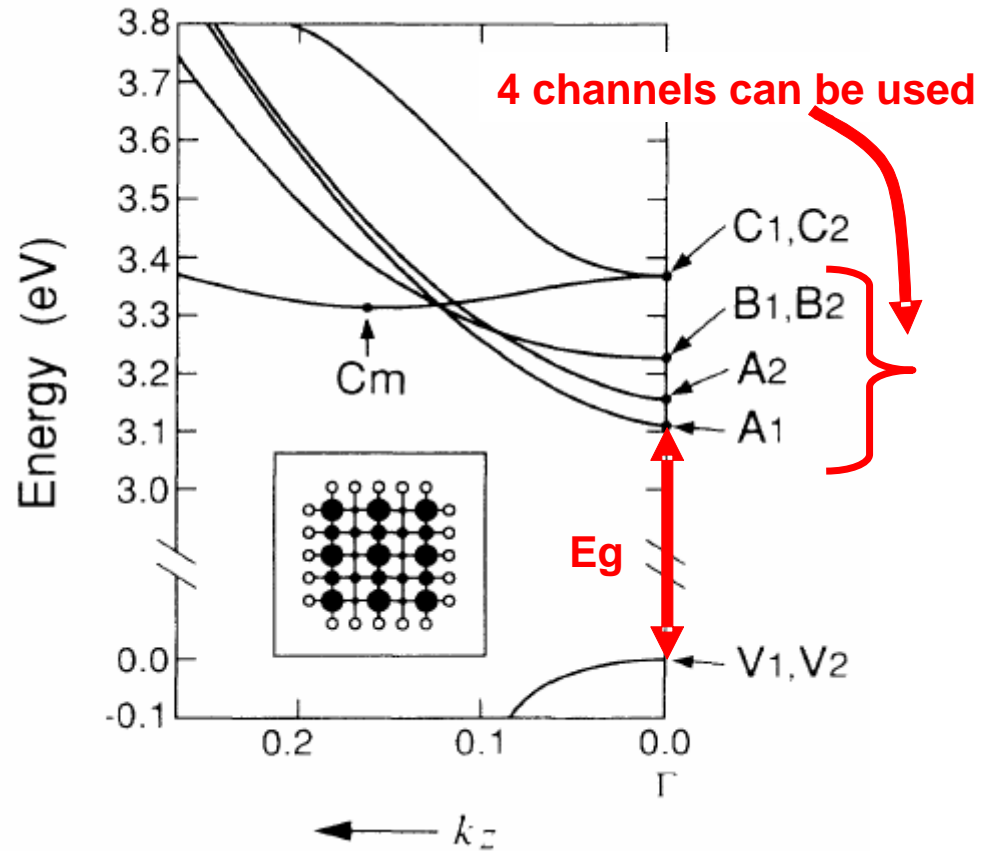


Increase the Number of quantum channels

By Prof. Shiraishi of Tsukuba univ.



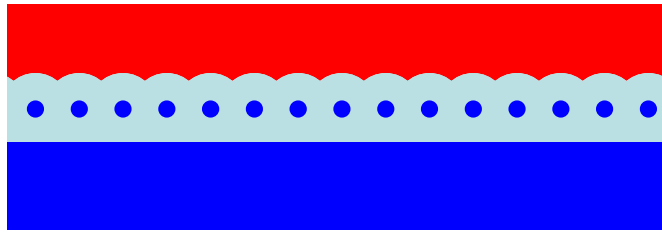
Energy band of Bulk Si



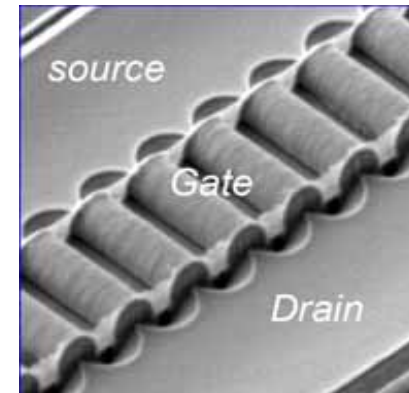
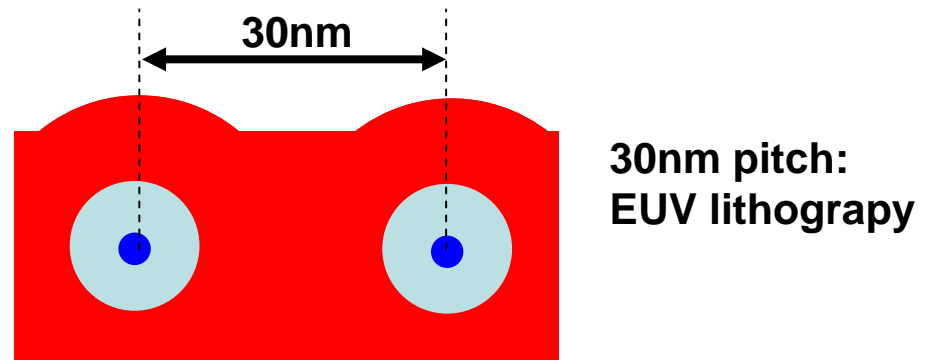
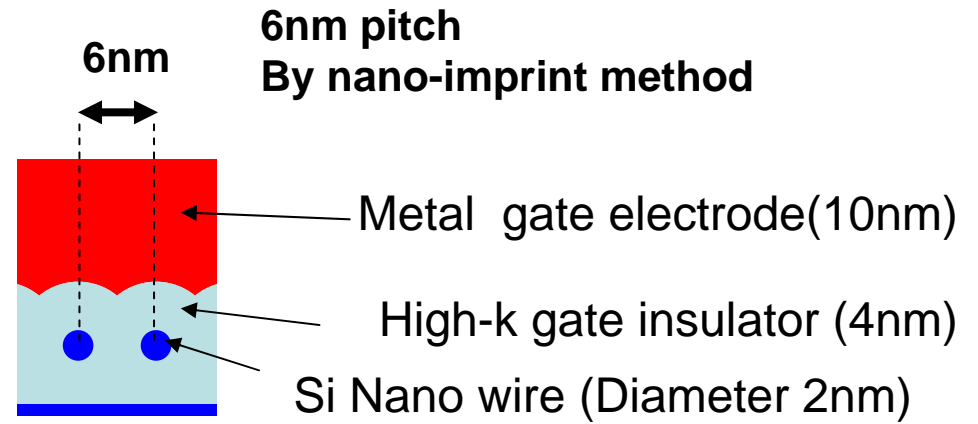
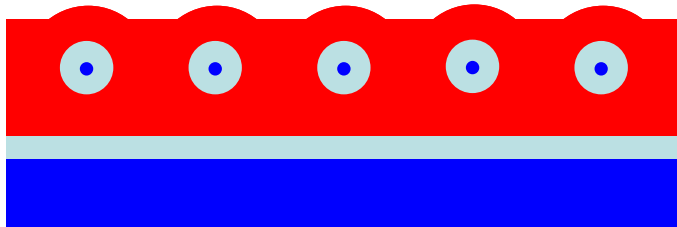
Energy band of 3 x 3 Si wire

Maximum number of wires per 1 μm

Front gate type MOS 165 wires / μm

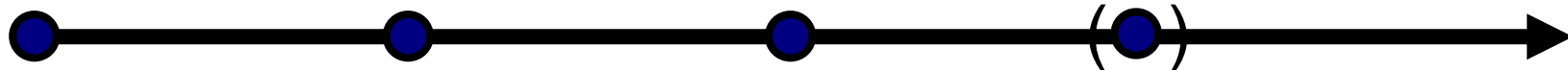


Surrounded gate type MOS 33 wires / μm

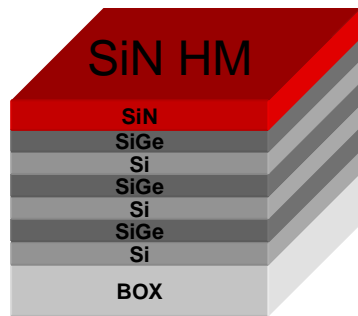


Surrounded gate MOS

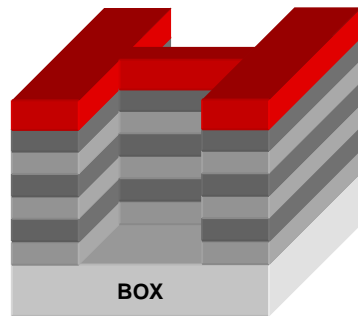
Device fabrication



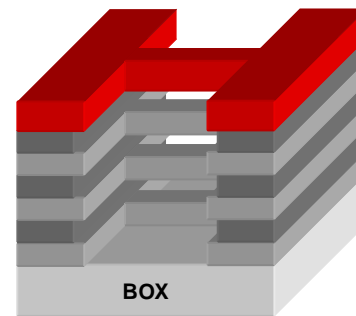
Si/Si_{0.8}Ge_{0.2}
superlattice
epitaxy on SOI



Anisotropic
etching
of these layers



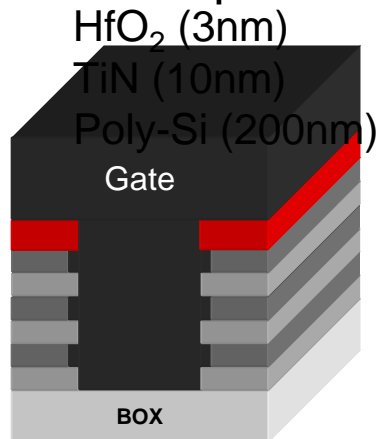
Isotropic
etching
of SiGe



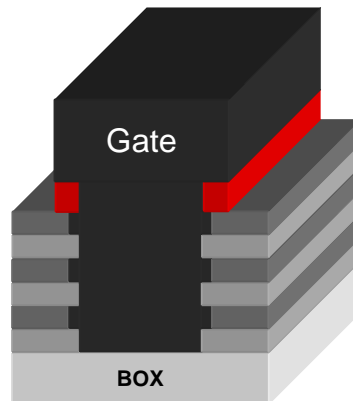
The NW diameter
is controllable
down to 5 nm
by self limited oxidation.



Gate depositions



Gate etching



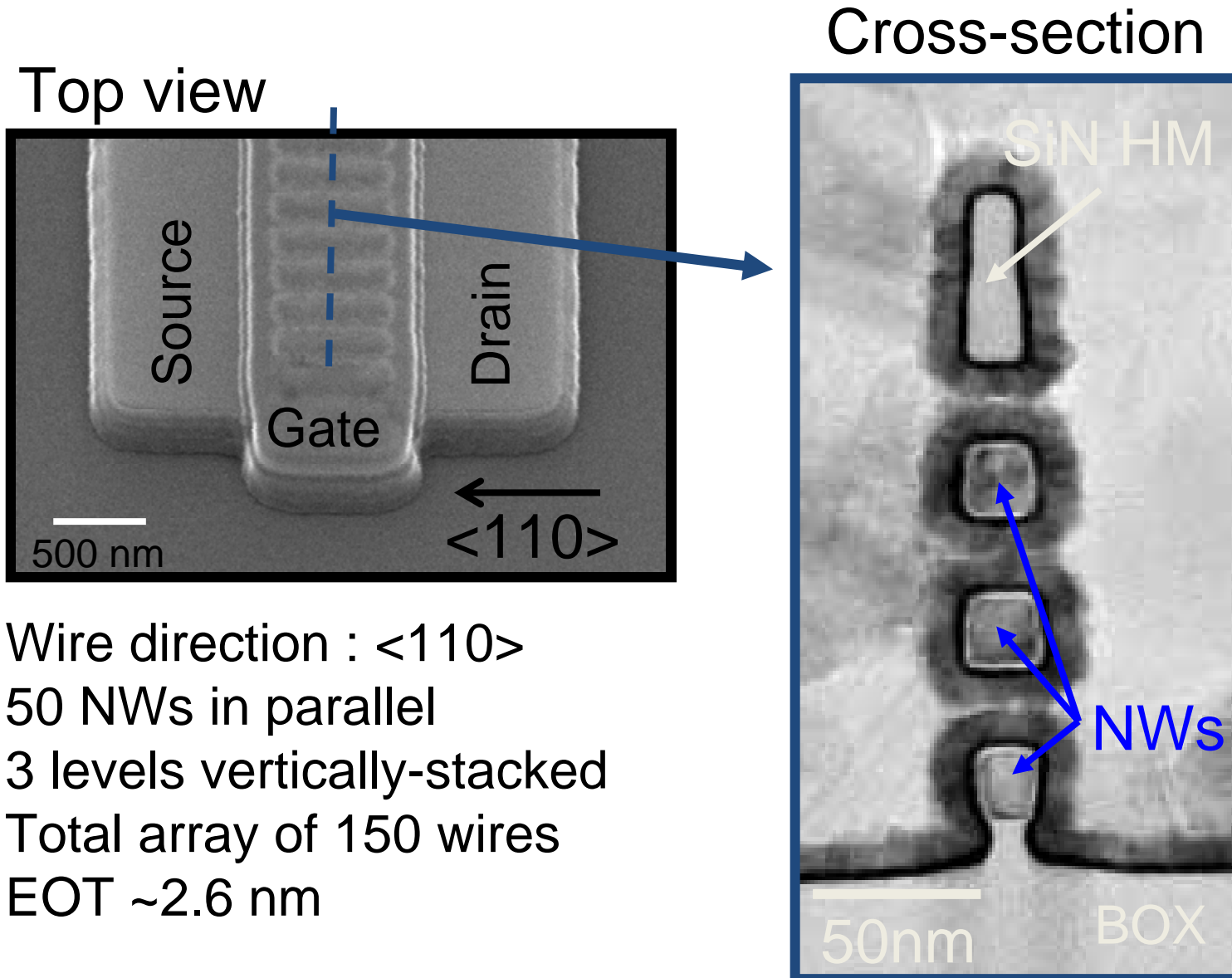
S/D implantation
Spacer formation
Activation anneal
Salicidation

