Future of NanoCMOS after Scaling Limit

October 28, 2008

@Shenyang University of Technology

Hiroshi Iwai,
Tokyo Institute of Technology

Tokyo Institute of Technology
東京工業大学

Founded in 1881, Promoted to Univ. 1929

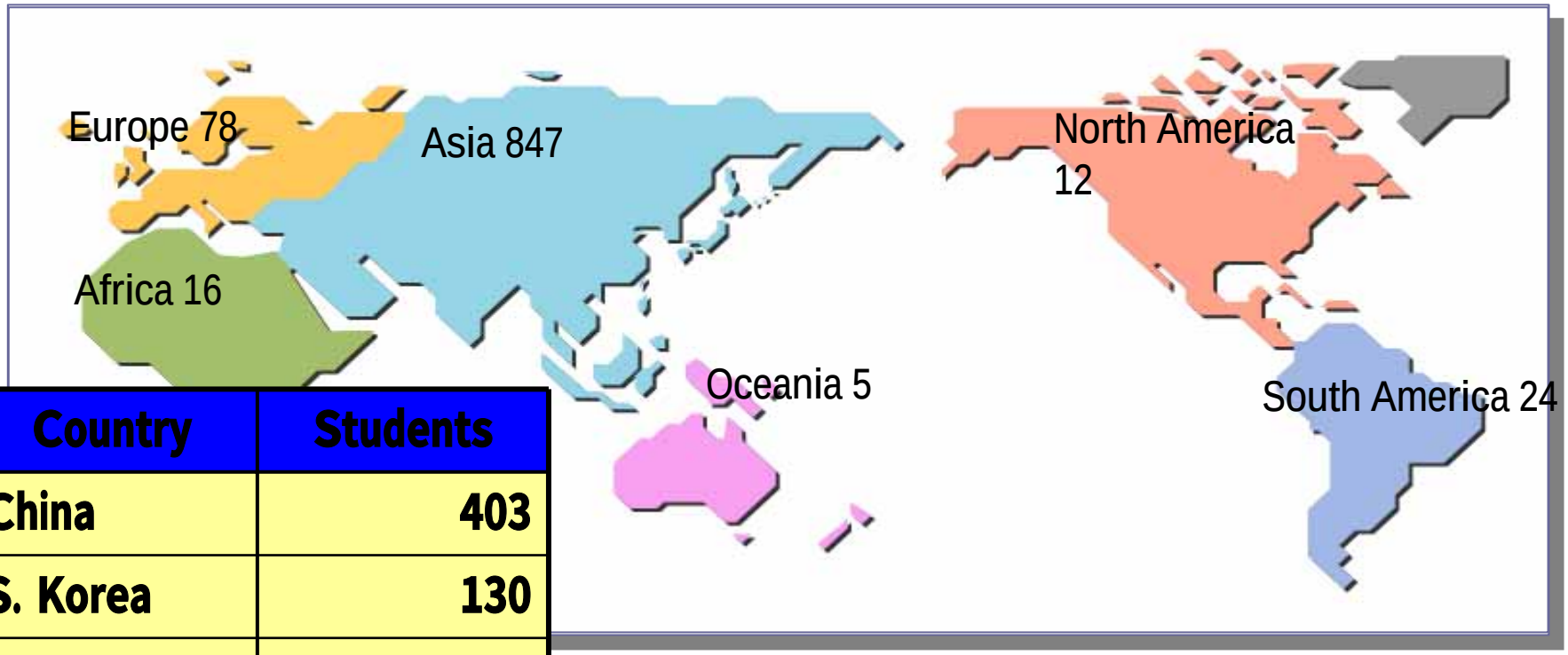
Tokyo Institute of Technology
東京工業大学

Promoted to Univ. 1929

Total 10,000 students: 5,000 under graduate

5,000 graduate

International Students



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

Total 982

(As of May. 1, 2005)

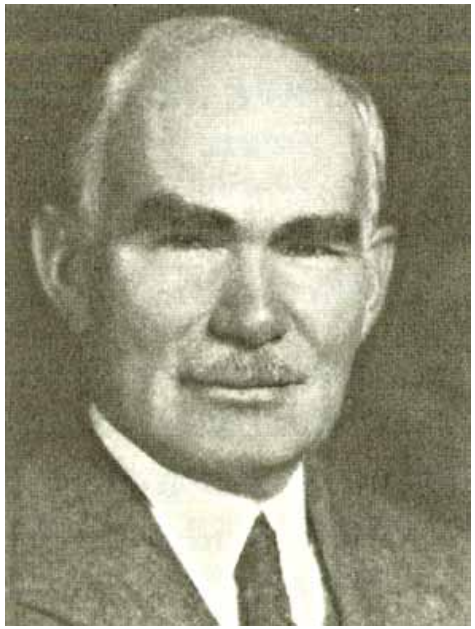
- There were many inventions in the 20th century:

  Airplane, Nuclear Power generation, Computer,

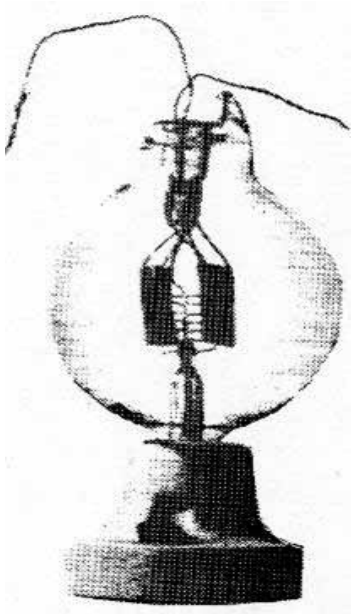
  Space aircraft, etc
- However, everything has to be controlled by electronics
- Electronics

  Most important invention in the 20th century
- What is Electronics: To use electrons,

  Electronic Circuits

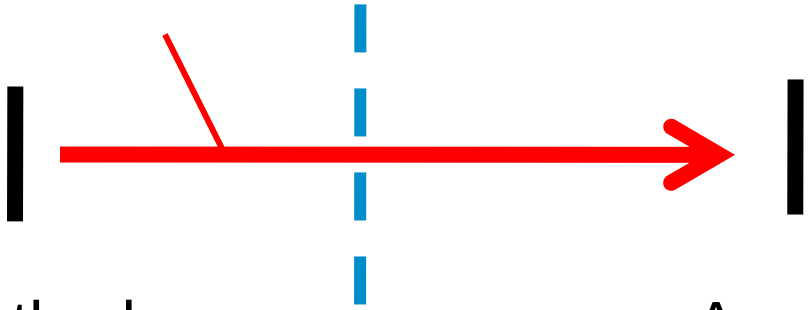


Lee De Forest



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

Thermal electrons from cathode controlled by grid bias



Cathode (heated)

Grid

Anode (Positive bias)

Same mechanism as that of transistor

4 wives of Lee De Forest

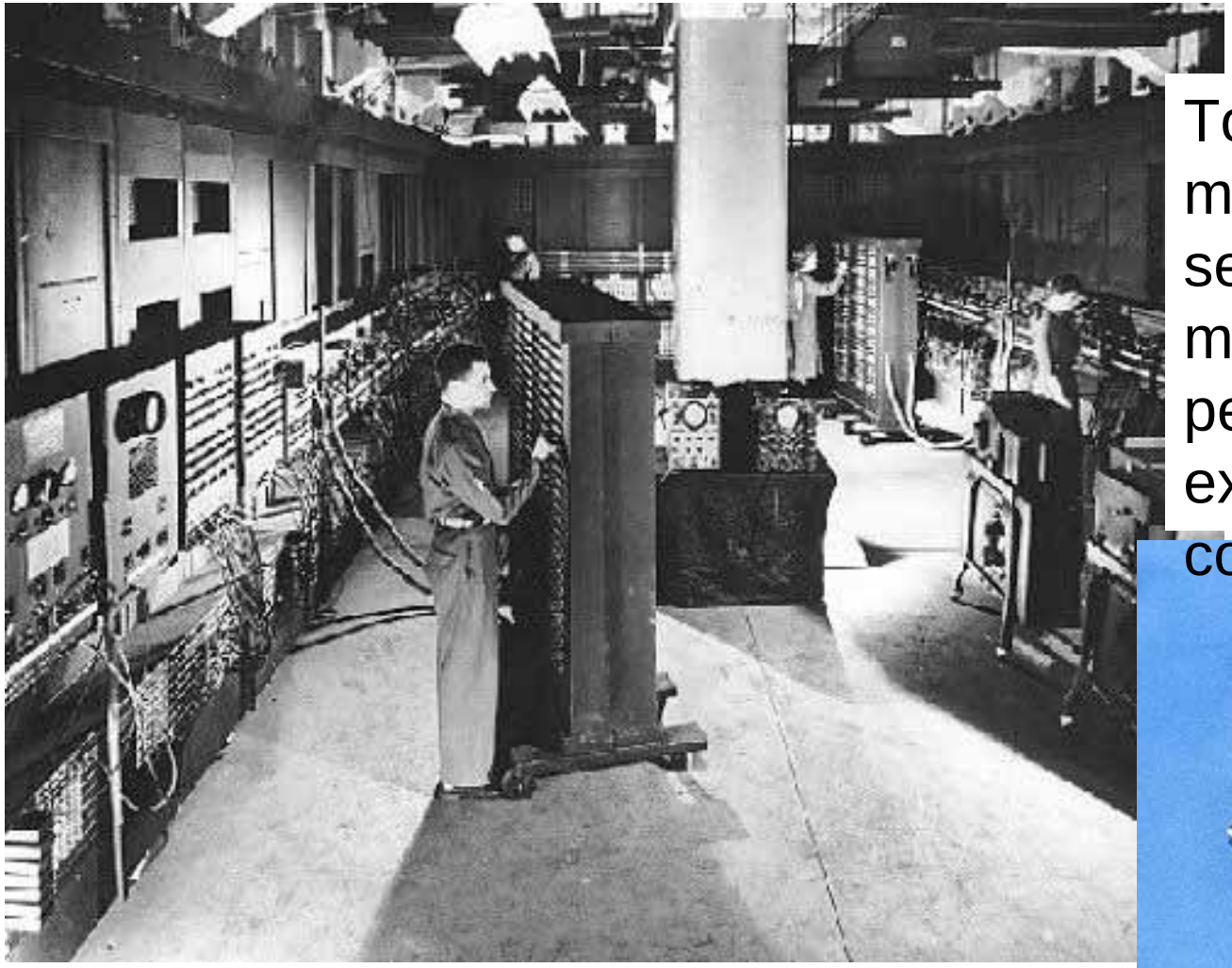
1906 Lucille Sheardown
1907 Nora Blatch
1912 Mary Mayo, singer
1930 Marie Mosquini, silent film actress

Mary

Marie

First Computer Eniac: made of huge number of vacuum tubes 19
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

History of Semiconductor devices

1947, 1st Point Contact Bipolar Transistor:
Ge Semiconductor, Bardeen, Brattin
→ Nobel Prize

1948, 1st Junction Bipolar Transistor,
Ge Semiconductor, Schokley
→ Nobel Prize

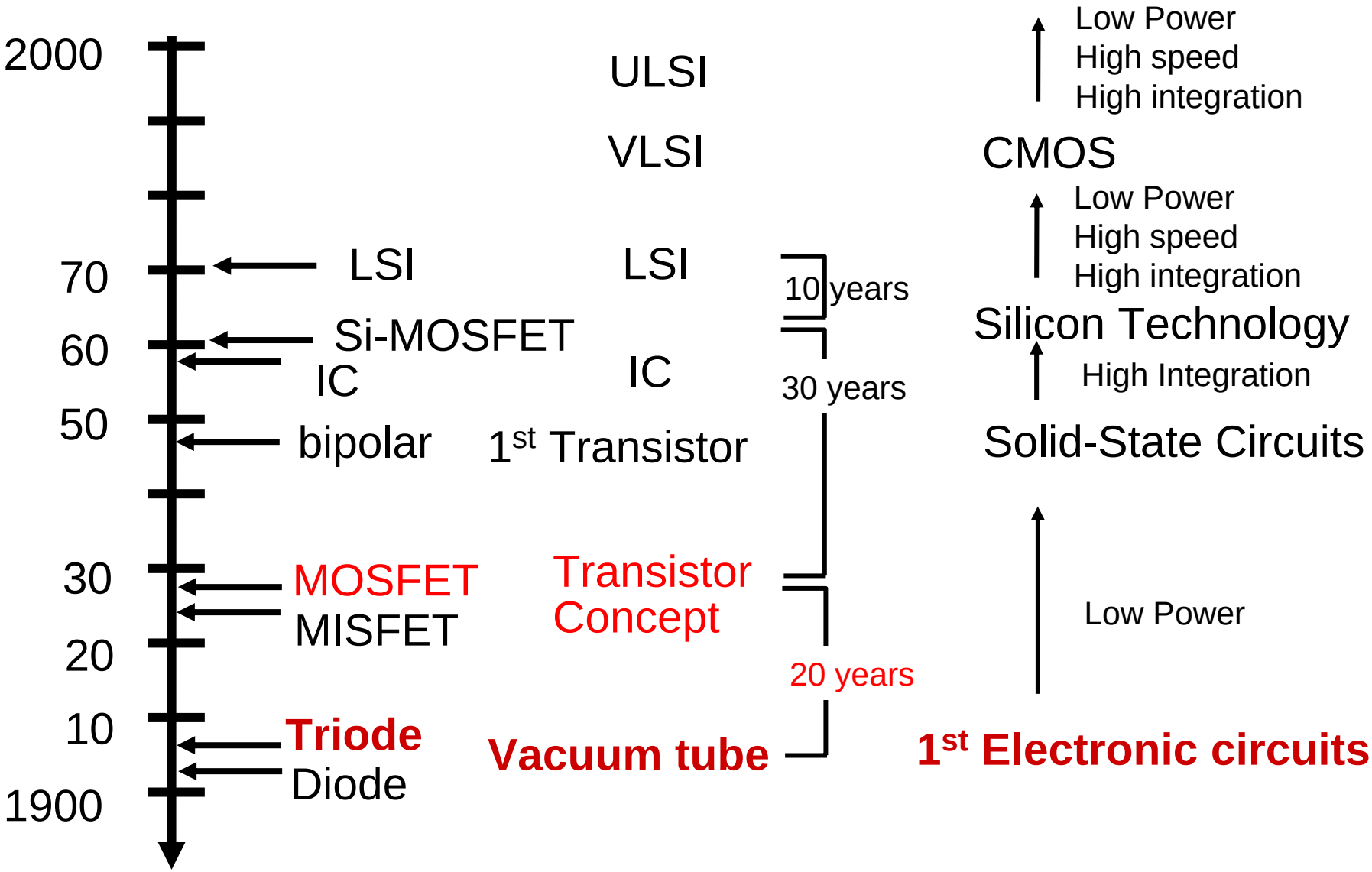
1958, 1st Integrated Circuits,
Ge Semiconductor, J.Kilby → Nobel Prize

1959, 1st Planar Integrated Circuits,
Noice

1960, 1st MOS Transistor, Kahng,
Si Semiconductor

1963, 1st CMOS Circuits, C.T. Sah and F. Wanlass

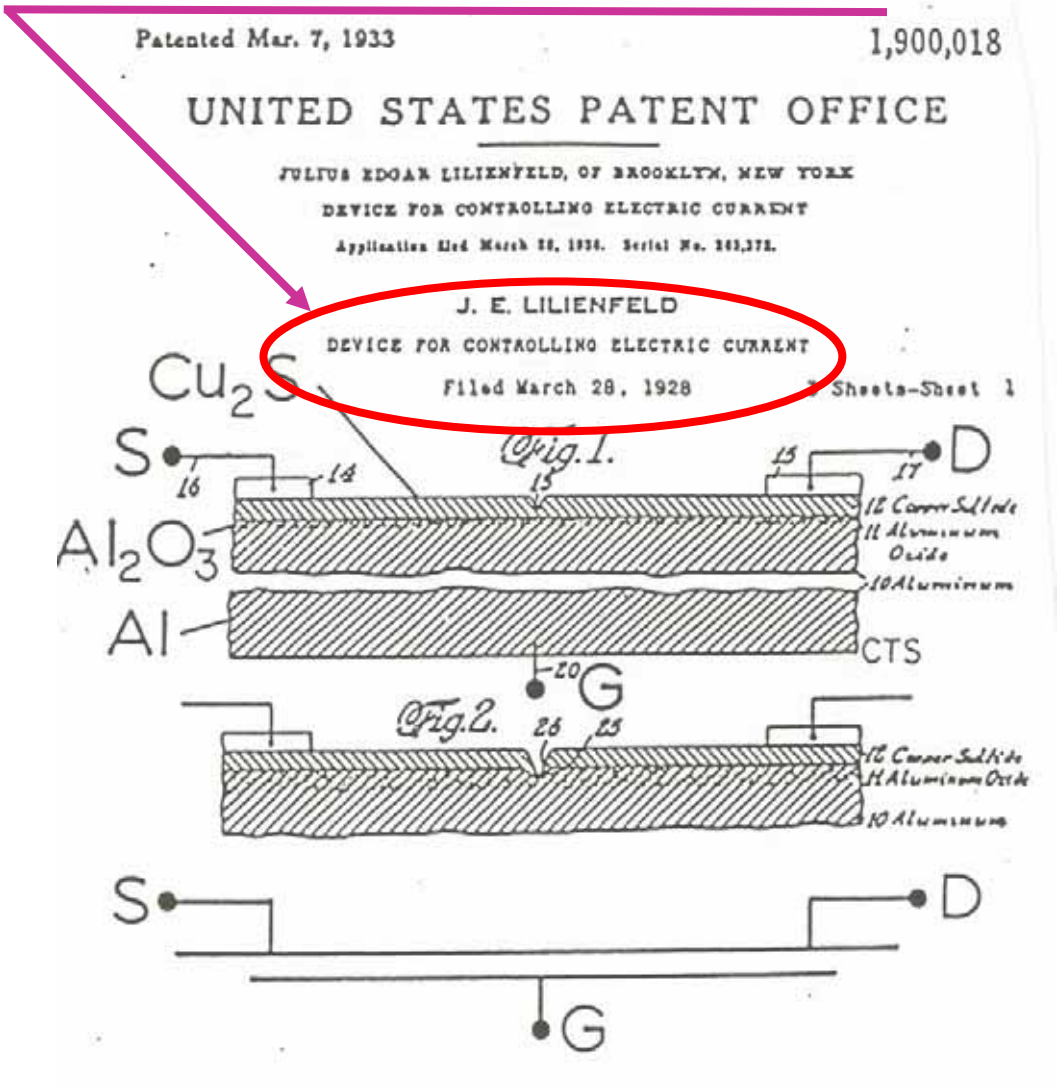
History of Electronic Devices



J. E. LILIENFELD

DEVICES FOR CONTROLLED ELECTRIC CURRENT

Filed March 28, 1928



Patented Mar. 7, 1933 1,900,018

UNITED STATES PATENT OFFICE

JULIUS EDGAR LILIENFELD, OF BROOKLYN, NEW YORK

DEVICE FOR CONTROLLING ELECTRIC CURRENT

Application filed March 28, 1928. Serial No. 264,378.

J. E. LILIENFELD

DEVICE FOR CONTROLLING ELECTRIC CURRENT

Filed March 28, 1928 2 Sheets-Sheet 1

Cu_2S

S

D

Al_2O_3

Al

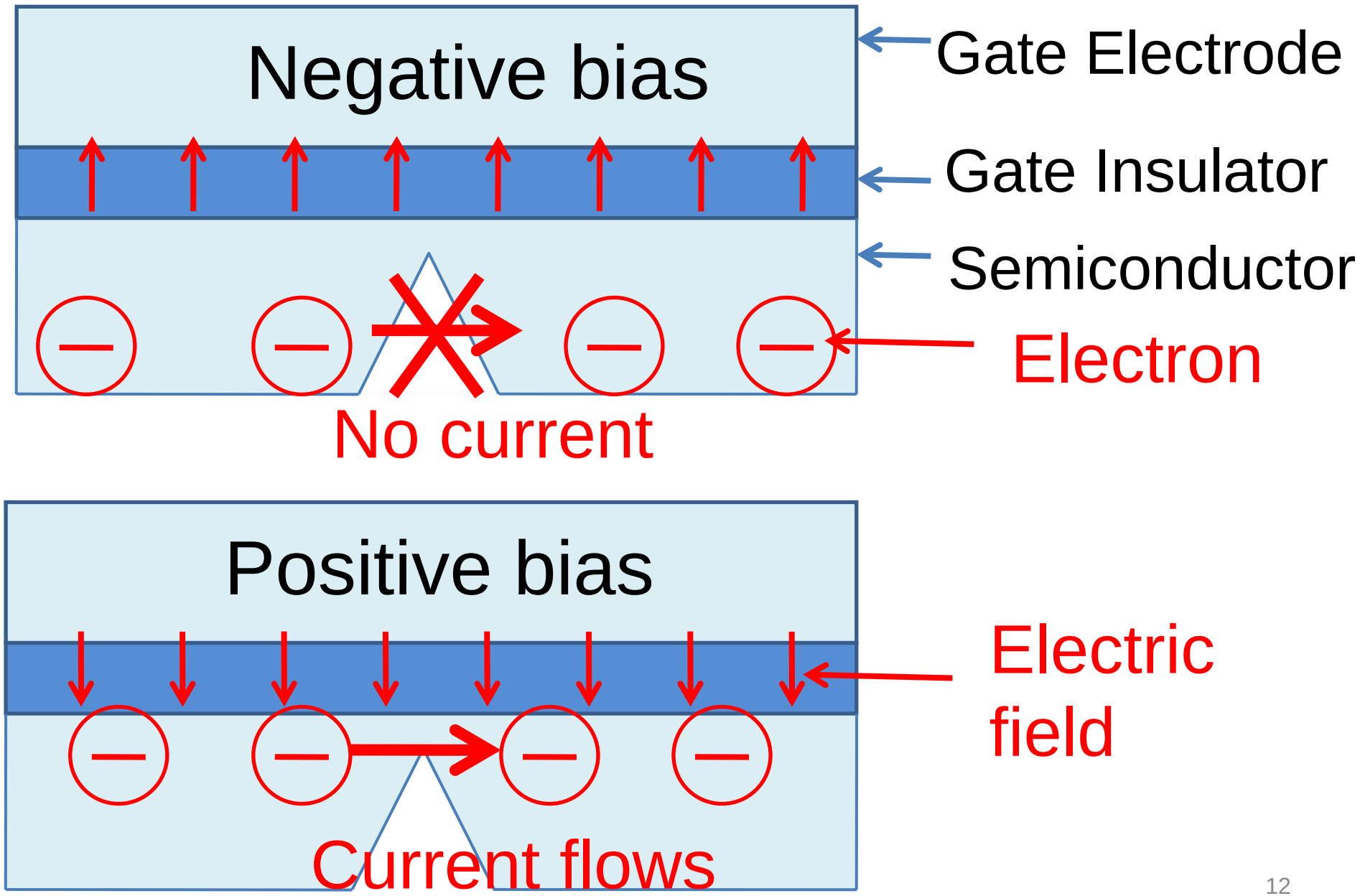
G

Fig. 1.

Fig. 2.

J.E.LILIENFELD

Capacitor structure with notch



Gate Electrode
Poly Si

Gate Insulator
SiO_2

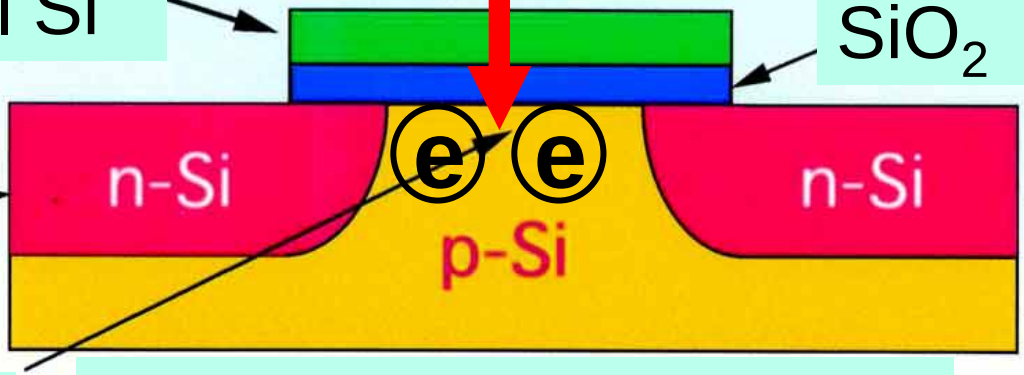
Substrate
Si

MOSFET: Metal Oxide Semiconductor Field Effect Transistor

Use Gate Field Effect for switching

Gate Electrode
Poly-crystal Si

Gate Insulator
SiO_2



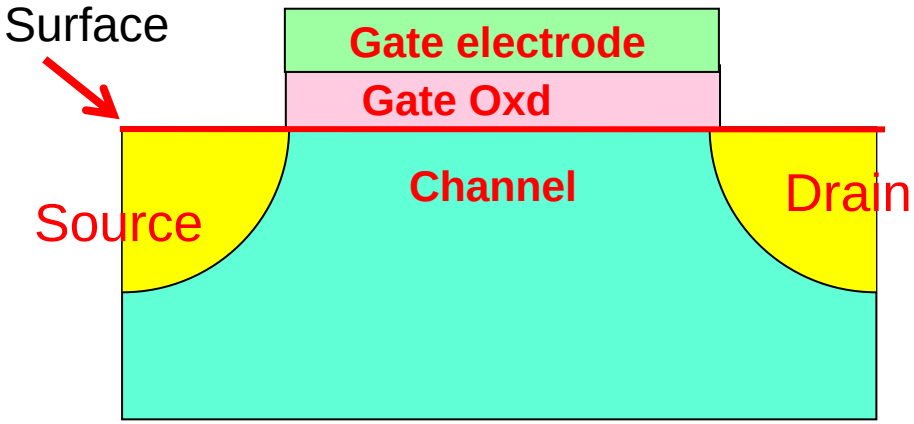
Source

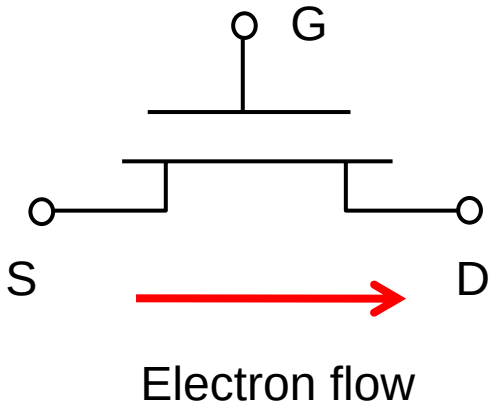
Drain

Si Substrate

Channel

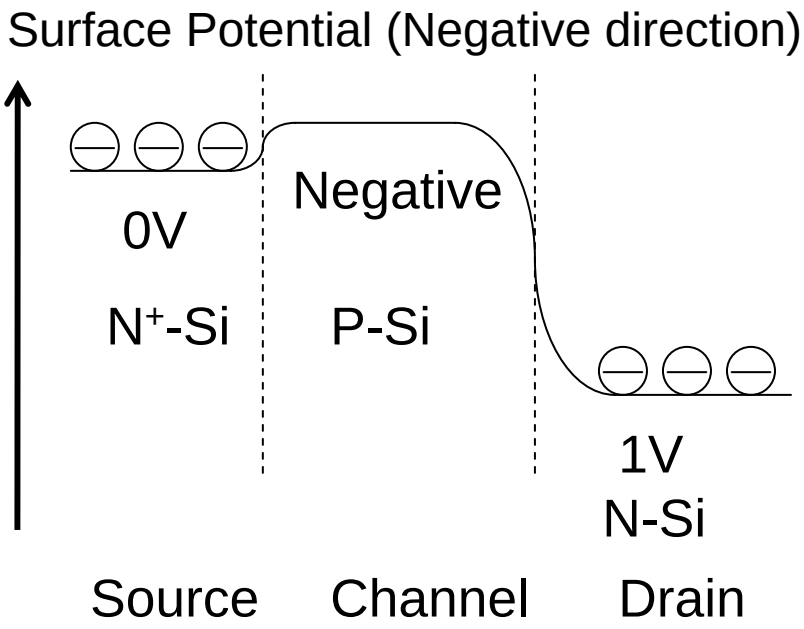
N-MOS (N-type MOSFET)

