The end of CMOS scaling - when is it ?

The end of CMOS scaling - when is it ?

The end of CMOS scaling - when is it ?

The end of CMOS scaling - when is it ?

The end of CMOS scaling - when is it ?

The end of CMOS scaling - when is it ?

The end of CMOS scaling - when is it ?

Jean-Pierre Colinge
Tyndall National Institute
University College Cork
Ireland

Schrödinger’s Equation

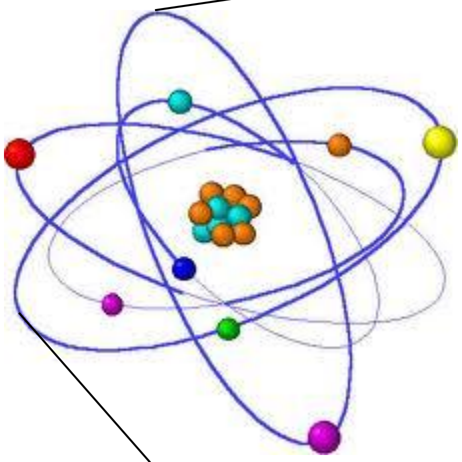
$$-\frac{\eta^2}{2m}\frac{d^2\psi}{dx^2}=(E-V)\psi$$

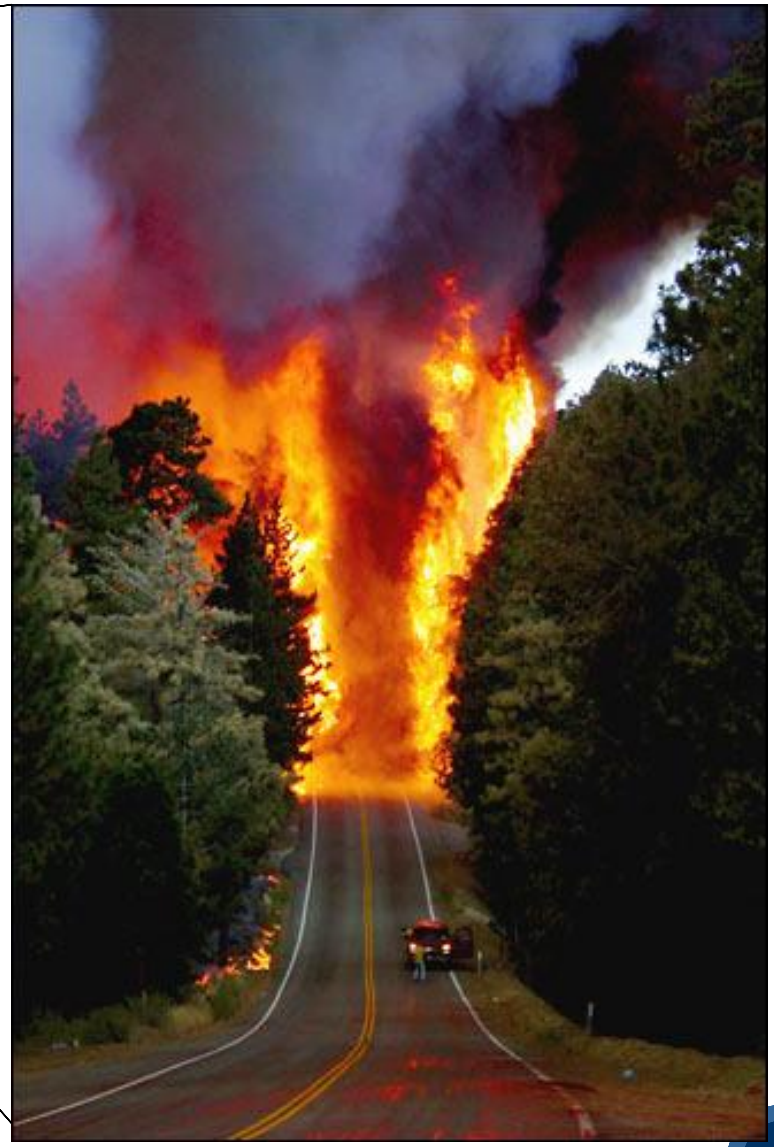
… if d^2/dx^2 gets smaller,

E gets bigger …

Schrödinger's Equation

$$-\frac{\eta^2}{2m}\frac{d^2\psi}{dx^2}=(E-V)\psi$$

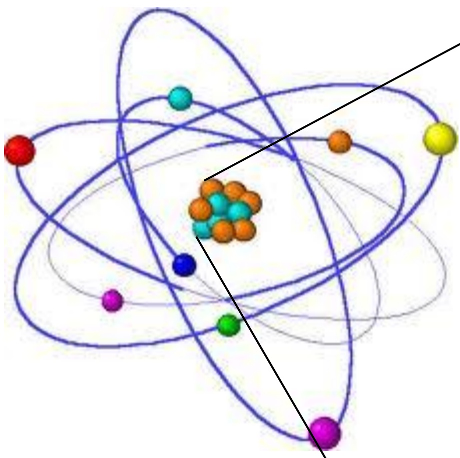




Atom
Chemical reaction
E=10eV
(10^1 eV)

Schrödinger's Equation

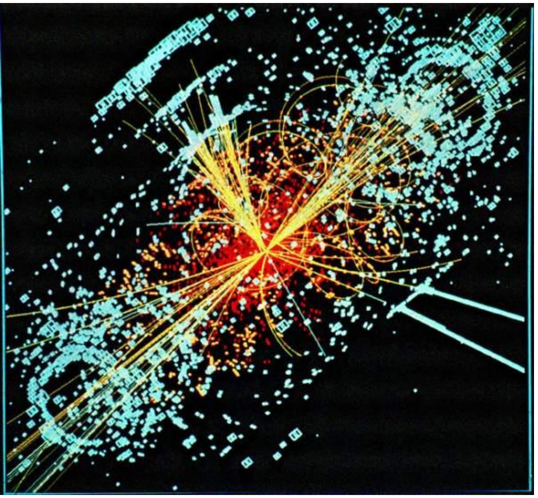
$$-\frac{\eta^2}{2m}\frac{d^2\psi}{dx^2}=(E-V)\psi$$



Nucleus
Nuclear reaction
E=10MeV
(10^7 eV)

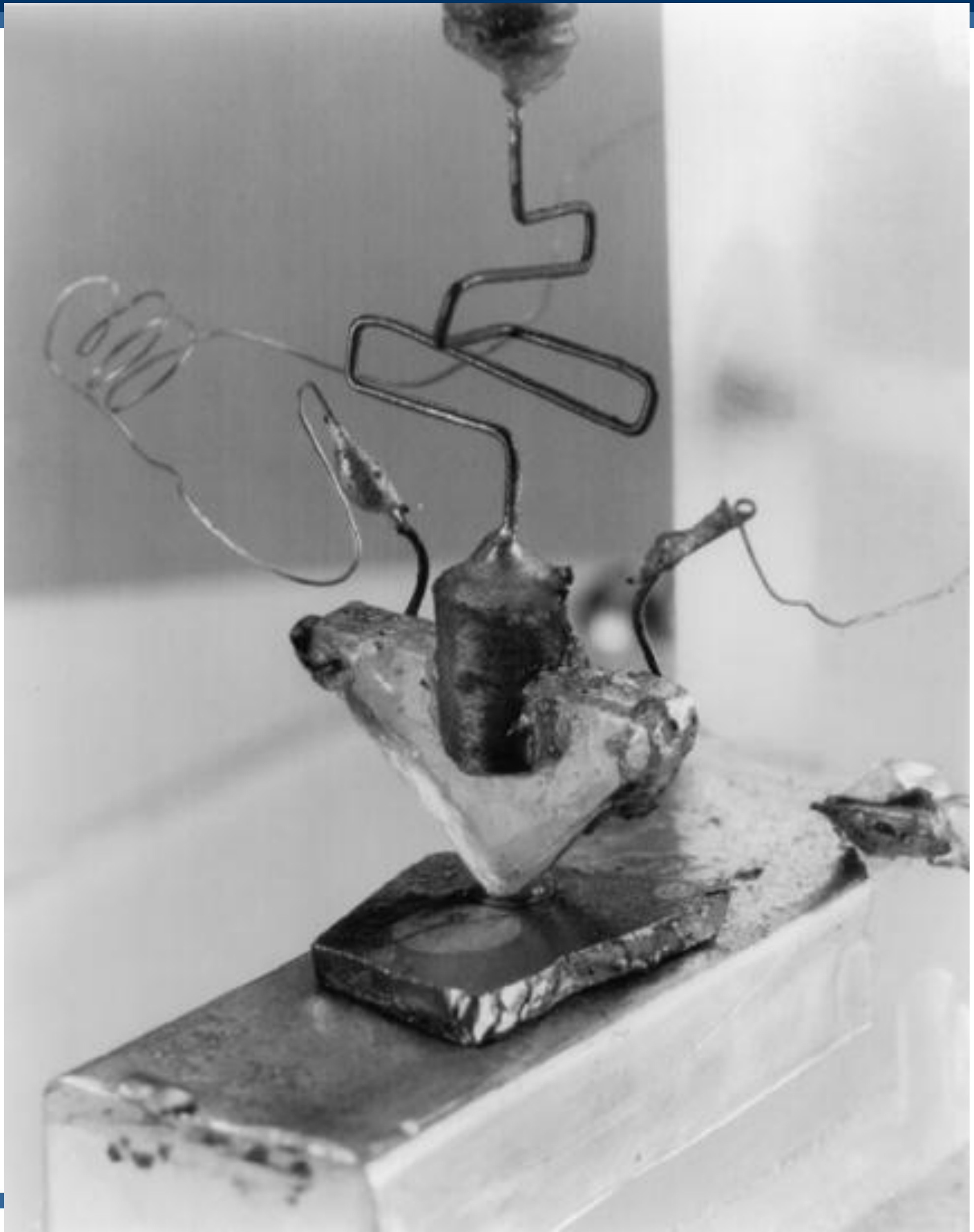
Schrödinger's Equation

$$-\frac{\eta^2}{2m}\frac{d^2\psi}{dx^2} = (E - V)\psi$$



Elementary Particles
E=14 TeV
(10^{13} eV)

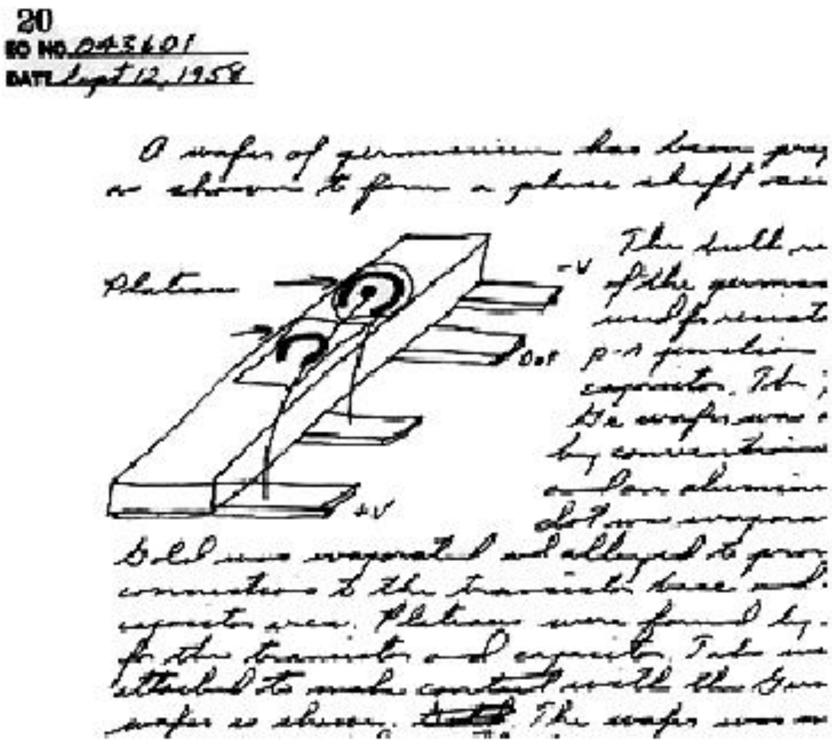
The first transistor

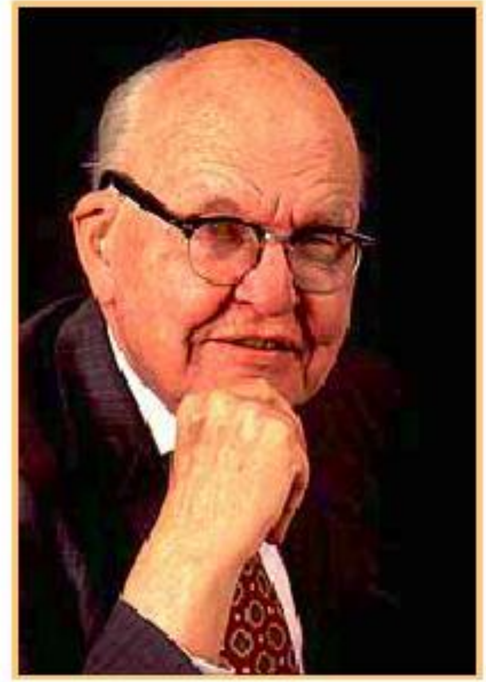


Bardeen, Brattain and Shockley (1947)

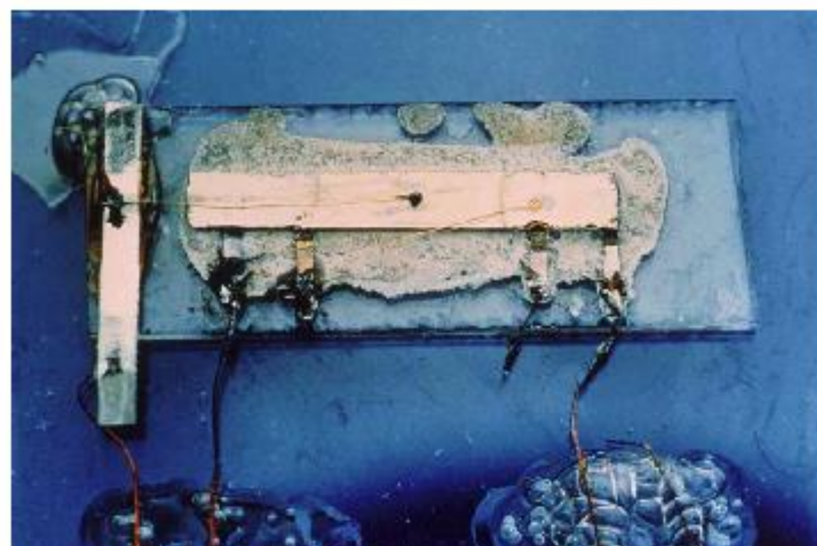
(point-contact transistor)