Standard
Back-End
of-Line
Process

Process Details :

C. Dupre *et al.*,
IEDM Tech. Dig., p.749, 2008

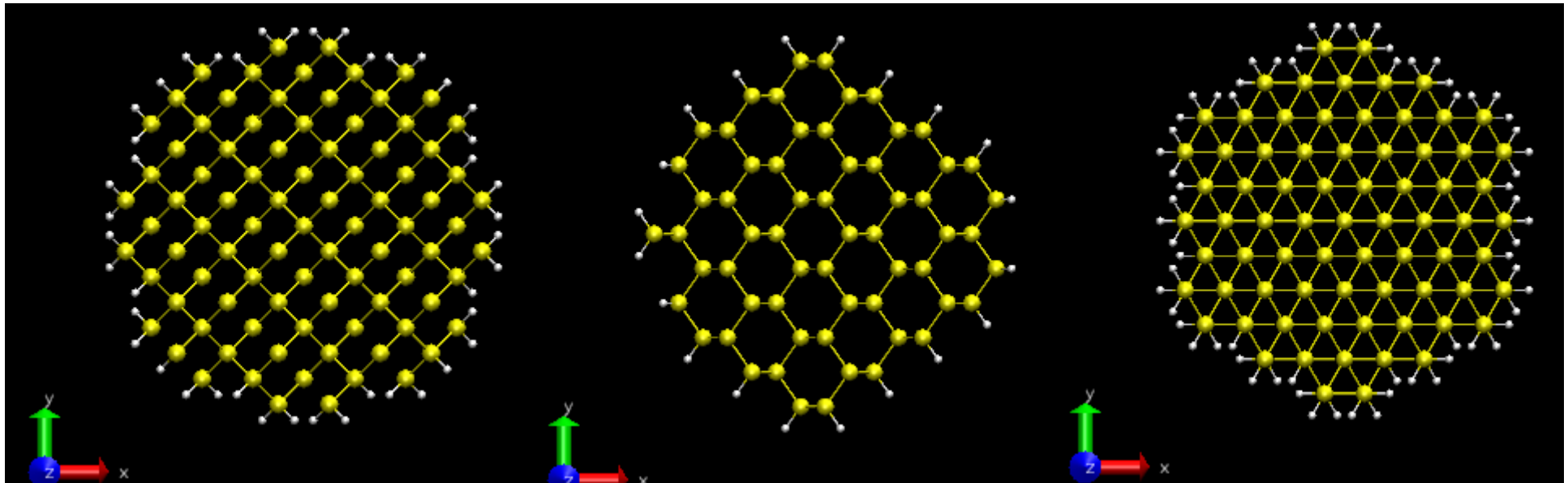
3D-stacked Si NWs with Hi-k/MG



SiNW Band structure calculation

Cross section of Si NW

First principal calculation,



$D=1.96\text{nm}$

[001]

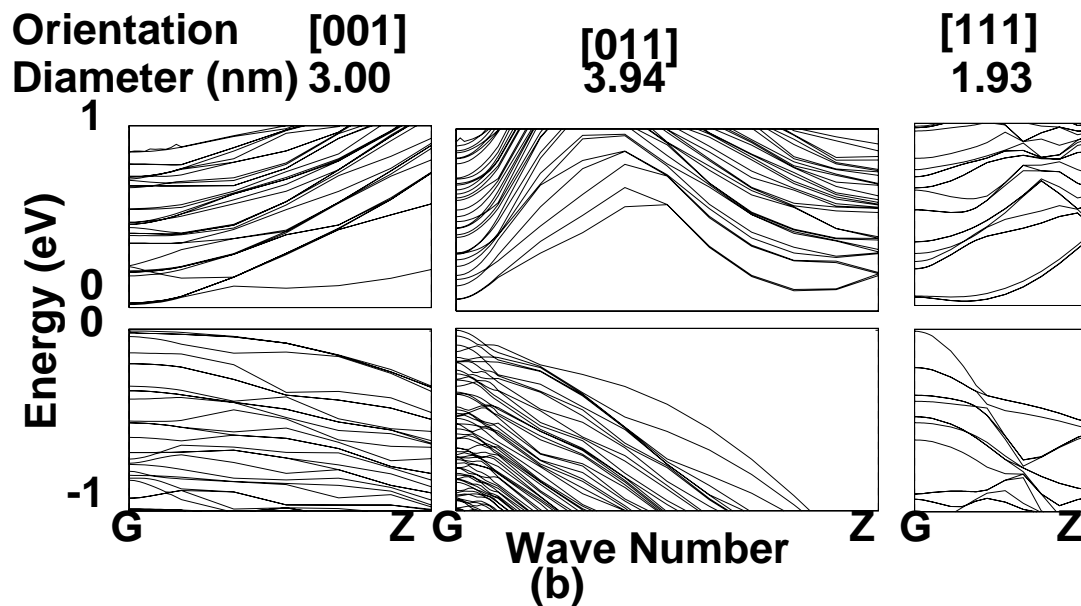
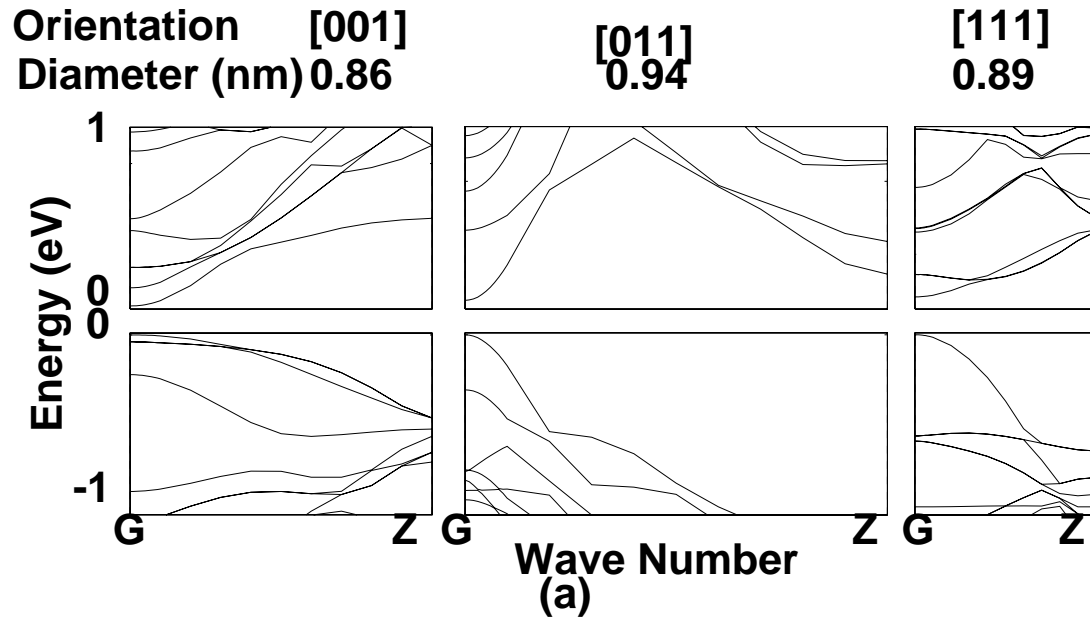
$D=1.94\text{nm}$

[011]

$D=1.93\text{nm}$

[111]

Si nanowire FET with 1D Transport

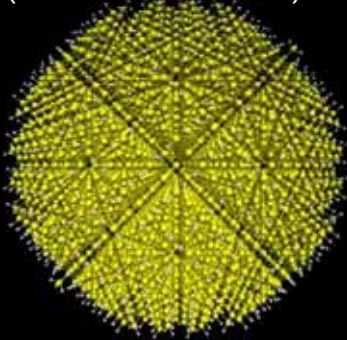


Small mass with [011]

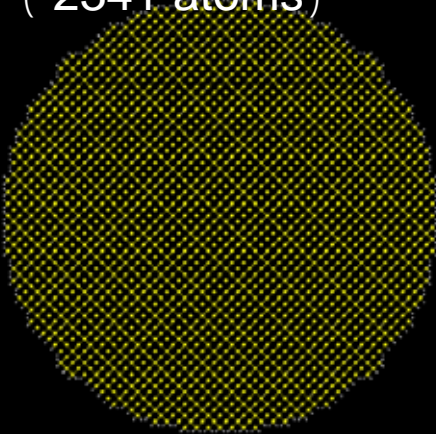
Large number of quantum channels with [001]

Atomic models of a Si quantum dot and Si nanowires

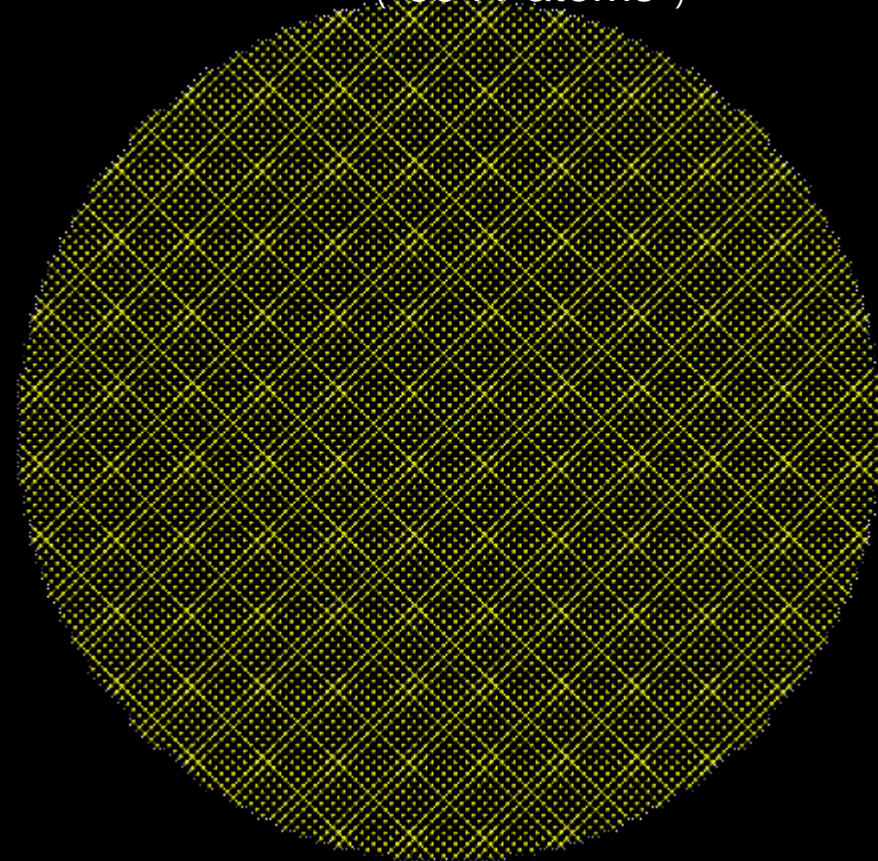
6.6 nm diameter SiQD
(8651 atoms)



10 nm diameter Si(100)NW
(2341 atoms)



20 nm diameter Si(100)NW
(8941 atoms)



RSDFT – suitable for parallel first-principles calculation -

- ✓ Real-Space Finite-Difference Higher-order finite difference pseudopotential method
- ✓ Sparse Matrix J. R. Chelikowsky et al., Phys. Rev. B, (1994)
- ✓ FFT free (FFT is inevitable in the conventional plane-wave code)
- ✓ MPI (Message Passing Interface) library

3D grid is divided by several regions for parallel computation.