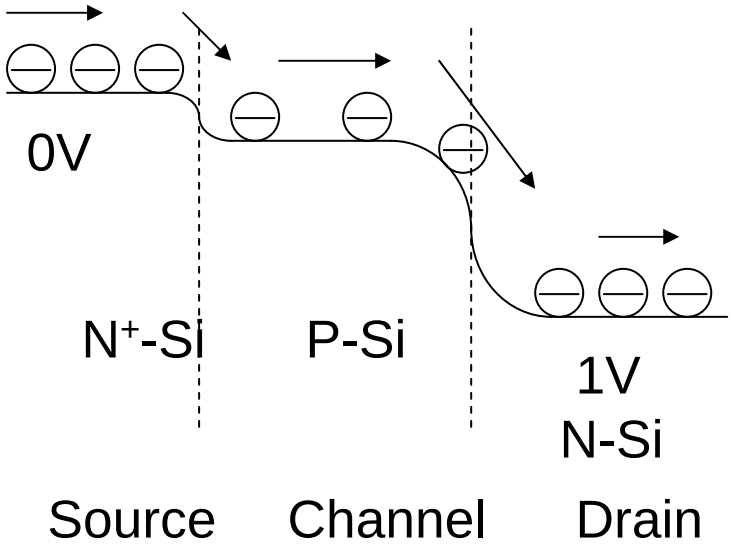


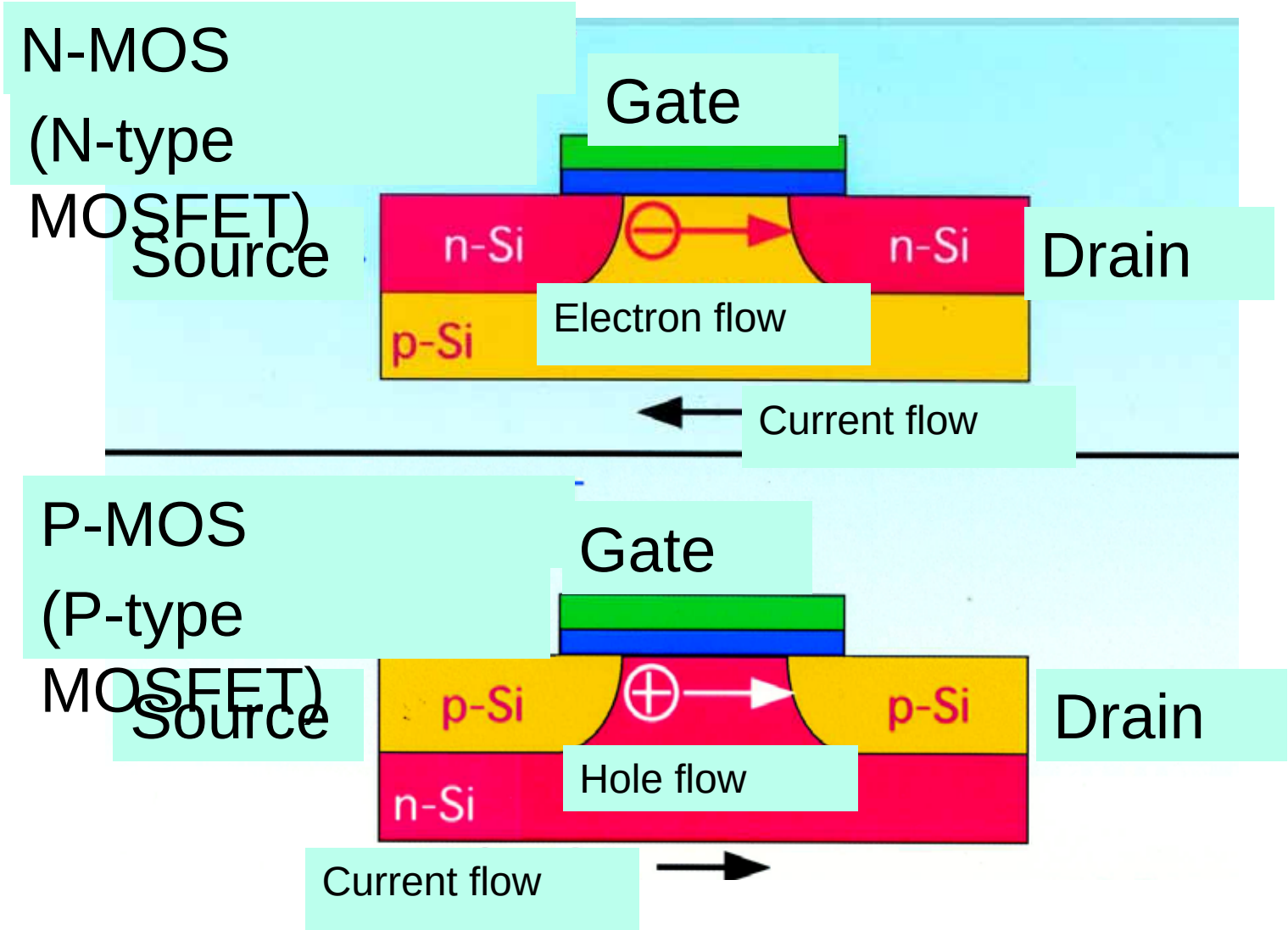


0 bias for gate

Positive bias for gate





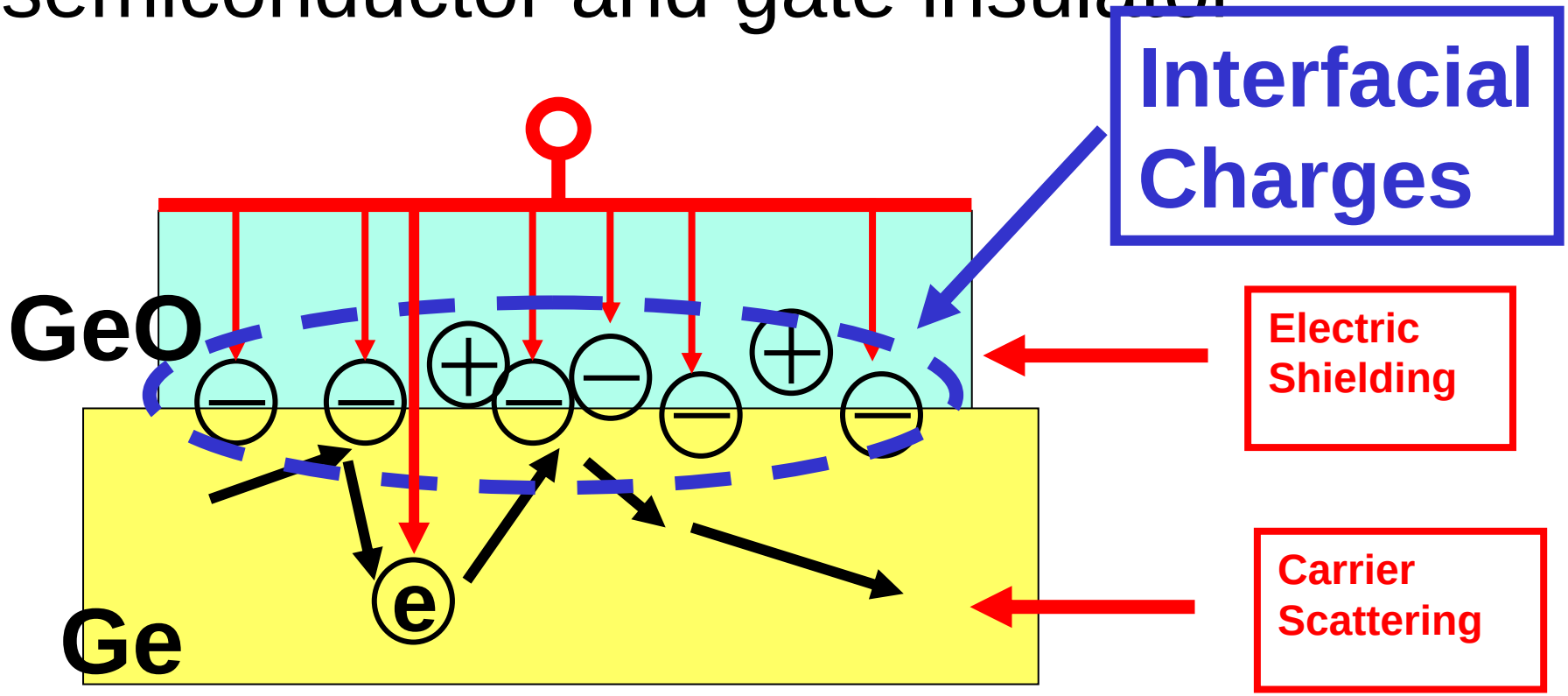

N-MOS
(N-type
MOSFET)
Gate
Source
n-Si
n-Si
Drain
p-Si
Electron flow
Current flow
P-MOS
(P-type
MOSFET)
Gate
Source
p-Si
p-Si
Drain
Hole flow
n-Si
Current flow

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 sm than expected

Even Shockley!

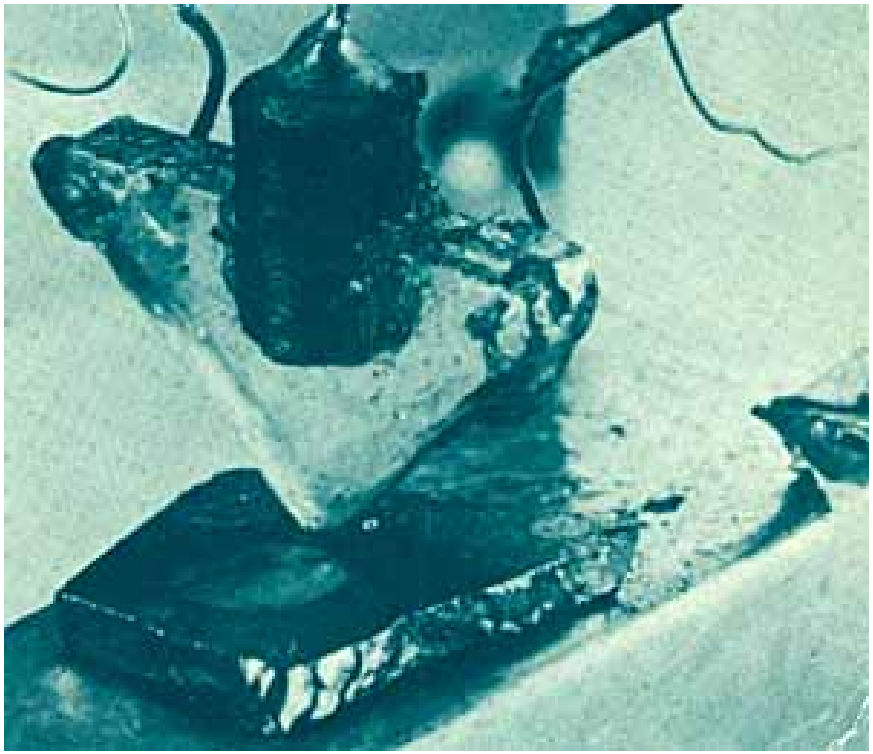
However, they found amplification phenomenon when investigating Ge surface when putting needles.
This is the 1st Transistor:

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

1947: 1st transistor

J. Bardeen W. Bratten,

W. Shockley

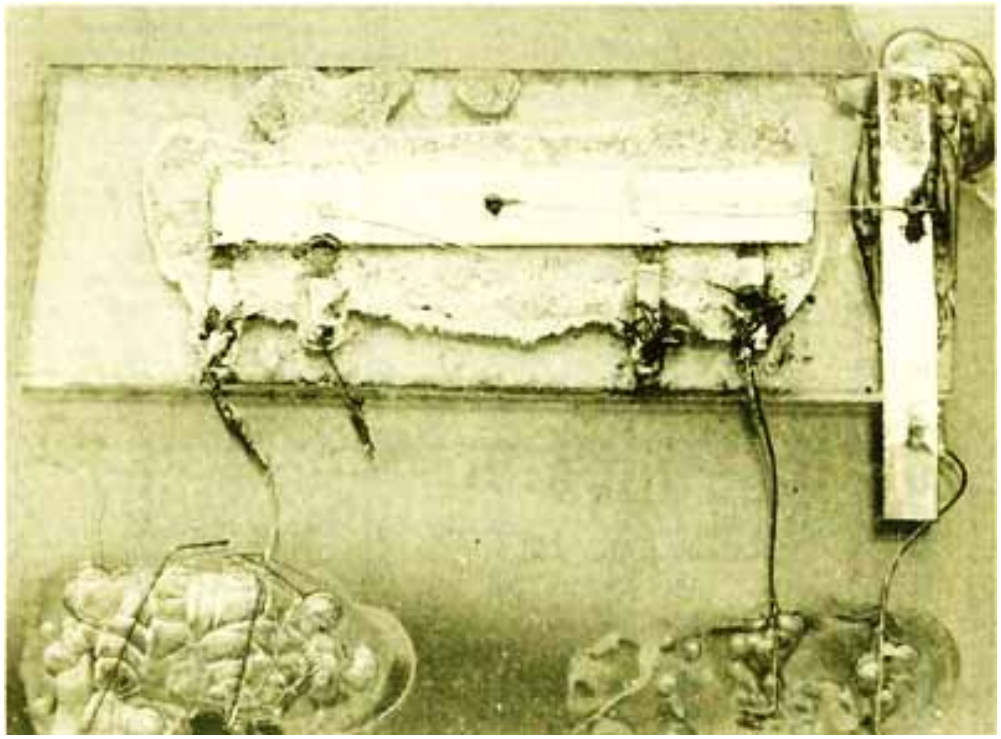


Bipolar using Ge

1958: 1st Integrated Circuit

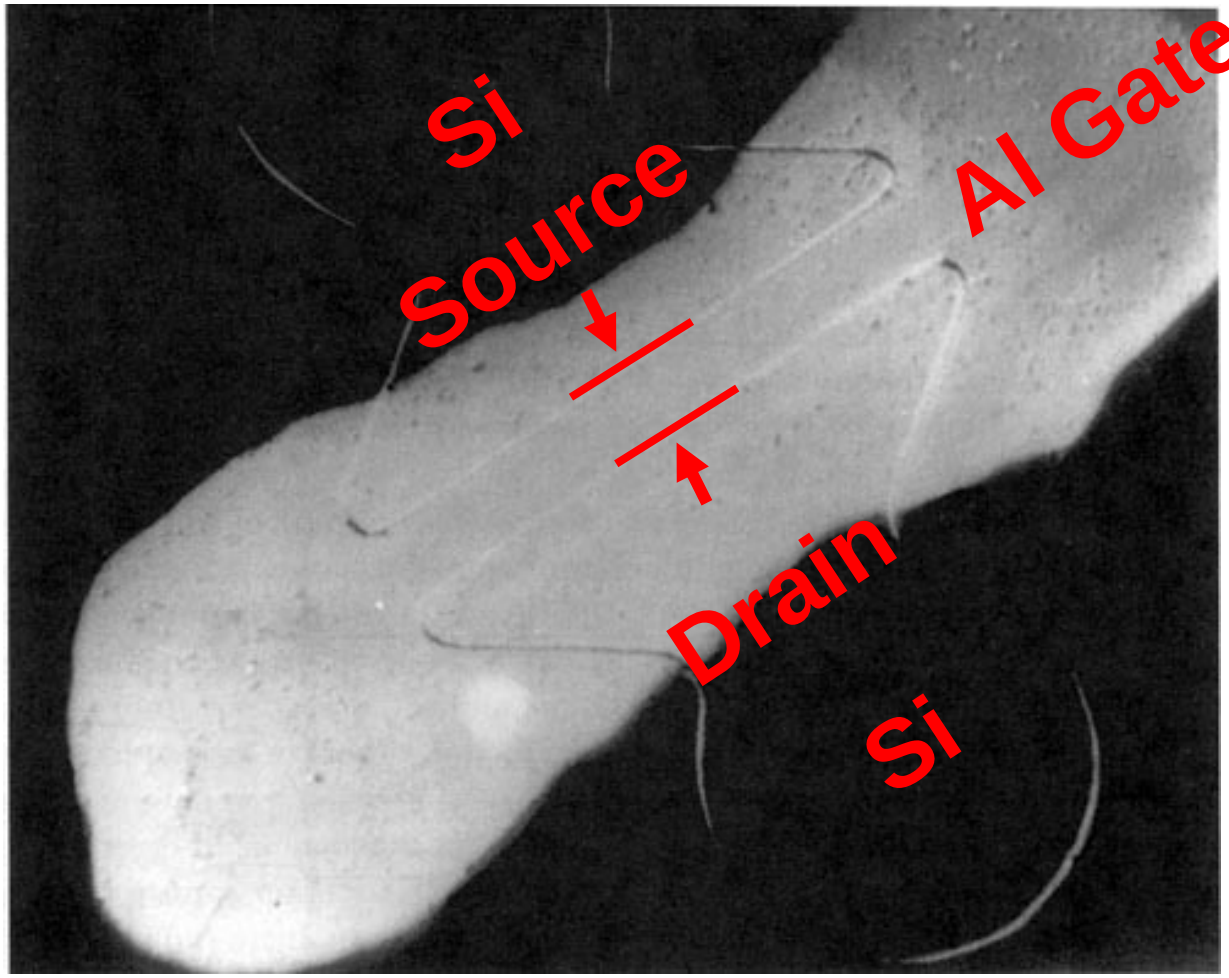
Jack S. Kilby

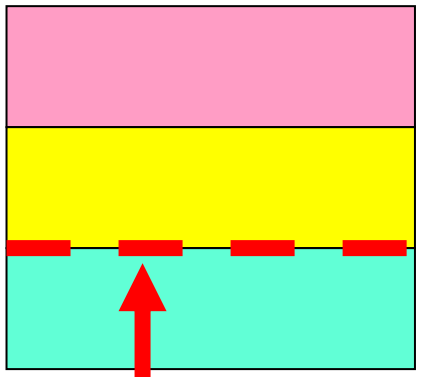
Connect 2 bipolar transistors in the
Same substrate by bonding wire.



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

Top View





Al

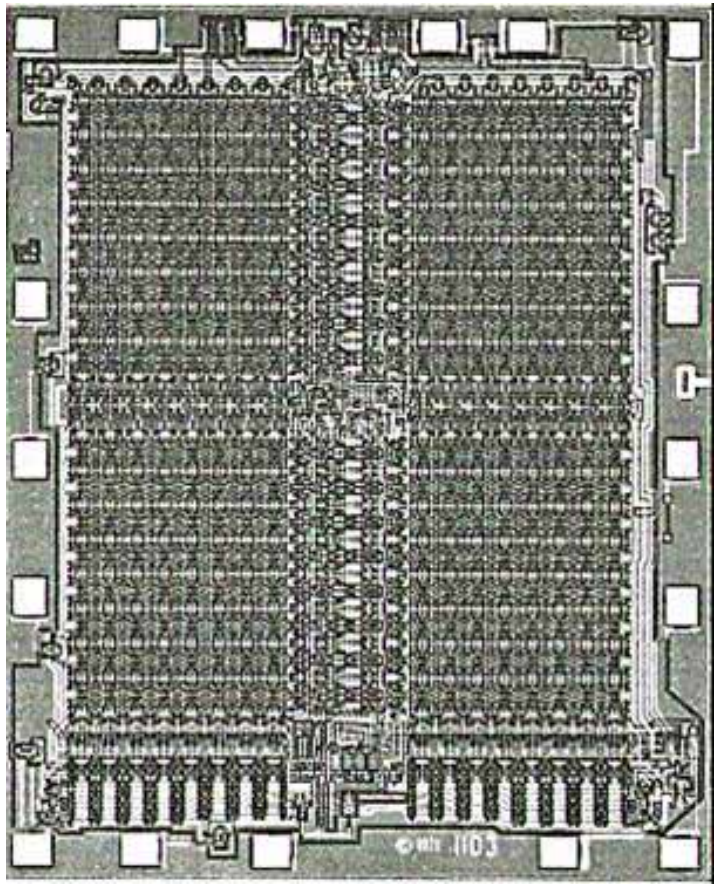
SiO_2

Si

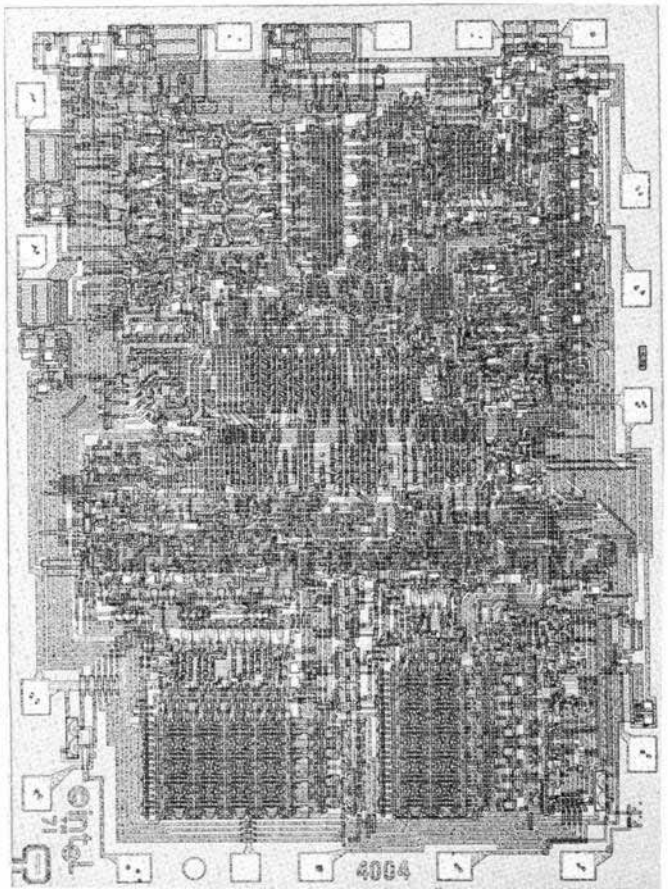
Si/SiO2 Interface is extraordinarily good

