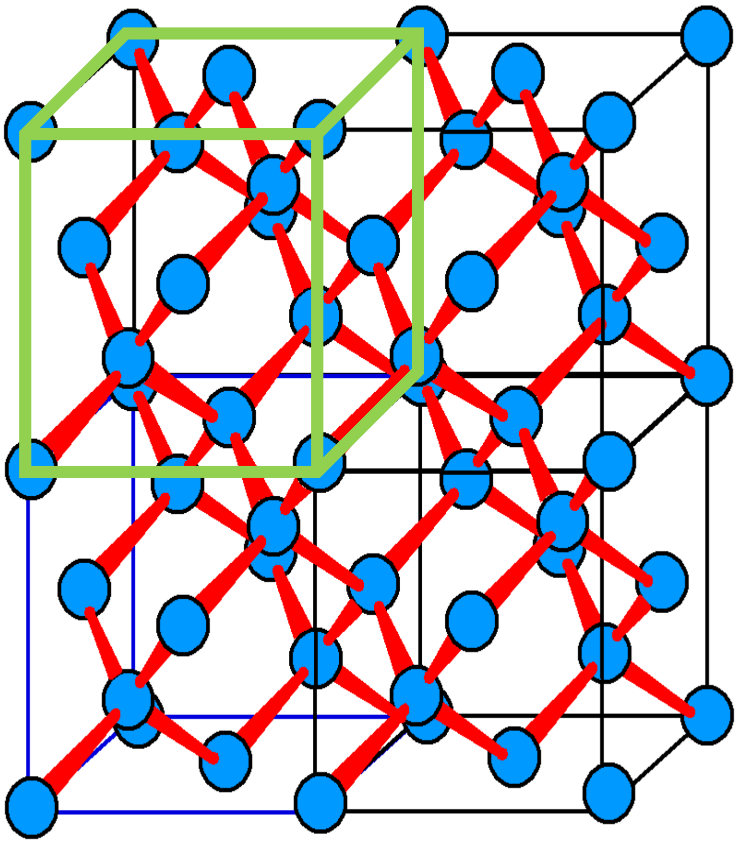
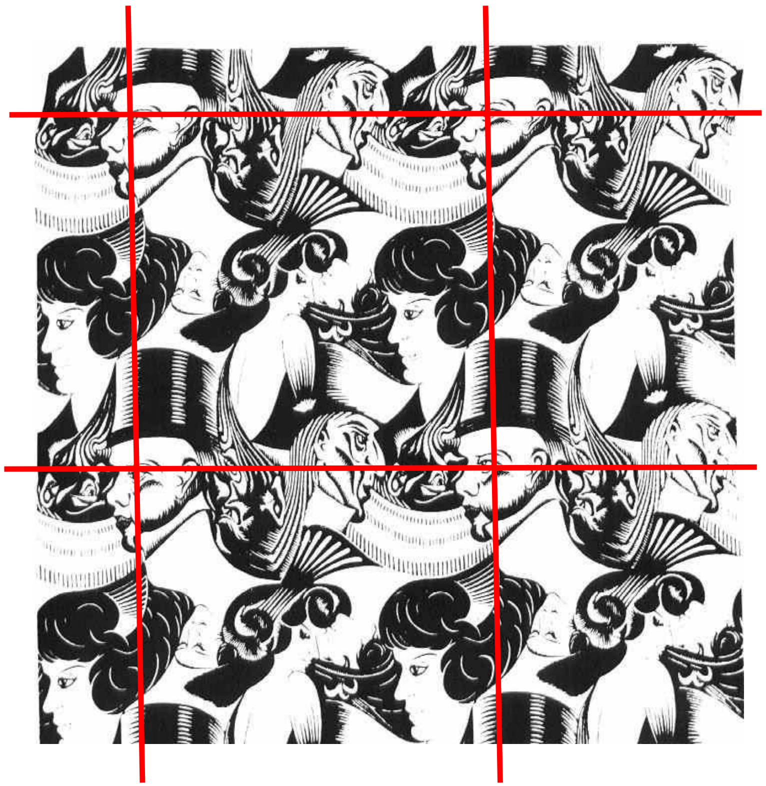
Lecture#2:

Essential Electrical Concept & Basic Structure of Transistor

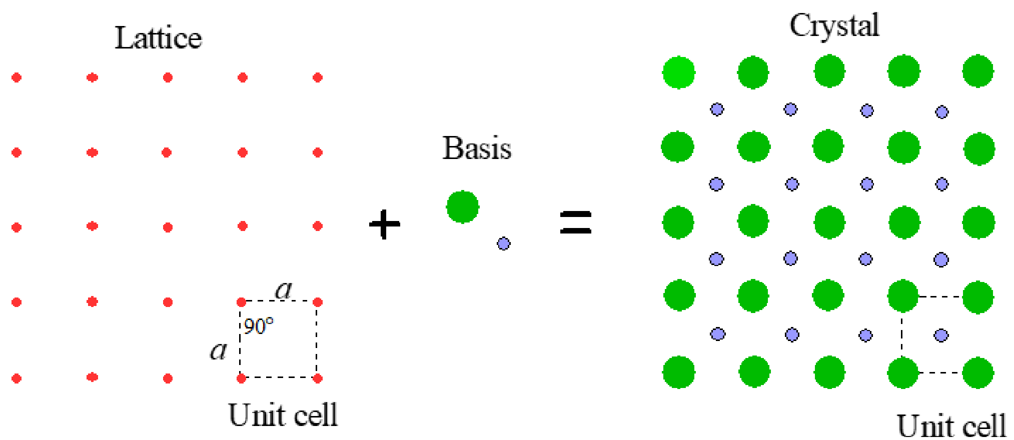
Lattice and Basis (1)

- **Crystal**

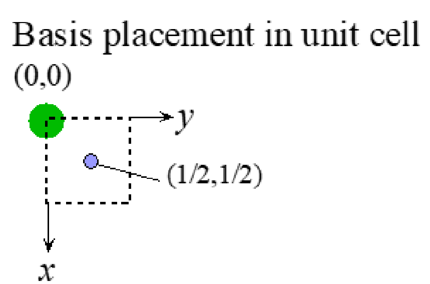




Crystal



(a) (b) (c)



(d)

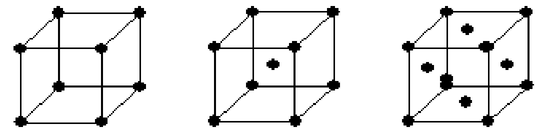
- Simple square lattice.
- The unit cell (the smallest repeating unit) is a square with a side *a*.
- Basis has two atoms.
- Crystal = Lattice + Basis. The unit cell is a simple square with two atoms.

All Possible Lattices

Unit cell geometry

CUBIC SYSTEM
$a = b = c \quad \alpha = \beta = \gamma = 90°$

Many metals, Al, Cu, Fe, Pb. Many ceramics and semiconductors, NaCl, CsCl, LiF, Si, GaAs

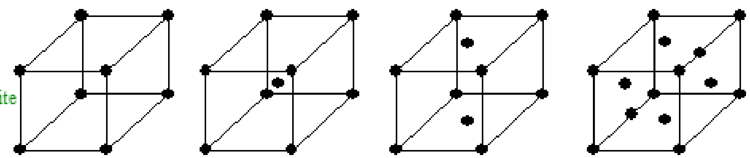


TETRAGONAL SYSTEM
$a = b - c \quad \alpha = \beta = \gamma = 90°$

In, Sn, Barium Titanate, TiO_2

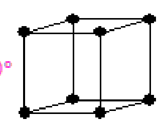
ORTHORHOMBIC SYSTEM
$a - b - c \quad \alpha = \beta = \gamma = 90°$

S, U, Pl, Ga (<30°C), Iodine, Cementite (Fe_3C), Sodium Sulfate



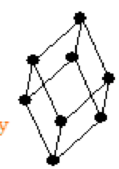
HEXAGONAL SYSTEM
$a = b - c \quad \alpha = \beta = 90° \, ; \, \gamma = 120°$

