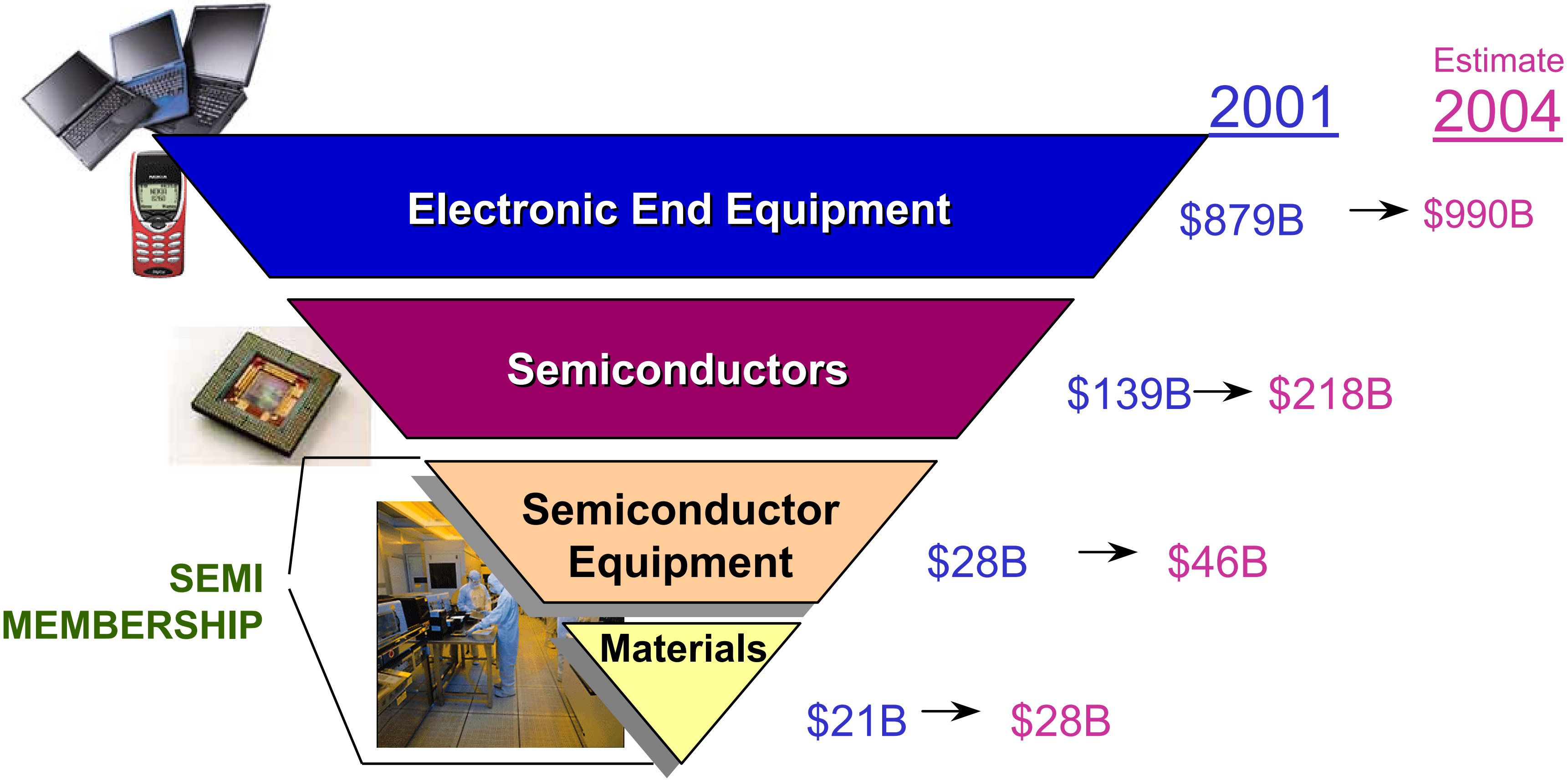
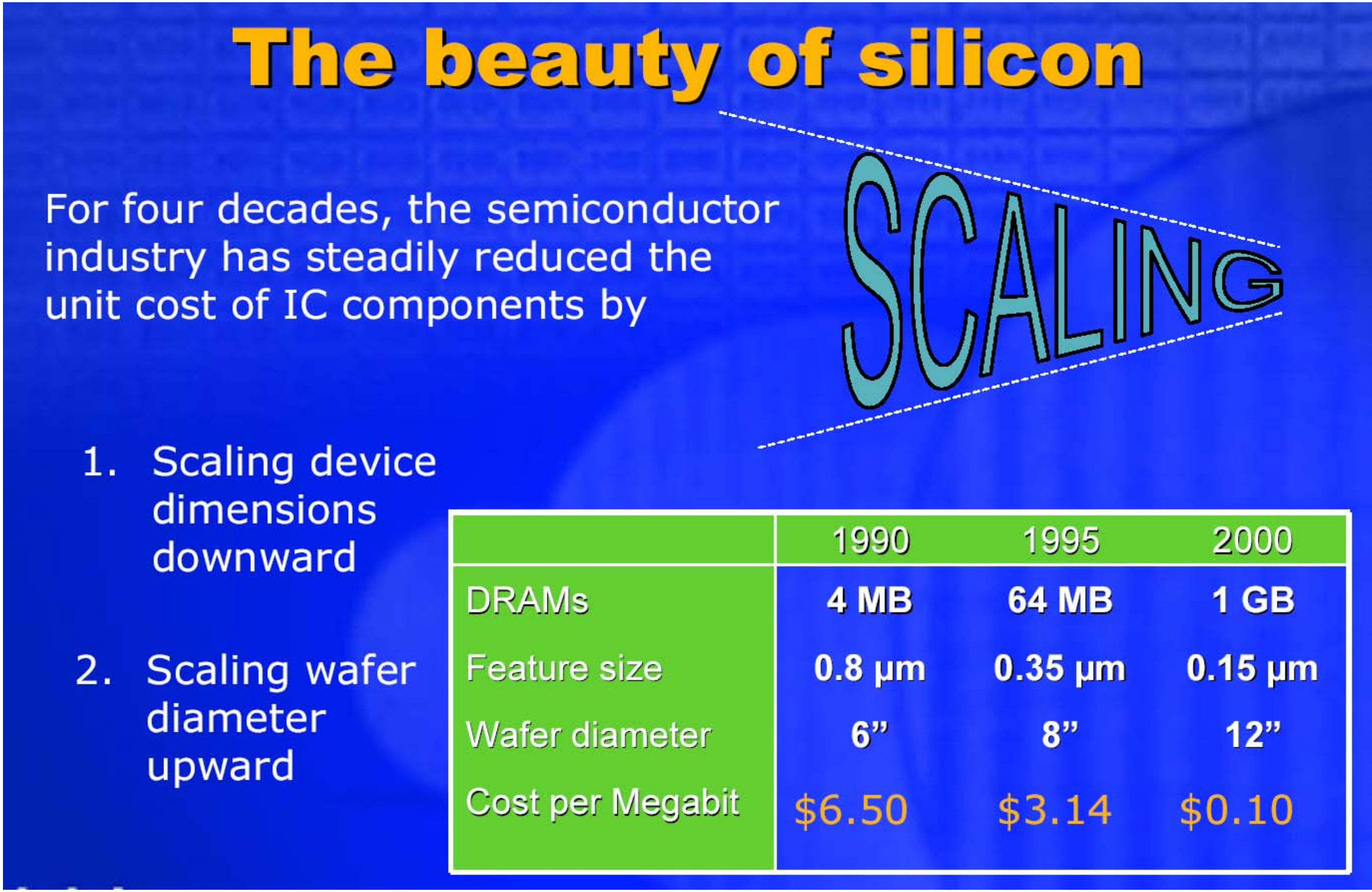
Trends of IC Microfabrication



	2001	Estimate 2004
Electronic End Equipment	$879B	$990B
Semiconductors	$139B	$218B
Semiconductor Equipment	$28B	$46B
Materials	$21B	$28B

SEMI MEMBERSHIP

Source: SEMI, SIA, IC Insights; Rev. January 14, 2002



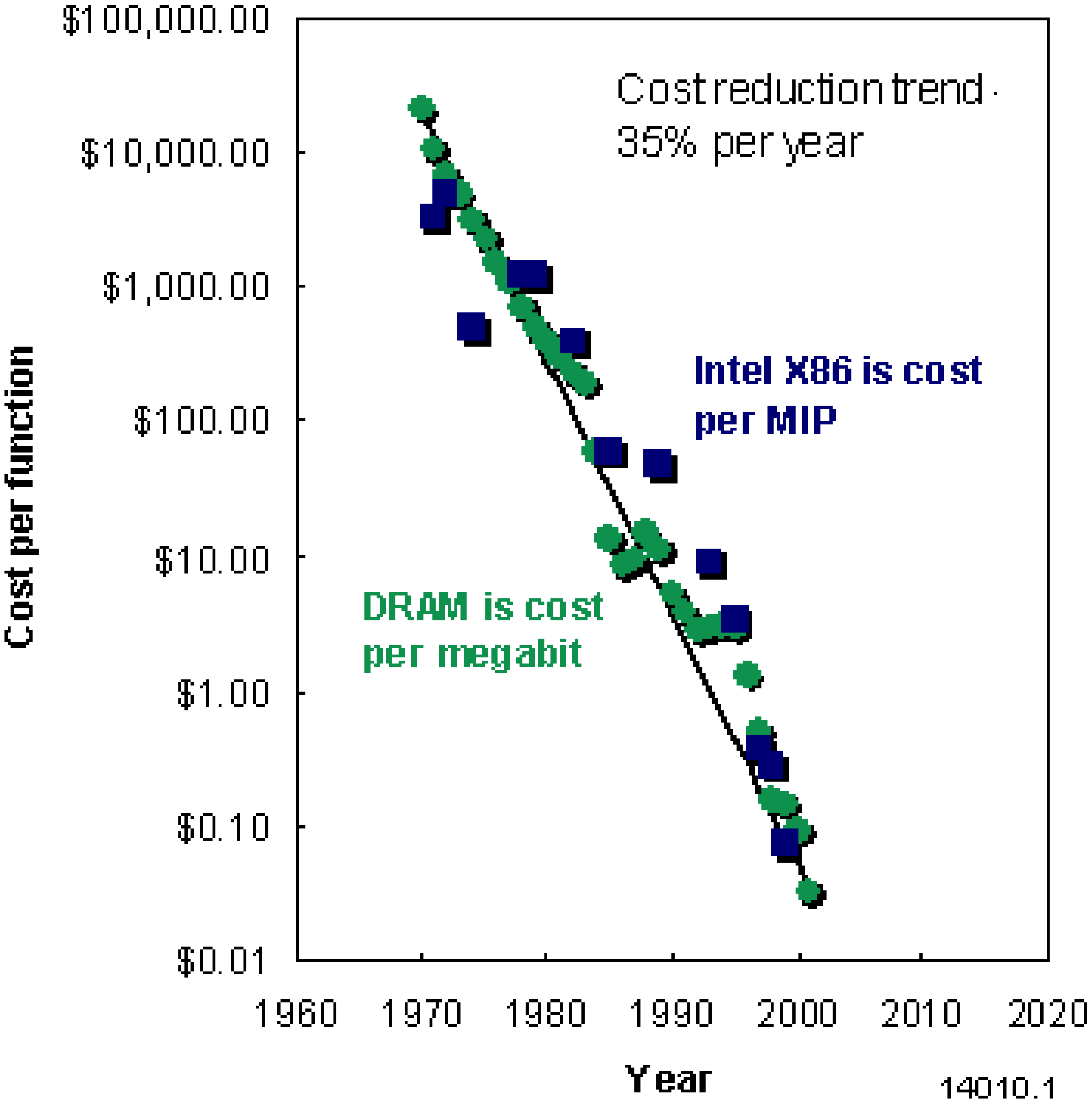
The beauty of silicon

For four decades, the semiconductor industry has steadily reduced the unit cost of IC components by