INTEGRATED CIRCUIT - 1958





Jack Kilby

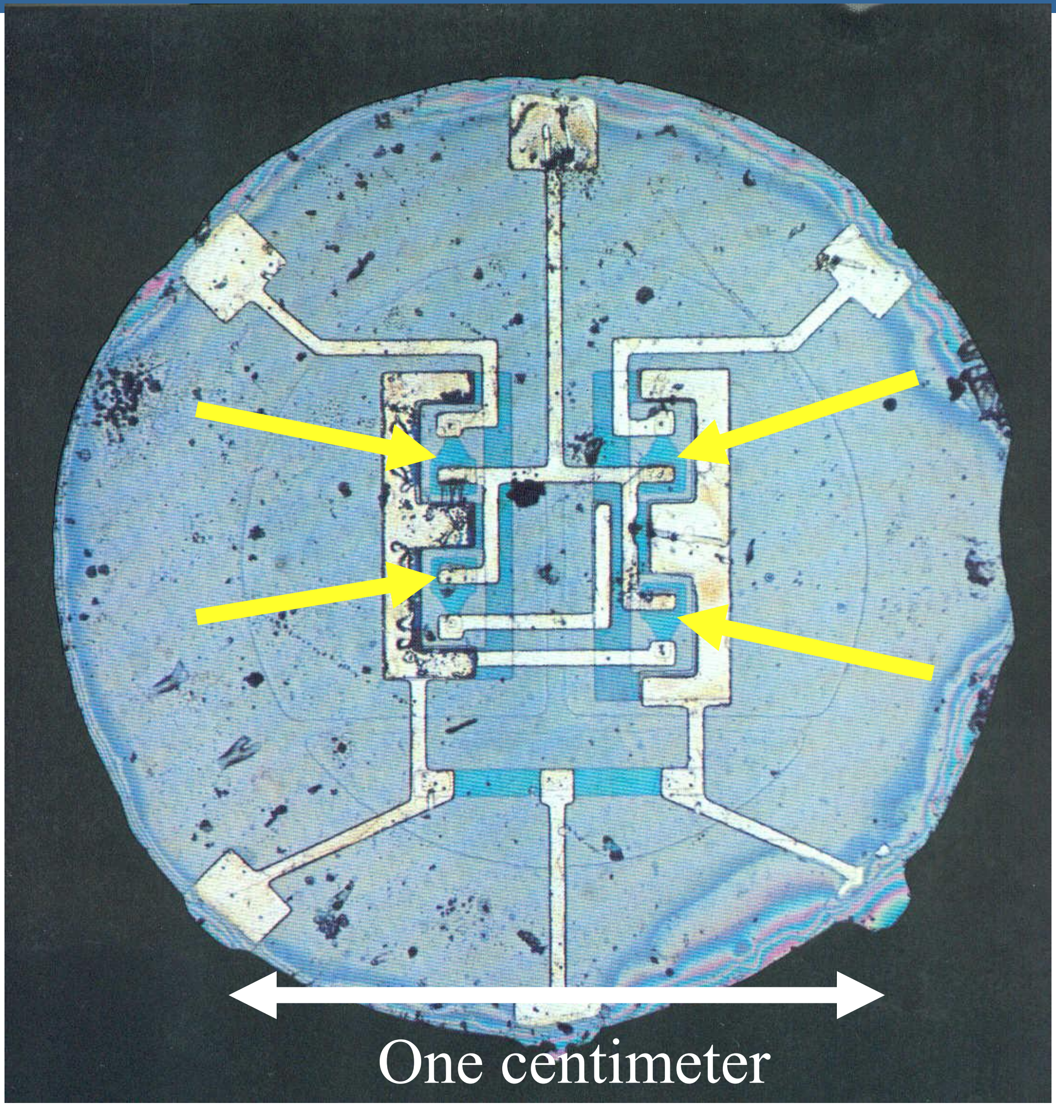


- US Patent # 3,138,743 filed Feb. 6, 1959

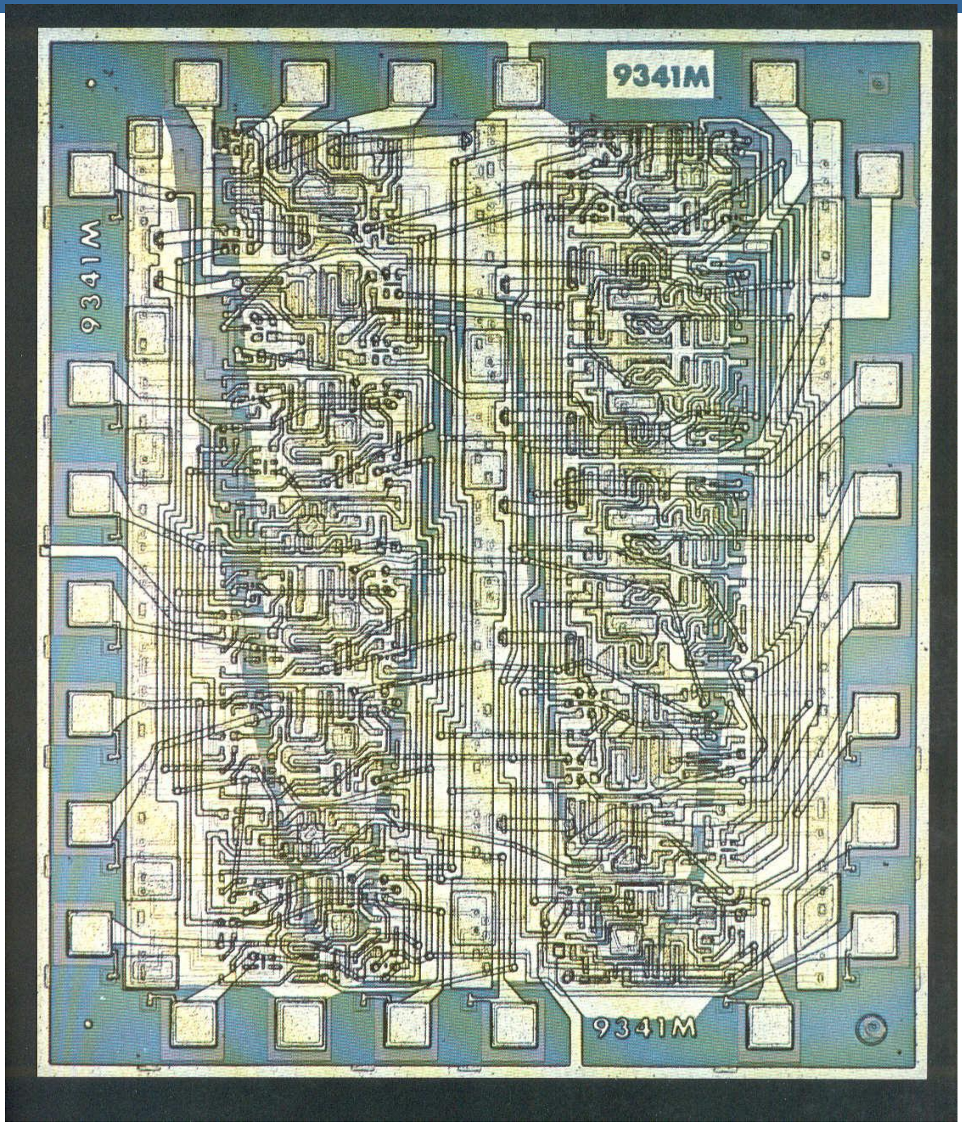
Early Integrated Circuit (4 transistors), 1959

Contains only 4 transistors !

(Bipolar transistors)



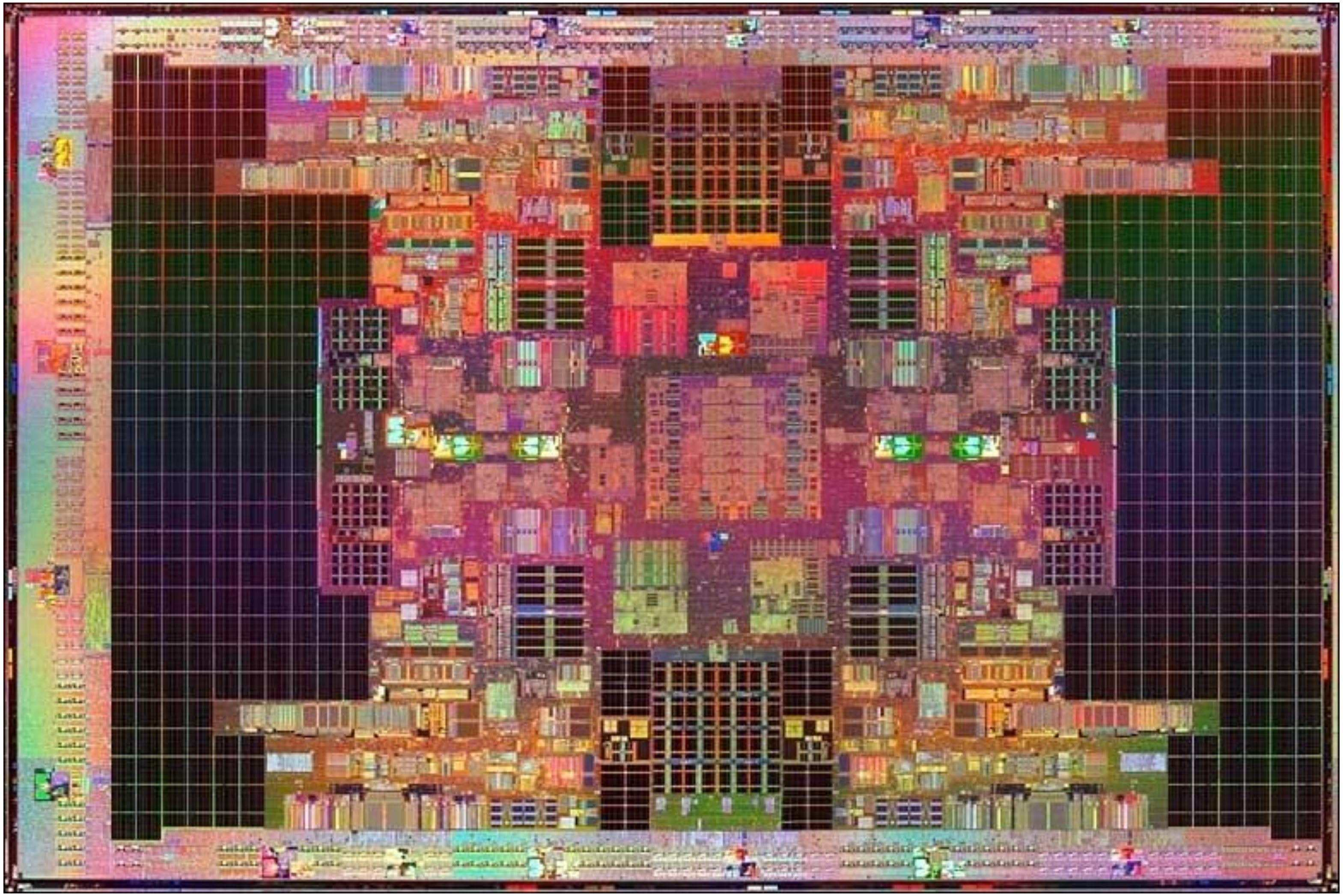
Early Integrated Circuit (200 transistors), 1969



(MOS transistors)