Cadmium, Magnesium, Zinc, Graphite



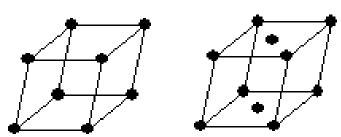
RHOMBOHEDRAL SYSTEM
$a = b = c \quad \alpha = \beta = \gamma - 90°$

Arsenic, Boron, Bismuth, Antimony, Mercury (<-39°C)



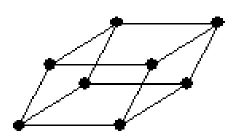
MONOCLINIC SYSTEM
$a - b - c \quad \alpha = \beta = 90° \, ; \, \gamma - 90°$

α–Selenium, Phosphorus
Lithium Sulfate
Tin Fluoride



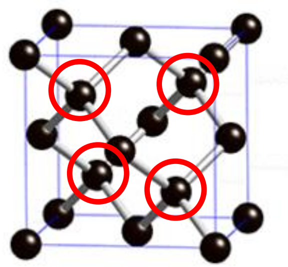
TRICLINIC SYSTEM
$a - b - c \quad \alpha - \beta - \gamma - 90°$

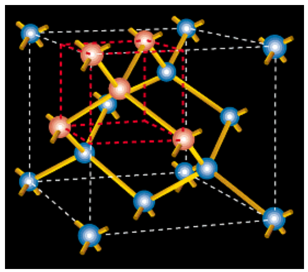
Potassium dicromate



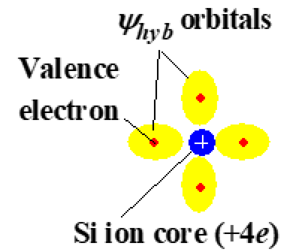
- Seven crystal systems (unit cell geometries)
- Fourteen Bravais lattices

Silicon structure (diamond cubic structure)





- Diamond structure has fcc sublattices

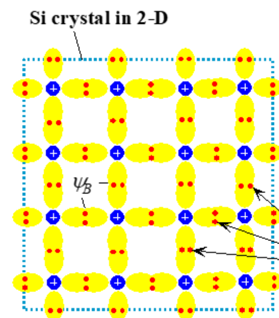


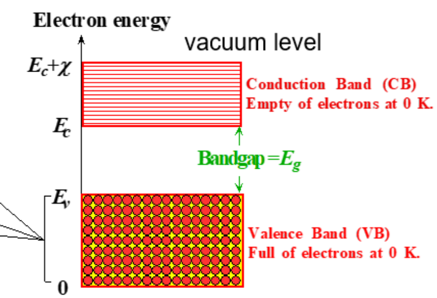
- Si has 4 outer electrons at M shell ([Ne] $3S^2 3P^2$)

S^2P^2

Group # / Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	*	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	**	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Uuq	115 Uup	116 Uuh	117 Uus	118 Uuo
* Lanthanoids			57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	
** Actinoids			89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr	

ı arrangement of the periodic table separates the lanthanoids and actinoids (the f-block) from other elements. The wide periodic ta
the f-block. The extended periodic table adds the 8th and 9th periods, incorporating the f-block and adding the theoretical g-block





- By covalent bonding, Si obtains stability with the shared 4 other electrons

- We call this state “intrinsic semiconductor”

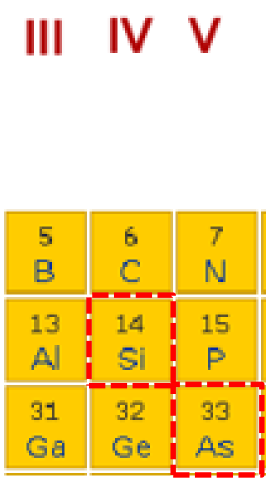
Substitution (doping)

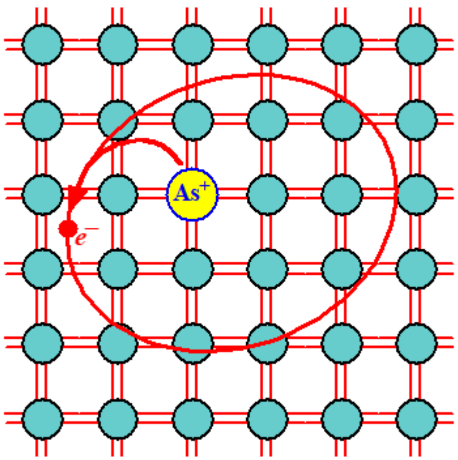
- Group M element is donor when substituting group M-1 element, acceptor when substituting group M+1 element, isoelectronic (no doping) when substituting group M element, double donor (double acceptor) when substituting group M-2 (M+2) elements.

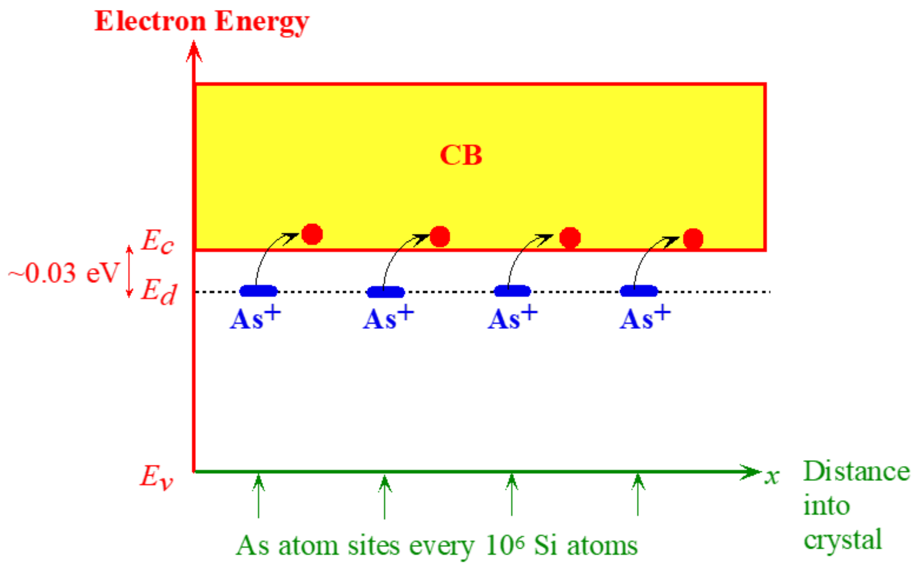
Group / Period	I	II											II	III	IV	V	VI	VII	VIII
1	1 H																		2 He
2	3 Li	4 Be												5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg												13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca		21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr		39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	*	71 Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	**	103 Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Uub	113 Uut	114 Uuq	115 Uup	116 Uuh	117 Uus	118 Uuo
*Lanthanoids			*	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb		
**Actinoids			**	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No		

n-type doping (Si:As)

- Arsenic doped Si crystal.
- The four valence electrons of As allow it to bond just like Si but the fifth electron is left orbiting the As site.
- The energy required to release to free fifth-electron into the CB is very small
  - → Free electron (negative)
  - → N-type Semiconductor; Major carrier is electron







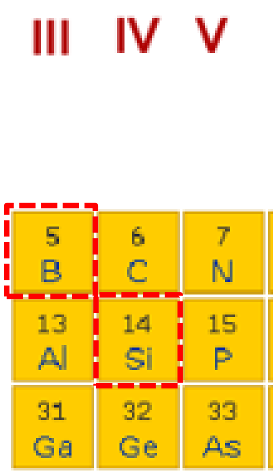
Extrinsic Semiconductor (3)

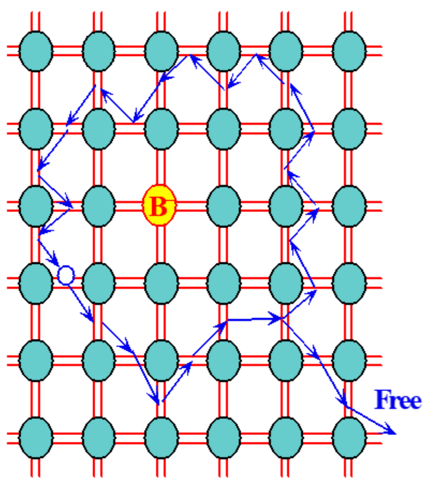
p-type doping (Si:B)