SCALING

1. Scaling device dimensions downward
2. Scaling wafer diameter upward

	1990	1995	2000
DRAMs	**4 MB**	**64 MB**	**1 GB**
Feature size	**0.8 µm**	**0.35 µm**	**0.15 µm**
Wafer diameter	**6”**	**8”**	**12”**
Cost per Megabit	$6.50	$3.14	$0.10


$100,000.00
$10,000.00
$1,000.00
$100.00
$10.00
$1.00
$0.10
$0.01
Cost per function
1960
1970
1980
1990
2000
2010
2020
Year
Cost reduction trend -
35% per year
Intel X86 is cost
per MIP
DRAM is cost
per megabit
14010.1

Transistor Per Integrated Circuit Trends

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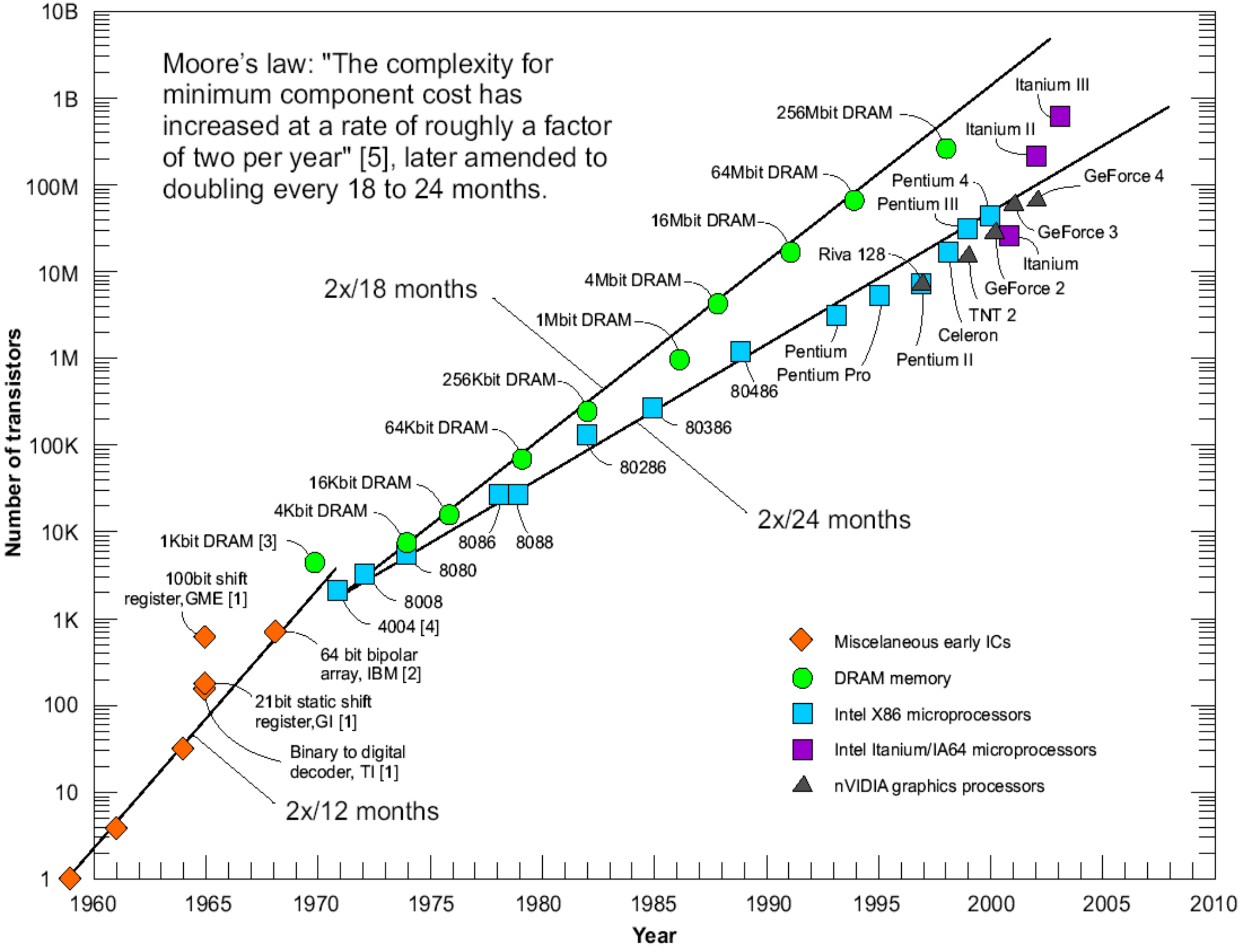
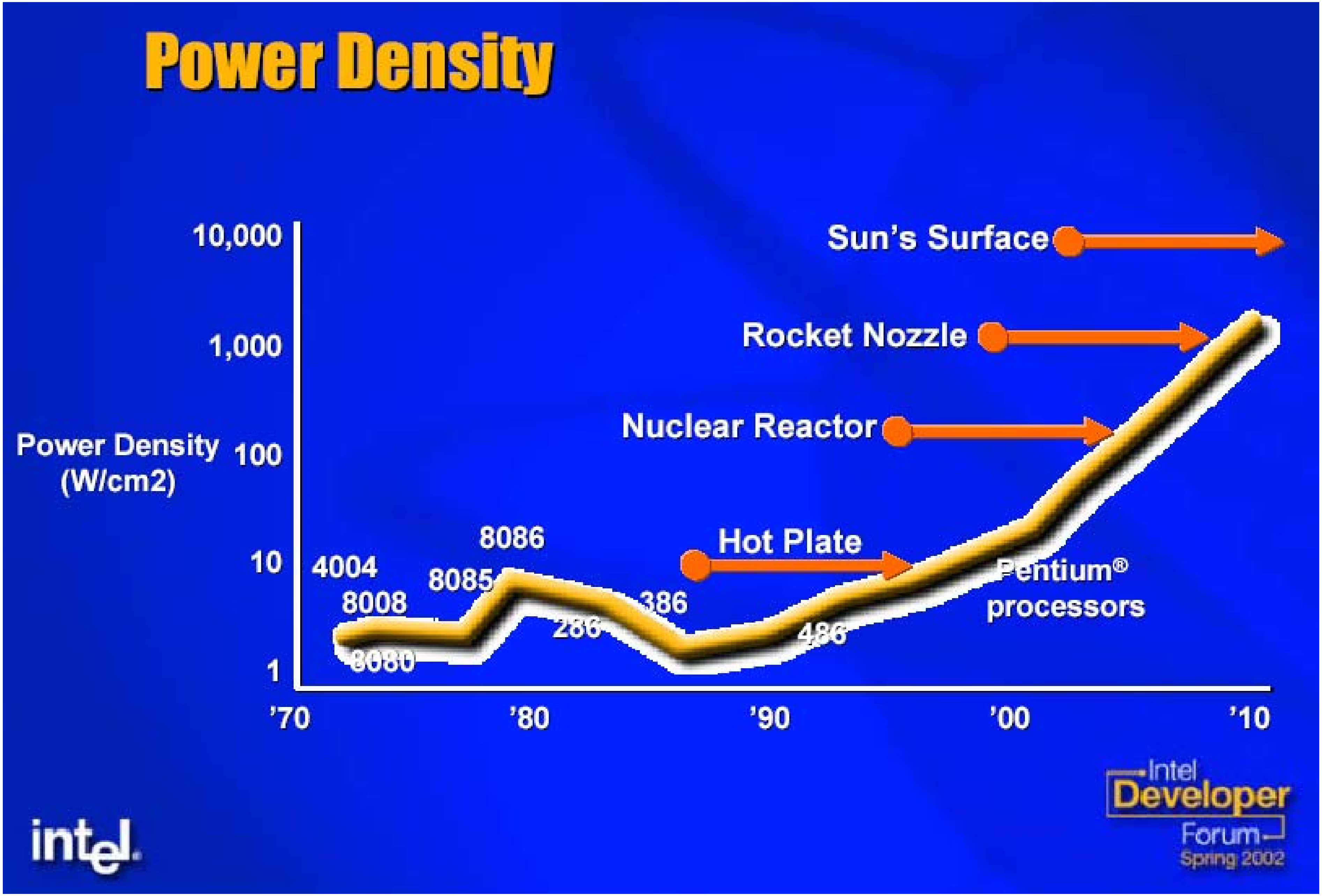


[1] Stanley Mazor, "The History of the Microcomputer - Invention and Evolution" http://www.dotpoint.com/xnumber/Microcomputer_invention.htm.
[2] Bob Donlan and David Pricer, "Pushing the Limits: Looking Forward...Looking Back," Microelectronic Design, Vol. 1., (1987).
[3] "Inventions of the Modern Computer: Intel 1103 The World's First Available DRAM Chip," http://inventors.about.com/science/inventors/library/weekly/aa100898.htm.
[4] Jonathan Cassell, "Who Really Invented the Microprocessor," http://www.ebnonline.com/25year/25_microprocessor2.html.
[5] Gordon E. Moore, "Cramming more components onto integrated circuits," Electronics, Vol. 38, N. 8, Apr. (1965).

IC KNOWLEDGE.COM

SIA roadmap
Memory and Logic Technology Requirements

Year of First Product Shipment Technology Generation	1999 180 nm	2001 150 nm	2003 130 nm	2006 100 nm	2009 70 nm	2012 50 nm
Min. Logic V_{dd} (V)	1.8-1.5	1.5-1.2	1.5-1.2	1.2-0.9	0.9-0.6	0.6-0.5
T_{ox} Equivalent (nm)	3-4	2-3	2-3	1.5-2	<1.5	<1.0
Equivalent Maximum E-field (MV/cm)	5	5	5	>5	>5	>5
Nominal I_{on} @ 25°C (mA/mm) (NMOS/PMOS)	600/280	600/280	600/280	600/280	600/280	600/280
S/D Extension Junction Depth, Nominal (nm)	36-72	30-60	26-52	20-40	15-30	10-20