1970,71: 1st generation of LSIs

DRAM Intel 1103

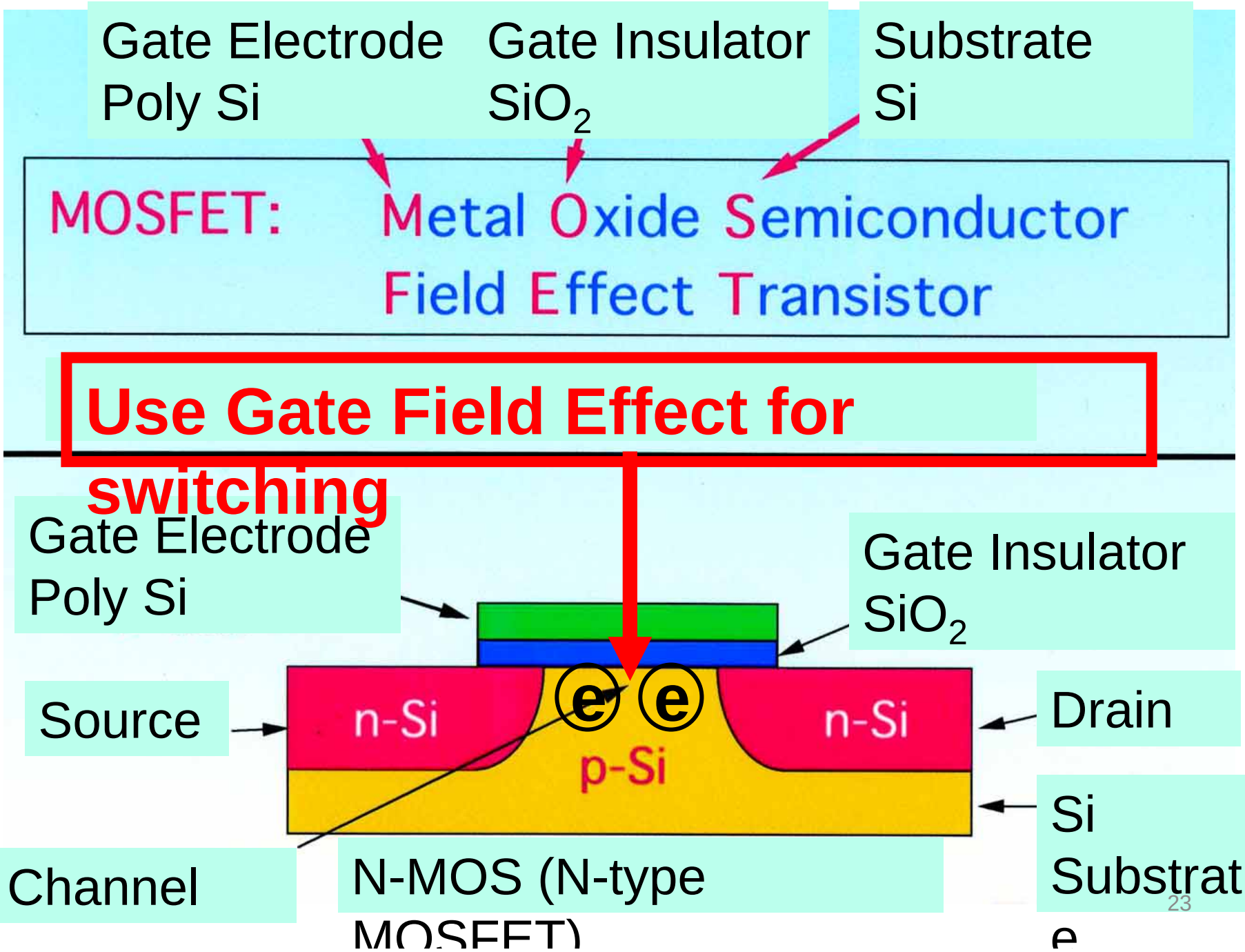


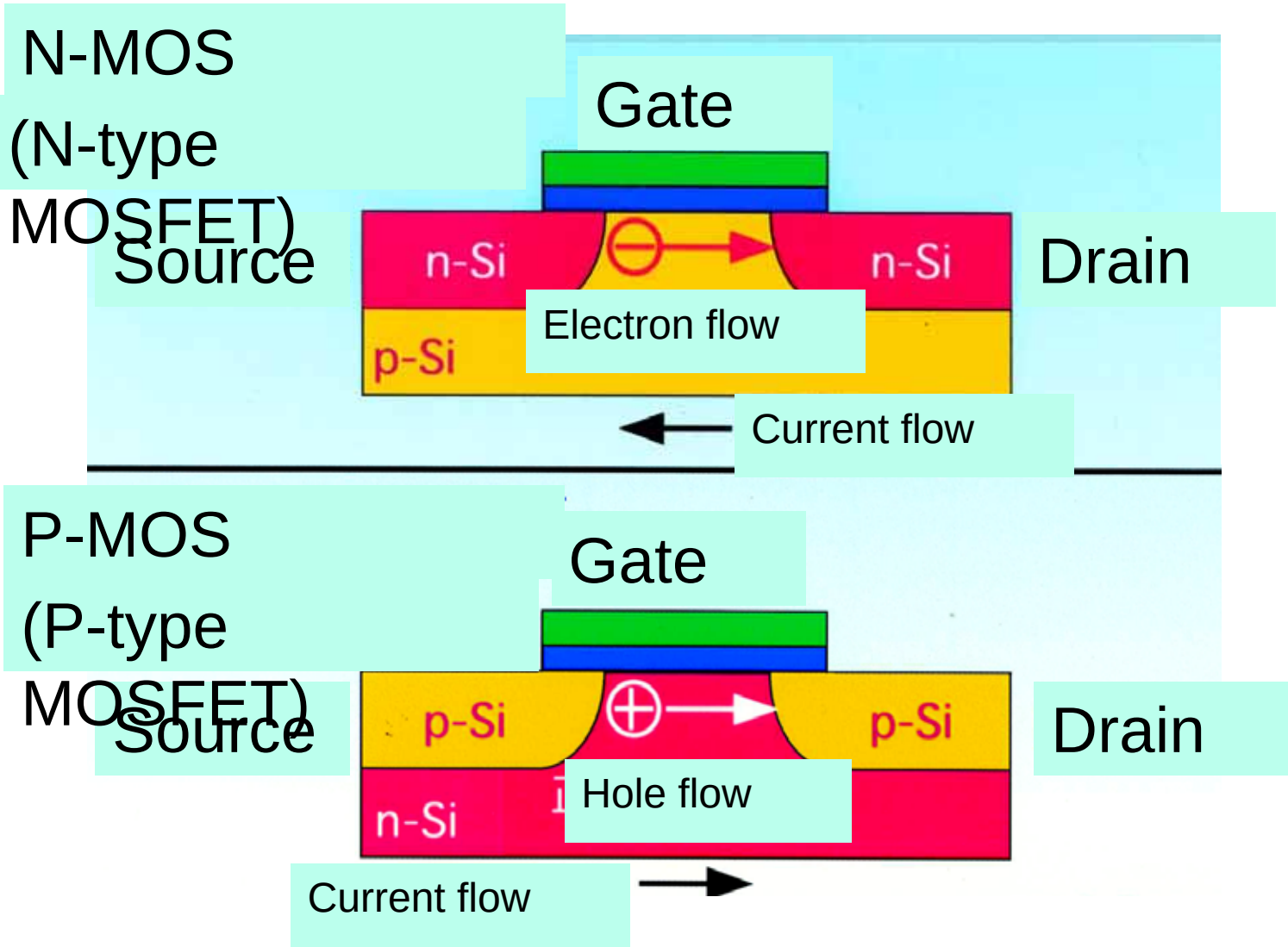
MPU Intel 4004

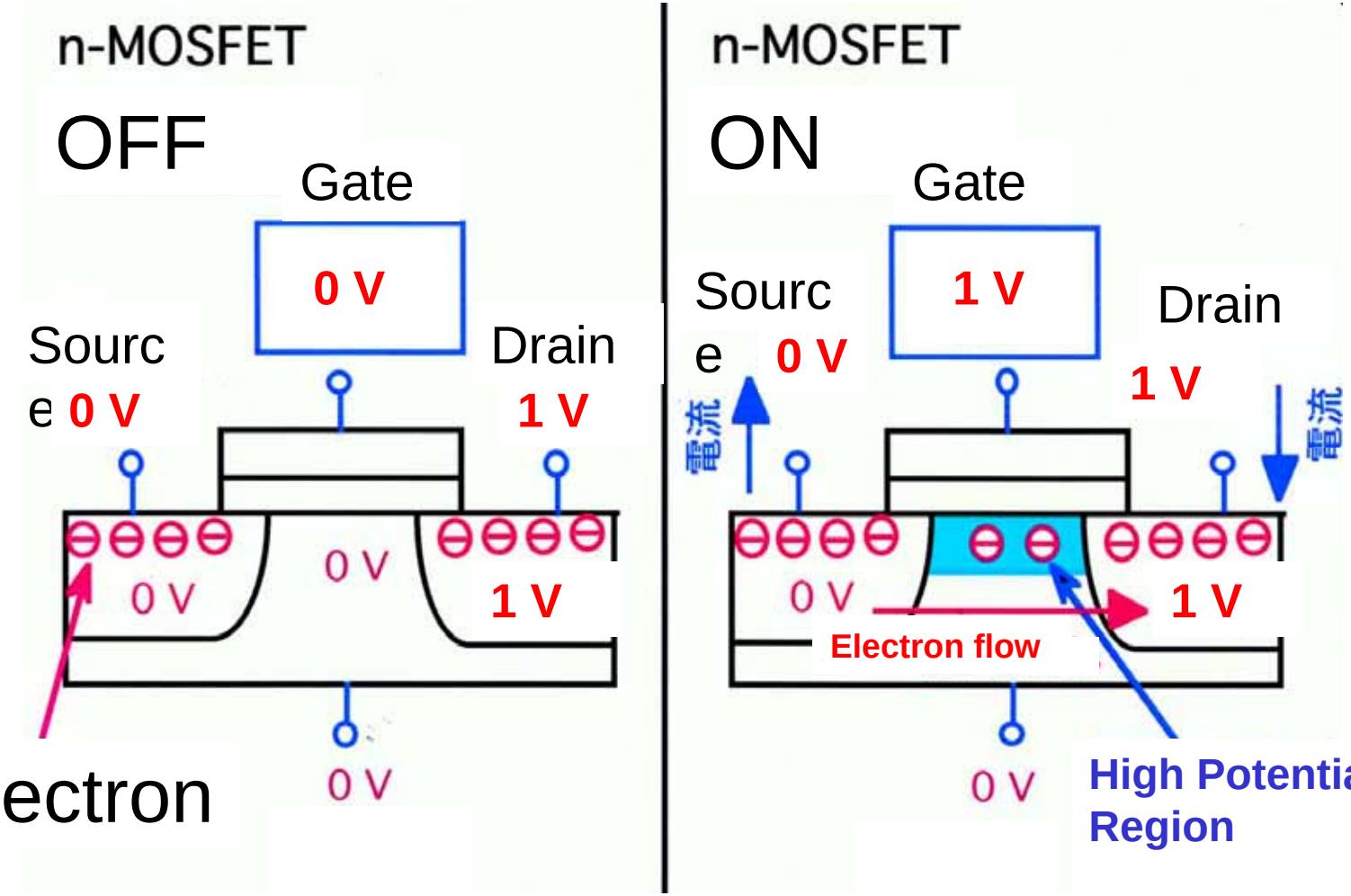


MOS LSI experienced continuous progress for many years

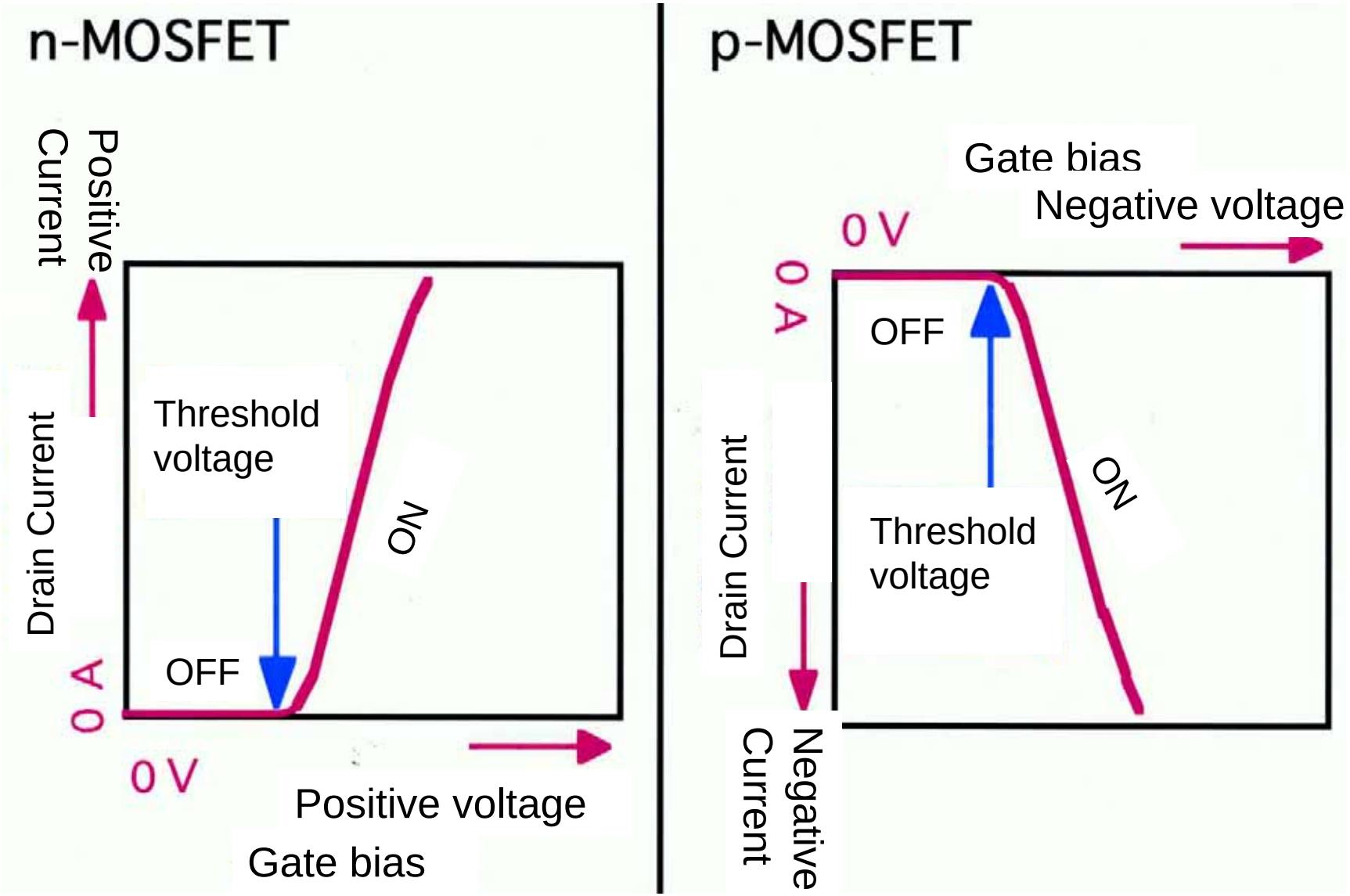
	Name of Integrated Circuits	Number of Transistors
1960s	IC (Integrated Circuits)	~
1970s	LSI (Large Scale Integrated Circuit)	~1,0
1980s	VLSI (Very Large Scale IC)	~10,0
1990s	ULSI (Ultra Large Scale IC)	~1,000,0
2000s	?LSI (? Large Scale IC)	~1000,000


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
e
e
n-Si
p-Si
Drain
Si
Substrat
e
Channel
N-MOS (N-type
MOSFET)


N-MOS
(N-type
MOSFET)
Gate
Source
n-Si
n-Si
Drain
Electron flow
p-Si
Current flow
P-MOS
(P-type
MOSFET)
Gate
Source
p-Si
p-Si
Drain
Hole flow
n-Si
Current flow

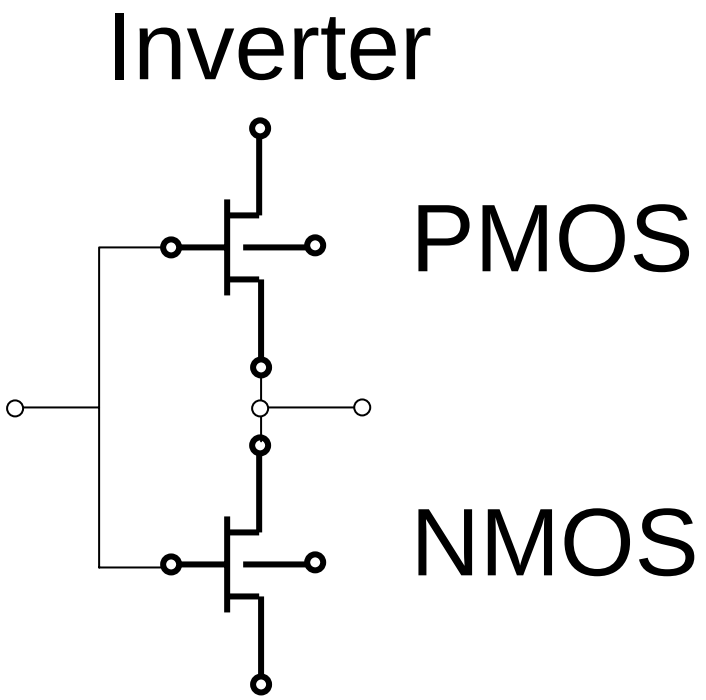

n-MOSFET
OFF
Gate
0 V
Sourc
e 0 V
Drain
1 V
0 V
0 V
1 V
0 V
n-MOSFET
ON
Gate
1 V
Sourc
e 0 V
Drain
1 V
電流
電流
0 V
1 V
Electron flow
0 V
High Potential
Region

Electron
s


n-MOSFET
Positive Current
Drain Current
Threshold voltage
ON
OFF
0 A
0 V
Positive voltage
Gate bias
p-MOSFET
Gate bias
Negative voltage
0 V
0 A
OFF
ON
Threshold voltage
Drain Current
Negative Current

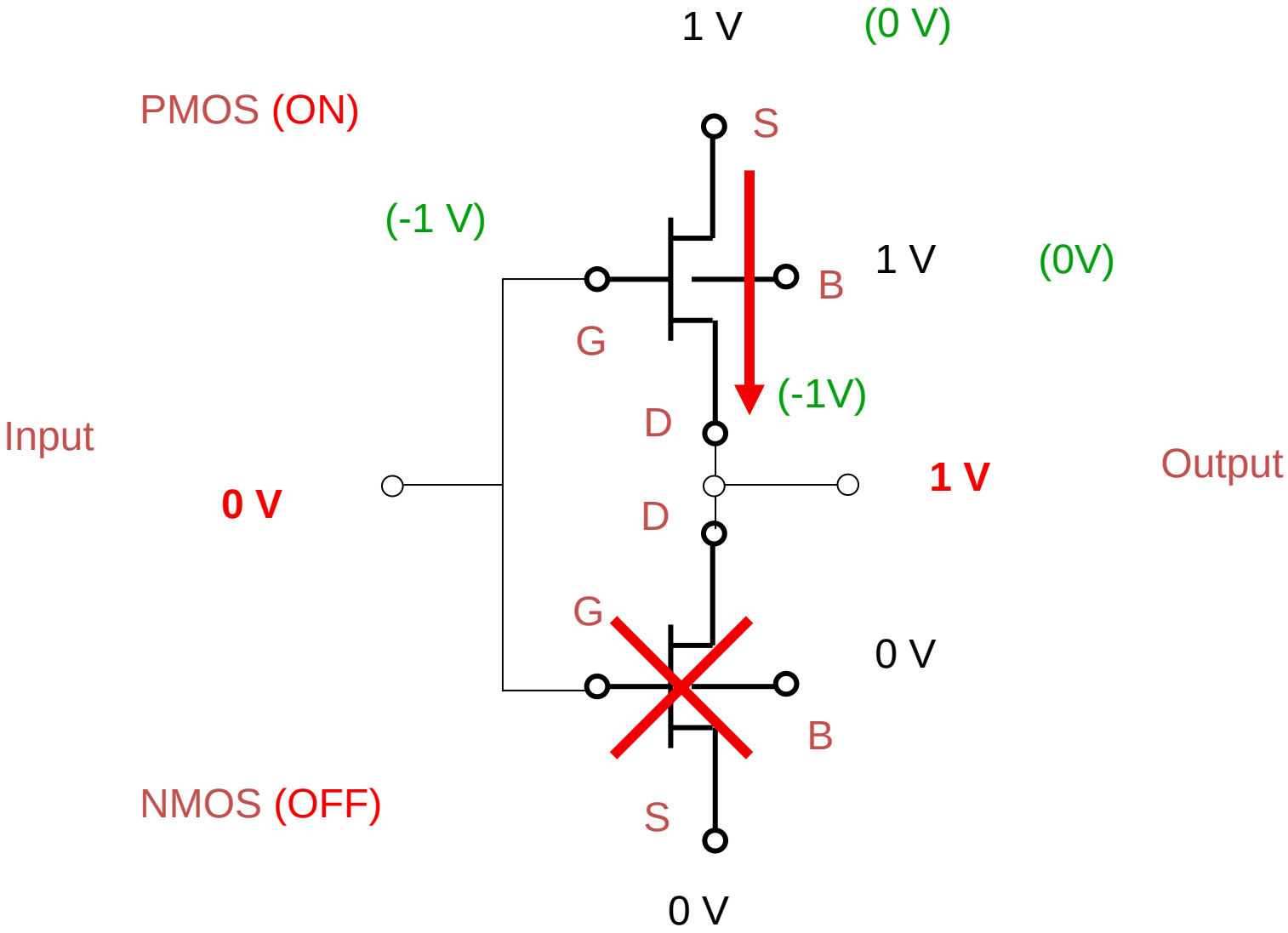
CMOS

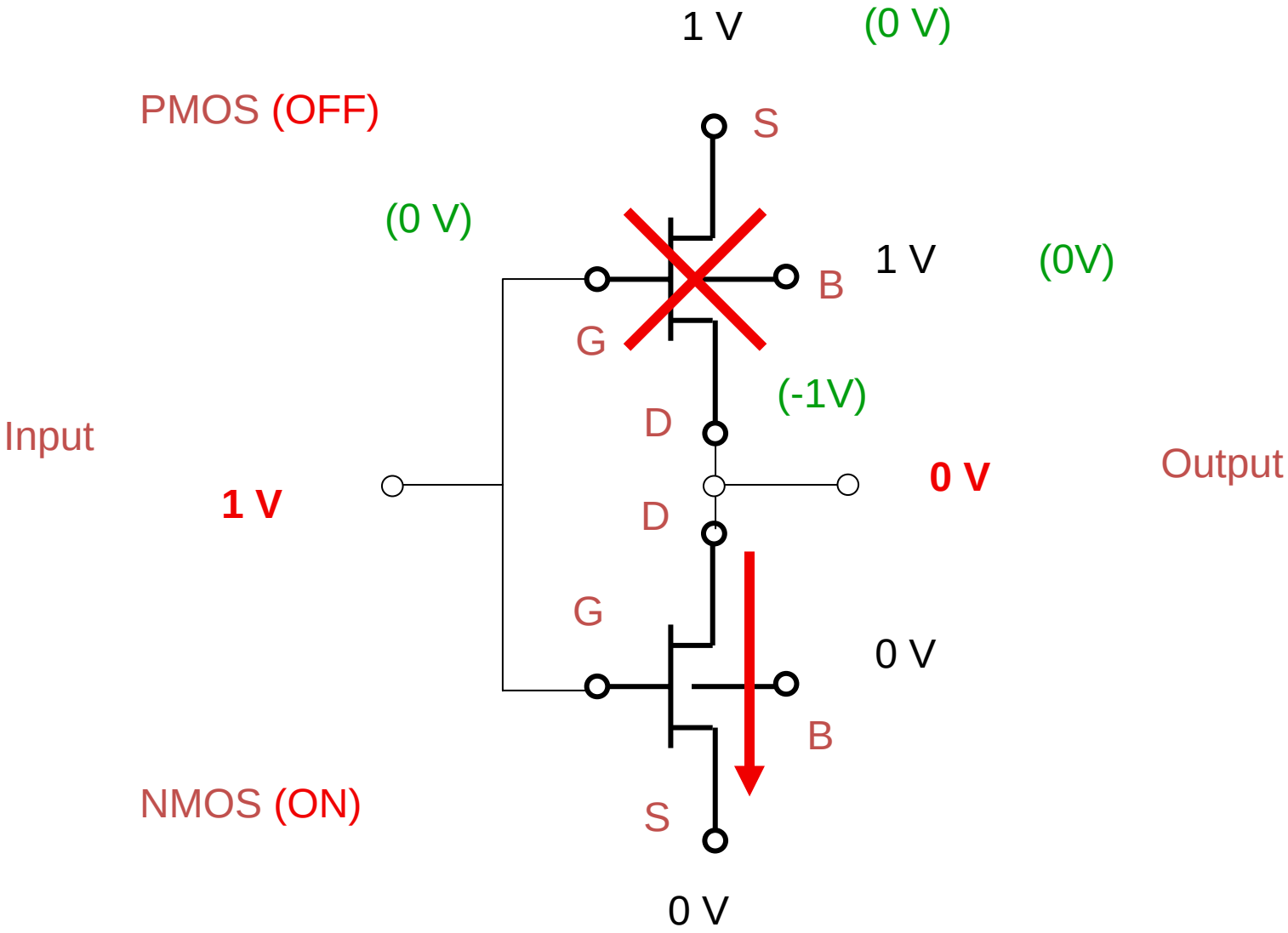
Complimentary MOS



When NMOS is ON, PMOS is OFF

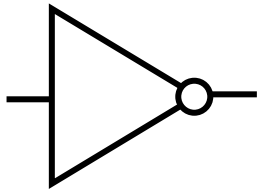
When PMOS is ON, NMOS is OFF


1 V
(0 V)
PMOS (ON)
S
(-1 V)
1 V
(0V)
B
G
(-1V)
D
Input
0 V
1 V
Output
D
G
0 V
B
NMOS (OFF)
S
0 V

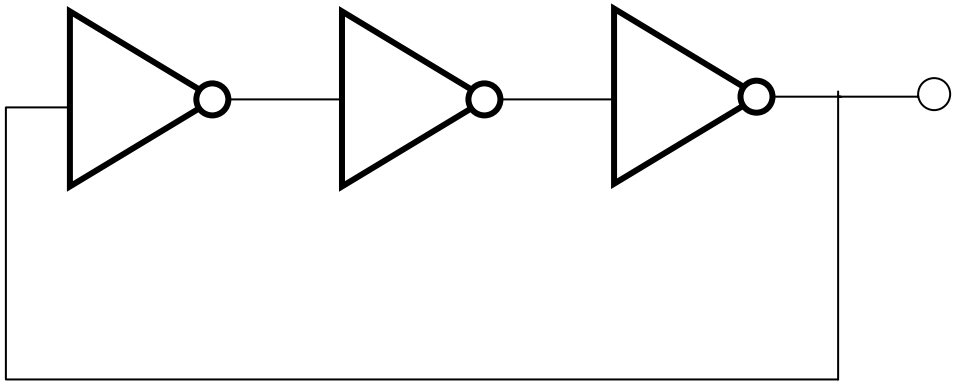

1 V
(0 V)
PMOS (OFF)
S
(0 V)
1 V
(0V)
B
G
(-1V)
D
Input
1 V
0 V
Output
D
G
0 V
B
NMOS (ON)
S
0 V

Inverter

Input

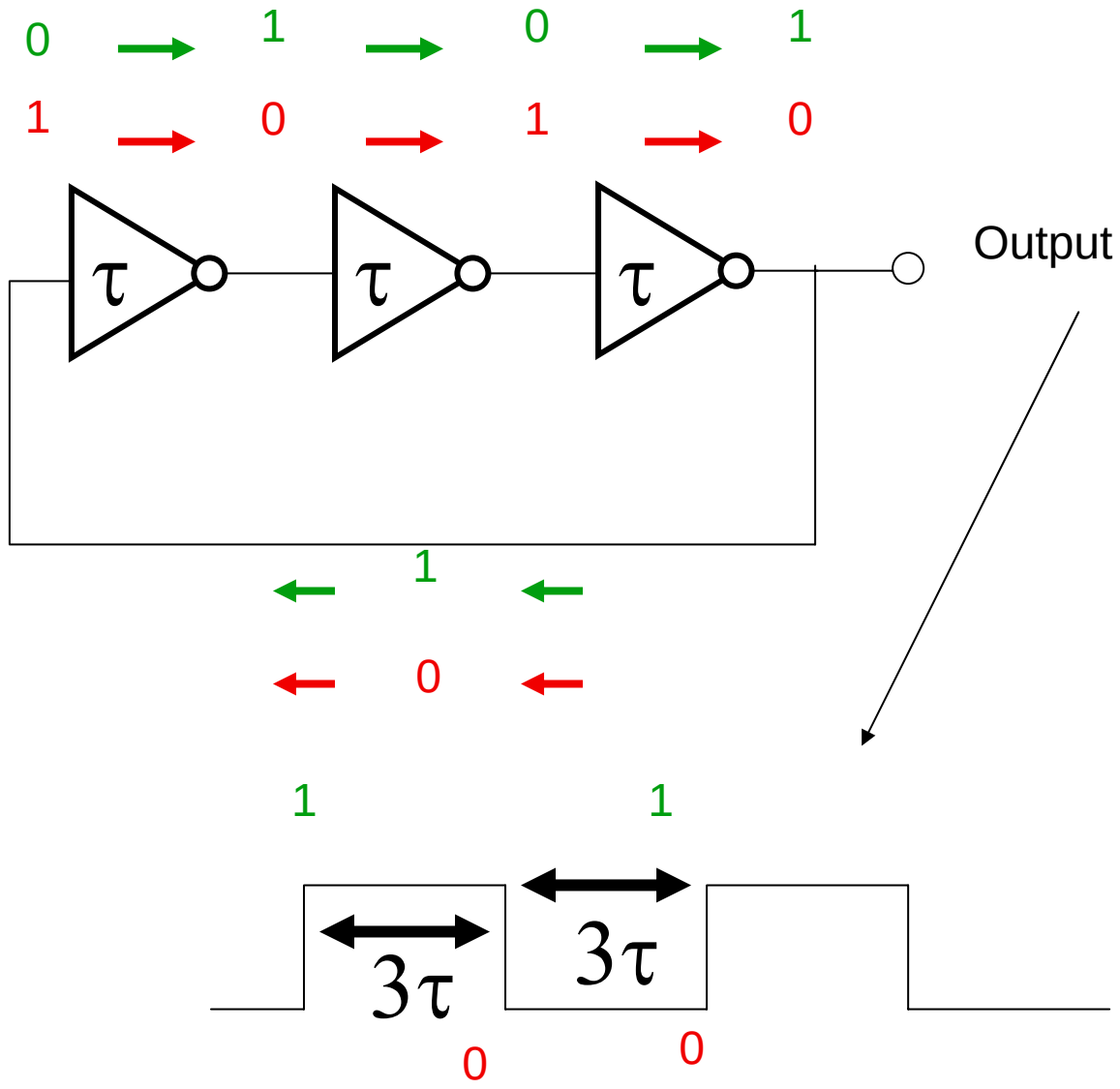


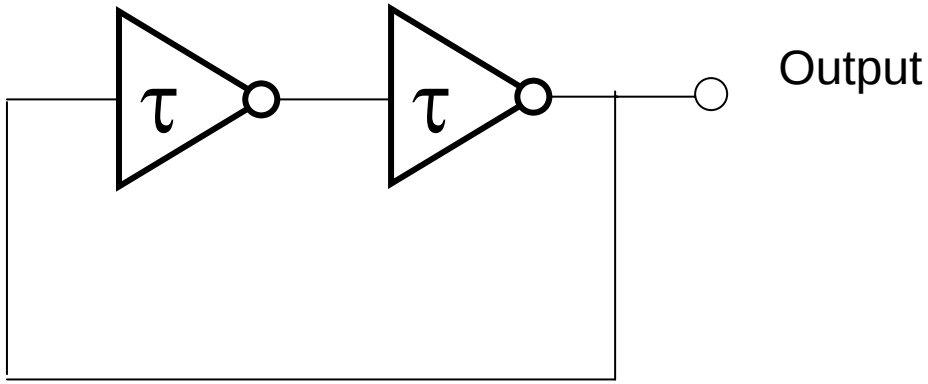
Output



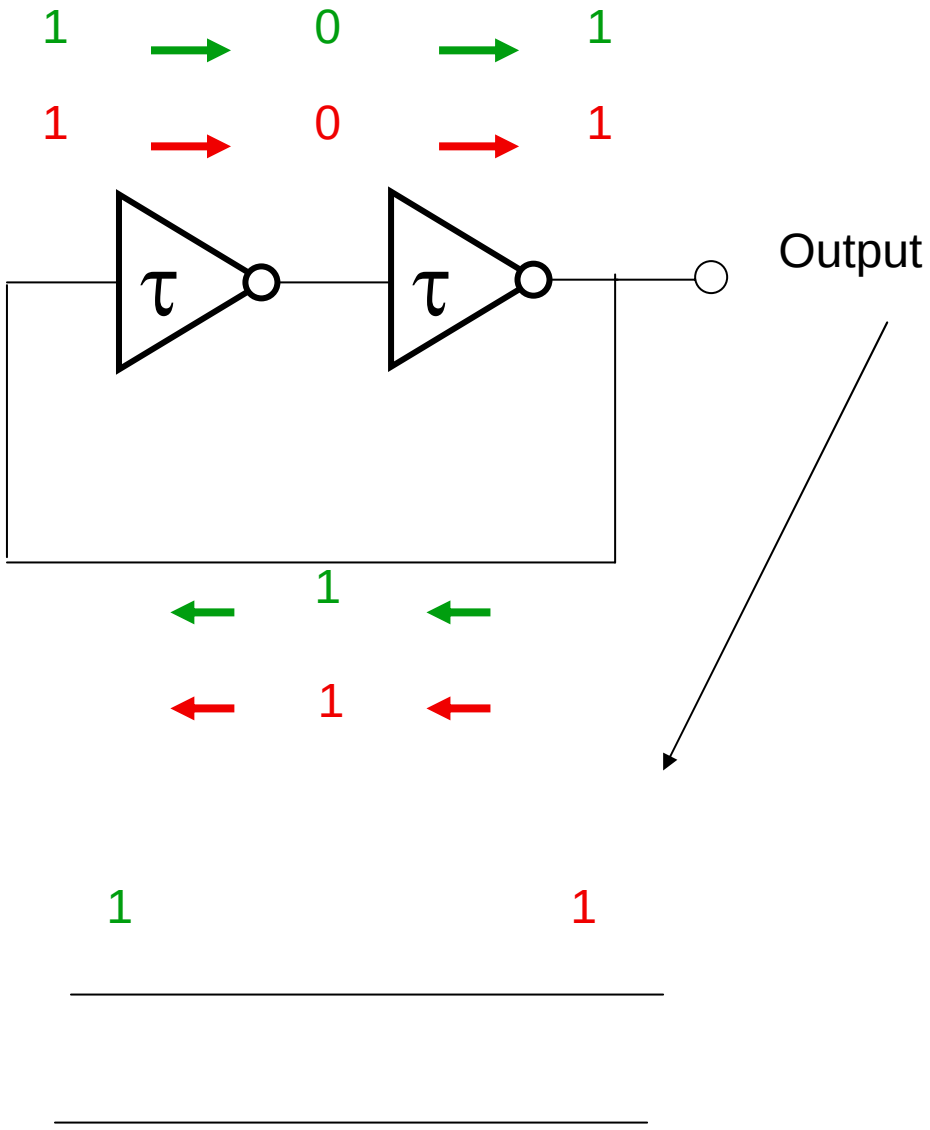
Output

Oscillator

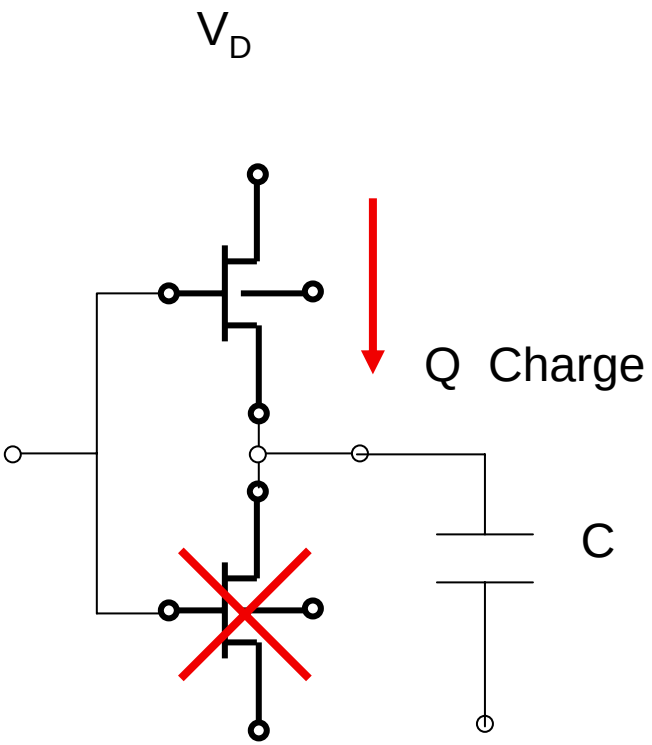



τ
τ
Output

Latch (Memory)

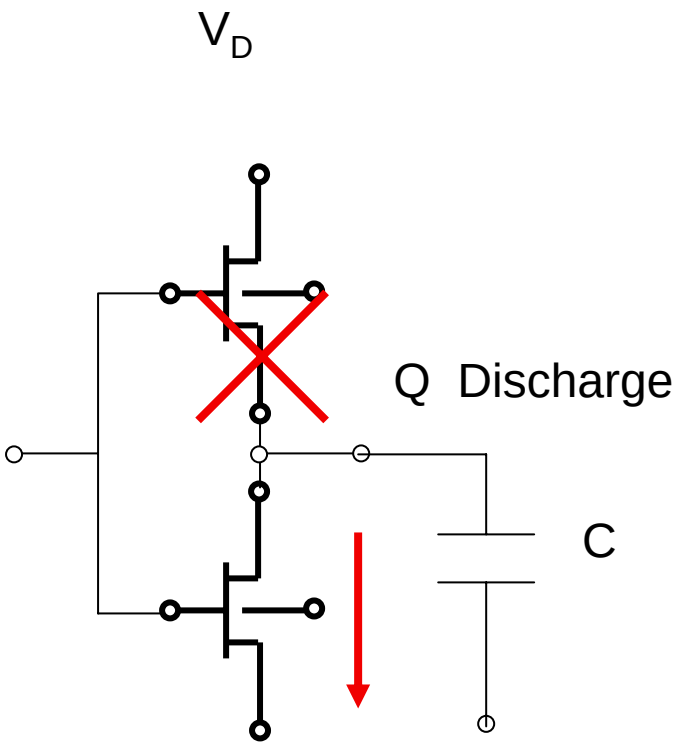


CMOS： Low Power: No DC current from Power supply to the ground



1 cycle

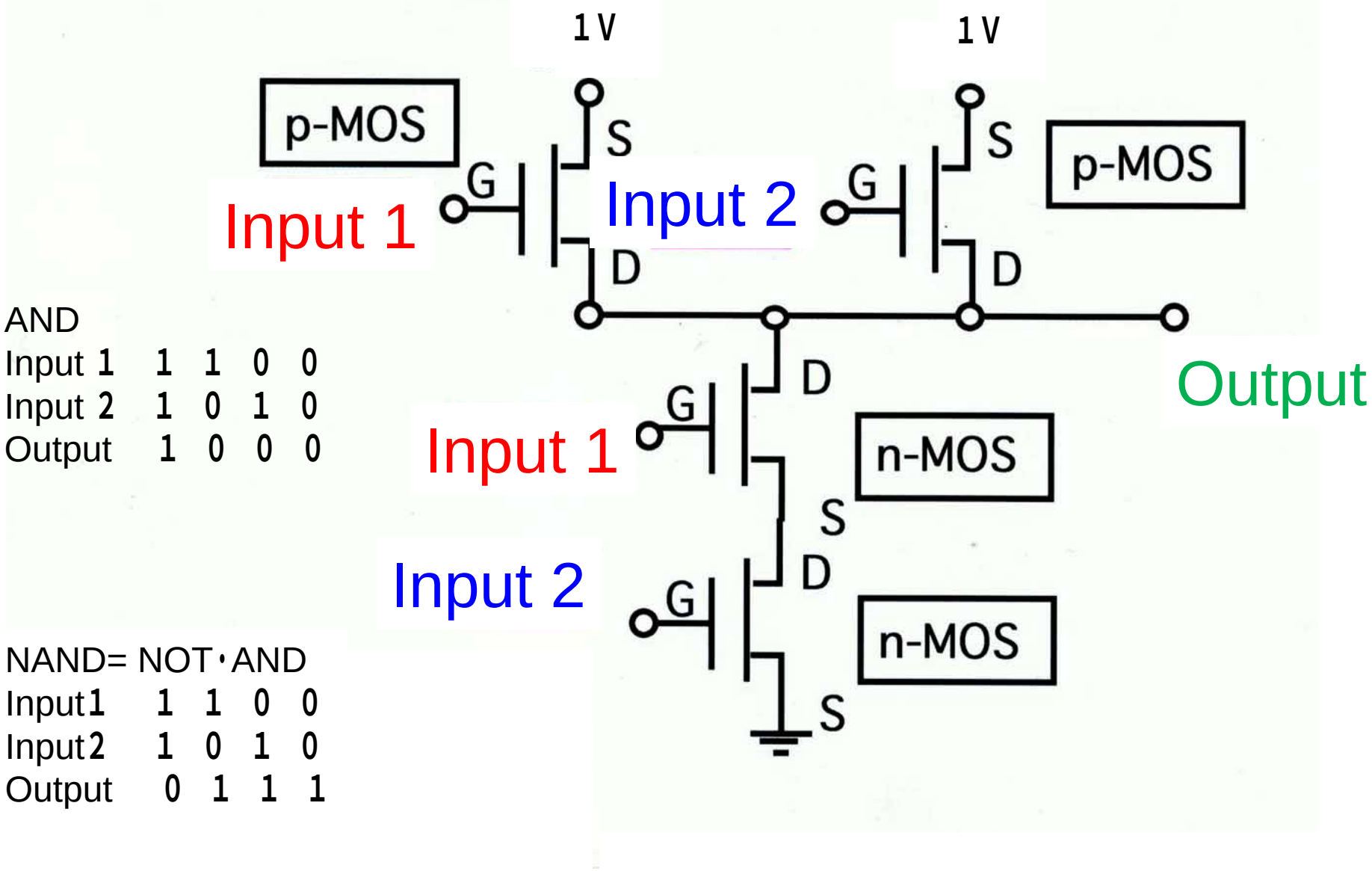
$$P = \frac{1}{2} CV_D^2$$



Clock frequency f

$$P = \frac{1}{2} fCV_D^2$$

2 input NAND Circuit



AND

Input 1	1	1	0	0
Input 2	1	0	1	0
Output	1	0	0	0

NAND= NOT･AND

Input1	1	1	0	0
Input2	1	0	1	0
Output	0	1	1	1

Needless to say, but….

