Chapter 3
Basics Semiconductor Devices and Processing

Hong Xiao, Ph. D.

www2.austin.cc.tx.us/HongXiao/Book.htm

Objectives

- Identify at least two semiconductor materials from the periodic table of elements
- List n-type and p-type dopants
- Describe a diode and a MOS transistor
- List three kinds of chips made in the semiconductor industry
- List at least four basic processes required for a chip manufacturing

Topics

- What is semiconductor
- Basic semiconductor devices
- Basics of IC processing

What is Semiconductor

- Conductivity between conductor and insulator
- Conductivity can be controlled by dopant
- Silicon and germanium
- Compound semiconductors
  - SiGe, SiC
  - GaAs, InP, etc.

Periodic Table of the Elements

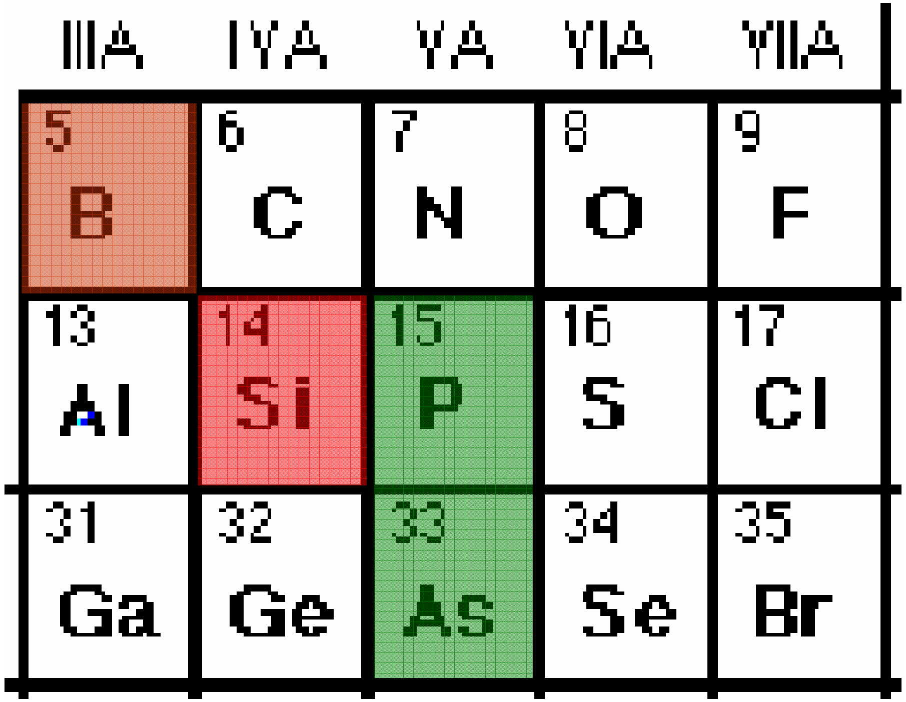
	IA	IIA	IIIB	IVB	VB	VIB	VIIB	VII	VII	VII	IB	IIB	IIIA	IVA	VA	VIA	VIIA	0
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 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	57 *La	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	89 +Ac	104 Rf	105 Ha	106 Sg	107 Ns	108 Hs	109 Mt	110 110	111 111	112 112	113 113					

* Lanthanide Series	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
+ Actinide Series	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

Semiconductor Substrate and Dopants

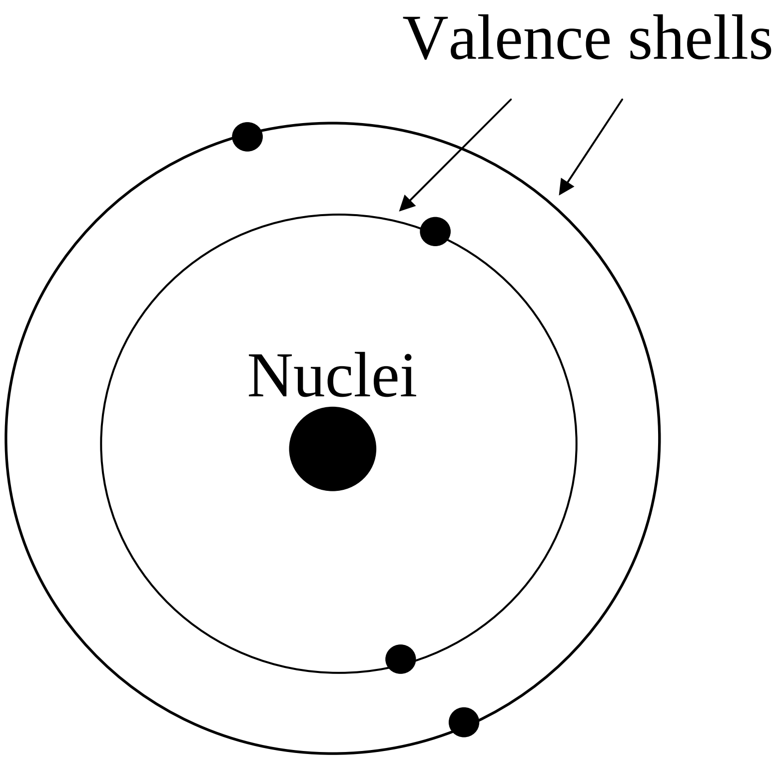
Substrate

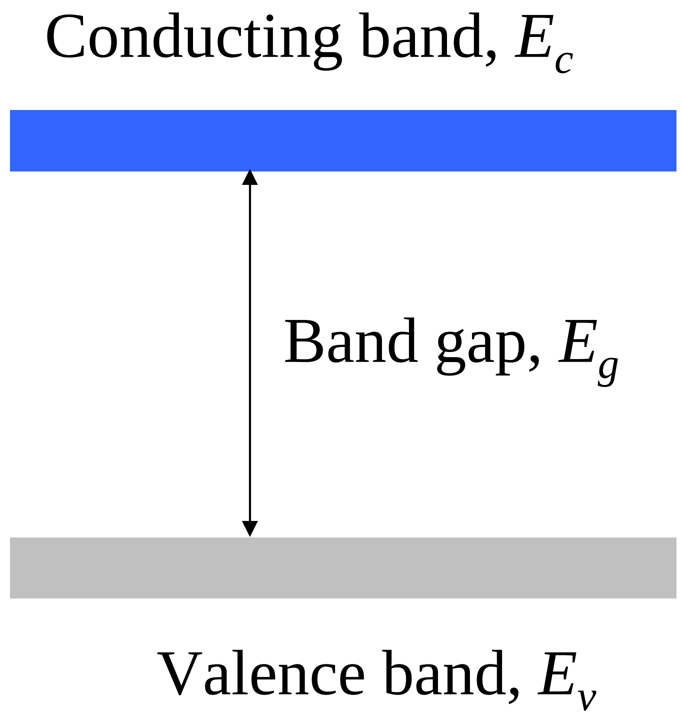
P-type Dopant



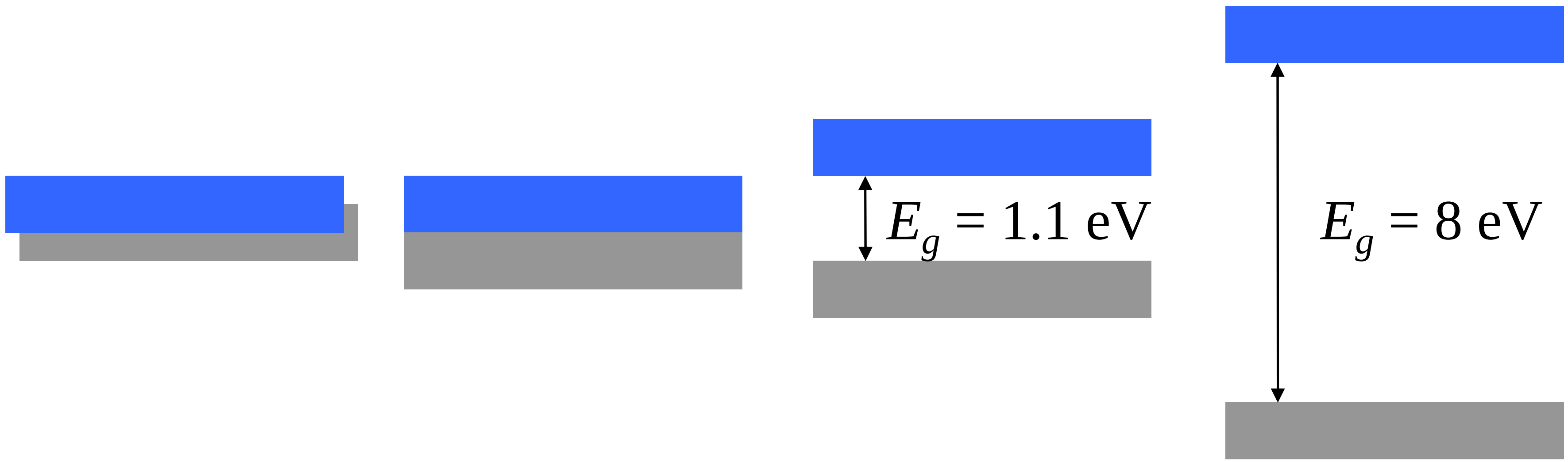
N-type Dopants

Orbital and Energy Band Structure of an Atom





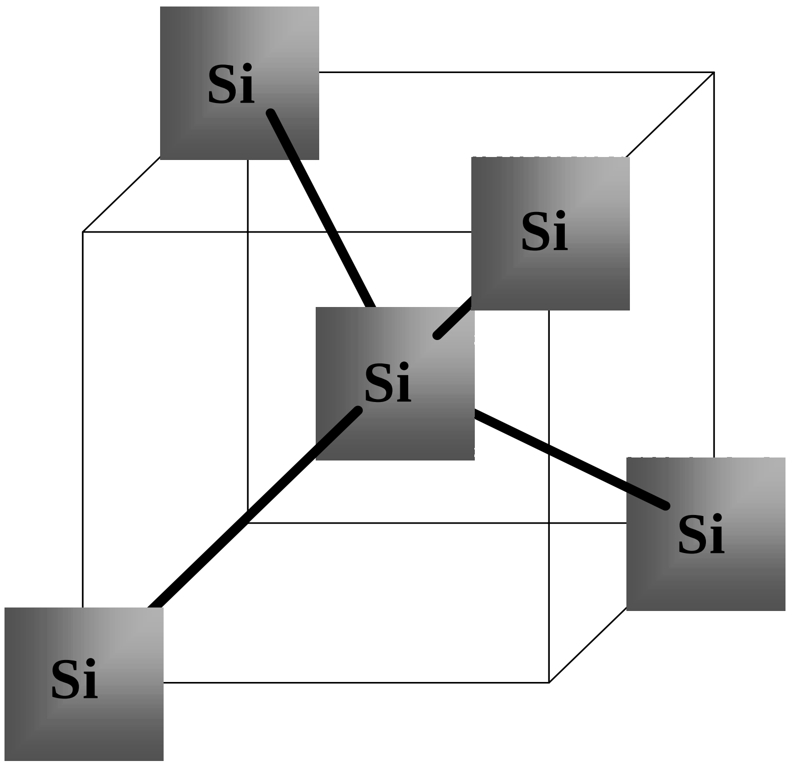
Band Gap and Resistivity

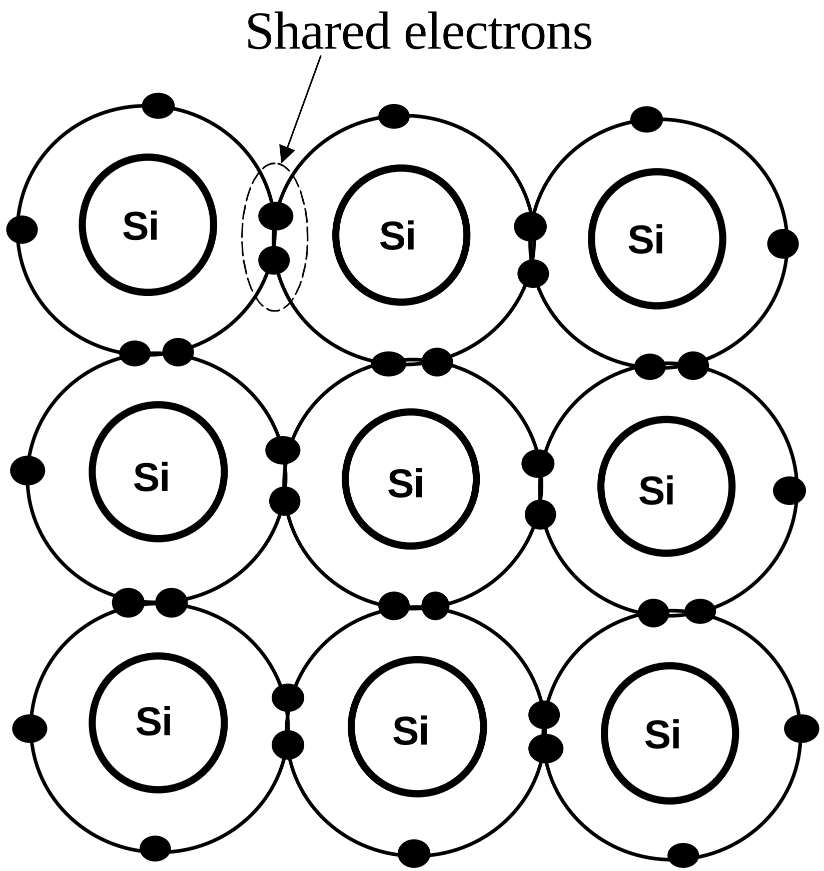


Aluminum	Sodium	Silicon	Silicon dioxide
2.7 μΩ•cm	4.7 μΩ•cm	~ 10^{10} μΩ•cm	> 10^{20} μΩ•cm

Conductors — Semiconductor — Insulator

Crystal Structure of Single Crystal Silicon

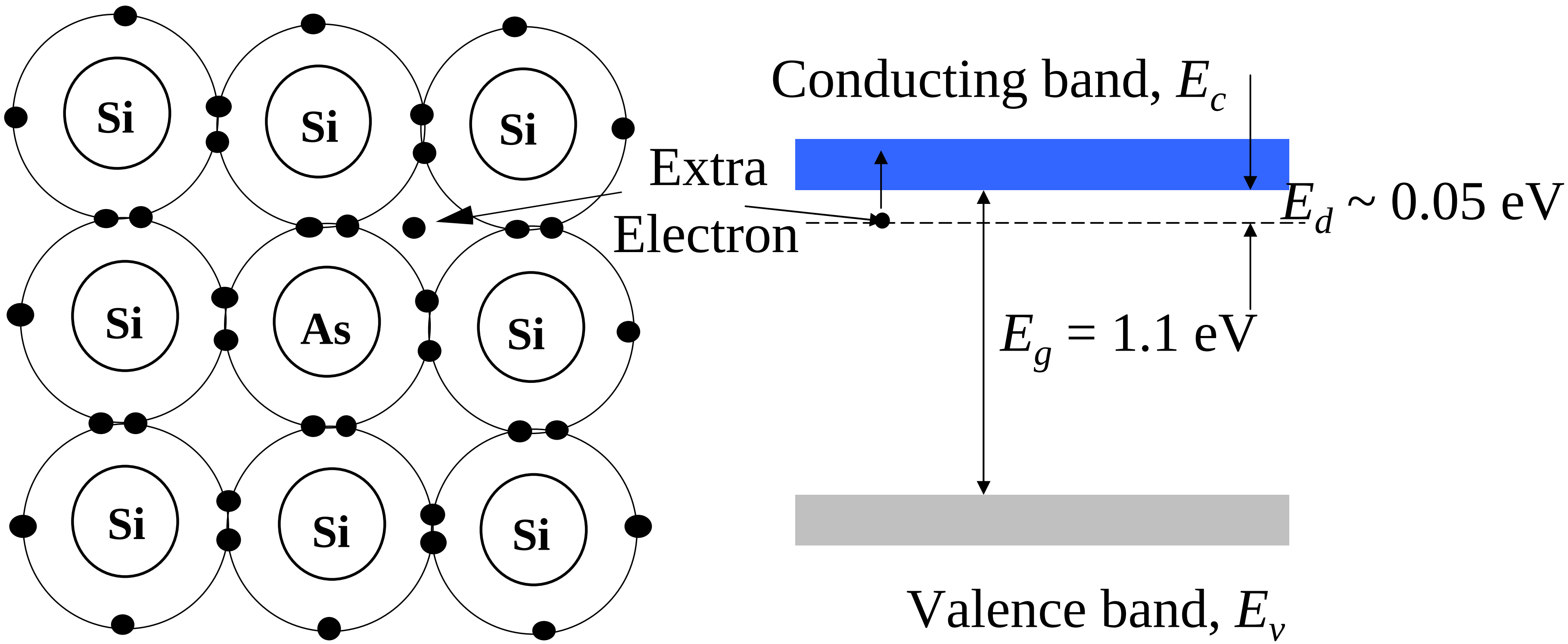




Why Silicon

- Abundant, inexpensive
- Thermal stability
- Silicon dioxide is a strong dielectric and relatively easy to form
- Silicon dioxide can be used as diffusion doping mask