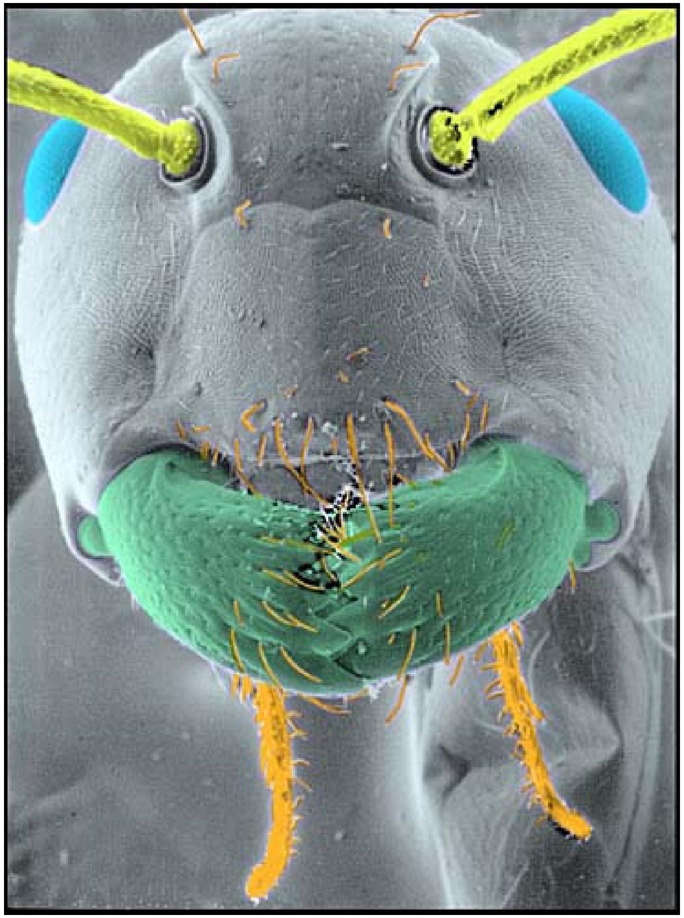


Power Density

intel

Intel Developer Forum Spring 2002

Another Perspective on Moore's Law

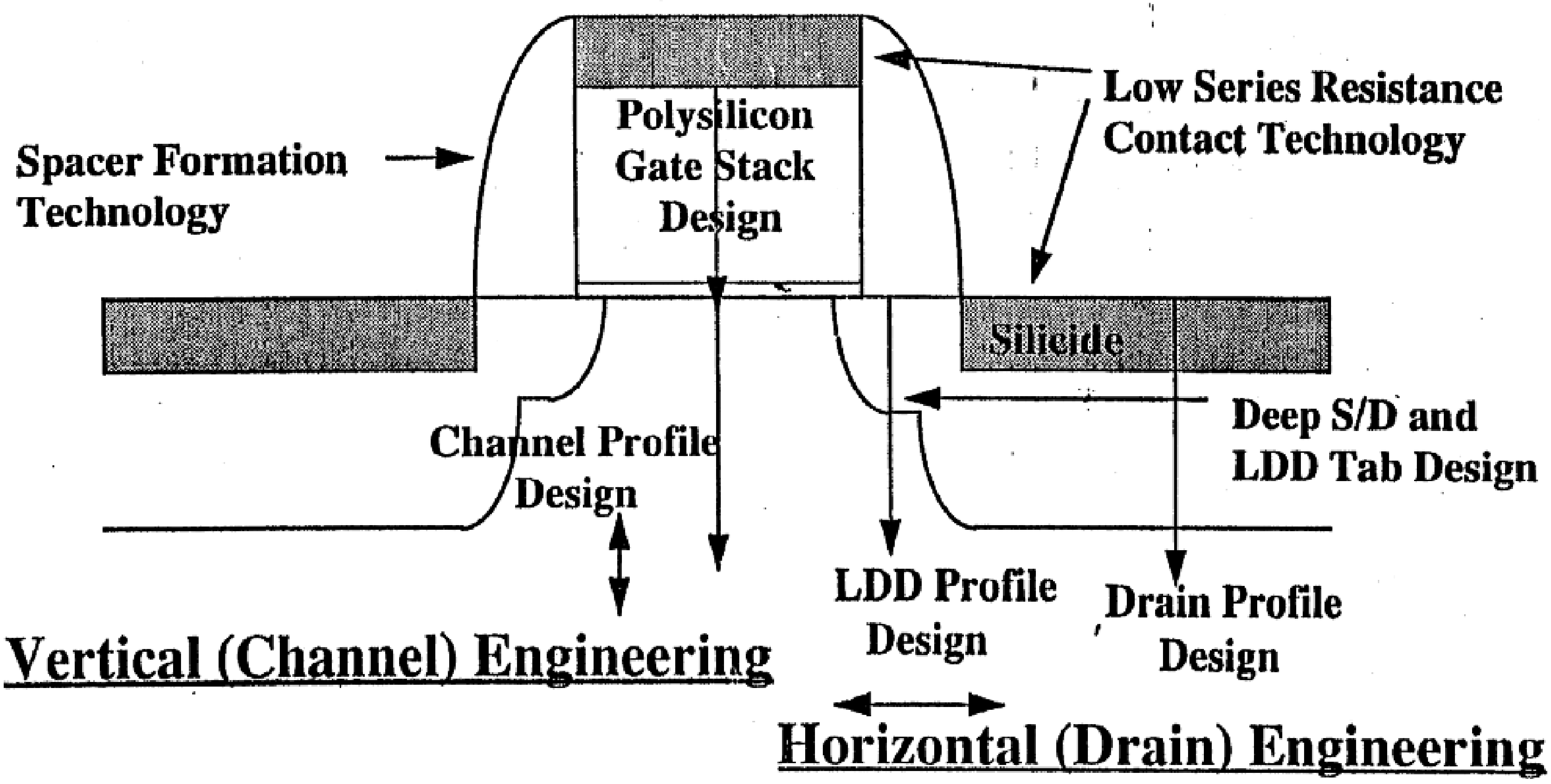


… we are already producing 10^{18} transistors per year. Enough to supply every ant on the planet with ten transistors.

Twenty years from now, if the trend continues, there will be more transistors than there will be cells in the total number of human bodies on Earth.

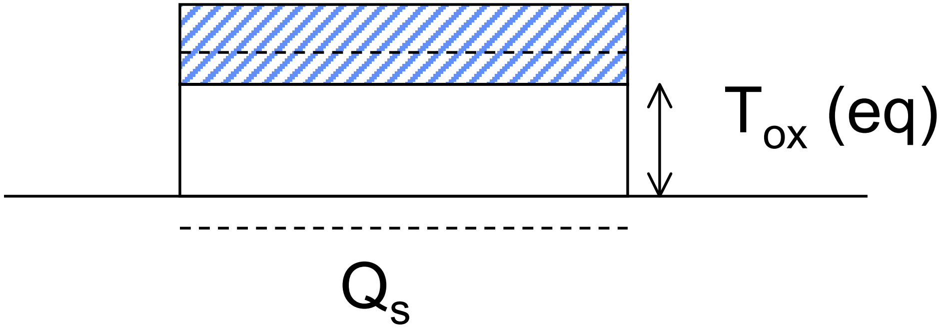
Channel Engineering

SUBMICRON DEVICE STRUCTURE AND DESIGN



Gate Stack Technology

Equivalent Oxide Thickness

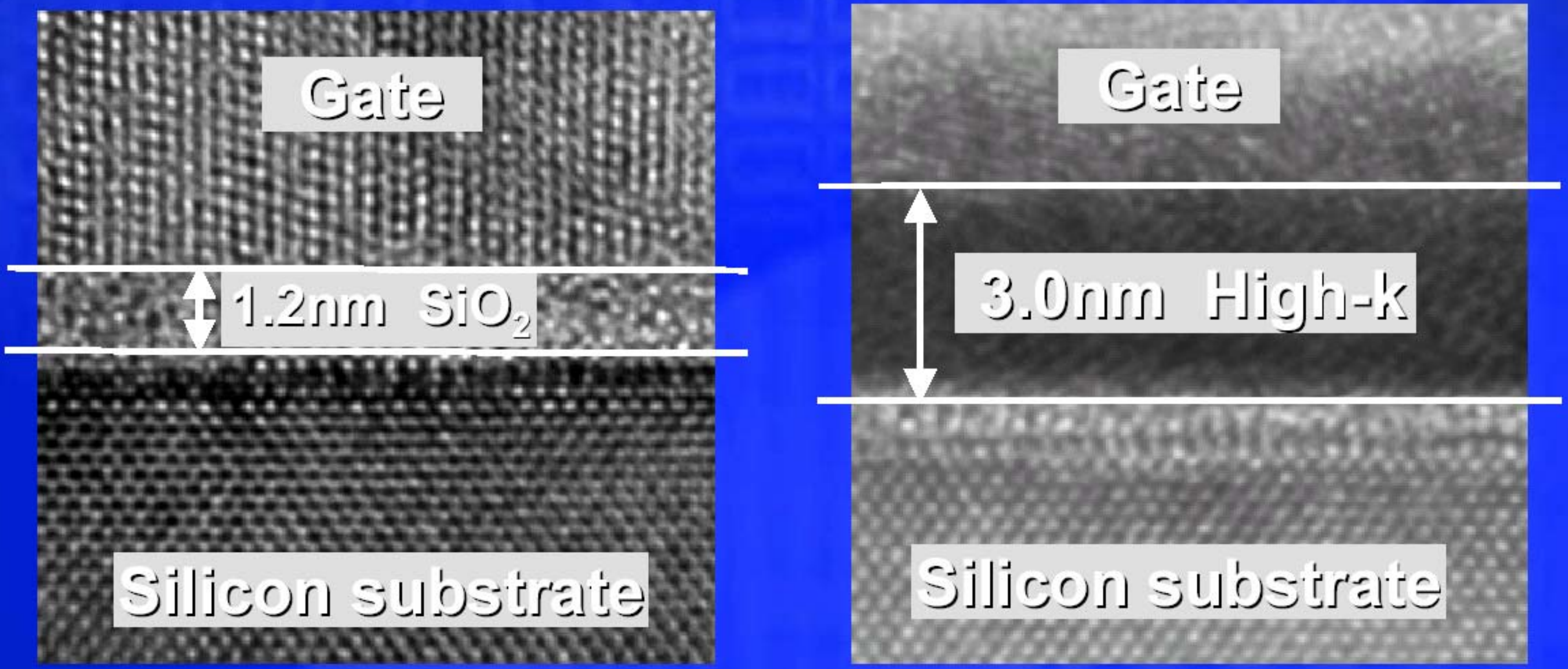


→ **high k-dielectric**
gives lower electrical thickness.