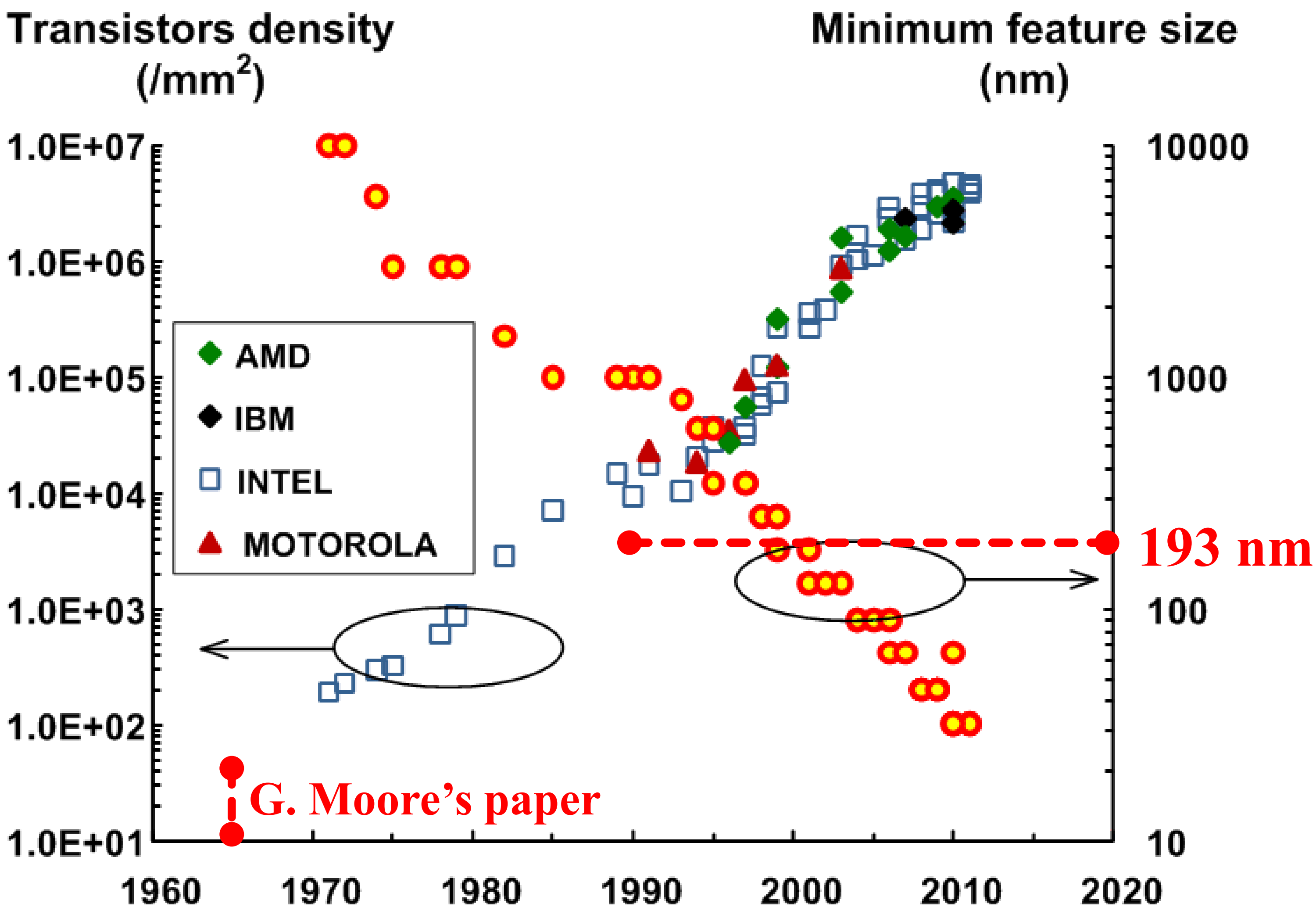
One centimeter

Intel Quad-Core Tuwilka (2,000,000,000 transistors), 2008

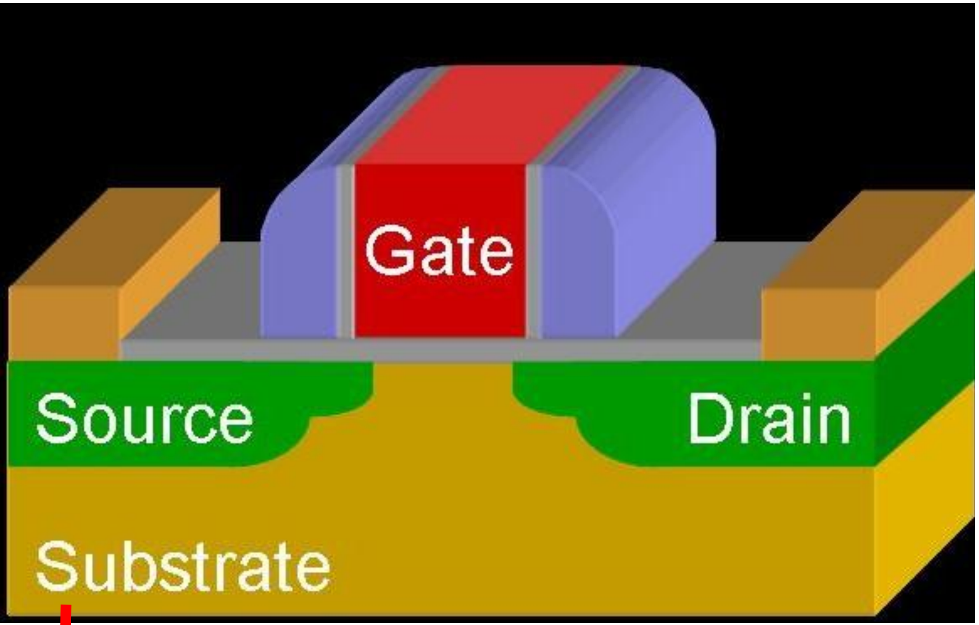


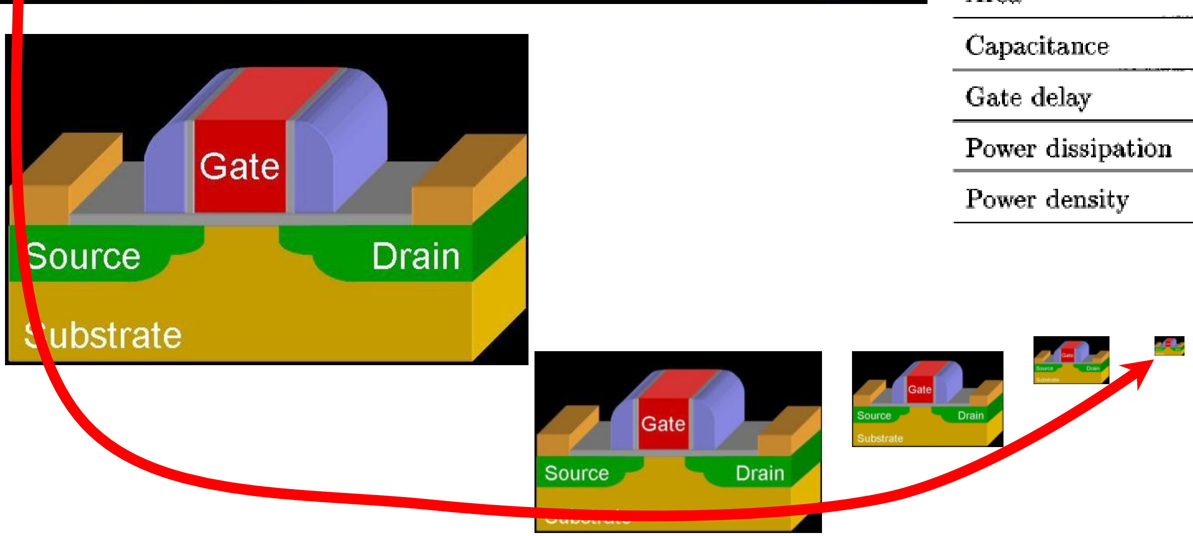
One centimeter

Moore's Law (1965 – 2011)



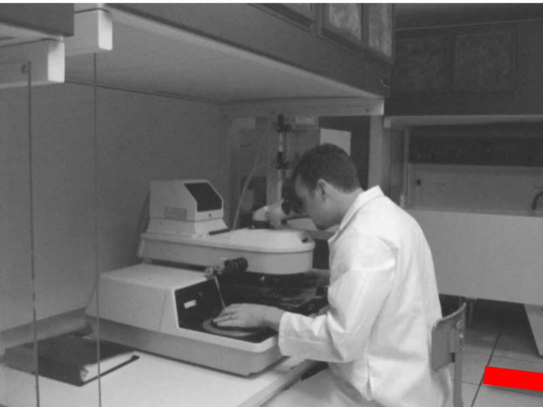
MOS Transistor Scaling





Physical parameter	Constant-Electric Field Scaling Factor	Generalized Scaling Factor	Generalized Selective Scaling Factor
Channel length, Insulator thickness	$1/\alpha$	$1/\alpha$	$1/\alpha_d$
Wiring width, channel width	$1/\alpha$	$1/\alpha$	$1/\alpha_w$
Electric field in device	1	ε	ε
Voltage	$1/\alpha$	ε/α	ε/α_d
On-current per device	$1/\alpha$	ε/α	ε/α_w
Doping	α	$\varepsilon\alpha$	$\varepsilon\alpha_d$
Area	$1/\alpha^2$	$1/\alpha^2$	$1/\alpha_w^2$
Capacitance	$1/\alpha$	$1/\alpha$	$1/\alpha_w$
Gate delay	$1/\alpha$	$1/\alpha$	$1/\alpha_d$
Power dissipation	$1/\alpha^2$	ε^2/α^2	$\varepsilon^2/\alpha_w\alpha_d$
Power density	1	ε^2	$\varepsilon^2\alpha_w/\alpha_d$

Printing small things: Photolithography

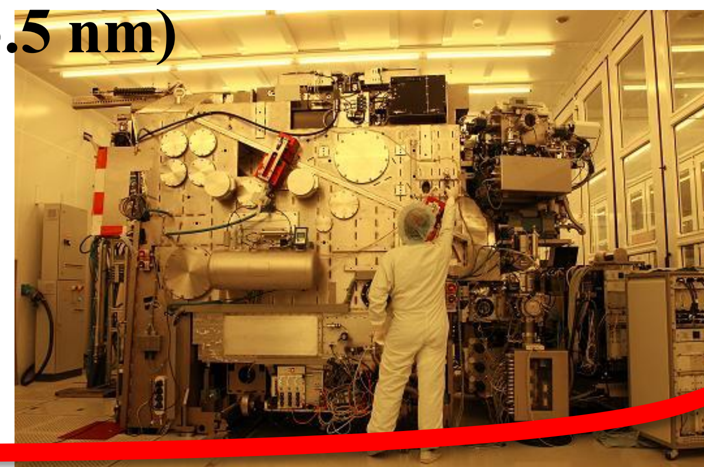


G-line (λ=436nm)

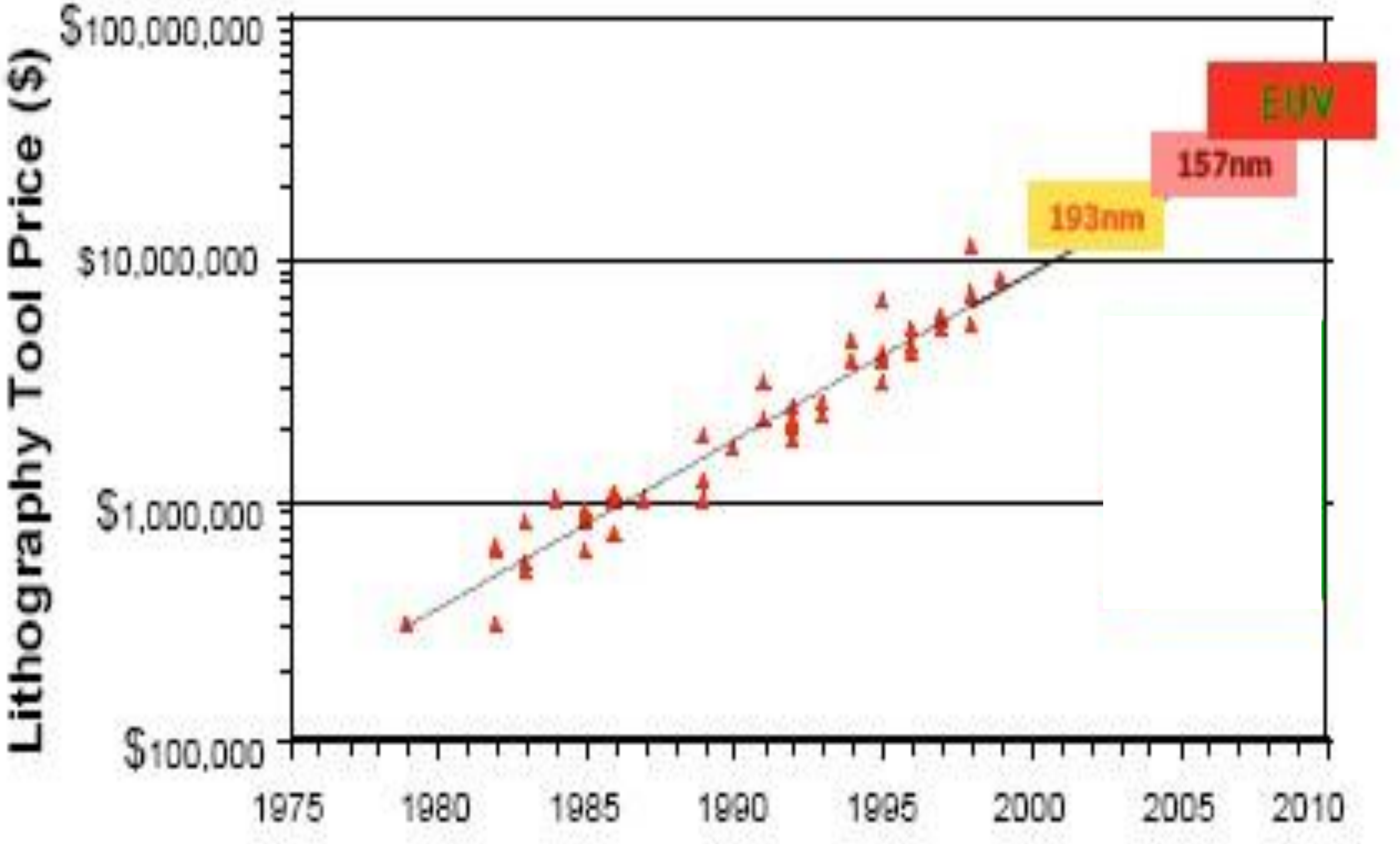
I-line (λ=365nm)

Deep UV (λ=193nm)

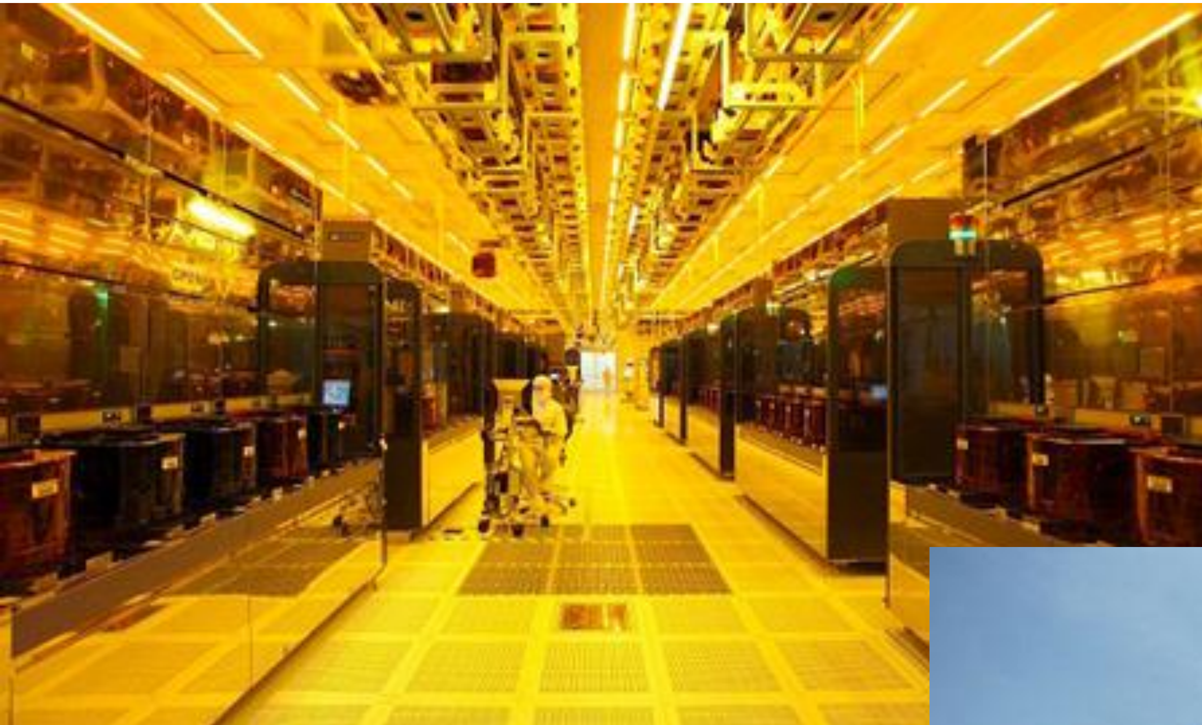
Extreme UV (λ=13.5 nm)



