

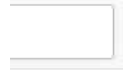
Physics of Semiconductor Devices

Peter Hadley

Oct. 4, 2023

Physics of Semiconductor Devices

- Diodes, solid state lasers, transistors
- Computing, communications
- Controllers: vacuum cleaners, coffee makers, etc.
- Transportation, autonomous driving, electric cars
- Efficient lighting, solar cells, displays
- Lasers



PHT.301 Physics of Semiconductor Devices

Outline

Home
Outline
Introduction
Electrons in crystals
Intrinsic Semiconductors
Extrinsic Semiconductors
Transport
pn junctions
Contacts
JFETs/MESFETs
MOSFETs
Bipolar transistors
Opto-electronics
Lectures
Books
Exam questions
Mathematical expressions
TUG students
Student projects

- **Introduction**
 - Semiconductors, transistors, and the electronics industry
- **Semiconductor crystals**
 - Energy bands W
 - Crystal structure W
 - Bravais lattice W
 - Miller indices W
 - Examples of crystal structures W
 - silicon, GaN (wurzite), SiC 4H, ZnO (wurzite), diamond
 - simple cubic, fcc, bcc, hcp, zinblende
 - Wave and particle nature of electrons
 - k-space
 - Density of states W Some examples: Al fcc, Au fcc, Cu fcc, Pt fcc, W bcc, Si diamond, Graf
 - Pauli exclusion principle W
 - Fermi function W
 - Fermi energy W
 - Metals, semiconductors, and insulators
 - Metal band structure
 - Semiconductor band structure
 - Absorption and emission of photons
 - Direct and indirect band gaps W
- **Intrinsic semiconductors**
 - Conduction band
 - Valence band
 - Effective mass W
 - Holes W
 - Boltzmann approximation
 - Law of mass action W
 - Fermi energy of an intrinsic semiconductor ► EN 2:36
 - Intrinsic semiconductors with a split-off band

Examination

1 hour written exam

One page of handwritten notes

1 Contribution to improve the course

Chapter summaries

Solutions to exam questions

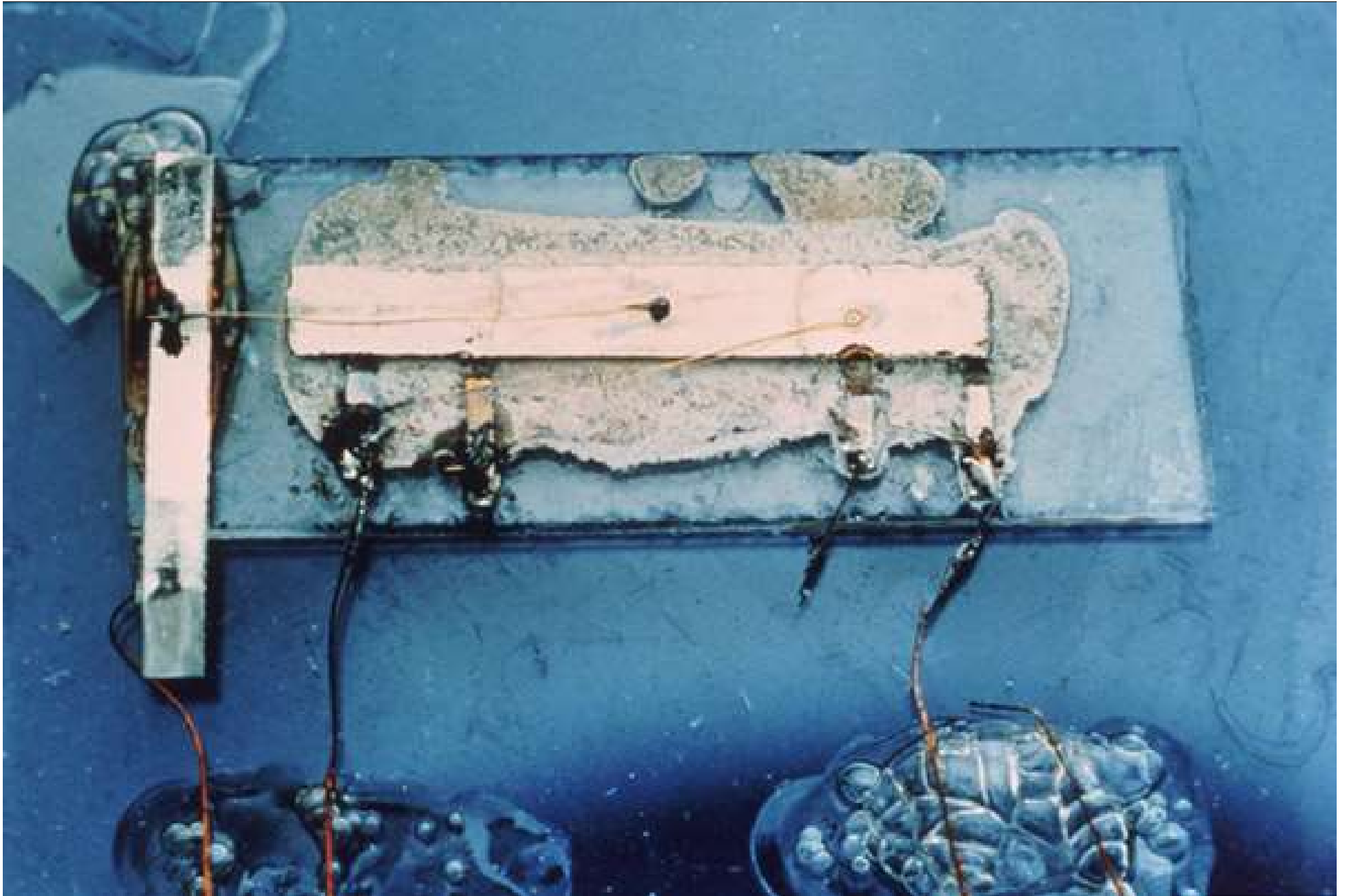
Simulations

Videos

Oral exam

The first point contact transistor
William Shockley, John Bardeen, and Walter Brattain
Bell Laboratories, Murray Hill, New Jersey (1947)