$$C_{ox} \propto \frac{\varepsilon}{X_{ox}}$$

Materials:
Ta2O5
BZT
Al2O3

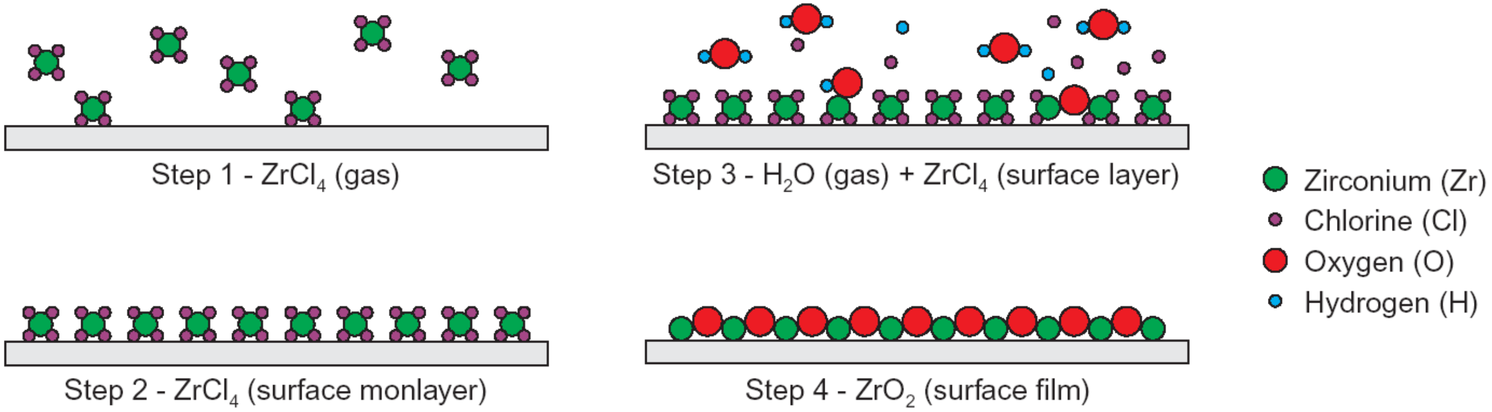
Nanotechnology for Gate Dielectrics



Source: Intel

	90nm process	Experimental high-k
Capacitance	1X	1.6X
Leakage	1X	< 0.01X

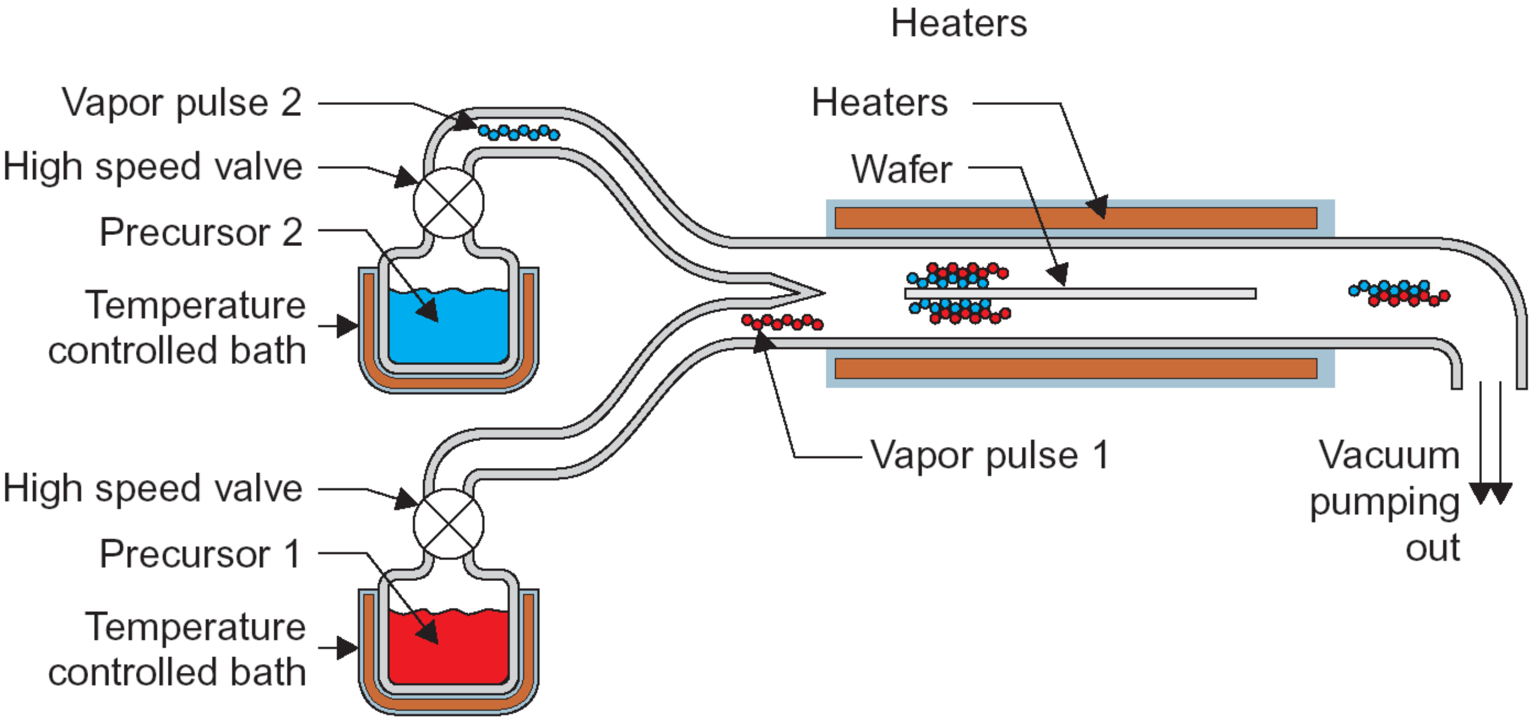
Atomic Layer Deposition (ALD)


Step 1 - $ZrCl_4$ (gas)

Step 3 - H_2O (gas) + $ZrCl_4$ (surface layer)

Step 2 - $ZrCl_4$ (surface monlayer)

Step 4 - ZrO_2 (surface film)



Step Coverage (Al2O3)

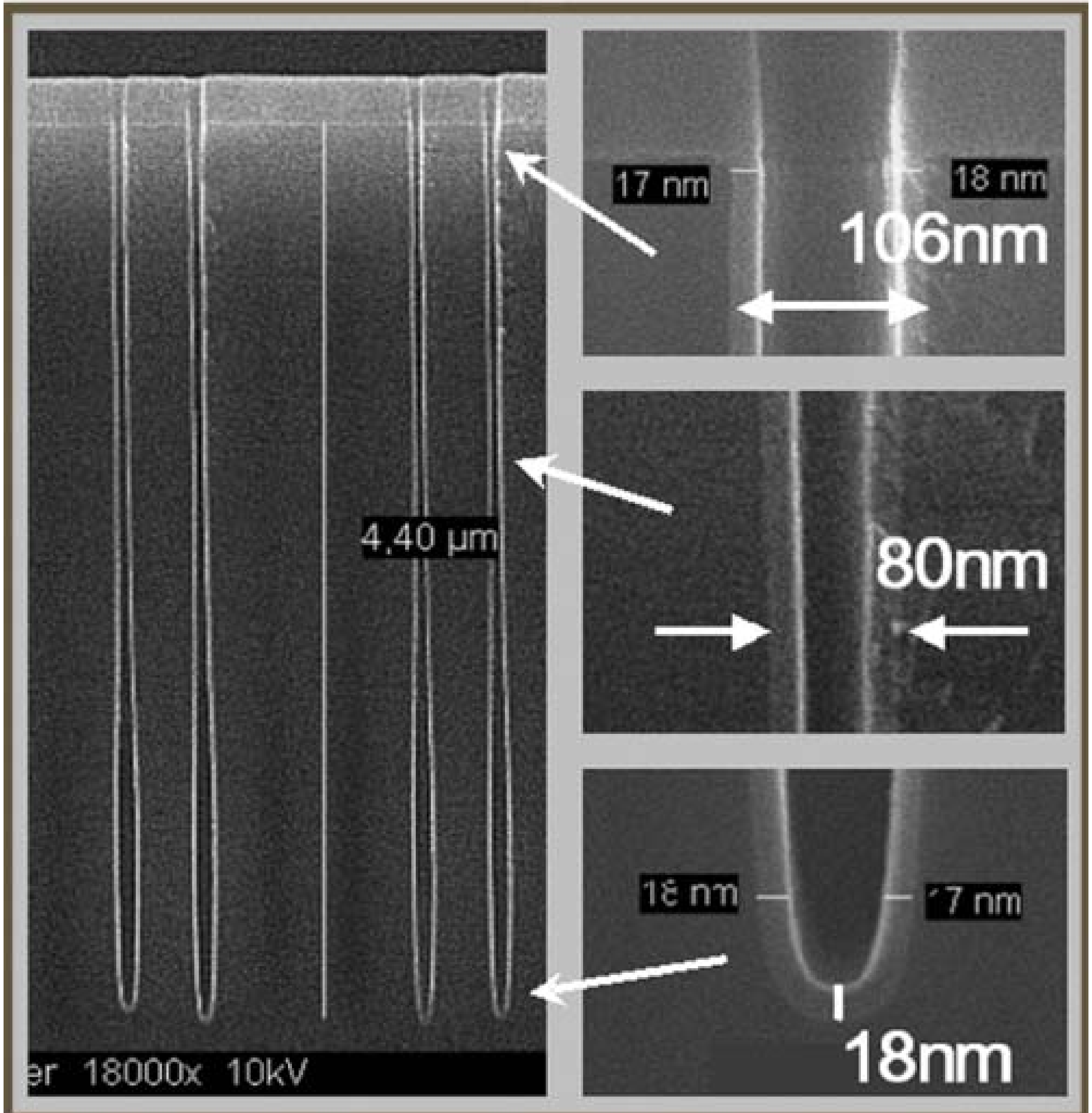


Figure 3. ALD features superb step coverage performance. The SEM images show close to 100% conformality for an 18nm thick Al_2O_3 film which was deposited by ALD into high aspect ratio trenches with a minimum lateral dimension of 80nm and a final aspect ratio of ~ 60.

