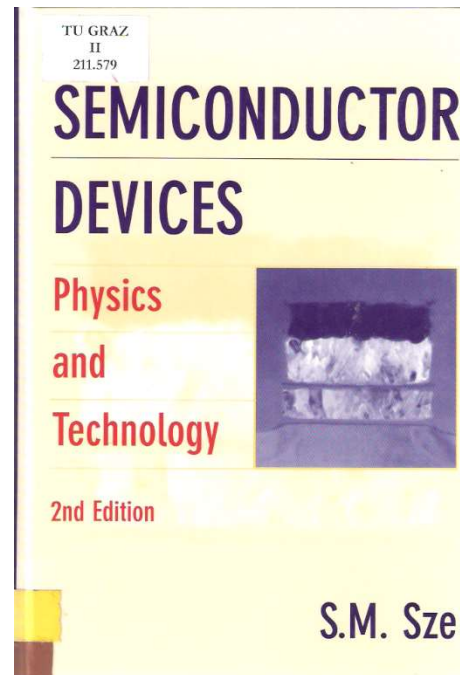
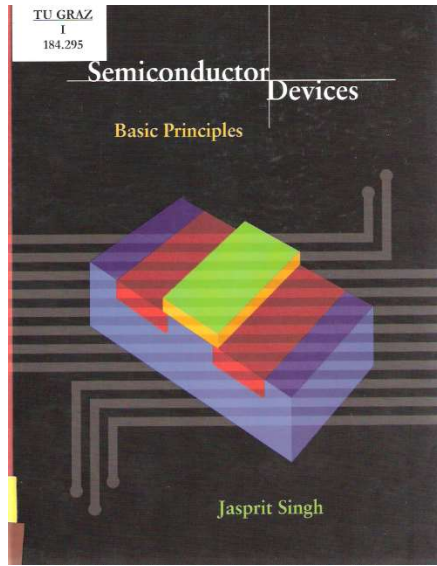


Physics of Semiconductor Devices

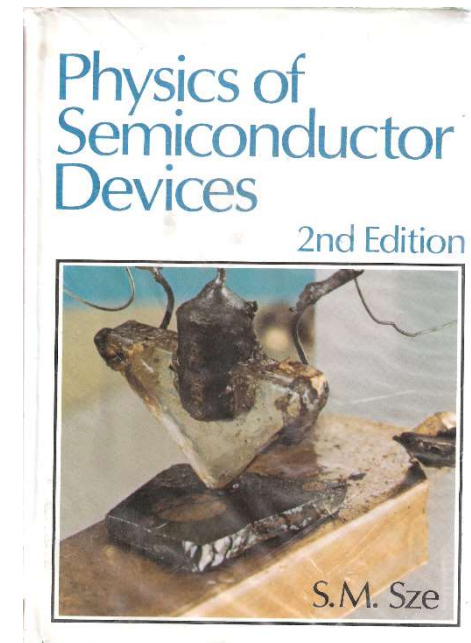
- Devices: diodes, solid state lasers, transistors
- Applications: computing, communications, controllers
- Energy: efficient lighting, solar cells

Peter Hadley

Books



Principles of
Semiconductor
Devices
by
Bart Van Zeghbroeck
e-book



Home
Outline
Introduction
Crystals
Intrinsic Semiconductors
Extrinsic Semiconductors
Transport
pn junctions
Contacts
JFETs/MESFETs
MOSFETs
Bipolar transistors
Opto-electronics
Lectures
Exam questions
Making presentations
TUG students
Student projects

<http://www.if.tugraz.at/psd.html>

The screenshot shows a Mozilla Firefox browser window. The address bar contains the URL `http://lamp.tu-graz.ac.at/~hadley/psd/L0/index.php`. The page header features the TU Graz logo and the text "Student: Not logged in". The main heading is "Physics of Semiconductor Devices".

Navigation Menu:

- Home
- Introduction
- Crystals
- Band structure
- Doping
- Transport
- pn junctions I
- pn junctions II
- Contacts
- JFETs/MESFETs
- MOSFETs I
- MOSFETs II
- MOSFETs III
- Bipolar I
- Bipolar II
- Opto-electronics
- Lectures
- Problems
- Login
- TUG students

Text Content:

Semiconductor devices are widely used in computation and control systems. Computers, telephones, medical instruments, automobiles, and household appliances make heavy use of semiconductors. This course explains the how semiconductor devices work. Before the devices themselves are discussed, a few concepts of solid state physics will be presented. Solid state physics is the study of how atoms arrange themselves into solids and what properties these solids have. Properties that can be calculated using the principles of solid state physics include electrical conductivity, thermal conductivity, elasticity, yield strength, speed of sound, dielectric constant, magnetism, and piezoelectricity.

A proper understanding of the electronic properties of materials is only possible when the electrons are described quantum mechanically. Therefore, a brief discussion of quantum mechanics will be necessary. After a few principles of quantum mechanics are introduced, the electronic properties of metals, insulators, and semiconductors will be described. Electronic devices typically consist of different materials and the behavior of the electrons at the interfaces between the materials is very important. The properties of electronic materials and the interfaces between electronic materials can be used to explain the behavior of a variety of semiconductor devices such as light emitting diodes, solid state lasers, sensors, bipolar transistors, and field effect transistors. A device that is used extensively in integrated circuits is the MOSFET (Metal Oxide Semiconductor Field Effect Transistor). We will spend several weeks discussing the properties of MOSFETs.