Printing small things: Photolithography



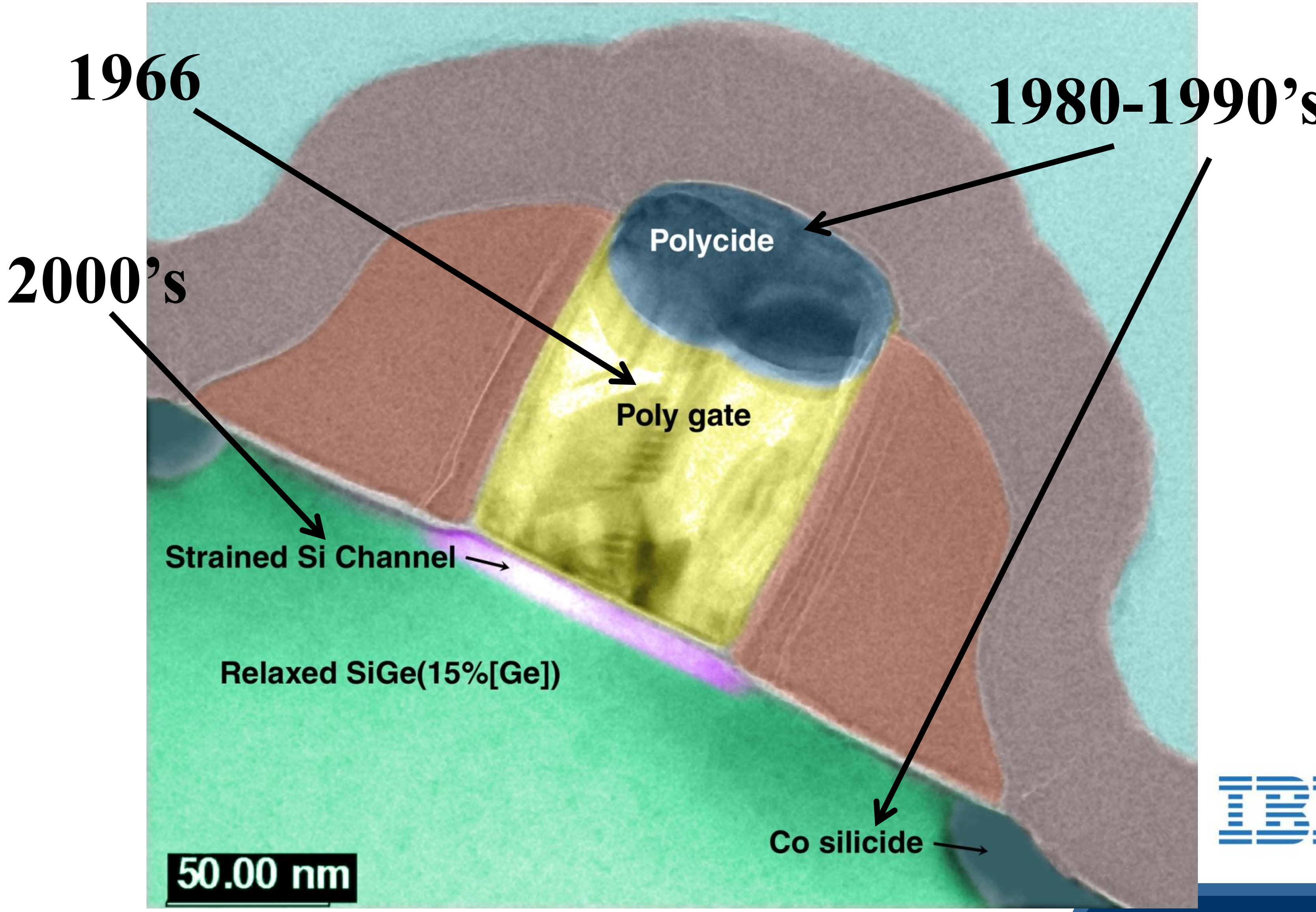
Semiconductor Fabs



TSMC’s Fab 12 Phase 4: 9.3 G$

Global Foundries new fab: 6-8 G$

Metal-Oxide-Semiconductor (MOS) Transistor



Elements used in Silicon Chip Fabrication

HgCdTe Chalcogenide fuses Excimer litho

Radioactive

1980's

1990's

2000's

	I	II											III	IV	V	VI	VII	O
1	hydrogen 1 H 1.00794(7)																	helium 2 He 4.002602(2)
2	lithium 3 Li 6.941(2)	beryllium 4 Be 9.012182(3)											boron 5 B 10.811(7)	carbon 6 C 12.0107(8)	nitrogen 7 N 14.00674(7)	oxygen 8 O 15.9994(3)	fluorine 9 F 18.9984032(5)	neon 10 Ne 20.1797(6)
3	sodium 11 Na 22.989770(2)	magnesium 12 Mg 24.305(?)											aluminium 13 Al 26.981538(2)	silicon 14 Si 28.0855(3)	phosphorus 15 P 30.973761(2)	sulfur 16 S 32.066(6)	chlorine 17 Cl 35.4527(9)	argon 18 Ar 39.948(1)
4	potassium 19 K 39.0983(1)	calcium 20 Ca 40.078(4)	scandium 21 Sc 44.955910(8)	titanium 22 Ti 47.867(1)	vanadium 23 V 50.9415(1)	chromium 24 Cr 51.9961(6)	manganese 25 Mn 54.938049(9)	iron 26 Fe 55.845(2)	cobalt 27 Co 58.933200(9)	nickel 28 Ni 58.6934(2)	copper 29 Cu 63.546(3)	zinc 30 Zn 65.39(2)	gallium 31 Ga 69.723(1)	germanium 32 Ge 72.61(2)	arsenic 33 As 74.92160(2)	selenium 34 Se 78.96(3)	bromine 35 Br 79.904(1)	krypton 36 Kr 83.80(1)
5	rubidium 37 Rb 85.4678(3)	strontium 38 Sr 87.62(1)	yttrium 39 Y 88.90585(2)	zirconium 40 Zr 91.224(2)	niobium 41 Nb 92.90638(2)	molybdenum 42 Mo 95.94(1)	technetium 43 Tc [98.9063]	ruthenium 44 Ru 101.07(2)	rhodium 45 Rh 102.90550(2)	palladium 46 Pd 106.42(1)	silver 47 Ag 107.8682(2)	cadmium 48 Cd 112.411(8)	indium 49 In 114.818(3)	tin 50 Sn 118.710(7)	antimony 51 Sb 121.760(1)	tellurium 52 Te 127.60(3)	iodine 53 I 126.90447(3)	xenon 54 Xe 131.29(2)
6	caesium 55 Cs 132.90545(2)	barium 56 Ba 137.327(7)	lanthanum 57 La 138.9055(2)	hafnium 72 Hf 178.49(2)	tantalum 73 Ta 180.9479(1)	tungsten 74 W 183.84(1)	rhenium 75 Re 186.207(1)	osmium 76 Os 190.23(3)	iridium 77 Ir 192.217(3)	platinum 78 Pt 195.078(2)	gold 79 Au 196.96655(2)	mercury 80 Hg 200.59(2)	thallium 81 Tl 204.3833(2)	lead 82 Pb 207.2(1)	bismuth 83 Bi 208.98038(2)	polonium 84 Po [208.9824]	astatine 85 At [209.9871]	radon 86 Rn [222.0176]
7	francium 87 Fr [223.0197]	radium 88 Ra [226.0254]																

cerium 58 Ce 140.116(1)	praseodymium 59 Pr 140.90765(2)	nedodymium 60 Nd 144.24(3)	promethium 61 Pm [144.9127]	samarium 62 Sm 150.36(3)	europium 63 Eu 151.964(1)	gadolinium 64 Gd 157.25(3)	terbium 65 Tb 158.92534(2)	dysprosium 66 Dy 162.50(3)	holmium 67 Ho 164.93032(2)	erbium 68 Er 167.26(3)	thulium 69 Tm 168.93421(2)	ytterbium 70 Yb 173.04(3)	lutetium 71 Lu 174.967(1)
thorium 90 Th 232.038(1)	protactinium 91 Pa 231.03588(2)	uranium 92 U 238.0289(1)	neptunium 93 Np [237.0482]	plutonium 94 Pu [244.0642]	americium 95 Am [243.0614]	curium 96 Cm [247.0703]	berkelium 97 Bk [247.0703]	californium 98 Cf [251.0796]	einsteinium 99 Es [252.0830]	fermium 100 Fm [257.0951]	mendelevium 101 Md [258.0984]	nobelium 102 No [259.1011]	lawrencium 103 Lr [262.110]

Classical Mechanics

$E_{ball} < V_{door}$

Classical Mechanics

$E_{ball} > V_{door}$

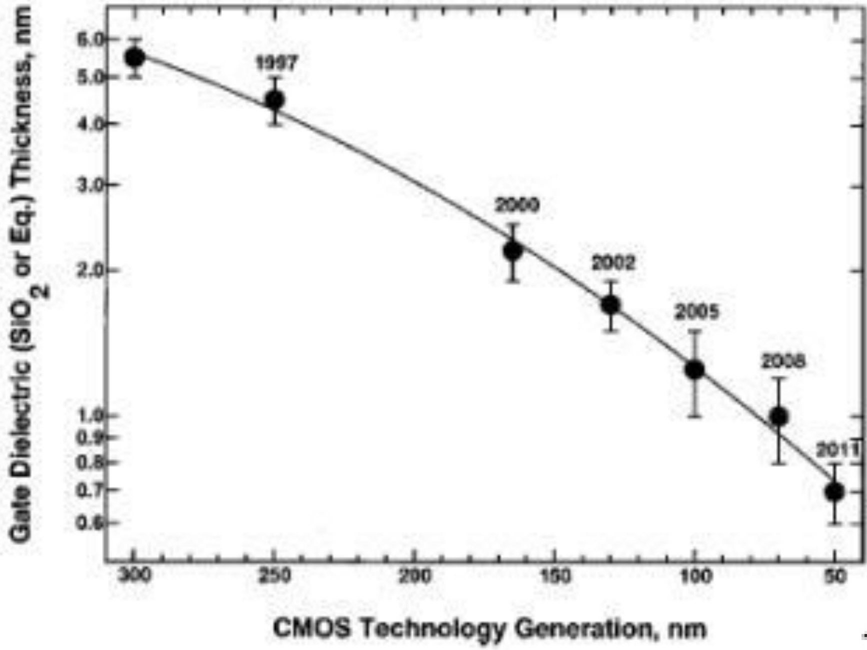
Quantum Mechanics

Schrödinger's Equation

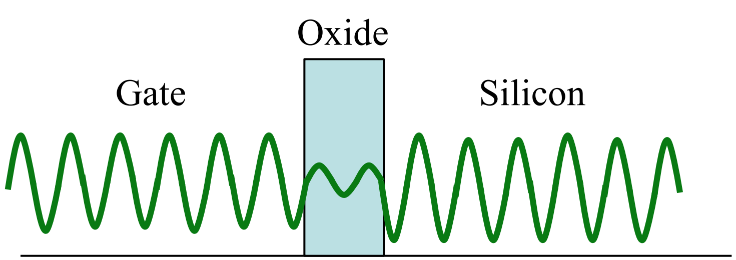
$$E_{sound} < V_{door}$$

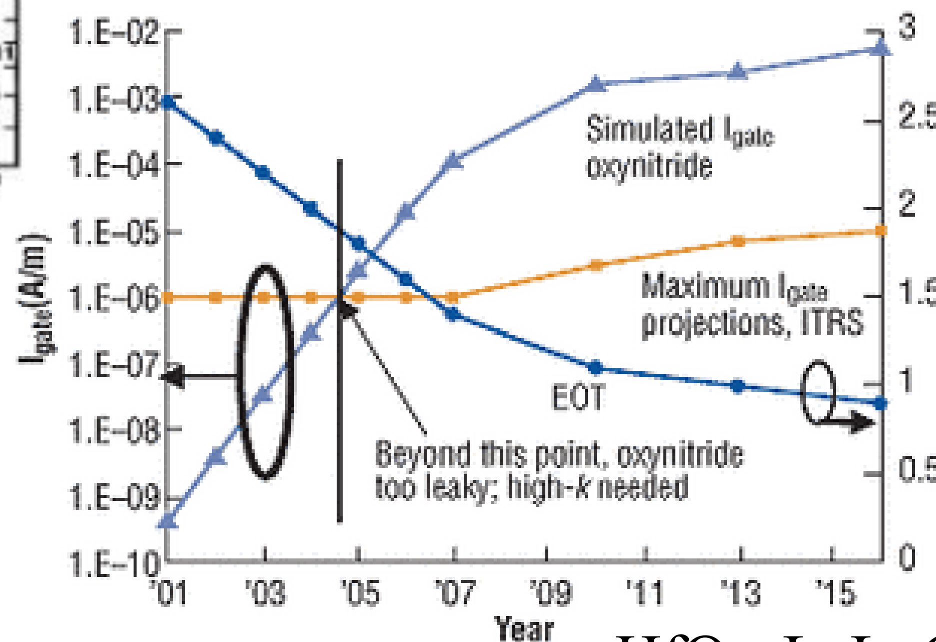
$$-\frac{\eta^2}{2m}\frac{d^2\psi}{dx^2}=\left(E-V\right)\psi$$

Schrödinger's Equation $-\frac{\hbar^2}{2m}\frac{d^2}{dx^2}\Psi = E\Psi$



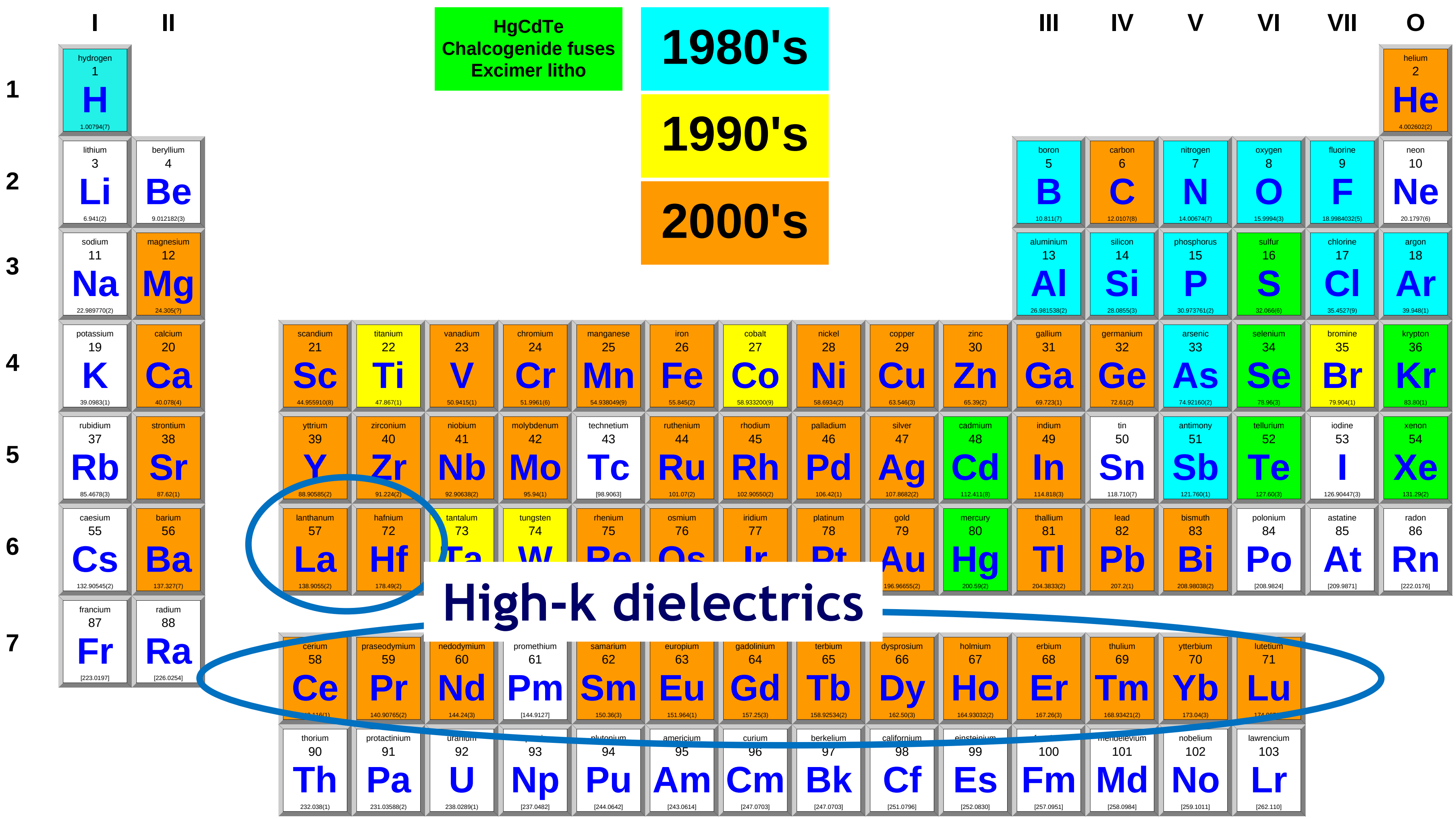
Electron tunneling





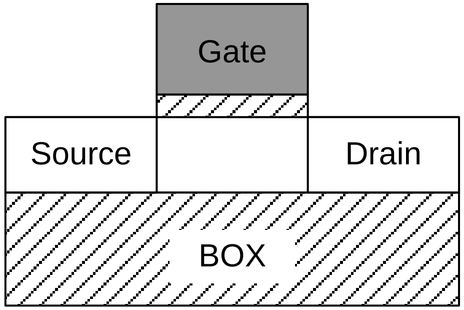
HfO_2, $LaLuO_3$

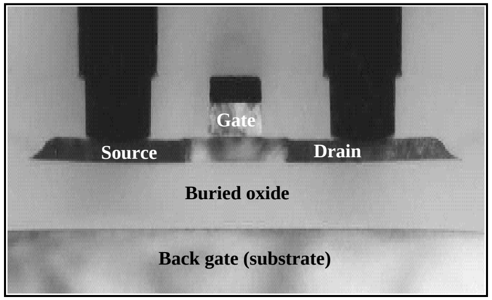
Elements used in Silicon Chip Fabrication