Kohn-Sham eq. (finite-difference)

$$\left(-\frac{1}{2}\nabla^2 + v_s[\rho](\mathbf{r}) + \hat{v}_{nloc}^{PP}(\mathbf{r}) \right) \phi_n(\mathbf{r}) = \varepsilon_n \phi_n(\mathbf{r})$$

Higher-order finite difference

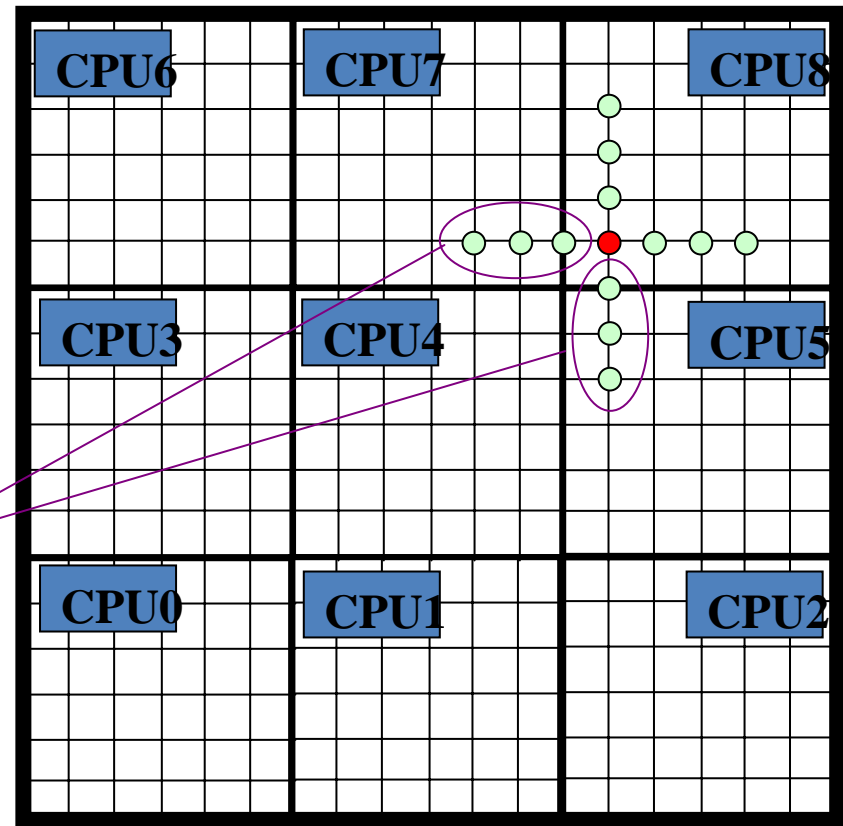
$$\frac{\partial^2}{\partial x^2} \psi_n(x, y, z) \approx \sum_{m=-6}^6 C_m \psi_n(x + m\Delta x, y, z)$$

MPI_ISEND, MPI_IRECV

Integration

$$\int \psi_m(\mathbf{r}) \psi_n(\mathbf{r}) d\mathbf{r} \approx \sum_{i=1}^{Mesh} \psi_m(\mathbf{r}_i) \psi_n(\mathbf{r}_i) \Delta x \Delta y \Delta z$$

MPI_ALLREDUCE



Massively Parallel Computing

with our recently developed code “RSDFT”

Iwata et al, J. Comp. Phys., to be published

Real-Space Density-Functional Theory code (RSDFT)

Based on the finite-difference pseudopotential method (J. R. Chelikowsky et al., PRB1994)

Highly tuned for massively parallel computers

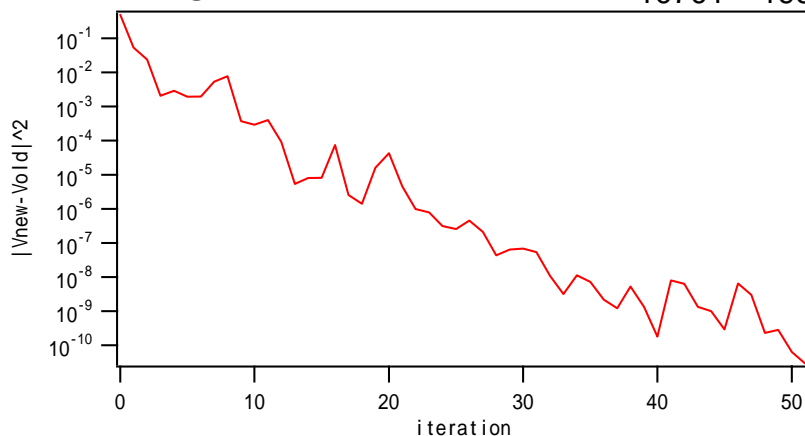
Computations are done on a massively-parallel cluster **PACS-CS** at University of Tsukuba.

(Theoretical Peak Performance = 5.6GFLOPS/node)



e.g.) The system over 10,000 atoms $\text{Si}_{10701}\text{H}_{1996}$
(7.6 nm diameter Si dot)

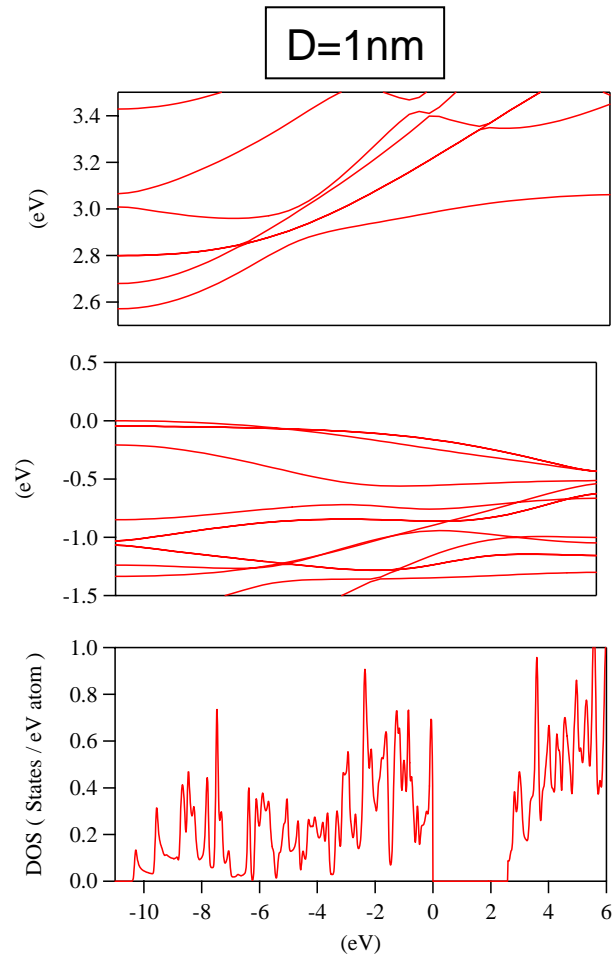
Convergence behavior for $\text{Si}_{10701}\text{H}_{1996}$ Grid points = 3,402,059
Bands = 22,432



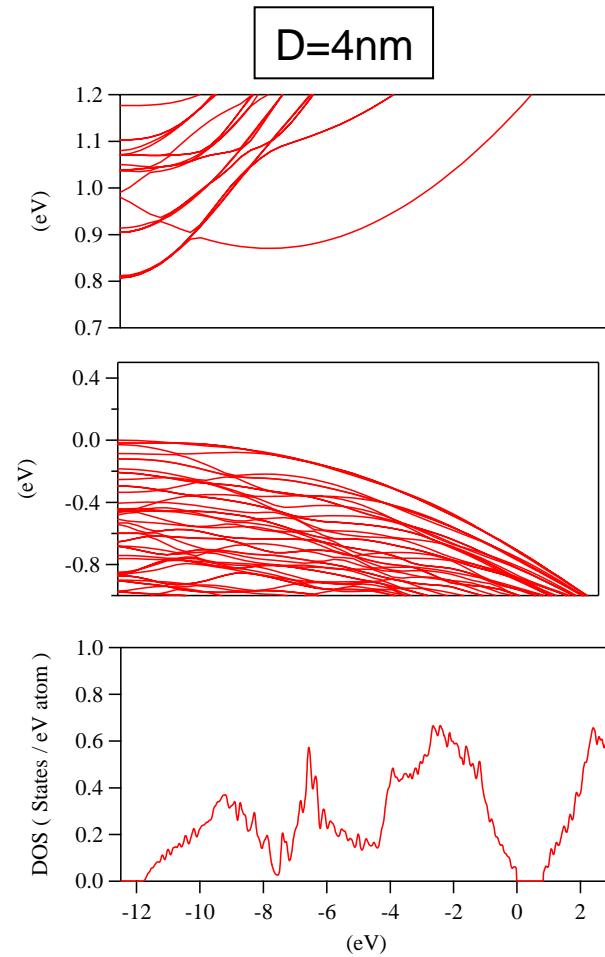
Computational Time (with 1024 nodes of PACS-CS)

6781 sec. \times 60 iteration step = 113 hour

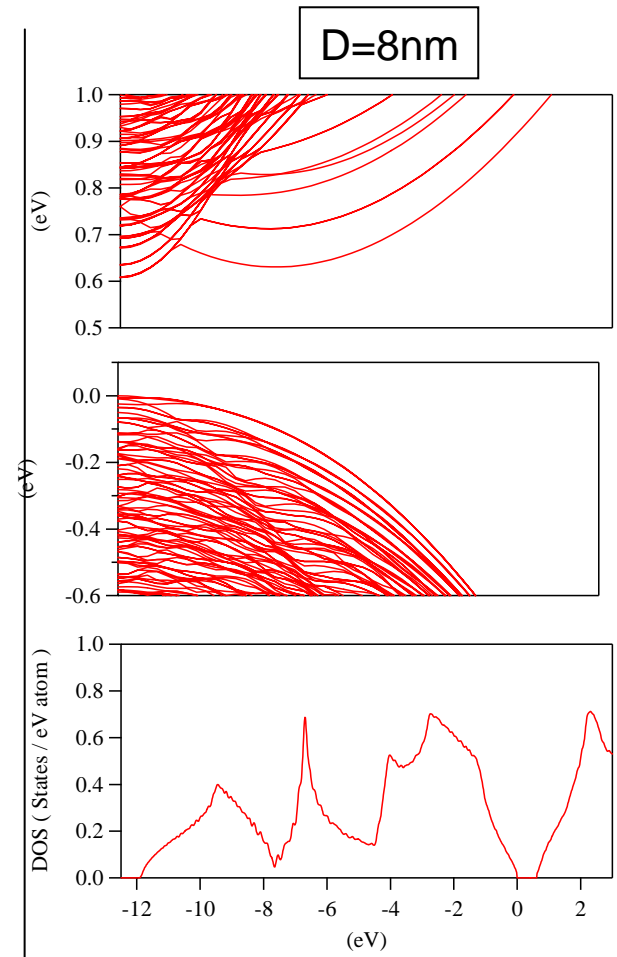
Band Structure and DOS of Si(100)NWs (D=1nm, 4nm, and 8nm)



D=1 nm
Si₂₁H₂₀ (41 atoms)
KS band gap=2.60eV



D = 4 nm
Si₃₄₁H₈₄ (425 atoms)
KS band gap = 0.81eV

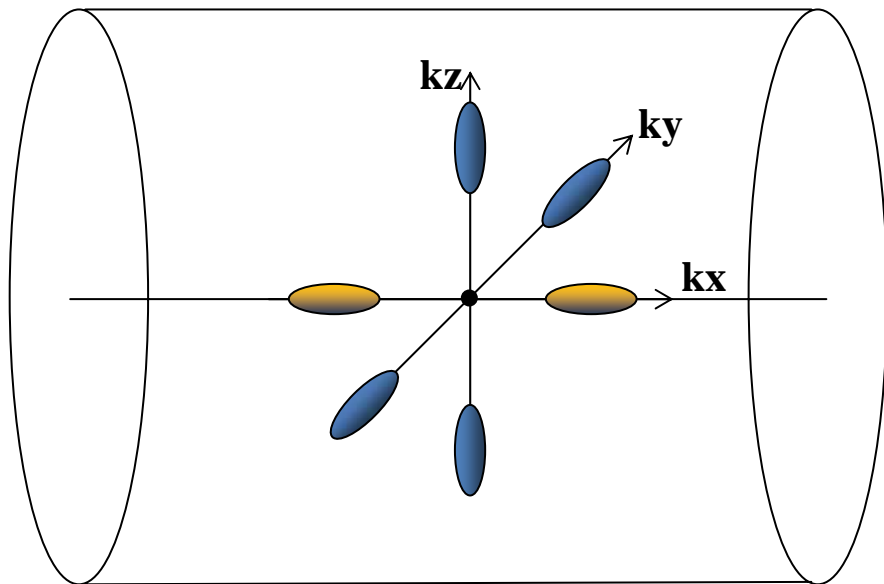
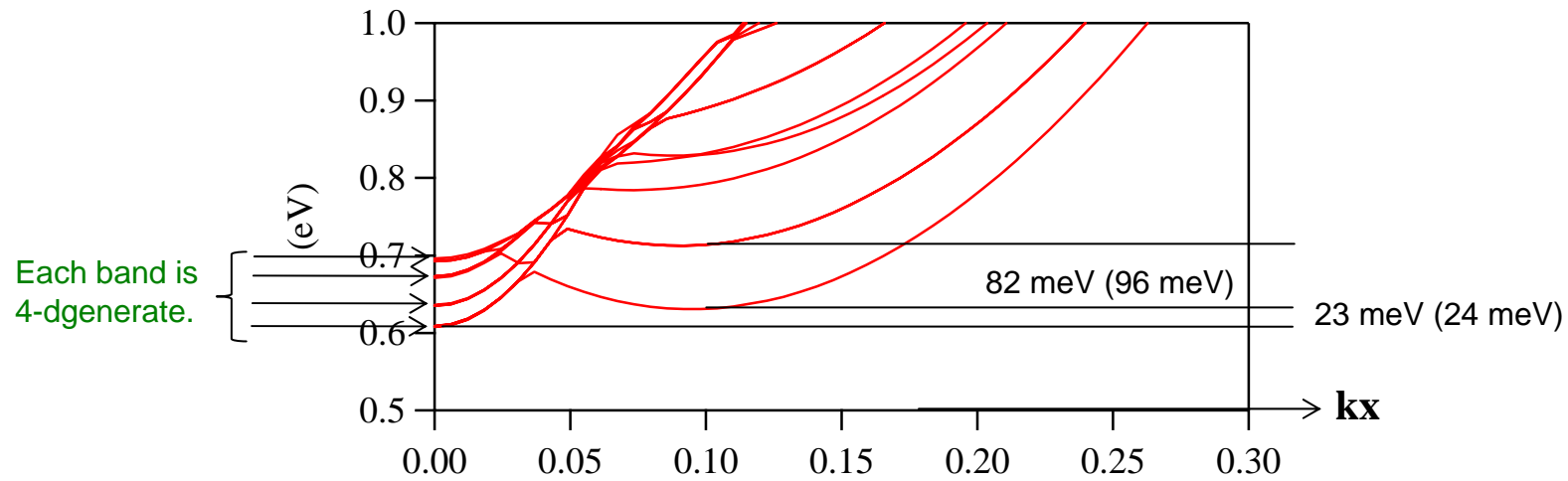