N-type (Arsenic) Doped Silicon and Its Donor Energy Band



P-type (Boron) Doped Silicon and Its Donor Energy Band

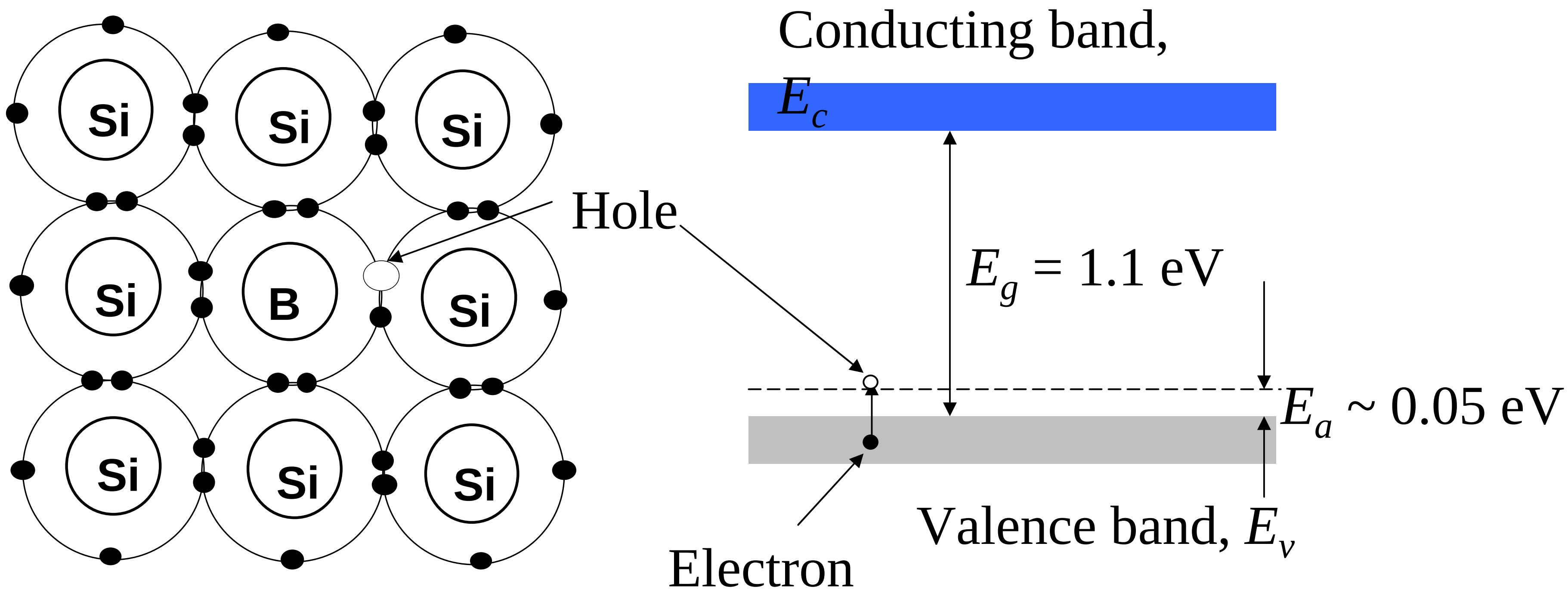
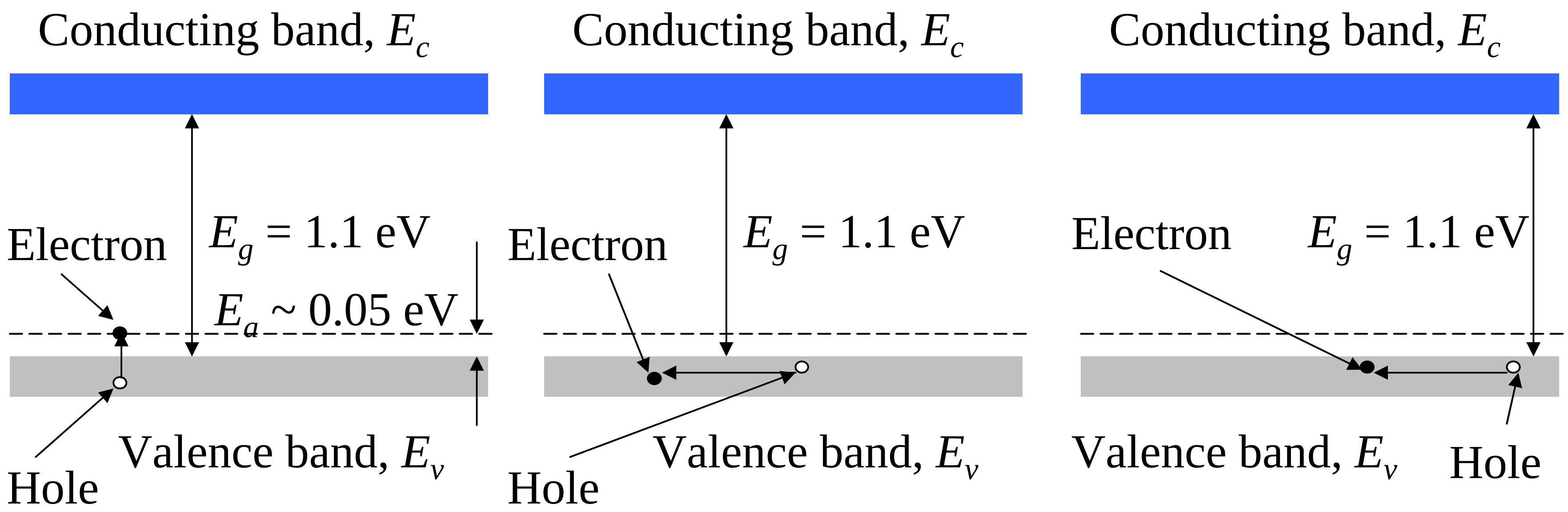
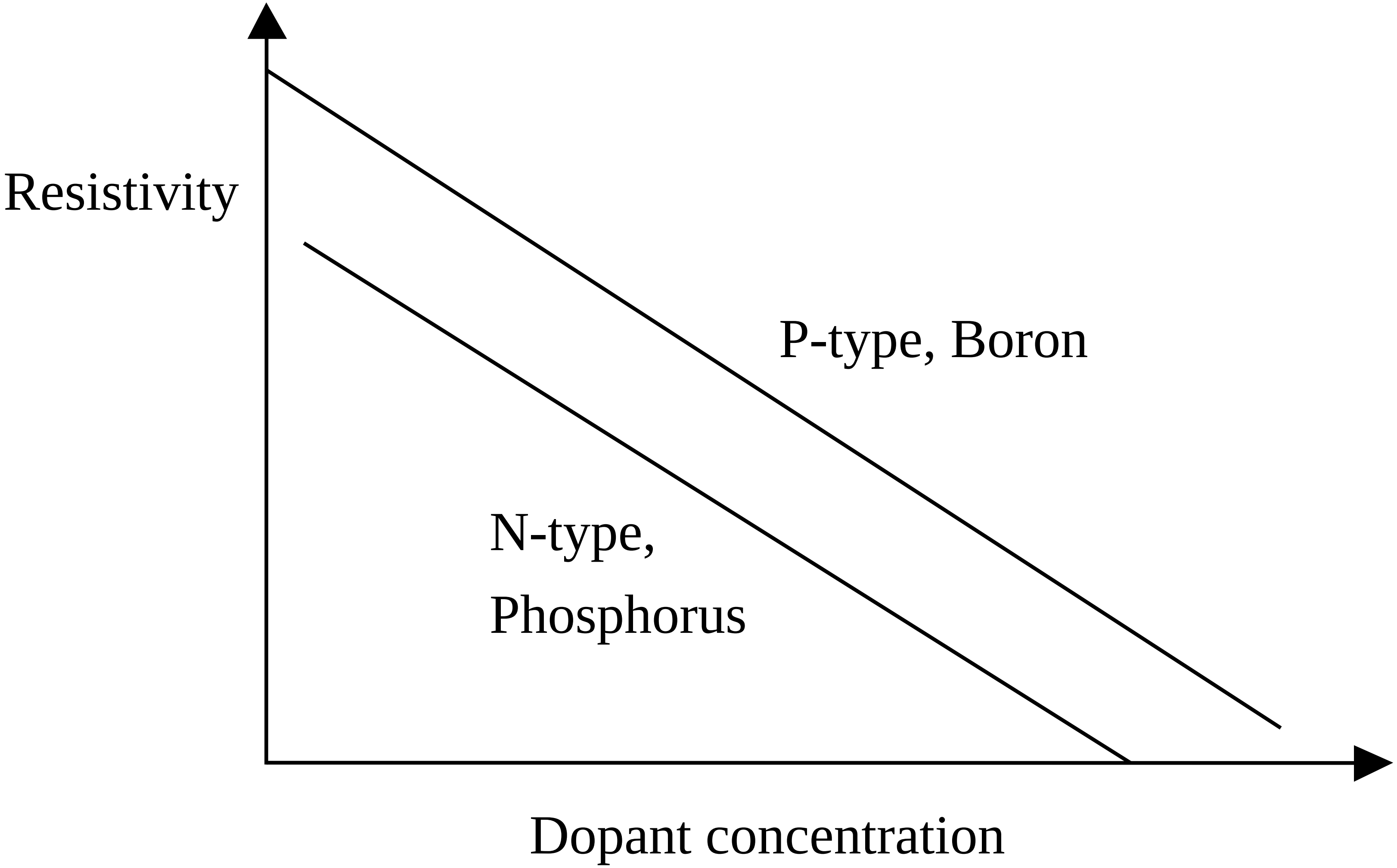


Illustration of Hole Movement



Dopant Concentration and Resistivity



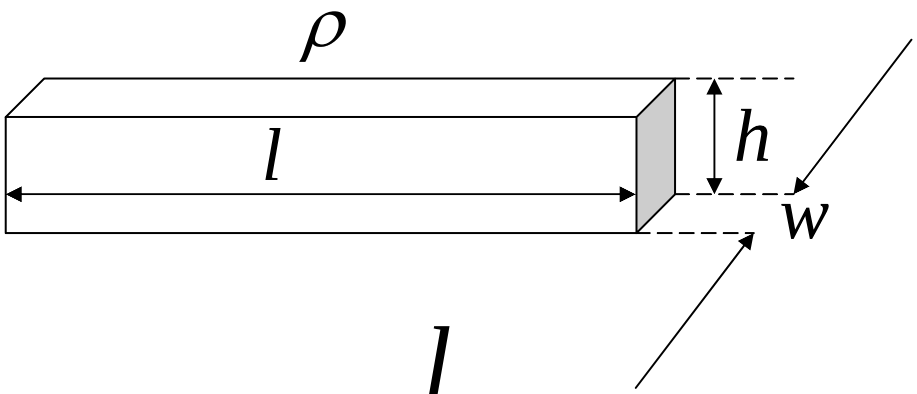
Dopant Concentration and Resistivity

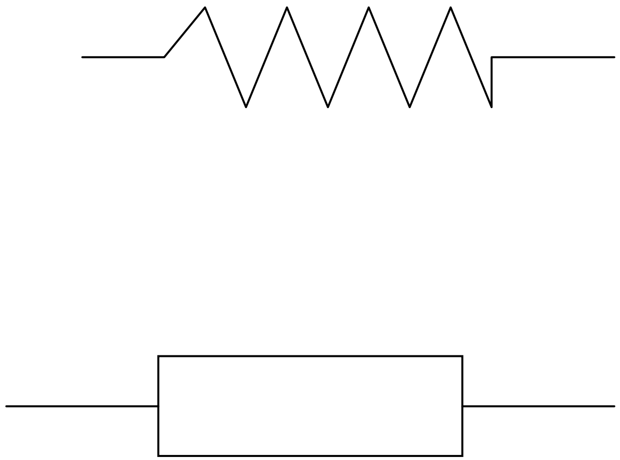
- Higher dopant concentration, more carriers (electrons or holes)
- Higher conductivity, lower resistivity
- Electrons move faster than holes
- N-type silicon has lower resistivity than p-type silicon at the same dopant concentration

Basic Devices

- Resistor
- Capacitor
- Diode
- Bipolar Transistor
- MOS Transistor

Resistor





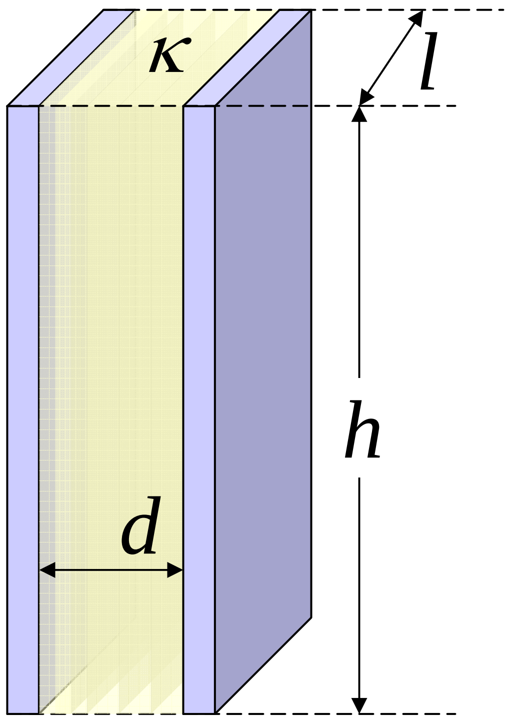
$$R = \rho \frac{l}{wh}$$

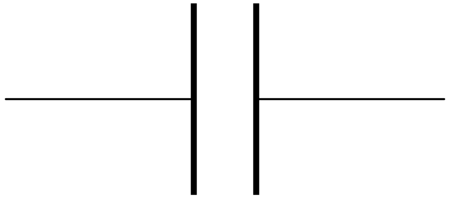
ρ: Resistivity

Resistor

- Resistors are made by doped silicon or polysilicon on an IC chip
- Resistance is determined by length, line width, height, and dopant concentration