Examination

1 hour written exam

2 of the problems come from the old exam questions

1 Contribution to improve the course

Solutions to exam questions

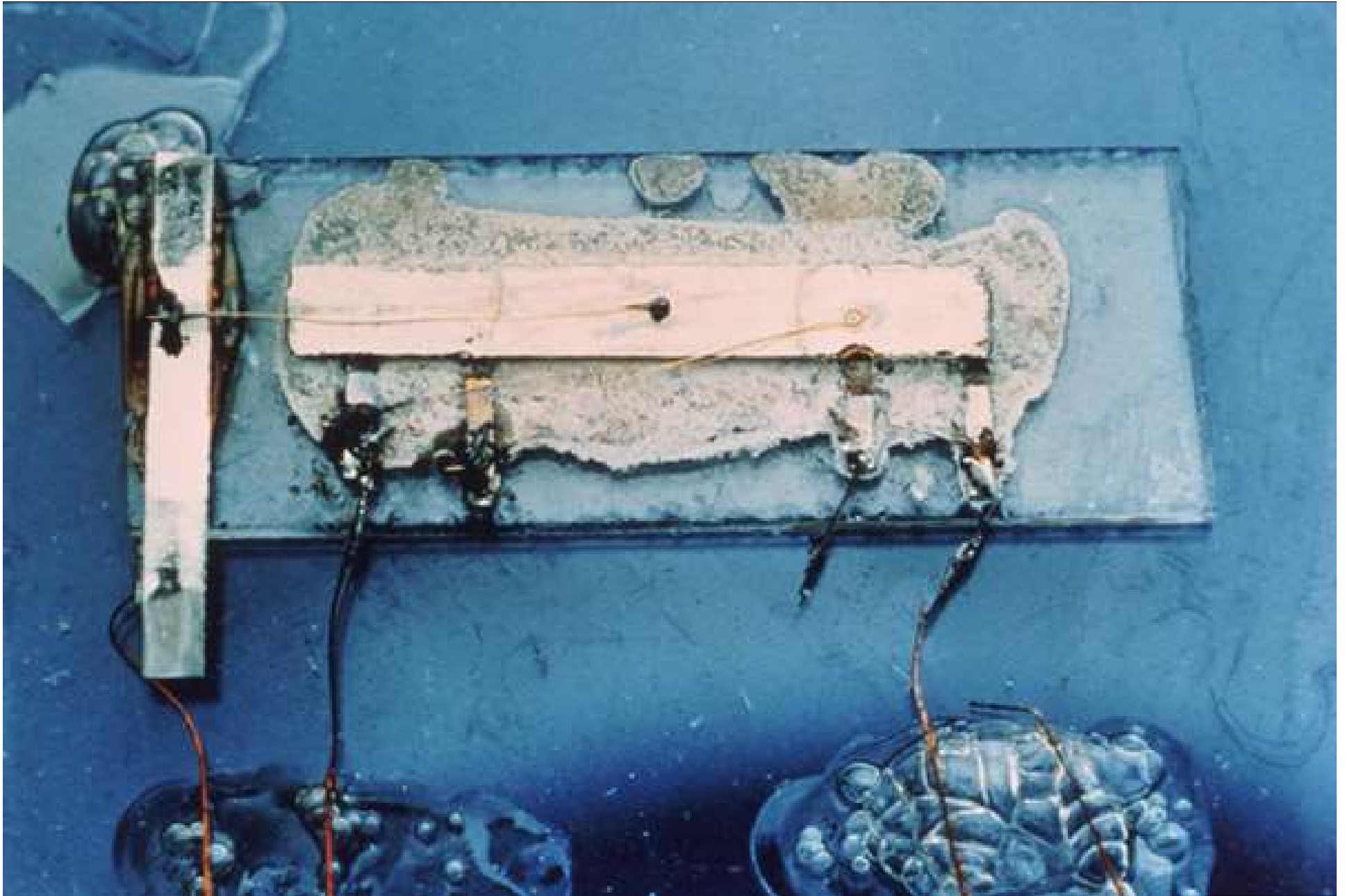
Simulations

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

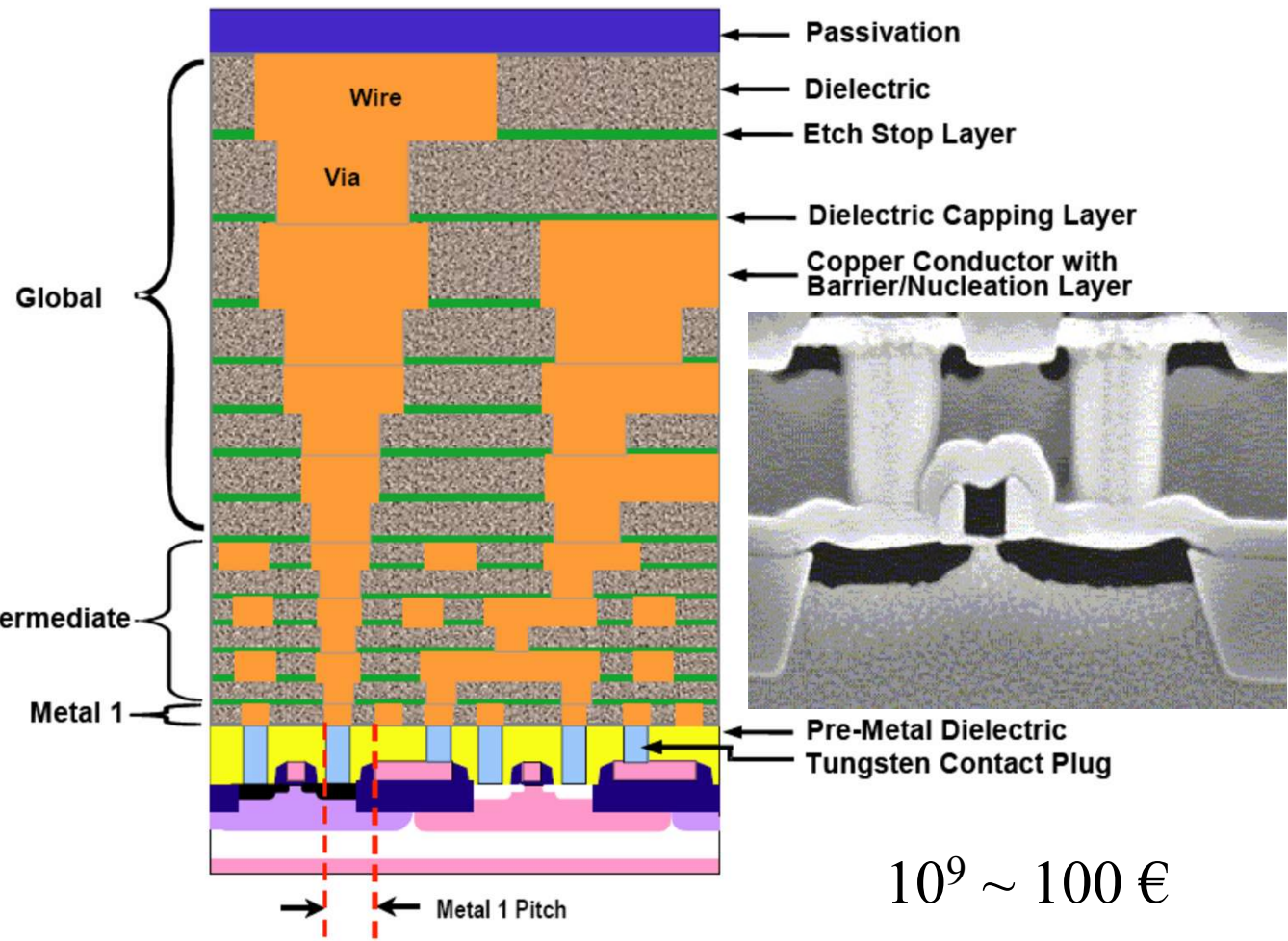
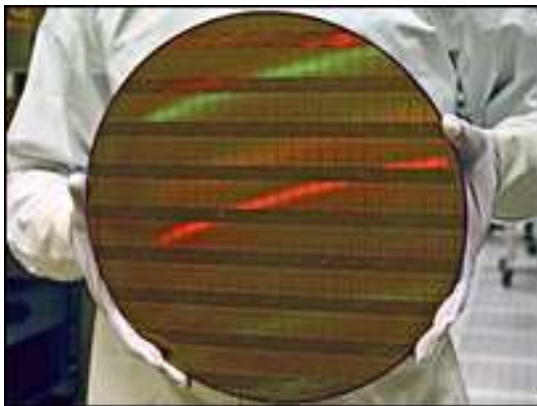
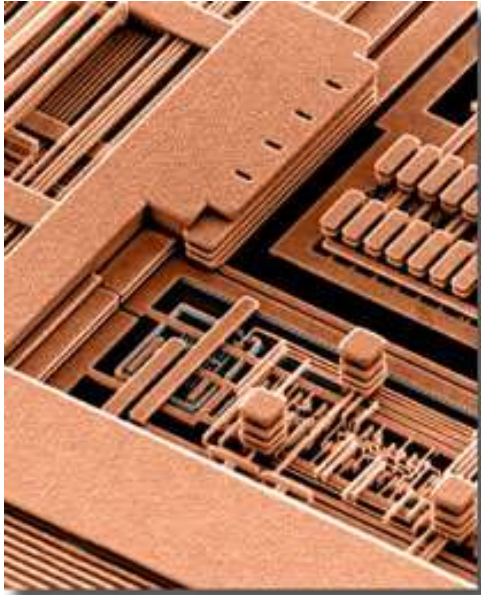


Table PIDS2a High-performance (HP) Logic Technology Requirements

	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



International Technology Roadmap for Semiconductors

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[Metrology](#)

[Modeling & Simulation](#)

[2009 ERRATA-Executive Summary, list of corrections](#)