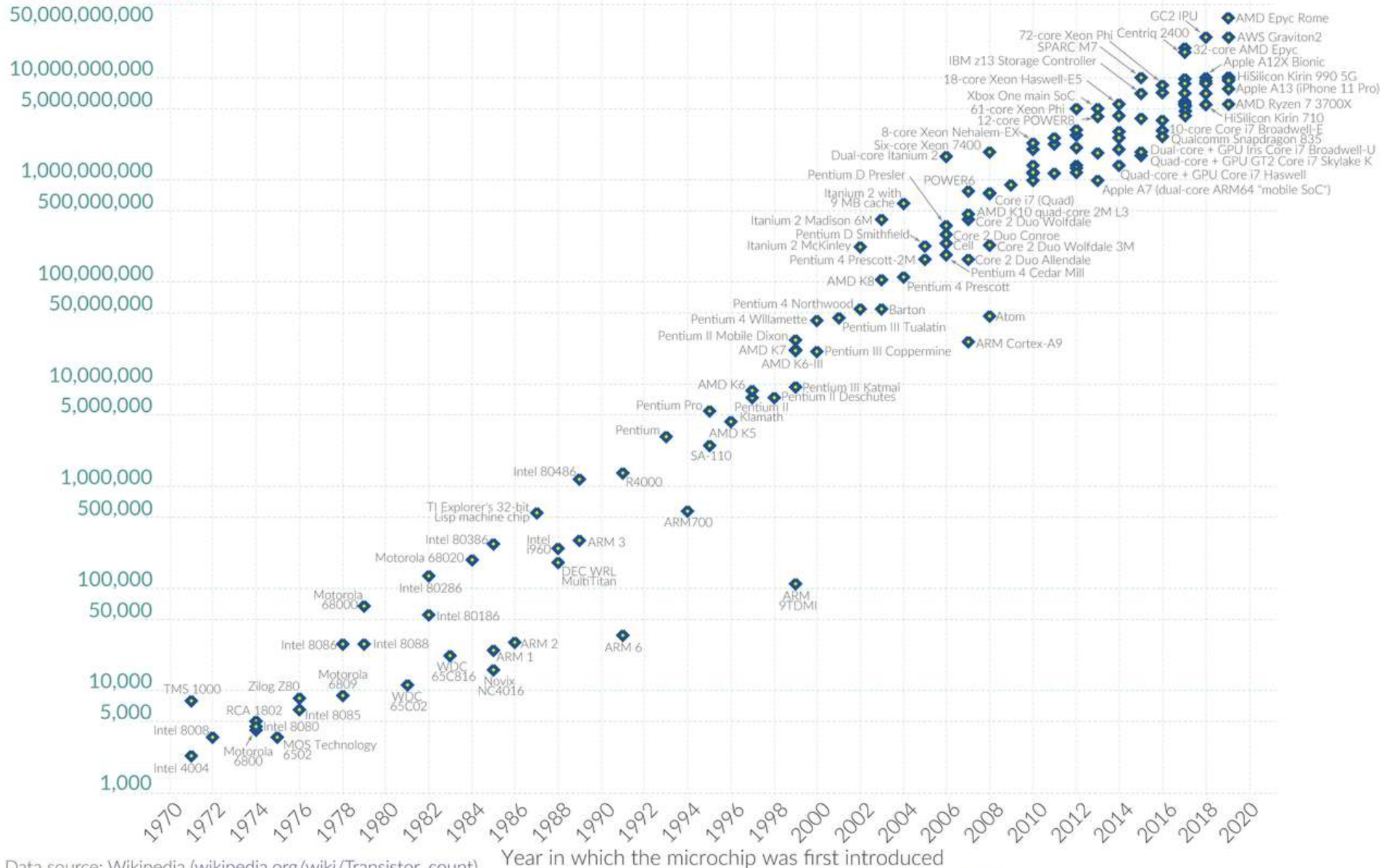


Jack Kilby's first integrated circuit 1958

Moore's Law: The number of transistors on microchips doubles every two years

Moore's law describes the empirical regularity that the number of transistors on integrated circuits doubles approximately every two years. This advancement is important for other aspects of technological progress in computing – such as processing speed or the price of computers.

Transistor count



Data source: Wikipedia (wikipedia.org/wiki/Transistor_count)

OurWorldinData.org – Research and data to make progress against the world's largest problems.

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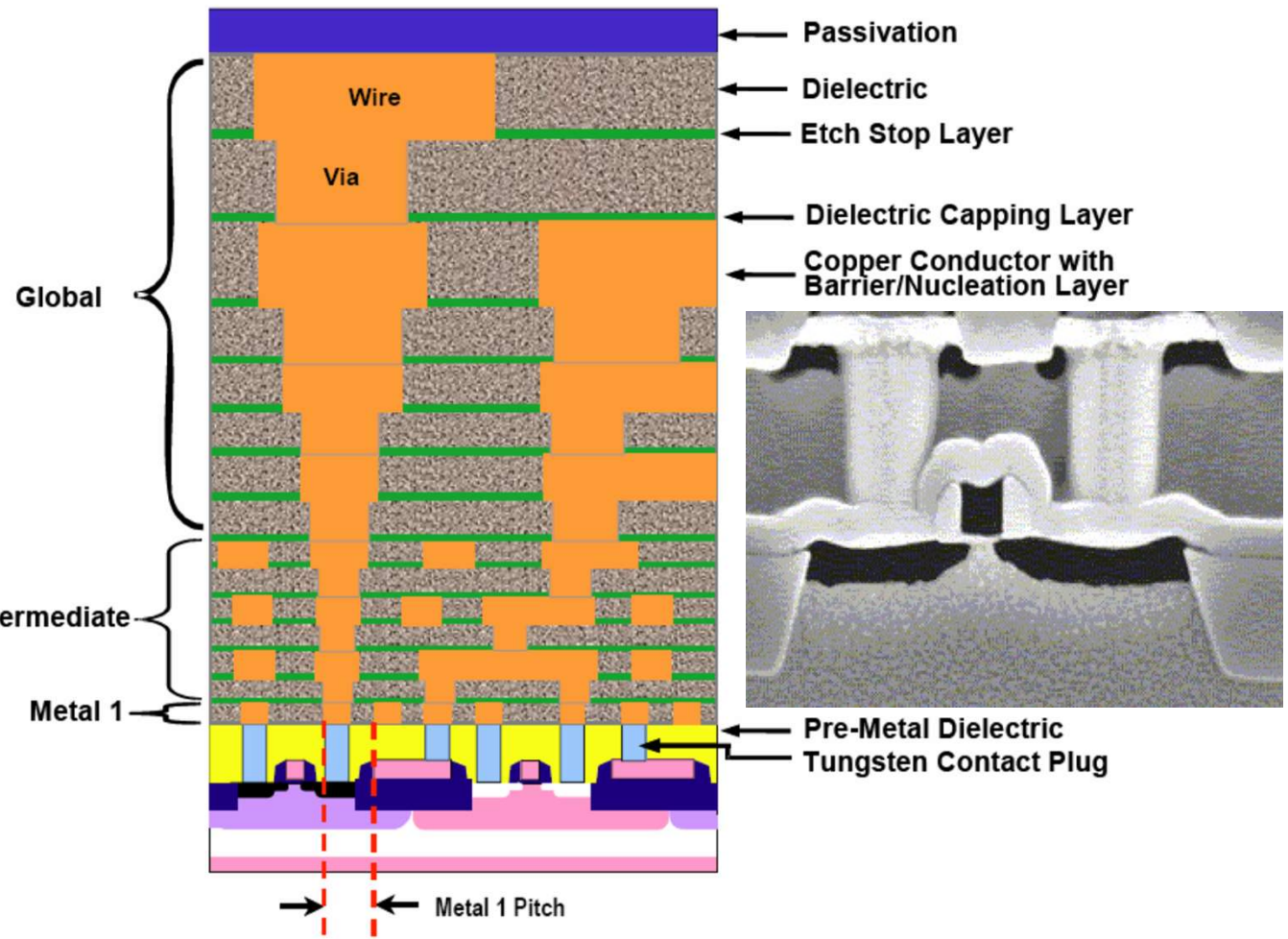
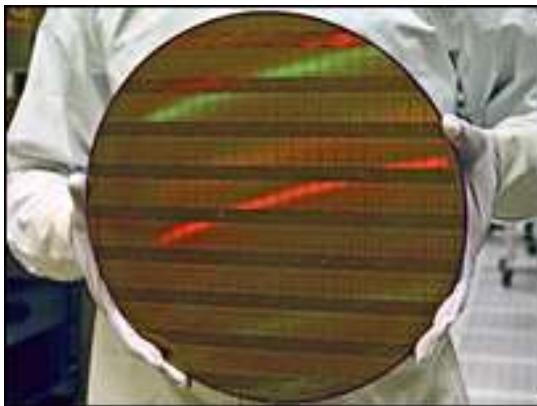
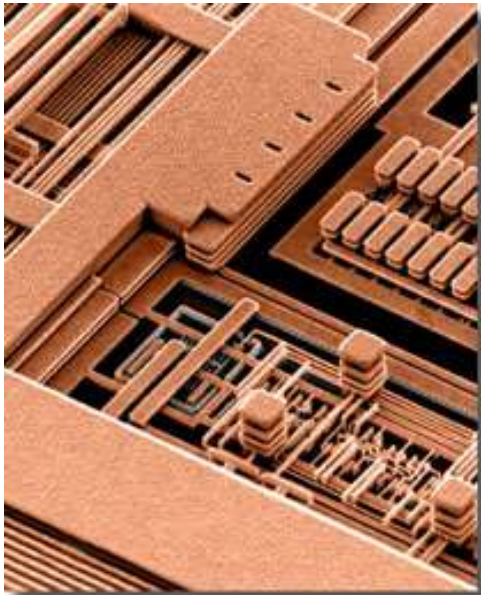
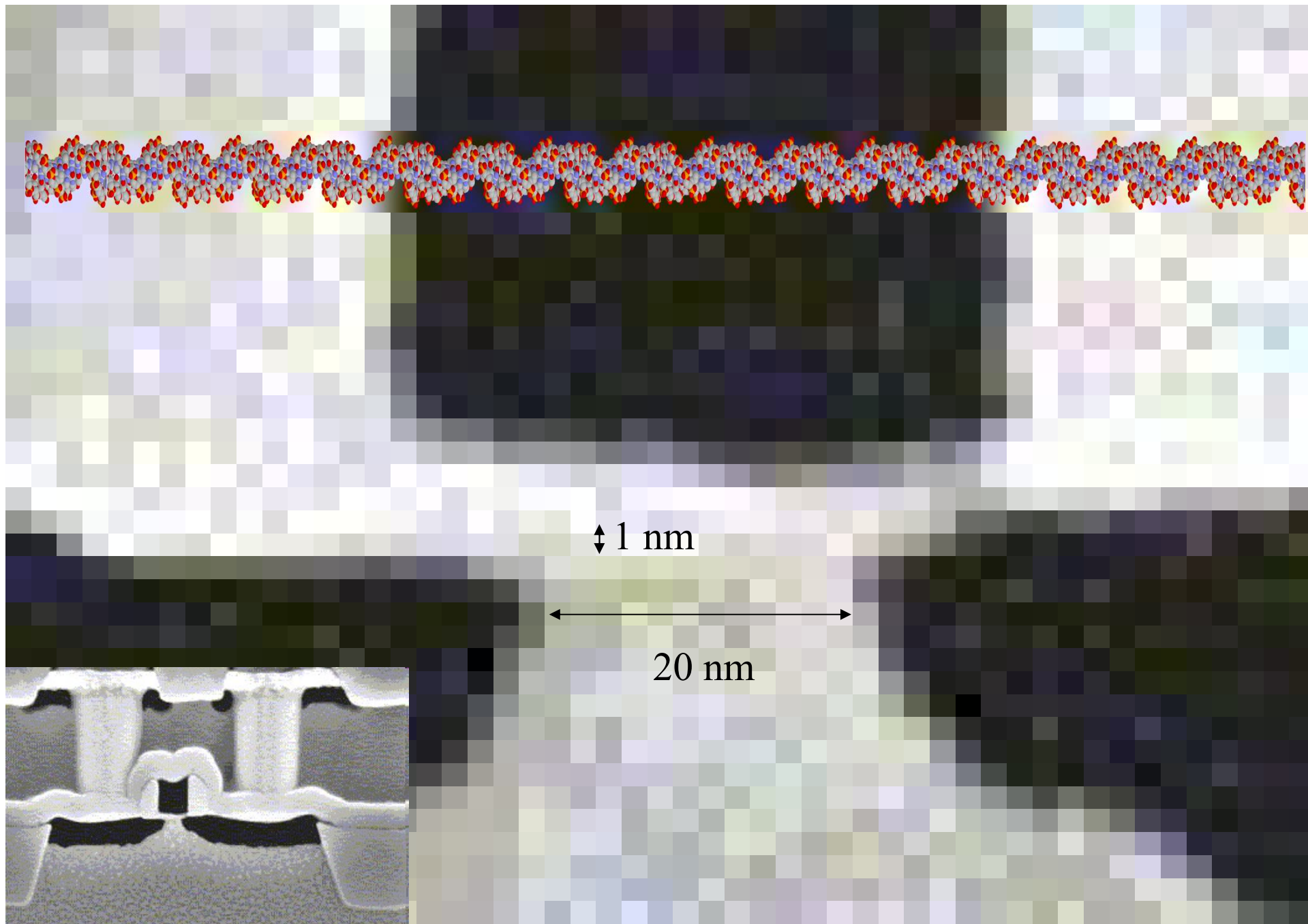