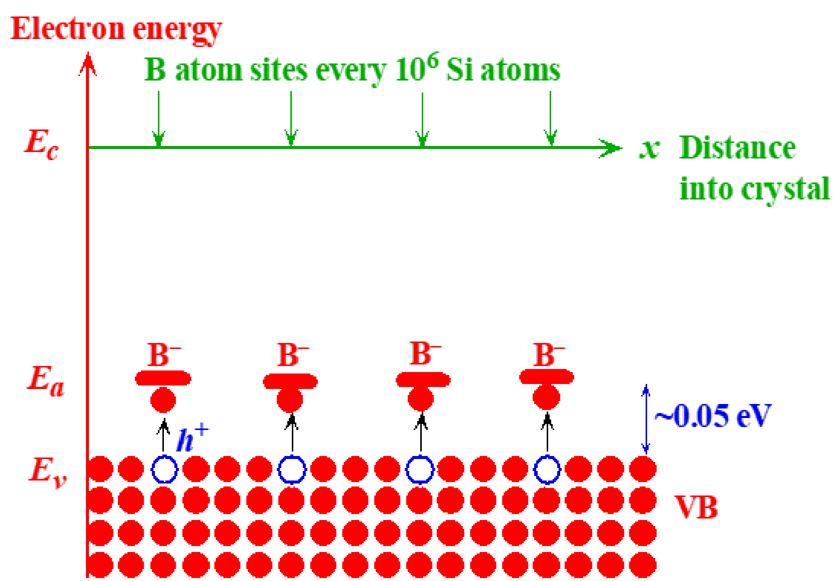
- Boron doped Si crystal.
- B has only three valence electrons.
- When it substitutes for a Si atom one of its bonds has an electron missing (a hole).
- The hole orbits around the B– site by the tunneling of electrons from neighboring bonds.
- Eventually, thermally vibrating Si atoms provides enough energy to free the hole from the B– site into the VB as shown.

  → Hole (positive)

  → P-type semiconductor; Major carrier is hole







Essential Electrical Concept & Basic Structure of Transistor

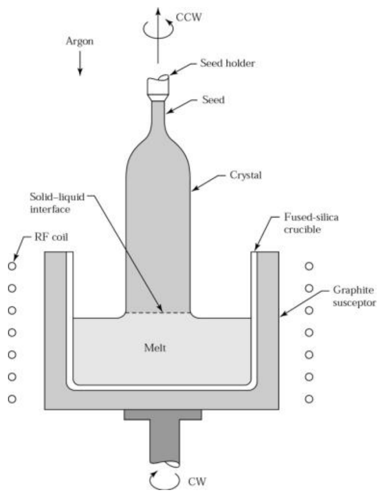
Substrate

- **Substrate : Base body to fabricate device   ex) Si, GaAs, GaN, Sapphire(Al_2O_3), Glass, Plastic**

1) Why Silicon?

- abundant (low-cost) ↔ GaAs
- wide band-gap (high-temp. operation)
  - * Ge : 0.67eV, Si : 1.12eV, GaAs : 1.42eV
- process advantage (SiO_2)

Czochralski crystal puller



2) Crystal growth & wafer production

- wafer growth
  - * Czochralski (CZ) method
  - * Float-zone (FZ) method

◆ Ingot → Flat (type, orientation) → Sawing → Etching → Polishing

Silicon Technology (2)

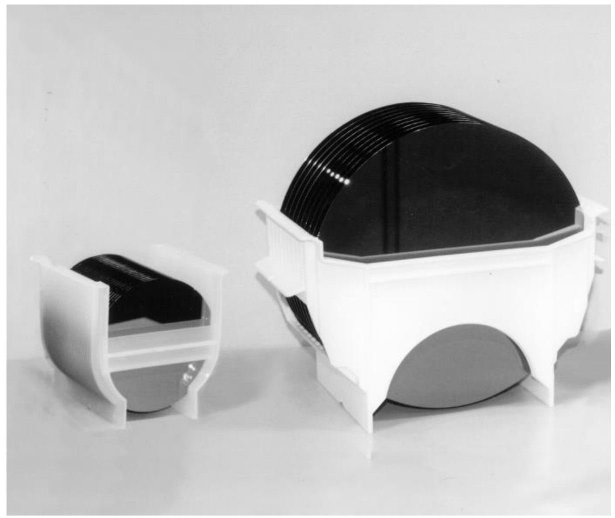
Essential Electrical Concept & Basic Structure of Transistor

- **Substrate (movie)**

Silicon Technology (3)

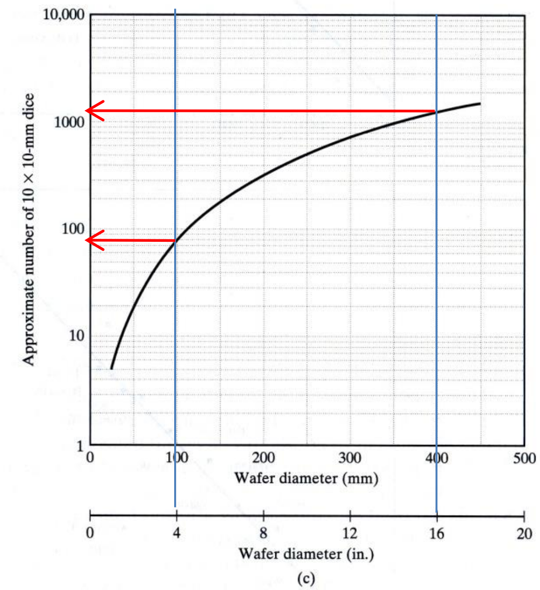
Essential Electrical Concept & Basic Structure of Transistor

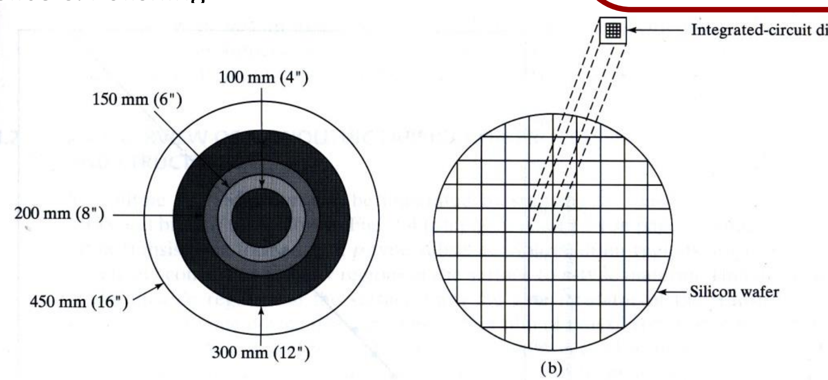
Mono crystal Si Ingot



Slice & Polishing

Size effect





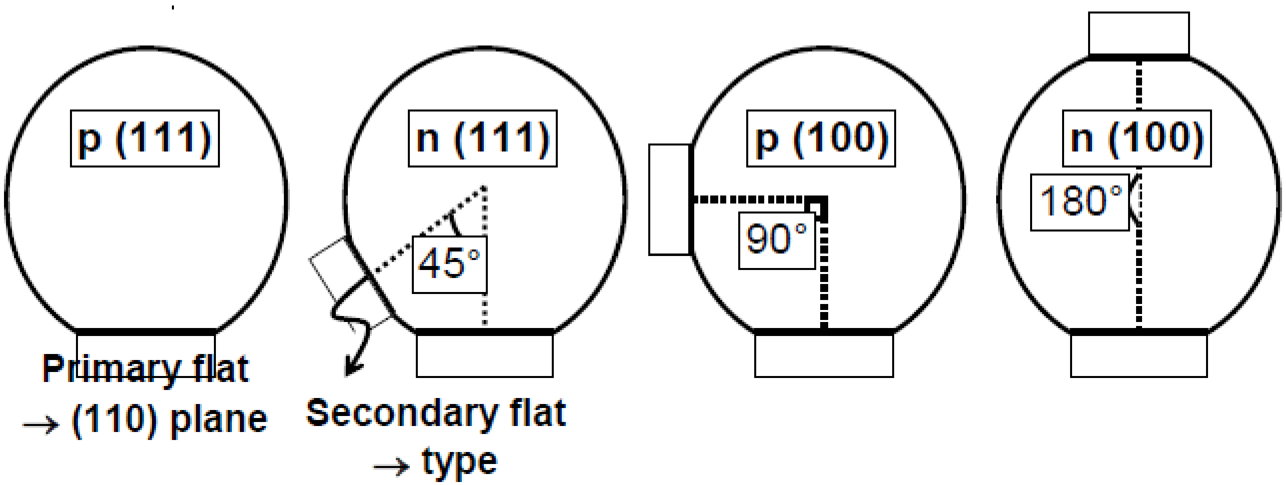
Silicon Technology (4)