CMOS Technology:

Indispensible for our human society

Al 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 → 一石二鳥

Thus, downsizing of Si devices is the most important and critical issu

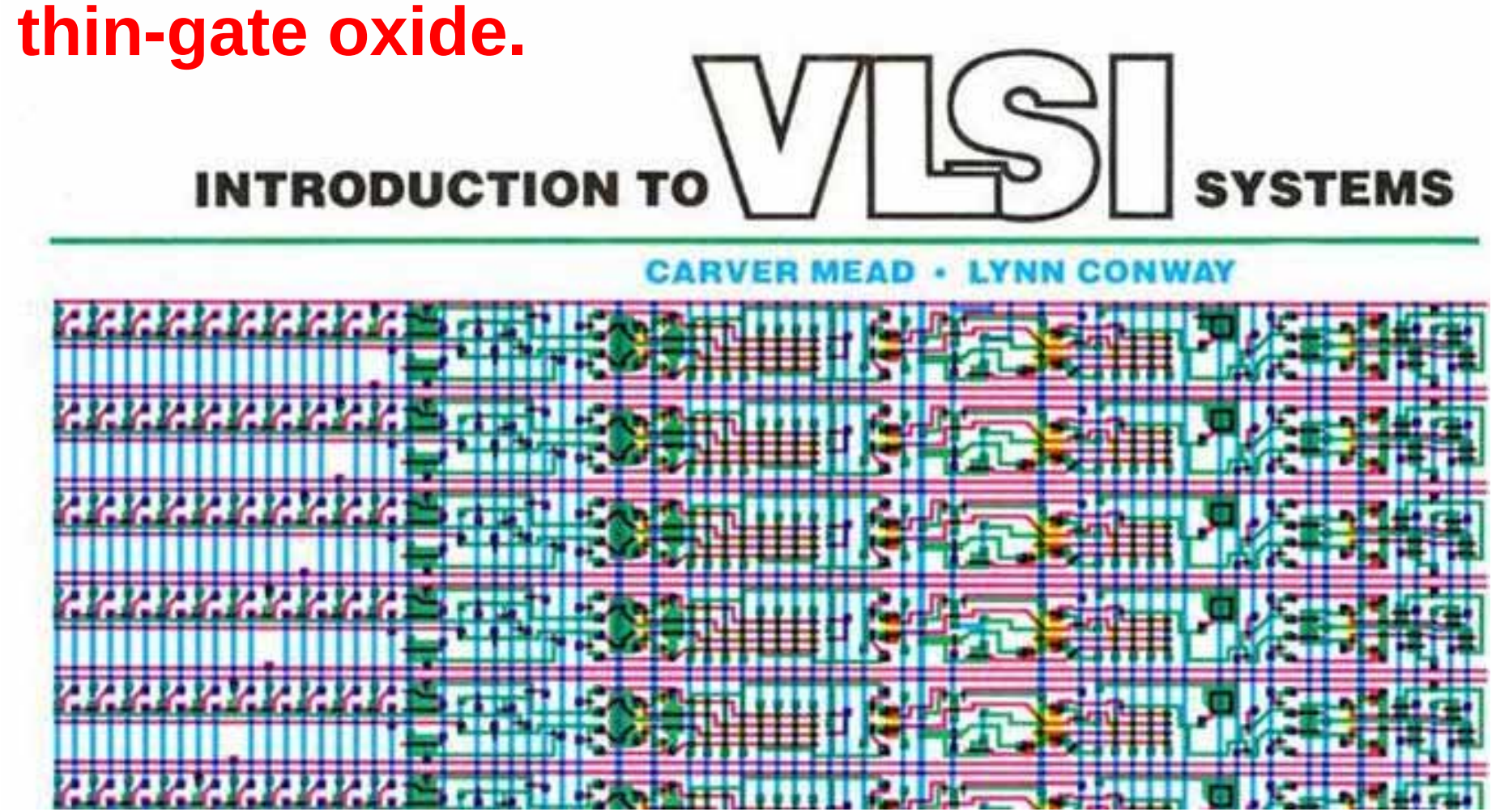
Many people wanted to say about the limit.

Past predictions were not correct!!

Period	Expected limit(size)	Cause
Late 1970's	1μm:	SCE
Early 1980's	0.5μm:	S/D resistance
Early 1980's	0.25μm:	Direct-tunneling of gate SiO
Late 1980's	0.1μm:	'0.1μm 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 micro-meter would be the limit because of direct-tunneling current through the very thin-gate oxide.

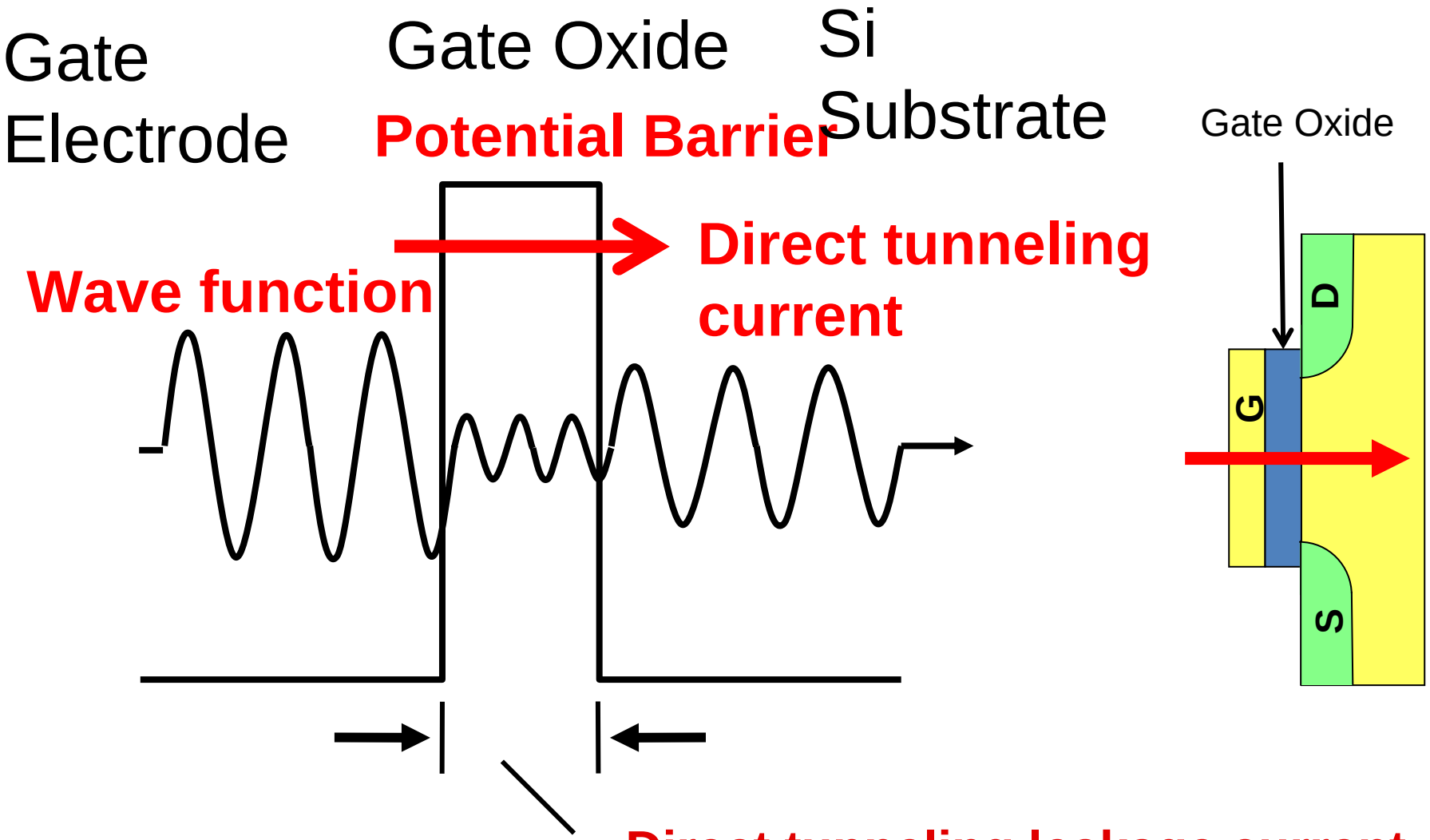


C. Mead L. Conway

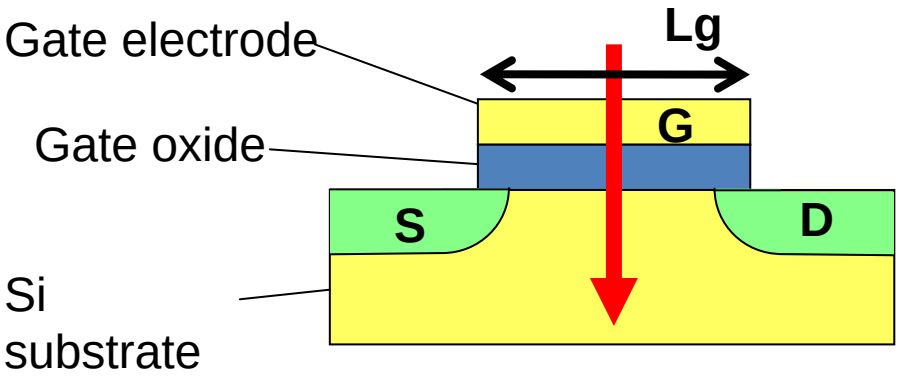
VLSI textbook

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



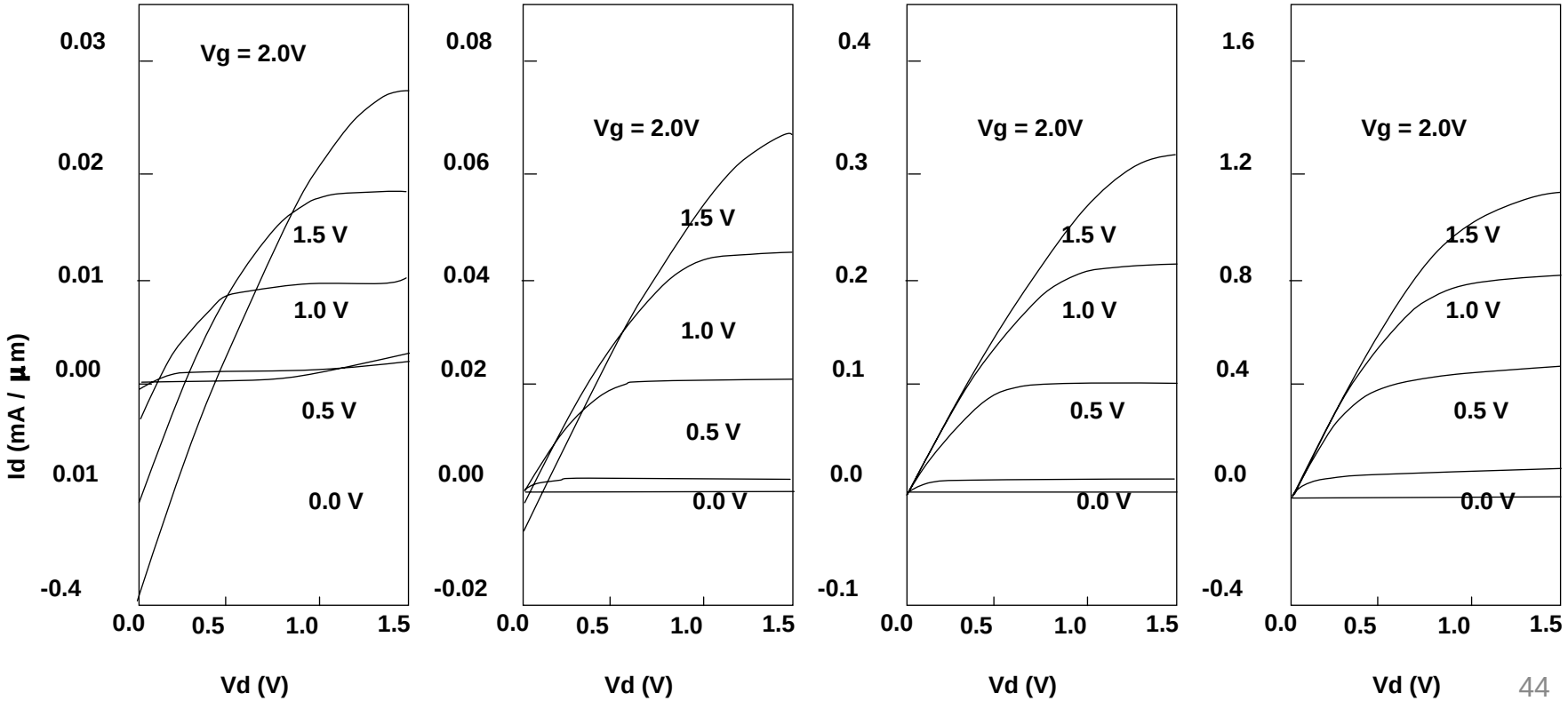
Direct tunneling leakage current start to flow when the thickness is 3 nm.

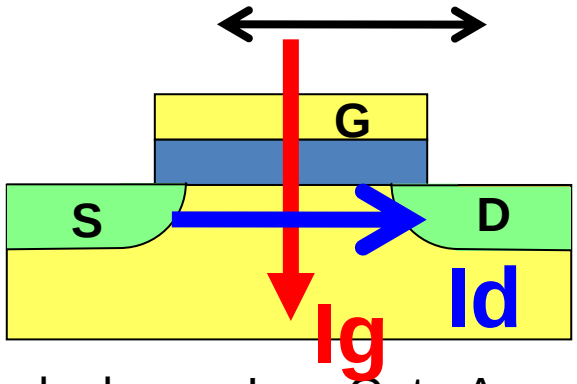


MOSFETs with 1.5 nm gate oxide

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

Lg = 10 μm | Lg = 5 μm | Lg = 1.0 μm | Lg = 0.1μm



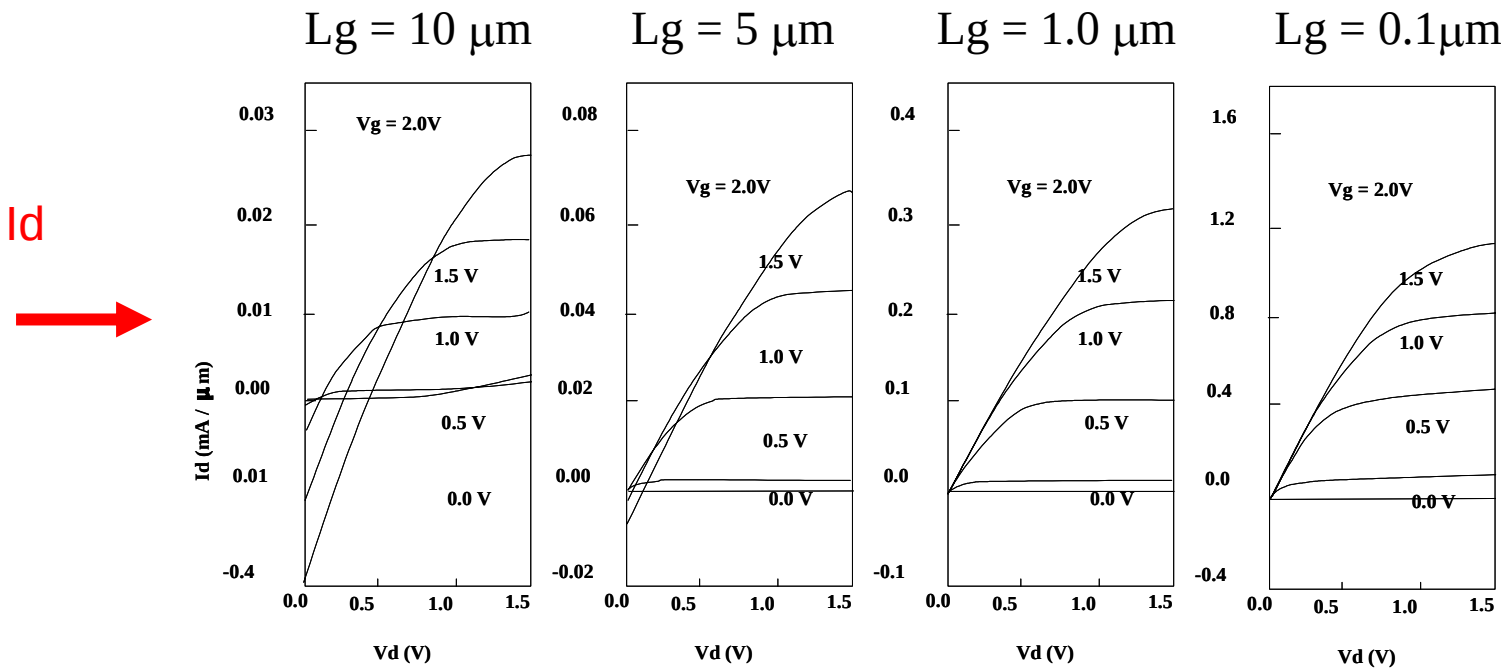


Gate leakage: Ig ∝ Gate Area ∝ Gate length (Lg)

Drain current: Id ∝ 1/Gate length (Lg)

Lg → small,

Then, Ig → small, Id → large, Thus, Ig/Id → very small



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

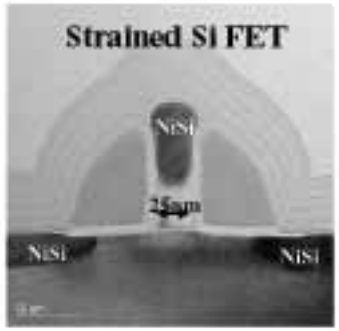
90nm node

Lg=50nm

65nm node

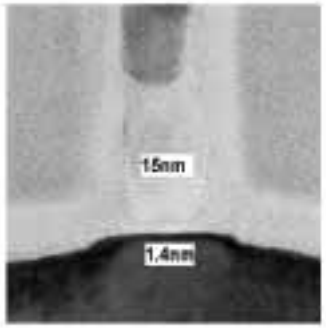
Lg=35nm

45nm node



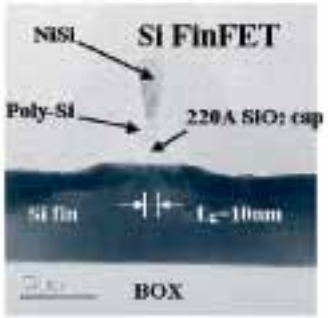
Lg=25nm

32nm node

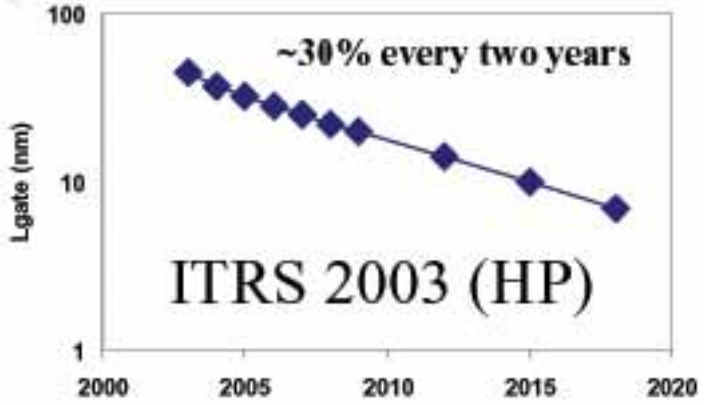


Lg=15nm

22nm node



Lg=10nm

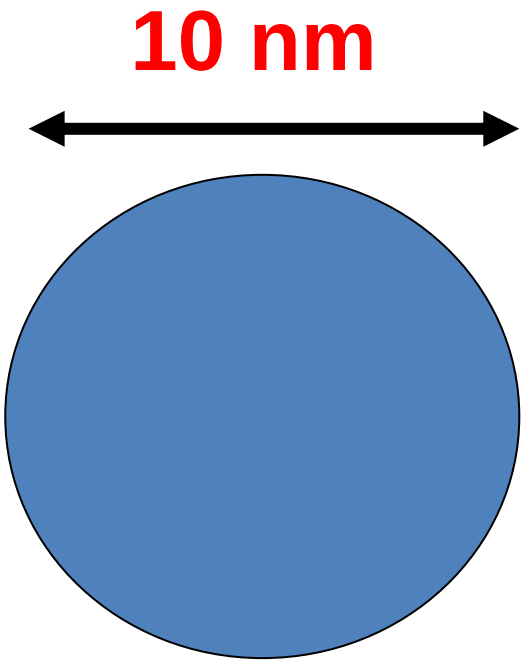


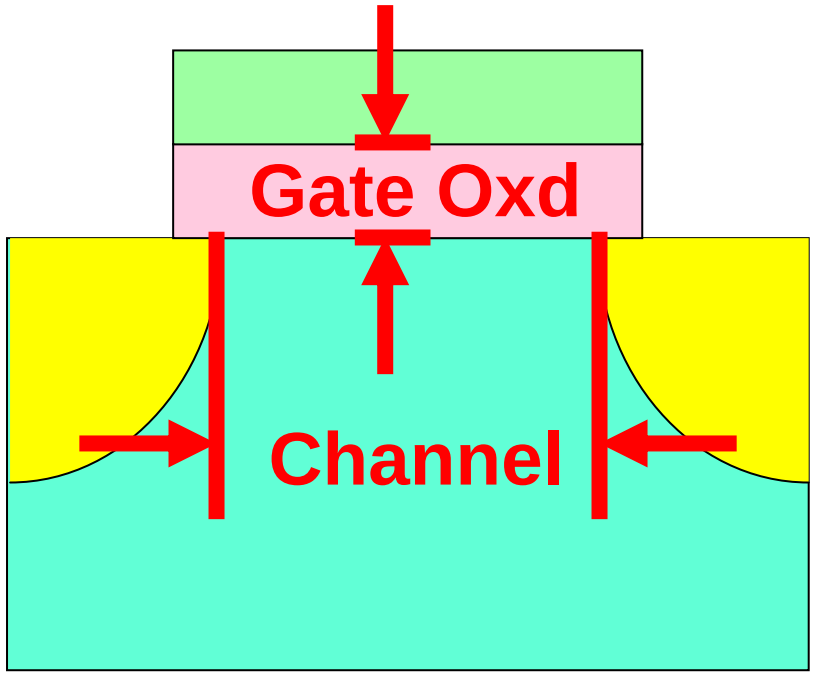
Qi Xinag, ECS 2004, AMI

Downsizing limit?

Channel length?

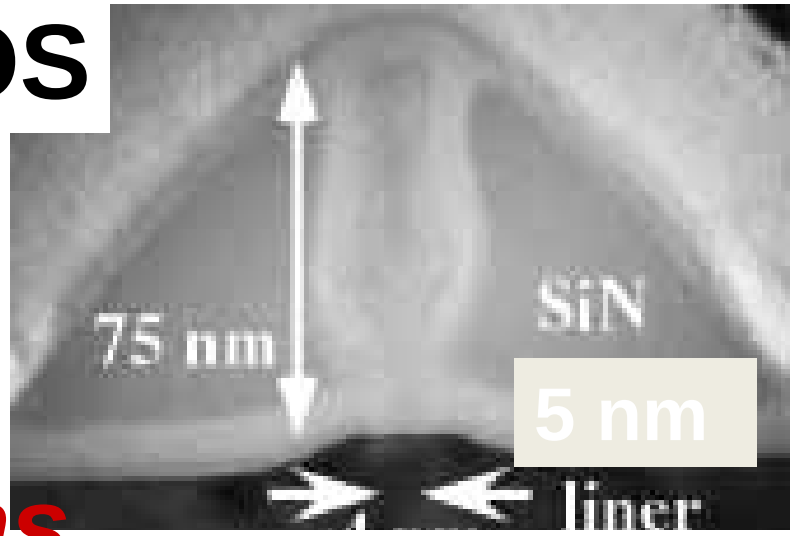
Electron wave length



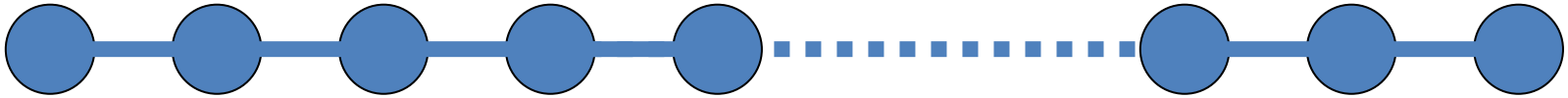


5 nm gate length CMOS

Is a Real Nano Device!!