Table PIDS2a High-performance (HP) Logic Technology Requirements

	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028
node	"16/14"		"11/10"		"8/7"		"6/5"		"4/3"		"3/2.5"		"2/1.5"		"1/0.75"	
metal 1/2 pitch	40	32	32	28.3	25.3	22.5	20.0	17.9	15.9	14.2	12.6	11.3	10.0	8.9	8	7.1
gate length	20	18	16.7	15.2	13.9	12.7	11.6	10.6	9.7	8.8	8.0	7.3	6.7	6.1	5.6	5.1





<https://irds.ieee.org>

INTERNATIONAL ROADMAP FOR DEVICES AND SYSTEMS™



INTERNATIONAL ROADMAP FOR DEVICES AND SYSTEMS

INTERNATIONAL
ROADMAP
FOR
DEVICES AND SYSTEMS

2017 EDITION

EXECUTIVE SUMMARY

1. Application Benchmarking (AB)
2. Systems and Architectures (SA)
3. Outside System Connectivity (OSC)
4. More Moore (MM) ←
5. Beyond CMOS (BC) ←
6. Packaging Integration (PI)
7. Factory Integration (FI)
8. Lithography (L)
9. Emerging Research Materials (ERM) ←
10. Yield Enhancement (YE)
11. Metrology (M)
12. Environment, Safety, Health (ESH/S), and Sustainability

YEAR OF PRODUCTION	2017	2019	2021	2024	2027	2030	2033
	P54M36	P48M28	P42M24	P36M21	P32M14	P32M14T2	P32M14T4
Logic industry "Node Range" Labeling (nm)	"10"	"7"	"5"	"3"	"2.1"	"1.5"	"1.0"
IDM-Foundry node labeling	i10-f7	i7-f5	i5-f3	i3-f2.1	i2.1-f1.5	i1.5-f1.0	i1.0-f0.7
Logic device structure options	finFET FDSOI	finFET LGAA	LGAA finFET	LGAA VGAA	LGAA VGAA	VGAA, LGAA 3DVLSI	VGAA, LGAA 3DVLSI
Logic device mainstream device	finFET	finFET	LGAA	LGAA	LGAA	VGAA	VGAA
DEVICE STRUCTURES							
LOGIC DEVICE GROUND RULES							
MPU/SoC Metalx 1/2 Pitch (nm)[1,2]	18.0	14.0	12.0	10.5	7.0	7.0	7.0
MPU/SoC Metal0/1 1/2 Pitch (nm)	18.0	14.0	12.0	10.5	7.0	7.0	7.0
Contacted poly half pitch (nm)	27.0	24.0	21.0	18.0	16.0	16.0	16.0
L _g : Physical Gate Length for HP Logic (nm) [3]	20	18	16	14	12	12	12
L _g : Physical Gate Length for LP Logic (nm)	22	20	18	16	14	14	14
Channel overlap ratio - two-sided	0.80	0.80	0.80	0.80	0.80	0.80	0.80
Spacer width (nm)	8	7	6	5	5	5	5
Contact CD (nm) - finFET, LGAA	18	16	14	12	10		
Contact CD (nm) - VGAA						12	12
Device architecture key ground rules							
FinFET Fin Half-pitch (nm)	16.0	14.0					
FinFET Fin Width (nm)	8.0	7.0					
FinFET Fin Height (nm)	45	50					
Footprint drive efficiency - finFET	3.06	3.82					
Lateral GAA lateral half-pitch (nm)			12.0	10.5	9.0		
Lateral GAA vertical half-pitch (nm)			8.0	8.0	8.0		
Lateral GAA (nanosheet) thickness (nm)			5.0	5.0	5.0		
Lateral GAA (nanosheet) minimum width (nm)			7.0	7.0	6.0		
Number of vertically stacked nanosheets			3	4	5		
Device height (nm)			47	63	79		
Footprint drive efficiency - lateral GAA			3.00	4.57	6.11		
Vertical GAA lateral half-pitch (nm)						7.0	7.0
Vertical GAA width (nm)						6.0	6.0
Contact-gate enclosure (nm)						2.0	2.0
Footprint drive efficiency - vertical GAA						1.7	1.7
Device effective width (nm)	98.0	107.0	72.0	96.0	110.0	24.0	24.0
Device lateral half pitch (nm)	16.0	14.0	12.0	10.5	9.0	7.0	7.0
Device height (nm)	45.0	50.0	47.0	63.0	79.0	24.0	24.0
Minimum device width (fin, nanosheet) or diameter (nm)	8.0	7.0	7.0	7.0	6.0	6.0	6.0

Conductivity

Al: $\sigma = 3.5 \times 10^7 \text{ 1}/\Omega \cdot \text{m}$

Si: $\sigma = 4.3 \times 10^{-4} \text{ 1}/\Omega \cdot \text{m}$

	B Boron 10.811	C Carbon 12.011	N Nitrogen 14.007
2	13 Al Aluminum 26.982	14 Si Silicon 28.086	15 P Phosphorus 30.974
3	31 Ga Gallium 69.723	32 Ge Germanium 72.64	33 As Arsenic 74.922