Capacitors





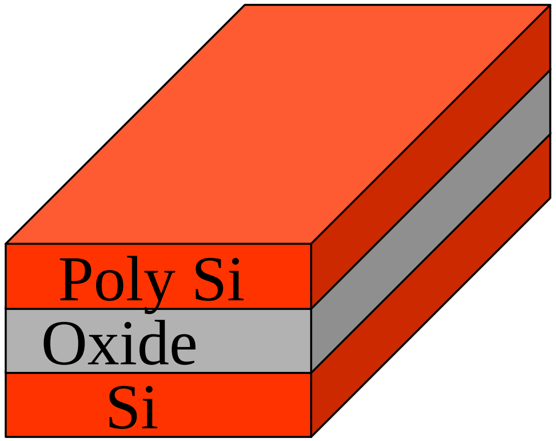
$$C = \kappa \frac{hl}{d}$$

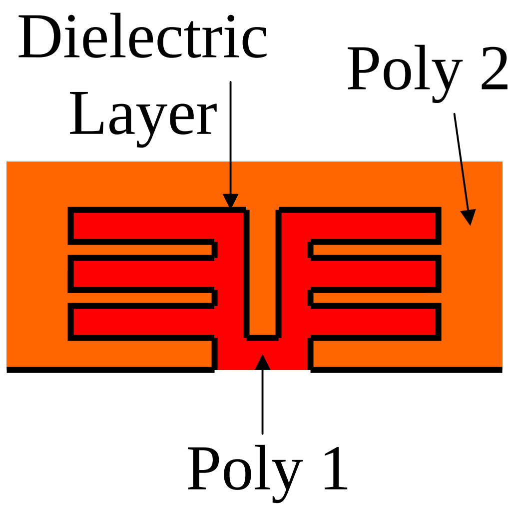
κ: Dielectric Constant

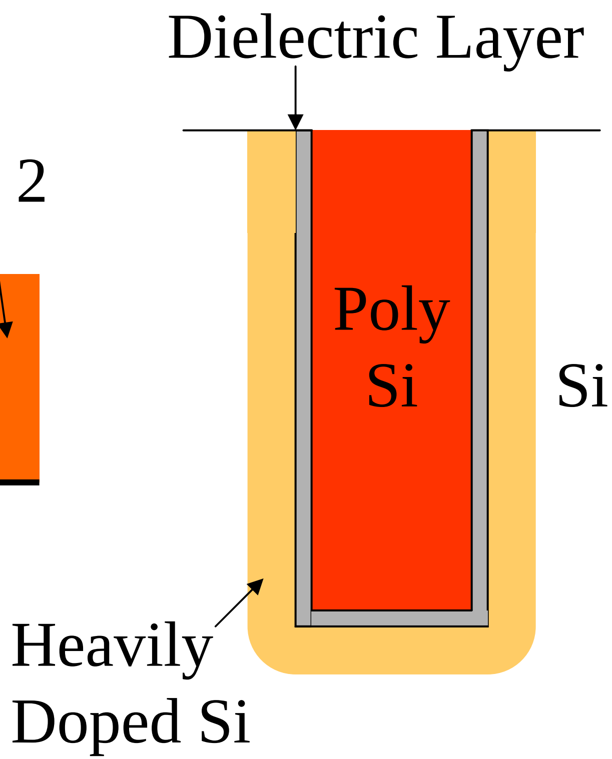
Capacitors

- Charge storage device
- Memory Devices, esp. DRAM
- Challenge: reduce capacitor size while keeping the capacitance
- High-κ dielectric materials

Capacitors





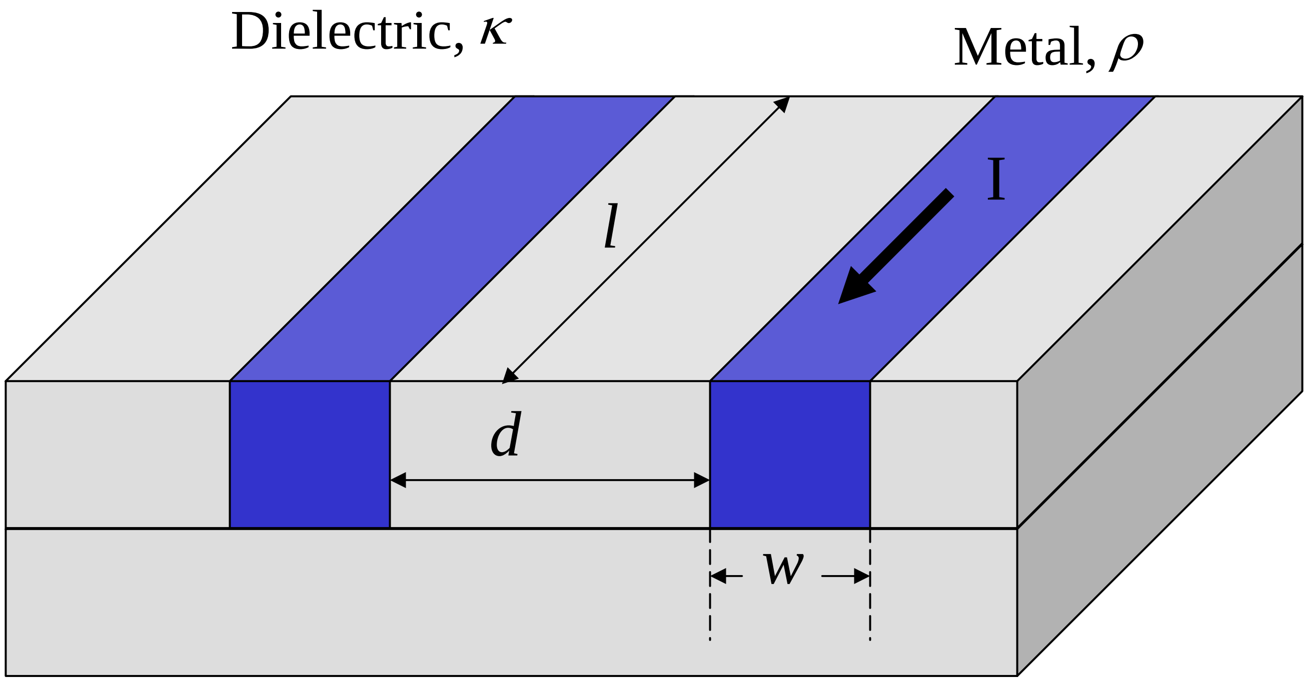


Parallel plate

Stacked

Deep Trench

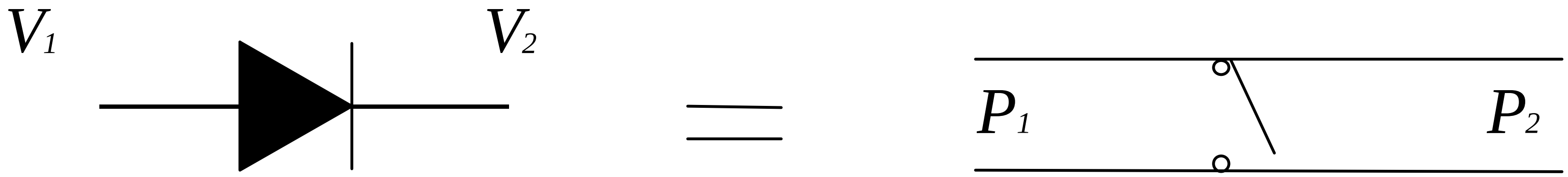
Metal Interconnection and RC Delay



Diode

- P-N Junction
- Allows electric current go through only when it is positively biased.