Essential Electrical Concept & Basic Structure of Transistor

3) Wafer quality

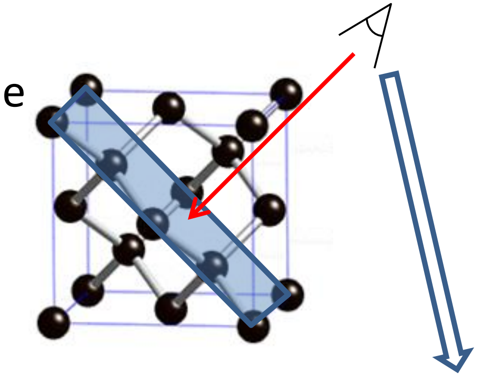
- silicon atoms ≈ 5×10^{22} /cm^3
- dopant concentration ≈ 10^{15} ~ 10^{20} / cm^3
- unintentional impurity concentration < 10^{13} /cm^3
  - → 1 impurity for every 10^9 silicon atoms
  - → 1 foreigner in china

4) Wafer type & orientation

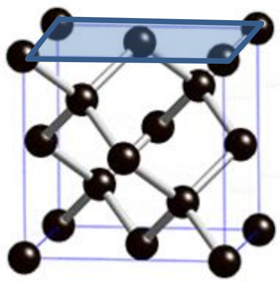


Lattice plane

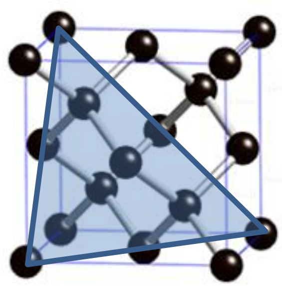
(110) plane

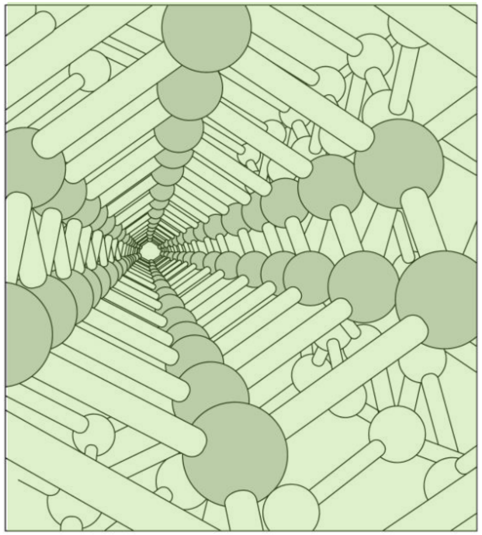


(100) plane



(111) plane

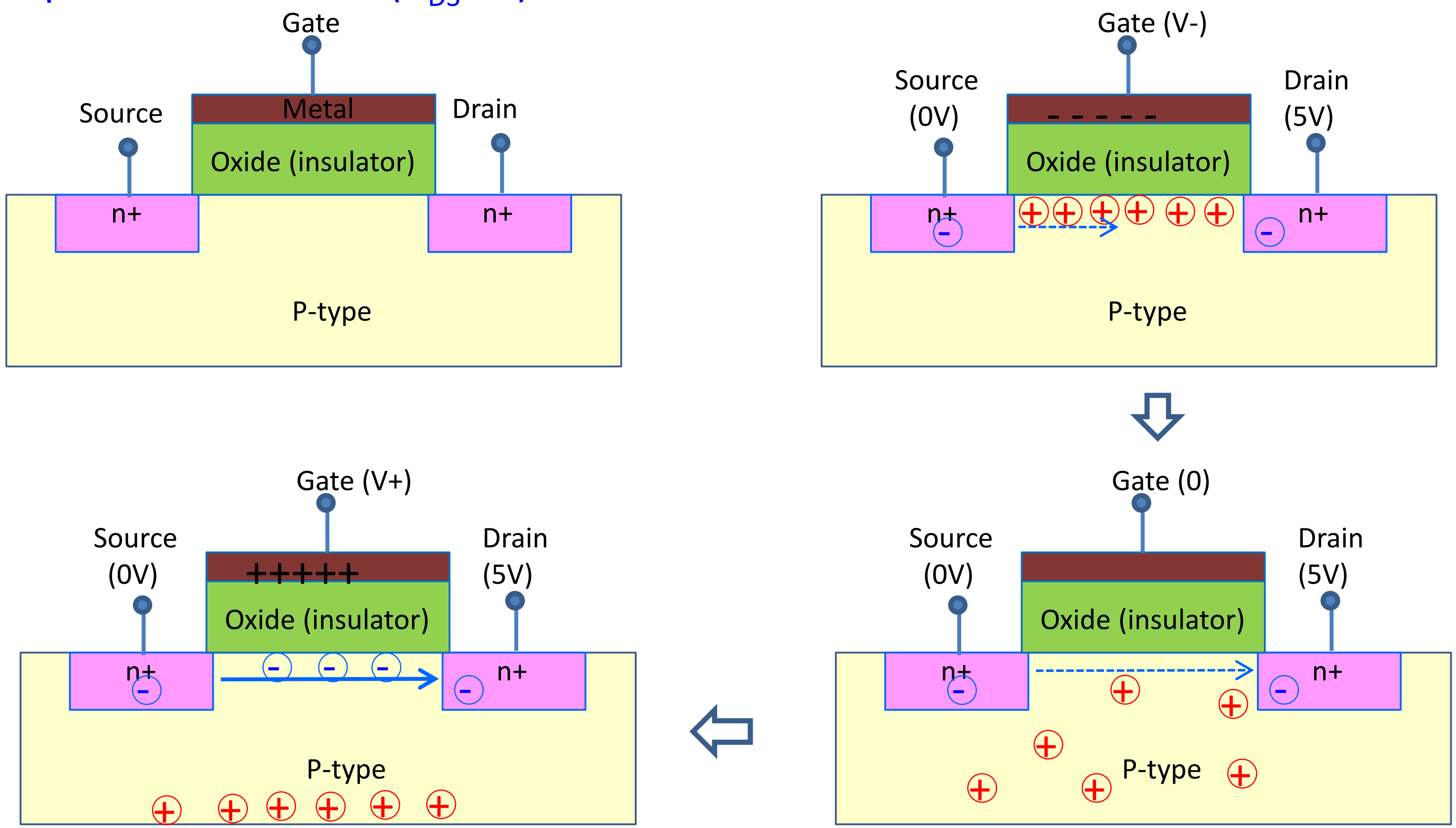




http://www.dawgsdk.org/crystal/en/library/diamond#0001

Essential Electrical Concept & Basic Structure of Transistor

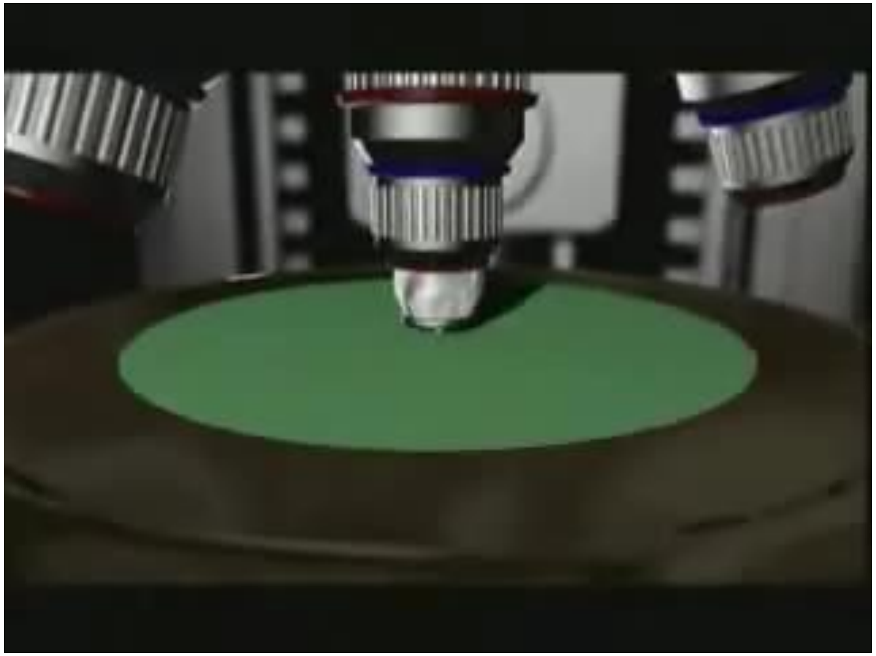
- **NMOS (n-type metal-oxide-semiconductor)**
  - In operation, a positive gate voltage (V_{GS}> 0) induces the accumulation of electrons near the dielectric–semiconductor interface, which flow from source to drain under a positive drain bias (V_{DS}> 0).

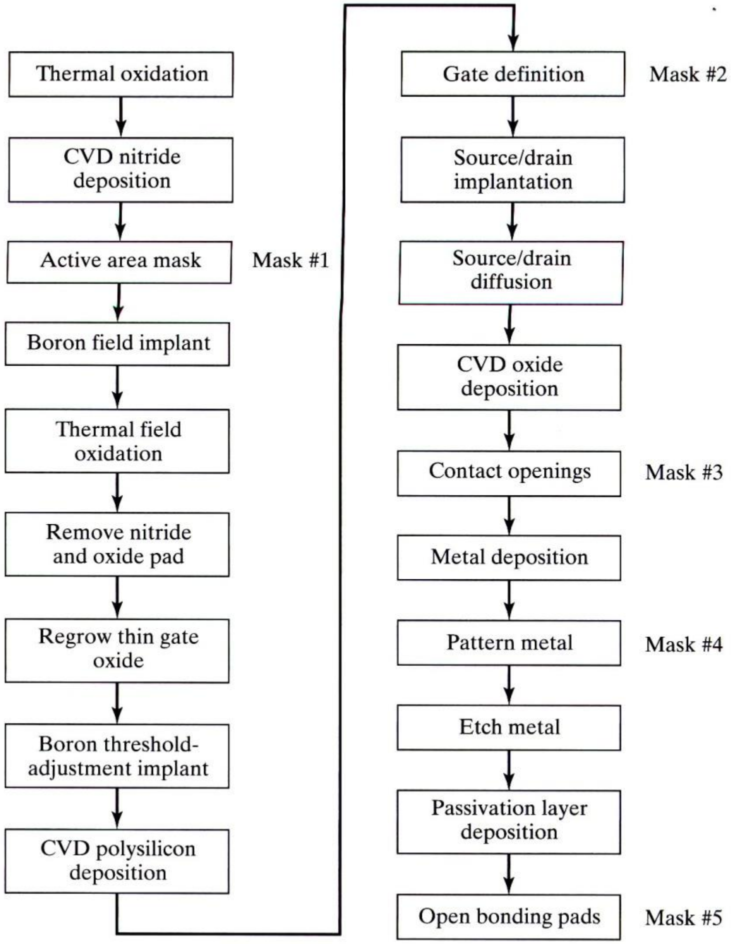