<http://www.itrs.net/reports.html>

Table PIDS2a High-performance (HP) Logic Technology Requirements - TCAD

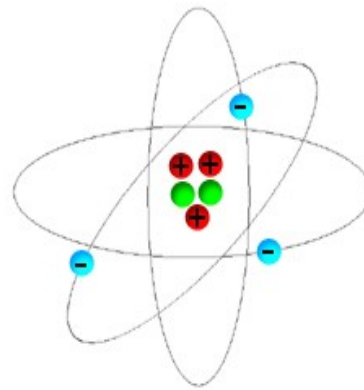
Year of Production	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028
Logic Industry "Node Range" Labeling (nm) [based on 0.71x reduction per "Node Range" ("Node" = 2x/Mx)]	"16/14"		"11/10"		"8/7"		"6/5"		"4/3"		"3/2.5"		"2/1.5"		"1/0.75"	
MPL/ASIC Metal 1 (M1)/Pitch (nm) (contacted)	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
L_g : Physical Gate Length for HP Logic (nm)	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
L_{ch} : Effective Channel Length (nm) [3]	16.0	14.4	13.4	12.2	11.1	10.2	9.3	8.5	7.8	7.0	6.4	5.8	5.4	4.9	4.5	4.1
V_{dd} : Power Supply Voltage (V)																
Bulk/SOI/IMG	0.86	0.85	0.83	0.81	0.80	0.78	0.77	0.75	0.74	0.72	0.71	0.69	0.68	0.66	0.65	0.64
EDT: Equivalent Oxide Thickness																
Bulk/SOI/IMG (nm)	0.80	0.77	0.73	0.70	0.67	0.64	0.61	0.59	0.56	0.54	0.51	0.49	0.47	0.45	0.43	0.41
Dielectric constant (K) of gate dielectrics	12.5	13.0	13.5	14.0	14.5	15.0	15.5	16.0	16.5	17.0	17.5	18.0	18.5	19.0	19.5	20.0
Physical gate oxide thickness (nm)	2.56	2.57	2.53	2.51	2.49	2.46	2.42	2.42	2.37	2.35	2.29	2.26	2.23	2.19	2.15	2.10
Channel Doping (10^{16} cm^{-3}) [4]																
Bulk	6.0	7.0	7.7	8.4	9.0											
SOI/IMG	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Body Thickness (nm) [5]																
SOI																
MG	6.4	5.8	5.3	4.9	4.4	4.1	3.7	3.4	3.1	2.8	2.6	2.3	2.1	2.0	1.8	1.6
T_{BOX} : Buried Oxide Thickness for SOI (nm) [6]																
SOI																
CET: Capacitance Equivalent Thickness (nm) [7]																
Bulk/SOI/IMG	1.10	1.07	1.03	1.00	0.97	0.94	0.91	0.89	0.86	0.84	0.81	0.79	0.77	0.75	0.73	0.71
C_{ch} intrinsic (fF/ μm) [8]																
Bulk/SOI/IMG	0.502	0.465	0.448	0.420	0.396	0.373	0.352	0.329	0.311	0.289	0.273	0.255	0.240	0.225	0.212	0.198
Mobility ($\text{cm}^2 \text{ V}^{-1} \text{ s}^{-1}$)																
Bulk	400	400	400	400	400											
SOI																
MG	250	250	250	250	250	250	200	200	200	200	200	150	150	150	150	150
I_{off} (nA/ μm) [9]																
Bulk/SOI/IMG	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
I_{drive} : NMOS Drive Current ($\mu\text{A}/\mu\text{m}$) [10]																
Bulk	1,348	1,355	1,340	1,295	1,267											
SOI																
MG	1670	1,680	1,700	1,660	1,660	1,610	1,600	1,480	1,450	1,350	1,330	1,170	1,100	1,030	970	900
$V_{t,th}$ (V) [11]																
Bulk	0.306	0.327	0.334	0.357	0.378											
SOI																
MG	0.219	0.225	0.231	0.239	0.264	0.266	0.265	0.276	0.295	0.303	0.306	0.319	0.334	0.340	0.354	0.364

Electrons

Charge = -1.6022×10^{-19} C

Mass = 9.11×10^{-31} kg

Radius = ?



0.15 nm



www.alnaden.ibm.com/vis/stm/atomo.html

Quantum Mechanics

Everything moves like a wave but exchanges energy and momentum like a particle.



Everything moves like a wave but exchanges energy and momentum like a particle.

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 B B	13 Al Aluminum 26.982	14 Si Silicon 28.086	15 P Phosphorus 30.974
3 B B	31 Ga Gallium 69.723	32 Ge Germanium 72.61	33 As Arsenic 74.922

Periodic Table of the Elements

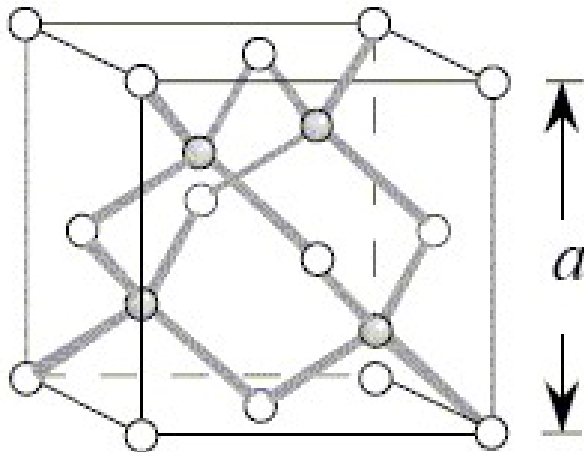
1 IA 11A	2 IIA 2A	3 IIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8 VIII 8	9 VIII 9	10 VIII 10	11 IB 1B	12 IIB 2B	13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	18 VIIIA 8A
1 H Hydrogen 1.008	2 He Helium 4.003	3 Li Lithium 6.941	4 Be Beryllium 9.012	5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180	11 Na Sodium 22.990	12 Mg Magnesium 24.305	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 118.71	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 [208.982]	85 At Astatine [208.987]	86 Rn Radon [222.018]
87 Fr Francium [223.028]	88 Ra Radium [226.025]	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]
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			
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

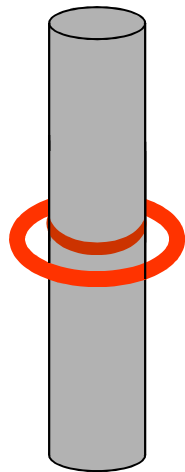
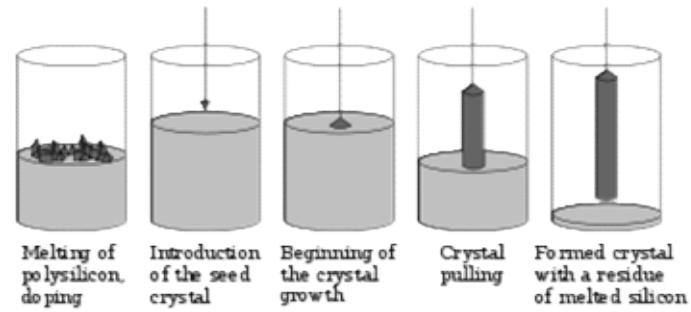