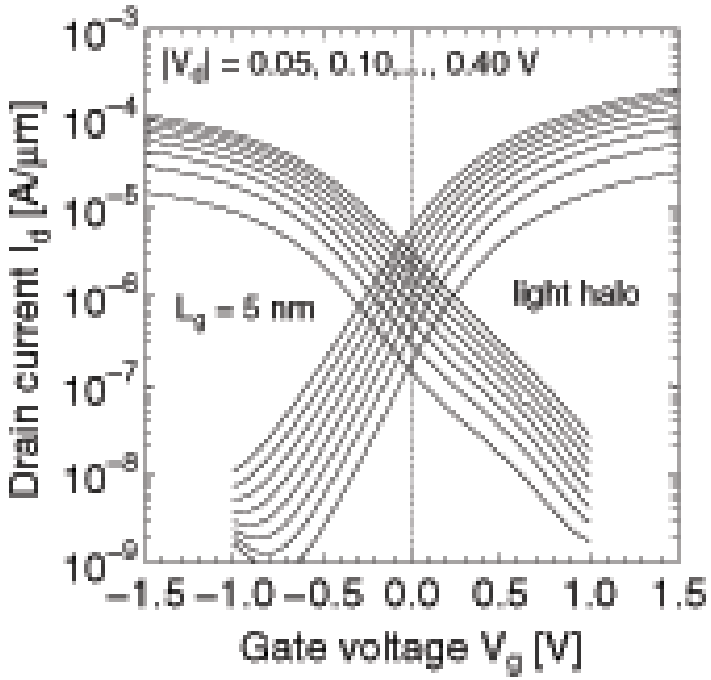


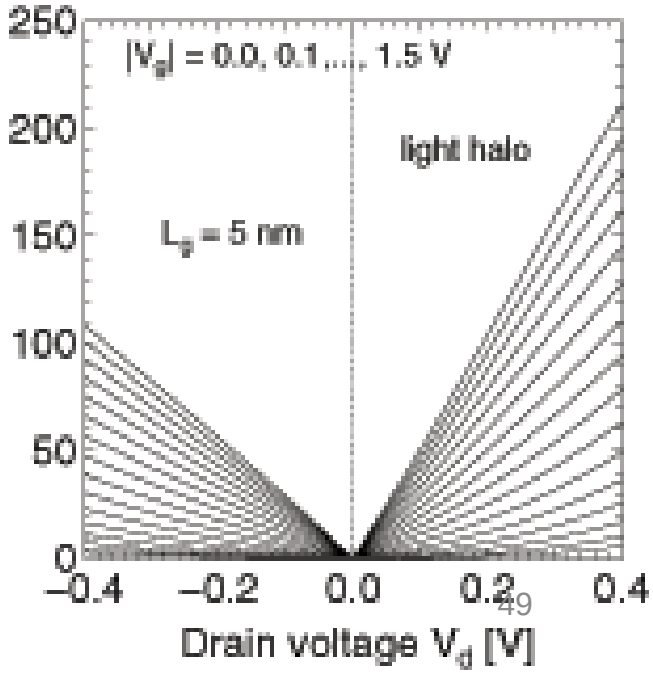
Length of 18 Si atoms



H. Wakabayashi
et.al, NEC

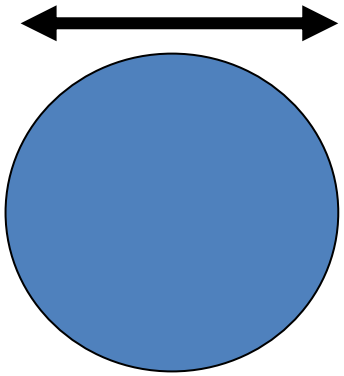
IEDM, 2003





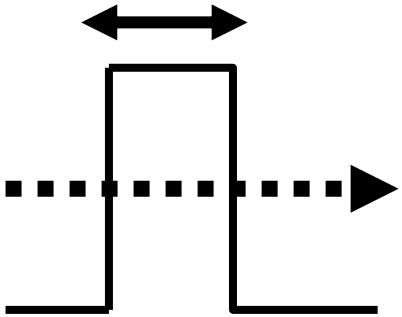
Electron wave length

10 nm



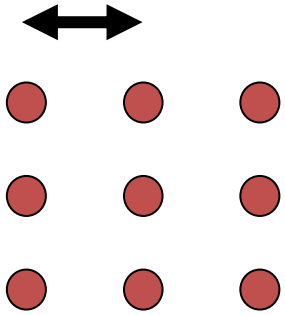
Tunneling distance

3 nm



Atom distance

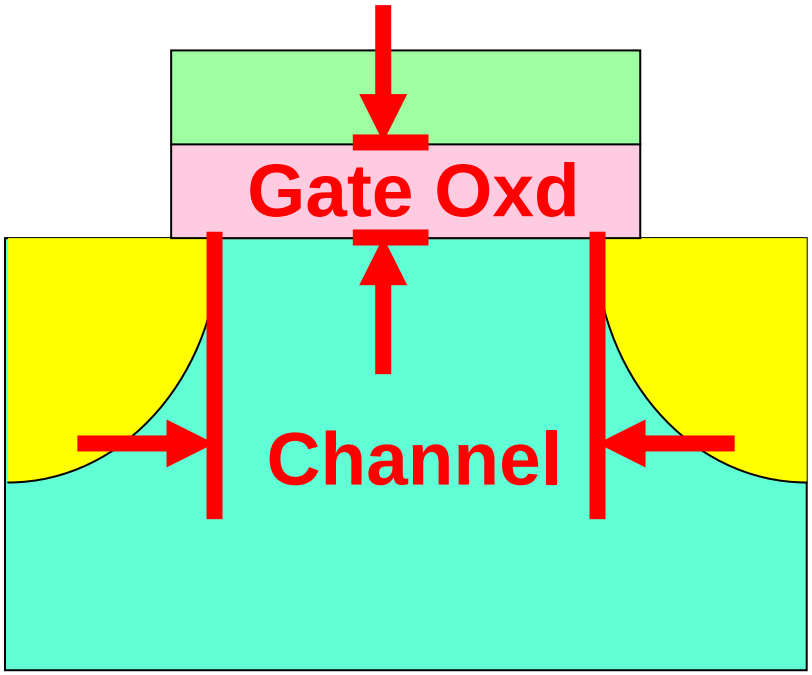
0.3 nm



Downsizing limit!

Channel length

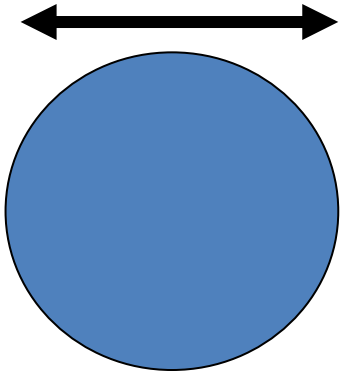
Gate oxide thickness



Prediction now!

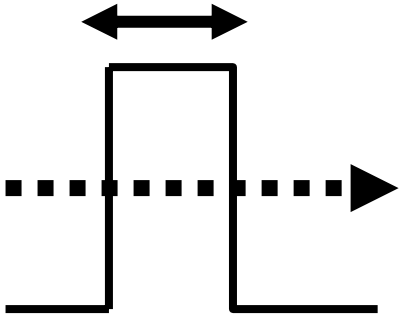
Electron wave length

10 nm



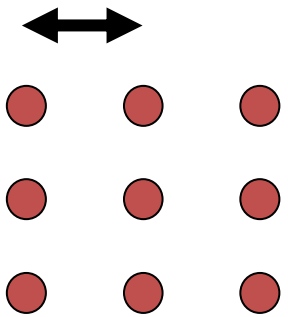
Tunneling distance

3 nm



Atom distance

0.3 nm



MOSFET operation

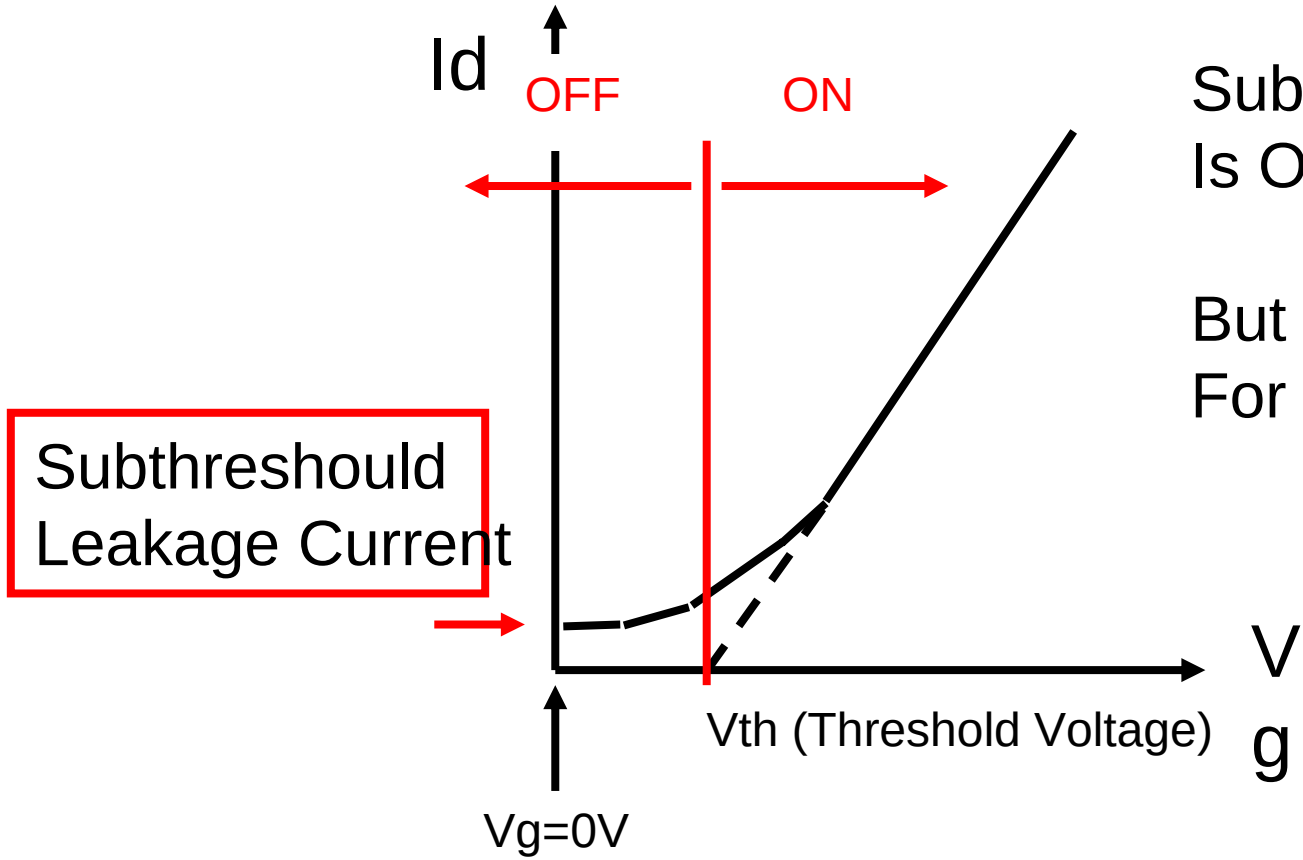
Lg = 2 ~ 1.5 nm?

Below this,
no one knows future!

Maybe, practical limit around 5 nm.

When Gate length Smaller,

→ Subthrehold Leakage Current Larger

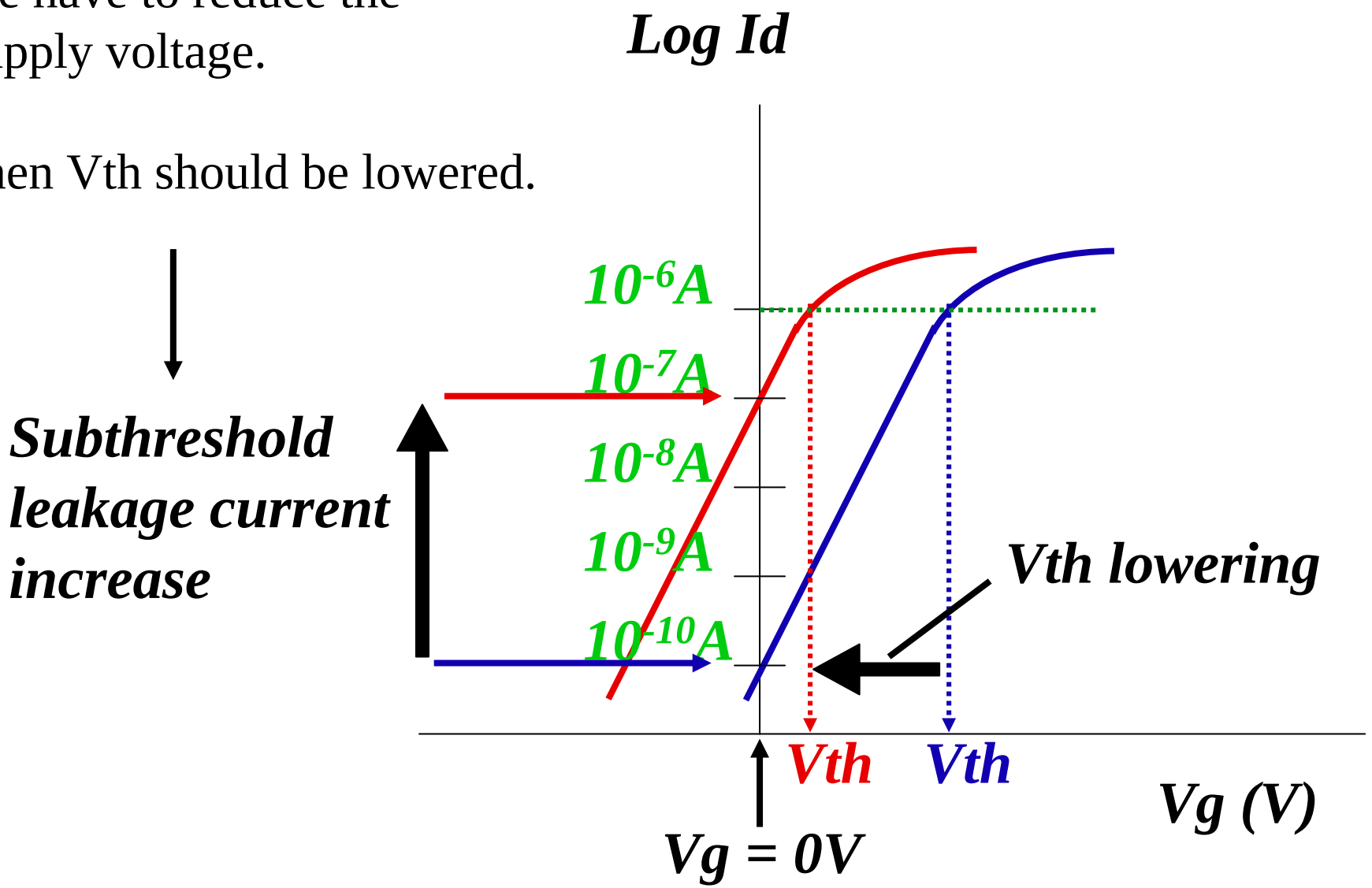


Subthreshold Current
Is OK at Single Tr.

But not OK
For Billions of Trs.

We have to reduce the Supply voltage.

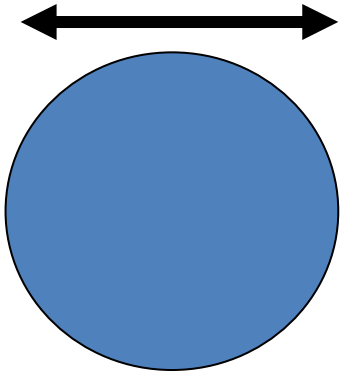
Then Vth should be lowered.



Prediction now!

Electron wave length

10 nm

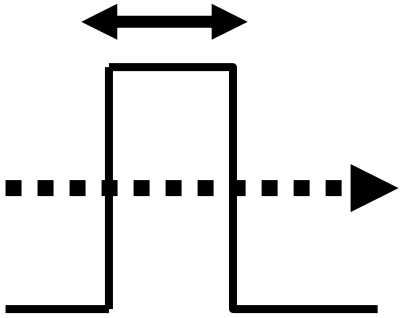


Practical limit for integration

Lg = 5 nm?

Tunneling distance

3 nm



MOSFET operation

Lg = 2 ~ 1.5 nm?

Atom distance

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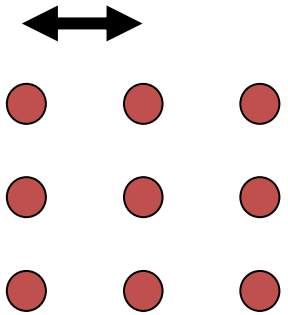
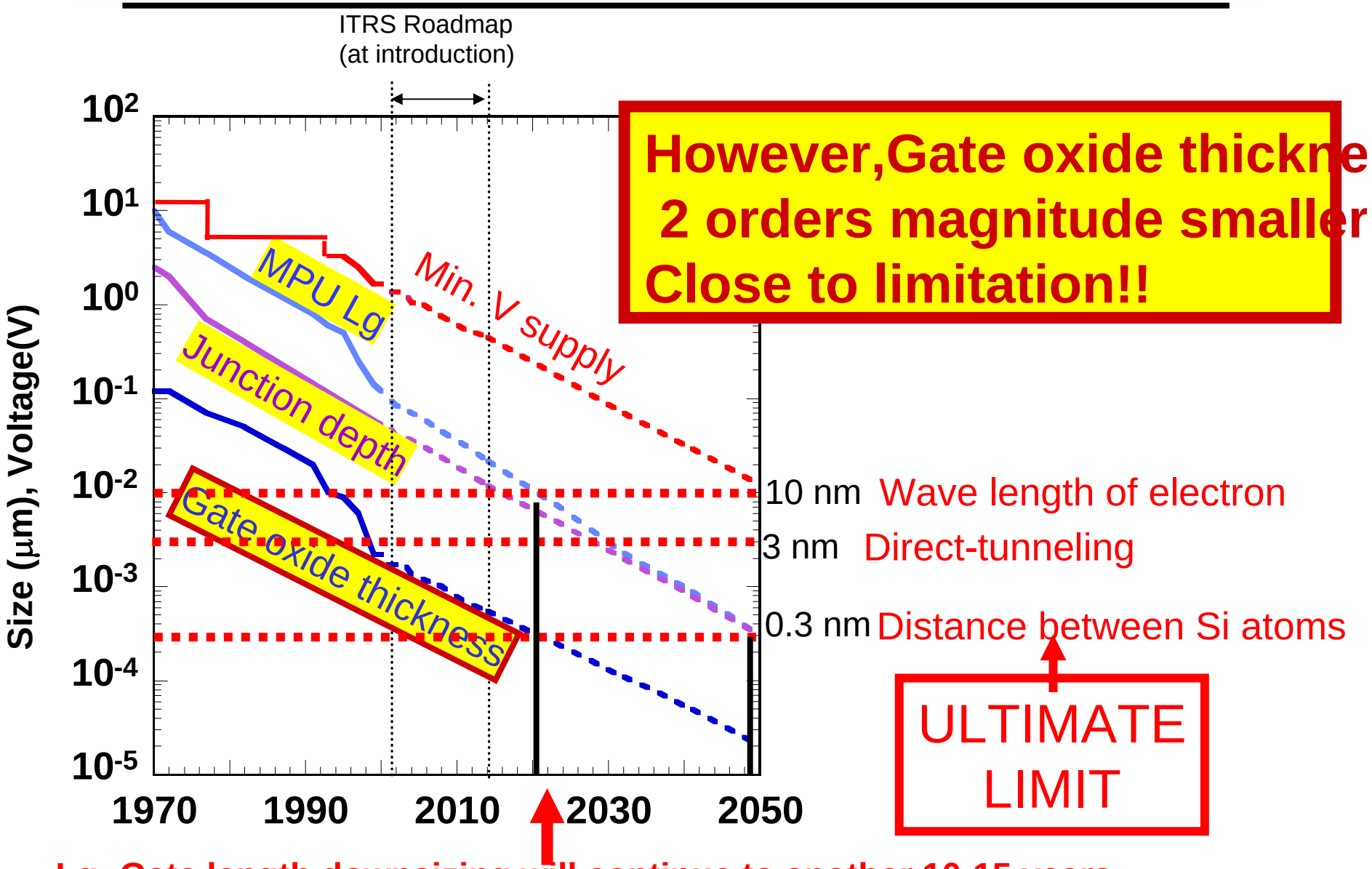


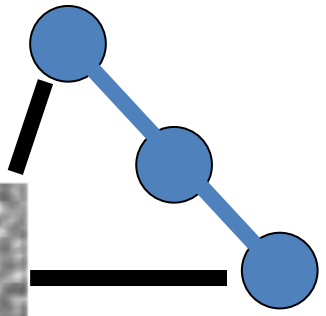
Below this, no one knows future!

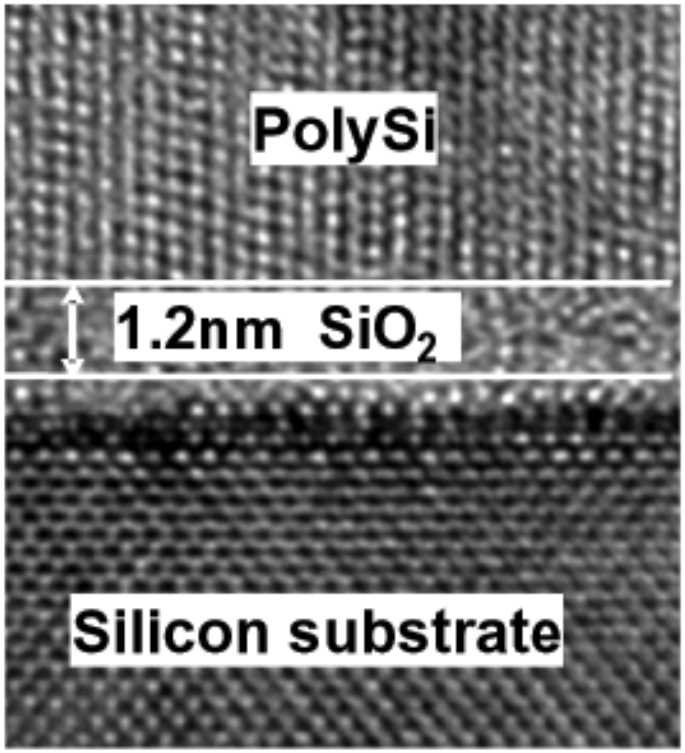
Ultimate limitation

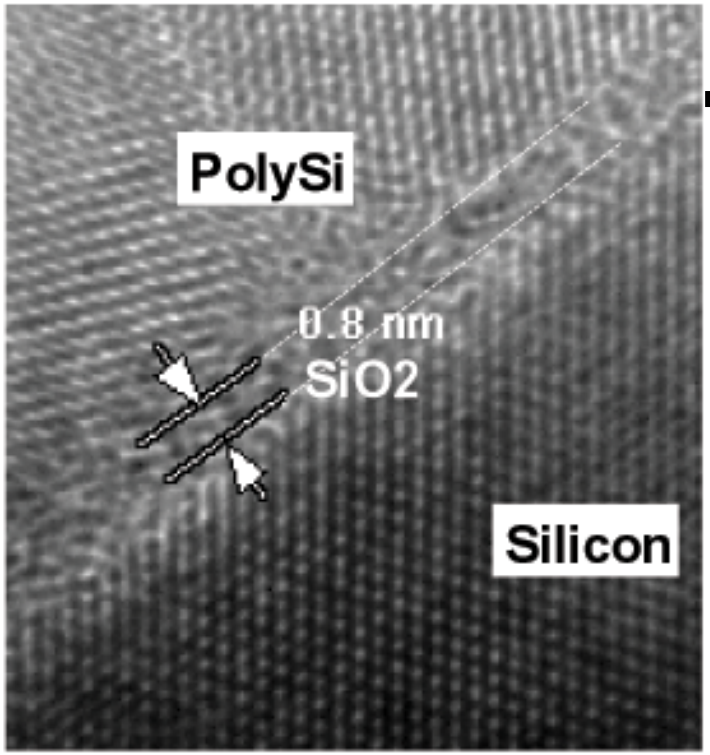


0.8 nm Gate Oxide Thickness MOSFETs operat

0.8 nm: Distance of 3 Si atoms!!







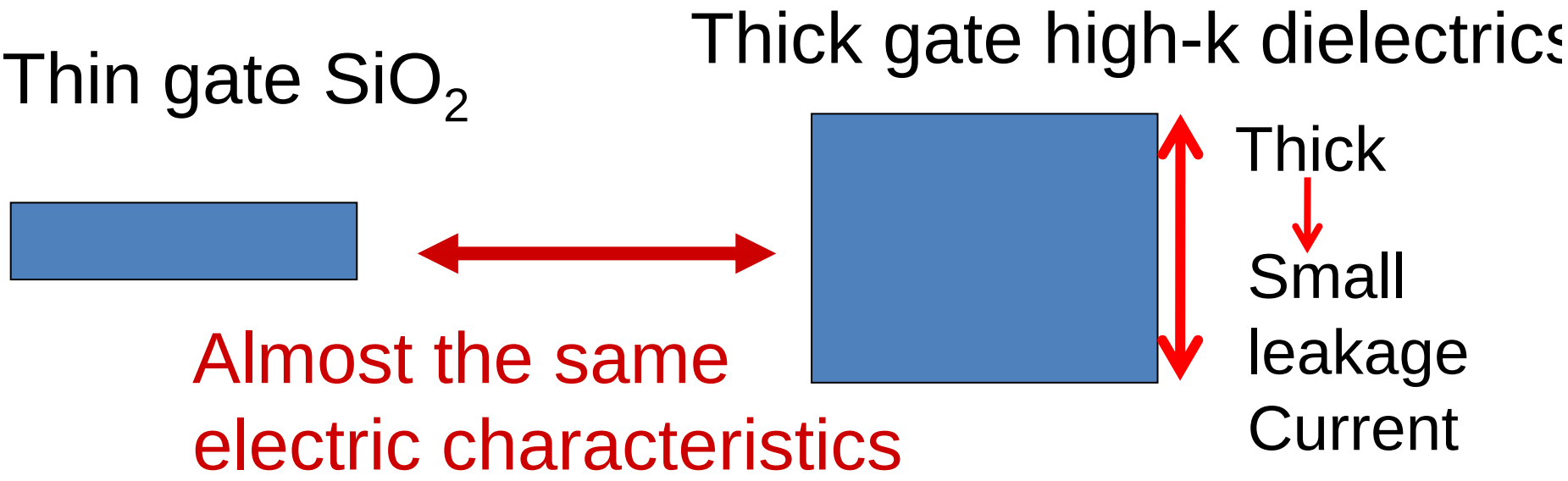
- 1.2nm physical SiO2 in production (90nm logic node)
- 0.8nm physical SiO2 in research transistors

By Robert Chau, IWGI 200

So, we are now in the limitation of downsizing?

Do you believe this or do not?