Elevated Source/Drain

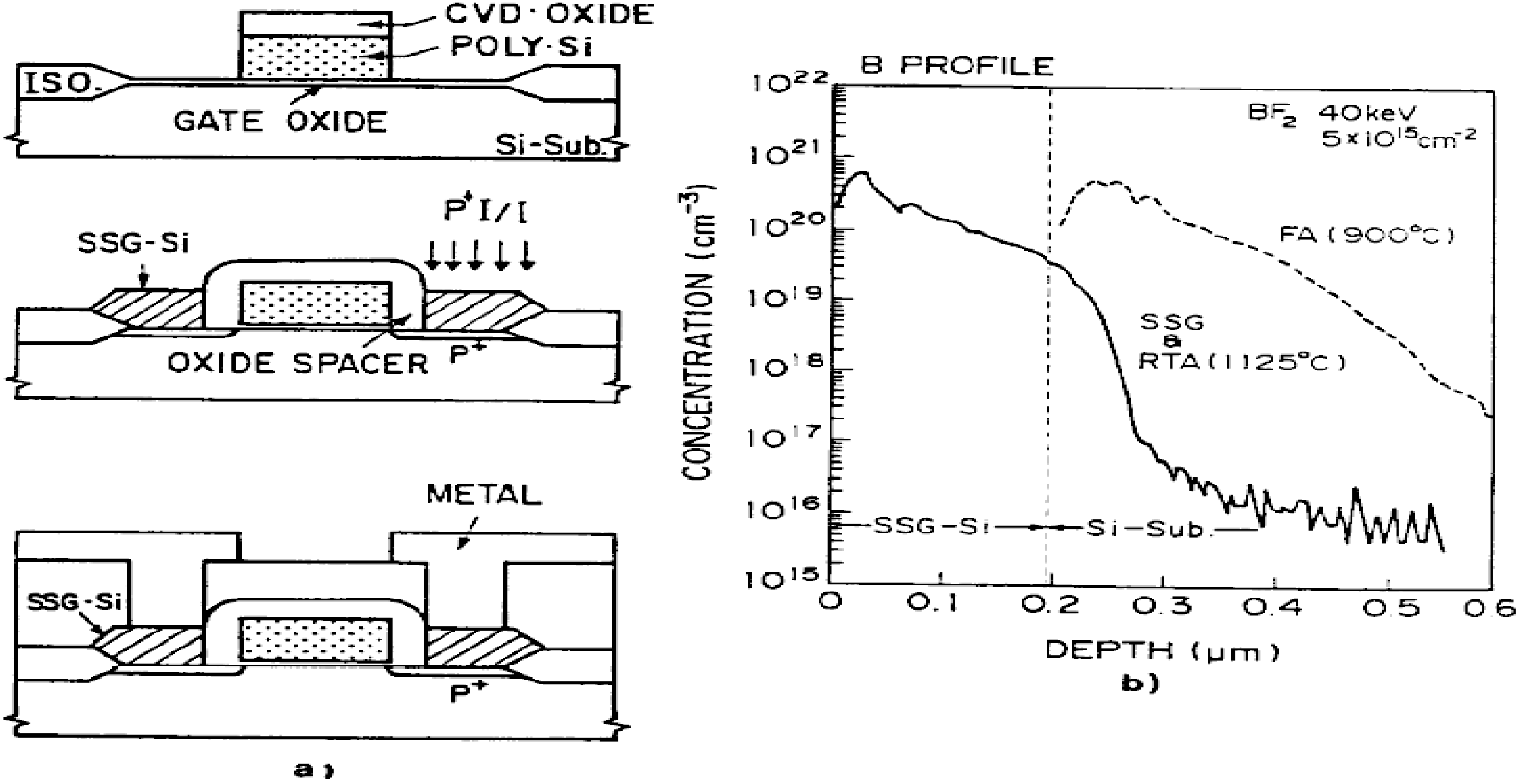
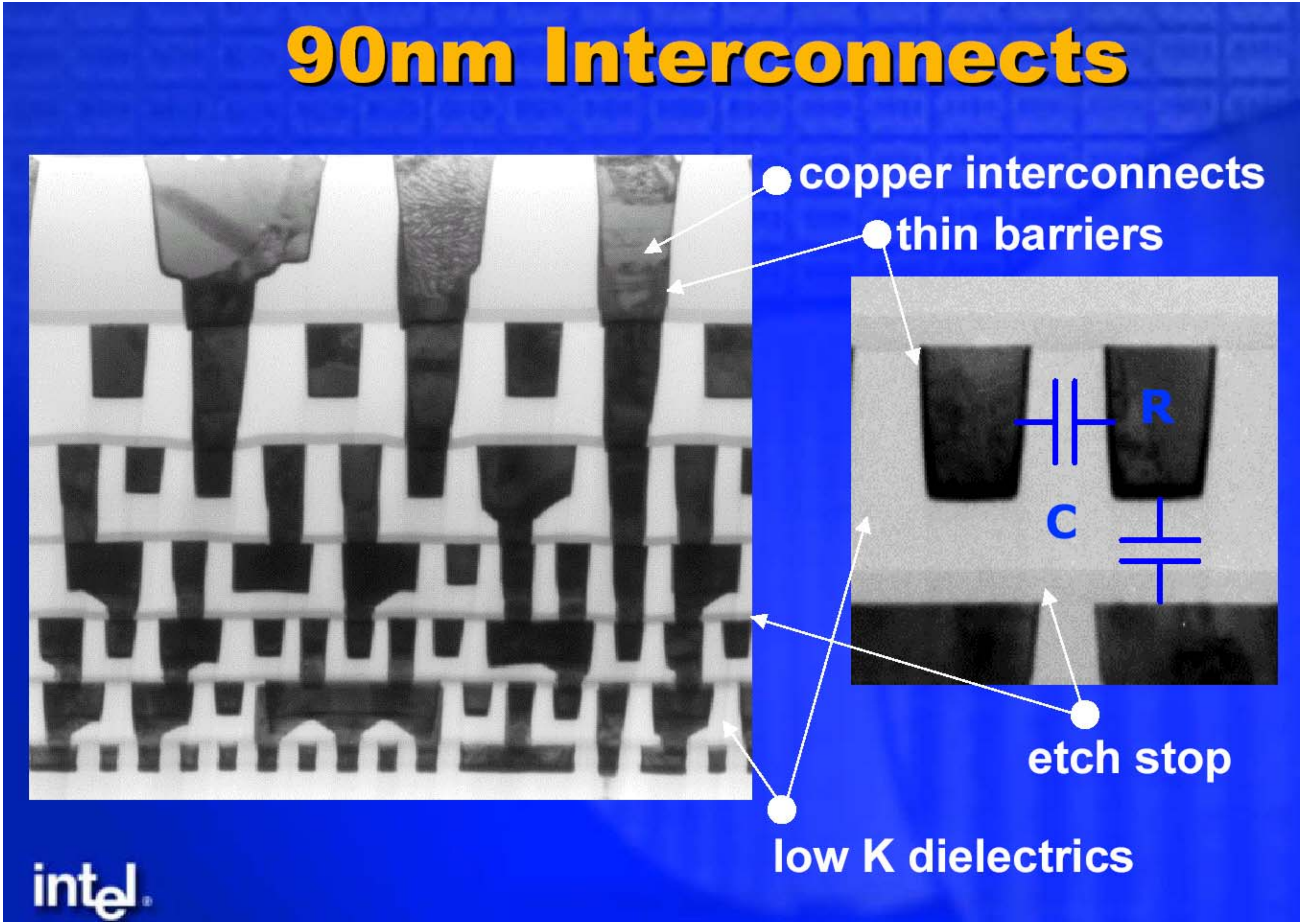
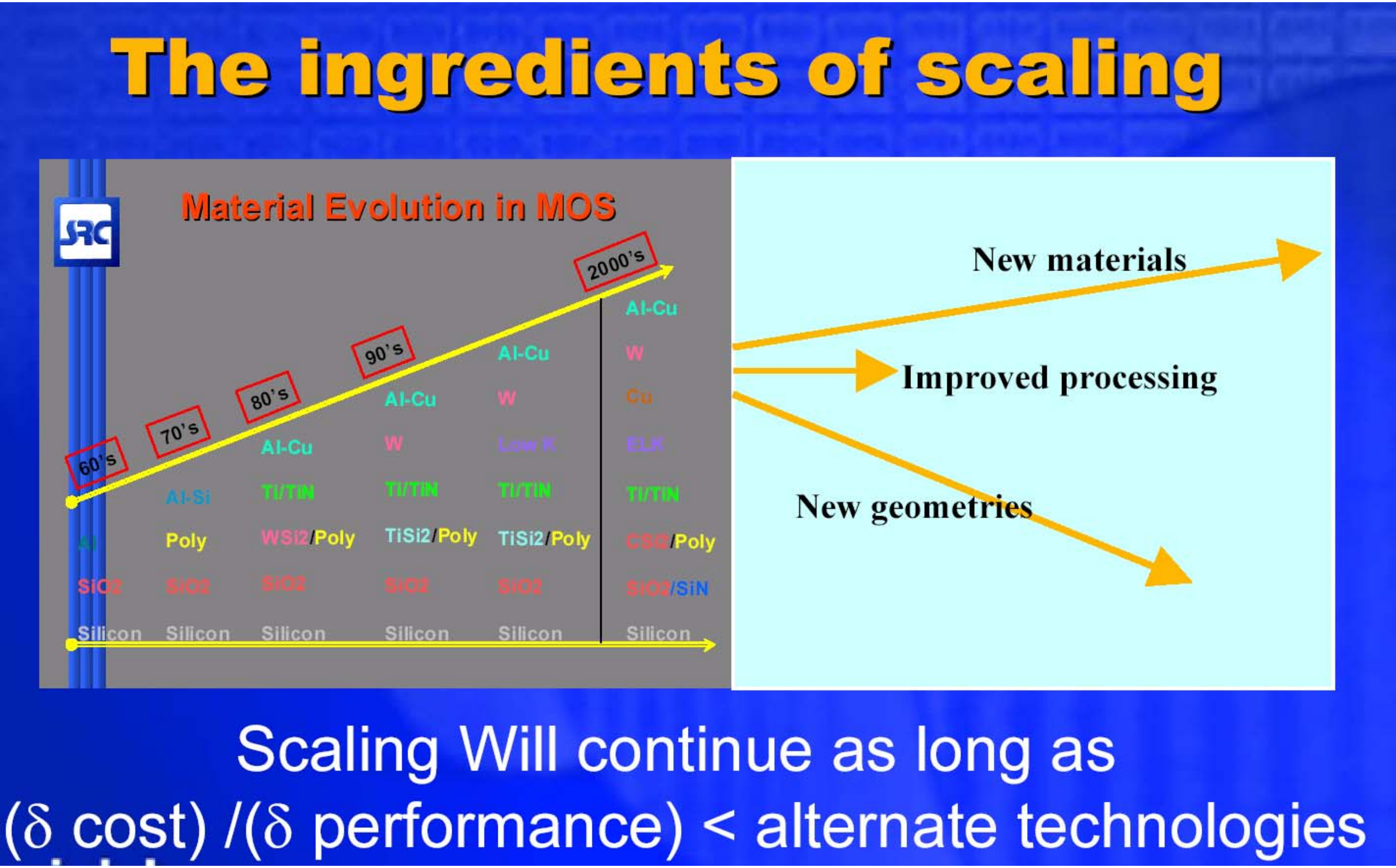


Fig. 6-41 Elevated source/drains. (a) Key process steps in forming elevated source/drains using SEG. (b) Comparison of the doping profile in source/drain regions of a PMOS device after a BF_2^+ implant directly into the regions (and a conventional furnace anneal) versus a BF_2^+ implant into the SEG regions and an RTP anneal.[79]



90nm Interconnects

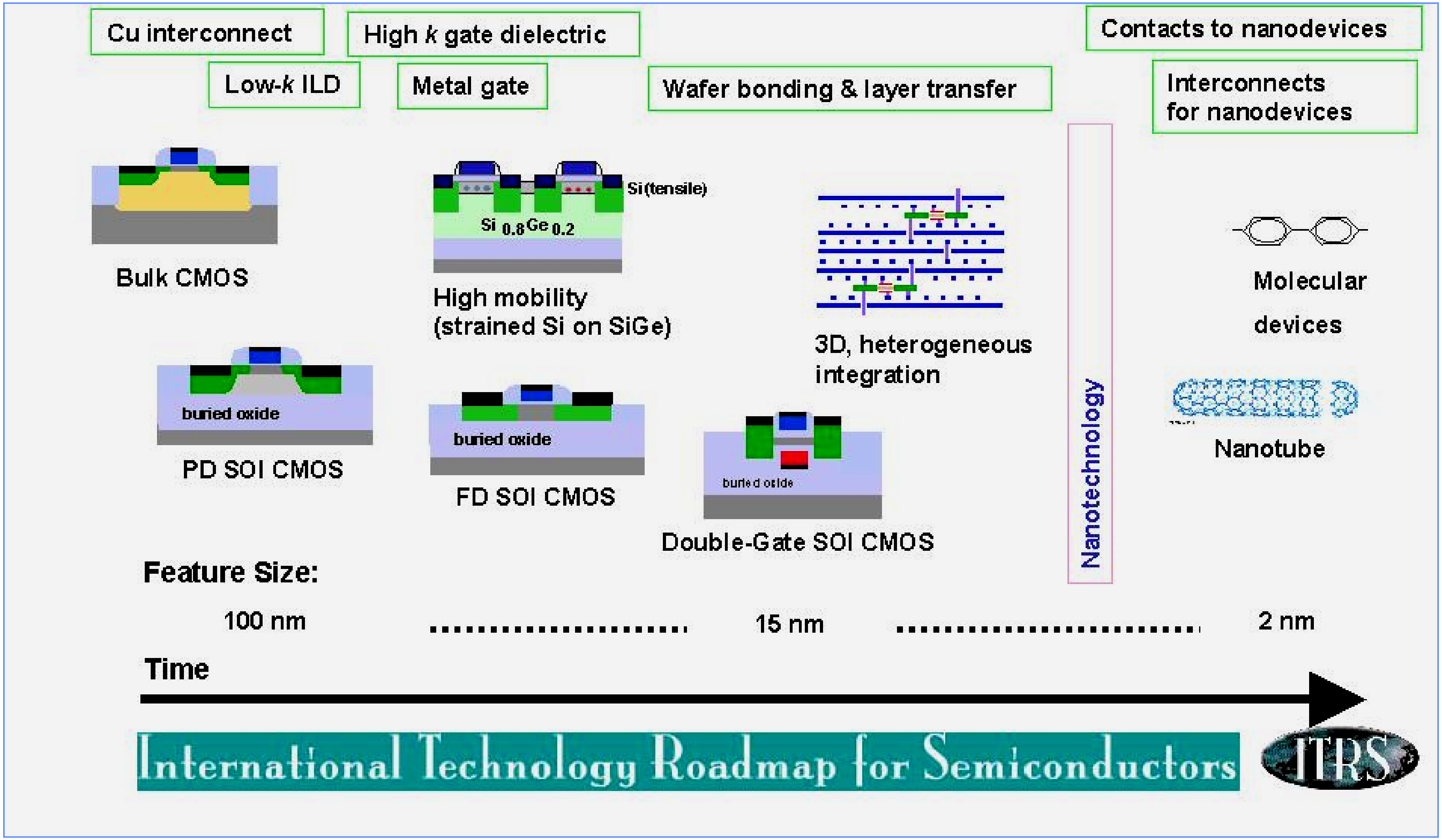
- copper interconnects
- thin barriers
- etch stop
- low K dielectrics



The ingredients of scaling

Scaling Will continue as long as

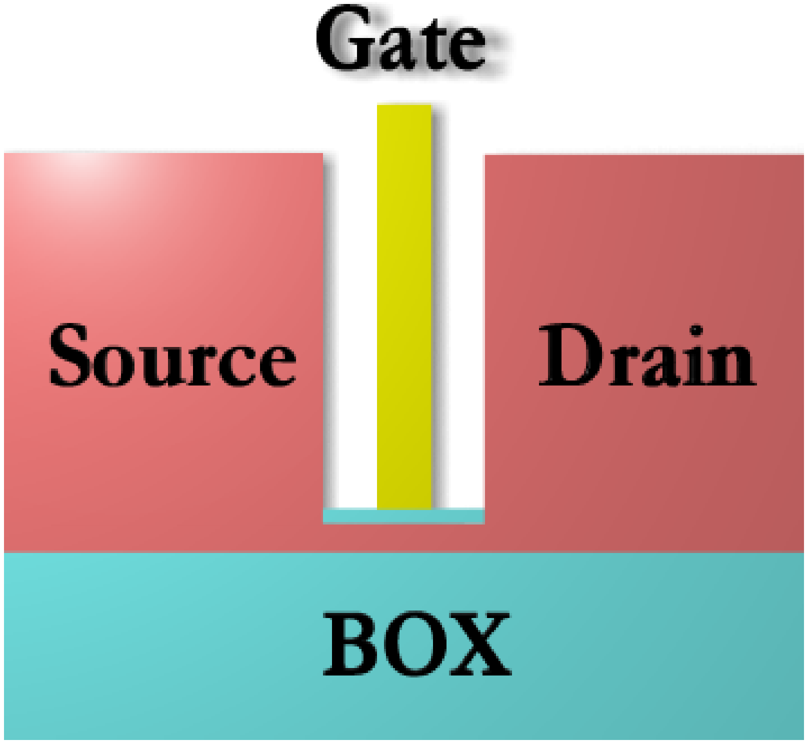
(δ cost) /(δ performance) < alternate technologies