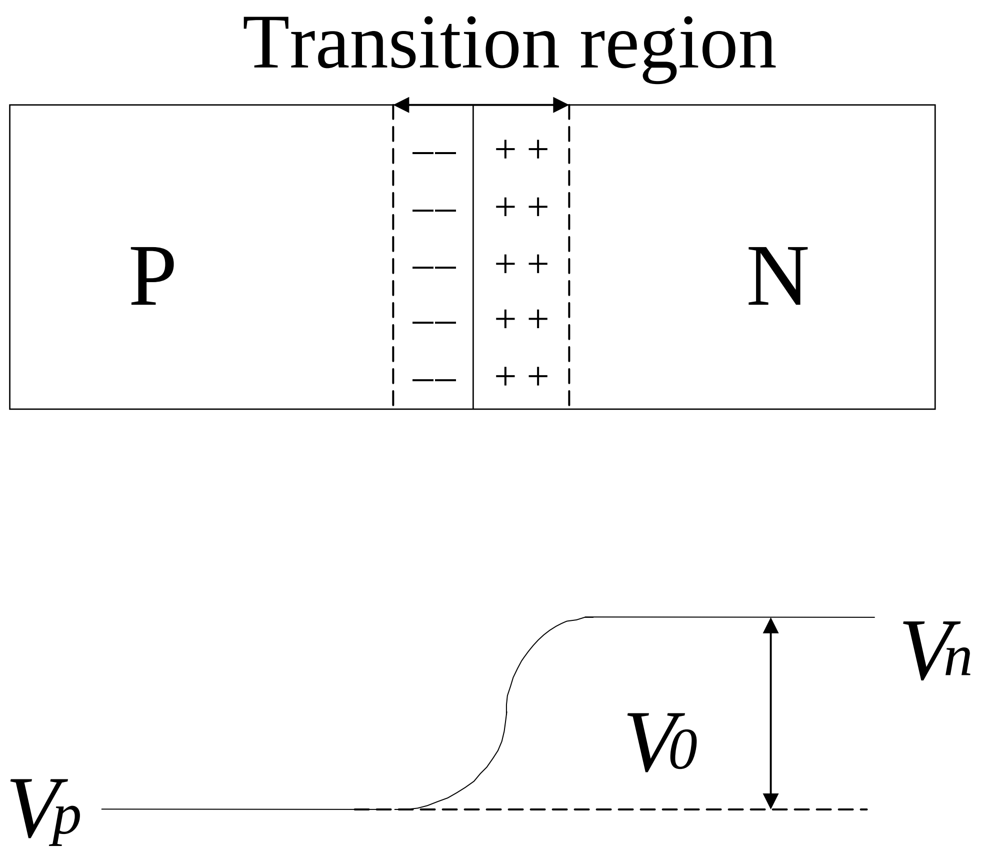
Diode



- $V_1 > V_2$, current $\longrightarrow$
- $V_1 < V_2$, no current

- $P_1 > P_2$, current $\longrightarrow$
- $P_1 < P_2$, no current

Figure 3.14

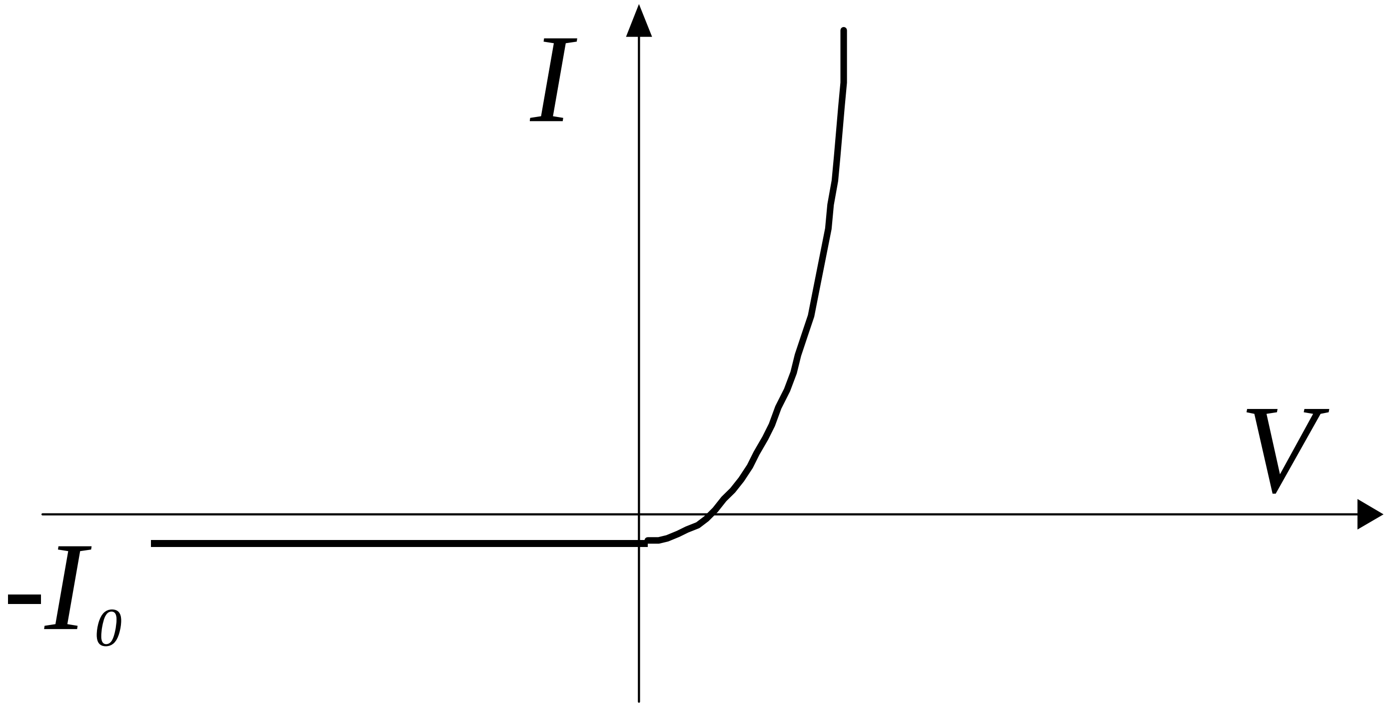


Intrinsic Potential

$$V_0 = \frac{kT}{q} \ln \frac{N_a N_d}{n_i^2}$$

- For silicon V_0 ~ 0.7 V

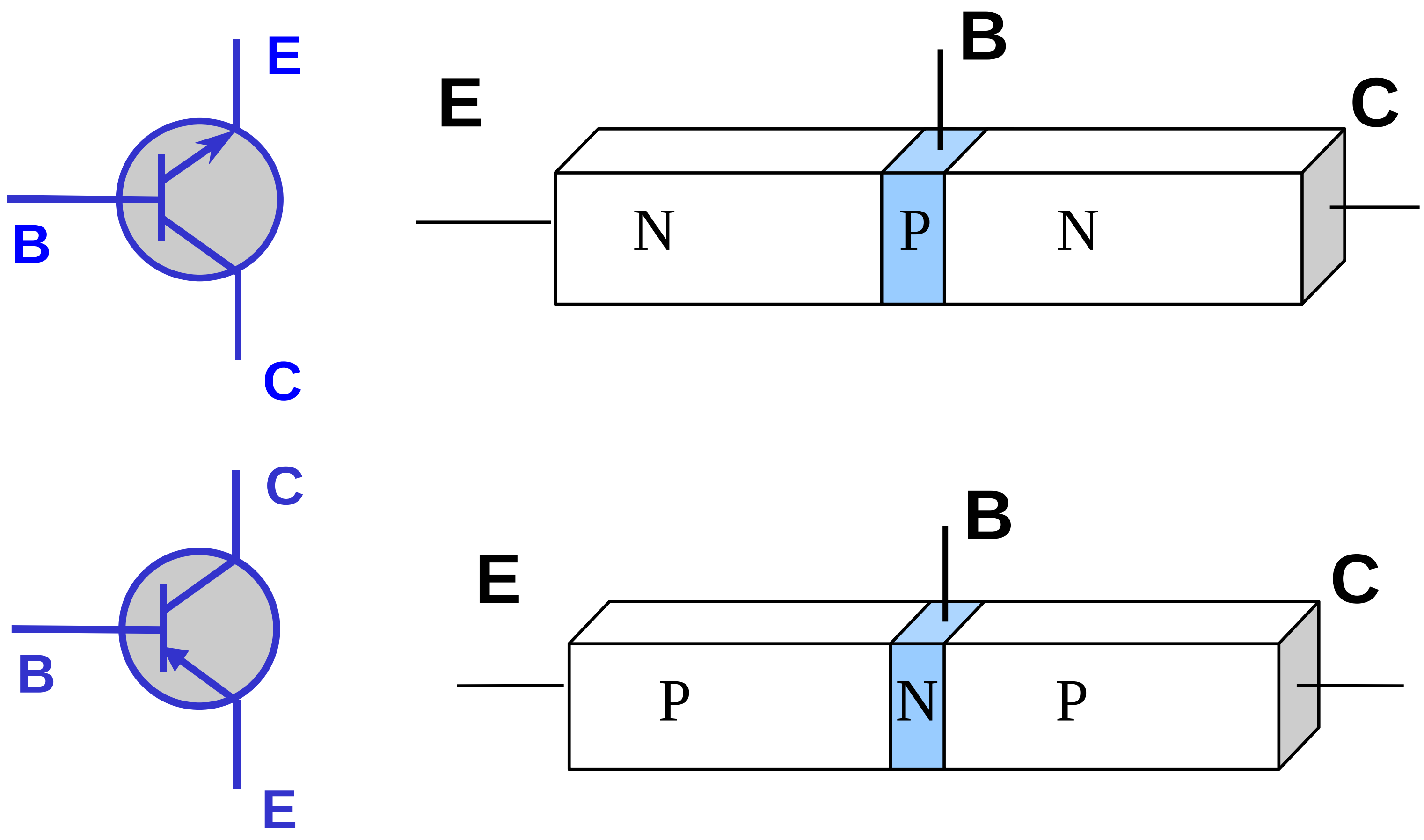
I-V Curve of Diode



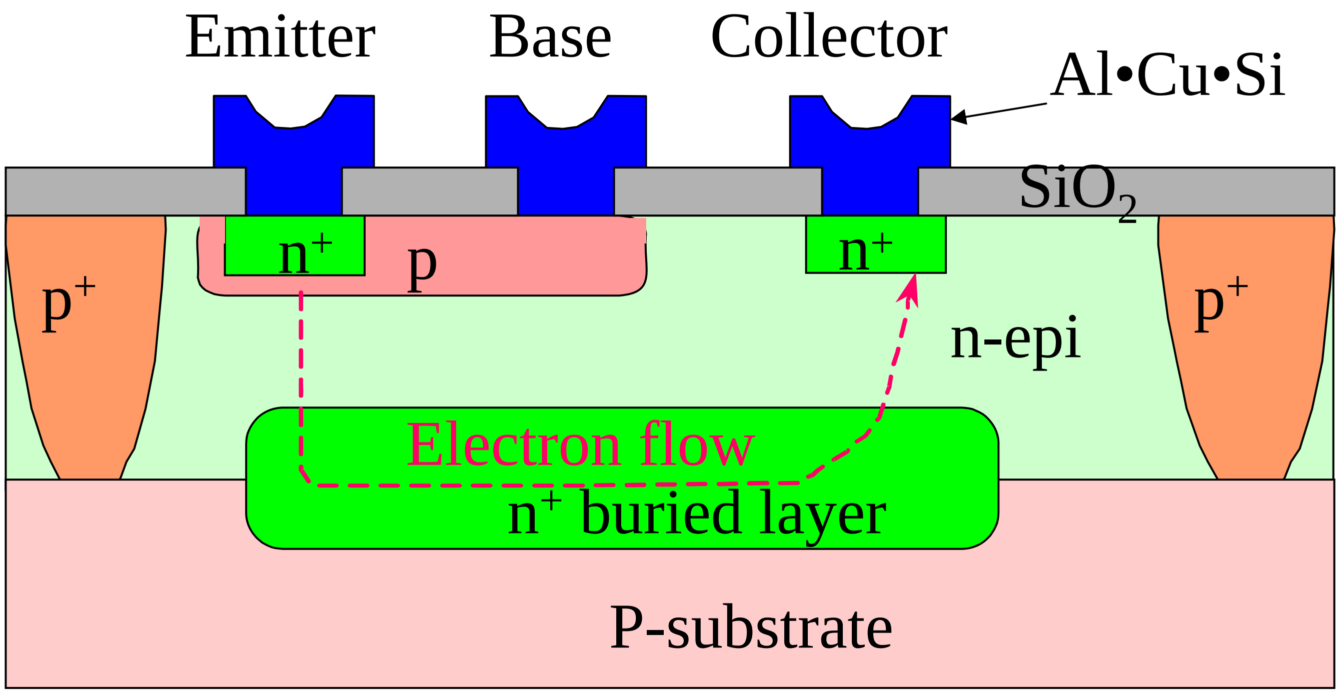
Bipolar Transistor

- PNP or NPN
- Switch
- Amplifier
- Analog circuit
- Fast, high power device

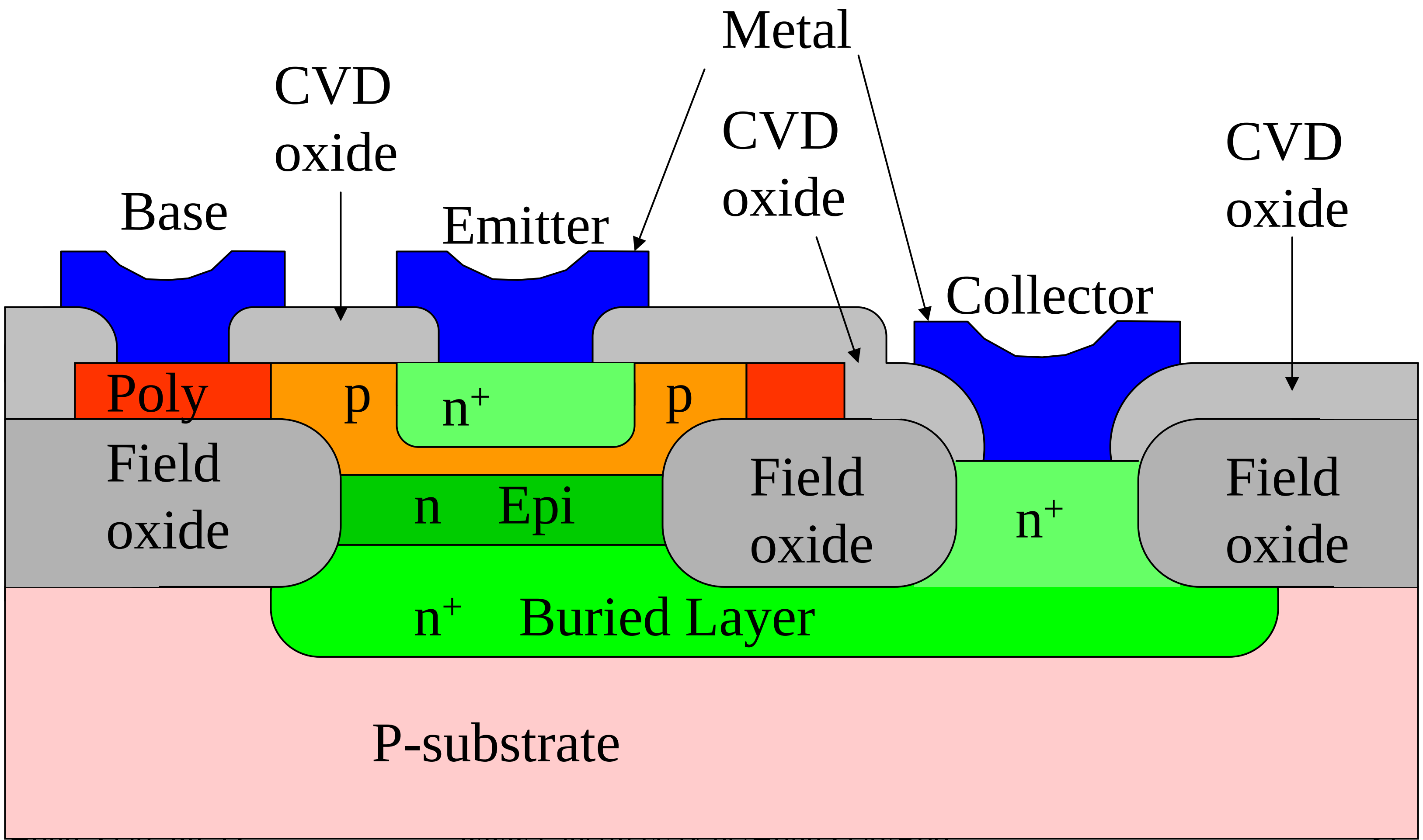
NPN and PNP Transistors



NPN Bipolar Transistor



Sidewall Base Contact NPN Bipolar Transistor

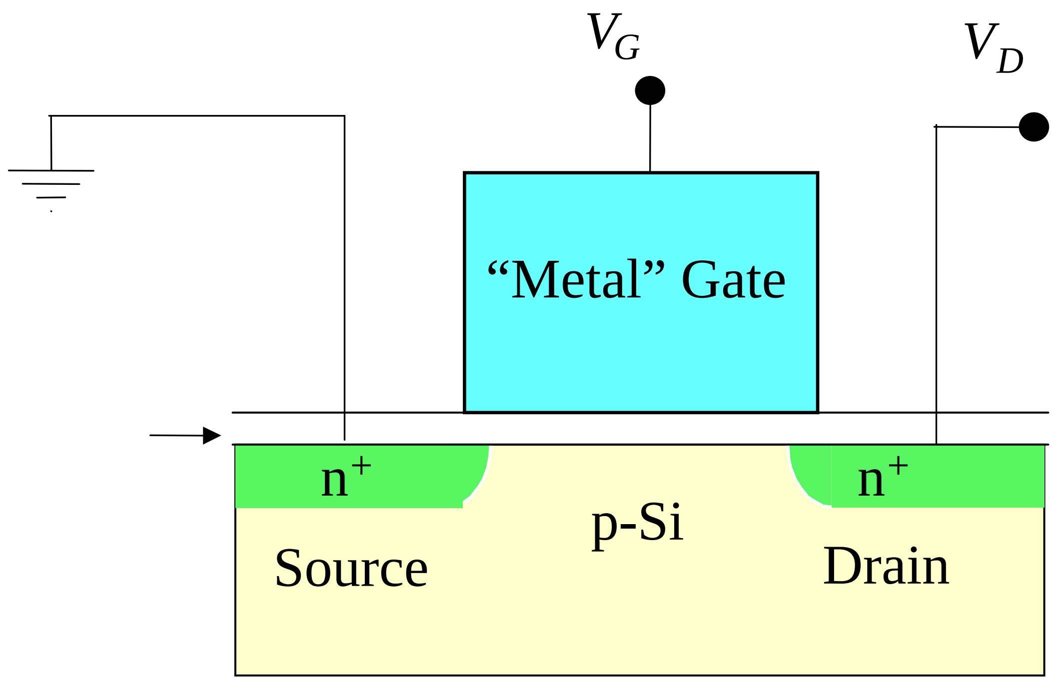


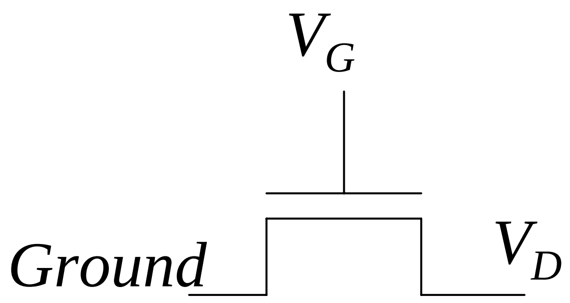
MOS Transistor

- Metal-oxide-semiconductor
- Also called MOSFET (MOS Field Effect Transistor)
- Simple, symmetric structure
- Switch, good for digital, logic circuit
- Most commonly used devices in the semiconductor industry