Periodic Table of the Elements

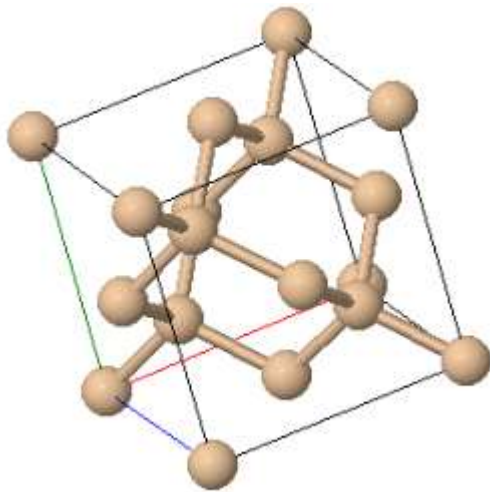
1 IA 11A	2 IIA 2A											13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	18 VIIIA 8A	
1 H Hydrogen 1.008	4 Be Beryllium 9.012											5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180	
3 Li Lithium 6.941	11 Na Sodium 22.990	3 IIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8 VIII 8	9 VIII 8	10 VIII 8	11 IB 1B	12 IIB 2B	13 Al Aluminum 26.982	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.066	17 Cl Chlorine 35.453	18 Ar Argon 39.948	
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.88	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.933	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.39	31 Ga Gallium 69.732	32 Ge Germanium 72.61	33 As Arsenic 74.922	34 Se Selenium 78.09	35 Br Bromine 79.904	36 Kr Krypton 84.80	
37 Rb Rubidium 84.467	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.94	43 Tc Technetium 98.907	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.905	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.904	54 Xe Xenon 131.29	
55 Cs Cesium 132.905	56 Ba Barium 137.327	57-71 Lanthanide Series		72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.85	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.22	78 Pt Platinum 195.08	79 Au Gold 196.967	80 Hg Mercury 200.59	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium [209]	85 At Astatine [210]	86 Rn Radon [222]
87 Fr Francium [223]	88 Ra Radium [226]	89-103 Actinide Series		104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [268]	110 Ds Darmstadtium [269]	111 Rg Roentgenium [272]	112 Cn Copernicium [277]	113 Uut Ununtrium [277]	114 Fl Flerovium [289]	115 Uup Ununpentium [289]	116 Lv Livermorium [293]	117 Uus Ununseptium [293]	118 Uuo Ununoctium [294]
Lanthanide Series		57 La Lanthanum 138.906	58 Ce Cerium 140.115	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.24	61 Pm Promethium [144.913]	62 Sm Samarium 150.36	63 Eu Europium 151.968	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.50	67 Ho Holmium 164.930	68 Er Erbium 167.26	69 Tm Thulium 168.934	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.967		
Actinide Series		89 Ac Actinium 227.028	90 Th Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.029	93 Np Neptunium 237.048	94 Pu Plutonium 244.064	95 Am Americium 243.061	96 Cm Curium 247.070	97 Bk Berkelium 247.070	98 Cf Californium 251.080	99 Es Einsteinium [254]	100 Fm Fermium 257.095	101 Md Mendelevium 258.1	102 No Nobelium 259.101	103 Lr Lawrencium [262]		

Alkali Metal
Alkaline Earth
Transition Metal
Semimetal
Nonmetal
Basic Metal
Halogen
Noble Gas
Lanthanide
Actinide

Silicon

- Important semiconducting material
- 2nd most common element on earth's crust (rocks, sand, glass, concrete)
- Often doped with other elements
- Oxide SiO_2 is a good insulator

2.33		28.086
	Si	14
5.43		
	$3s^2 3p^2$	
1683	DIA	625

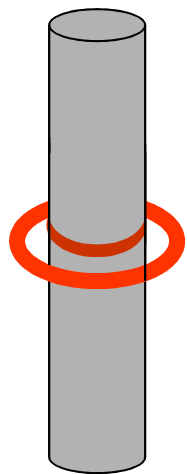
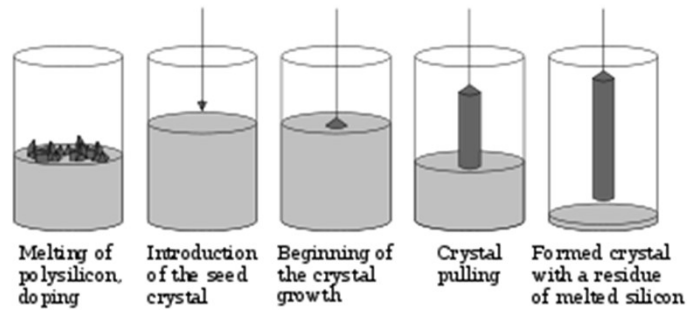