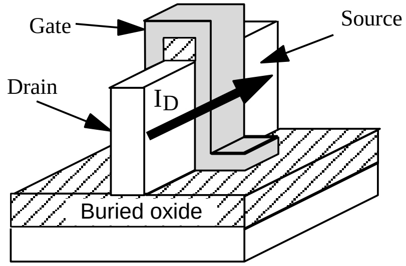
Evolution of Transistors Geometry

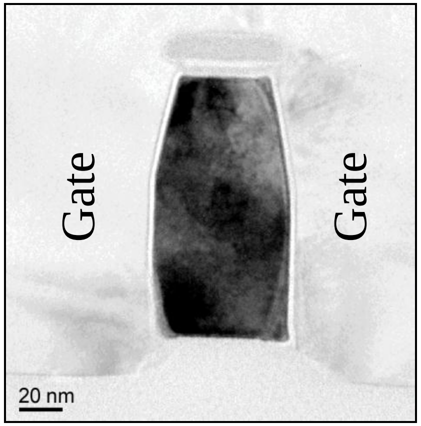
“1 Gate”



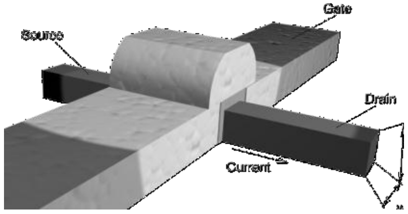


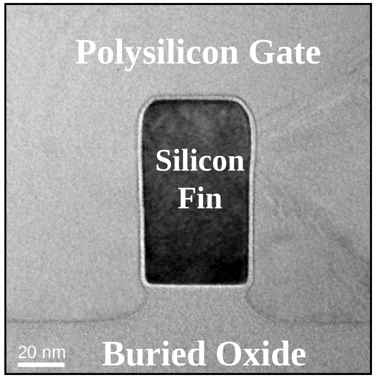
“2 Gates”



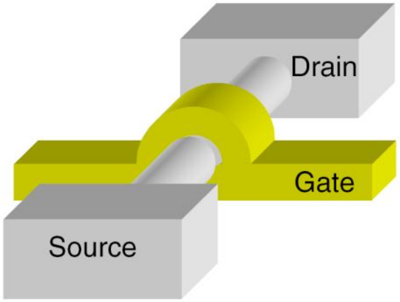


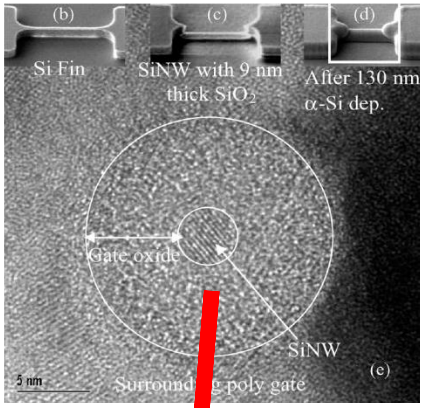
“3 Gates”

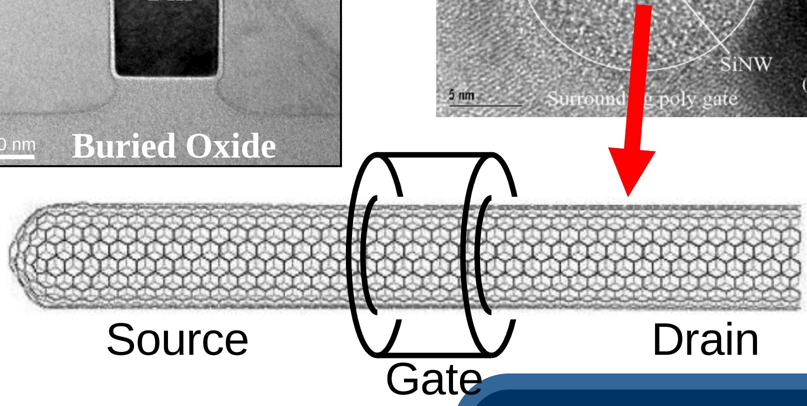




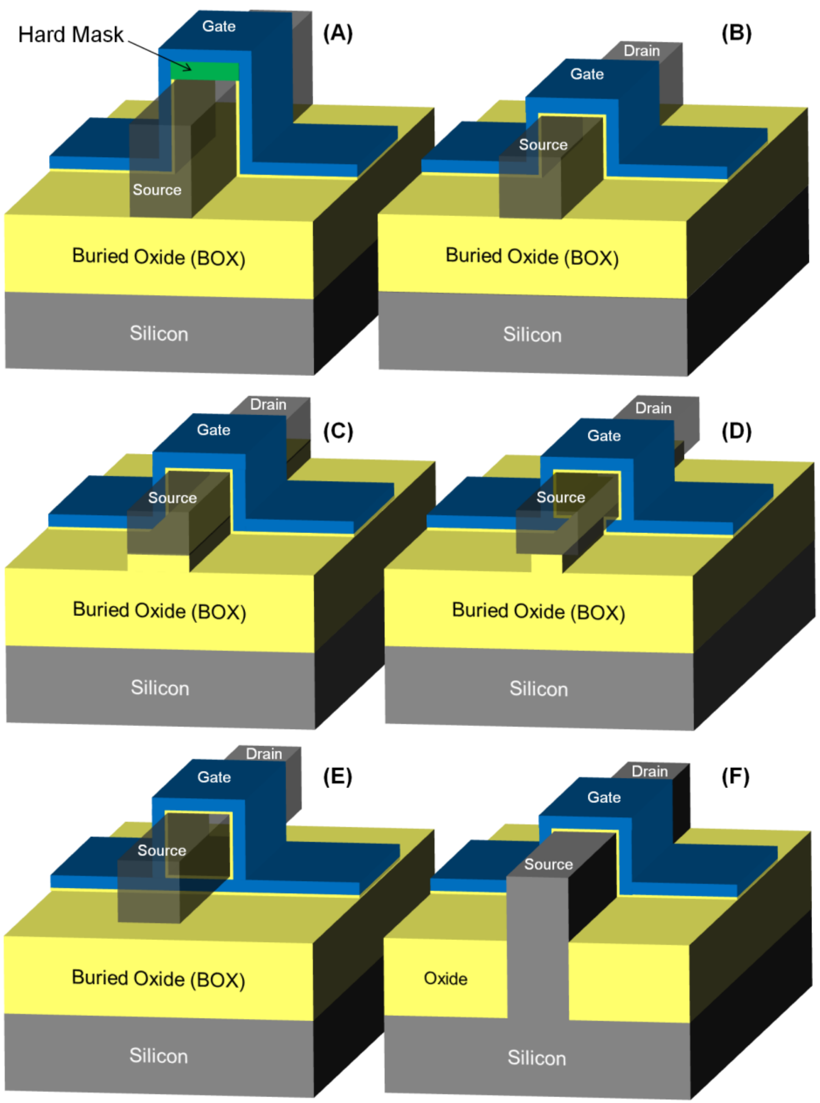
“Gate-all-Around”







“Multigate Transistor Geometries



A: SOI FinFET; the “hard mask” is a thick dielectric that prevents the formation of an inversion channel at the top of the silicon “fin”. Gate control is exerted on the channel from the two lateral sides of the device.

B: SOI Triple-gate (or trigate) MOSFET. Gate control is exerted on the channel from three sides of the device (top, as well as left and right side).

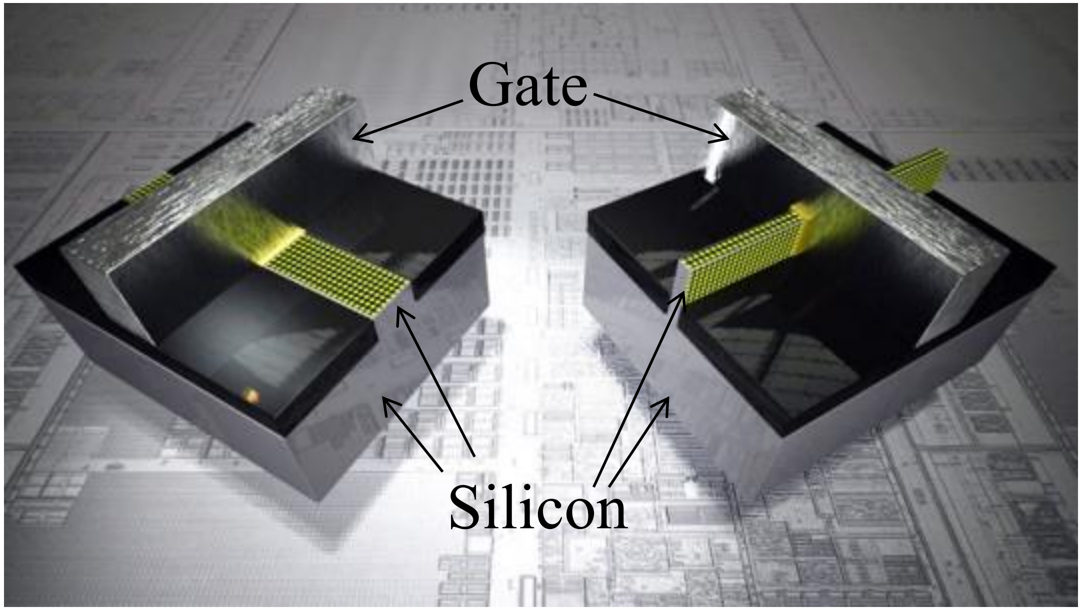
C: SOI Π-gate MOSFET. Gate control is improved over (B) because the electric field from lateral sides of the gate exerts some control on the bottom side of the channel.

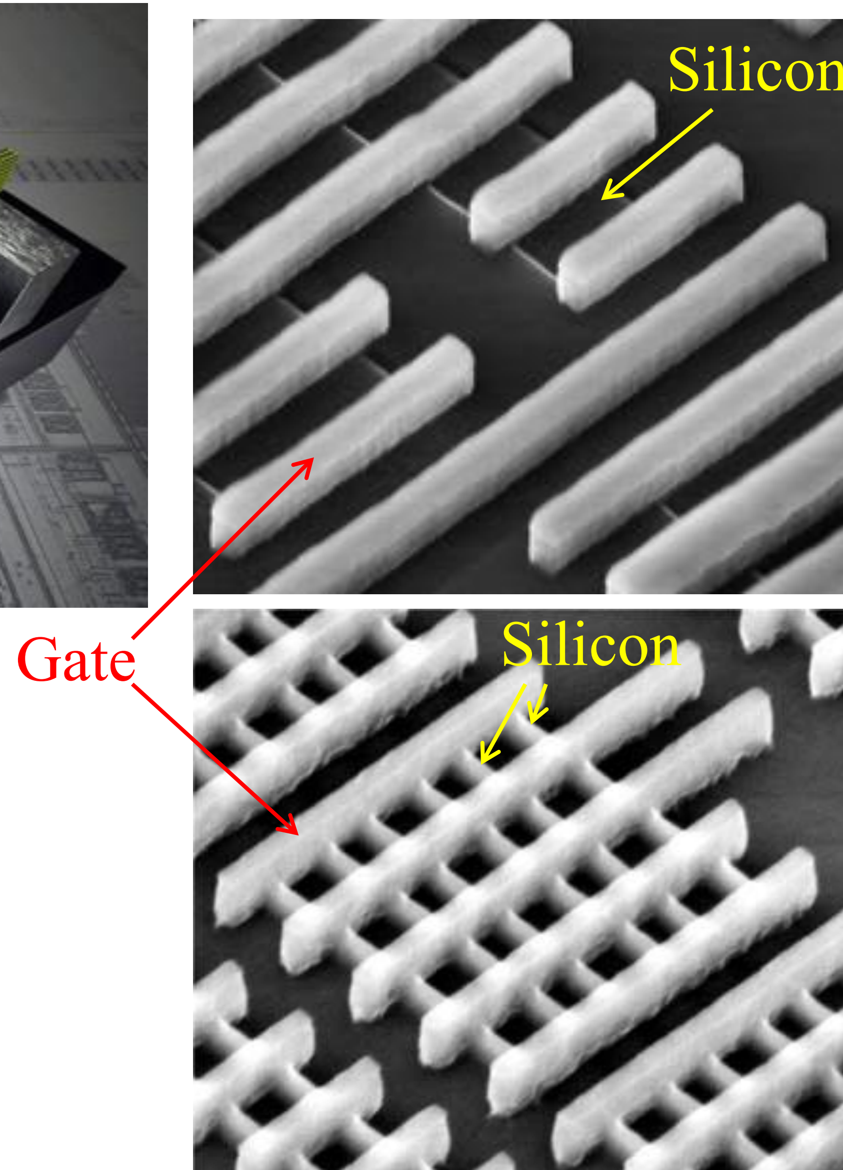
D: SOI Ω-gate MOSFET. Gate control of the bottom of the channel region is improved over (C).

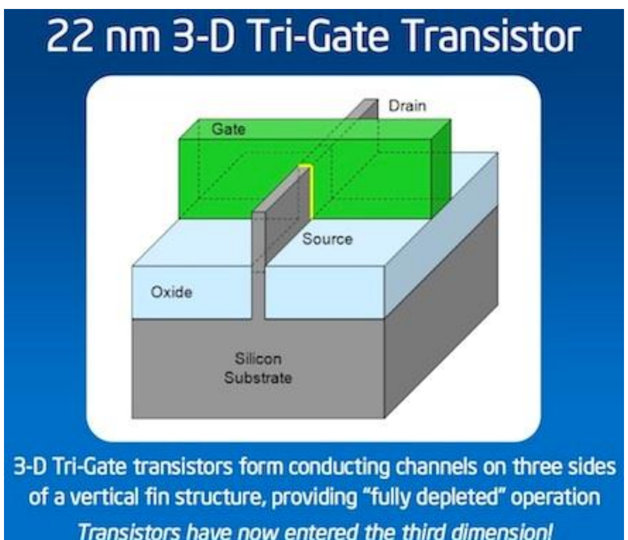
E: SOI Gate-all-Around MOSFET. Gate control is exerted on the channel from all four sides of the device.