silicon crystal = diamond crystal structure

Silicon

Large (2 m) single crystals are grown

Czochralski process

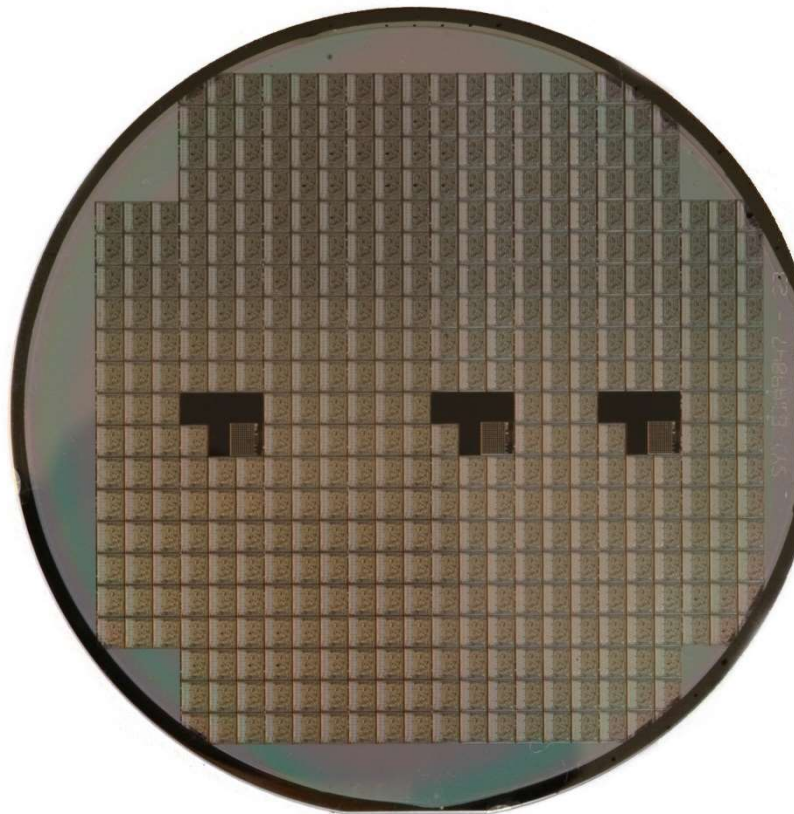


Float zone

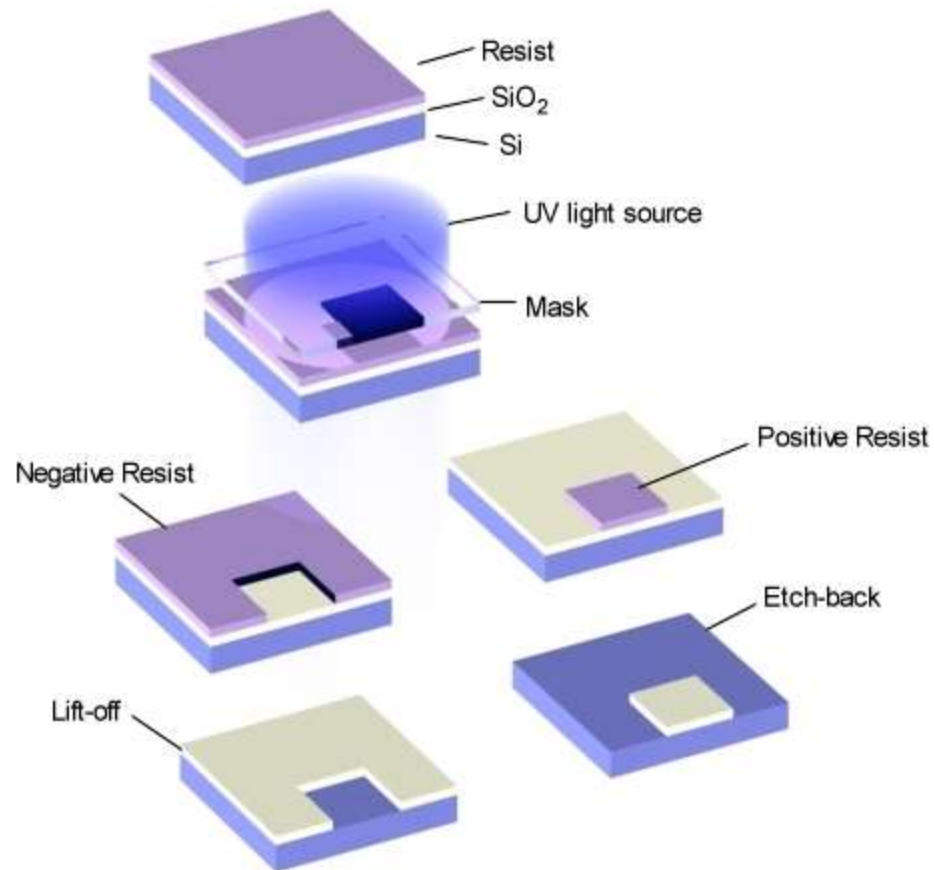


Silicon wafers

50 μm - 0.5 mm thick



Photolithography



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

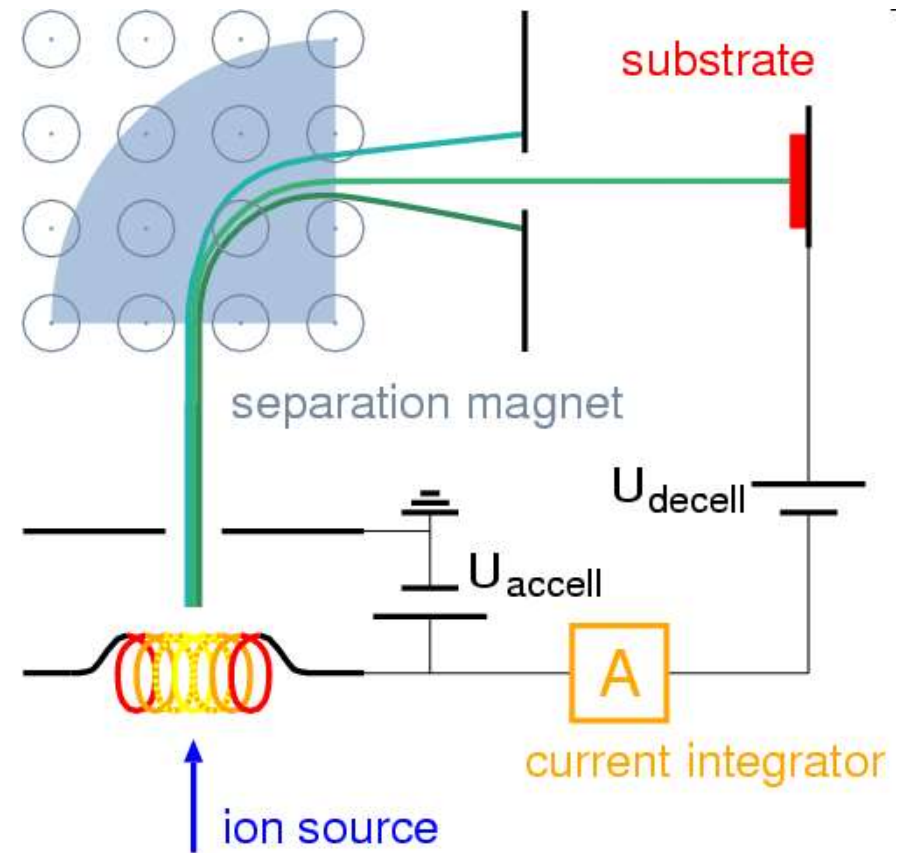
<http://cleanroom.byu.edu/lithography.parts/Lithography.html>

EBPG (Electron beam pattern generator)