silicon crystal = diamond crystal structure

Silicon

Large (2 m) single crystals are grown

Czochralski process

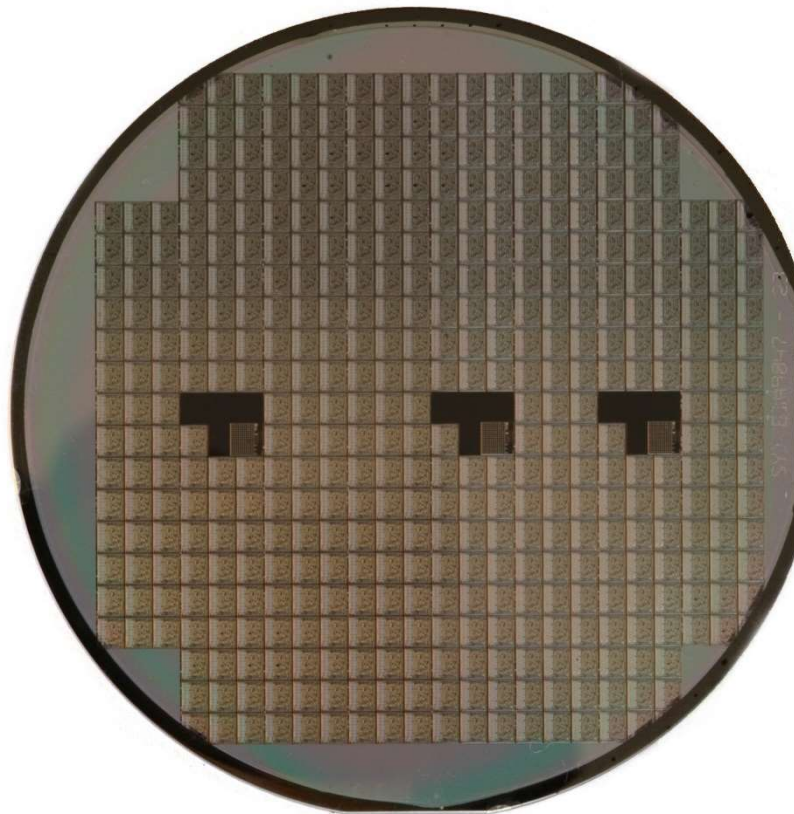


Float zone

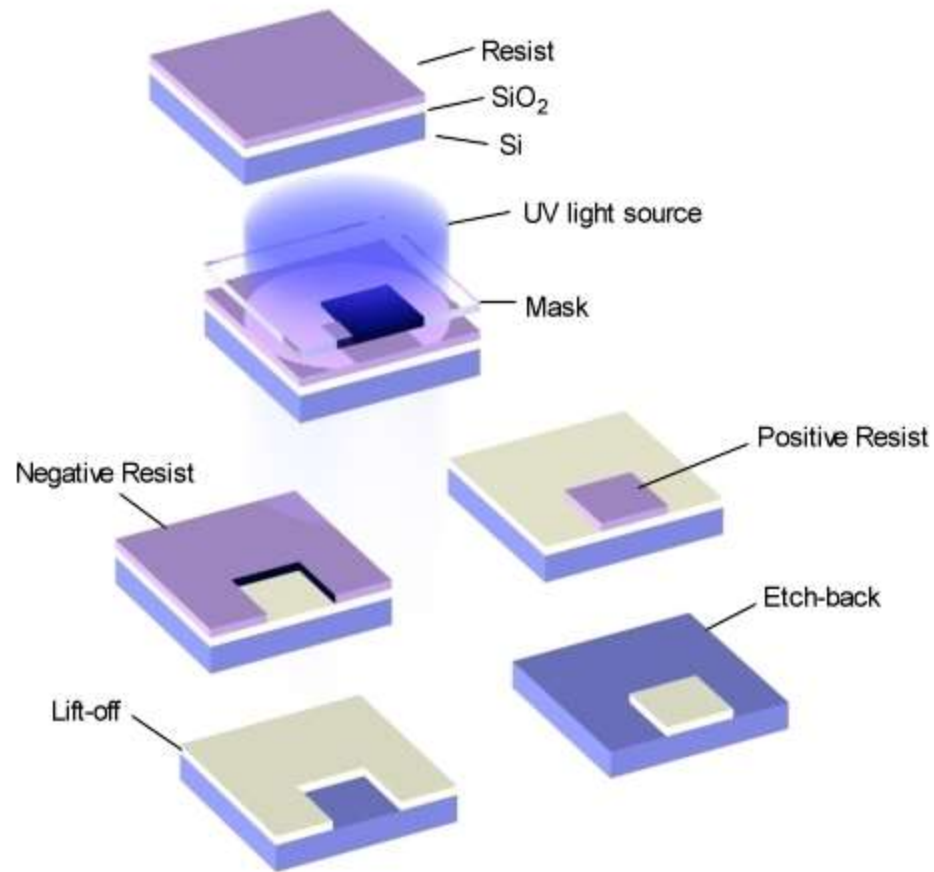


Silicon wafers

50 μm - 0.5 mm thick



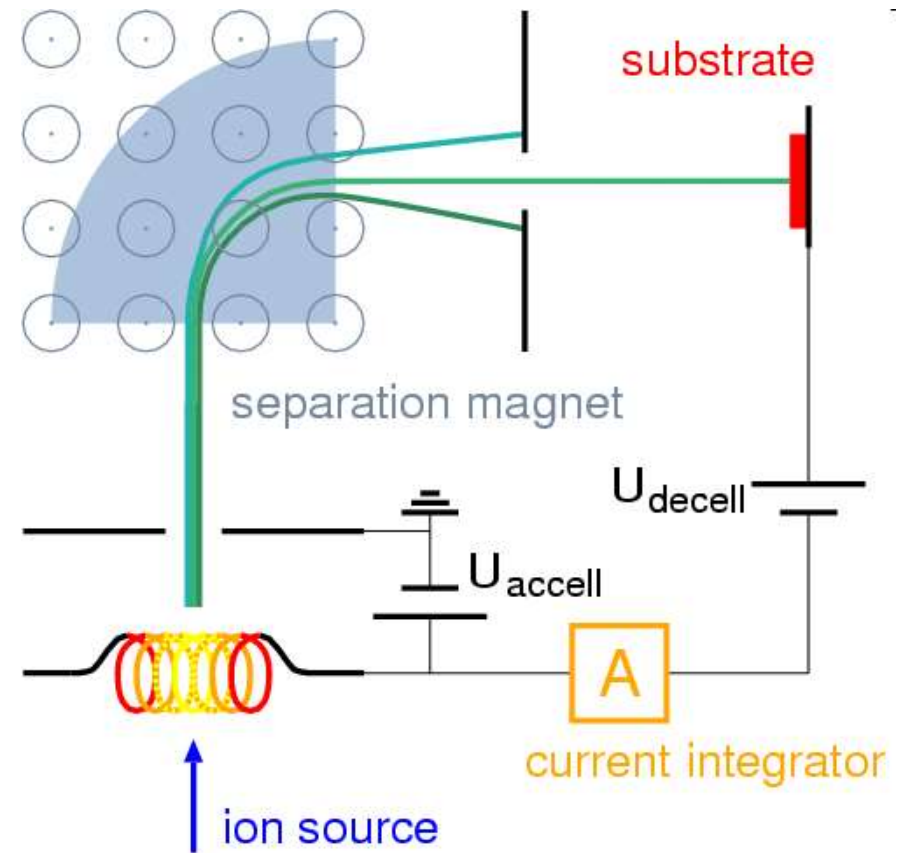
Photolithography



<http://britneyspears.ac/physics/fabrication/photolithography.htm>