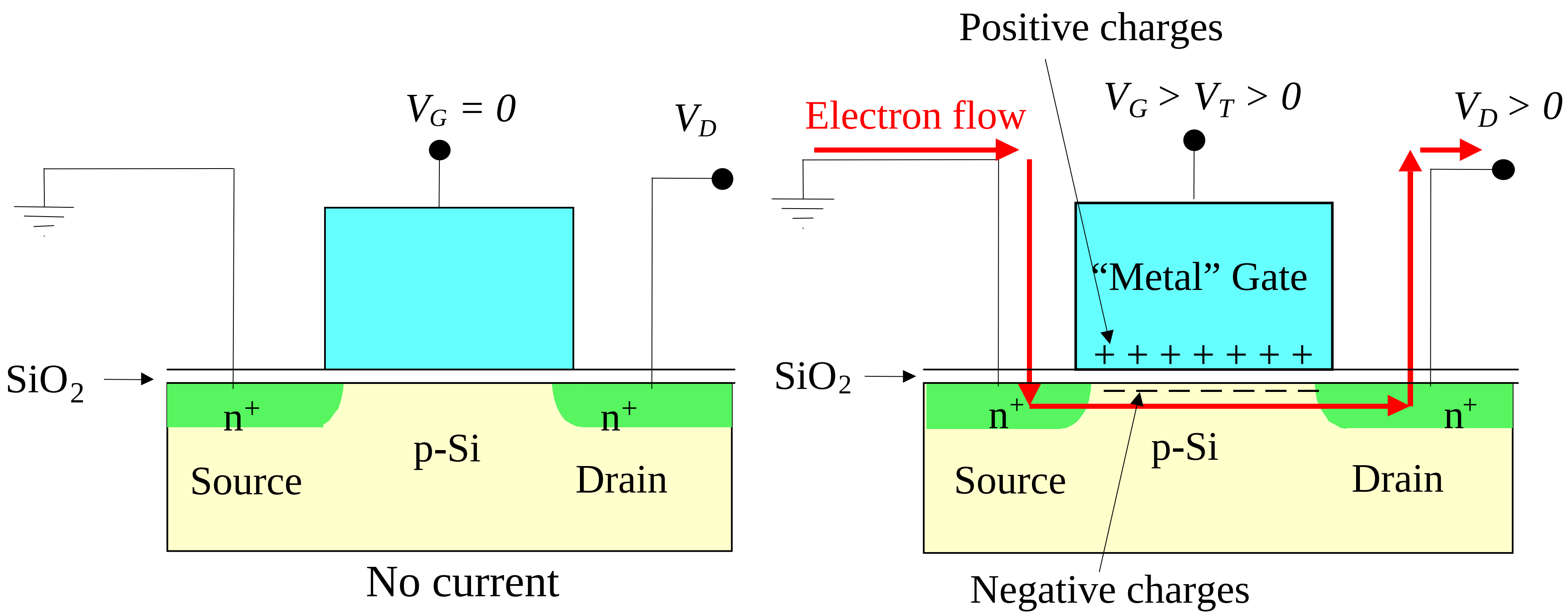
NMOS Device

Basic Structure



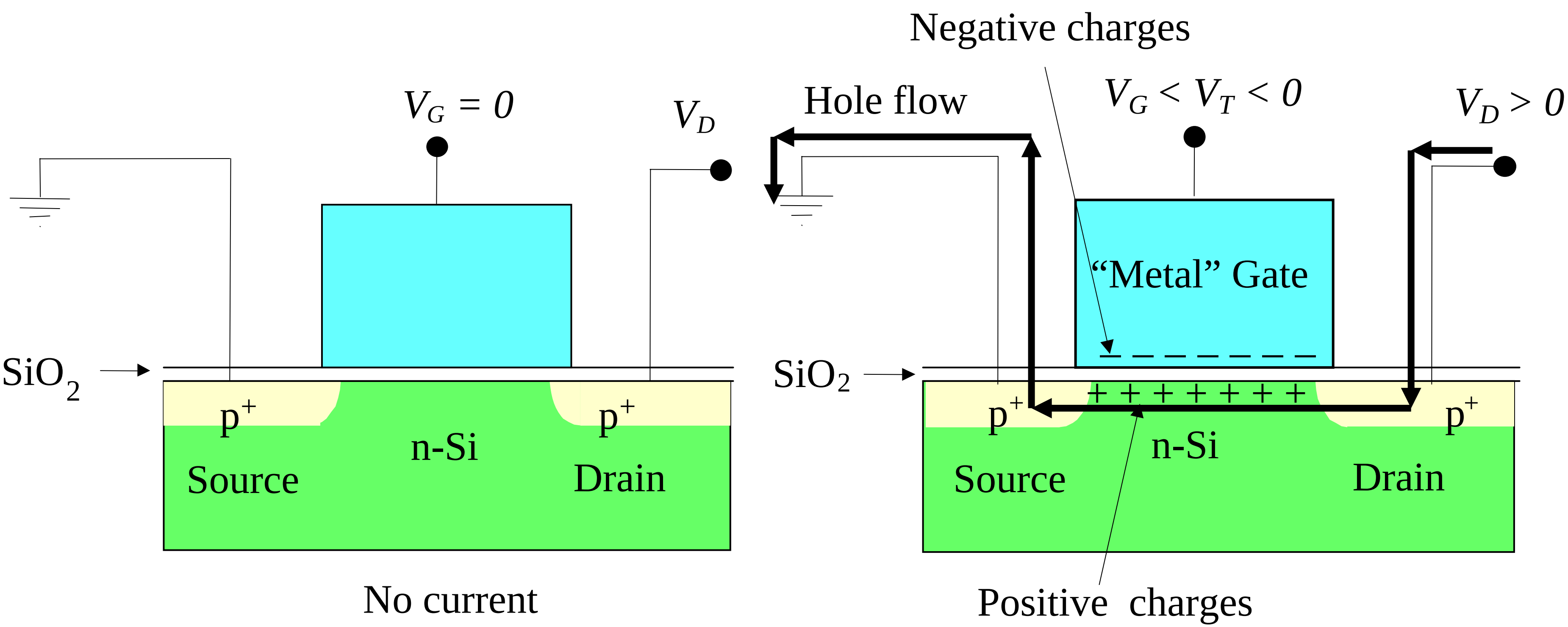


NMOS Device



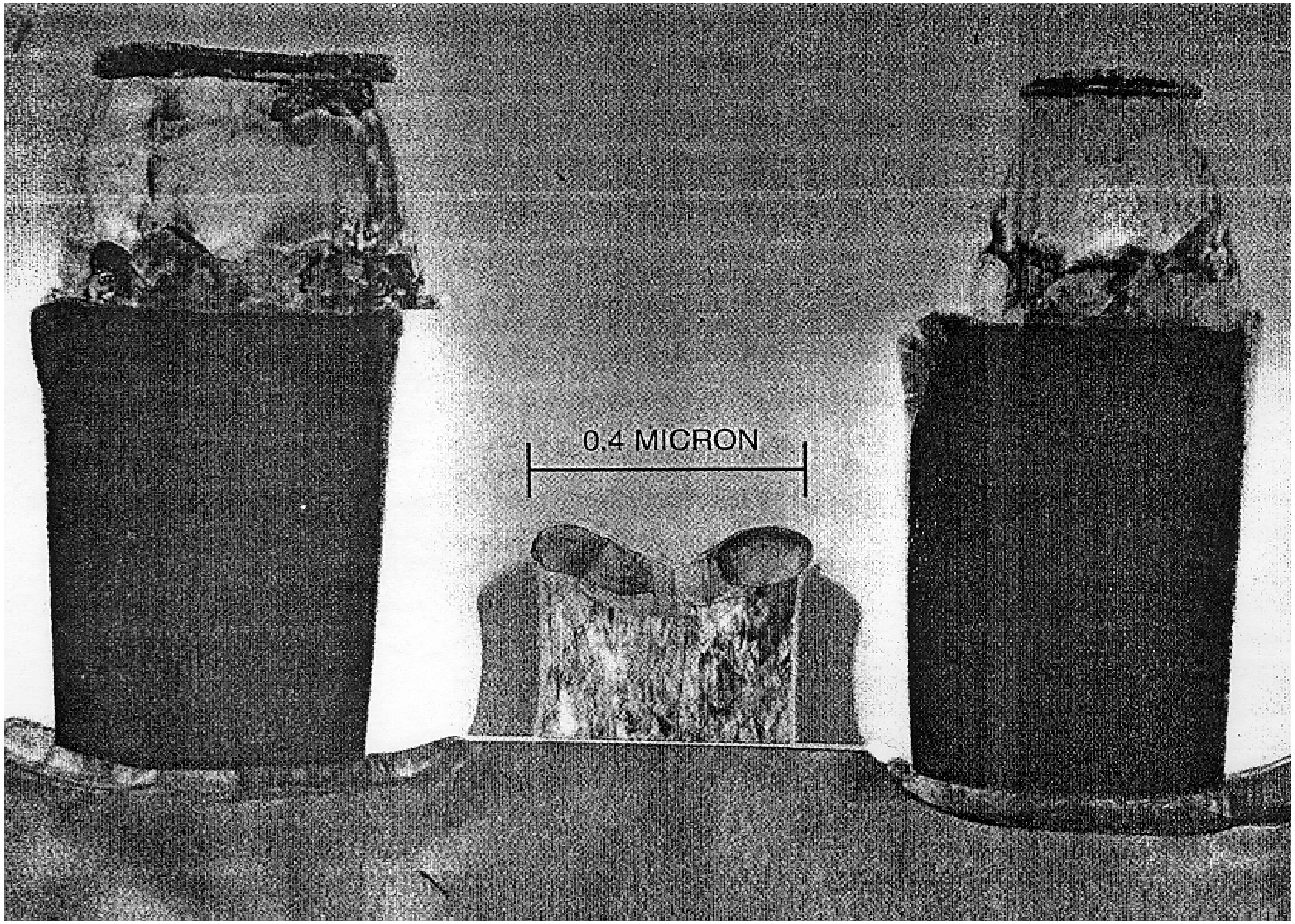
$V_G = 0$
V_D
SiO_2
n^+
n^+
p-Si
Source
Drain
No current
Positive charges
Electron flow
$V_G > V_T > 0$
$V_D > 0$
"Metal" Gate
+ + + + + + +
SiO_2
n^+
n^+
p-Si
Source
Drain
Negative charges

PMOS Device



$V_G = 0$
V_D
SiO_2
p^+
p^+
n-Si
Source
Drain
No current
Negative charges
Hole flow
$V_G < V_T < 0$
$V_D > 0$
"Metal" Gate
SiO_2
+ + + + + + +
p^+
p^+
n-Si
Source
Drain
Positive charges

MOSFET



MOSFET and Drinking Fountain

MOSFET	**Drinking Fountain**
• Source, drain, gate	• Source, drain, gate valve
• Source/drain biased	• Pressurized source
• Voltage on gate to turn-on	• Pressure on gate (button) to turn-on
• Current flow between source and drain	• Current flow between source and drain

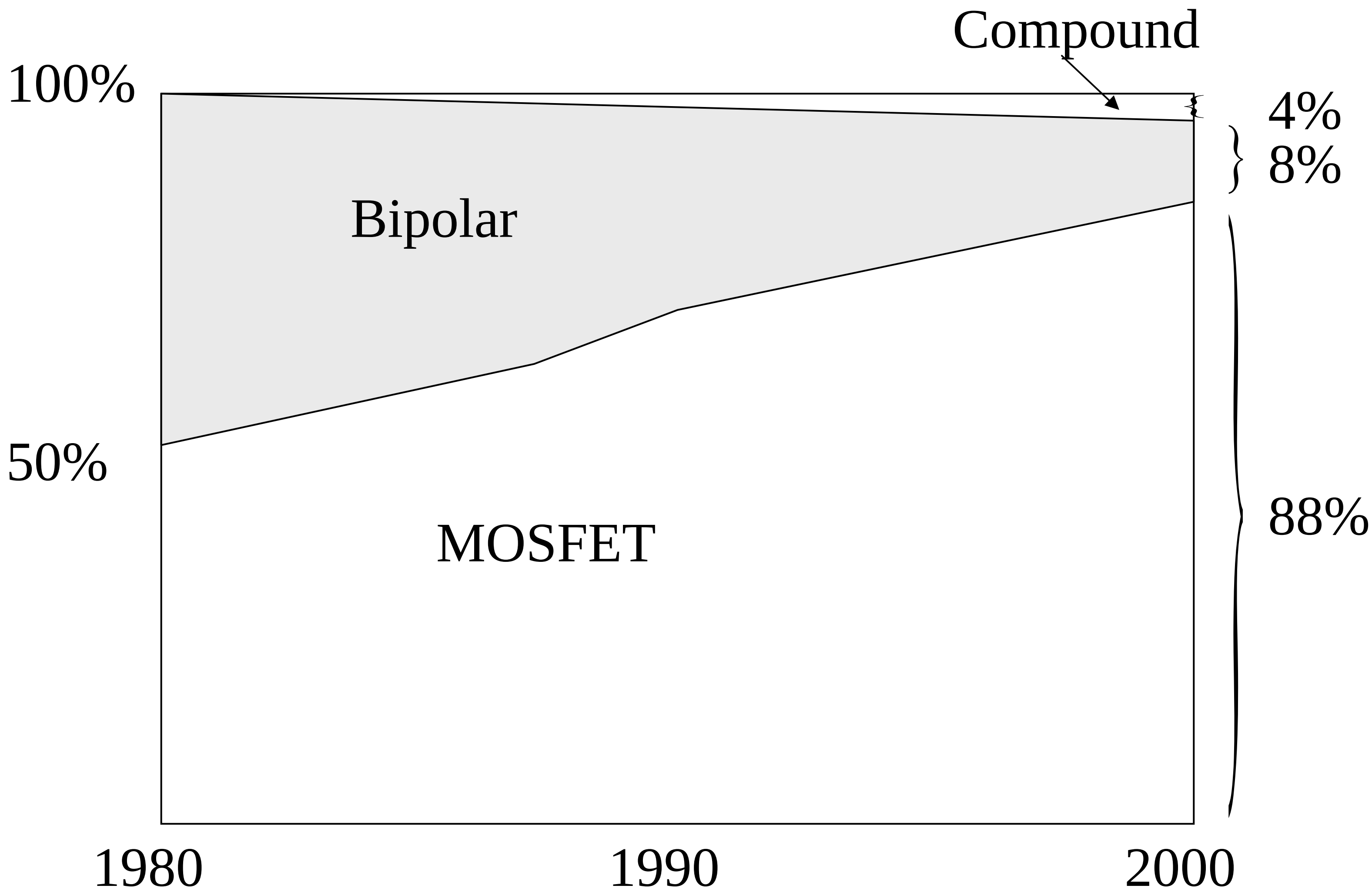
Basic Circuits

- Bipolar
- PMOS
- NMOS
- **CMOS**
- BiCMOS

Devices with Different Substrates

Silicon	• Bipolar • MOSFET • BiCMOS	Dominate IC industry
Germanium	• Bipolar: high speed devices	
Compound	• GaAs: up to 20 GHz device • Light emission diode (LED)	

Market of Semiconductor Products



Bipolar IC

- Earliest IC chip
- 1961, four bipolar transistors, $150.00
- Market share reducing rapidly
- Still used for analog systems and power devices
- TV, VCR, Cellar phone, etc.

PMOS

- First MOS field effect transistor, 1960
- Used for digital logic devices in the 1960s
- Replaced by NMOS after the mid-1970s

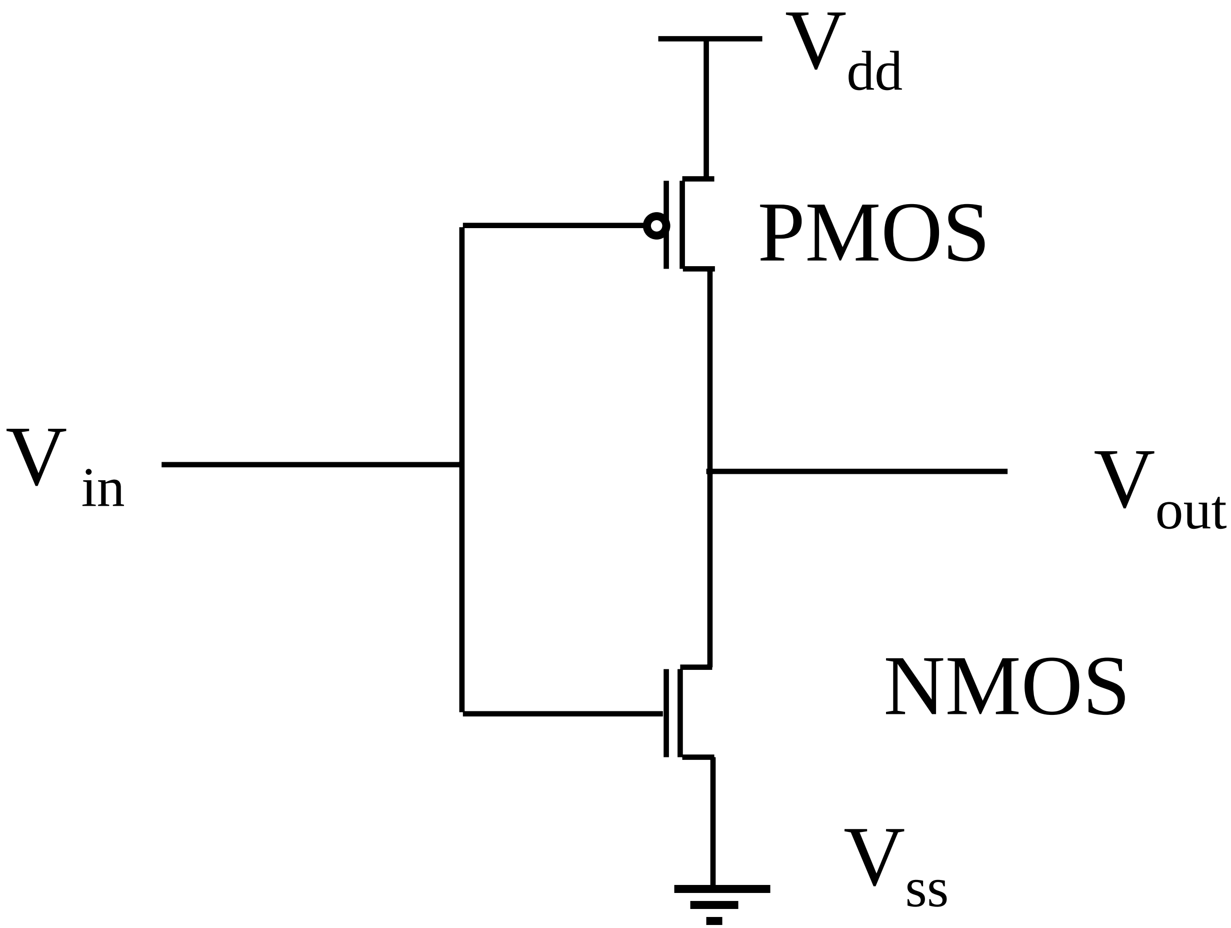
NMOS

- Faster than PMOS
- Used for digital logic devices in 1970s and 1980s
- Electronic watches and hand-hold calculators
- Replaced by CMOS after the 1980s