100 kV \rightarrow $\lambda = 0.12$ nm

Ion implantation



Implant at 7° to avoid channeling

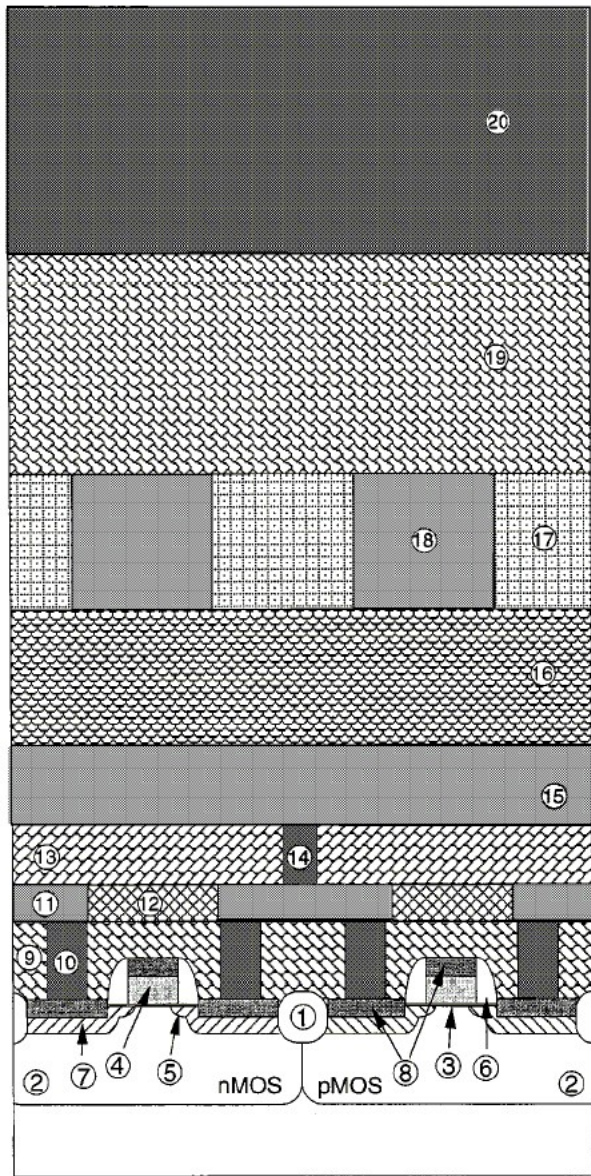
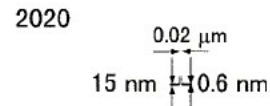
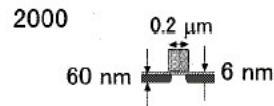
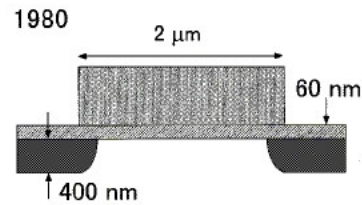
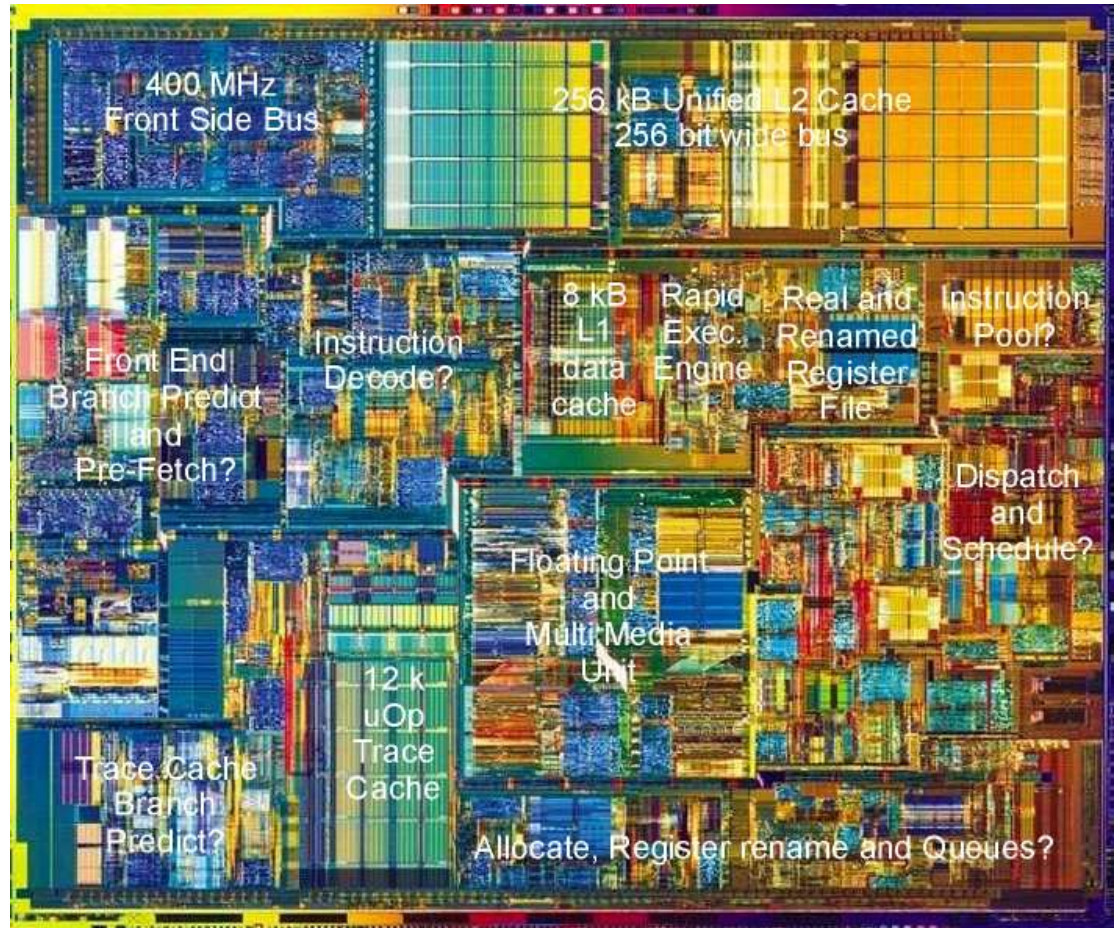
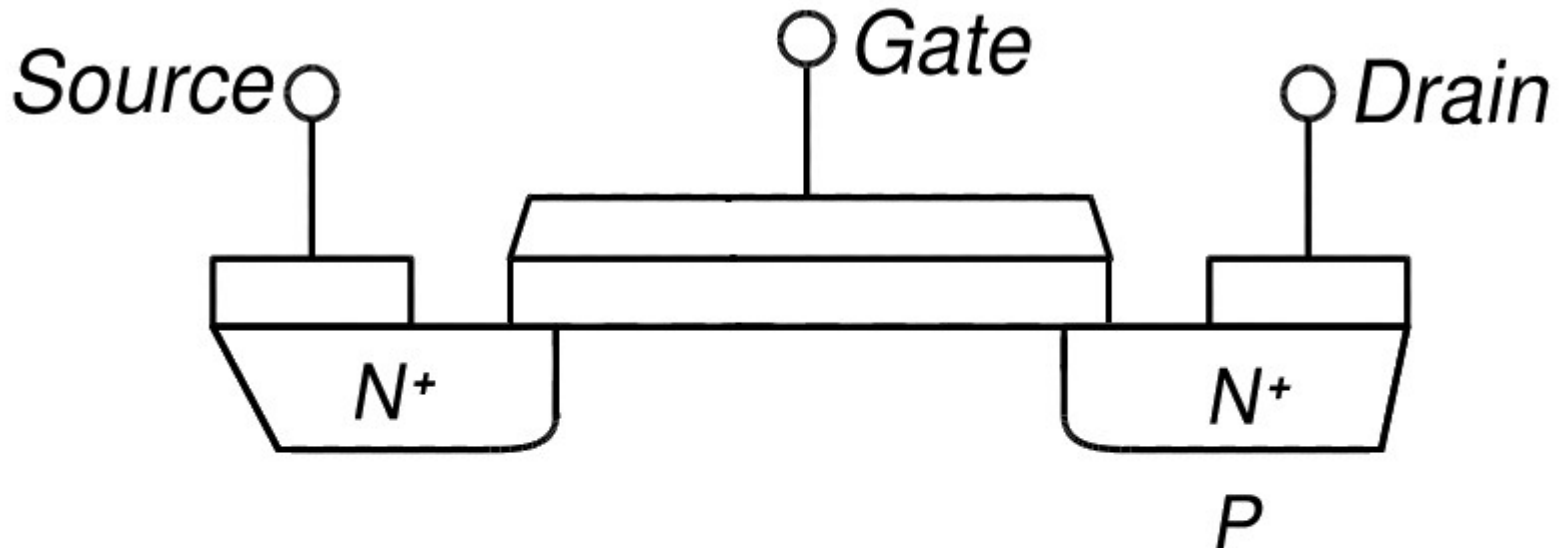


Fig. 2 Schematic cross section of present CMOS FETs with multilayered wiring.