<http://cleanroom.byu.edu/lithography.parts/Lithography.html>

Ion implantation



Implant at 7° to avoid channeling

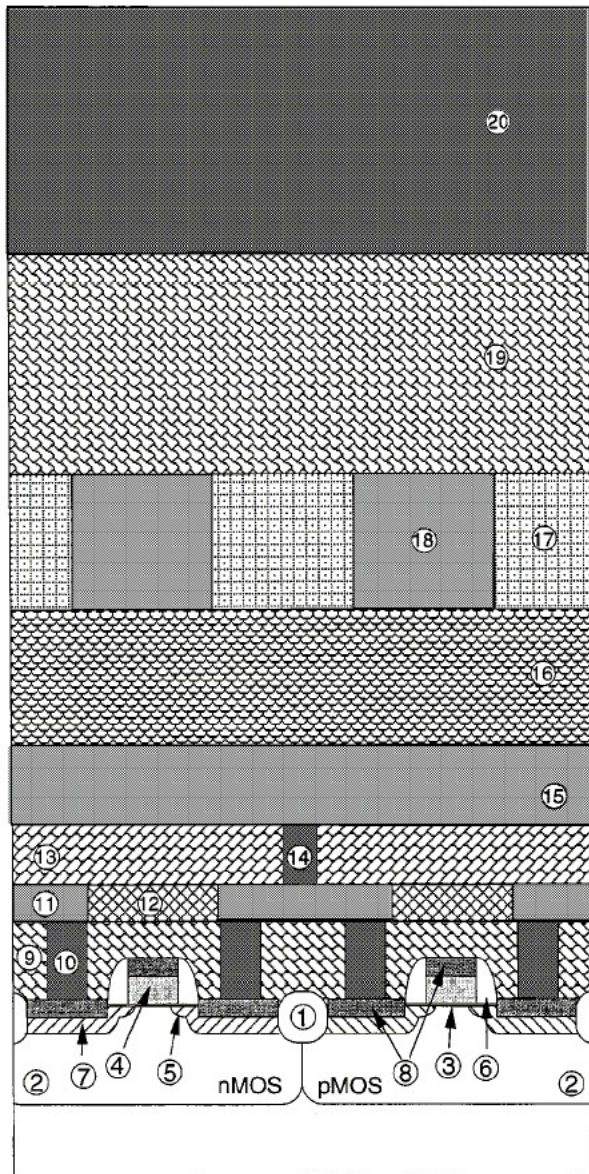
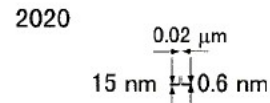
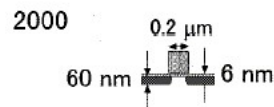
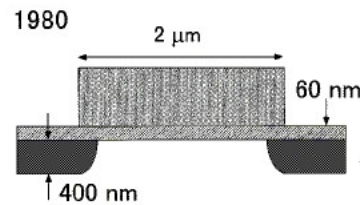
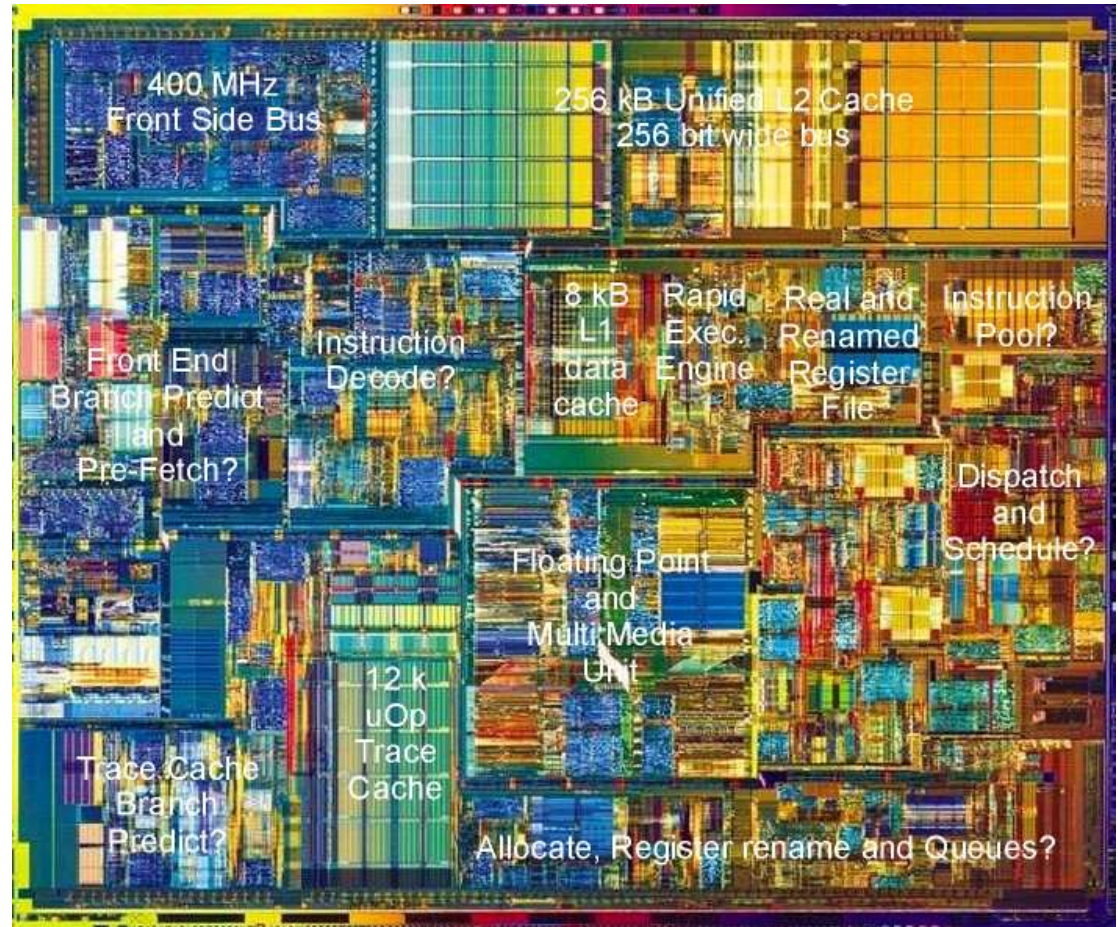
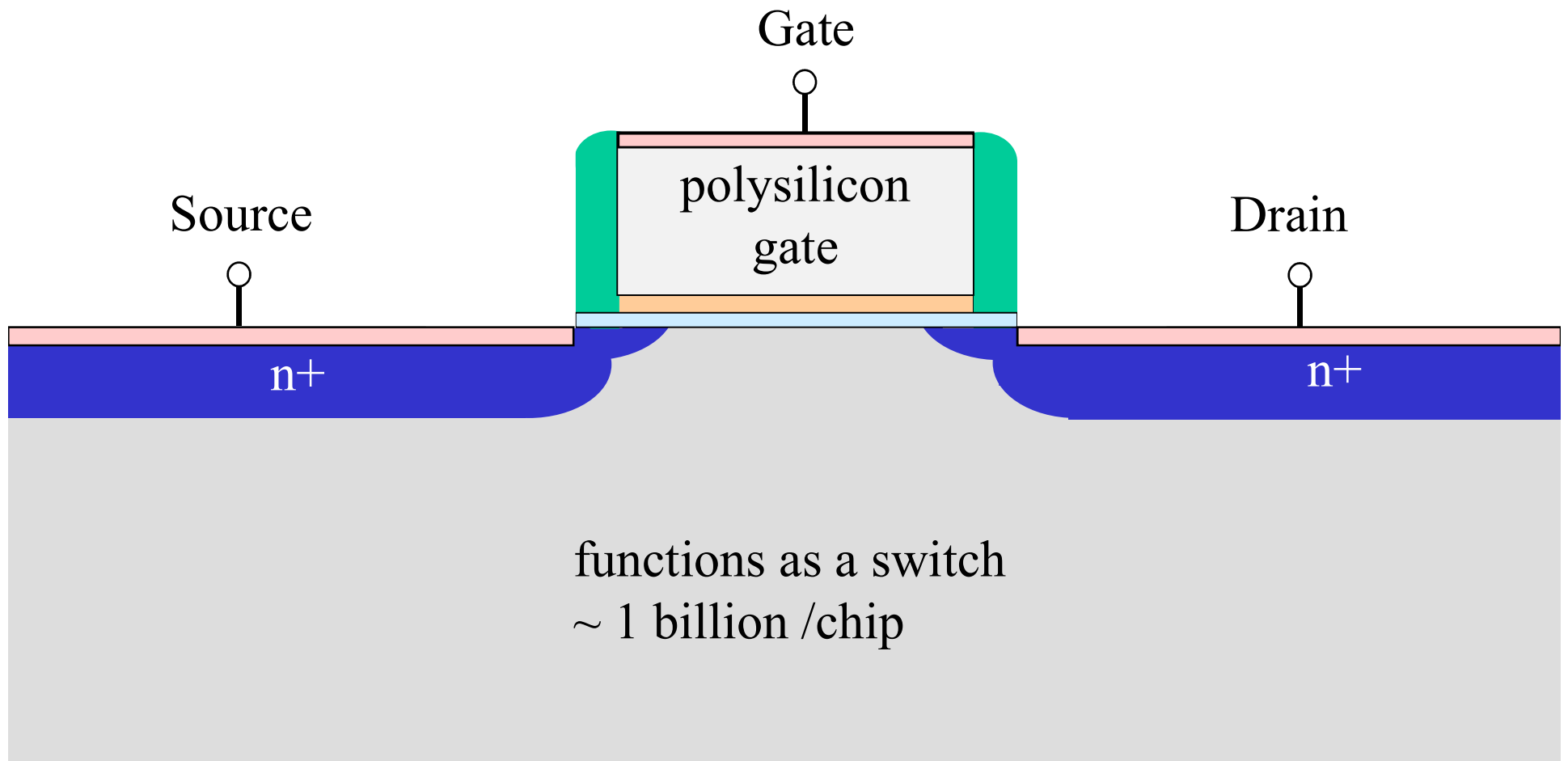