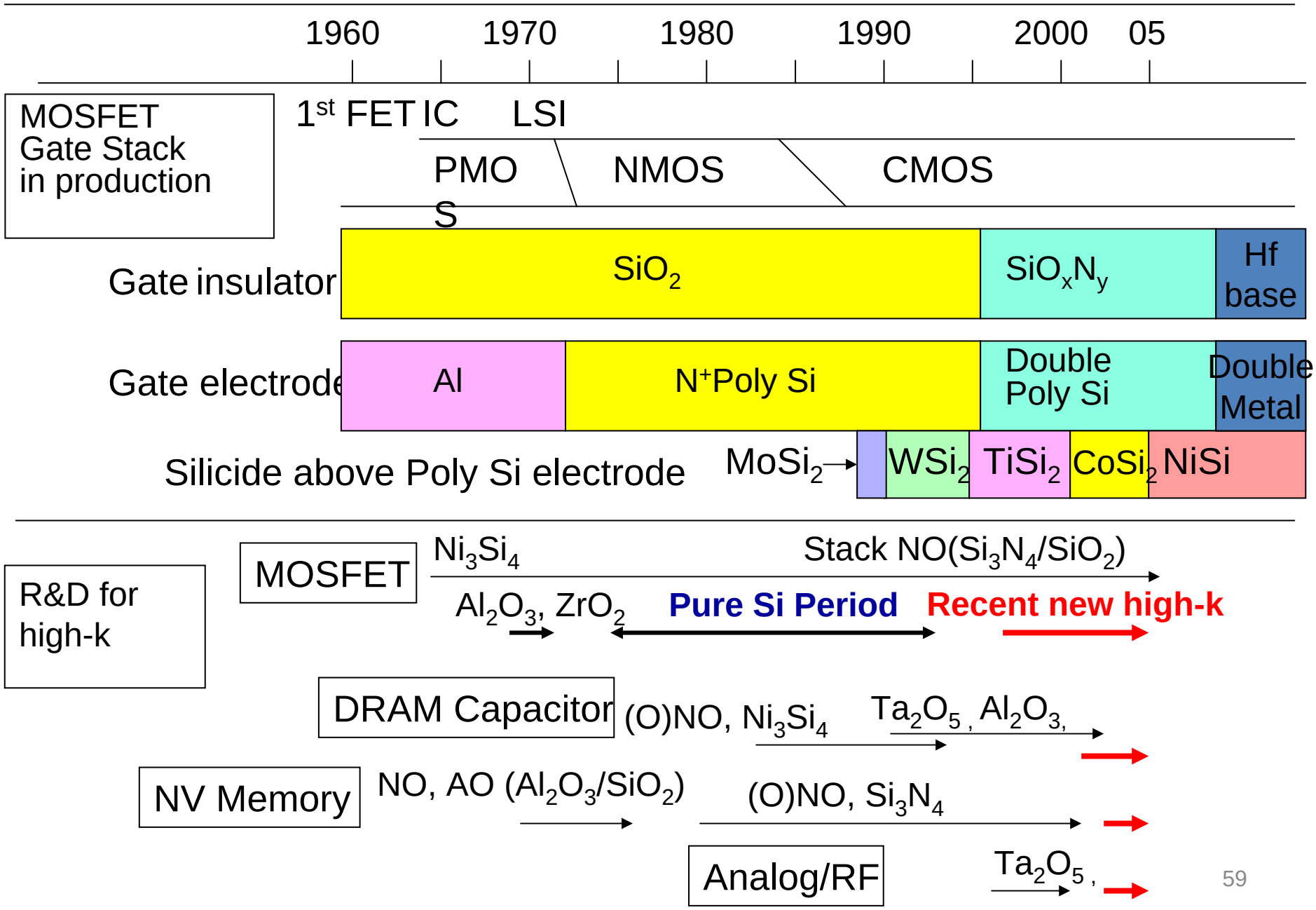
There is a solution! K: Dielectric Constan
To use high-k dielectrics



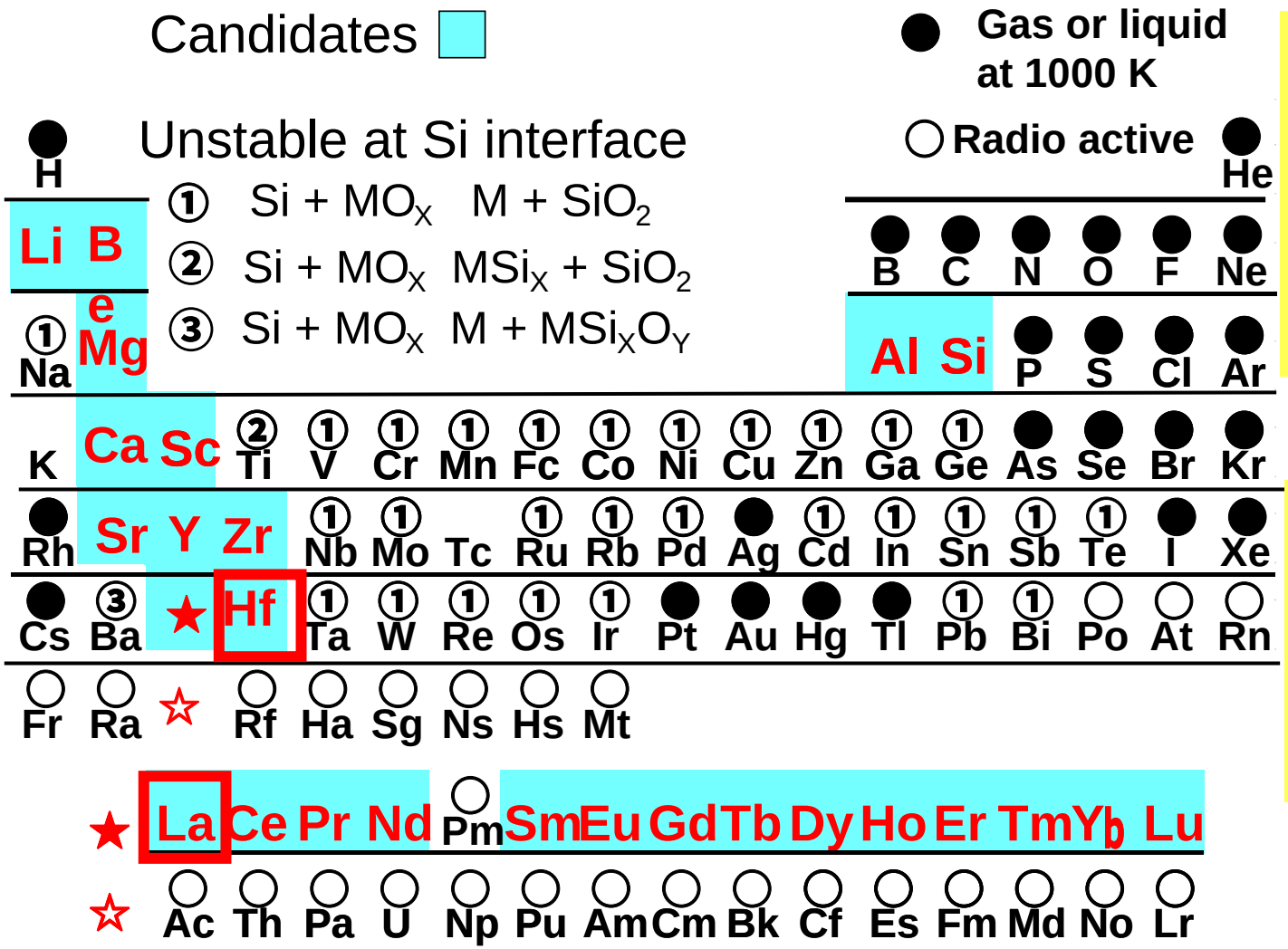
However, very difficult and big challenge!

Remember MOSFET had not been realize
without Si/SiO_2!

Historical Trend of New Material for Gate Stack



Choice of High-k elements for oxide



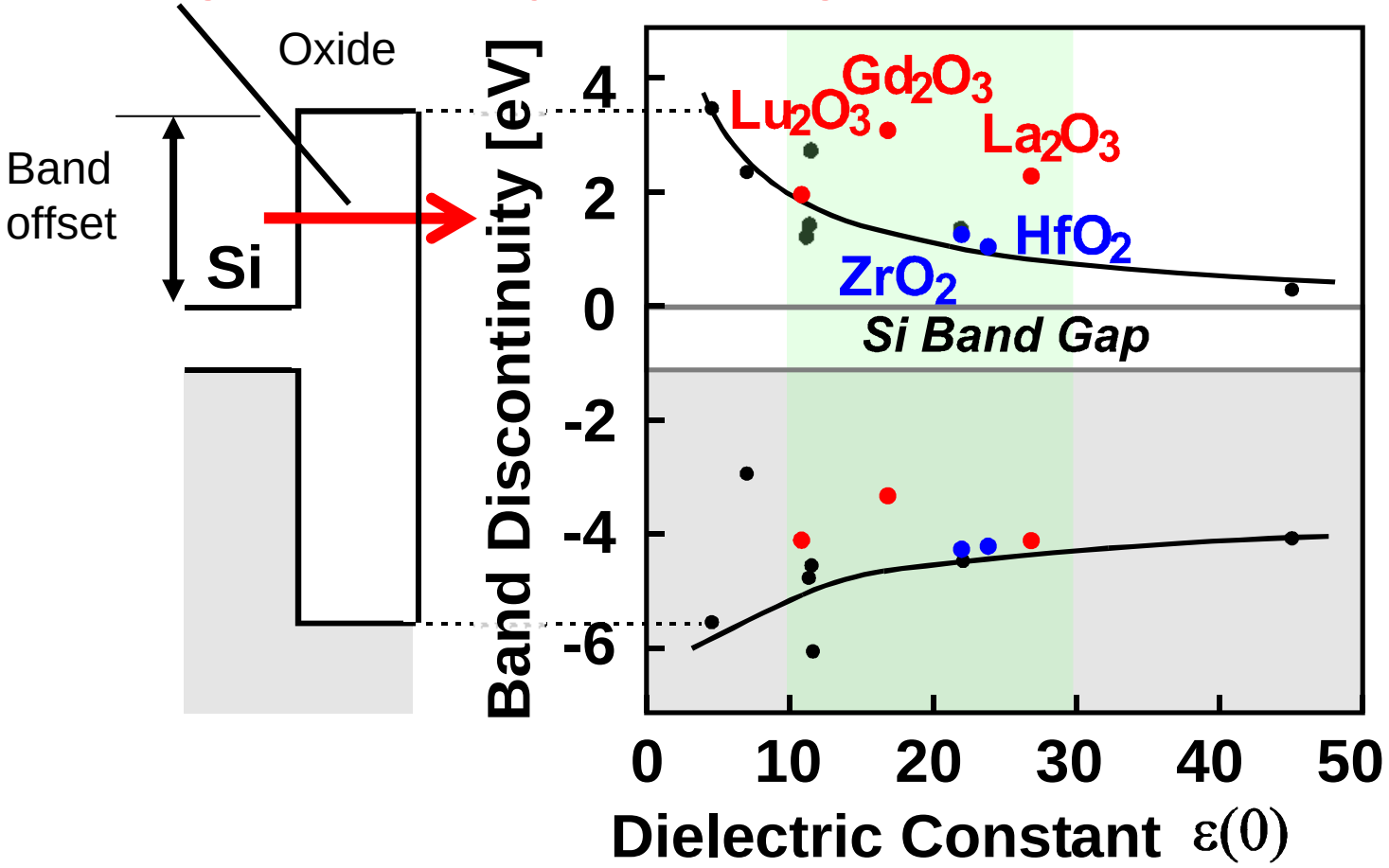
HfO_2 based dielectrics are selected as the first generation materials, because of their merit in
1) band-offset,
2) dielectric constant
3) thermal stability

La_2O_3 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 Constan

Leakage Current by Tunneling



XPS measurement by Prof. T. Hattori, INFOS 2003

Intel’s announcement, January 26, 2007, and IEDM Dec 2007

Hafnium-based high-k material by ALD: EOT= 1nm
Specific gate metals (Intel’s trade secret)
    Different Metals for NMOS and PMOS
Use of 193nm dry lithography

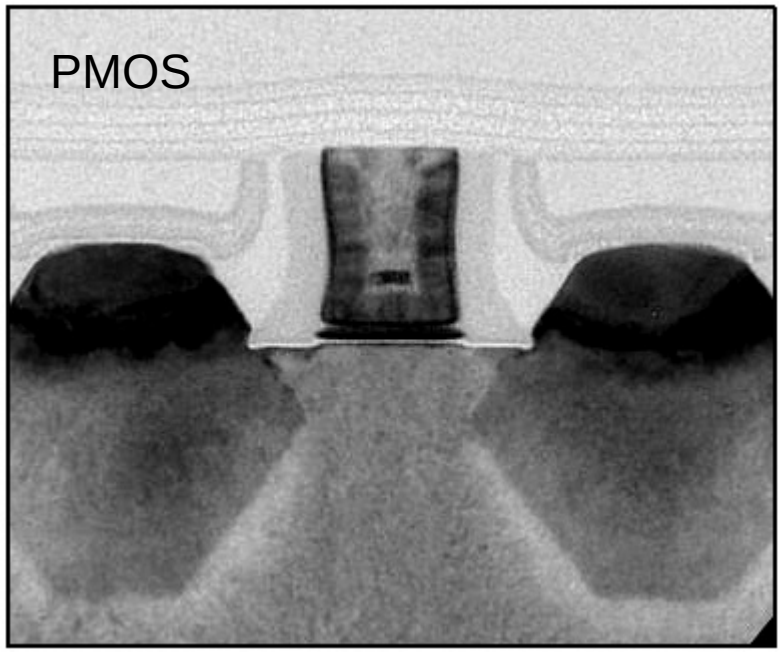
From 65 nm to 45 nm Tech.
    Tr density: 2 times increase
    Tr switching power: 30% reduction
    Tr switching speed: 20% improvement
    S-D leakage power: 5 times reduction
    Gate oxide leakage: 10 times reduction

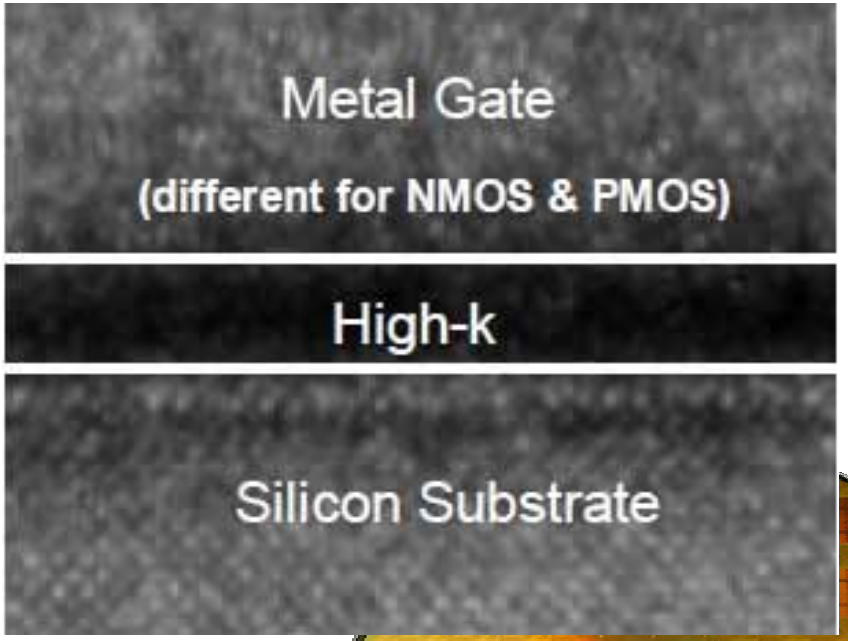
45nm processors (Core™2 family processors "Penryn") running Windows* Vista*, Linux* etc.

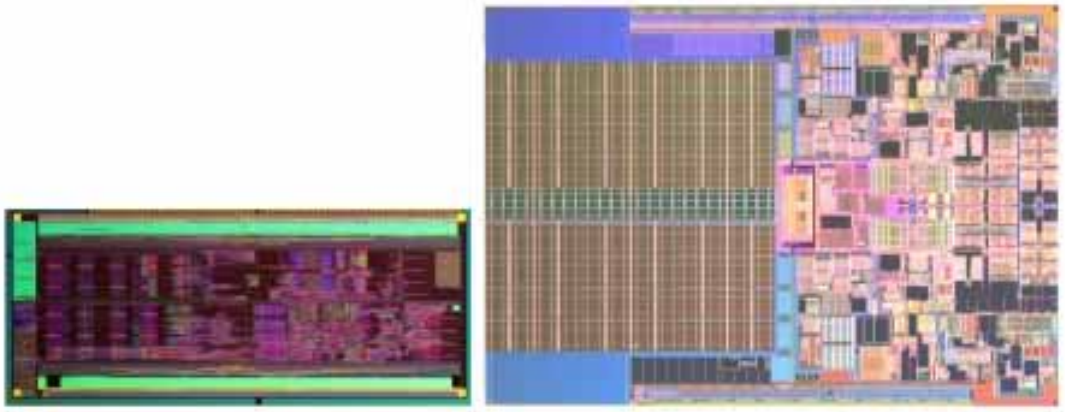
45nm production in the second half of 2007

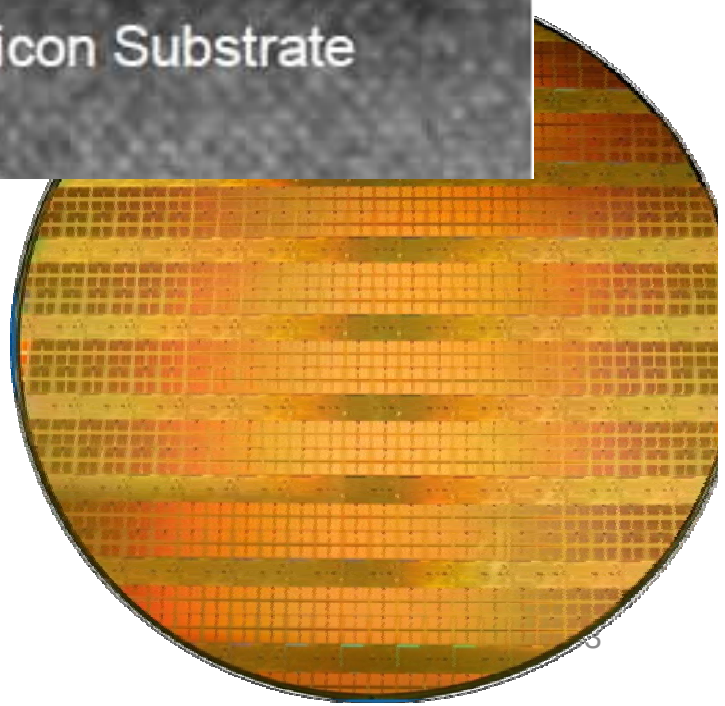
High-k gate insulator MOSFETs for Intel: EOT=1nm

EOT: Equivalent Oxide Thickness









History and future of Transistor

Shrinking, Shrinking, and Shrinking!

and then, Shrinking, Shrinking, and Shrinking!

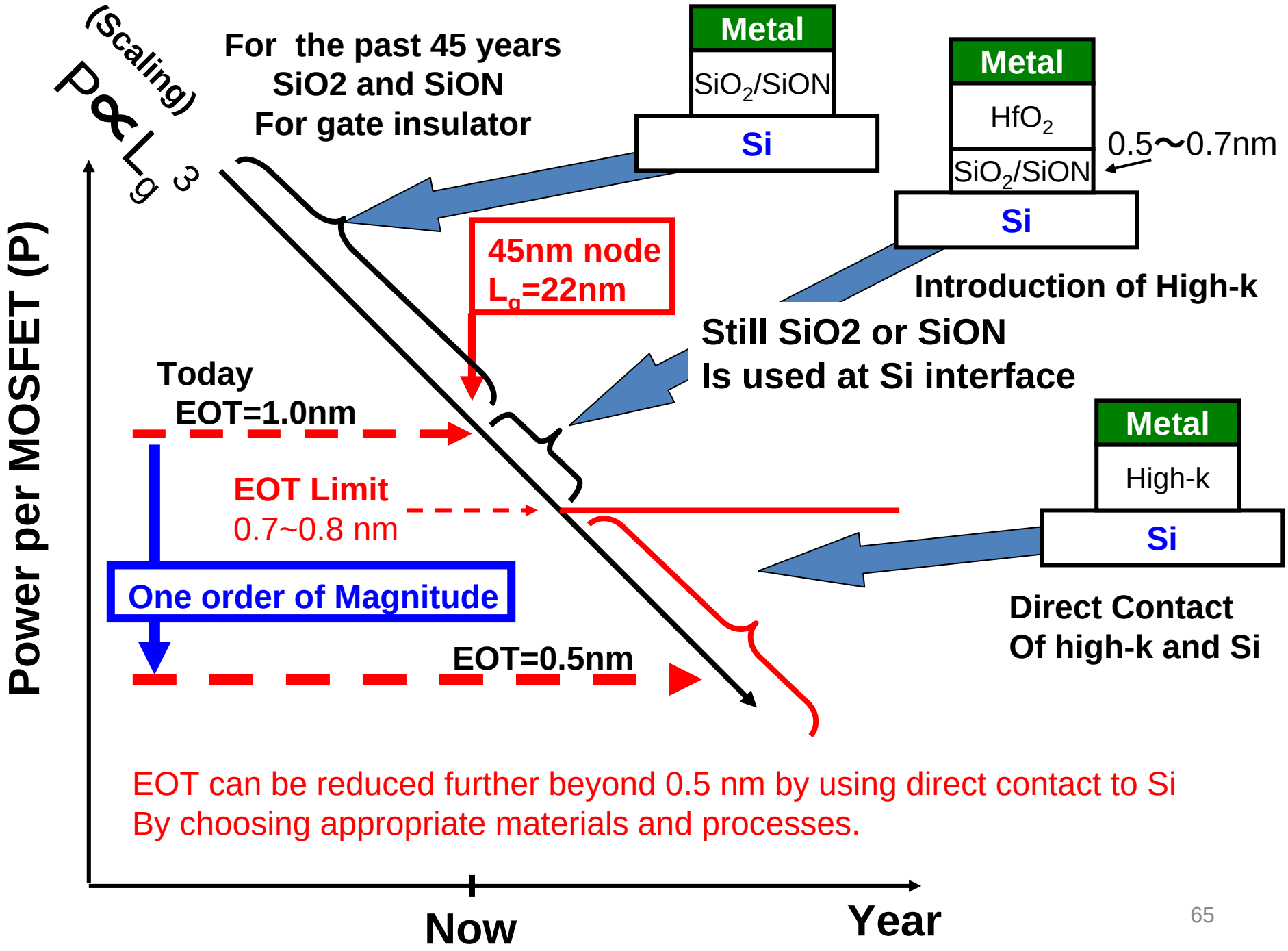
C, V $\propto$ L C: Capacitance V: Voltage

Switching speed CV/I → Decrease

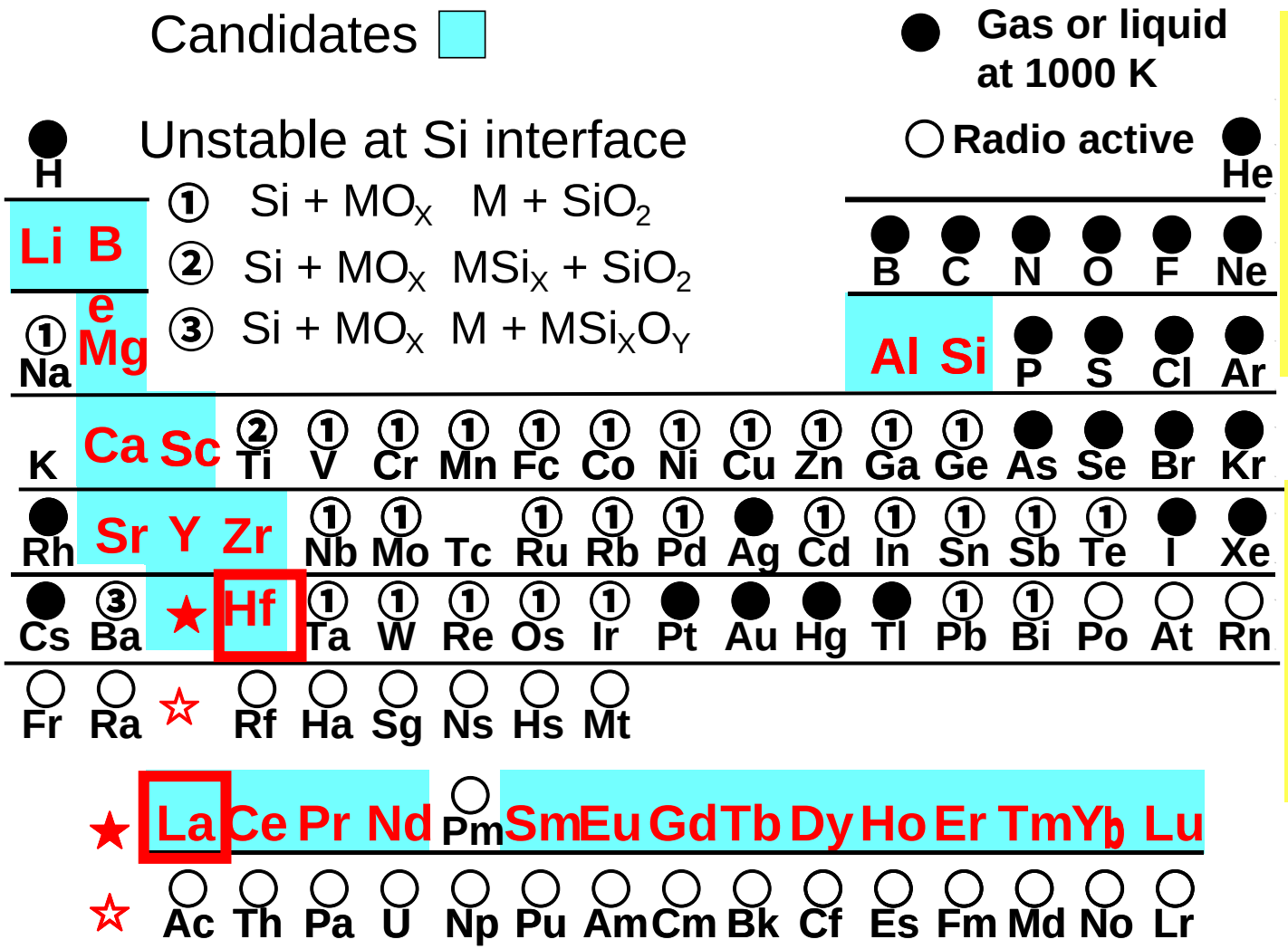
Power consumption $CV^2/2$ → Decrease

Integration density: $1/L^2$ → Increase

	1970	2007
Gate length	10,000 nm	25 nm
Gate Oxd Thickness	100 nm	1 nm


(scaling)
$P \propto L_g^3$
For the past 45 years
SiO2 and SiON
For gate insulator
Metal
SiO_2/SiON
Si
Metal
HfO_2
SiO_2/SiON
Si
0.5~0.7nm
45nm node
L_g=22nm
Introduction of High-k
Still SiO2 or SiON
Is used at Si interface
Today
EOT=1.0nm
EOT Limit
0.7~0.8 nm
One order of Magnitude
EOT=0.5nm
Metal
High-k
Si
Direct Contact
Of high-k and Si
Power per MOSFET (P)
Now
Year
EOT can be reduced further beyond 0.5 nm by using direct contact to Si
By choosing appropriate materials and processes.

Choice of High-k elements for oxide



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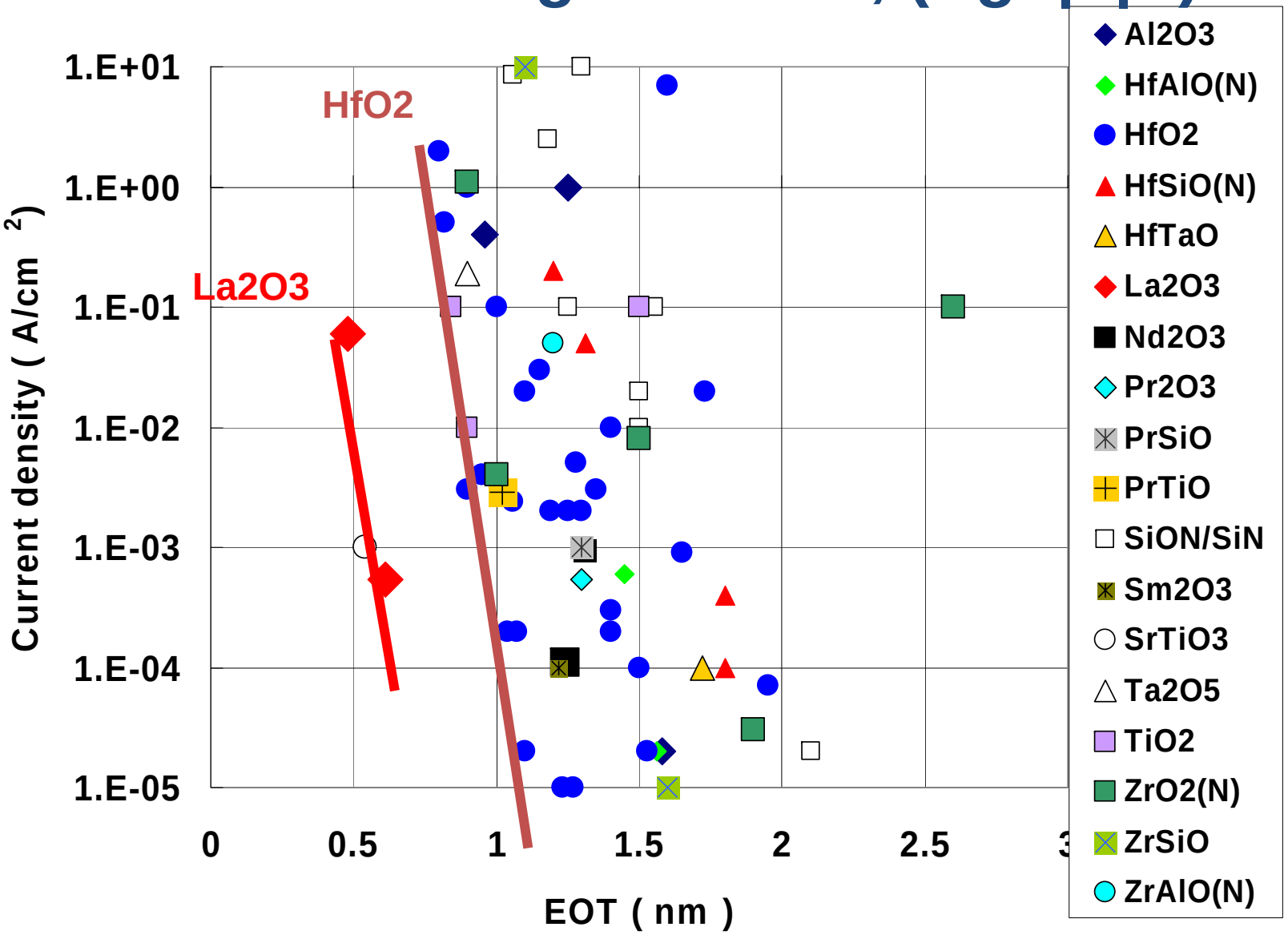
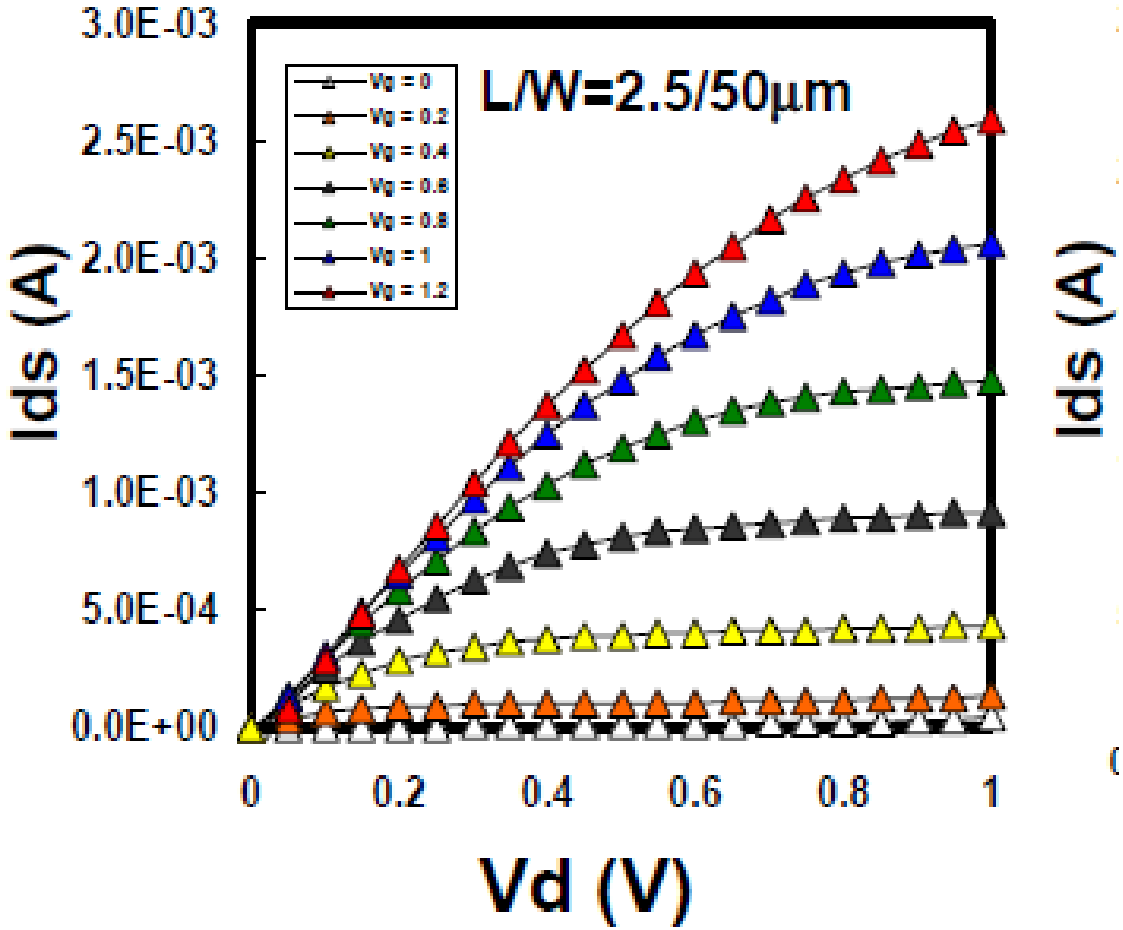
R. Hauser, IEDM Short Course, 1999
Hubbard and Schlom, J Mater Res 11 2757 (1996)