NMOS Process

Essential Electrical Concept & Basic Structure of Transistor

Basic NMOS process flow

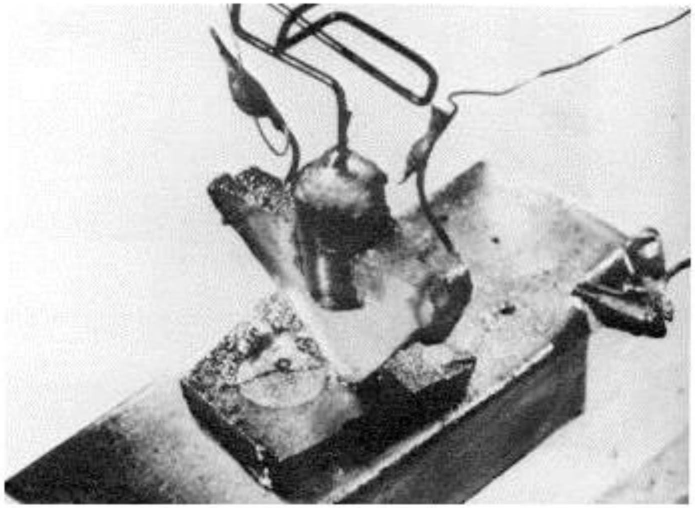




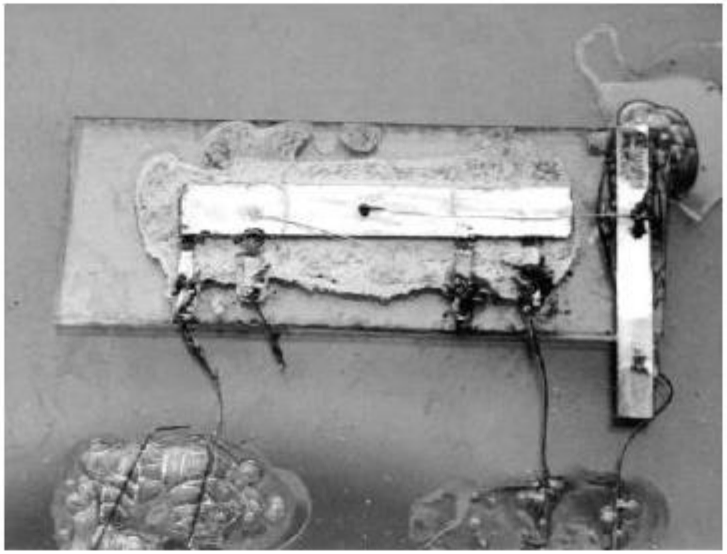
History of Transistors (1)

Essential Electrical Concept & Basic Structure of Transistor

- **1948 - 1958**



First point-contact transistor invented at Bell Labs. (Source: Bell Labs.)



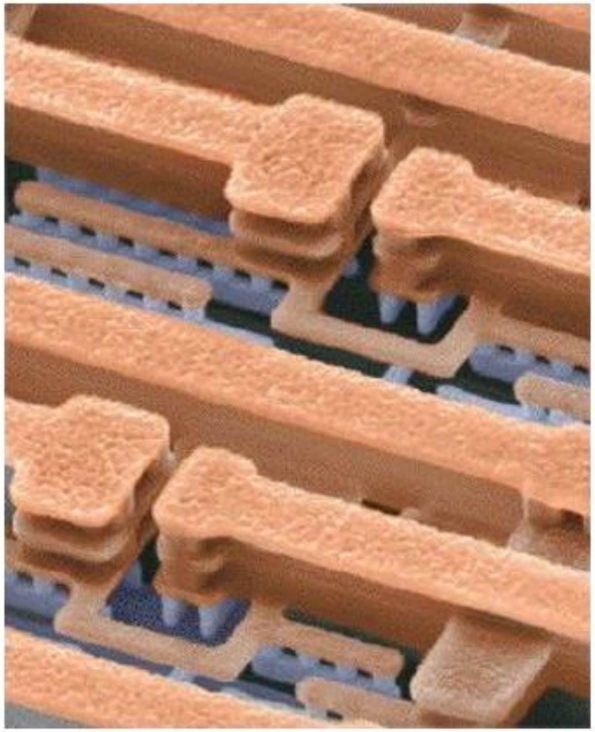
The first monolithic integrated circuit, about the size of a finger tip, was documented and developed at Texas Instruments by Jack Kilby in 1958. The IC was a chip of a single Ge crystal containing one transistor, one capacitor, and one resistor. (Source: Texas Instruments)

History of Transistors (2)

Essential Electrical Concept & Basic Structure of Transistor

- **1990s**

A contemporary transistor, shown in profile through a transmission electron microscope, measures about two micron across and has elements as small as 0.4 micron. (From article entitled "Toward Point One" in *Scientific American*, February 1995, Page 90.)