Fig. 2 Schematic cross section of present CMOS FETs with multilayered wiring.



MOSFET

Metal Oxide Semiconductor Field Effect Transistor



Self-aligned fabrication

p-Si 100 wafer

Dry oxidation

SiO₂ gate oxide

p-Si

A cross-sectional diagram of a semiconductor device. The top layer is a thin, bright green horizontal band representing the gate oxide. Below this is a thick, light gray rectangular region representing the p-type silicon substrate. The text 'SiO2 gate oxide' is positioned above the green layer with a black arrow pointing to its right edge. The text 'p-Si' is centered within the gray substrate. The text 'Dry oxidation' is located in the upper right area of the image.

photoresist

polysilicon

CVD: SiH_4 @ 580 to 650 °C

SiO_2

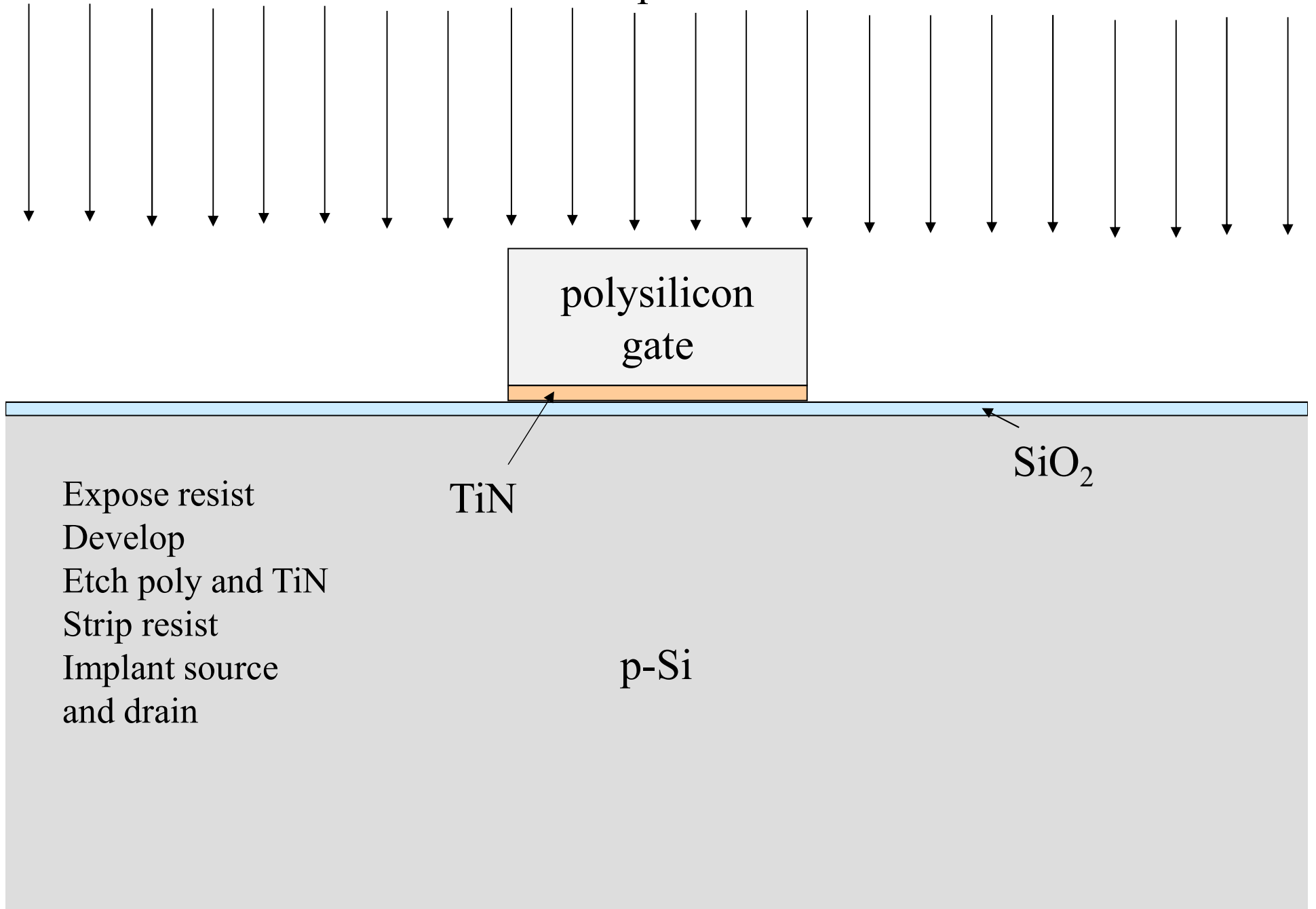
TiN (CVD)