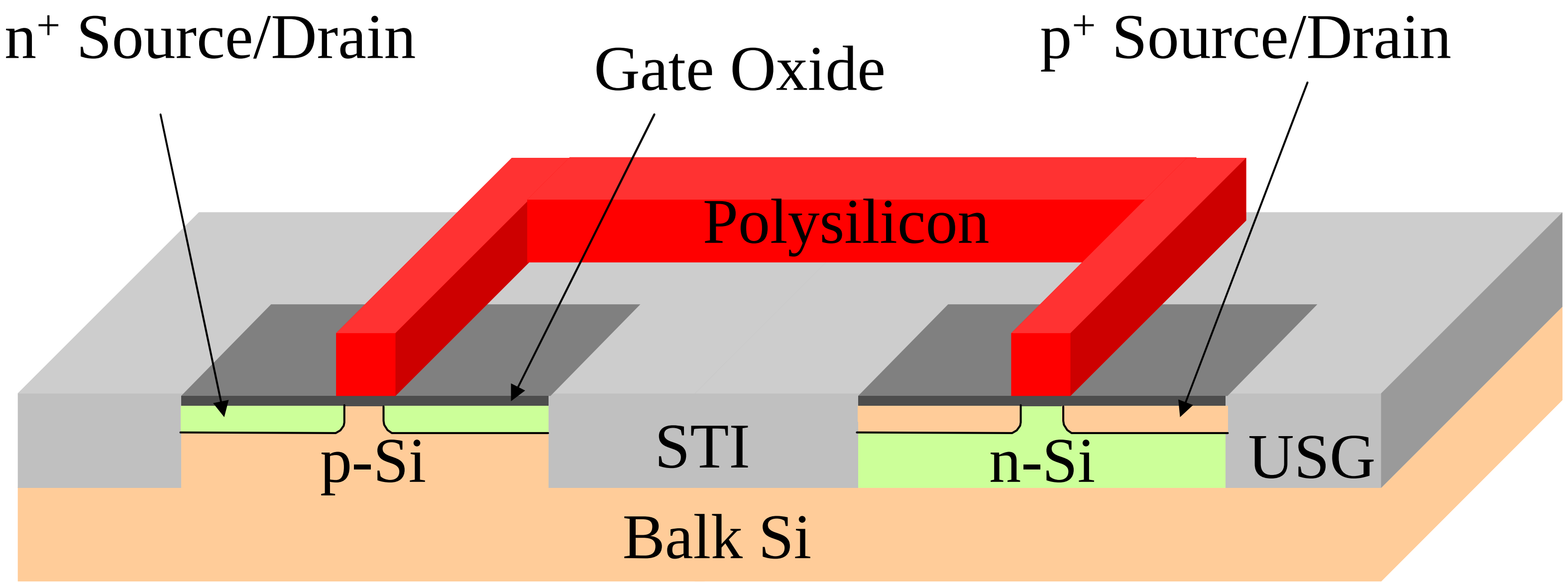
CMOS

- Most commonly used circuit in IC chip since 1980s
- Low power consumption
- High temperature stability
- High noise immunity
- Symmetric design

CMOS Inverter



CMOS IC



n+ Source/Drain
Gate Oxide
p+ Source/Drain
Polysilicon
STI
p-Si
n-Si
USG
Balk Si

BiCMOS

- Combination of CMOS and bipolar circuits
- Mainly in 1990s
- CMOS as logic circuit
- Bipolar for input/output
- Faster than CMOS
- Higher power consumption
- Likely will have problem when power supply voltage dropping below one volt

IC Chips

- Memory
- Microprocessor
- Application specific IC (ASIC)

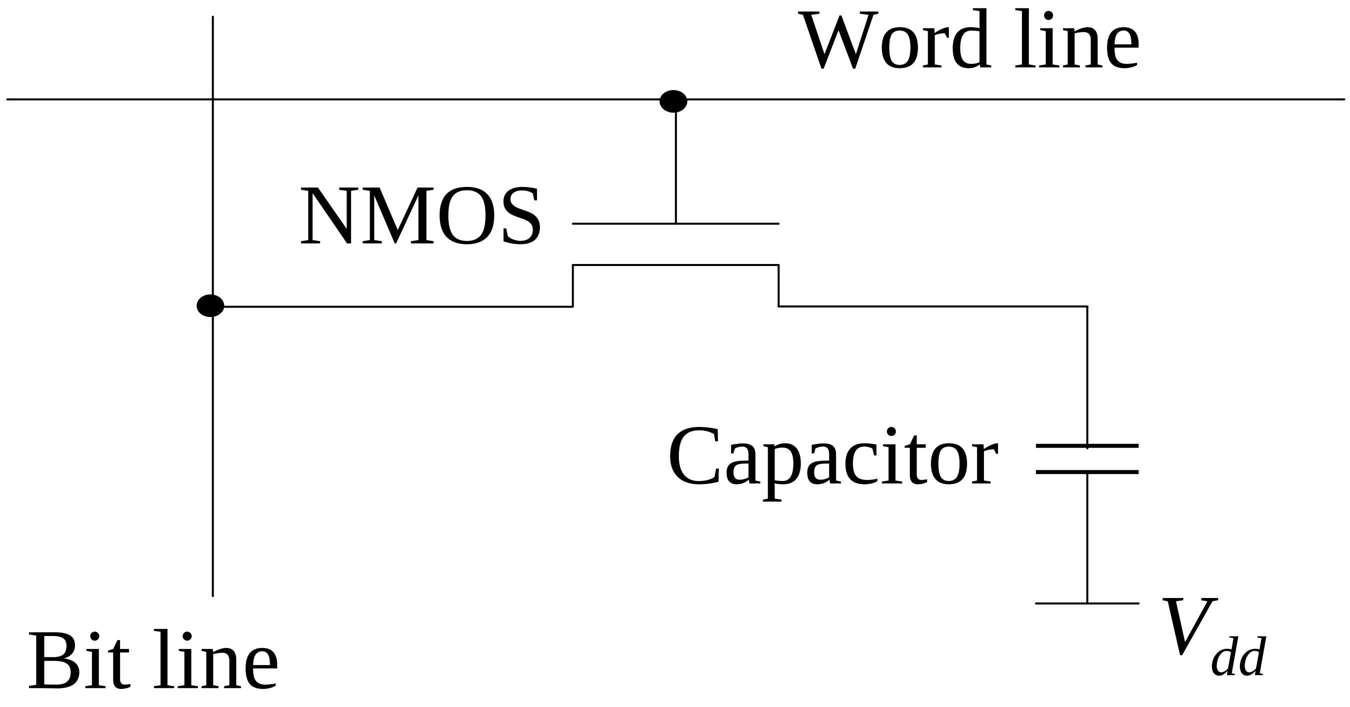
Memory Chips

- Devices store data in the form of electric charge
- Volatile memory
  - Dynamic random access memory (DRAM)
  - S random access memory (SRAM)
- Non-volatile memory
  - Erasable programmable read only memory (EPROM)
  - FLASH

DRAM

- Major component of computer and other electronic instruments for data storage
- Main driving force of IC processing development
- One transistor, one capacitor

Basic DRAM Memory Cell



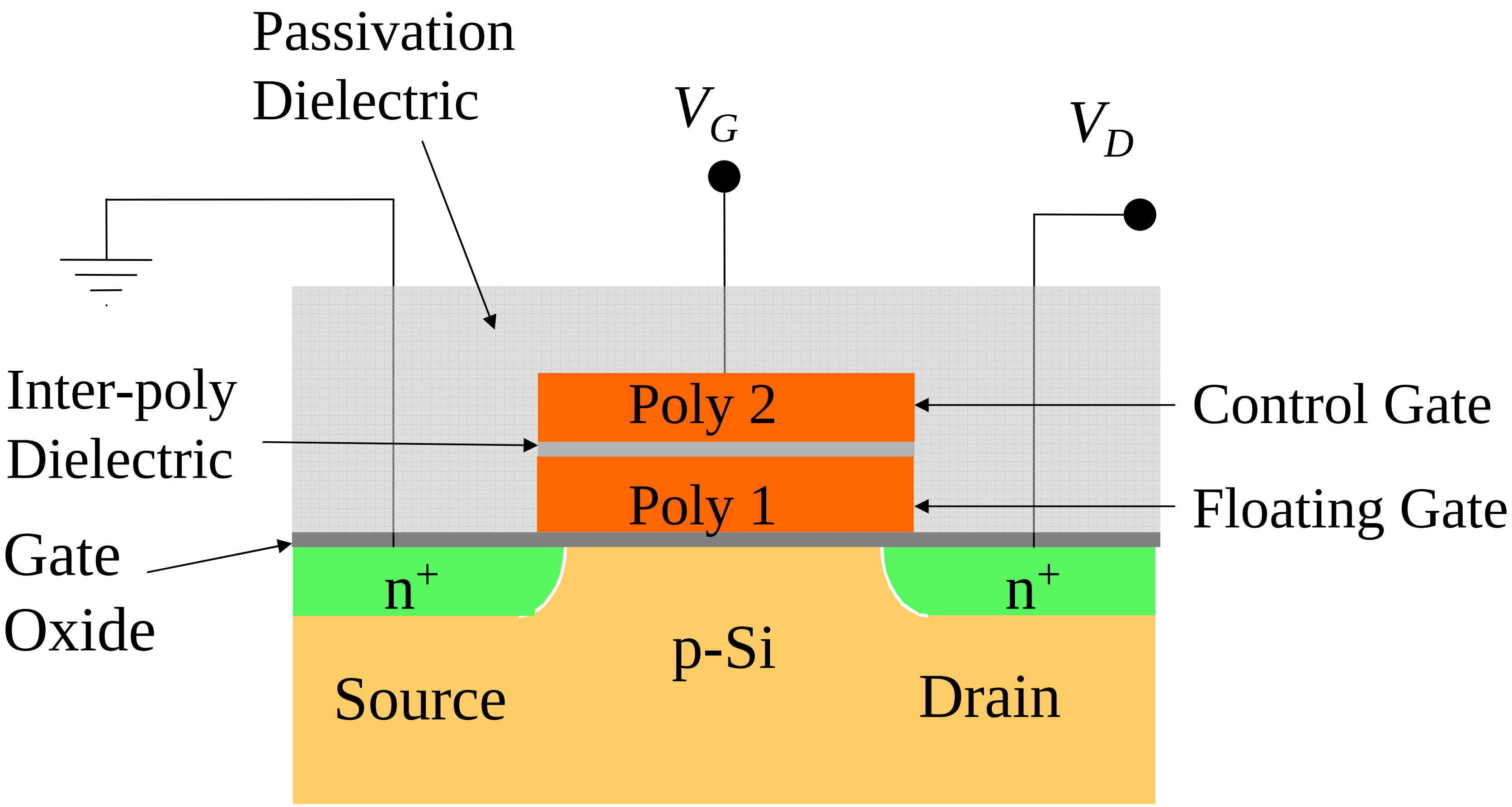
SRAM

- Fast memory application such as computer cache memory to store commonly used instructions
- Unit memory cell consists of six transistors
- Much faster than DRAM
- More complicated processing, more expensive

EPROM

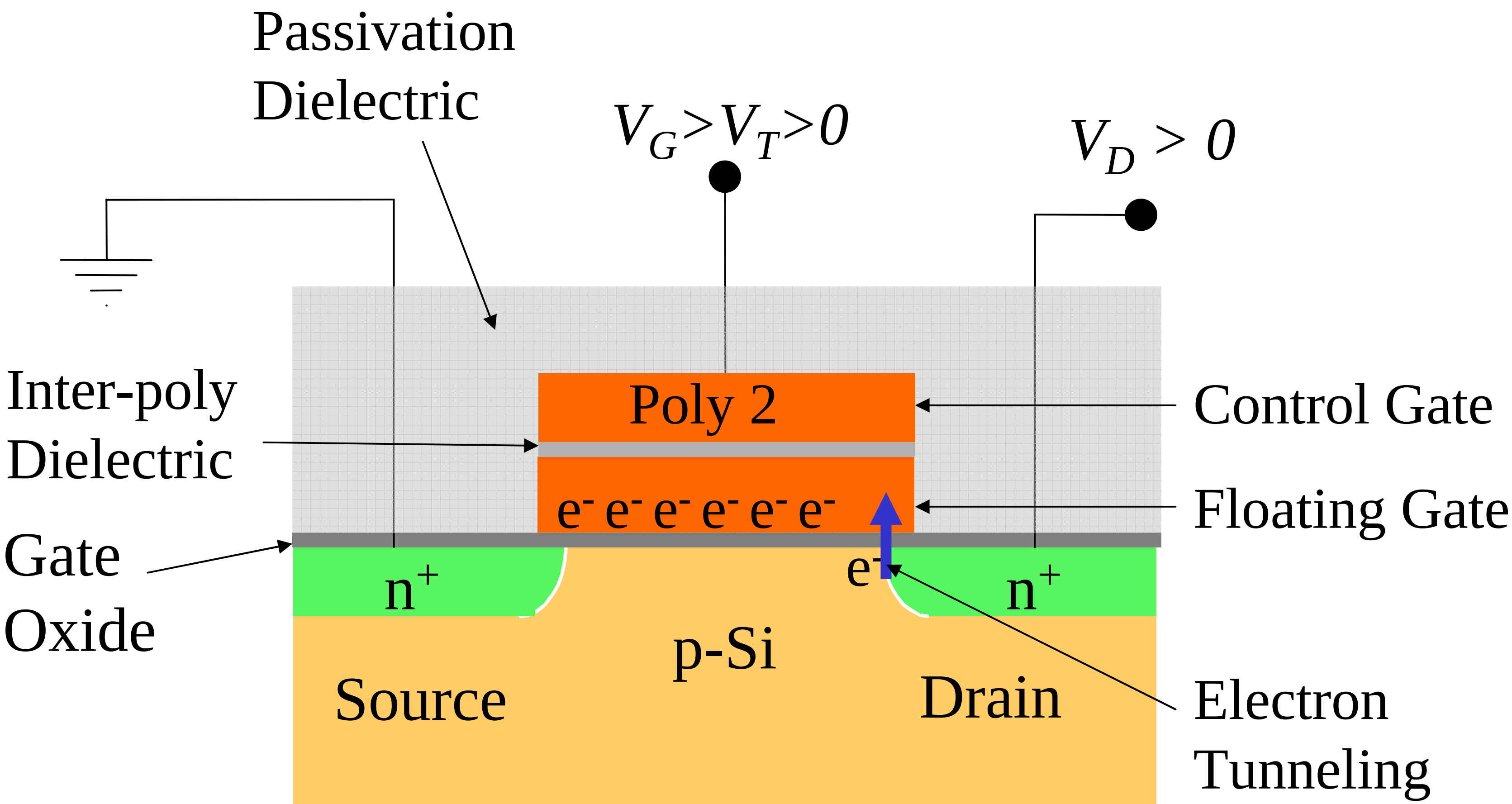
- Non-volatile memory
- Keeping data ever without power supply
- Computer bios memory which keeps boot up instructions
- Floating gate
- UV light memory erase