F: Bulk trigate MOSFET

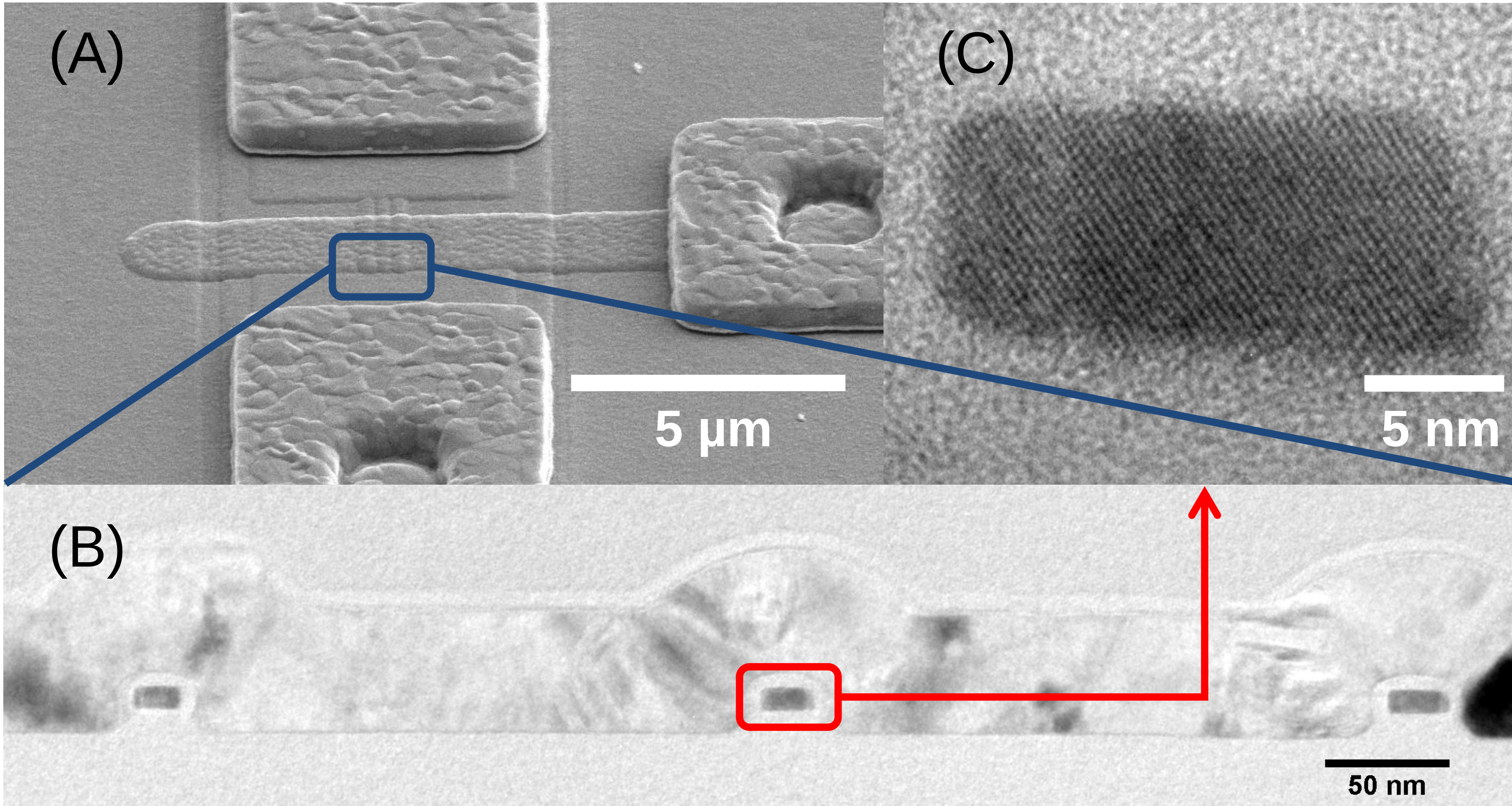
Intel's TrigateTransistor for 22nm node





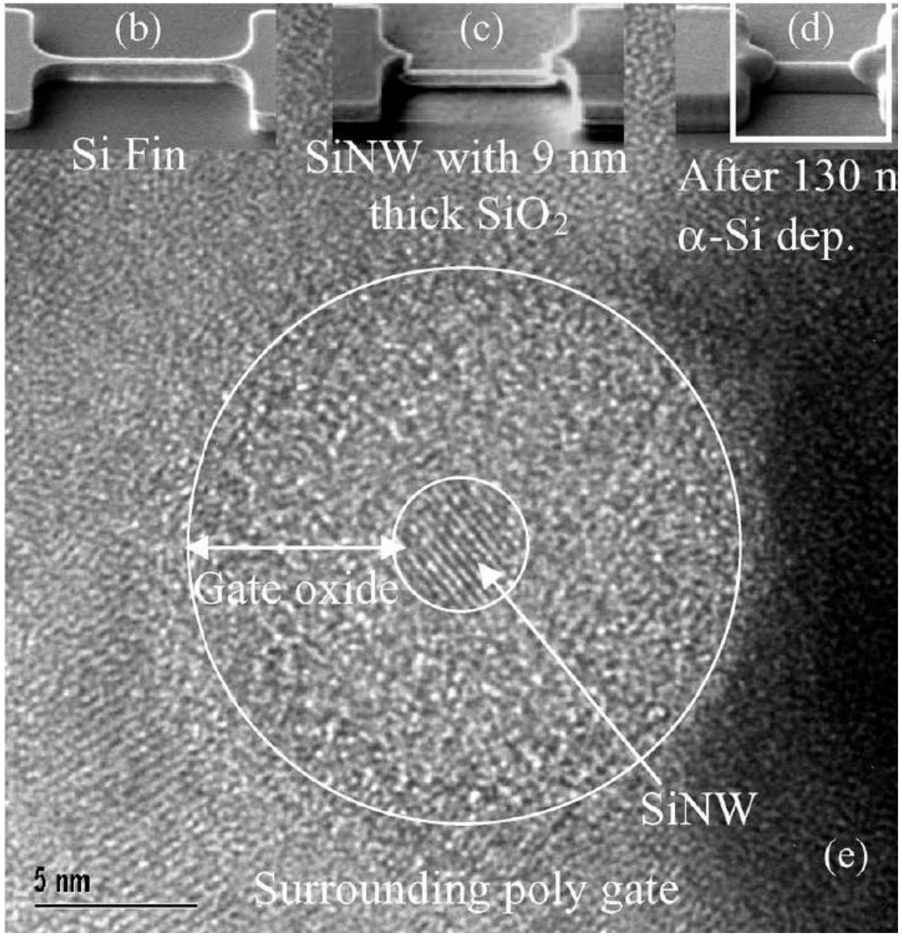


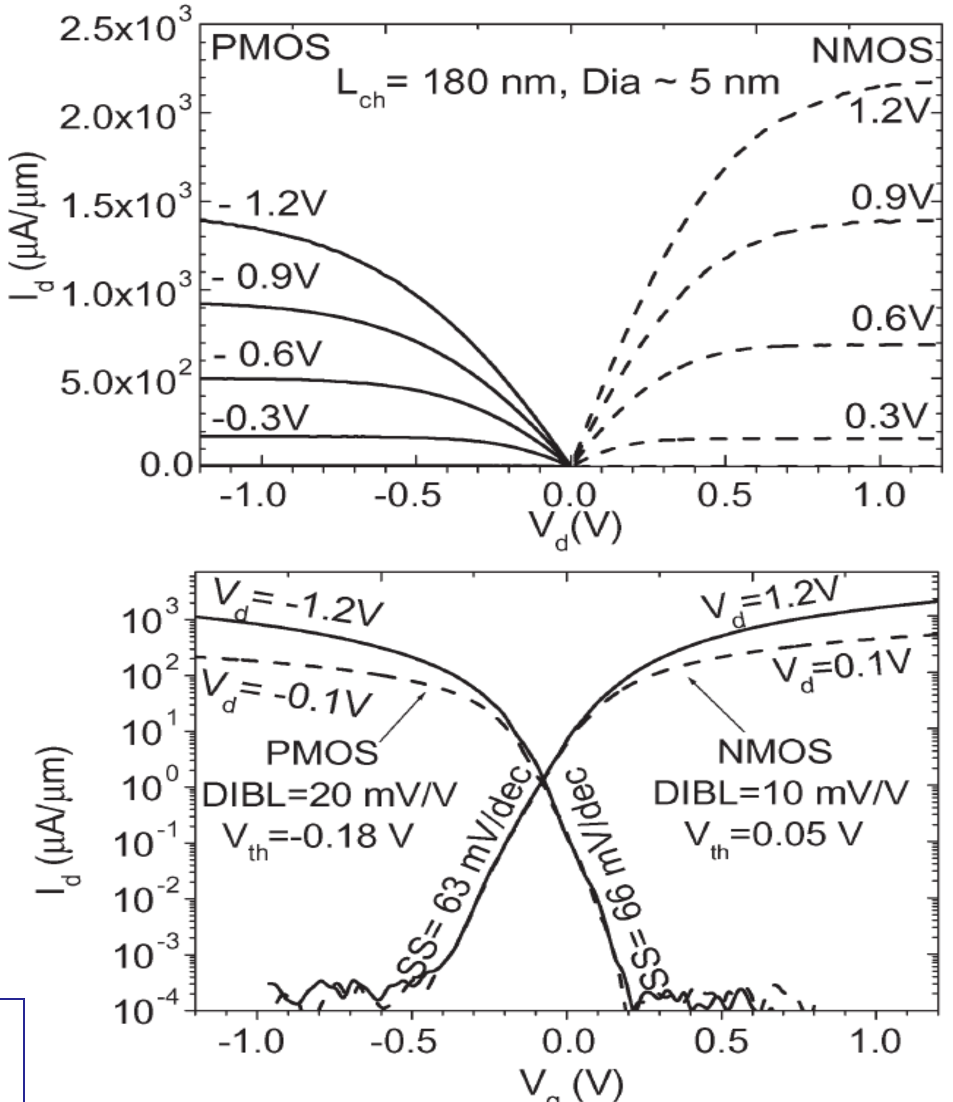
Pi-gate transistor



Electron microscope photographs of a multifingered (three fingers) silicon nanowire transistor.
A: Scanning electron microscope of a device with three parallel nanowires sharing a common gate electrode.
B: Transmission electron microscope photograph of the three silicon nanowires and the common polysilicon gate electrode in an omega-gate electrode configuration.
C: High-resolution transmission electron microscope photograph of a single silicon nanowire.

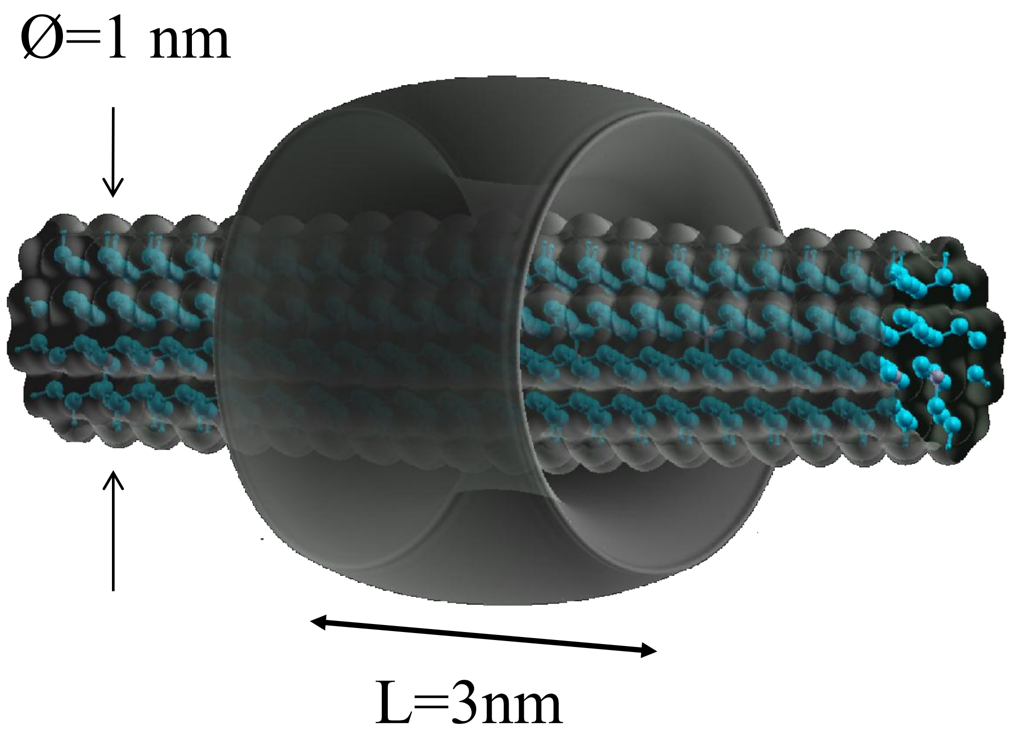
Nanowire MOSFET

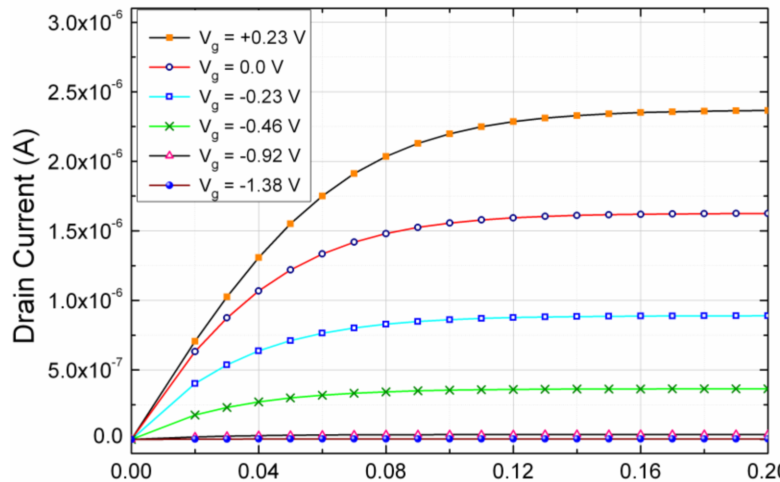


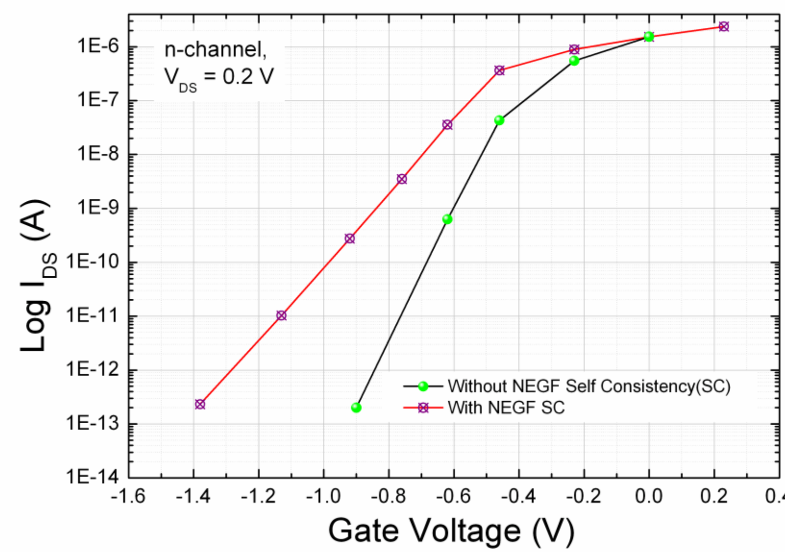


"High-performance fully depleted silicon nanowire (diameter /spl les/ 5 nm) gate-all-around CMOS devices", Singh, N.; Agarwal, A.; Bera, L.K.; Liow, T.Y.; Yang, R.; Rustagi, S.C.; Tung, C.H.; Kumar, R.; Lo, G.Q.; Balasubramanian, N.; Kwong, D.-L., IEEE Electron Device Letters, Vol. 27, no. 5, pp. 383- 386, 2006

How small can you go?