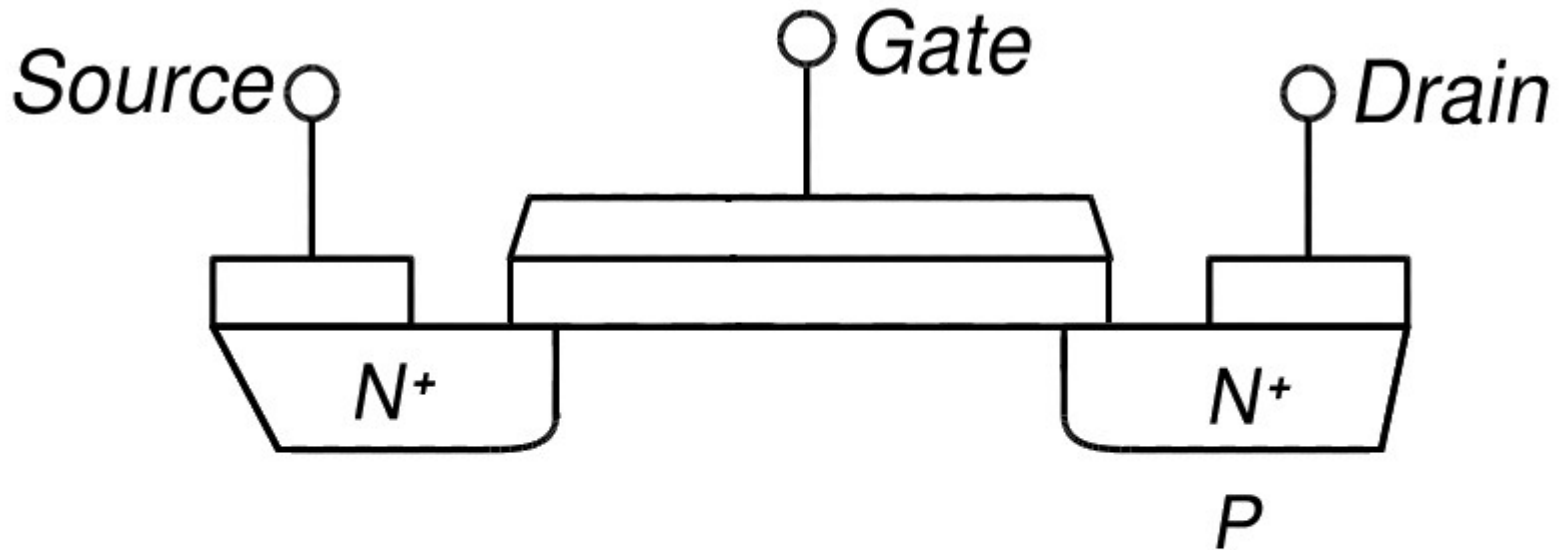
MOSFET

Metal Oxide Semiconductor Field Effect Transistor



functions as a switch
~ 1 billion /chip

Self-aligned gate



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. Below it is a thick, light gray rectangular region. The text 'SiO2 gate oxide' is positioned above the green band with a small black arrow pointing to its right edge. The text 'p-Si' is centered within the gray region.

photoresist

polysilicon

CVD: SiH_4 @ 580 to 650 °C

SiO_2

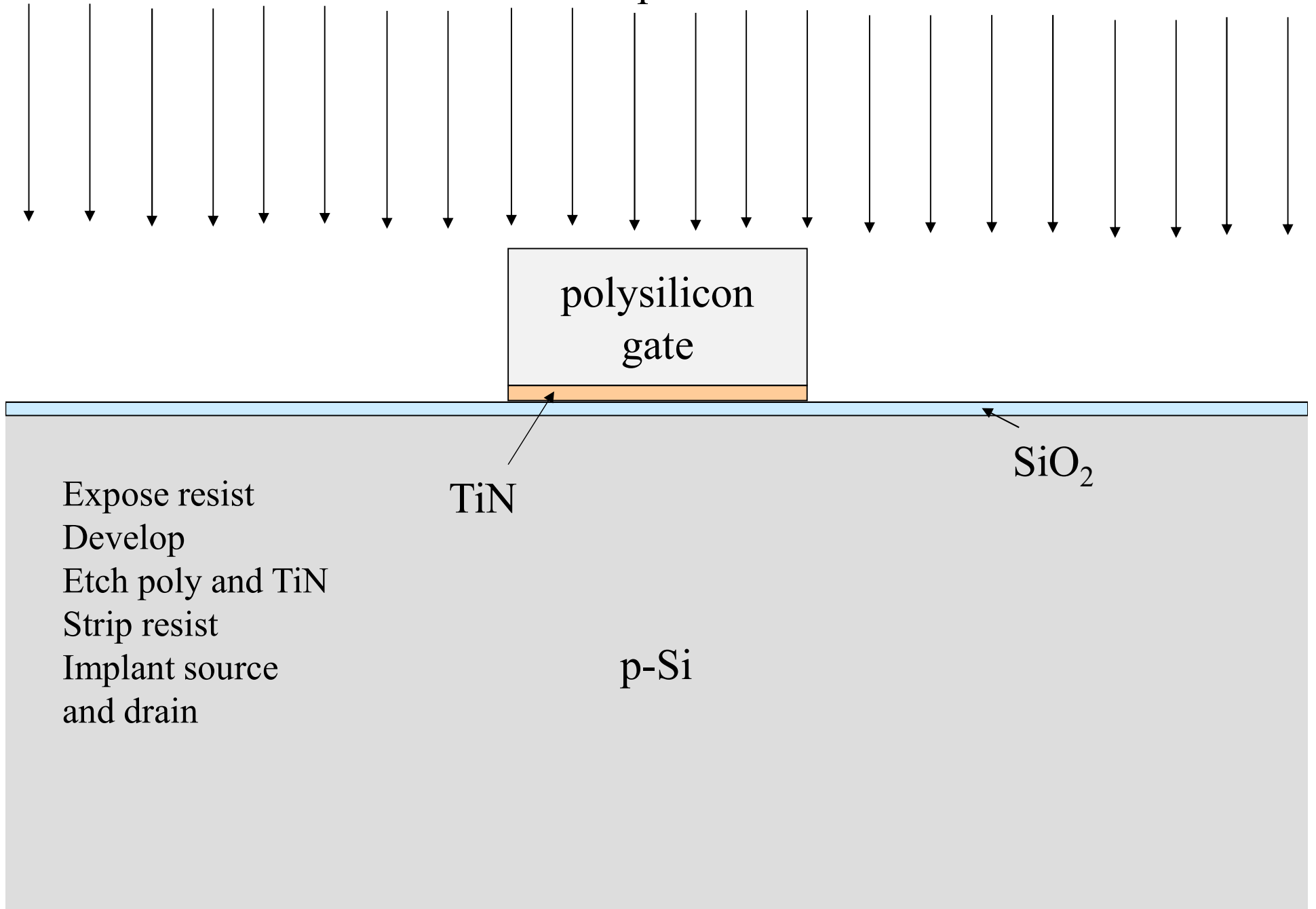
TiN (CVD)