D=8 nm
Si₁₃₆₁H₁₆₄ (1525 atoms)
KS band gap=0.61eV

KS band gap of bulk (LDA) = 0.53eV

Band structure of 8-nm-diameter Si nanowire near the CBM

- KS band gap = 0.608 eV (@ Γ)

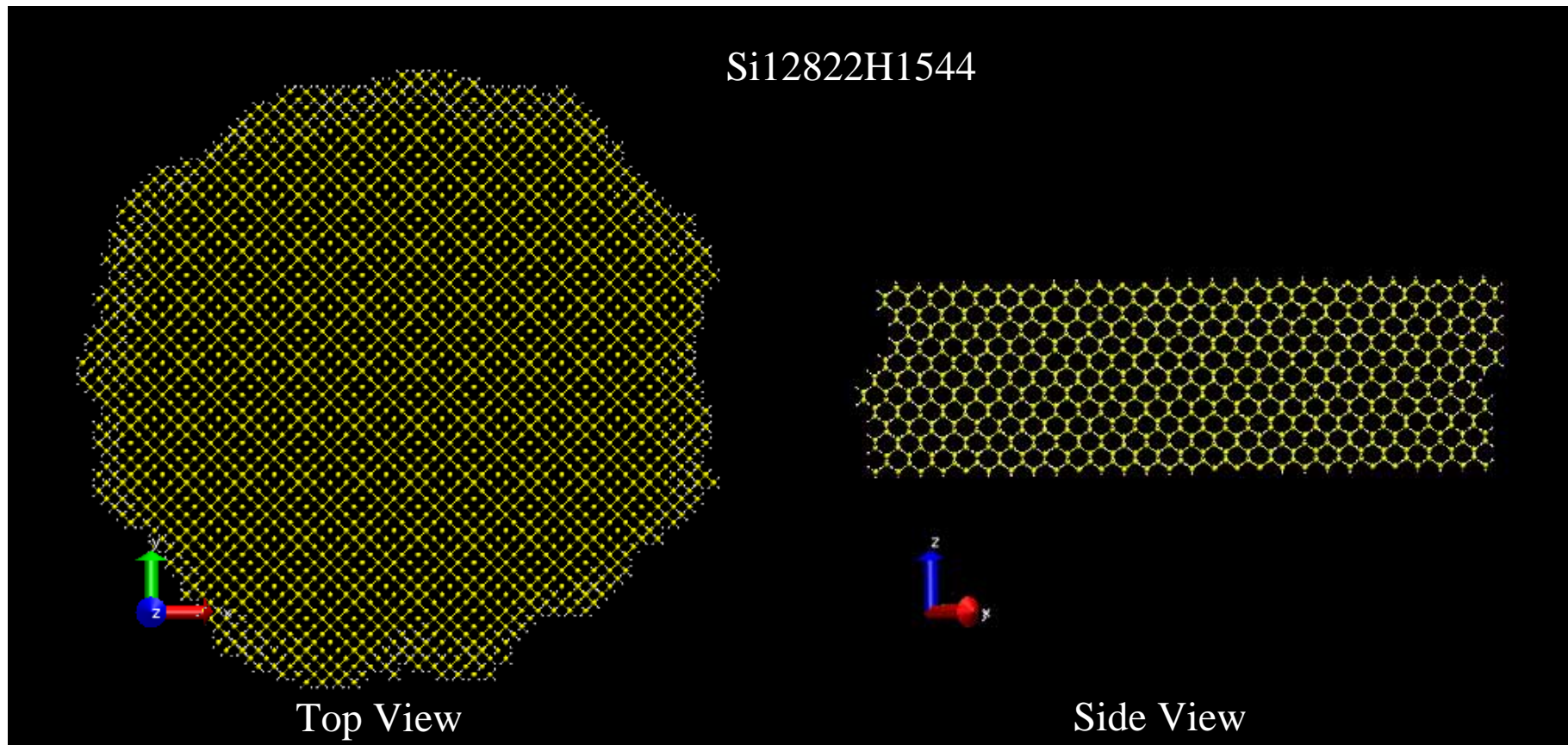


Effective mass equation

$$\left[-\frac{\hbar^2}{2m_t^*} \left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} \right) - \frac{\hbar^2}{2m_l^*} \frac{\partial^2}{\partial z^2} \right] \Phi(\mathbf{r}) = (\varepsilon - \varepsilon_{CBM}) \Phi(\mathbf{r})$$

The band structure can be understood that electrons near the CBM in the bulk Si are Confined within a cylindrical geometry.

Si nano wire with surface roughness

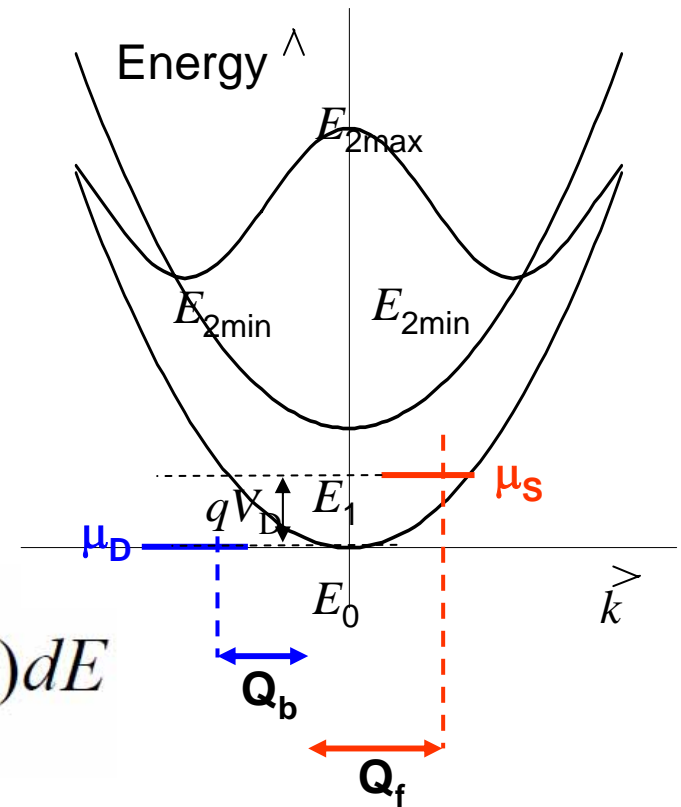
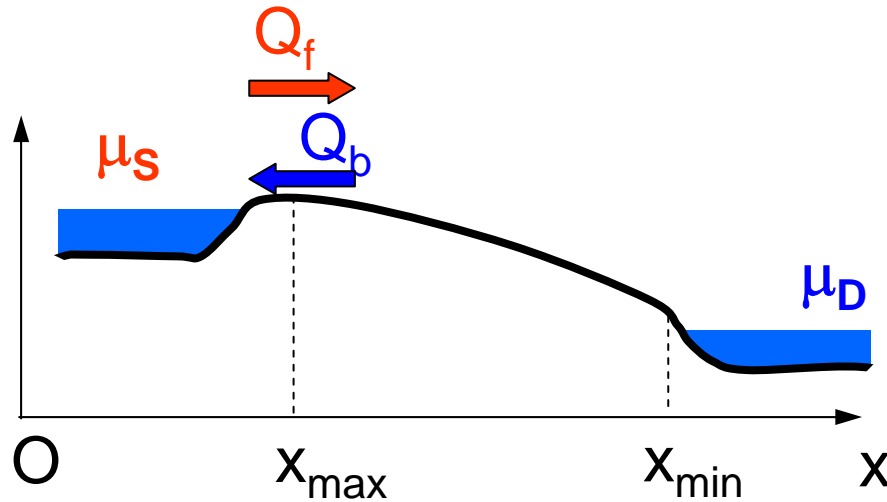


Si12822H1544 (14,366 atoms)

- 10nm diameter, 3.3nm height, (100)
- Grid spacing: 0.45\AA ($\sim 14\text{Ry}$)
- # of grid points: 4,718,592
- # of bands: 29,024
- Memory: 1,022GB \sim 2,044GB

SiNW Band compact model

Landauer Formalism for Ballistic FET

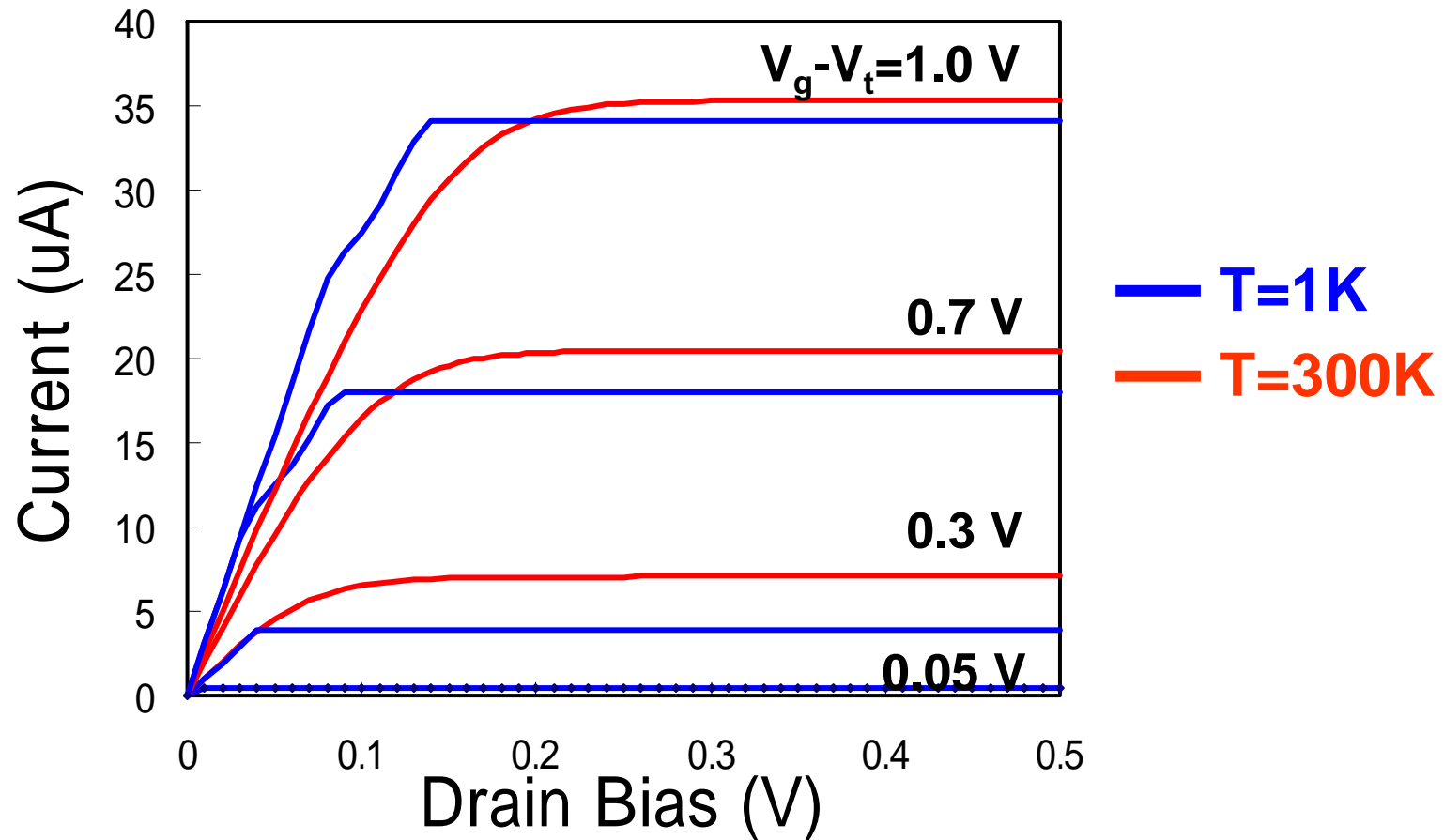


$$I_D = \frac{q}{\pi\hbar} \sum_i \int [f(E, \mu_S) - f(E, \mu_D)] T_i(E) dE$$

From x_{\max} to x_{\min} $T_i(E) \approx 1$

$$I_D = G_0 \left(\frac{k_B T}{q} \right) \sum_i g_i \ln \left\{ \frac{1 + \exp[(\mu_S - E_{i0}) / k_B T]}{1 + \exp[(\mu_D - E_{i0}) / k_B T]} \right\}$$