Gate Leakage vs EOT, (Vg=|1|V)



EOT = 0.48 nm Our results

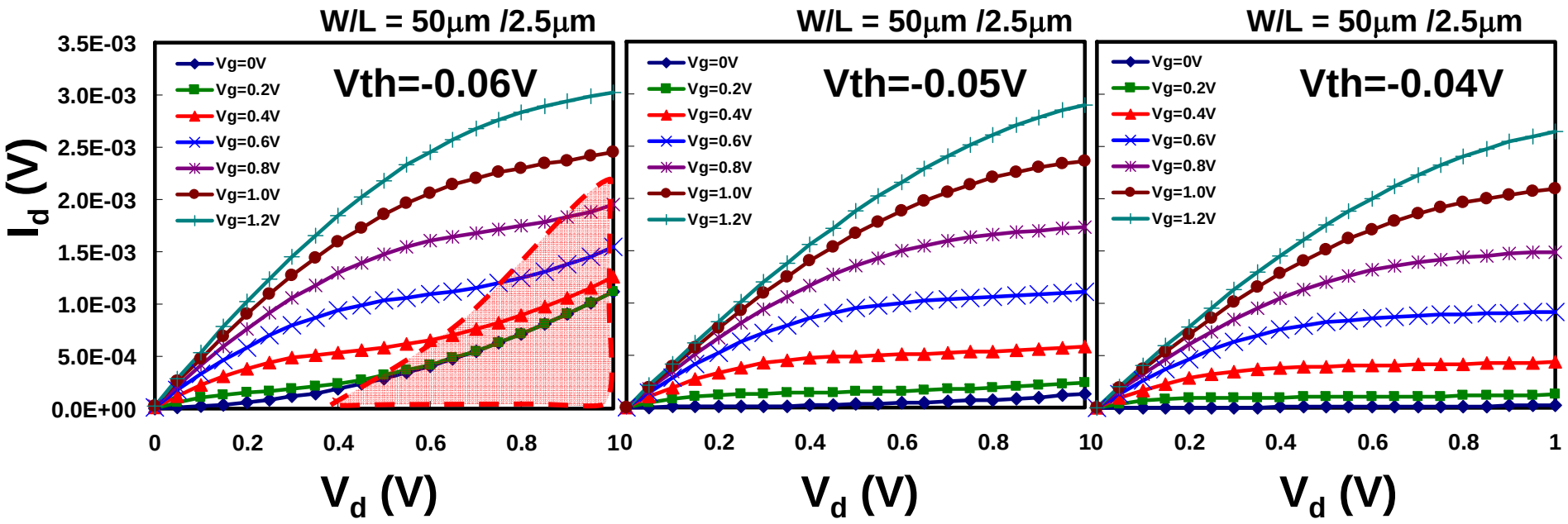
Transistor with La2O3 gate insulator



EOT=0.37nm

La2O3

EOT=0.37nm EOT=0.40nm EOT=0.48nm

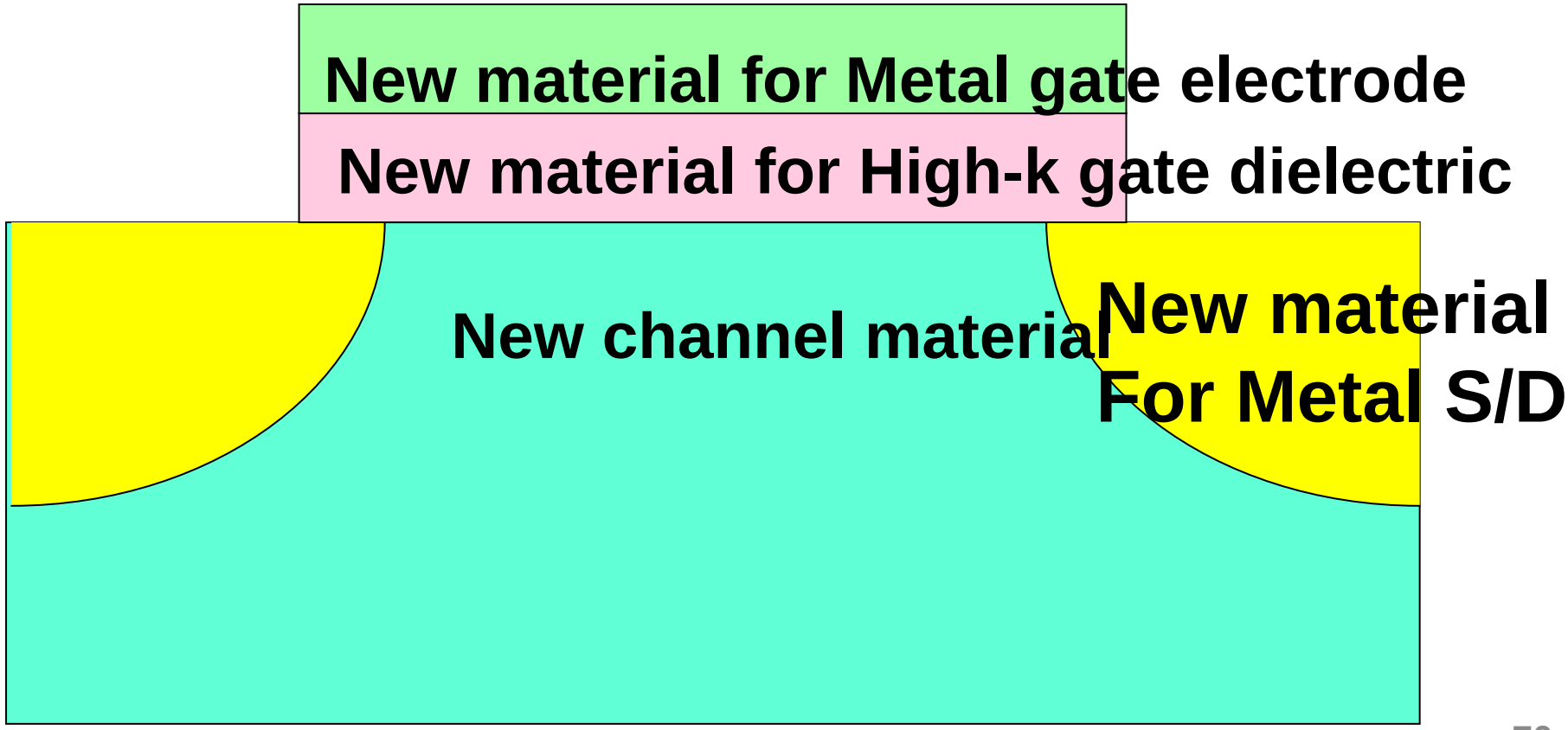


0.48 →0.37nm Increase of Id at 30%

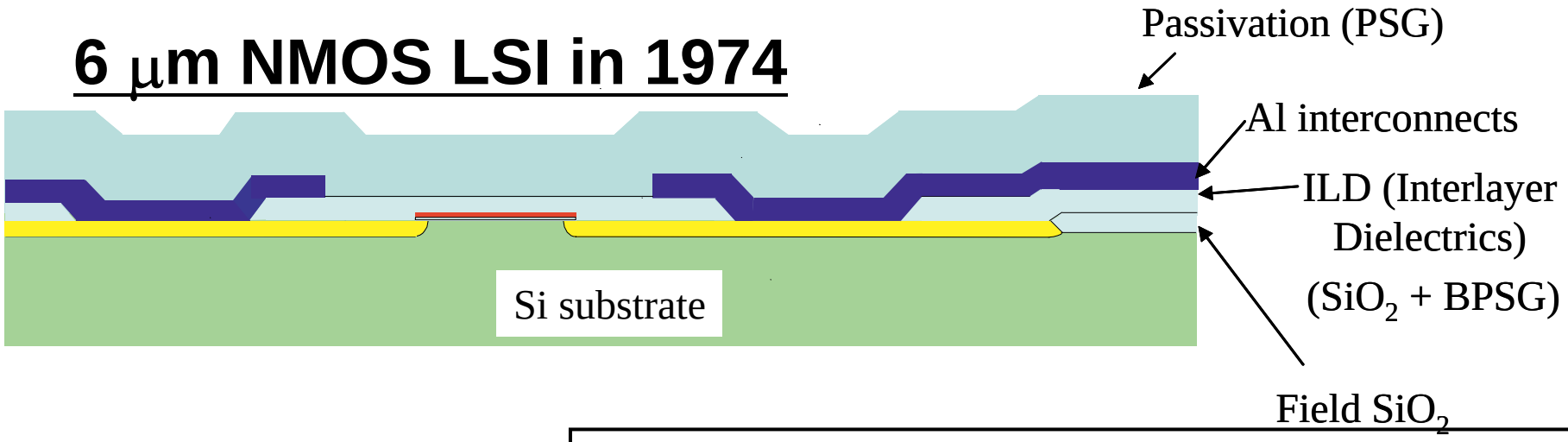
New material research will give us many future possibilities and the most important

for Nano-CMOS!

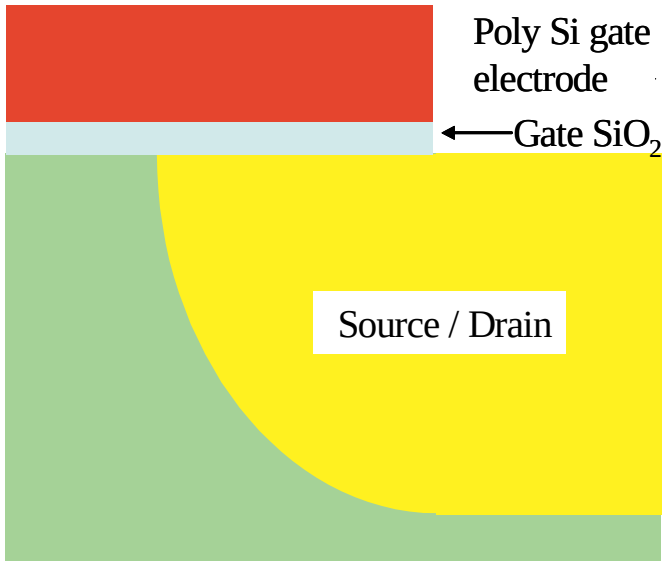
Not only for high-k!



6 μm NMOS LSI in 1974



magnification



Layers

1. Si substrate
2. Field oxide
3. Gate oxide
4. Poly Si
5. S/D
6. Interlayer
7. Aluminum
8. Passivation

Materials

1. Si
2. SiO_2
3. BPSG
4. Al
5. PSG

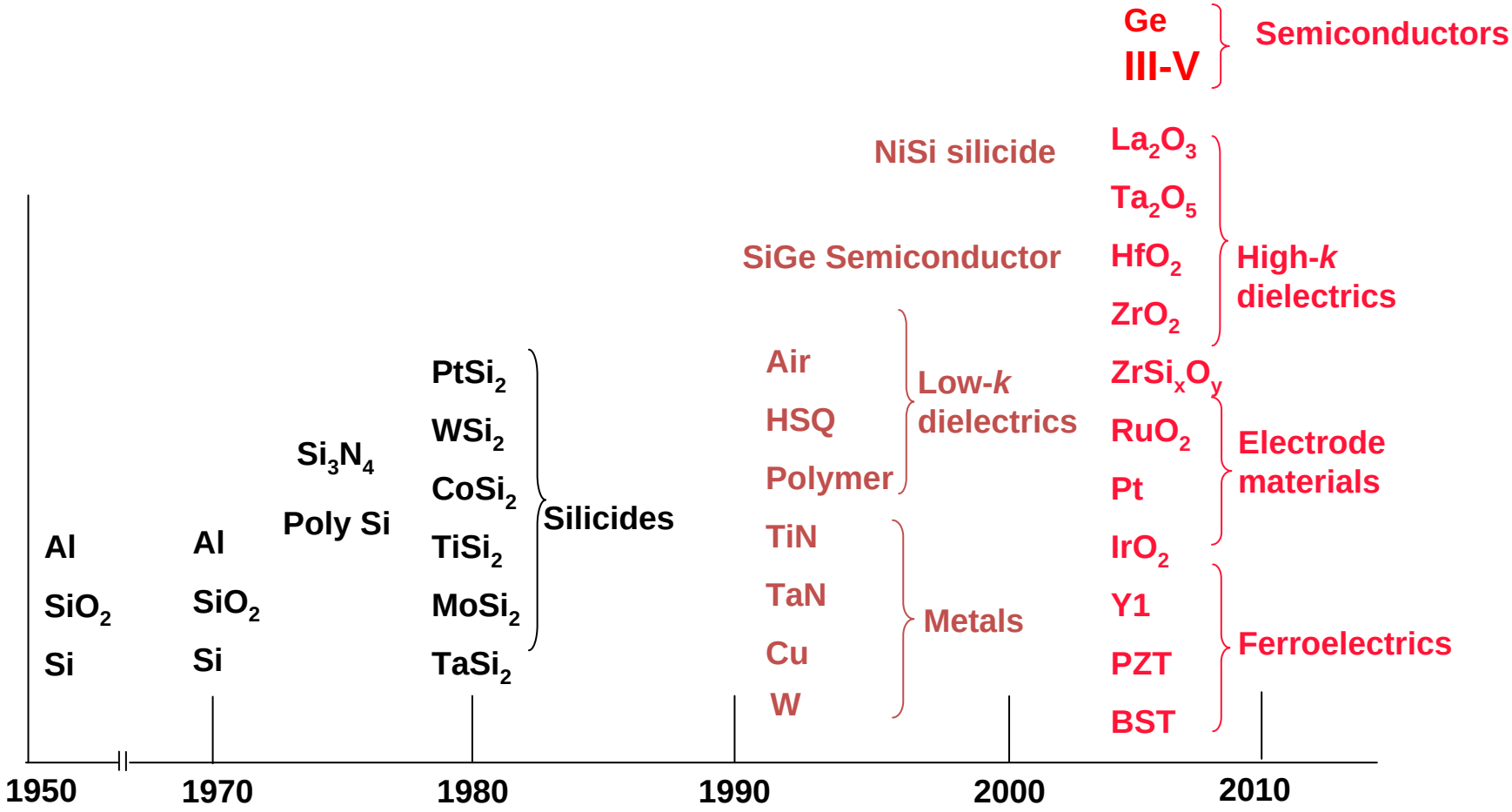
Atoms

1. Si
2. O
3. P
4. B
5. Al

(H, N, Cl)

New materials

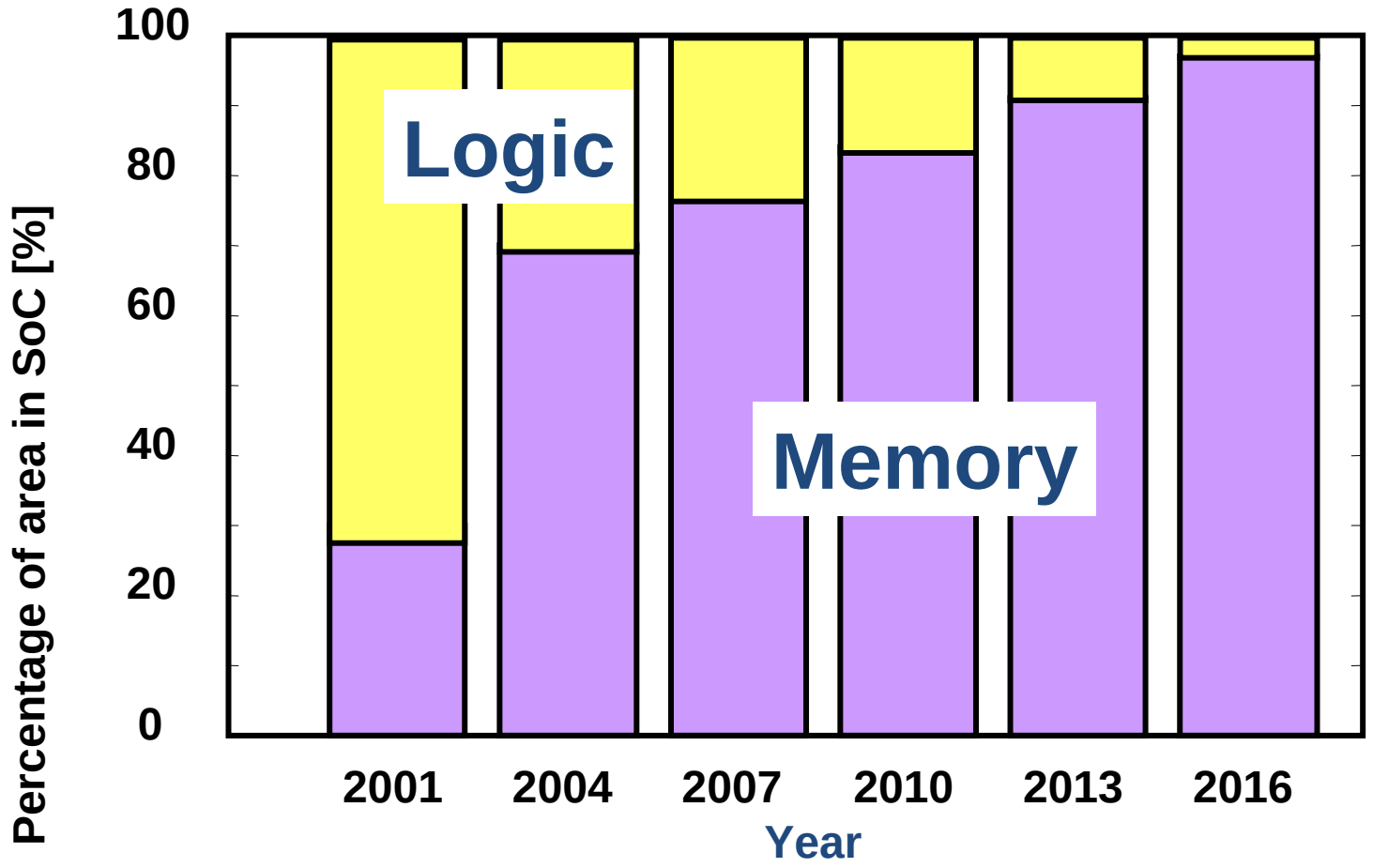
Just examples!
Many other candidates



Y. Nishi, Si Nano Workshop, 2006,

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

Memory area will increase



Due to design productivity, yield, and power

ITRS' 2000: Y, Nishi, Si Nano Workshop, 2006

Now: After 45 Years from the 1st single MOSFE

32 Gb and 16Gb NAND, SAMSUNG

Samsung's NAND flash trend

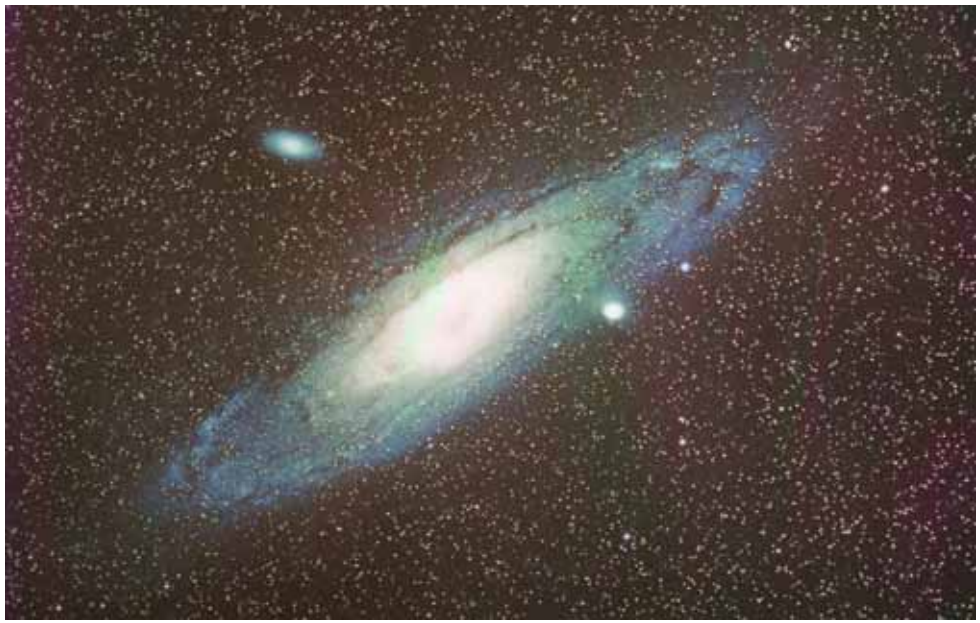
Capacity	Node	1st Fabrication	Production
512Mbit	120nm	2000	2001
1Gbit	100nm	2001	2002
2Gbit	90nm	2002	2003
4Gbit	70nm	2003	2004
8Gbit	60nm	2004	2005
16Gbit	50nm	2005	2006
32Gbit	**40nm**		
256Gbit	**20nm**		

Even Tbit would be possible in future!

Already 32 Gbit:

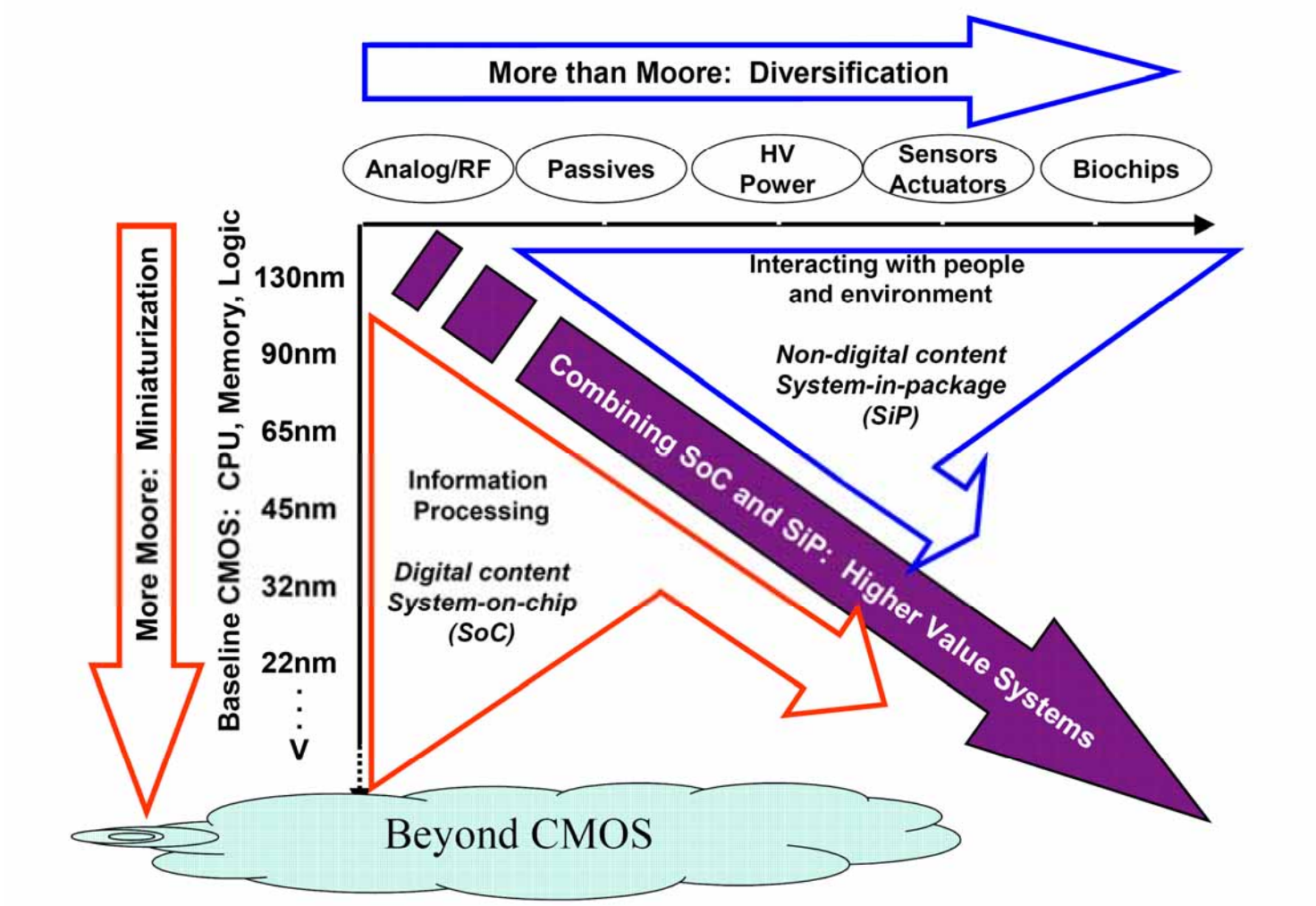
larger than that of world population
comparable for the numbers of neurons
in human brain

Samsung announced 256 Gbit will be produced in 2010.
Only 4 years from now.
256Gbit: larger than those of # of stars in galaxies



More Moore and More than Moore

Moore's Law & More



Question what is the other side of the cloud?

ITRS 2005 Edition

http://strj-jeita.elisasp.net/pdf_ws_2005nendo/9A_WS2005IRC_Ishiuchi.pdf

We could keep the Moore's law after 2020
Without downswing the gate length

What is Moore's law.

→ to increase the number (#) of Tr. In a chip

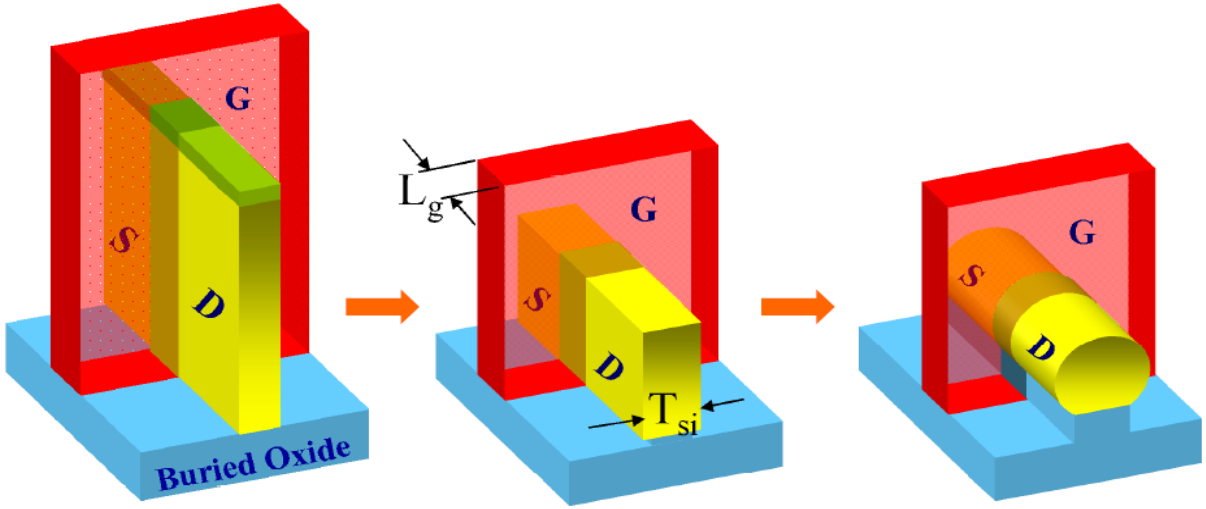
Now, # of Tr. in a chip is limited by power.

→ key issue is to reduce the power.

→ to reduce the supply voltage is still effective

To develop devices with sufficiently high drain current under low supply voltage is important.