30–70 $\mu\Omega\cdot\text{cm}$ Conductive diffusion barrier

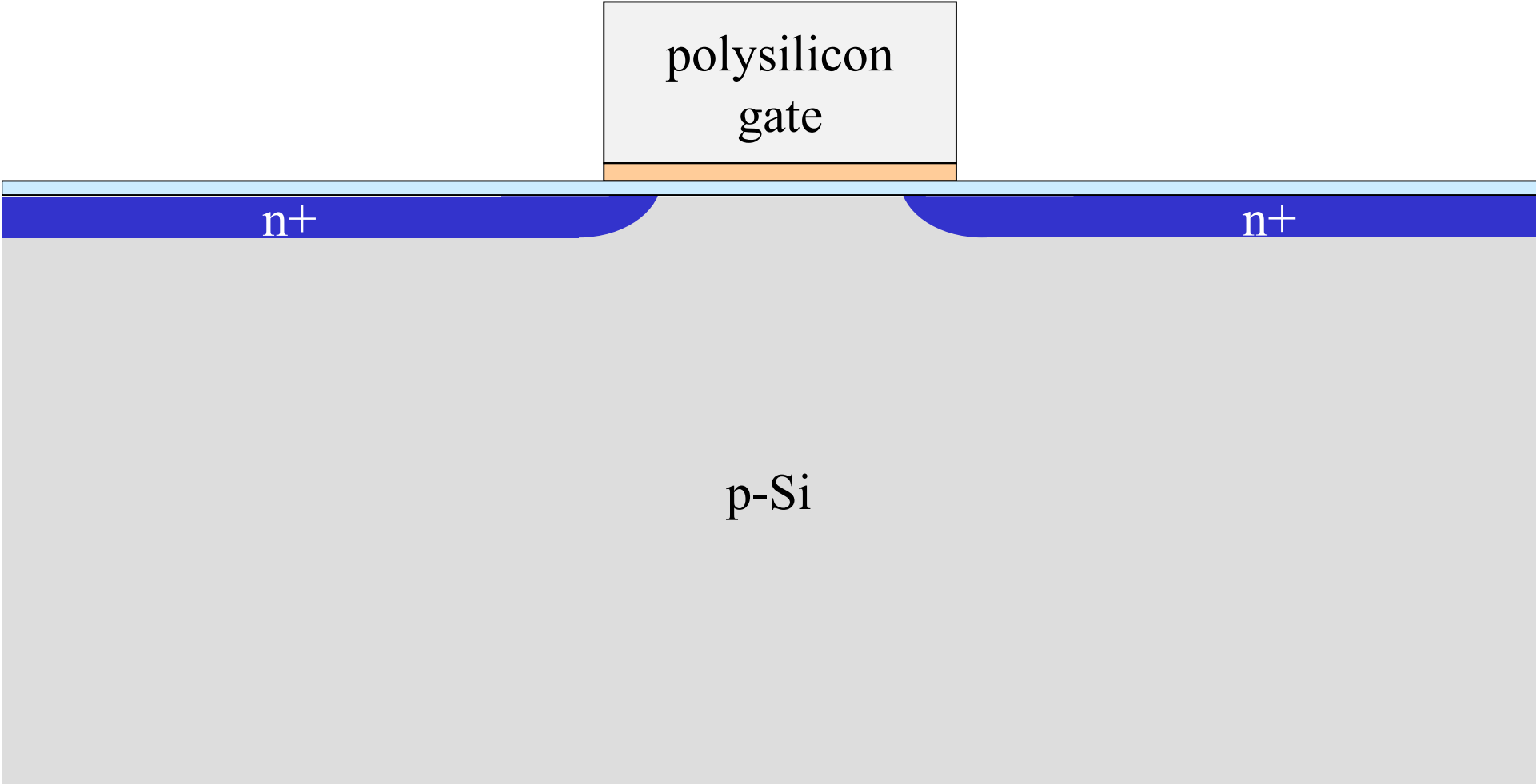
p-Si



Implant



Self-aligned fabrication



Spacer

PECVD SiN_x

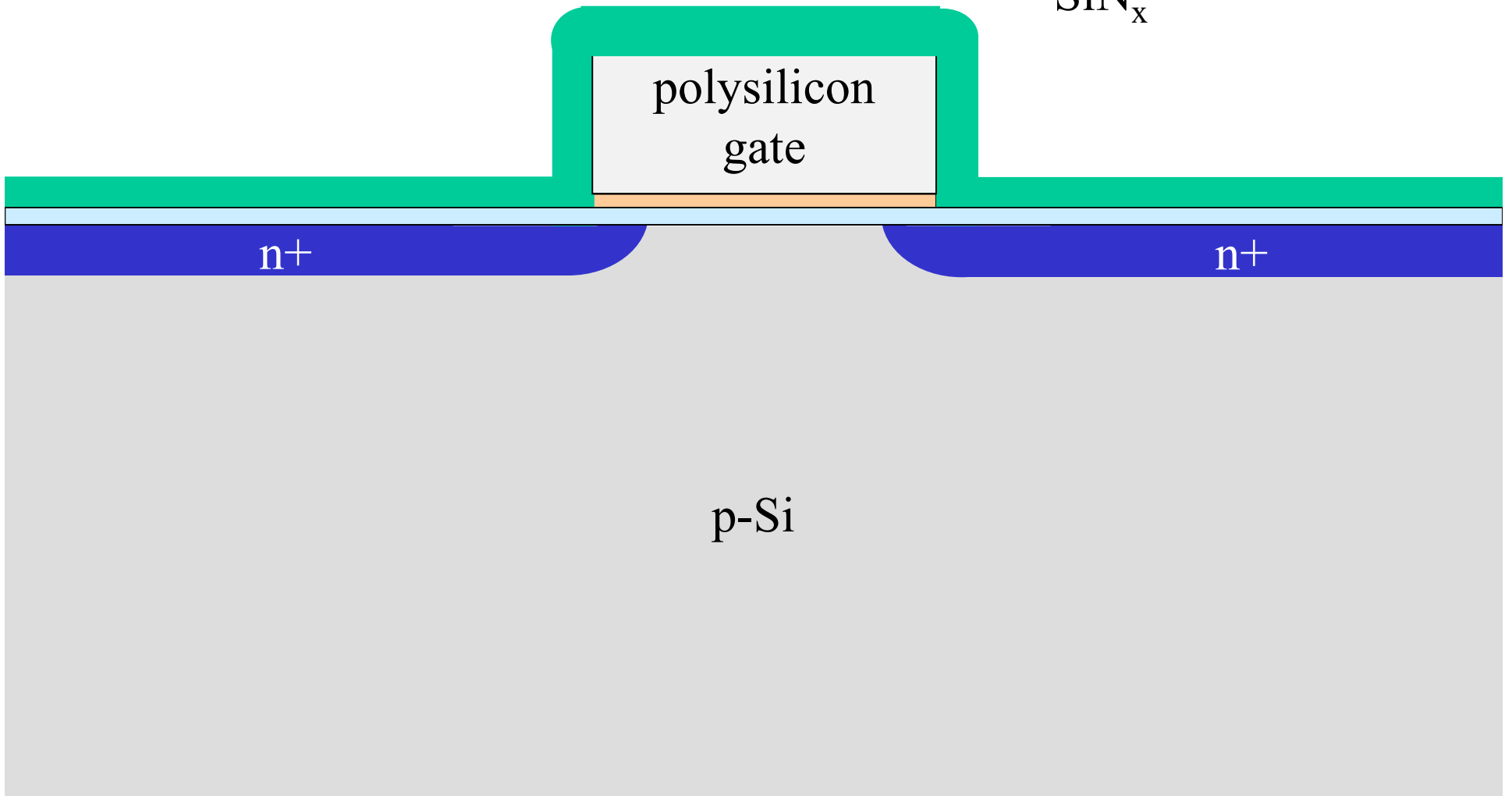
SiN_x

polysilicon
gate

n+

n+

p-Si



Spacer

Etch back to
leave only
sidewalls

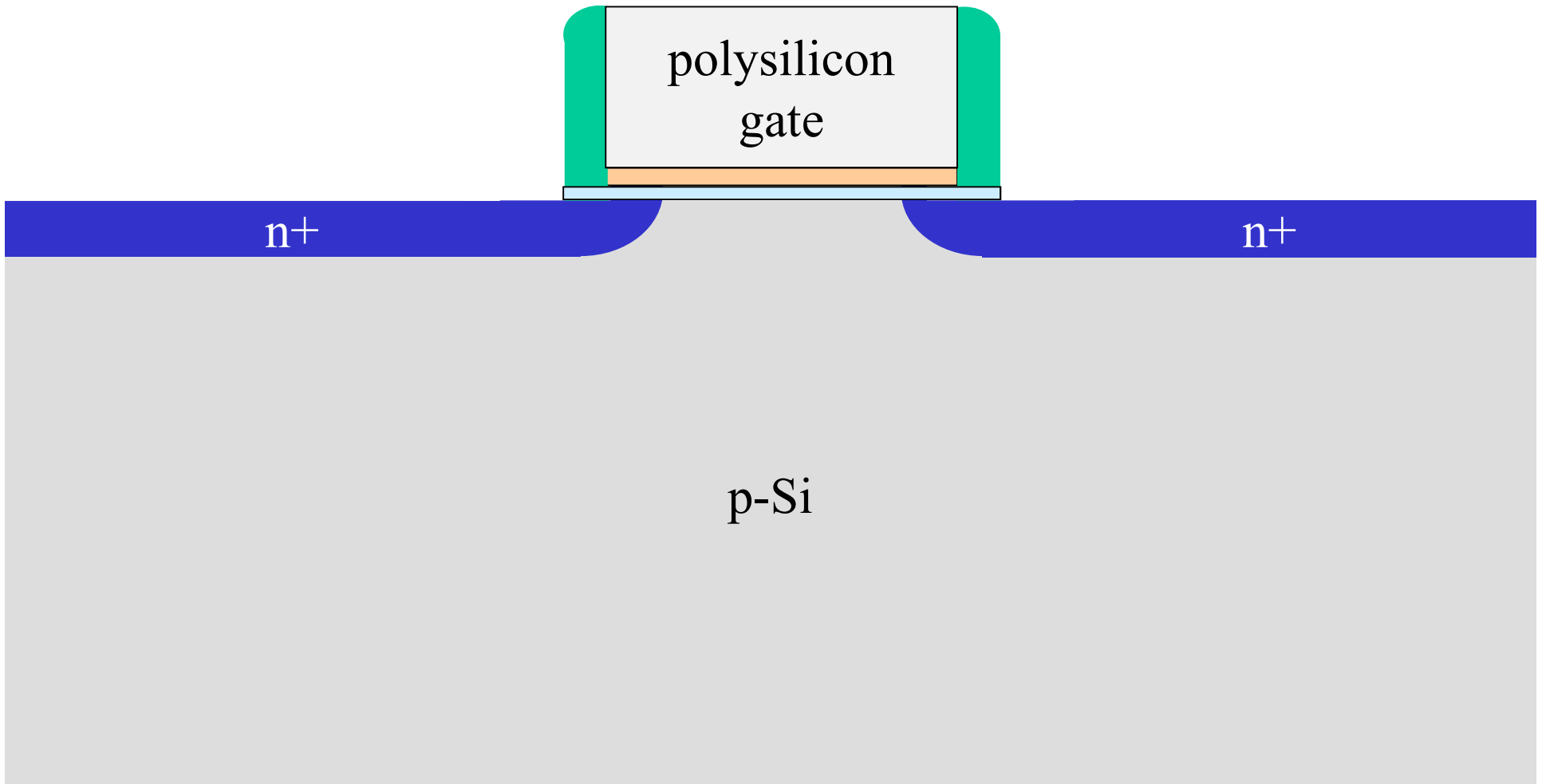
SiN_x

polysilicon
gate

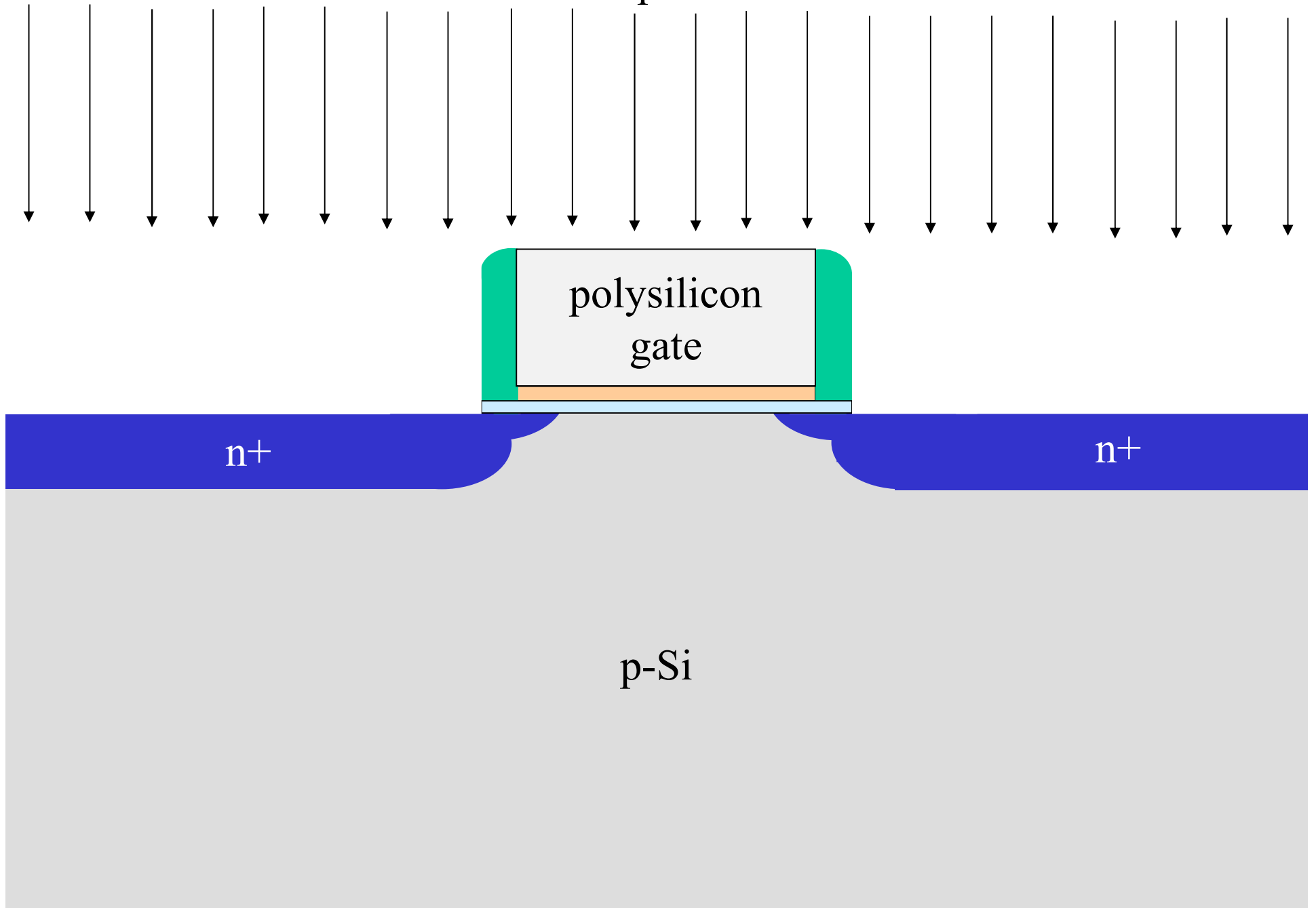
n+

n+

p-Si



Implant



Salicide (Self-aligned silicide)

Transition metal (Ti, Co, W) is deposited (CVD). During a high temperature step it reacts to a silicide (TiSi_2). Not silicide is formed on nitride or oxide.