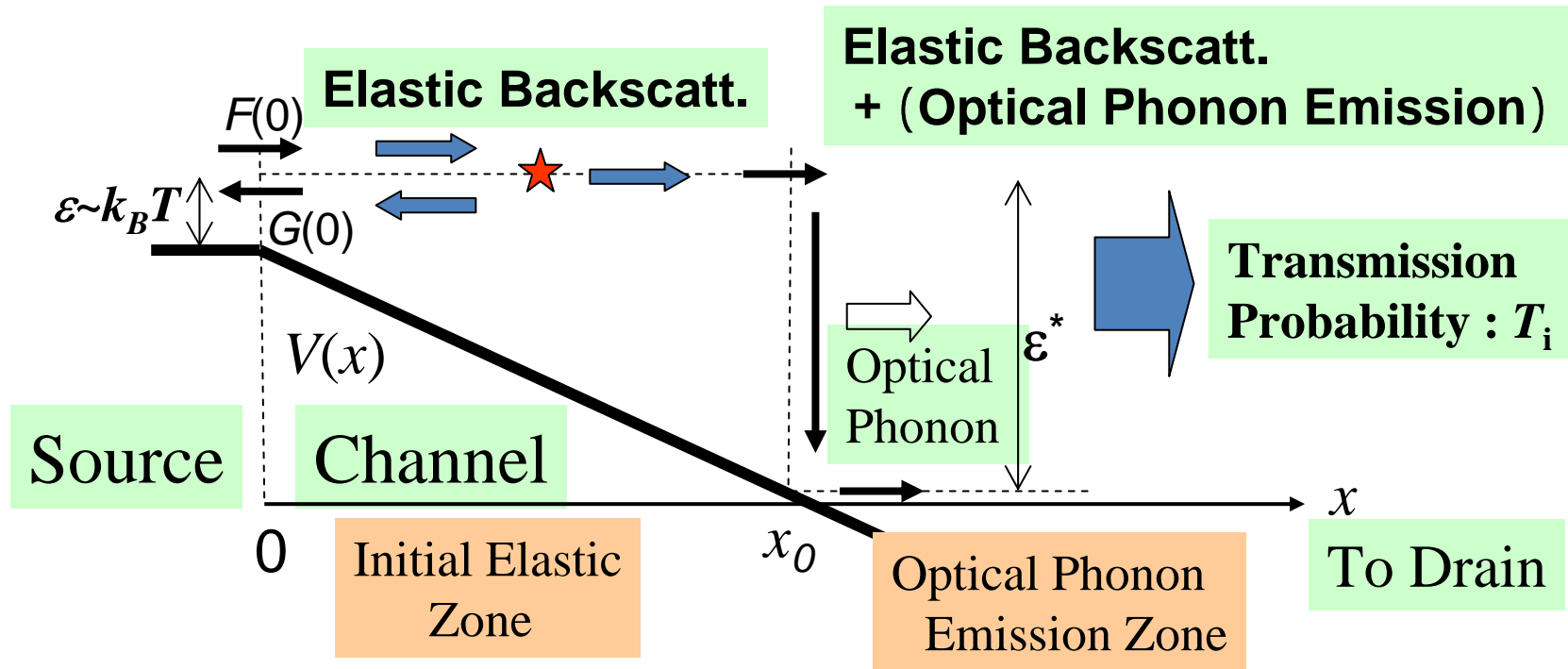
IV Characteristics of Ballistic SiNW FET



Small temperature dependency
 $35\mu A/wire$ for 4 quantum channels

Model of Carrier Scattering

Linear Potential Approx. : Electric Field E



Transmission Probability to Drain

$$T(\epsilon) = \frac{F(0) - G(0)}{F(0)} \quad \text{Injection from Drain}=0$$

Résumé of the Compact Model

$$I = \frac{q}{\pi \hbar} \sum_i g_i \int [f(\varepsilon, \mu_S) - f(\varepsilon, \mu_D)] T_i d\varepsilon$$

$$C_G = \frac{2\pi \varepsilon_{ox}}{\ln \left\{ \frac{\sqrt{2r+t_{ox}} + \sqrt{t_{ox}}}{\sqrt{2r+t_{ox}} - \sqrt{t_{ox}}} \right\}}$$

Planar Gate

$$(V_G - V_t) - \alpha \frac{\mu_S - \mu_0}{q} = \frac{|Q_f + Q_b|}{C_G}$$

$$\mu_S - \mu_D = qV_D$$

$$C_G = \frac{2\pi \varepsilon_{ox}}{\ln \left(\frac{r+t_{ox}}{r} \right)}$$

GAA

(Electrostatics requirement)

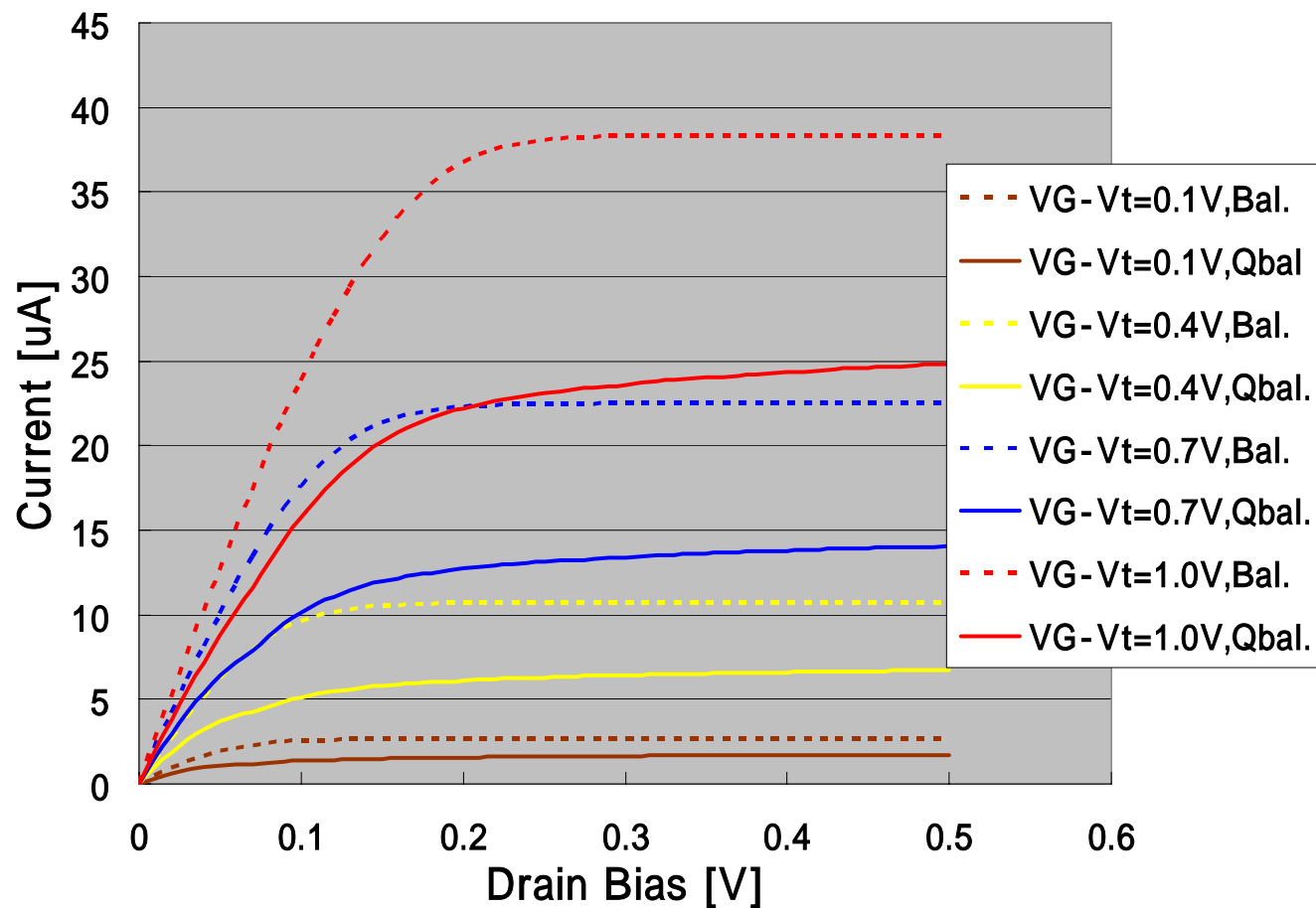
$$|Q_f + Q_b| = \frac{q}{\pi} \sum_i g_i \left[\int_{-\infty}^{\infty} \frac{dk}{1 + \exp \left\{ \frac{\varepsilon_i(k) - \mu_S}{k_B T} \right\}} - \int_{-\infty}^0 \left\{ \frac{1}{1 + \exp \left\{ \frac{\varepsilon_i(k) - \mu_S}{k_B T} \right\}} - \frac{1}{1 + \exp \left\{ \frac{\varepsilon_i(k) - \mu_D}{k_B T} \right\}} \right\} T_i(\varepsilon_i(k)) dk \right]$$

$$T(\varepsilon) = \frac{\sqrt{2D_0} qE}{\left(\sqrt{B_0 + D_0} + \sqrt{D_0} \right) qE + \sqrt{2mD_0} B_0 \ln \left(\frac{qEx_0 + \varepsilon}{\varepsilon} \right)}$$

(Carrier distribution in Subbands)

Unknowns are $I_D, (\mu_S - \mu_0), (\mu_D - \mu_0), (Q_f + Q_b)$

I- V_D Characteristics (RT)