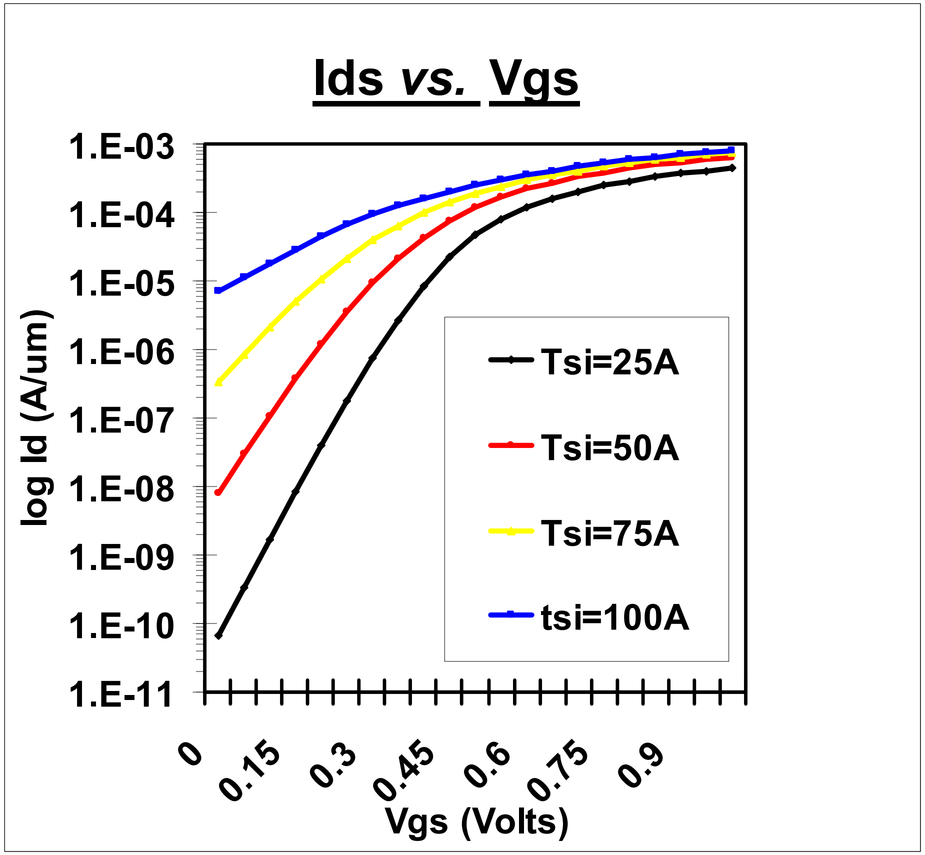

Cu interconnect
High *k* gate dielectric
Contacts to nanodevices
Low-*k* ILD
Metal gate
Wafer bonding & layer transfer
Interconnects for nanodevices
Si(tensile)
Si 0.8 Ge 0.2
Bulk CMOS
High mobility (strained Si on SiGe)
3D, heterogeneous integration
Molecular devices
Nanotechnology
buried oxide
PD SOI CMOS
buried oxide
FD SOI CMOS
Nanotube
buried oxide
Double-Gate SOI CMOS
Feature Size:
100 nm
15 nm
2 nm
Time
International Technology Roadmap for Semiconductors
ITRS

Thin-Body MOSFET

- T_{ox} = 2 nm
- L_{gate} = 25 nm
- V_{dd} = 1 V

- Thin body to control short-channel effects
- Elevated S/D to reduce R_{sd}





Dual Gate MOSFET

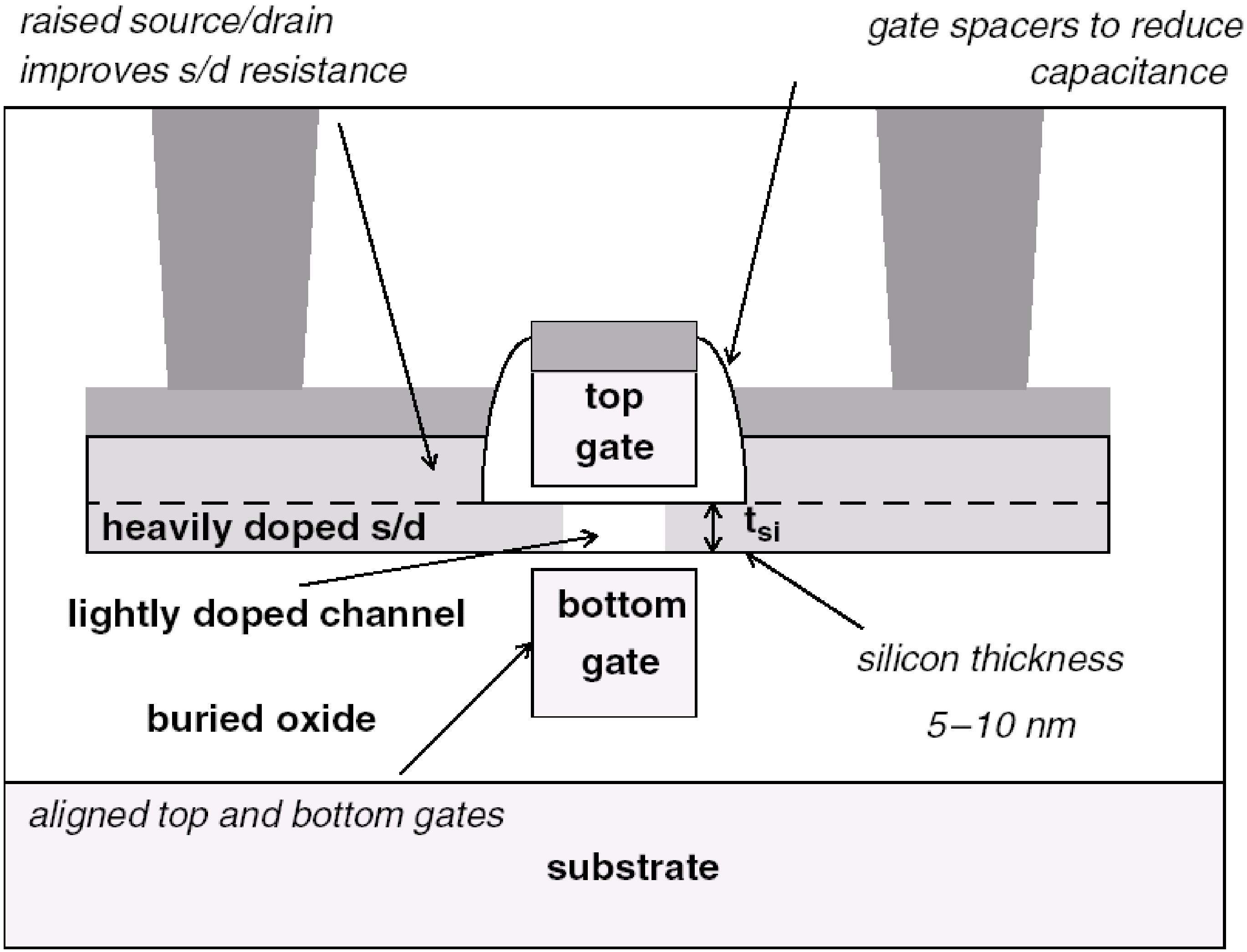
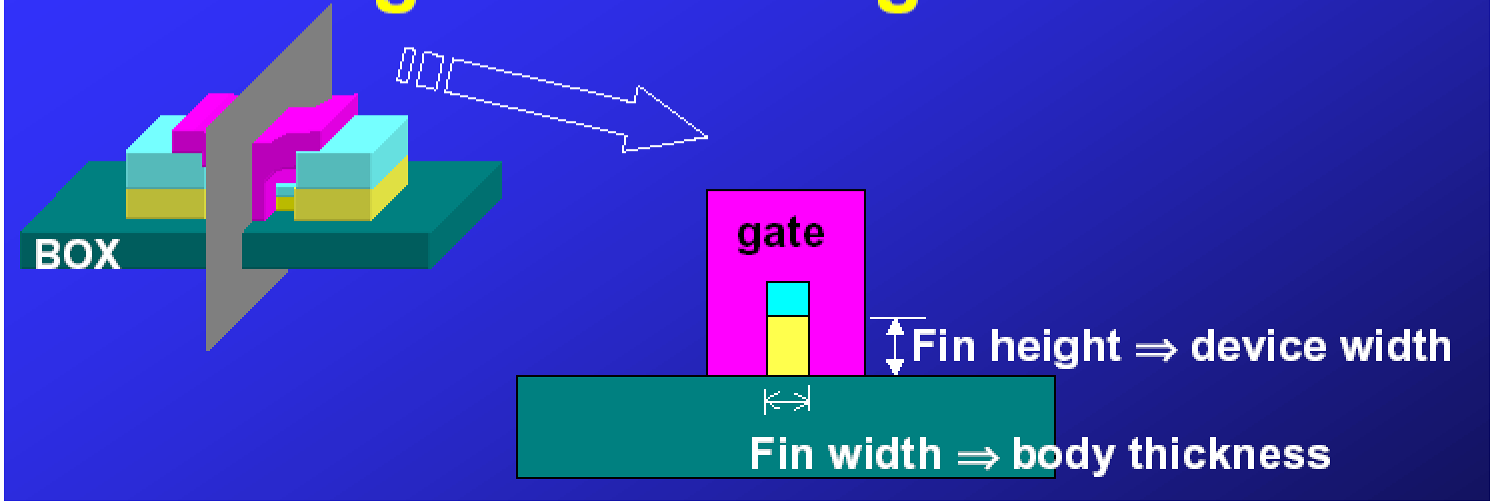


FIGURE 6.2 Generic features of double gate MOSFET device.

FinFET

* self-aligned double-gate structure *



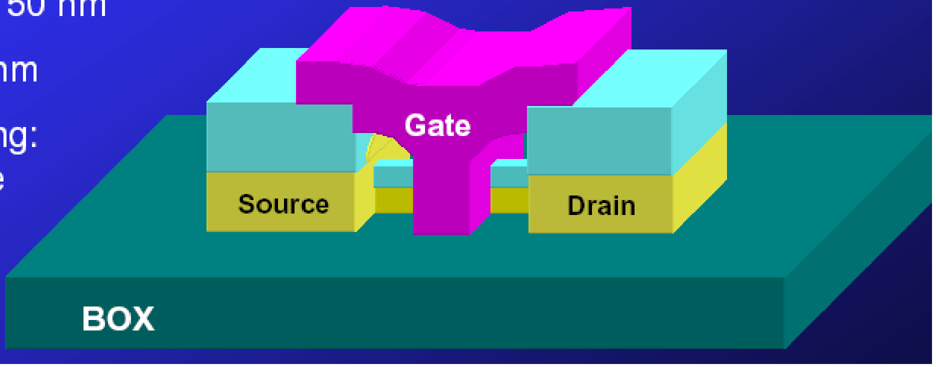
Lg ~ (10 nm – 45nm)

Fin width ~ (<10 nm – 120 nm)