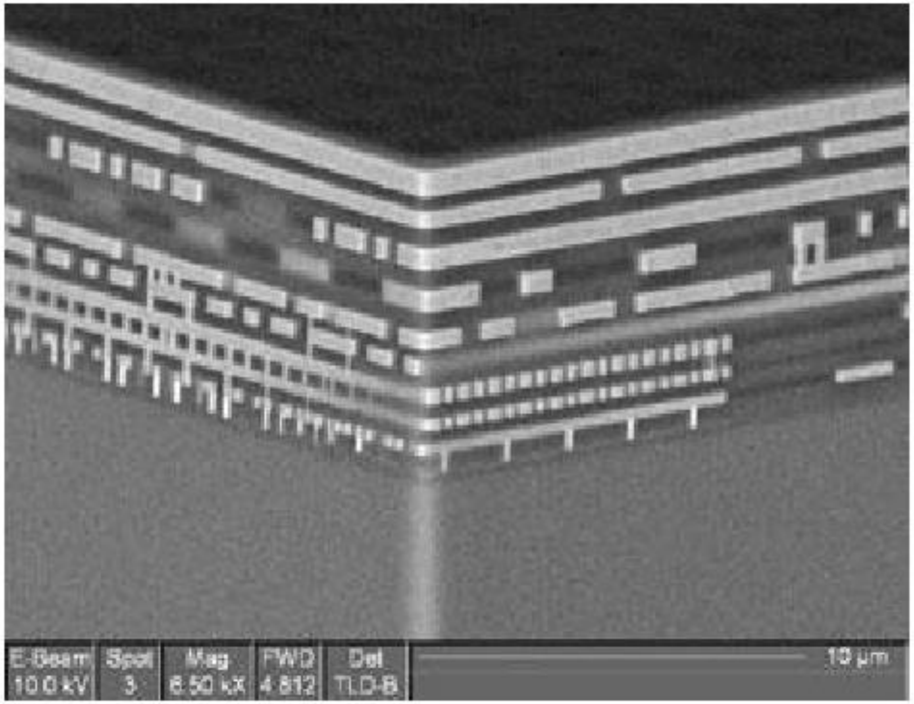


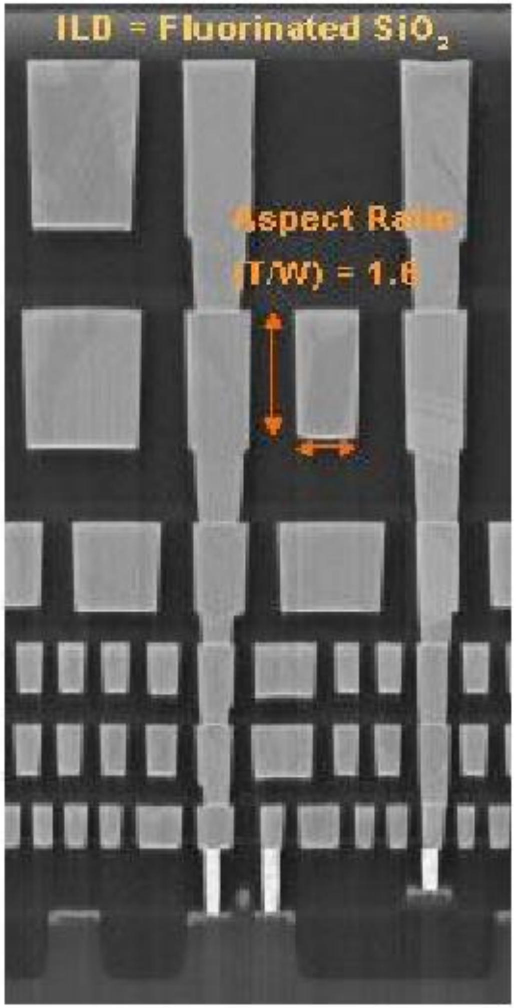
SEM view of three levels of copper interconnect metallization in IBM's new faster CMOS integrated circuits (Photograph courtesy of IBM Corporation, 1997.)

History of Transistors (3)