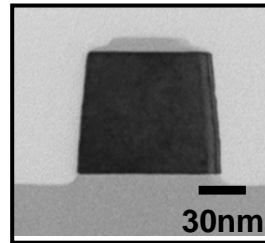


- Electric current 20 ~ 25 μA
- No saturation at Large V_D

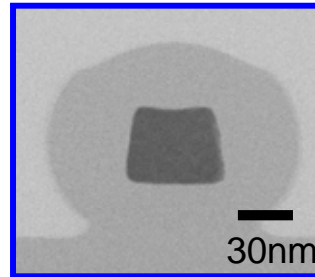
SiNW FET Fabrication

SiNW FET Fabrication

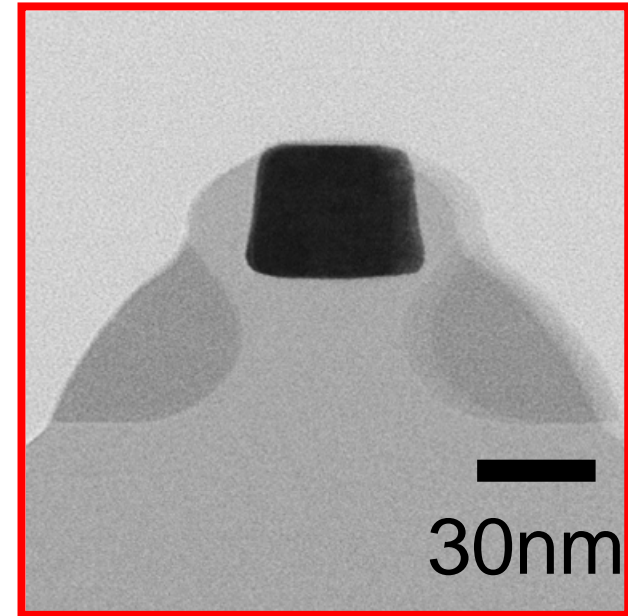
○ S/D & Fin Patterning



○ Sacrificial Oxidation



○ Oxide etch back



○ SiN sidewall support formation

○ Gate Oxidation & Poly-Si Deposition

○ Gate Lithography & RIE Etching

○ Gate Sidewall Formation

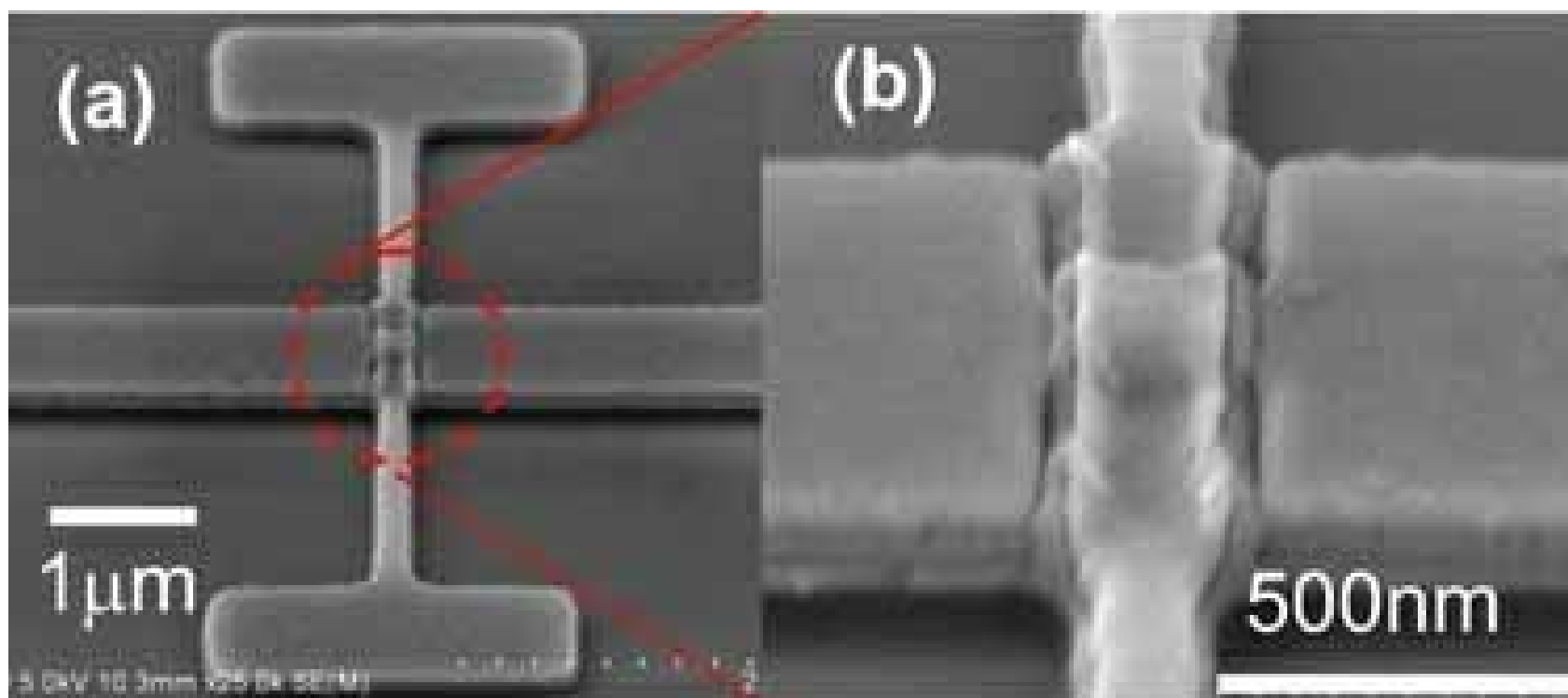
○ Ni SALISIDE Process (Ni 9nm / TiN 10nm)

○ Backend

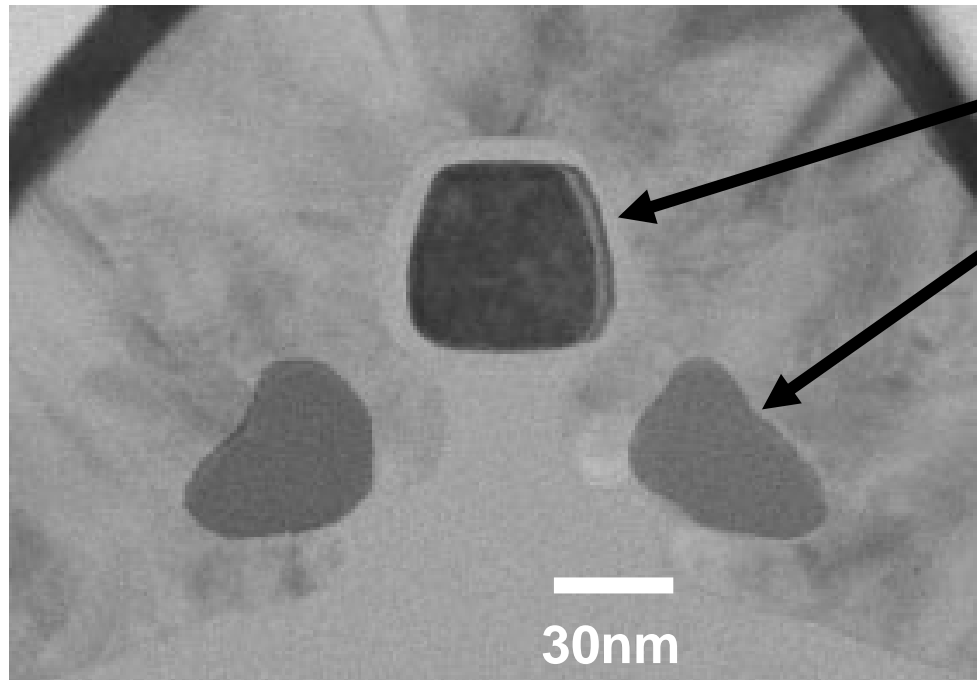
Standard recipe for gate stack formation

(a) SEM image of Si NW FET ($L_g = 200\text{nm}$)

(b) high magnification observation of gate and its sidewall.

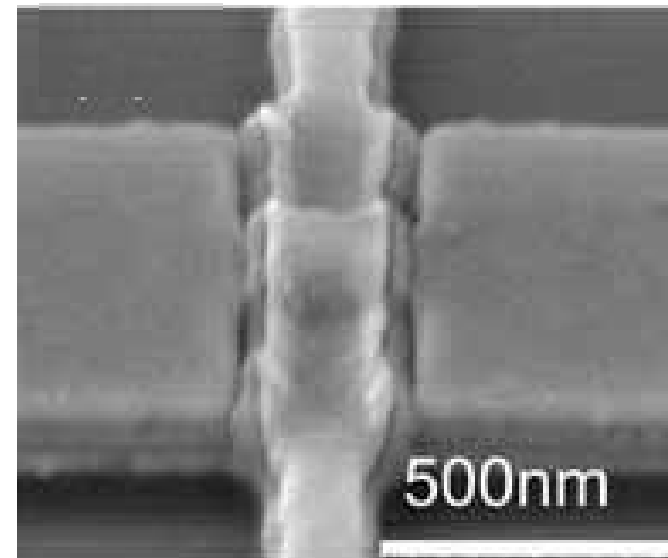
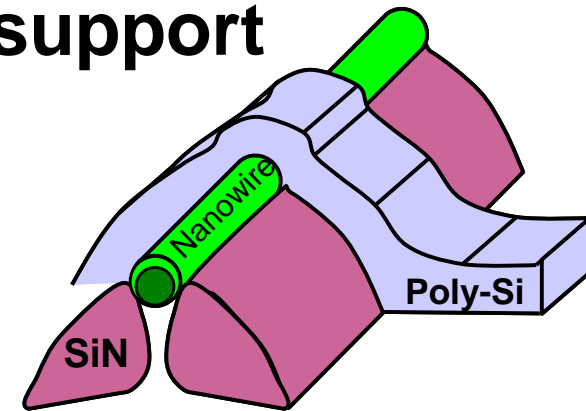


Fabricated SiNW FET



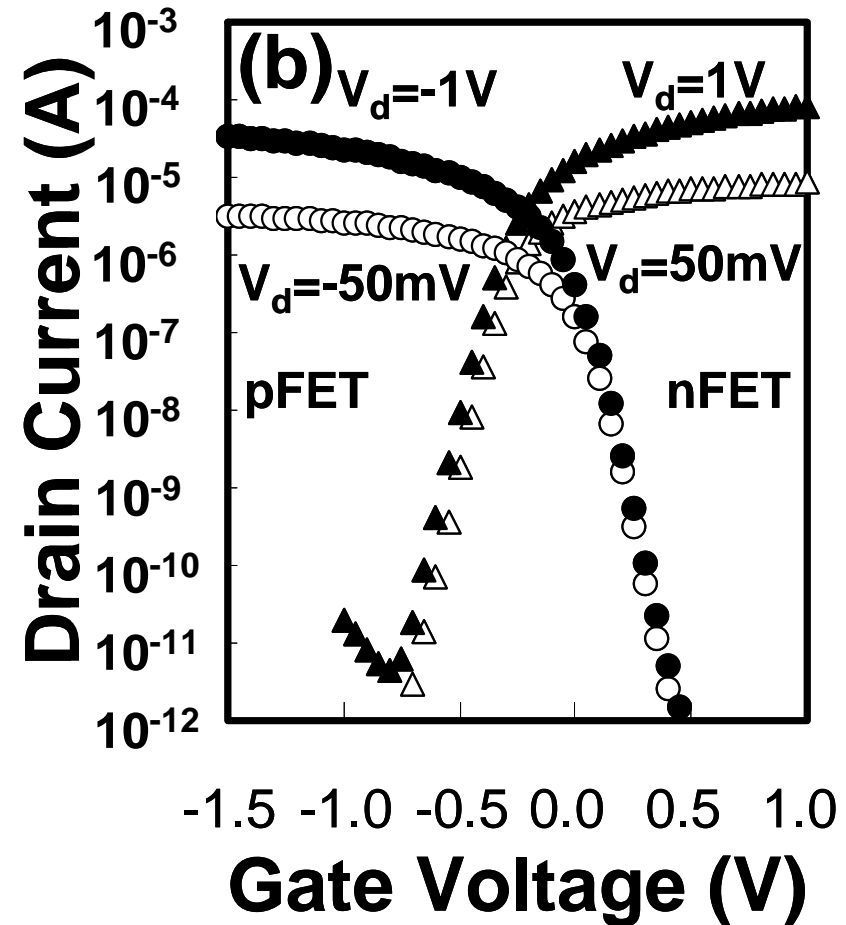
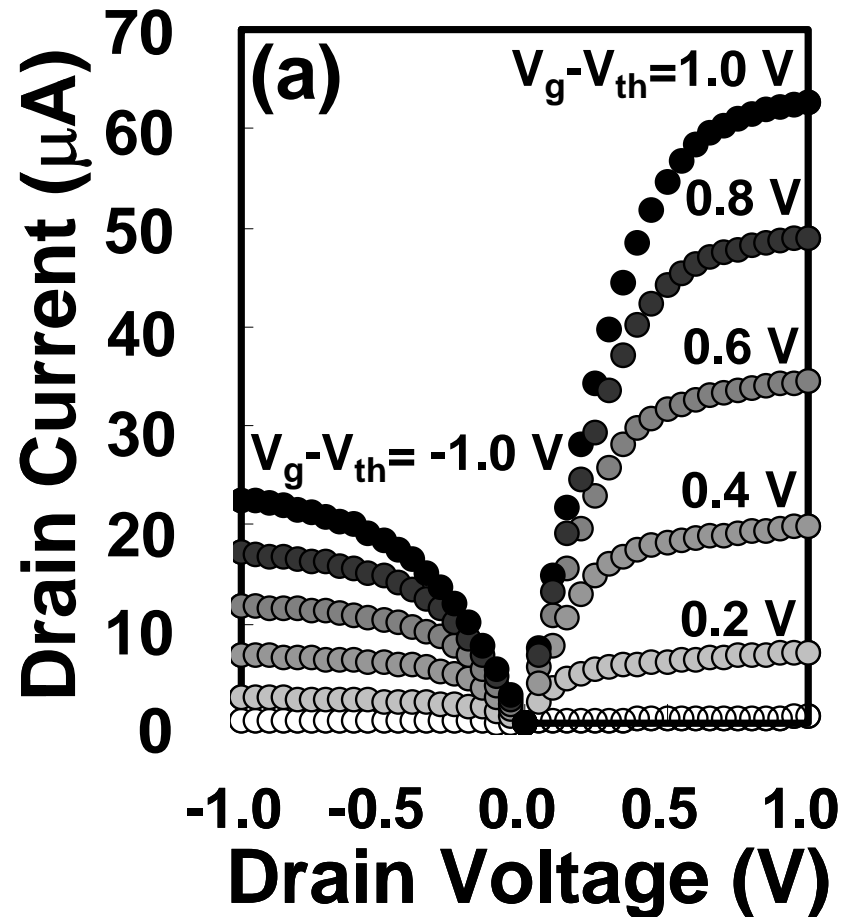
SiNW