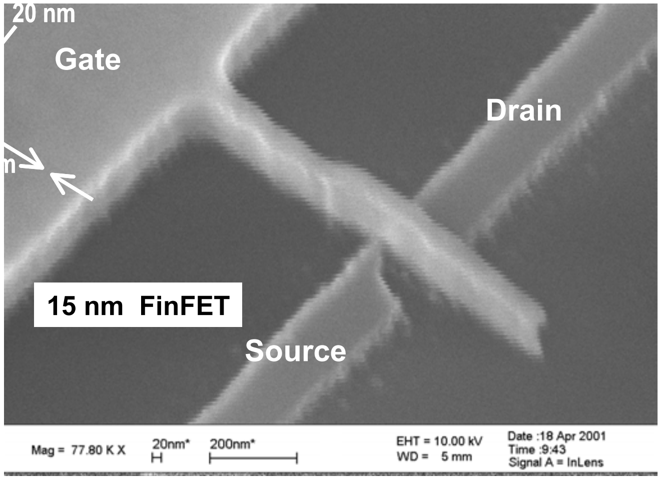
Fin height: 50 nm

Tox ~ 2.5 nm

Body doping:
10^{16} n-type

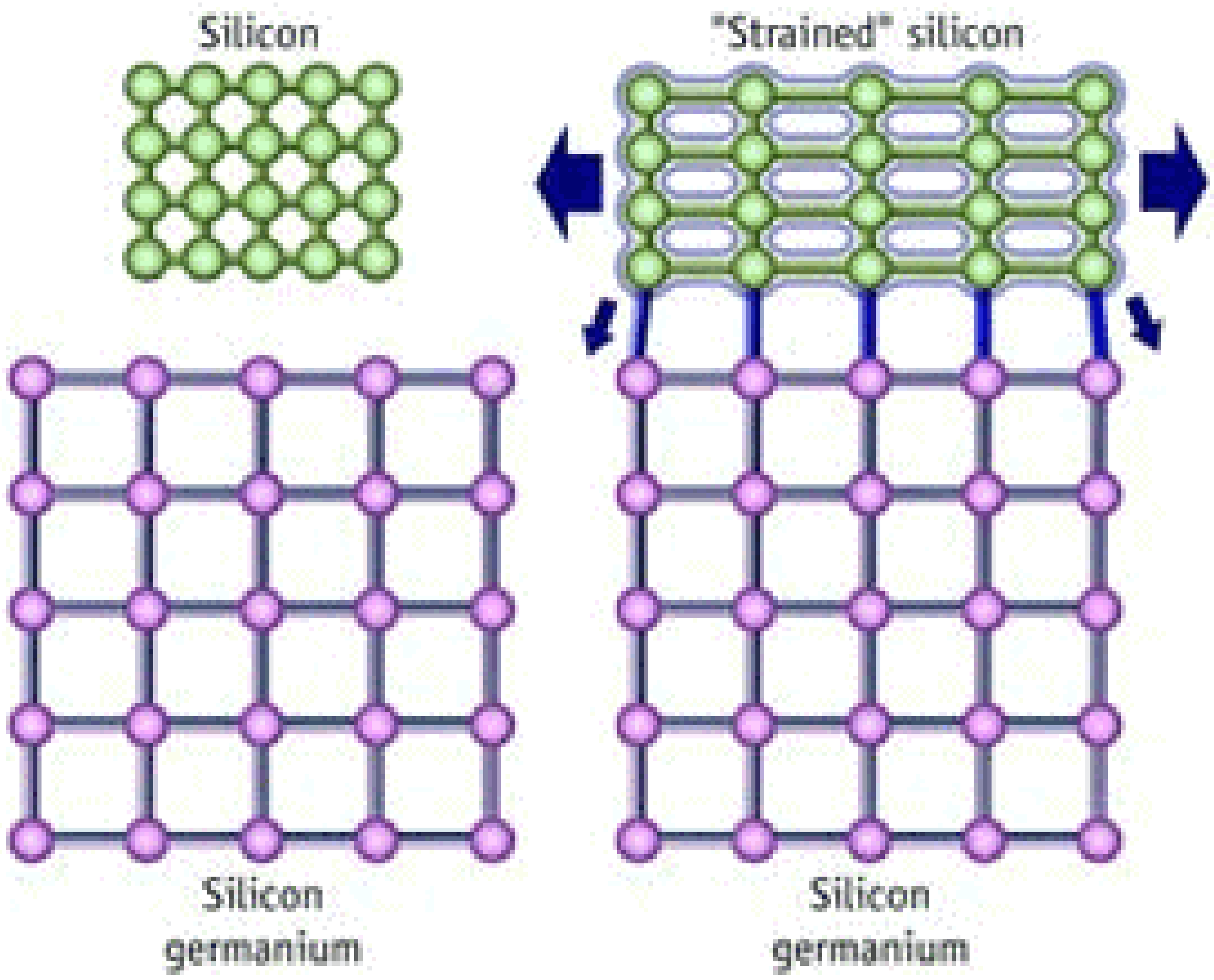


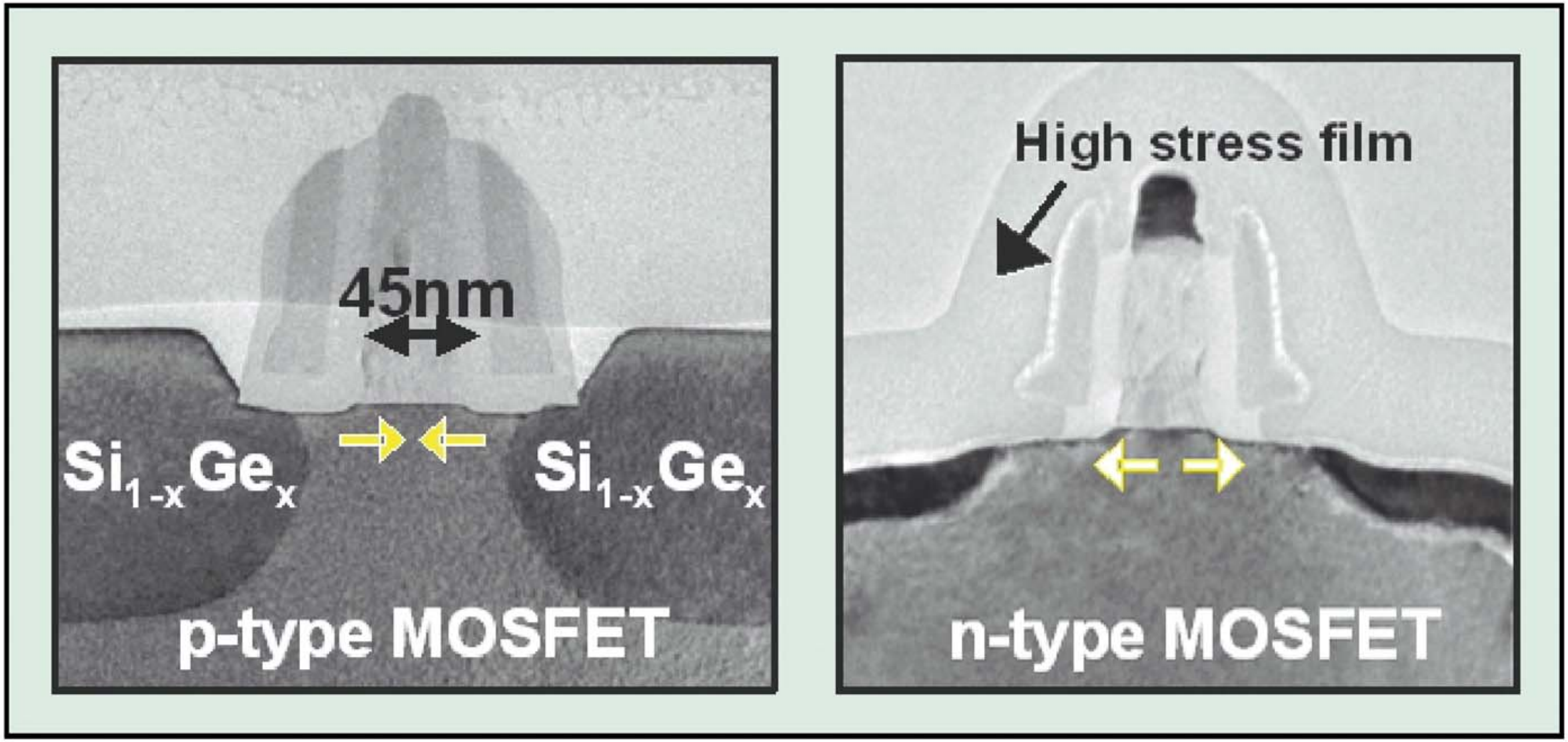
Scanning Electron Micrograph



Huang et al, IEDM, 1999

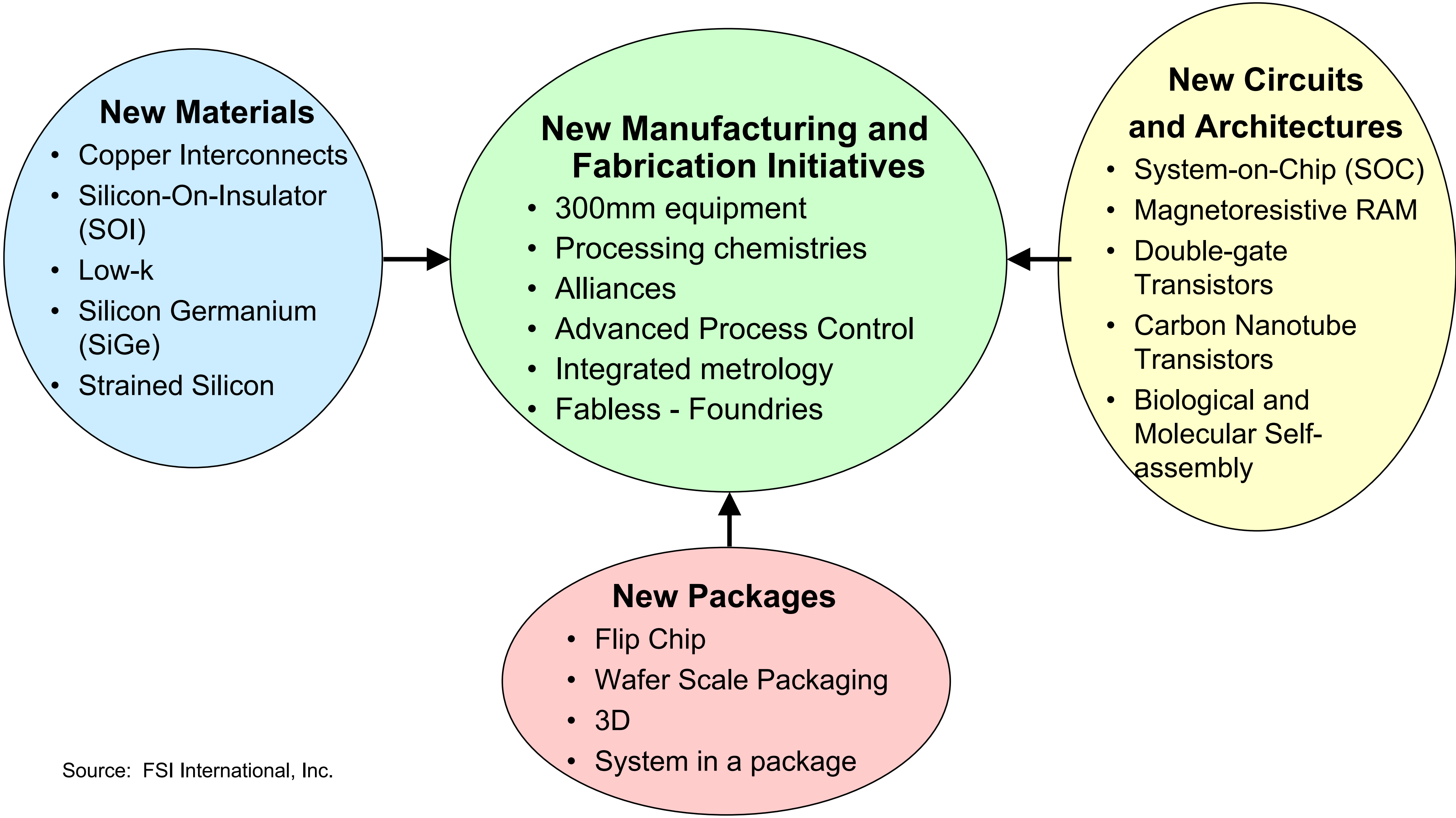
Strained Silicon





TEM micrographs of 45 nm p-type and n-type MOSFET.
Image courtesy of ScottThompson, Intel.