EPROM

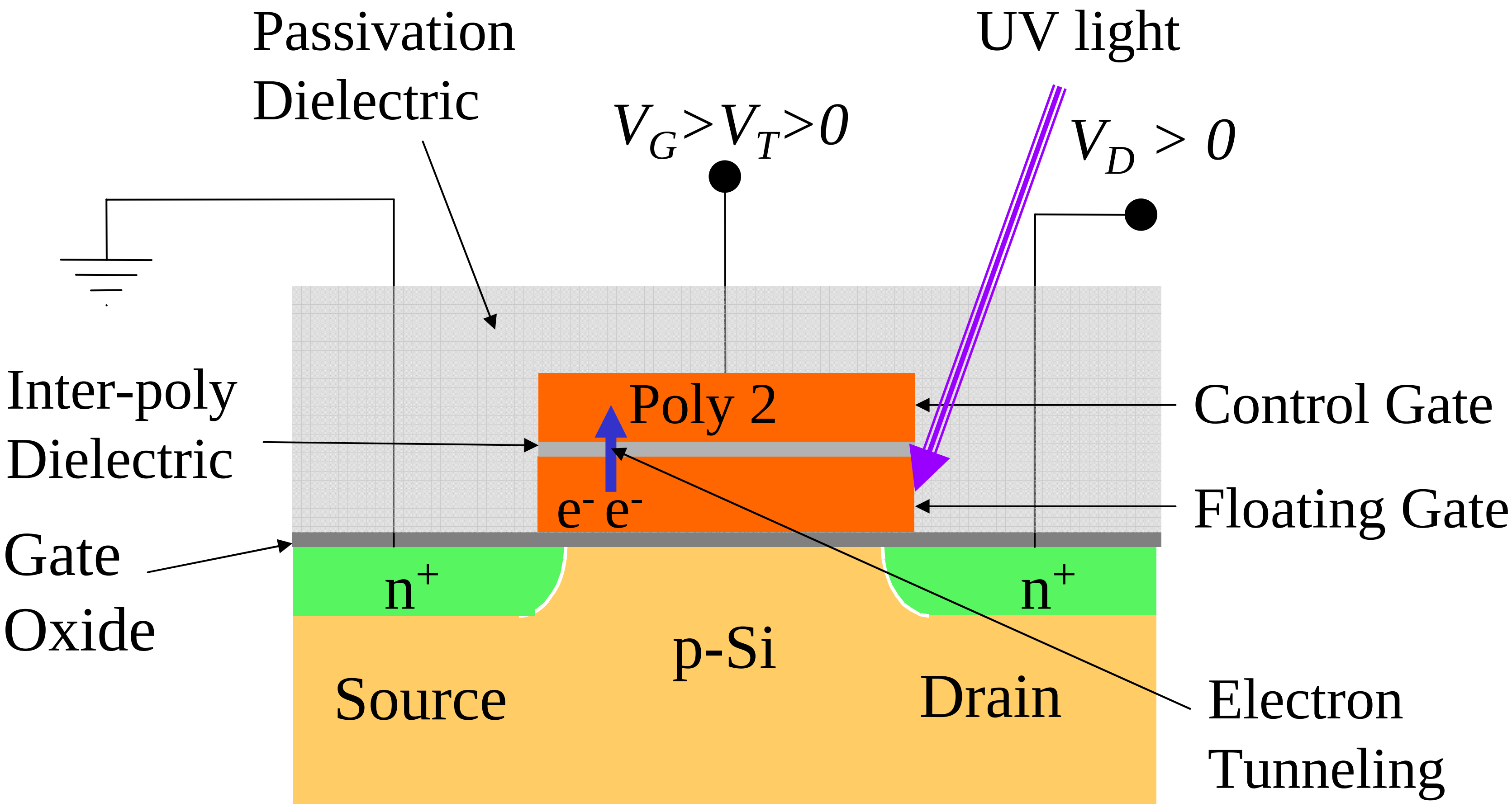


Passivation Dielectric
V_G
V_D
Inter-poly Dielectric
Poly 2
Control Gate
Poly 1
Floating Gate
Gate Oxide
n^+
n^+
p-Si
Source
Drain

EPROM Programming



EPROM Programming



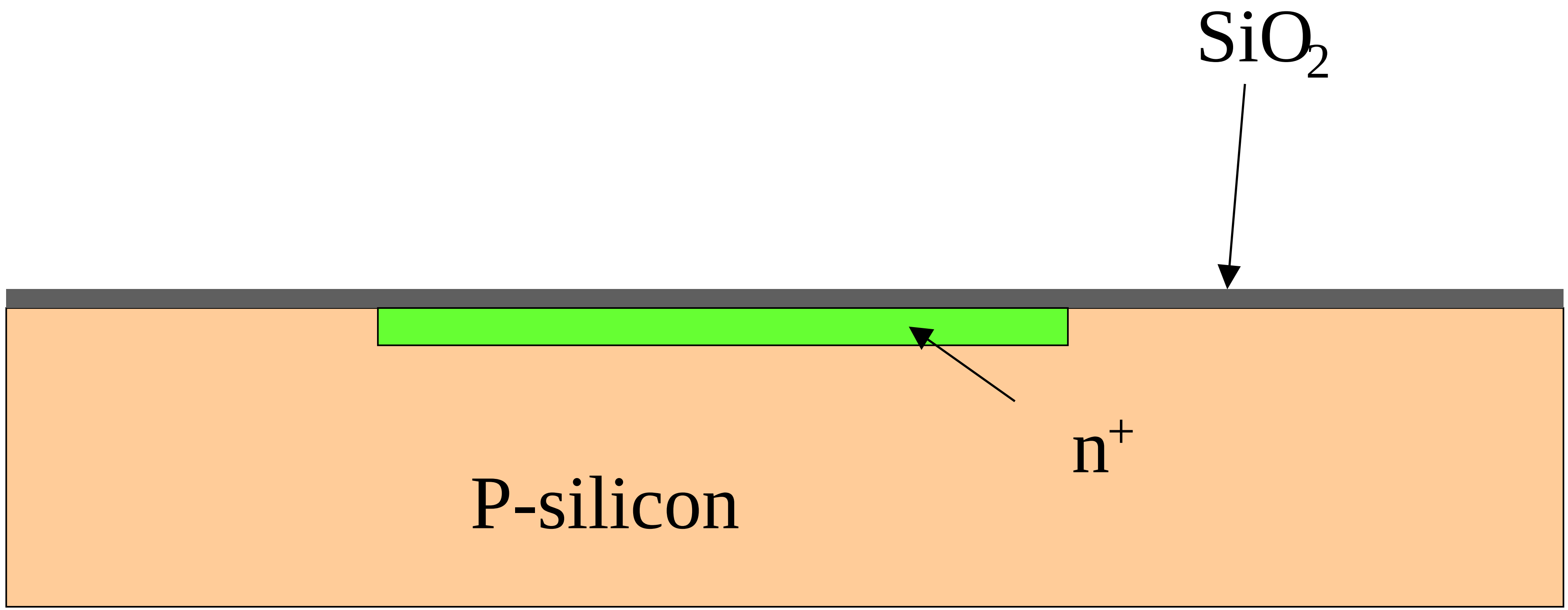
IC Fabrication Processes

- IC Fab.
  - Adding
    - Ion implantation, Diffusion
    - Grown thin film, SiO_2
    - Deposited thin film
      - CV
        - Epi, Poly
        - Dielectri
        - Meta
      - PVD
      - Electrical
  - Removing
    - Wafer Clean
    - Etch
      - Patterned etch
      - Blanket
      - Strip
    - CMP
      - Dielectri
      - Meta
  - Heating
    - Annealing
      - Meta
      - Oxid
      - Implantati
    - Reflow
    - Alloying
  - Patterning
    - Photolithography
      - Exposure (*heating*)
      - PR coating (adding)
      - Baking (heating,
      - Developing

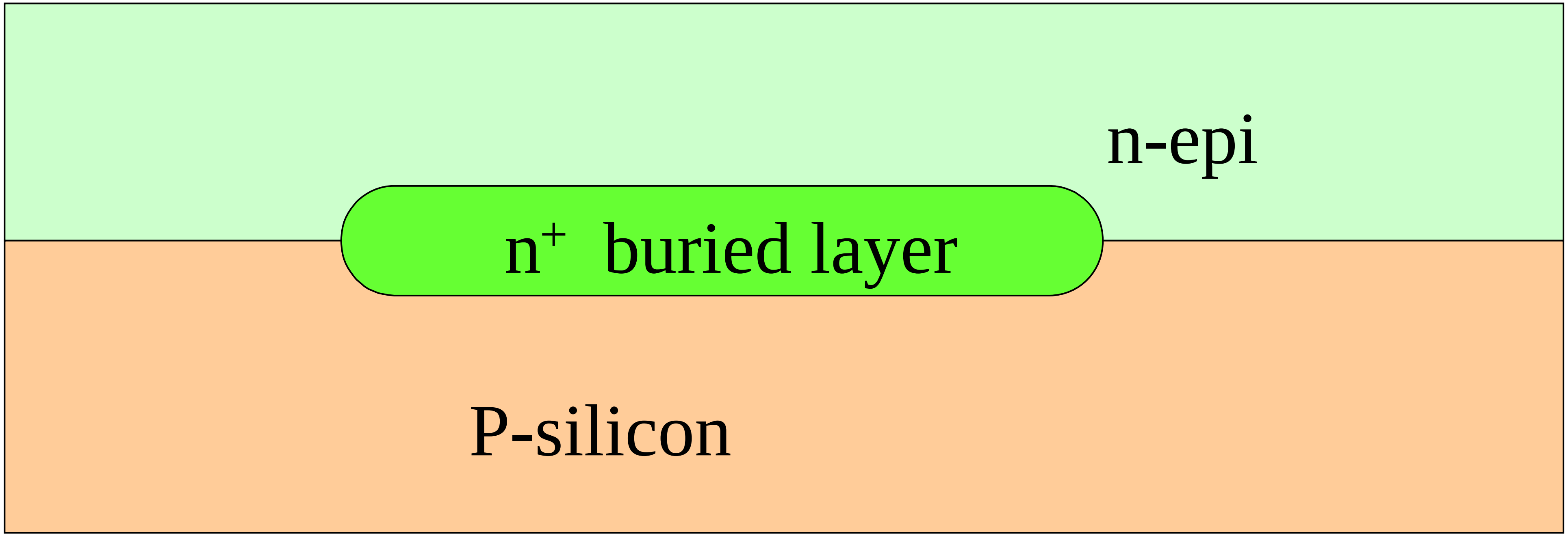
Basic Bipolar Process Steps

- Buried layer doping
- Epitaxial silicon growth
- Isolation and transistor doping
- Interconnection
- Passivation