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

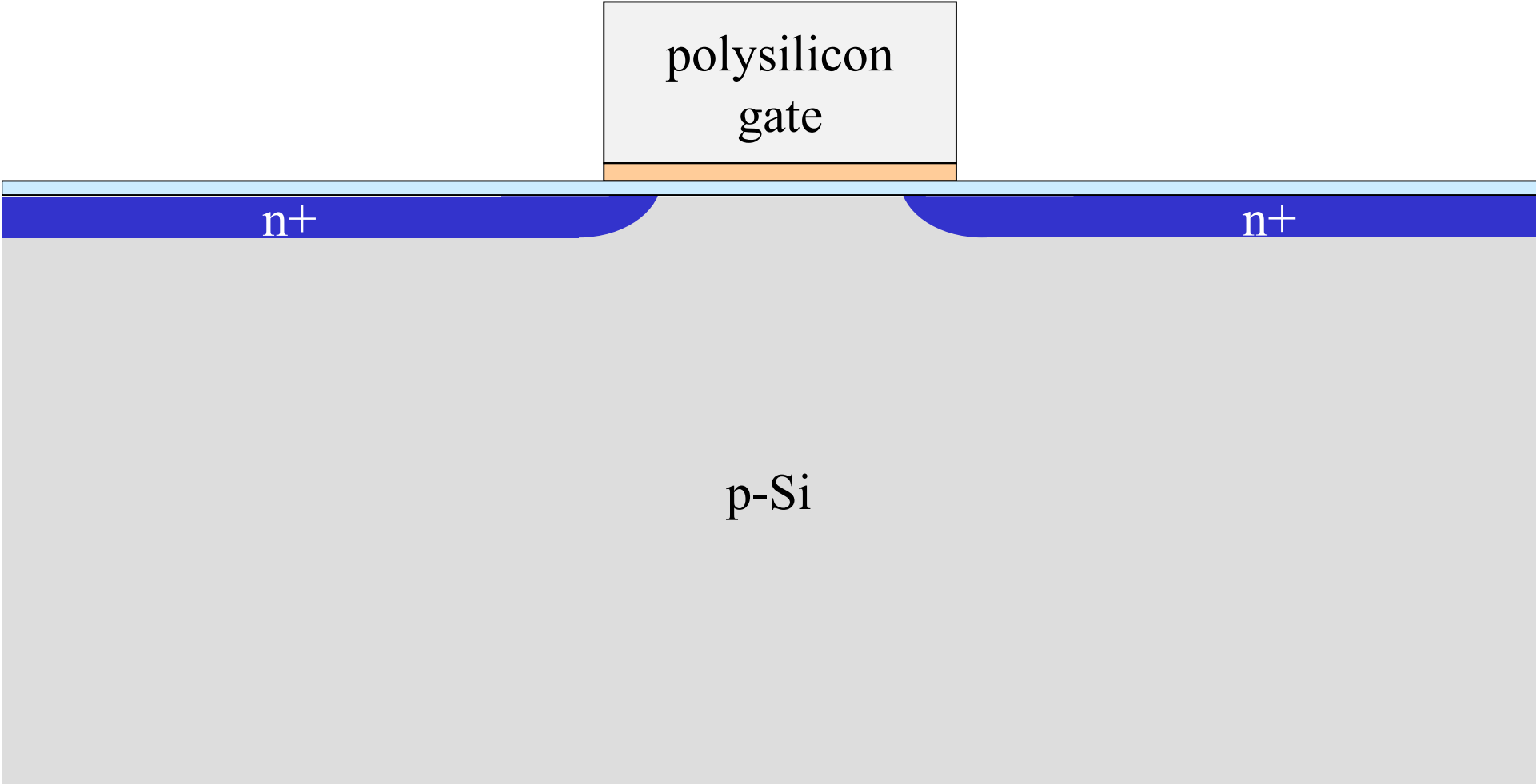
p-Si



Implant



Self-aligned fabrication



Spacer

PECVD SiN_x

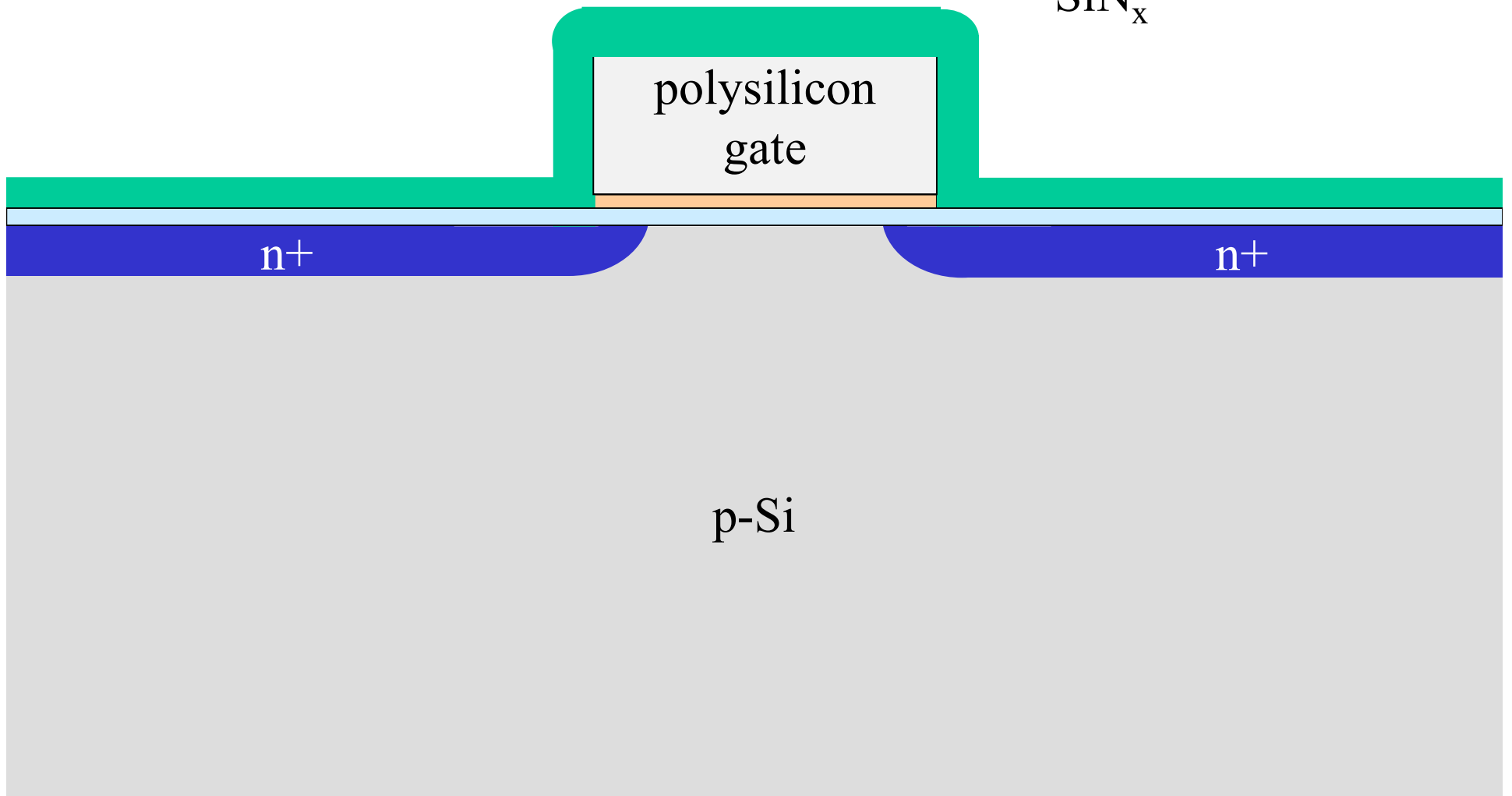
SiN_x

polysilicon
gate