Essential Electrical Concept & Basic Structure of Transistor

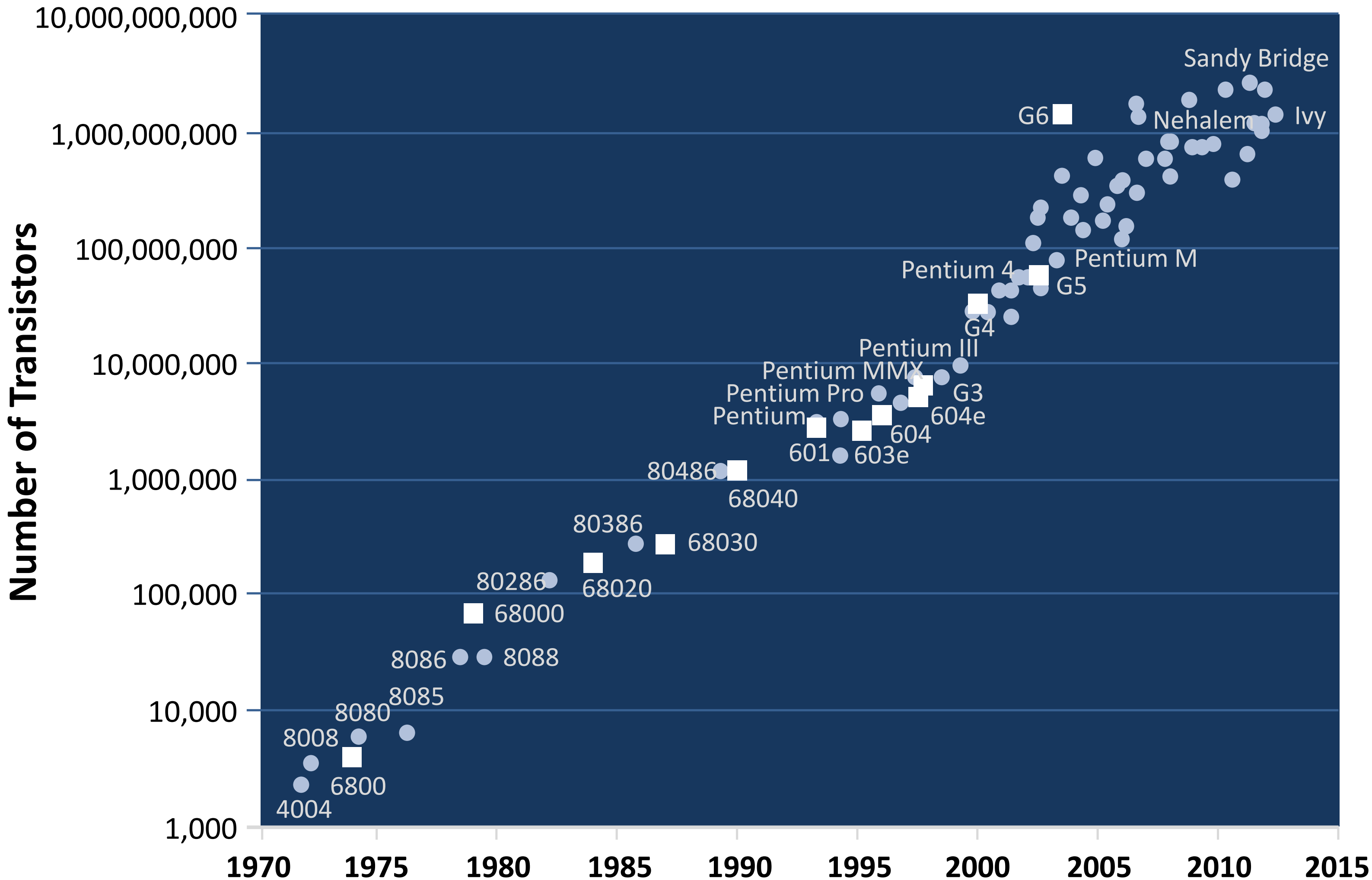
- **Multilayer Interconnects**





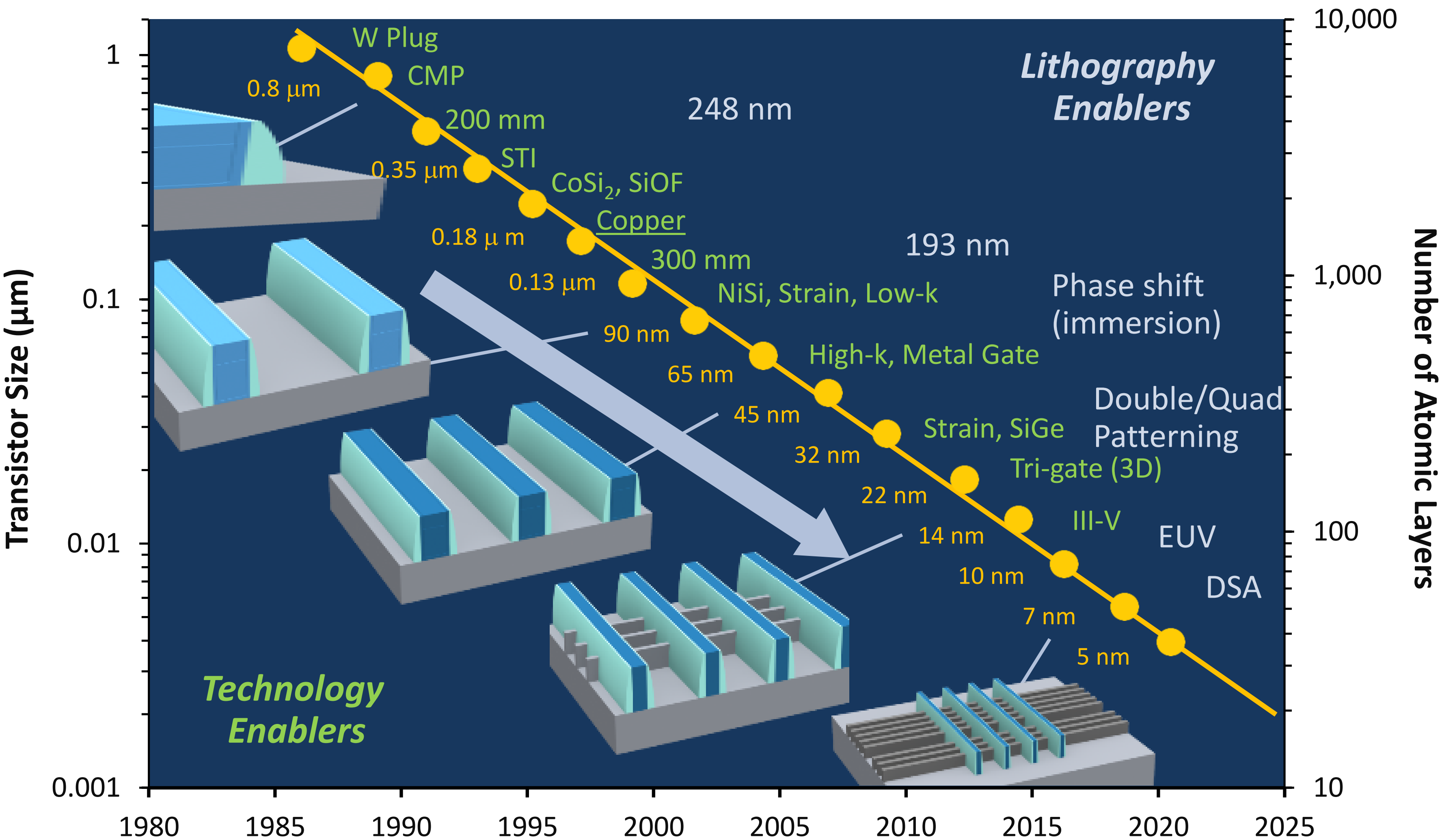
Classic View of Moore's Law

Essential Electrical Concept & Basic Structure of Transistor



Continuous Innovation Enables Continuation of Moore's Law

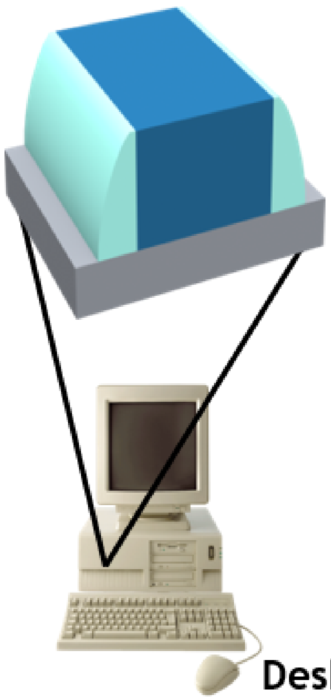
Essential Electrical Concept & Basic Structure of Transistor



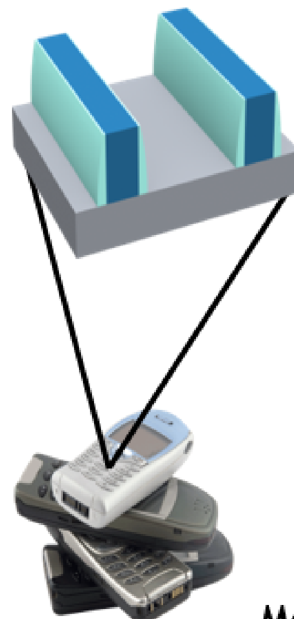
Scaling Progression: Entering the Atomic Scale Era

Essential Electrical Concept & Basic Structure of Transistor

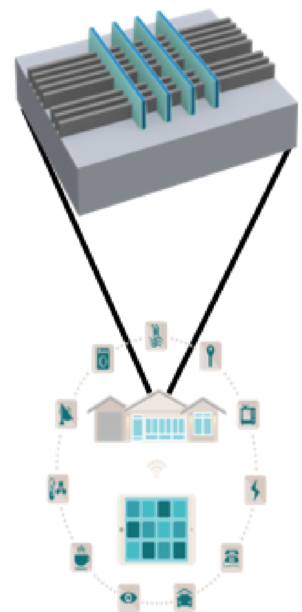
1980s	2000s	What's Next?
Microelectronics	**Nanoelectronics**	**Atomic Scale Era**
10,000 atoms	1,000 atoms	~50 atoms
	Precision Important	*Every Atom Matters*