SiN support



Recent results to be presented by ESSDERC 2010 next week in Seville

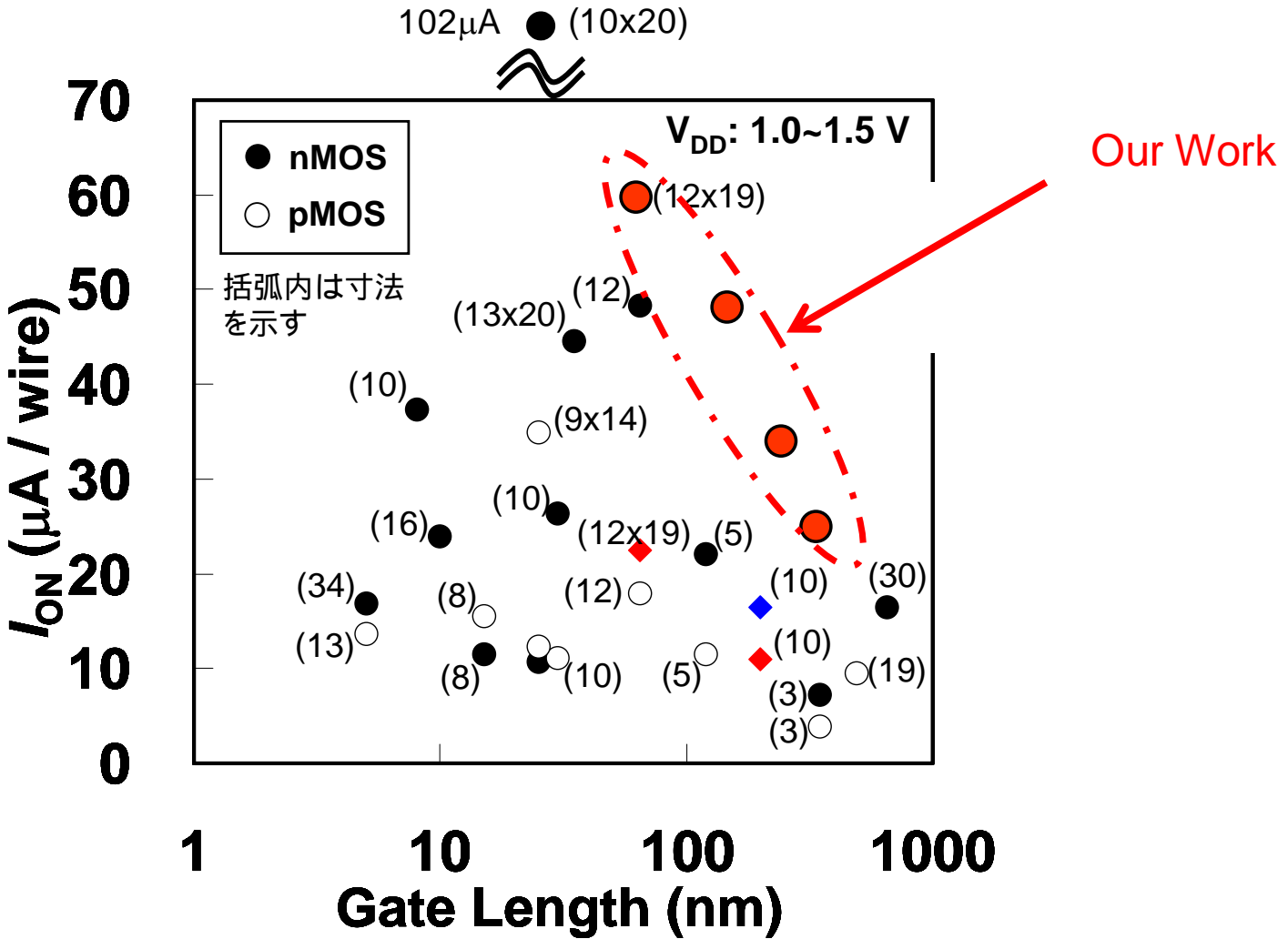
Wire cross-section: 20 nm X 10 nm



On/Off $> 10^6$, 60 μA /wire

$L_g = 65\text{ nm}$, $T_{ox} = 3\text{ nm}$

Bench Mark



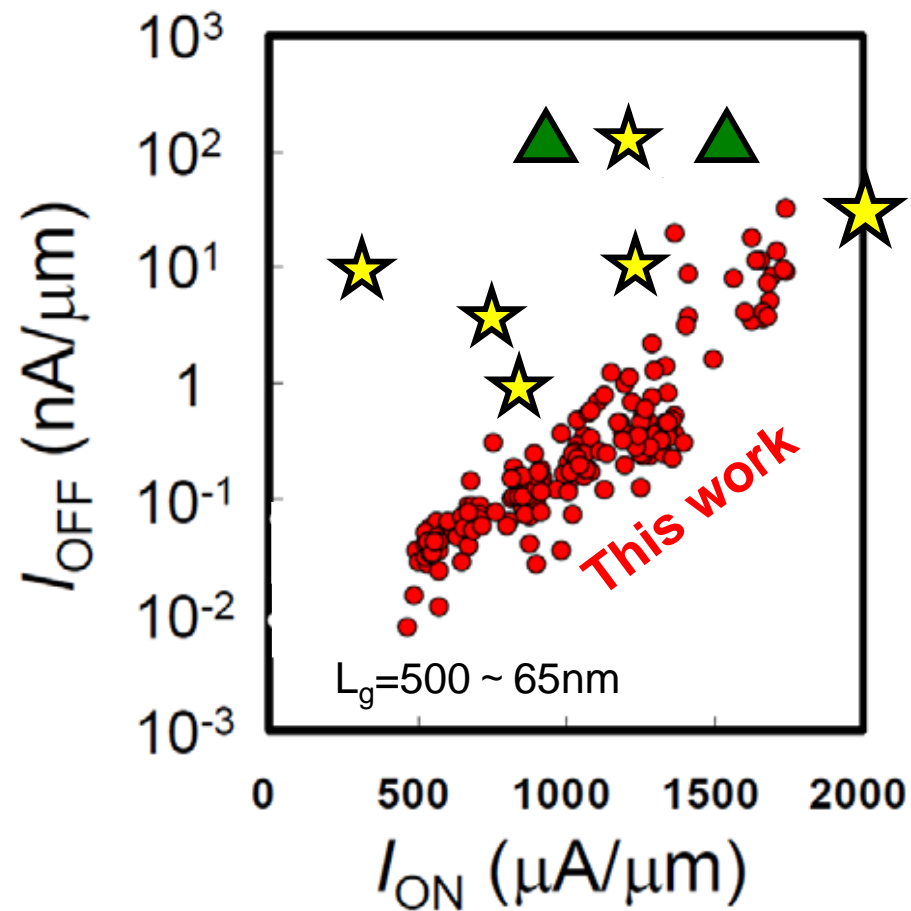
Bench Mark

	This work	Ref[11]	Ref[12]	Ref[13]	Ref[14]	Ref[15]	Ref[4]
NW Cross-section (nm)	Rect.	Rect.	Rect.	Cir.	Cir.	Elliptical	Elliptical
NW Size (nm)	10x20	10x20	14	10	10	12	13x20
Lg (nm)	65	25	100	30	8	65	35
EOT or Tox (nm)	3	1.8	1.8	2	4	3	1.5
Vdd (V)	1.0	1.1	1.2	1.0	1.2	1.2	1.0
Ion(uA) per wire	60.1	102	30.3	26.4	37.4	48.4	43.8
Ion(uA/um) by dia.	3117	5010	2170	2640	3740	4030	2592
Ion(uA/um) by cir.	1609	2054	430	841	1191	1283	825
SS (mV/dec.)	70	79	68	71	75	~75	85
DIBL (mV/V)	62	56	15	13	22	40-82	65
Ion/Ioff	~1E6	>1E6	>1E5	~1E6	>1E7	>1E7	~2E5

Ref[11] by Stmicro Lg=25nm, Tox=1.8nm

This work Lg=65nm, Tox=3nm

I_{ON}/I_{OFF} Bench mark



Planer FET



1.0 ~ 1.1V

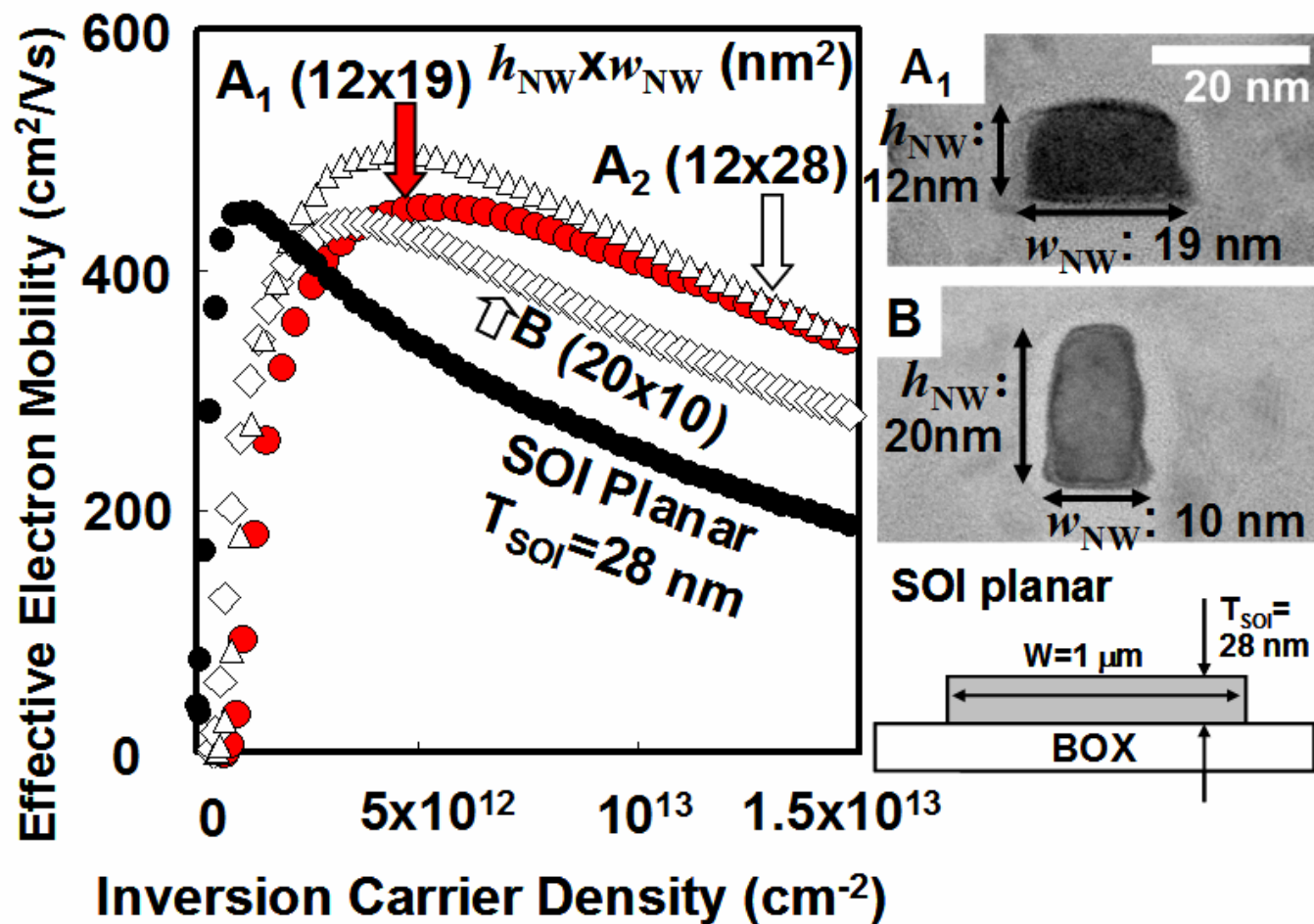
S. Kamiyama, IEDM 2009, p. 431
P. Packan, IEDM 2009, p.659