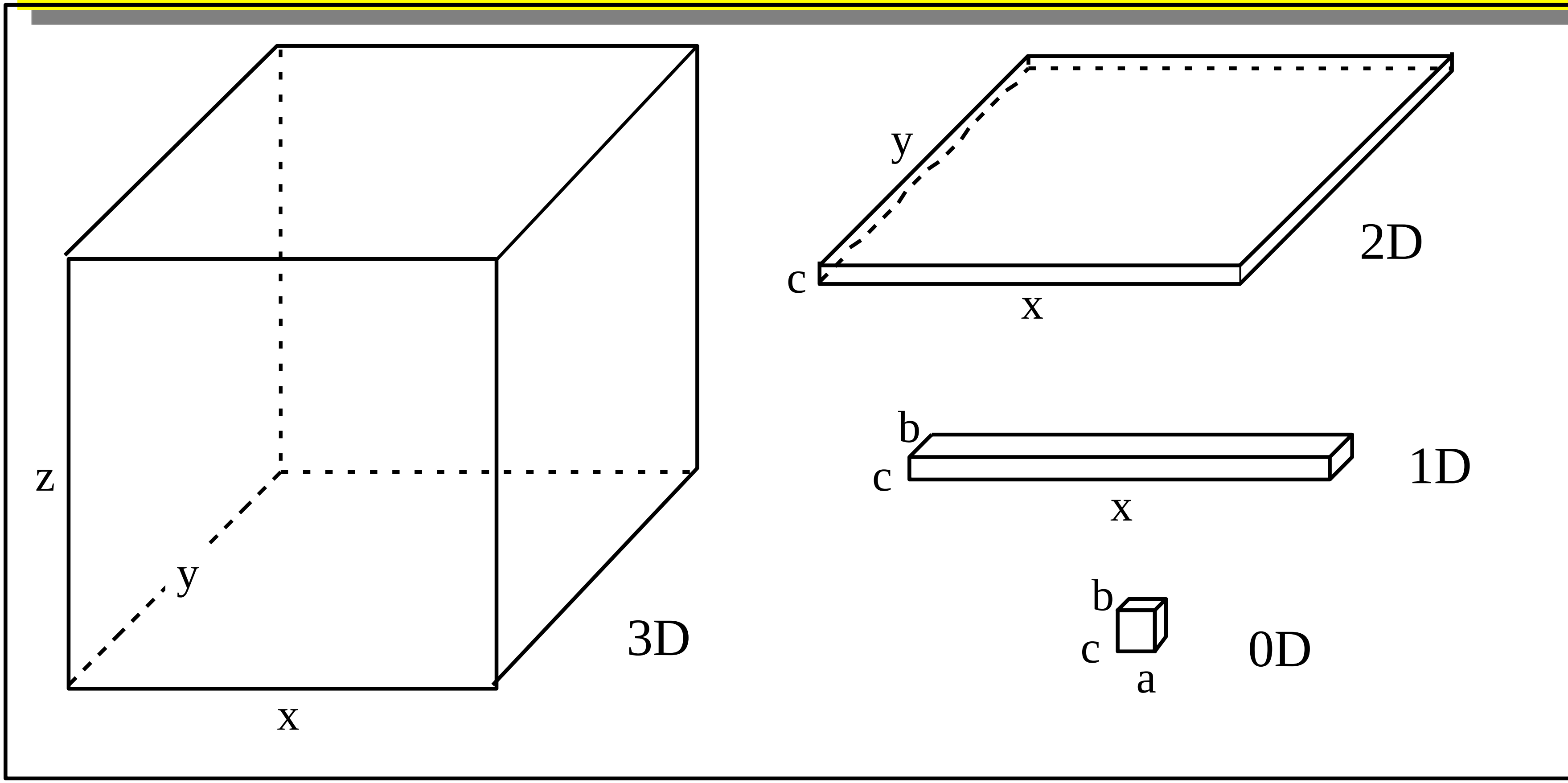




Schrödinger's Equation

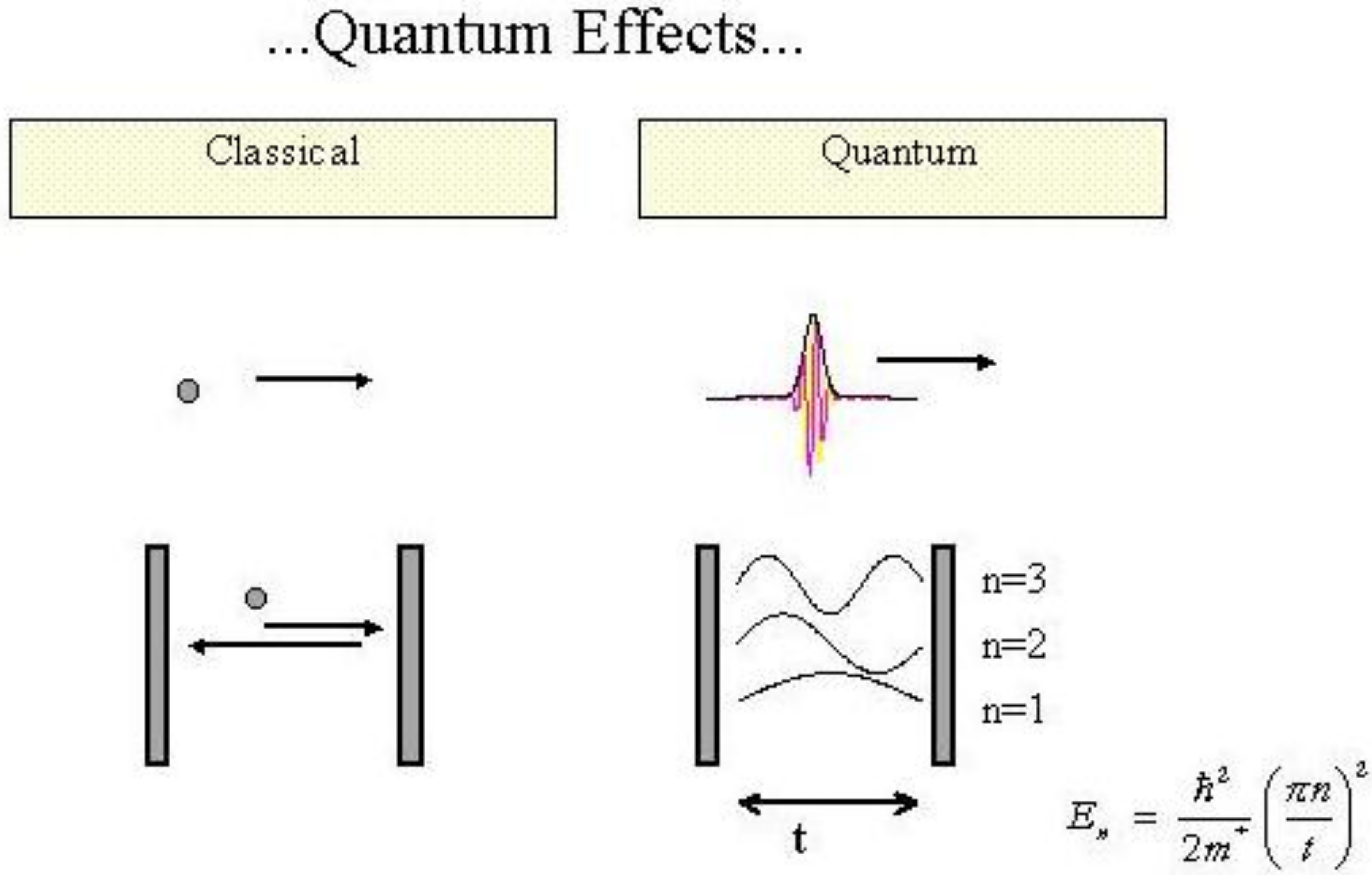
$$-\frac{\eta^2}{2m}\frac{d^2\psi}{dx^2}=(E-V)\psi$$

Low-dimensional devices: 3D, 2D, 1D and 0D

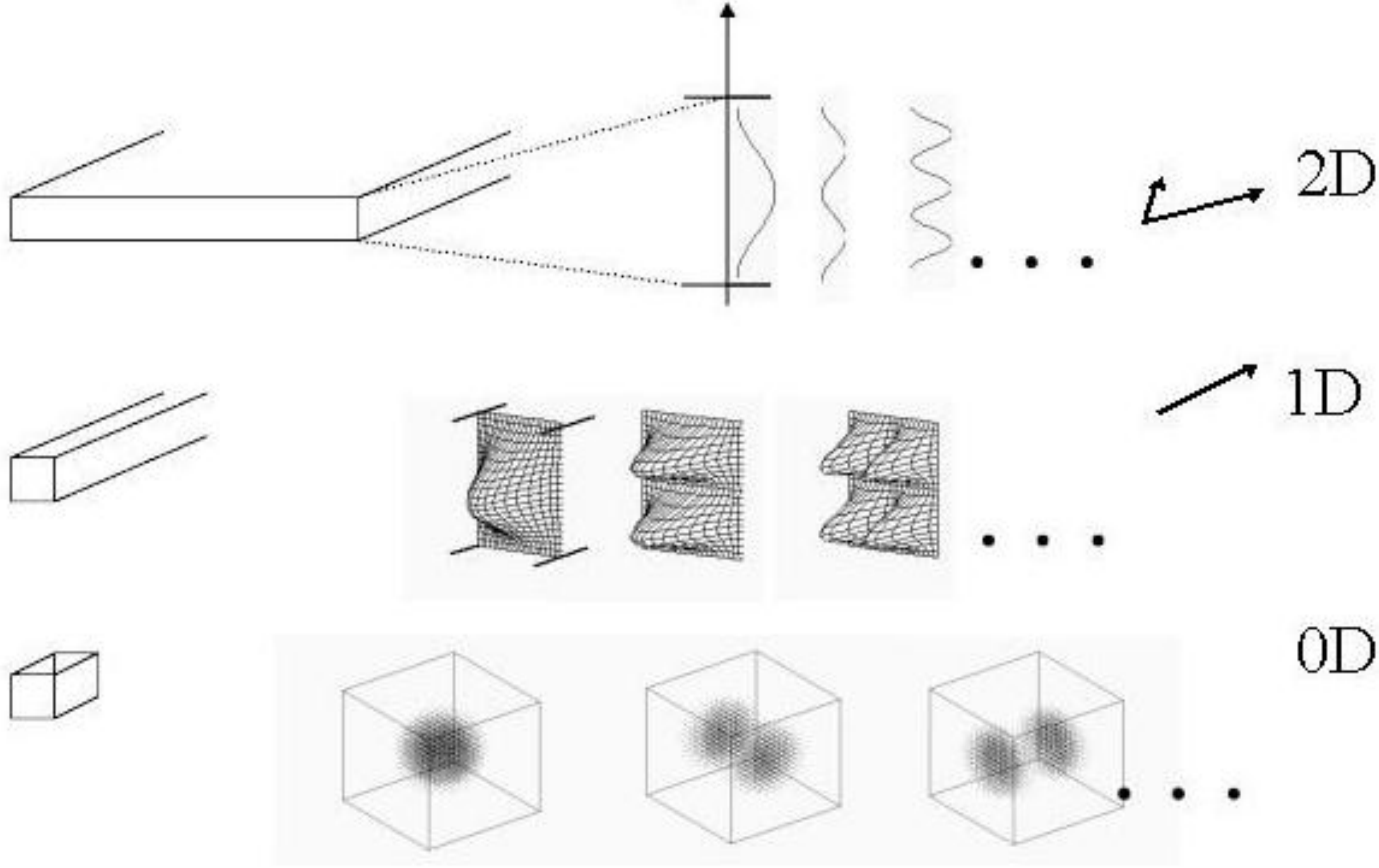


Geometry of 3D, 2D, 1D and 0D samples. x, y, and z represent spatial directions and a, b, and c represent small dimensions in the x, y, and z direction, respectively.

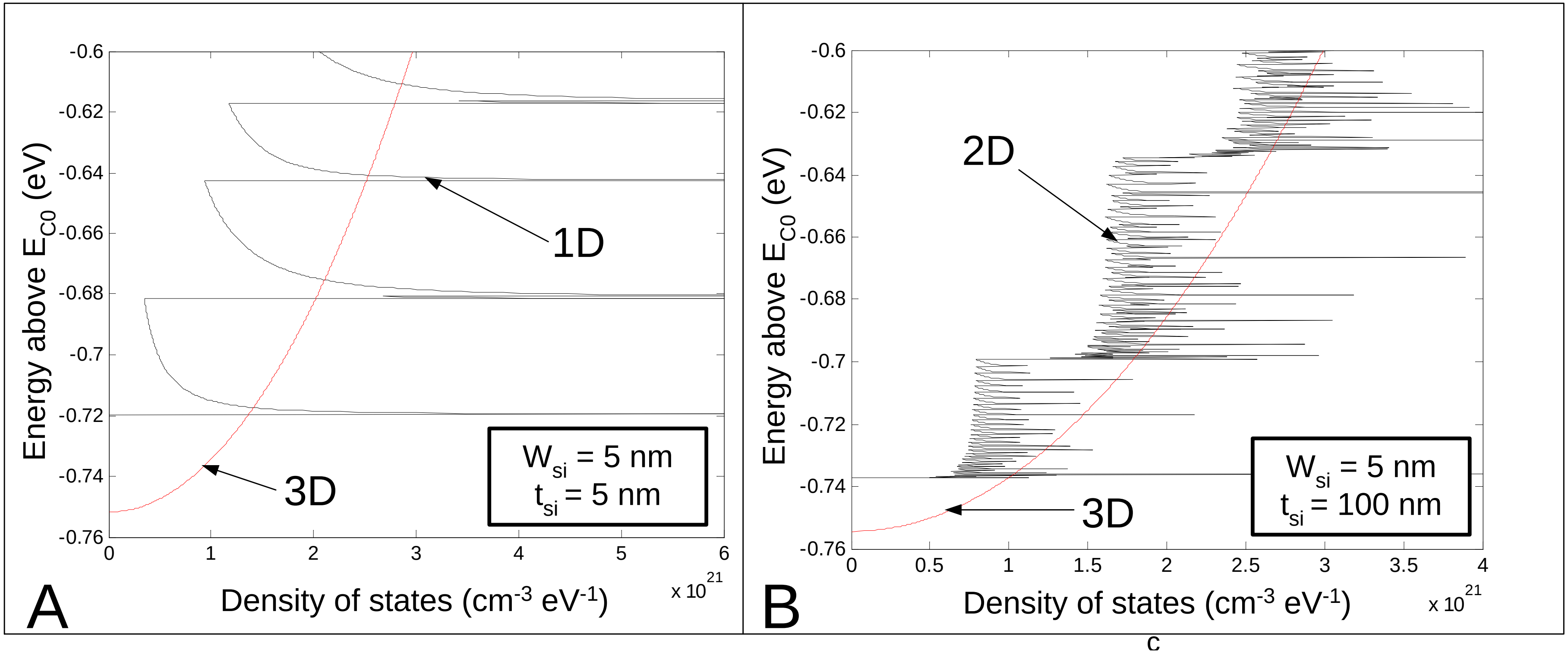
The electron behaves like a wave in direction of confinement



...Dimensional Quantum Effects...