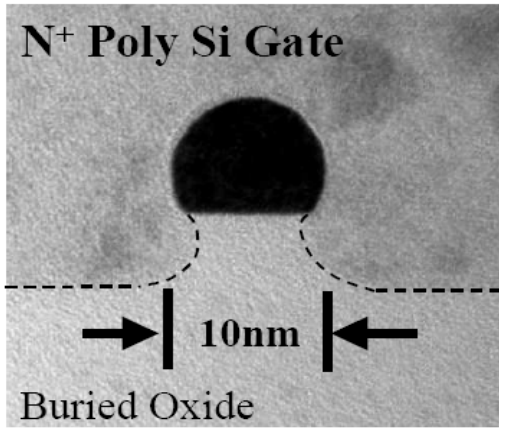
FinFET to Nanowire

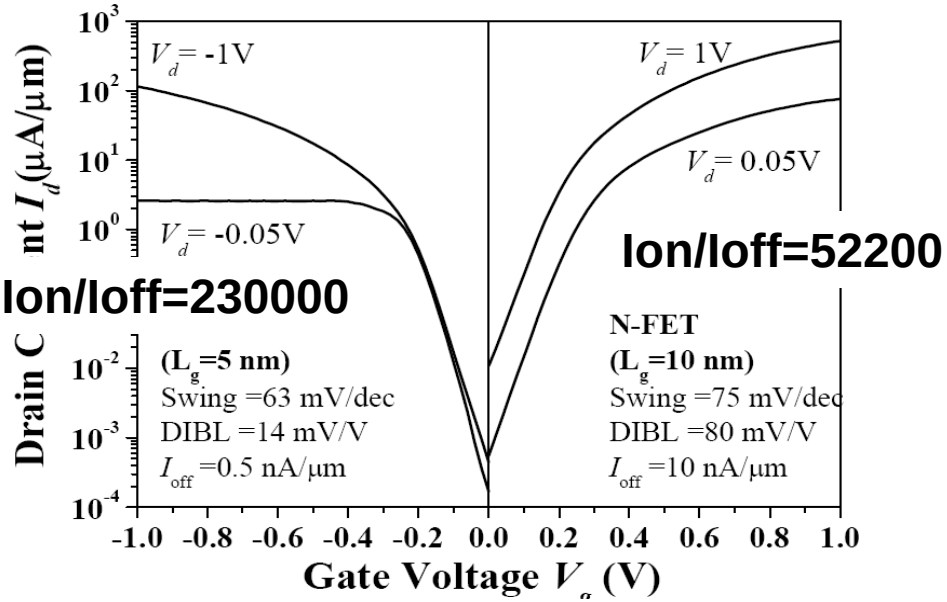


Double-Gate FinFET ($T_{si} = {}^{2}/_{3}\, L_g$)

Omega FinFET ($T_{si} = L_g$)

Nanowire FinFET ($T_{si} = 2L_g$)





Channel conductance is well controlled by Gate even at L=5nm

F.-L.Yang, VLSI2004

Selection of MOSFET structure for high conduction:
Nano-wire or Nano-tube FETs is promising

3 methods to realize High-conduction at Low voltage

M1. Use 1D ballistic conduction

M2. Increase number of quantum channel

M3. Increase the number of wire or tube per area
3D integration of wire and tubes

For suppression of Ioff, the Nanowire/tube is also good.

1D conduction per one quantum channel:

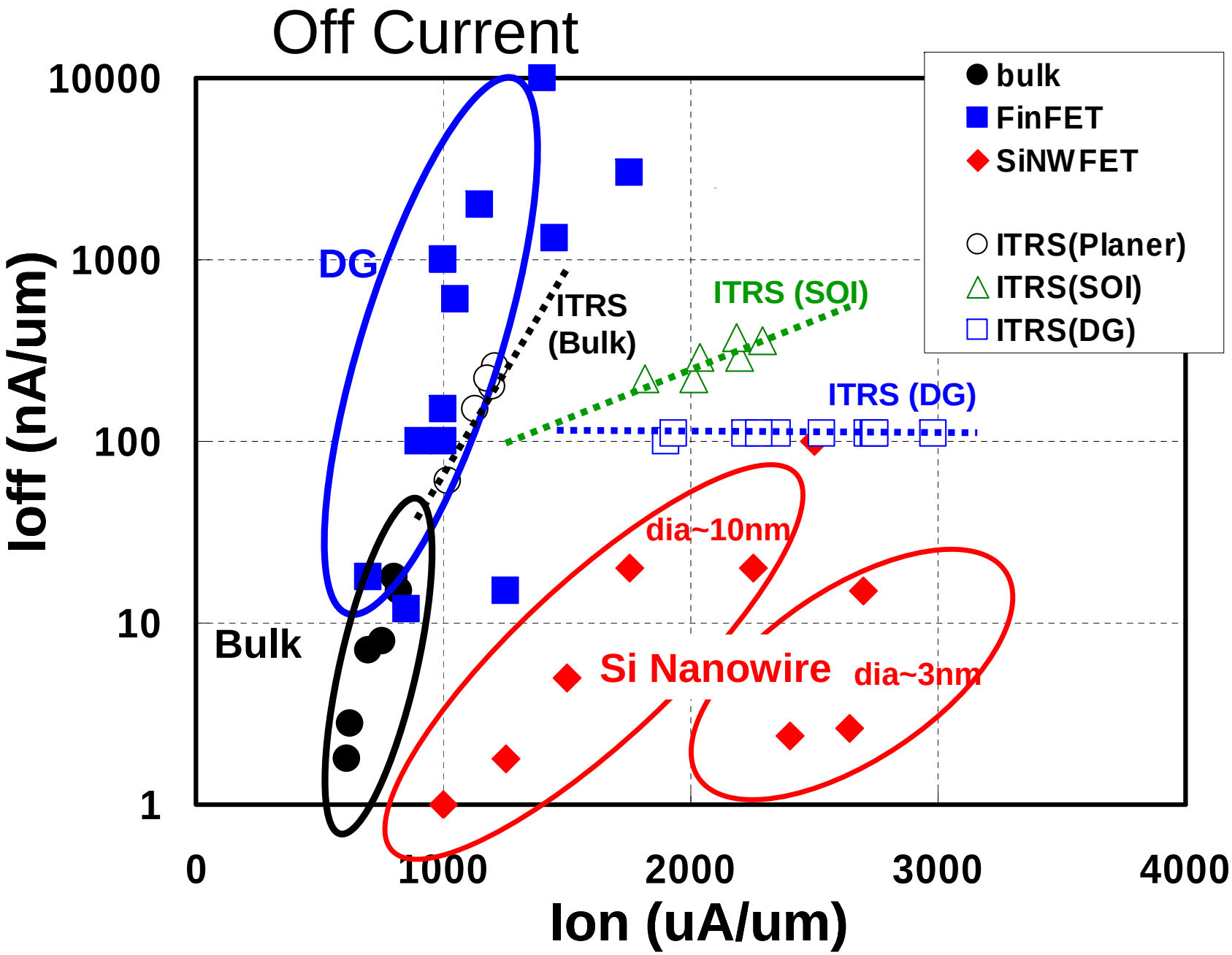
$G = 2e^2/h = 77.8\ \mu S$/wire or tube

regardless of gate length and channel material

That is 77.8 μA/wire at 1V supply

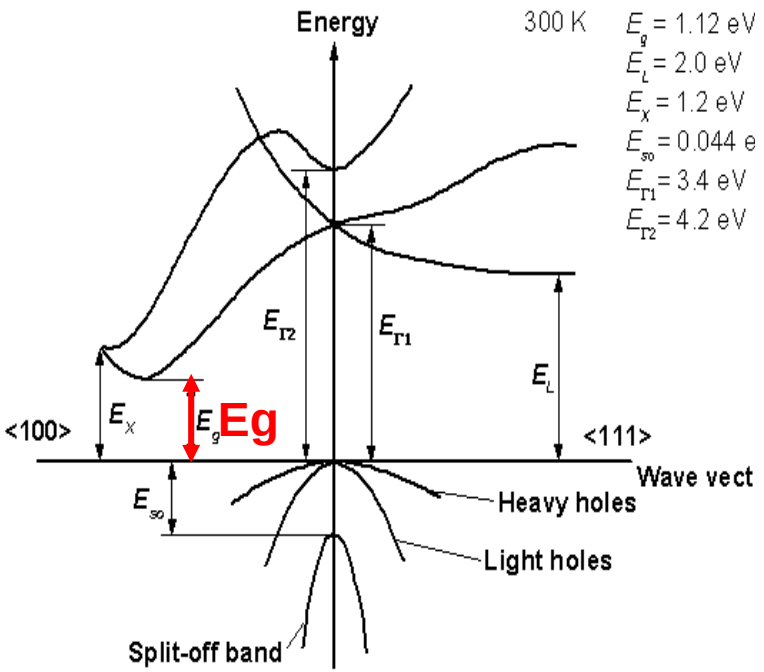
This an extremely high value

However, already 20mA/wire was obtained experimentaly by Samsung

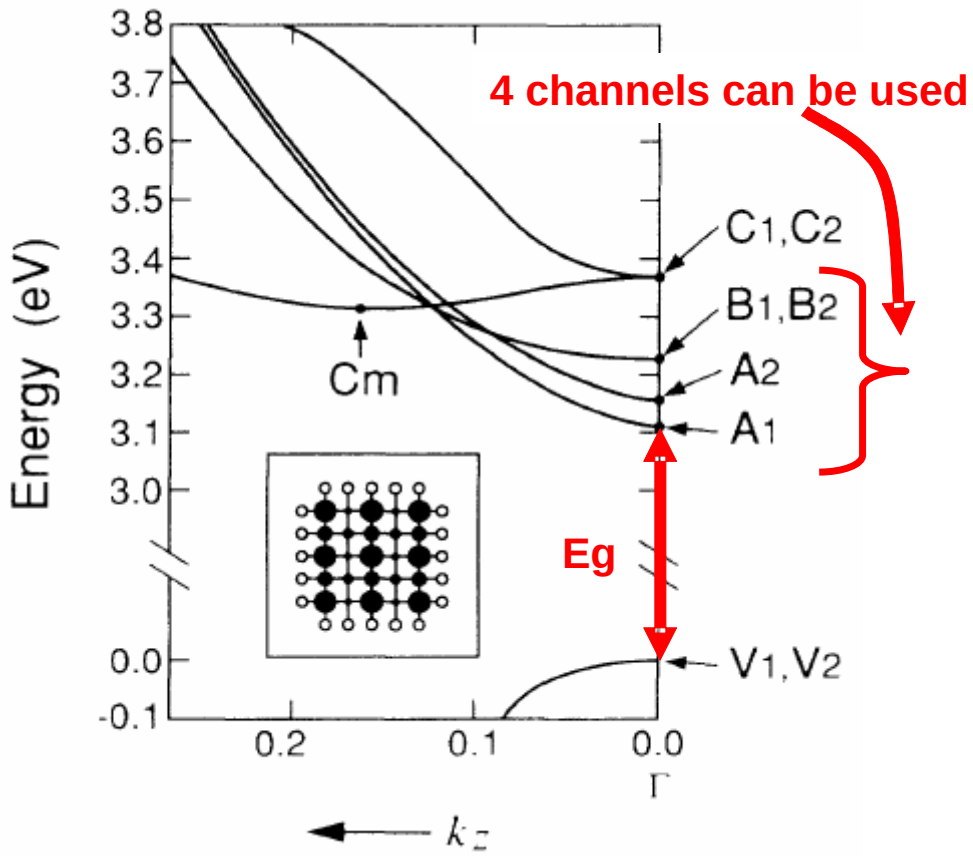

Off Current
10000
1000
100
10
1
Ioff (nA/um)
0
1000
2000
3000
4000
Ion (uA/um)
bulk
FinFET
SiNWFET
ITRS(Planer)
ITRS(SOI)
ITRS(DG)
DG
ITRS
(Bulk)
ITRS (SOI)
ITRS (DG)
dia~10nm
Bulk
Si Nanowire
dia~3nm

Increase the Number of quantum channels

By Prof. Shiraishi of Tsukuba univ.



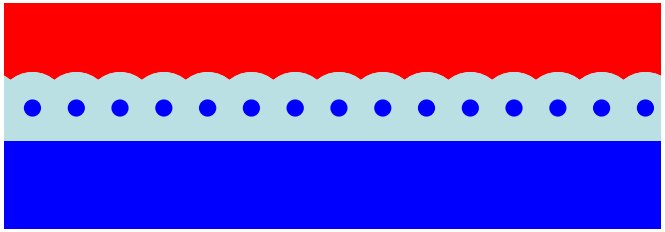
Energy band of Bulk Si



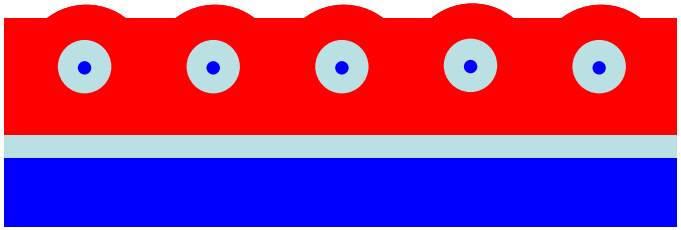
Energy band of 3 x 3 Si wire

Maximum number of wires per 1 μm

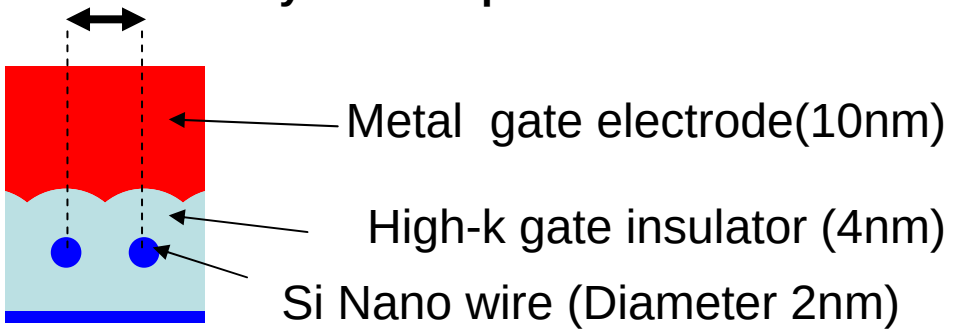
Front gate type MOS 165 wires /μm

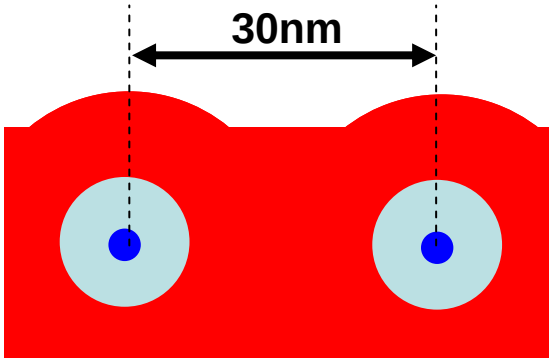


Surrounded gate type MOS 33 wires/μm

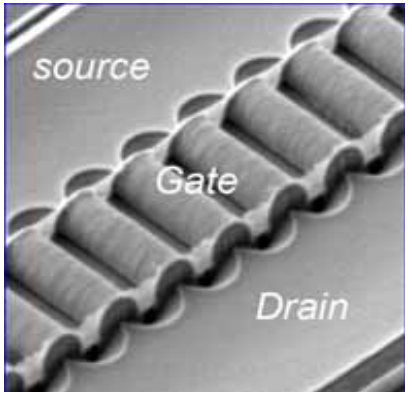


6nm pitch
By nano-imprint method



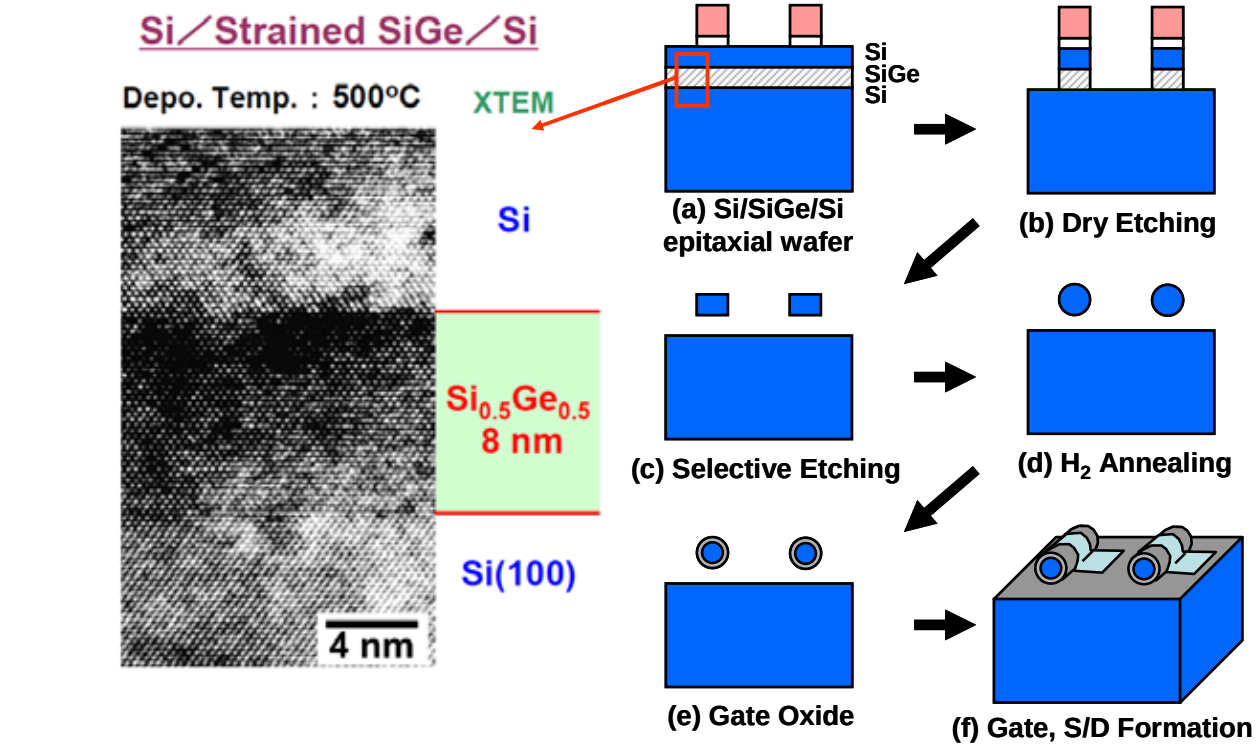


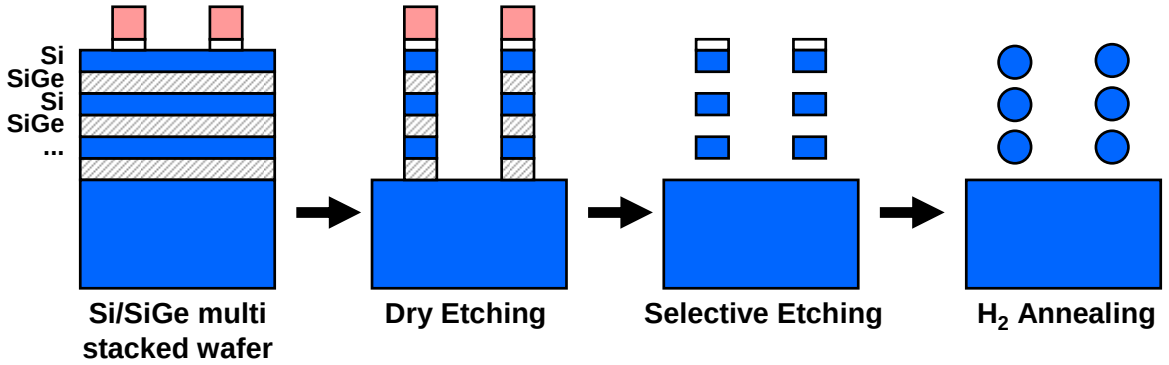
30nm pitch:
EUV lithograpy

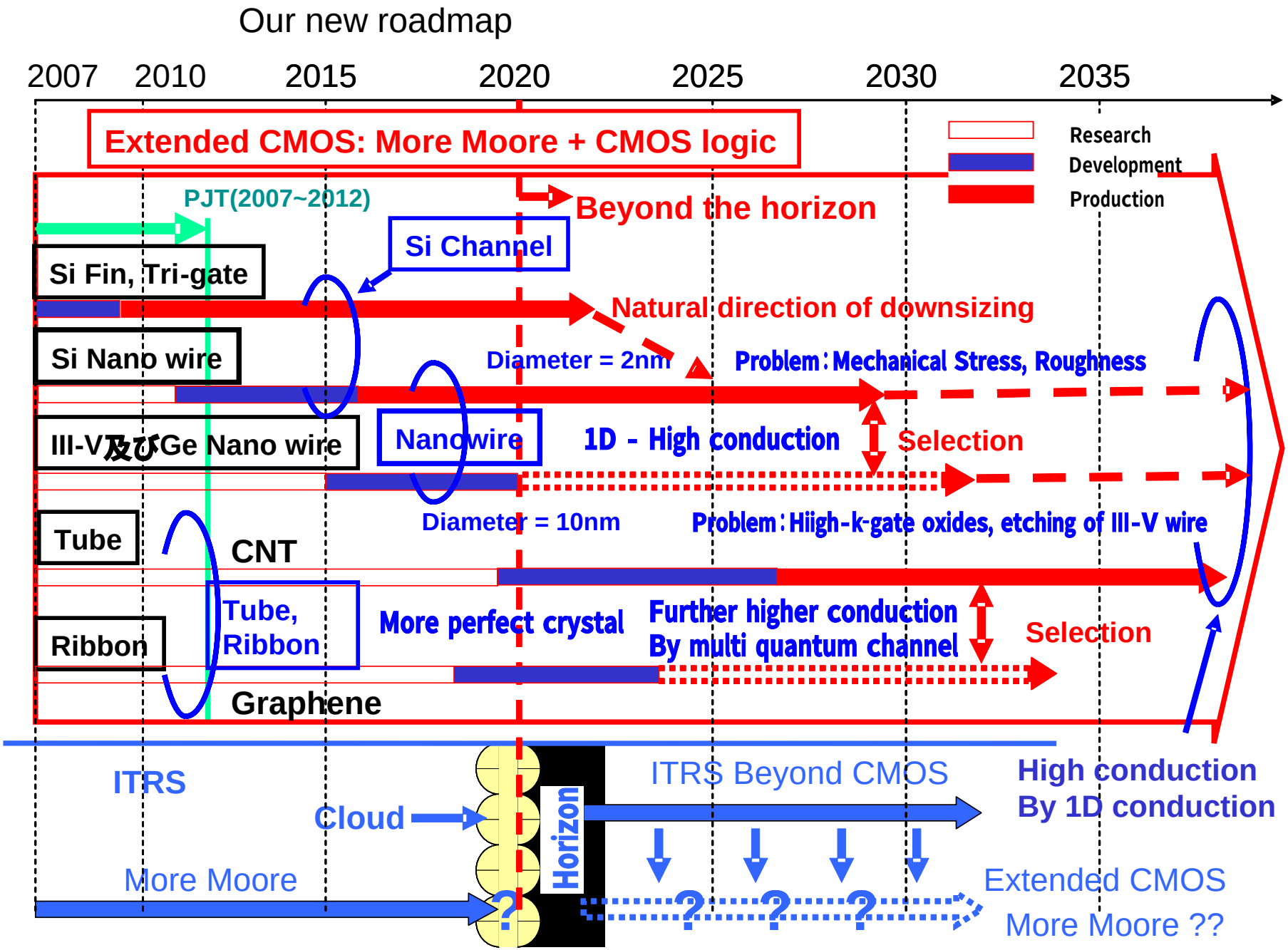


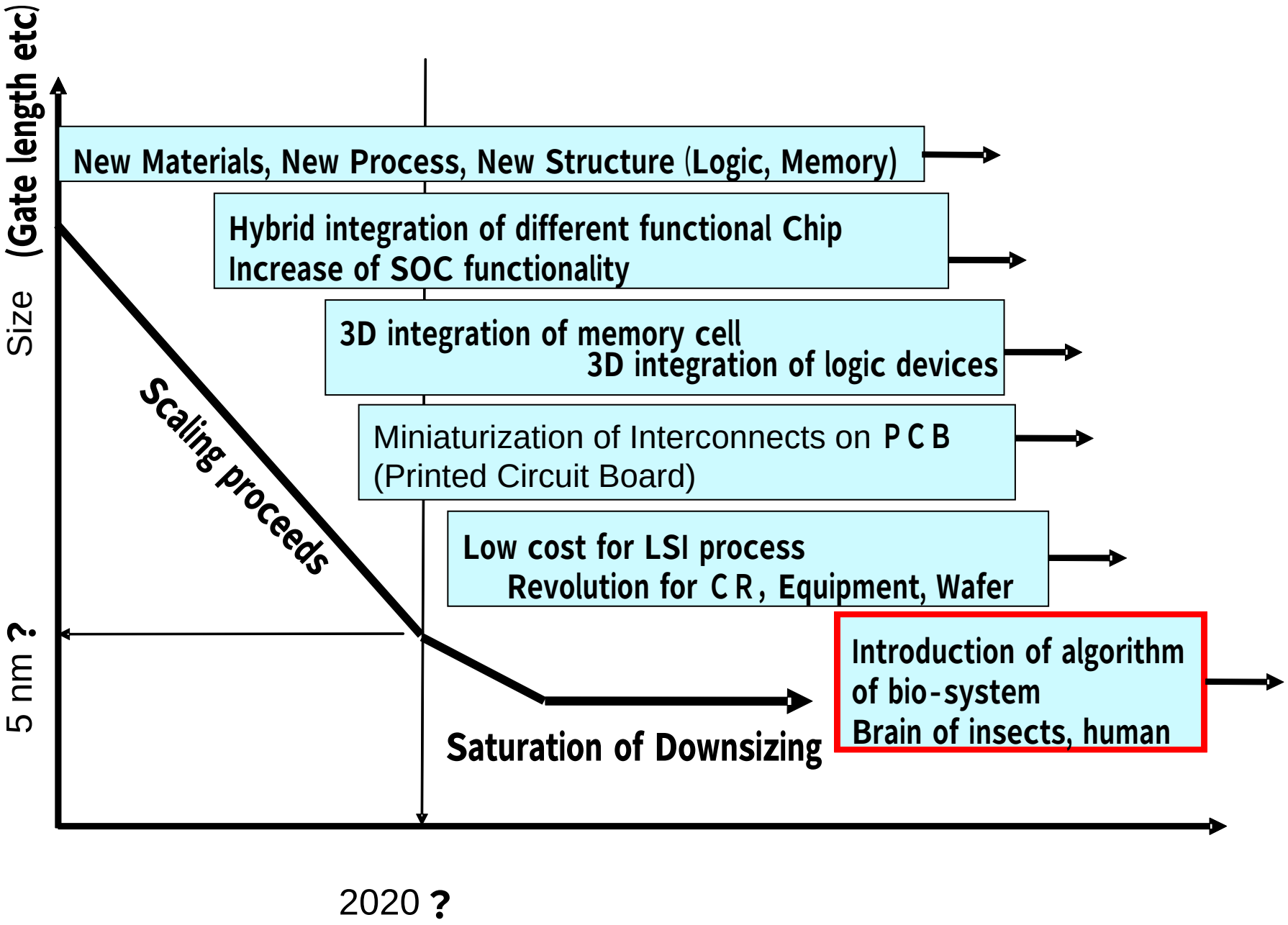
Surrounded gate MOS

Increase the number of wires towards vertical dimension






Our new roadmap
2007
2010
2015
2020
2025
2030
2035
Extended CMOS: More Moore + CMOS logic
Research
Development
Production
PJT(2007~2012)
Beyond the horizon
Si Channel
Si Fin, Tri-gate
Natural direction of downsizing
Si Nano wire
Diameter = 2nm
Problem：Mechanical Stress, Roughness
III-V及びGe Nano wire
Nanowire
1D - High conduction
Selection
Diameter = 10nm
Problem：Hiigh-k-gate oxides, etching of III-V wire
Tube
CNT
Tube,
Ribbon
Ribbon
More perfect crystal
Further higher conduction
By multi quantum channel
Selection
Graphene
ITRS
Cloud
More Moore
Horizon
ITRS Beyond CMOS
High conduction
By 1D conduction
Extended CMOS
More Moore ??


Size (Gate length etc)
New Materials, New Process, New Structure (Logic, Memory)
Hybrid integration of different functional Chip
Increase of SOC functionality
3D integration of memory cell
3D integration of logic devices
Miniaturization of Interconnects on P C B
(Printed Circuit Board)
Low cost for LSI process
Revolution for C R, Equipment, Wafer
Introduction of algorithm
of bio-system
Brain of insects, human
Scaling proceeds
Saturation of Downsizing
5 nm ?
2020 ?

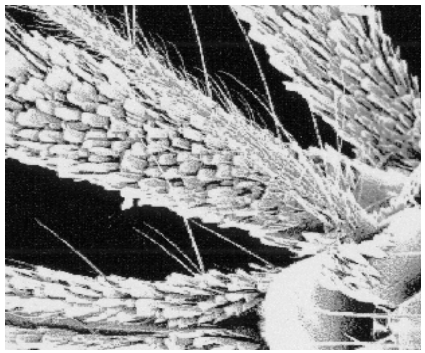
Brain

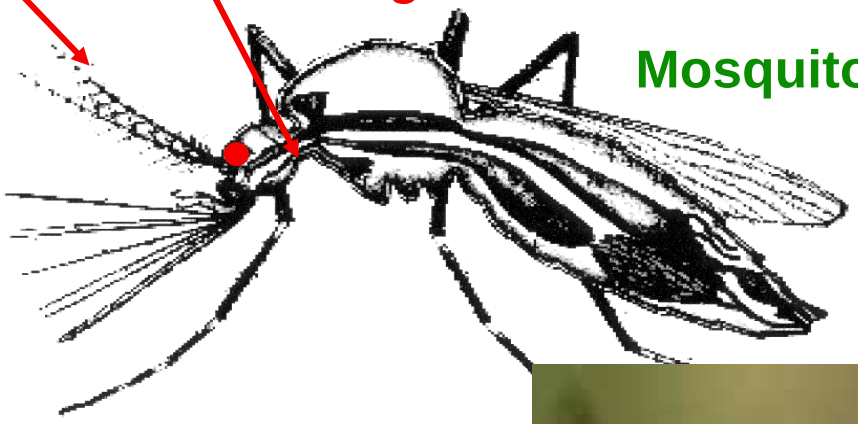
Sensor

Ultra small volume
Small number of neuron cells
Extremely low power

Infrared
Humidity
CO_2

Real time image processing
(Artificial) Intelligence
3D flight control





Mosquito

System and Algorism becomes more important !

But do not know how?

Dragonfly is further high performance

Thank you
for your attention!