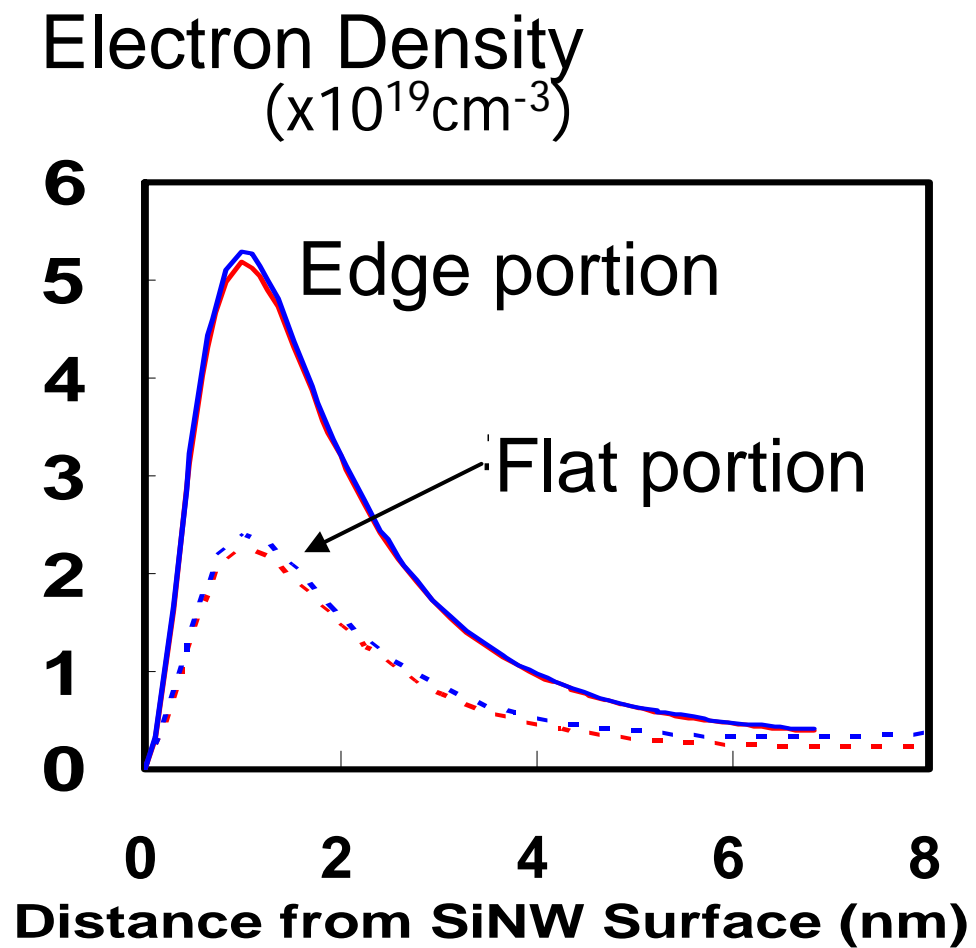
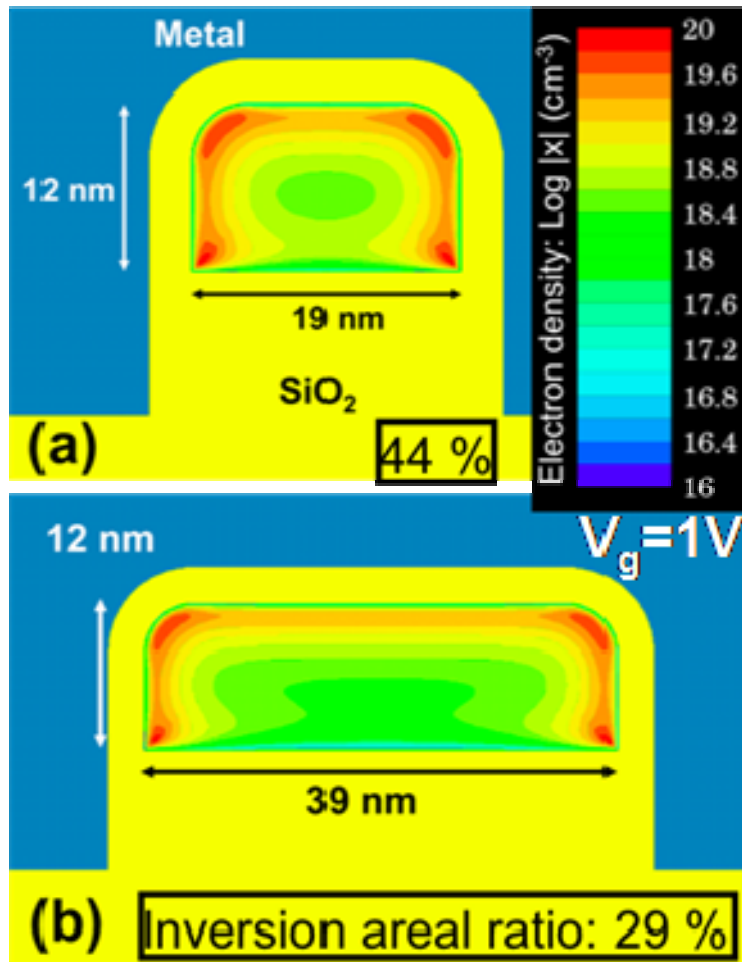
SiナノワイヤFET



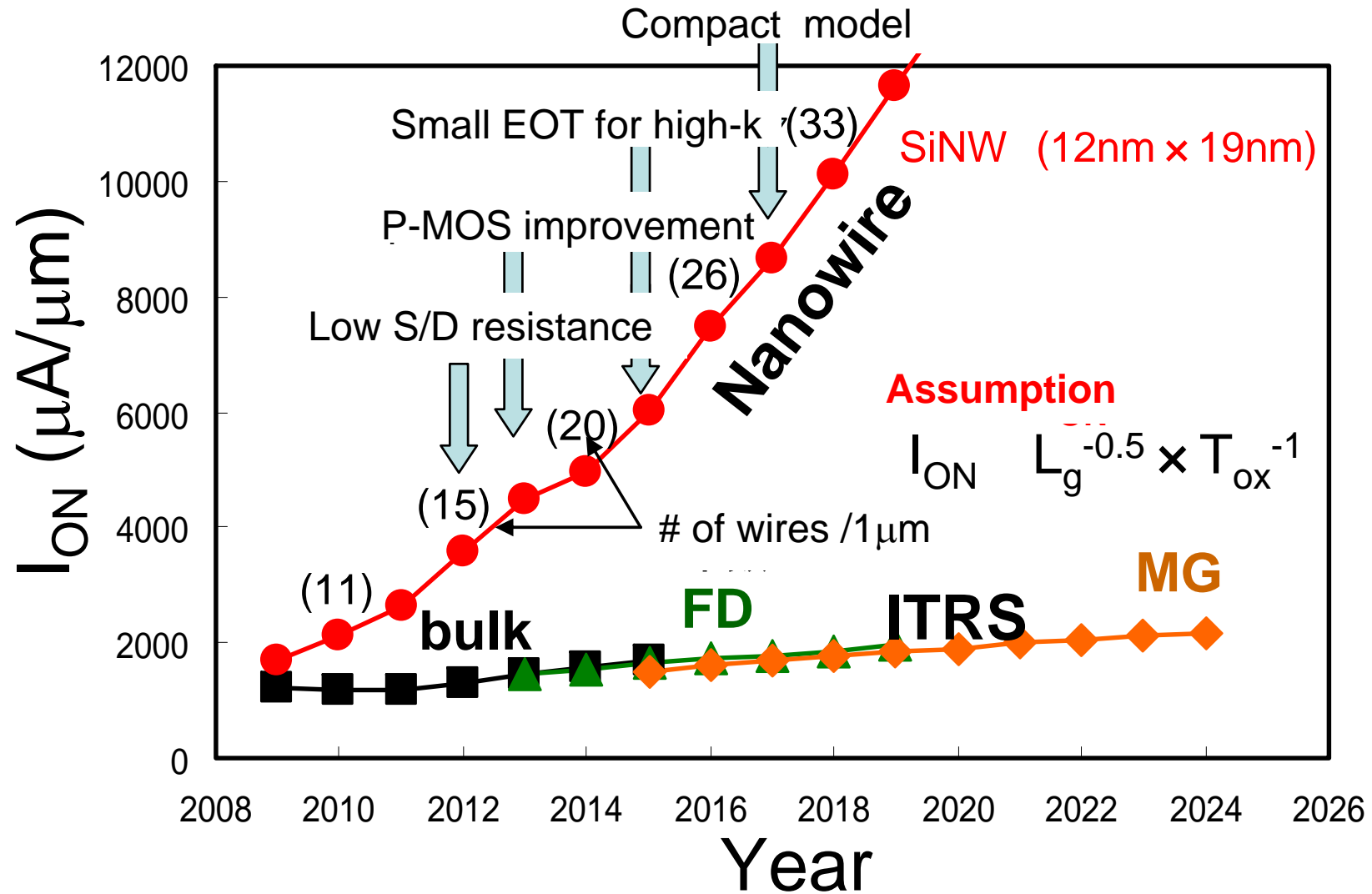
1.2 ~ 1.3V

Y. Jiang, VLSI 2008, p.34
H.-S. Wong, VLSI 2009, p.92
S. Bangsaruntip, IEDM 2009, p.297
C. Dupre, IEDM 2008, p. 749
S.D.Suk, IEDM 2005, p.735
G.Bidel, VLSI 2009, p.240





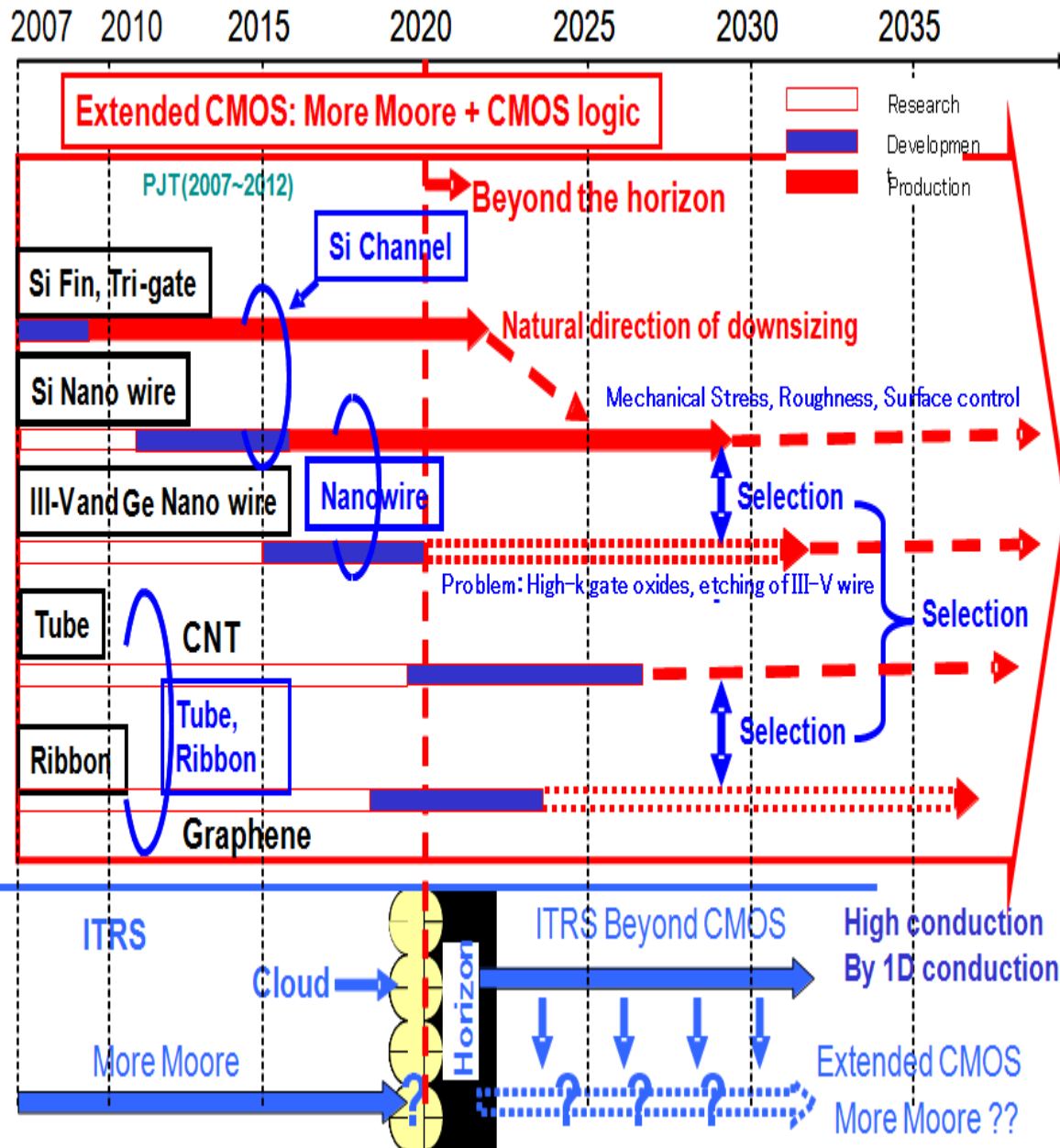
Primitive estimation !



Our roadmap for R & D

Source: H. Iwai, IWJT 2008

Current Issues



Si Nanowire

- Control of wire surface property
- Source Drain contact
- Optimization of wire diameter
- Compact I-V model

III-V & Ge Nanowire

- High-k gate insulator
- Wire formation technique

CNT:

- Growth and integration of CNT
- Width and Chirality control
- Chirality determines conduction types: metal or semiconductor

Graphene:

- Graphene formation technique
- Suppression of off-current
- Very small bandgap or no bandgap (semi-metal)
- Control of ribbon edge structure which affects bandgap

Thank you
for your attention!