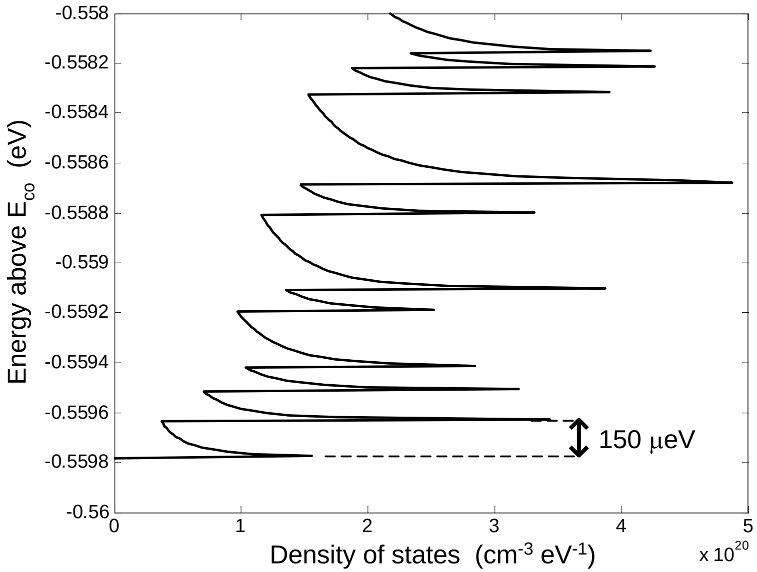


1D/2D Density of States



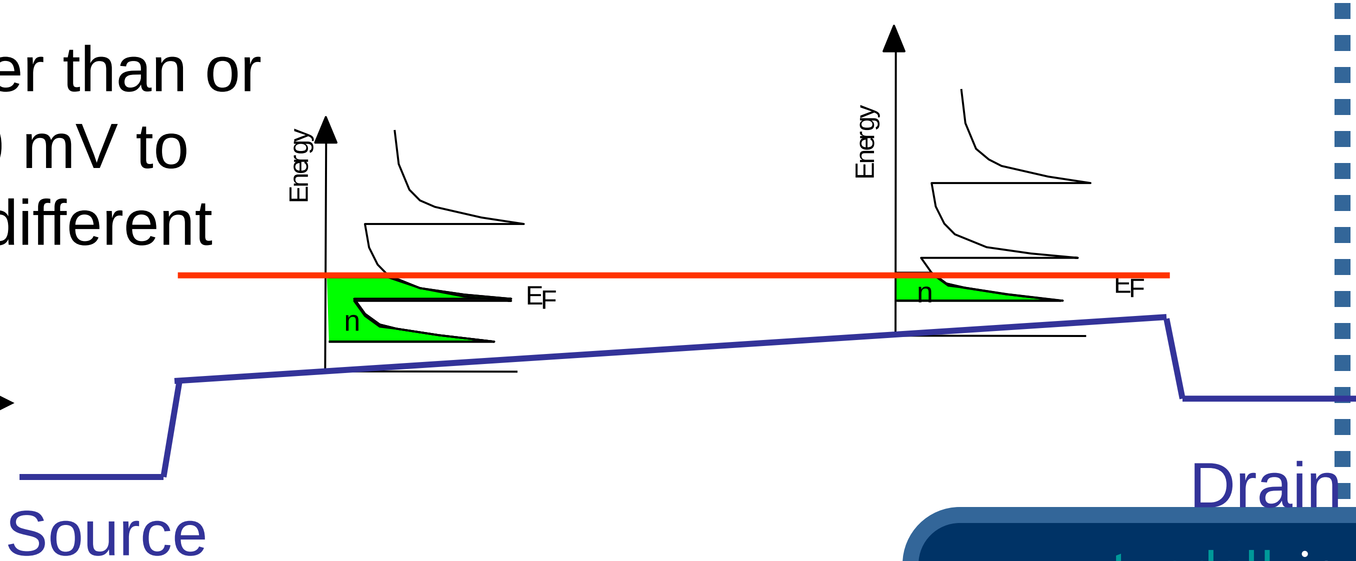
Density of sates vs. energy above Eco for a 1D system (A) and a 2D system (B)

Subband Current Measurement

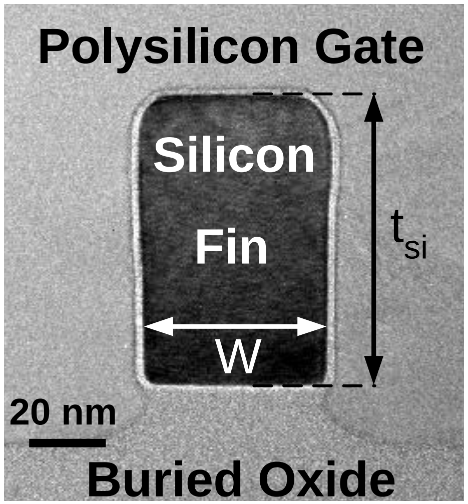


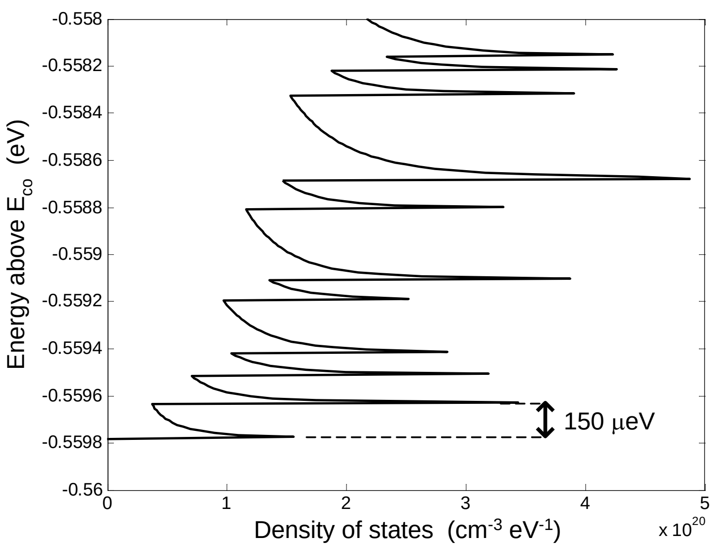
kT must be smaller than or comparable to 150 meV to resolve current in different subbands.

V_{DS} must be smaller than or comparable to 150 mV to resolve current in different subbands.

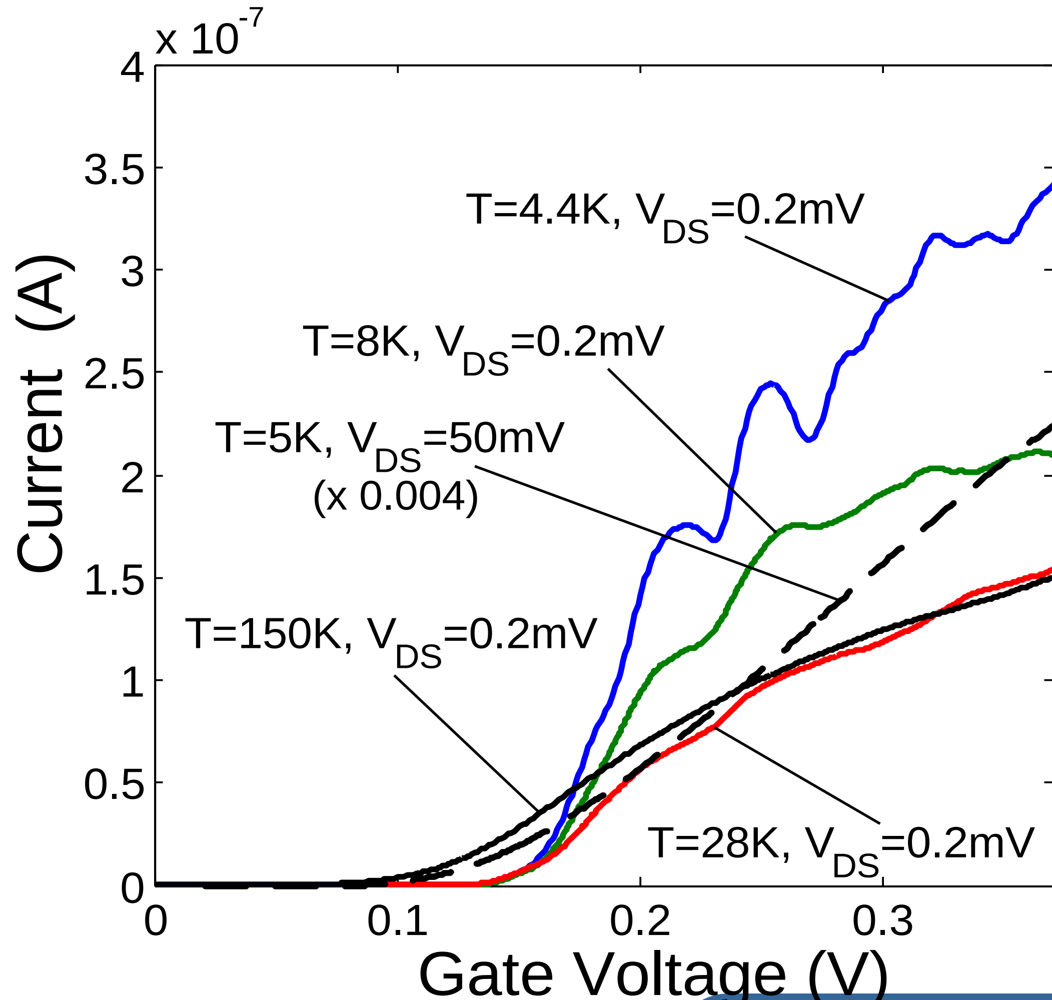


Quantum effect: Inter-subband scattering

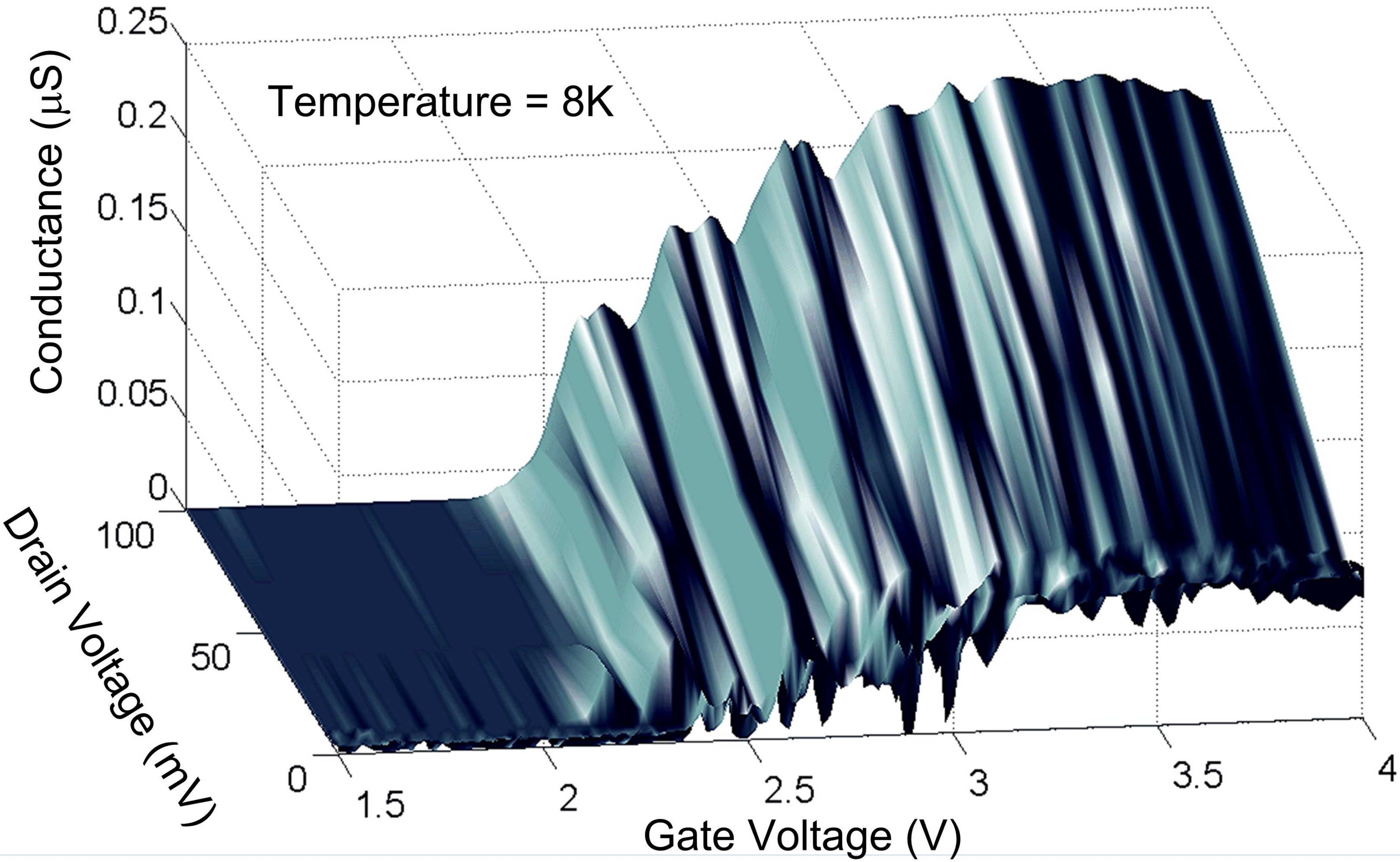




At low temperature



Quantum effect: Inter-subband scattering



Conclusion

$$-\frac{\eta^2}{2m}\frac{d^2\psi}{dx^2}=(E-V)\psi$$