New Technologies



New Materials
- Copper Interconnects
- Silicon-On-Insulator (SOI)
- Low-k
- Silicon Germanium (SiGe)
- Strained Silicon

New Manufacturing and Fabrication Initiatives
- 300mm equipment
- Processing chemistries
- Alliances
- Advanced Process Control
- Integrated metrology
- Fabless - Foundries

New Circuits and Architectures
- System-on-Chip (SOC)
- Magnetoresistive RAM
- Double-gate Transistors
- Carbon Nanotube Transistors
- Biological and Molecular Self-assembly

New Packages
- Flip Chip
- Wafer Scale Packaging
- 3D
- System in a package

Source: FSI International, Inc.

Environmental Impact of the Semiconductor Industry

Impact per square inch of Si

Output from the Fab		Input to the Fab	
Liquid Waste	75 Gal/in^2	Water	30 gal/in^2
Hazardous Waste	0.1 Kg/in^2	Electricity	10 KWhr/in^2
Toxic Releases	0.01 Kg/in^2	Chemicals	0.2 kg/in^2

Silicon Integrated Circuit Periodic Table

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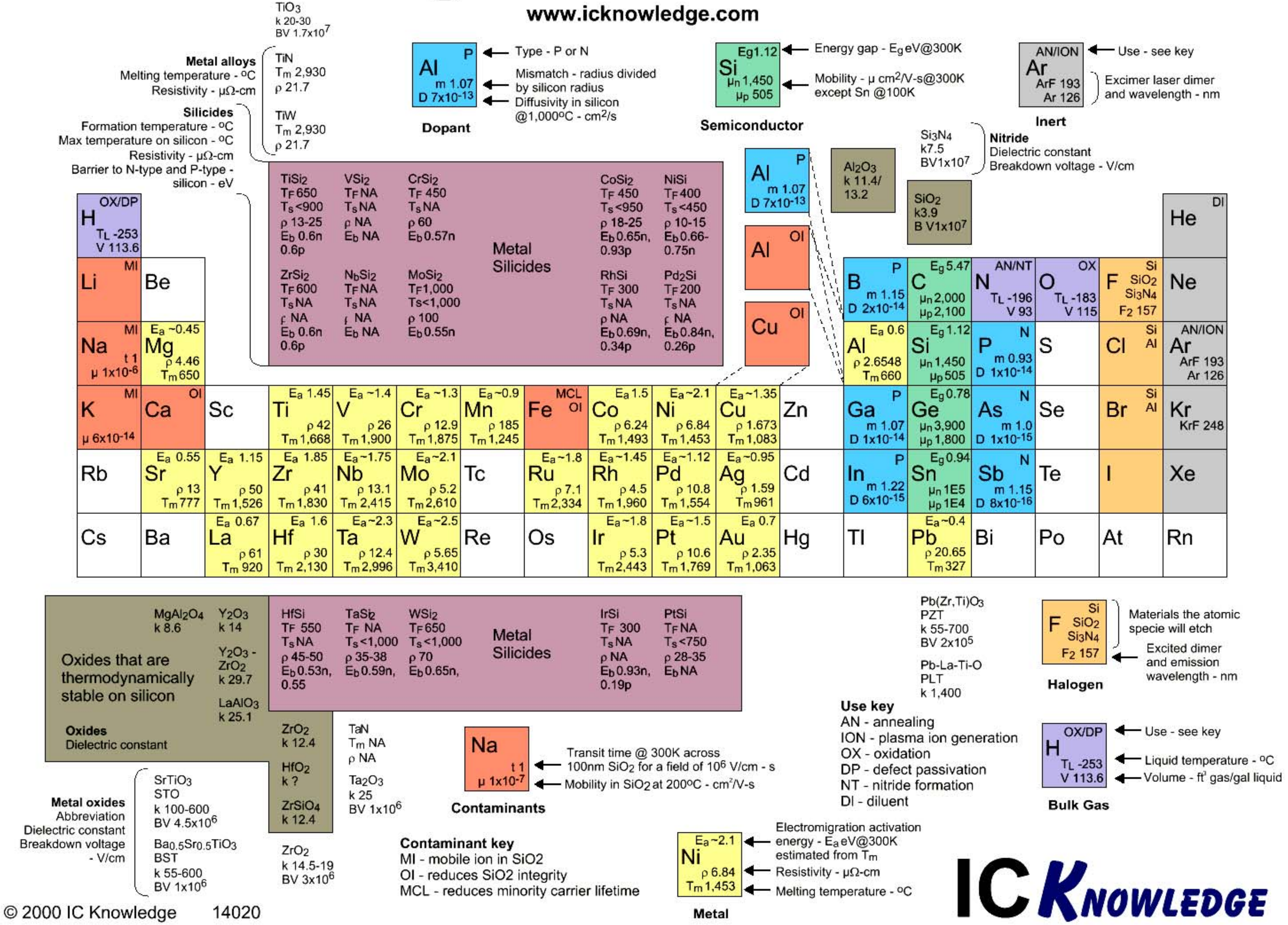

OX/DP H T_L -253 V 113.6																	DI He
MI Li	Be											P B m 1.15 D 2x10^{-14}	E_g 5.47 C μ_n 2,000 μ_p 2,100	AN/NT N T_L -196 V 93	OX O T_L -183 V 115	Si F SiO_2 Si_3N_4 F_2 157	Ne
MI Na t 1 μ 1x10^{-6}	E_a ~0.45 Mg ρ 4.46 T_m 650											E_a 0.6 Al ρ 2.6548 T_m 660	E_g 1.12 Si μ_n 1,450 μ_p 505	N P m 0.93 D 1x10^{-14}	S	Si Cl Al	AN/ION Ar ArF 193 Ar 126
MI K μ 6x10^{-14}	OI Ca	Sc	E_a 1.45 Ti ρ 42 T_m 1,668	E_a ~1.4 V ρ 26 T_m 1,900	E_a ~1.3 Cr ρ 12.9 T_m 1,875	E_a ~0.9 Mn ρ 185 T_m 1,245	MCL Fe OI	E_a 1.5 Co ρ 6.24 T_m 1,493	E_a ~2.1 Ni ρ 6.84 T_m 1,453	E_a ~1.35 Cu ρ 1.673 T_m 1,083	Zn	P Ga m 1.07 D 1x10^{-14}	E_g 0.78 Ge μ_n 3,900 μ_p 1,800	N As m 1.0 D 1x10^{-15}	Se	Si Br Al	Kr KrF 248
Rb	E_a 0.55 Sr ρ 13 T_m 777	E_a 1.15 Y ρ 50 T_m 1,526	E_a 1.85 Zr ρ 41 T_m 1,830	E_a ~1.75 Nb ρ 13.1 T_m 2,415	E_a ~2.1 Mo ρ 5.2 T_m 2,610	Tc	E_a ~1.8 Ru ρ 7.1 T_m 2,334	E_a ~1.45 Rh ρ 4.5 T_m 1,960	E_a ~1.12 Pd ρ 10.8 T_m 1,554	E_a ~0.95 Ag ρ 1.59 T_m 961	Cd	P In m 1.22 D 6x10^{-15}	E_g 0.94 Sn μ_n 1E5 μ_p 1E4	N Sb m 1.15 D 8x10^{-16}	Te	I	Xe
Cs	Ba	E_a 0.67 La ρ 61 T_m 920	E_a 1.6 Hf ρ 30 T_m 2,130	E_a ~2.3 Ta ρ 12.4 T_m 2,996	E_a ~2.5 W ρ 5.65 T_m 3,410	Re	Os	E_a ~1.8 Ir ρ 5.3 T_m 2,443	E_a ~1.5 Pt ρ 10.6 T_m 1,769	E_a 0.7 Au ρ 2.35 T_m 1,063	Hg	Tl	E_a ~0.4 Pb ρ 20.65 T_m 327	Bi	Po	At	Rn

TiO_3
k 20-30
BV 1.7x10^7

Metal alloys
Melting temperature - °C
Resistivity - μΩ-cm

TiN
T_m 2,930
ρ 21.7

TiW
T_m 2,930
ρ 21.7

Silicides
Formation temperature - °C
Max temperature on silicon - °C
Resistivity - μΩ-cm
Barrier to N-type and P-type - silicon - eV

Metal Silicides

$TiSi_2$ T_F 650 T_s <900 ρ 13-25 E_b 0.6n 0.6p	VSi_2 T_F NA T_s NA ρ NA E_b NA	$CrSi_2$ T_F 450 T_s NA ρ 60 E_b 0.57n	$CoSi_2$ T_F 450 T_s <950 ρ 18-25 E_b 0.65n, 0.93p	NiSi T_F 400 T_s <450 ρ 10-15 E_b 0.66- 0.75n
$ZrSi_2$ T_F 600 T_s NA ρ NA E_b 0.6n 0.6p	$NbSi_2$ T_F NA T_s NA ρ NA E_b NA	$MoSi_2$ T_F 1,000 Ts<1,000 ρ 100 E_b 0.55n	RhSi T_F 300 T_s NA ρ NA E_b 0.69n, 0.34p	Pd_2Si T_F 200 T_s NA ρ NA E_b 0.84n, 0.26p
HfSi T_F 550 T_s NA ρ 45-50 E_b 0.53n, 0.55	$TaSi_2$ T_F NA T_s <1,000 ρ 35-38 E_b 0.59n,	WSi_2 T_F 650 T_s <1,000 ρ 70 E_b 0.65n,	IrSi T_F 300 T_s NA ρ NA E_b 0.93n, 0.19p	PtSi T_F NA T_s <750 ρ 28-35 E_b NA

Al P, m 1.07, D 7x10^{-13} ← Type - P or N; ← Mismatch - radius divided by silicon radius; ← Diffusivity in silicon @1,000°C - cm^2/s

Dopant

Si E_g 1.12, μ_n 1,450, μ_p 505 ← Energy gap - E_g eV@300K; ← Mobility - μ cm^2/V-s@300K except Sn @100K

Semiconductor

Ar AN/ION, ArF 193, Ar 126 ← Use - see key; Excimer laser dimer and wavelength - nm

Inert

Al P, m 1.07, D 7x10^{-13}

Al OI

Cu OI

Al_2O_3
k 11.4/
13.2

SiO_2
k3.9
B V1x10^7

Si_3N_4
k7.5
BV1x10^7

Nitride
Dielectric constant
Breakdown voltage - V/cm

Oxides that are thermodynamically stable on silicon

$MgAl_2O_4$
k 8.6

Y_2O_3
k 14

Y_2O_3 - ZrO_2
k 29.7

$LaAlO_3$
k 25.1

ZrO_2
k 12.4

HfO_2
k ?

$ZrSiO_4$
k 12.4

Oxides
Dielectric constant

Metal oxides
Abbreviation
Dielectric constant
Breakdown voltage - V/cm

$SrTiO_3$
STO
k 100-600
BV 4.5x10^6

$Ba_{0.5}Sr_{0.5}TiO_3$
BST
k 55-600
BV 1x10^6

ZrO_2
k 14.5-19
BV 3x10^6

TaN
T_m NA
ρ NA

Ta_2O_3
k 25
BV 1x10^6

Na t 1, μ 1x10^{-7} ← Transit time @ 300K across 100nm SiO_2 for a field of 10^6 V/cm - s; ← Mobility in SiO_2 at 200°C - cm^2/V-s

Contaminants

Contaminant key
MI - mobile ion in SiO2
OI - reduces SiO2 integrity
MCL - reduces minority carrier lifetime

Ni E_a ~2.1, ρ 6.84, T_m 1,453 ← Electromigration activation energy - E_a eV@300K estimated from T_m; ← Resistivity - μΩ-cm; ← Melting temperature - °C

Metal

$Pb(Zr,Ti)O_3$
PZT
k 55-700
BV 2x10^5

Pb-La-Ti-O
PLT
k 1,400

Use key
AN - annealing
ION - plasma ion generation
OX - oxidation
DP - defect passivation
NT - nitride formation
DI - diluent

F Si, SiO_2, Si_3N_4 – Materials the atomic specie will etch; F_2 157 ← Excited dimer and emission wavelength - nm

Halogen

H OX/DP ← Use - see key; T_L -253 ← Liquid temperature - °C; V 113.6 ← Volume - ft^3 gas/gal liquid

Bulk Gas

IC KNOWLEDGE

14020