Desktop

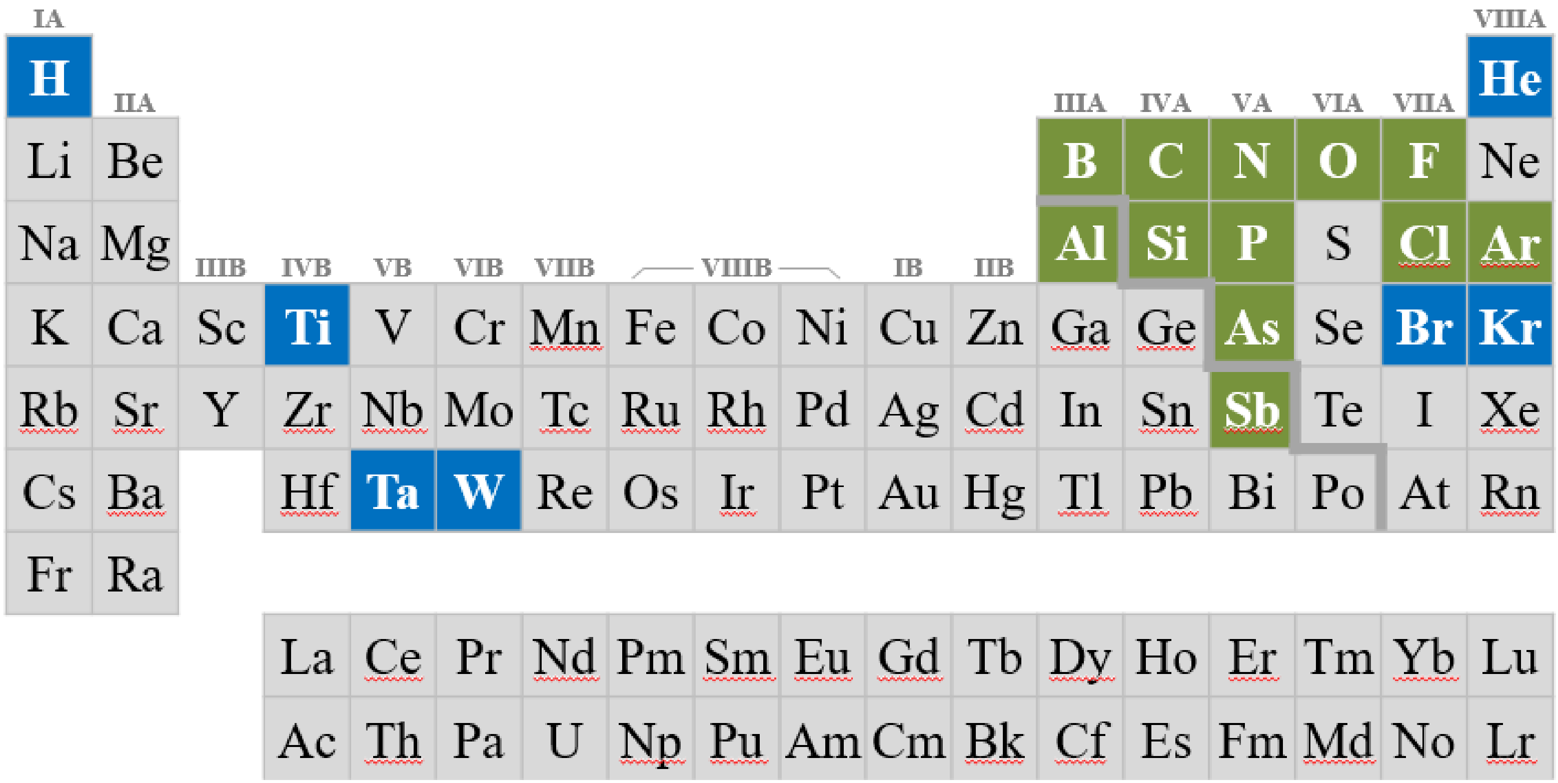


Mobile



IoT

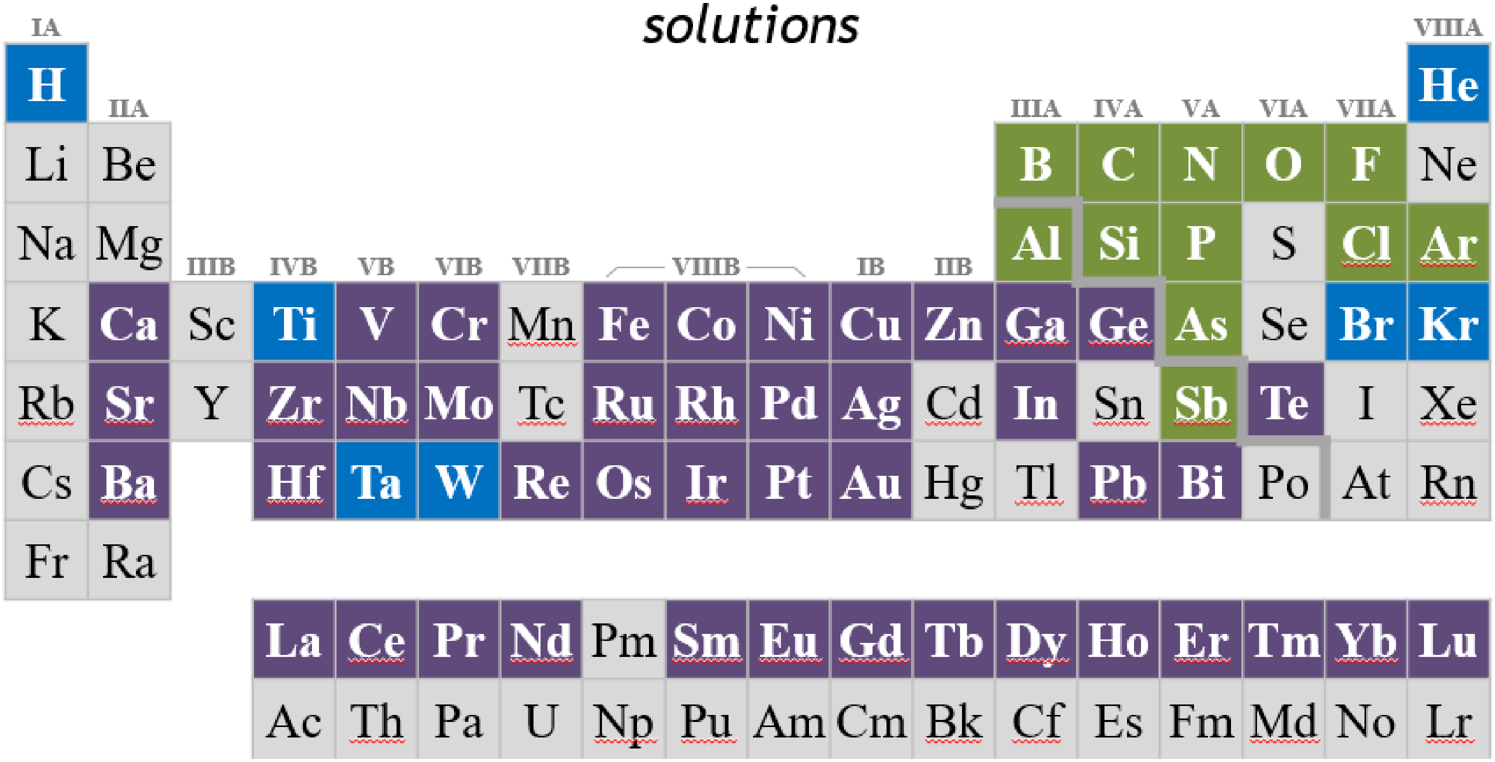
- **Pre-2000**



■ *Materials used in the 80s* ■ *Added in the 90s*

Source: ITRS 2005, Lam Research

Full periodic table is being explored for potential solutions



■ *Materials used in the 80s* ■ *Added in the 90s* ■ *Added or evaluated since 2000*

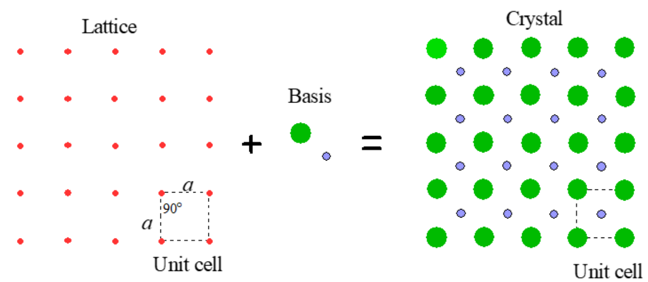
Source: ITRS 2005, Lam Research

Summary

Essential Electrical Concept & Basic Structure of Transistor

- **The unit cell:** the smallest repeating unit

- Crystal = Lattice + Basis.



- **Silicon:** Diamond structure / 4 outer electrons at M shell ([Ne] $3S^2 3P^2$) / by covalent bonding, Si obtains stability with the shared 4 other electrons.

- Doping: Group M element is donor when substituting group M-1 element, acceptor when substituting group M+1 element.
  : n-type → Free electron (negative), major carrier is electron
  : p-type → Hole (positive), major carrier is hole

- **NMOS transistor:** In operation, a positive gate voltage ($V_{GS} > 0$) induces the accumulation of electrons near the dielectric–semiconductor interface, which flow from source to drain under a positive drain bias ($V_{DS} > 0$).