n+

n+

p-Si



Spacer

Etch back to
leave only
sidewalls

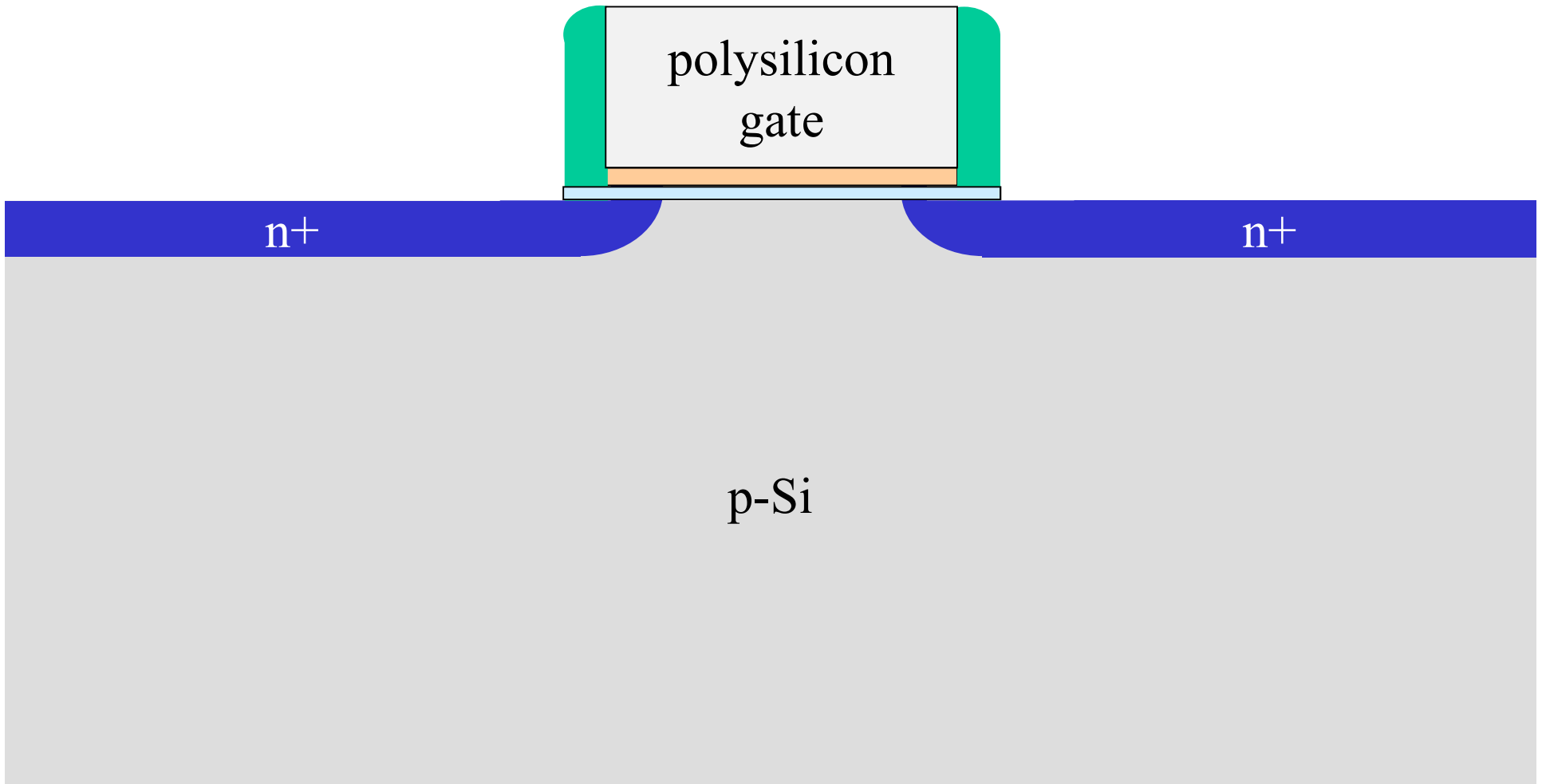
SiN_x

polysilicon
gate

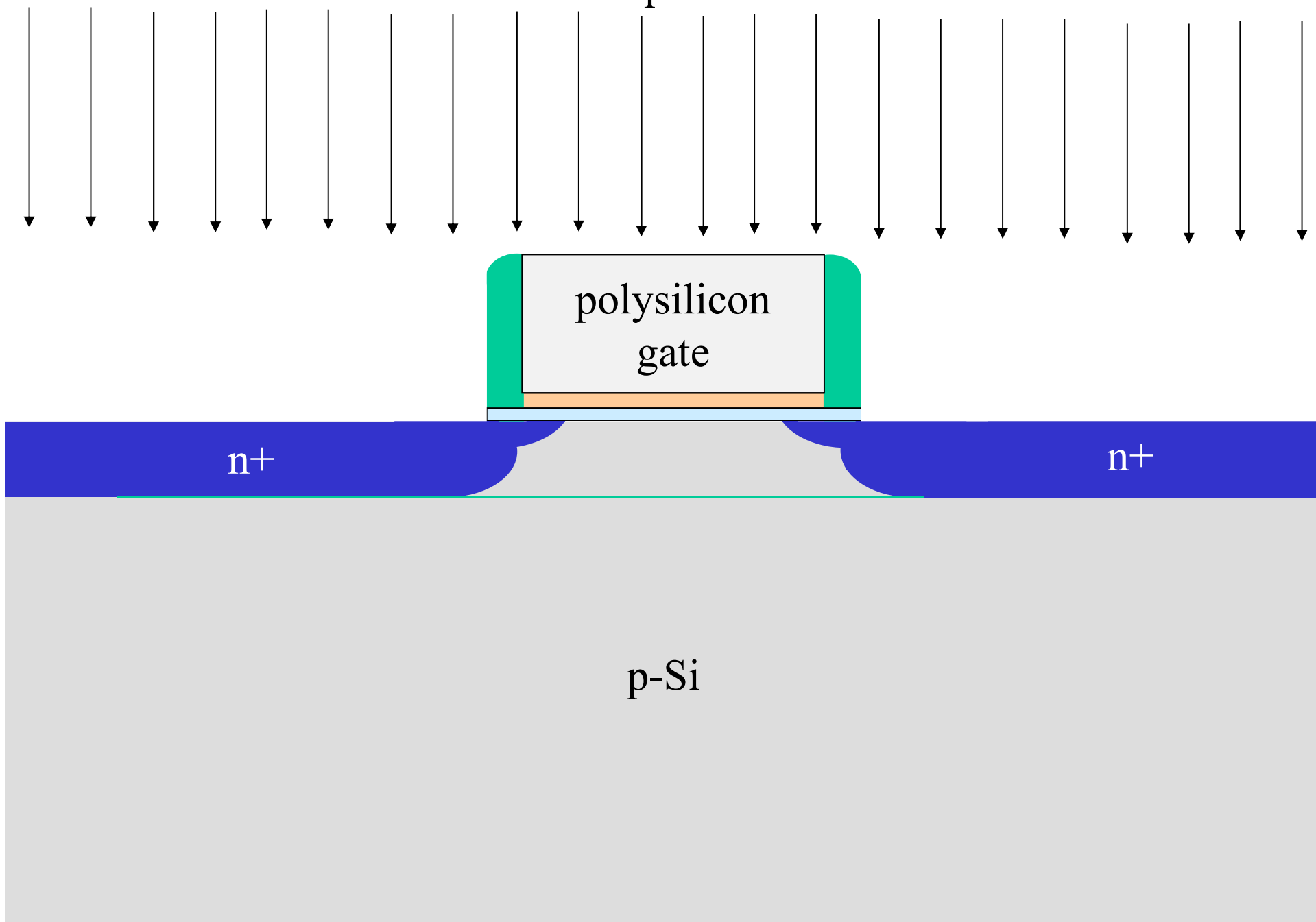
n+

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.