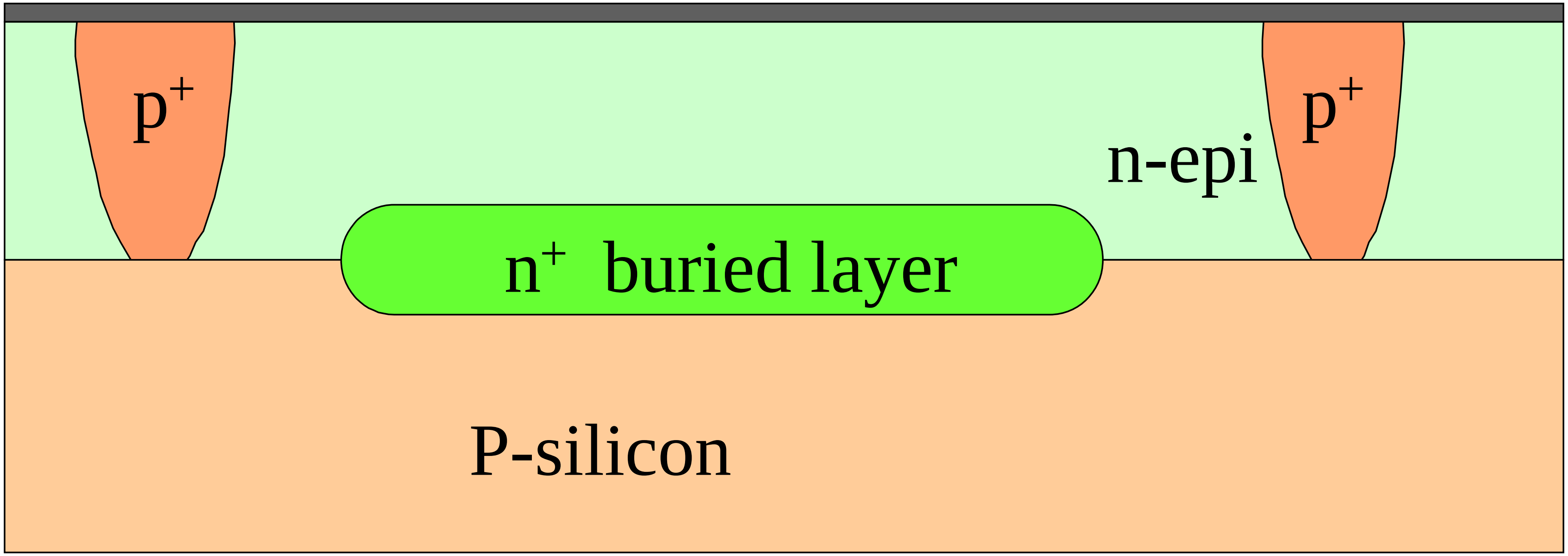
Buried Layer Implantation



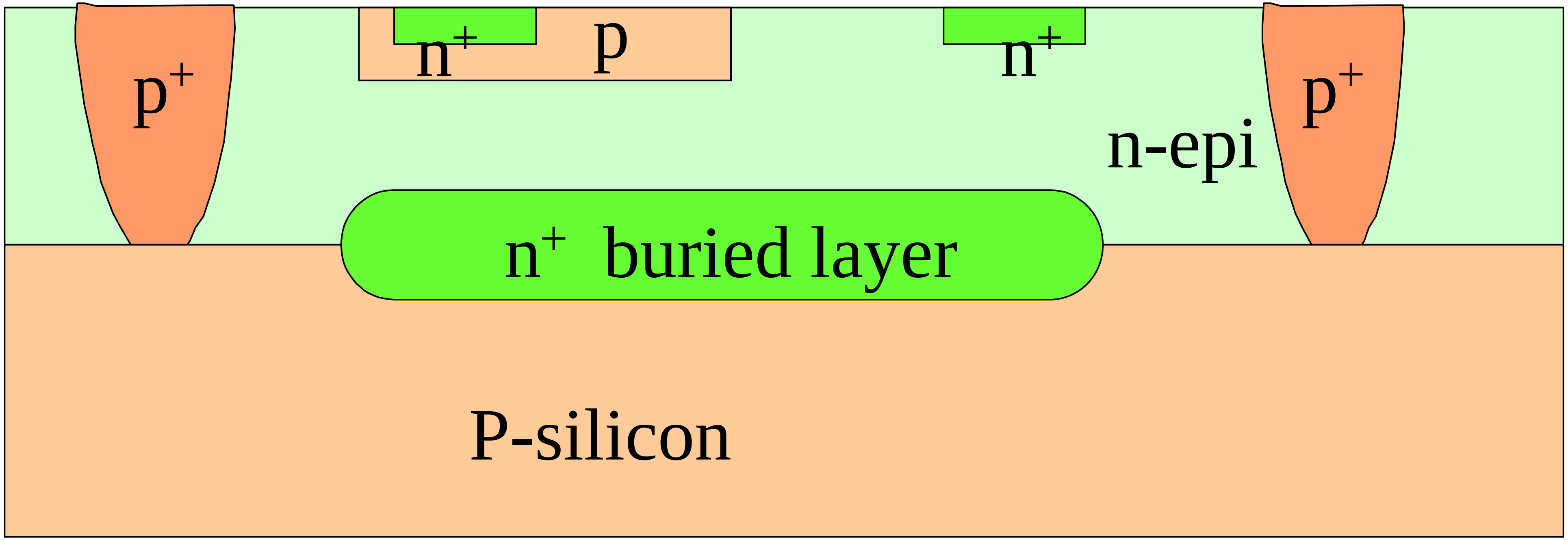
Epitaxy Grow



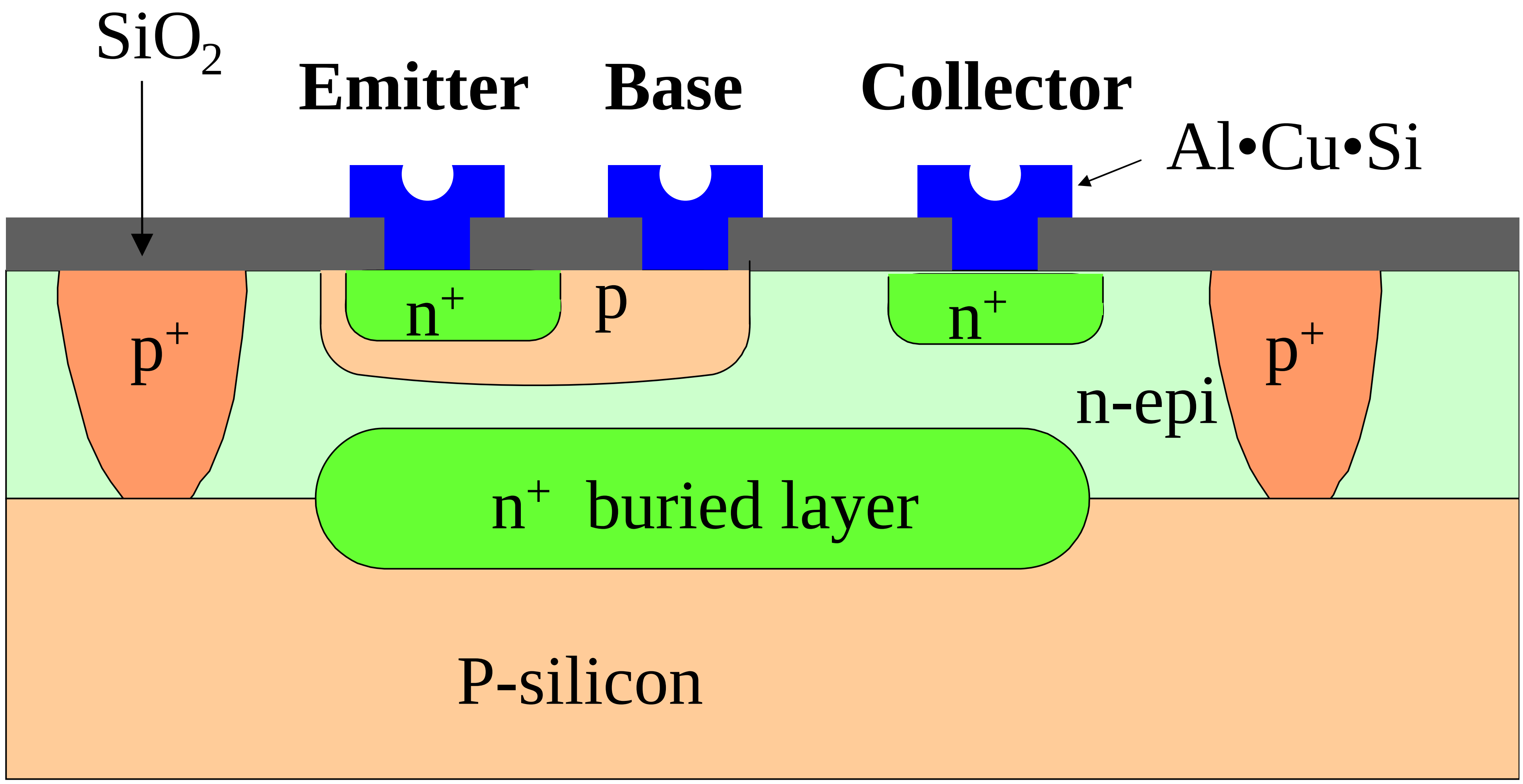
Isolation Implantation



Emitter/Collector and Base Implantation

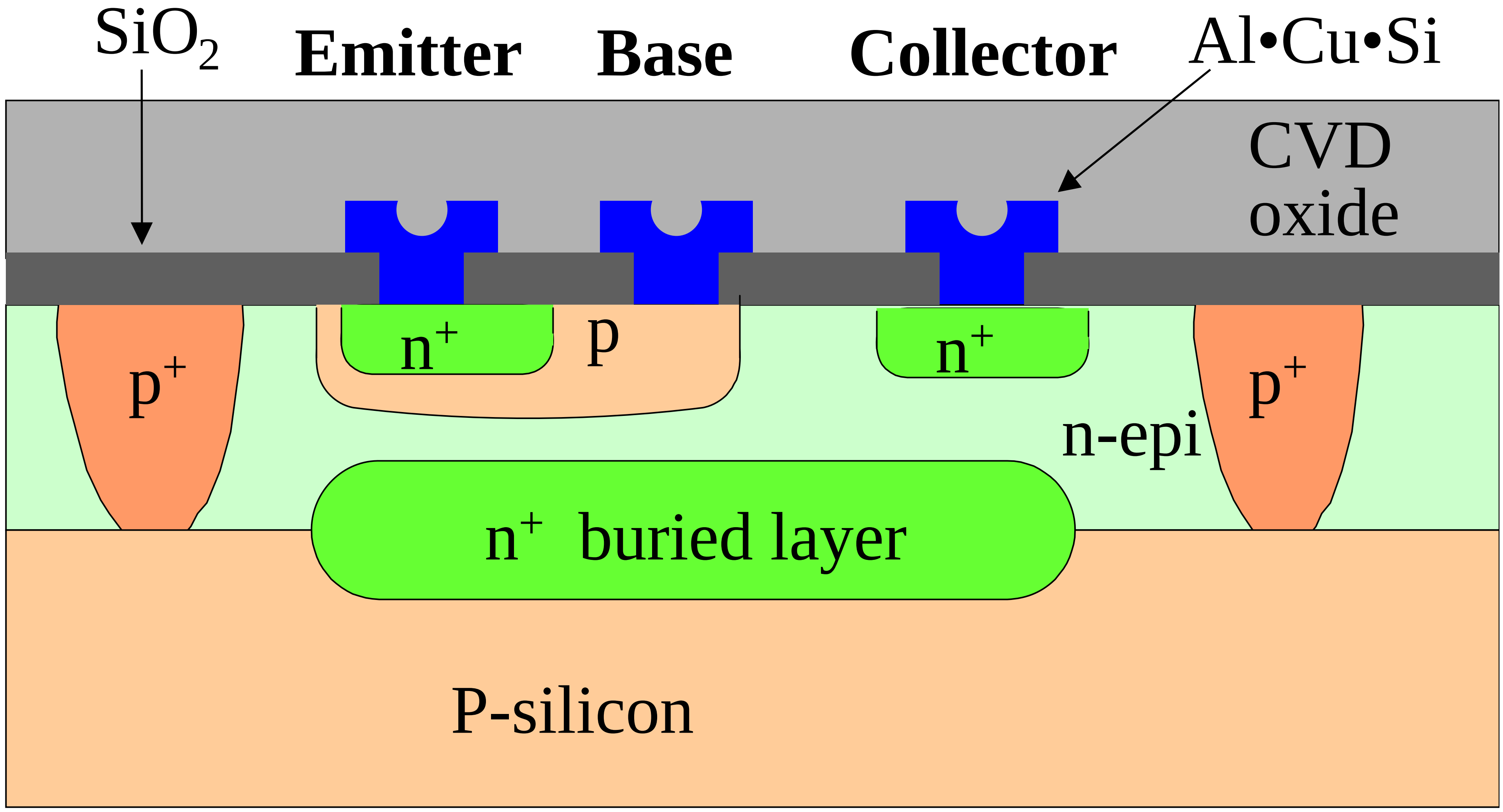


Metal Etch



SiO2
Emitter
Base
Collector
Al•Cu•Si
n+
p
n+
p+
p+
n-epi
n+ buried layer
P-silicon

Passivation Oxide Deposition



MOSFET

- Good for digital electronics
- Major driving forces:
  - Watches
  - Calculators
  - PC
  - Internet
  - Telecommunication

1960s: PMOS Process

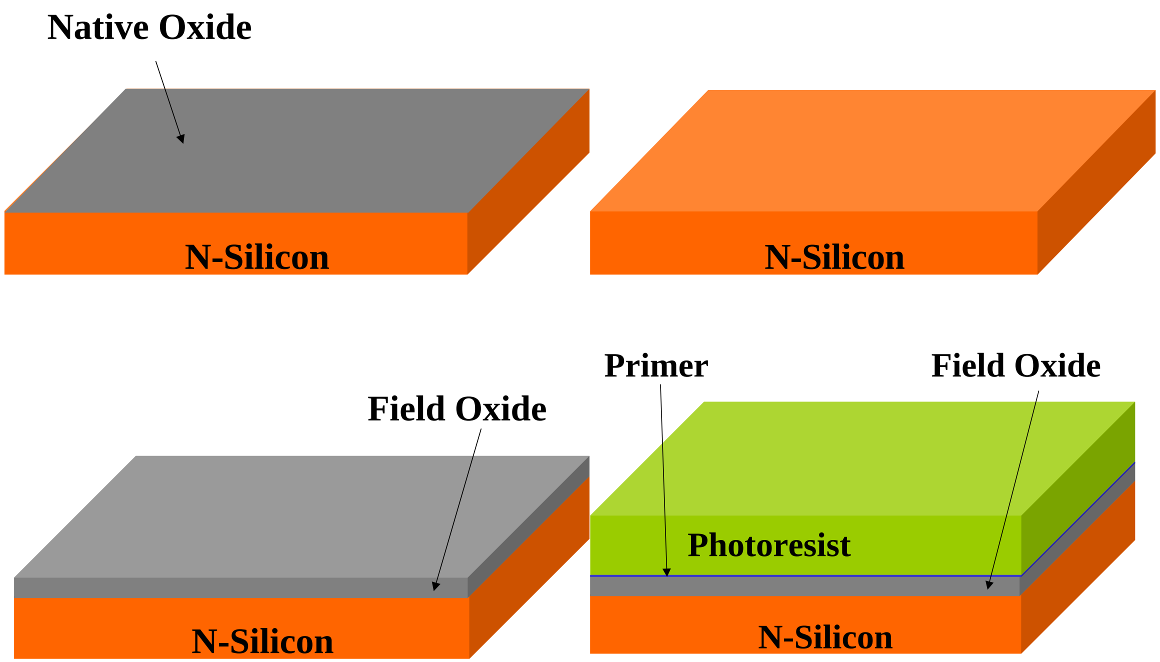
- Bipolar dominated
- First MOSFET made in Bell Labs
- Silicon substrate
- Diffusion for doping
  - Boron diffuses faster in silicon
  - PMOS

PMOS Process Sequence (1960s)

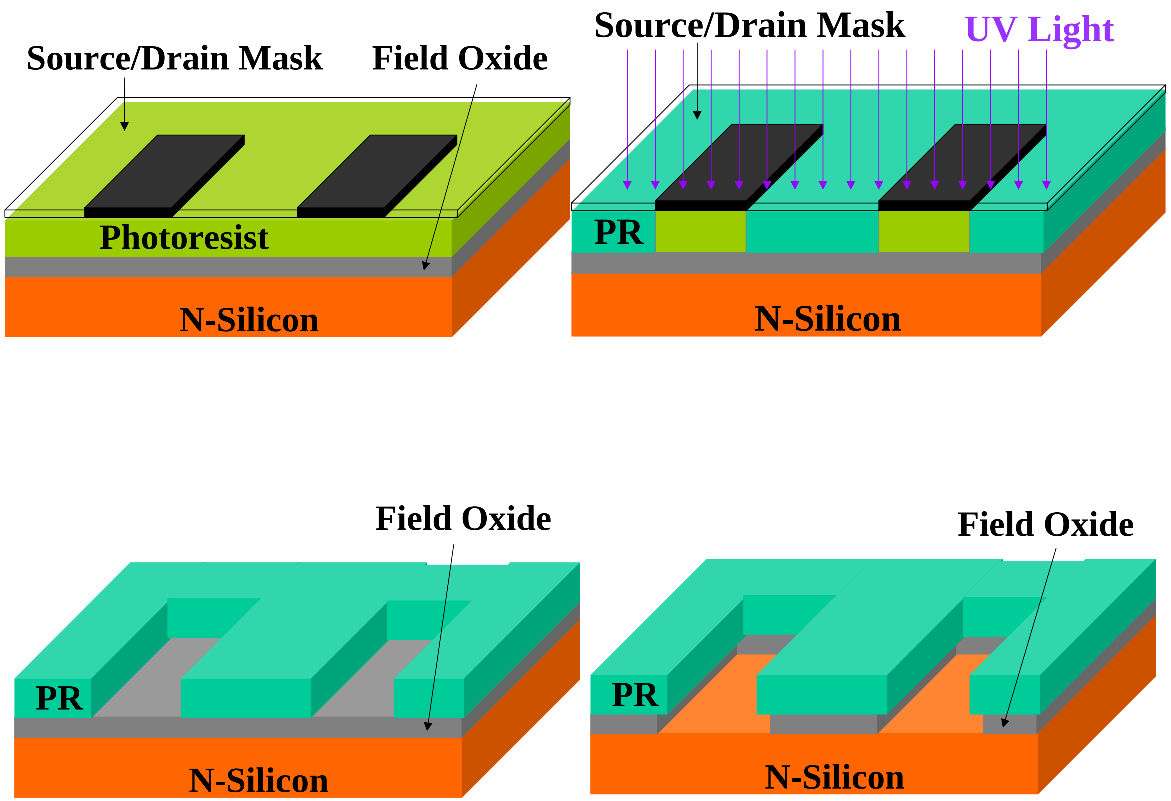
Wafer clean	(R)
Field oxidation	(A)
Mask 1. (Source/Drain)	(P)
Etch oxide	(R)
Strip photo resist/Clean	(R)
S/D diffusion (B)/Oxidation	(A)
Mask 2. (Gate)	(P)
Etch oxide	(R)
Strip photo resist/Clean	(R)
Gate oxidation	(A)
Mask 3. (Contact)	(P)
Etch oxide	(R)
Strip photo resist	(R)
Al deposition	(A)
Mask 4. (Metal)	(P)
Etch Aluminum	(R)
Strip photo resist	(R)
Metal Anneal	(H)
CVD oxide	(A)
Mask 5. (Bonding pad)	(P)
Etch oxide	(R)

Test and packaging

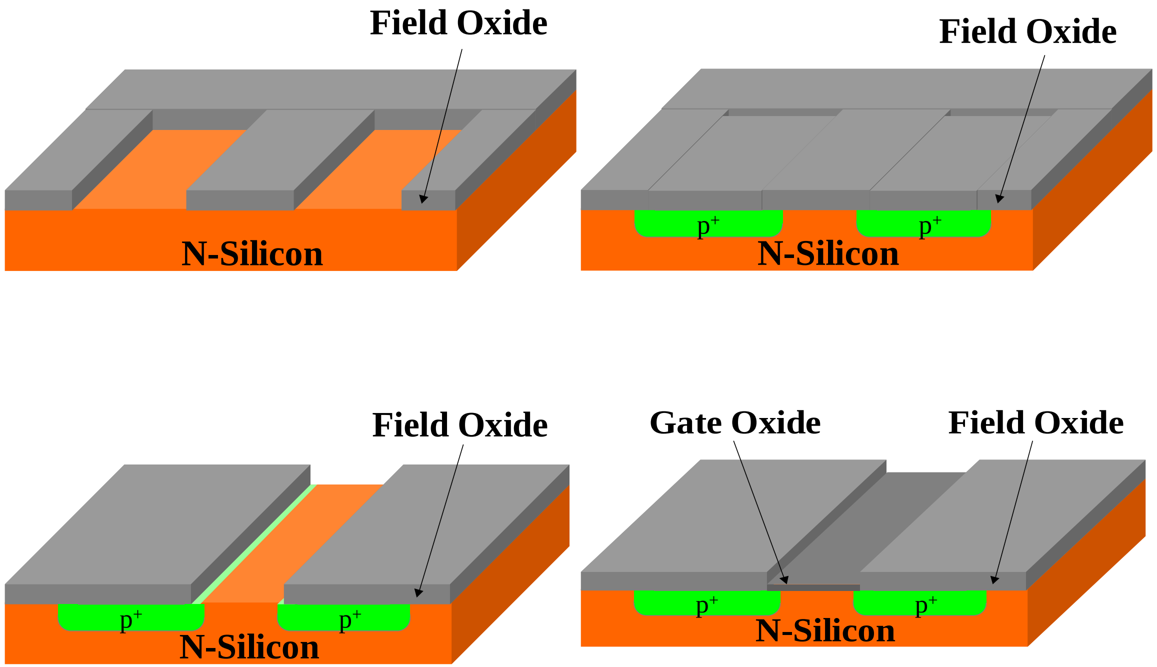
Wafer clean, field oxidation, and photoresist coating



Photolithography and etch



Source/drain doping and gate oxidation



Contact, Metallization, and Passivation

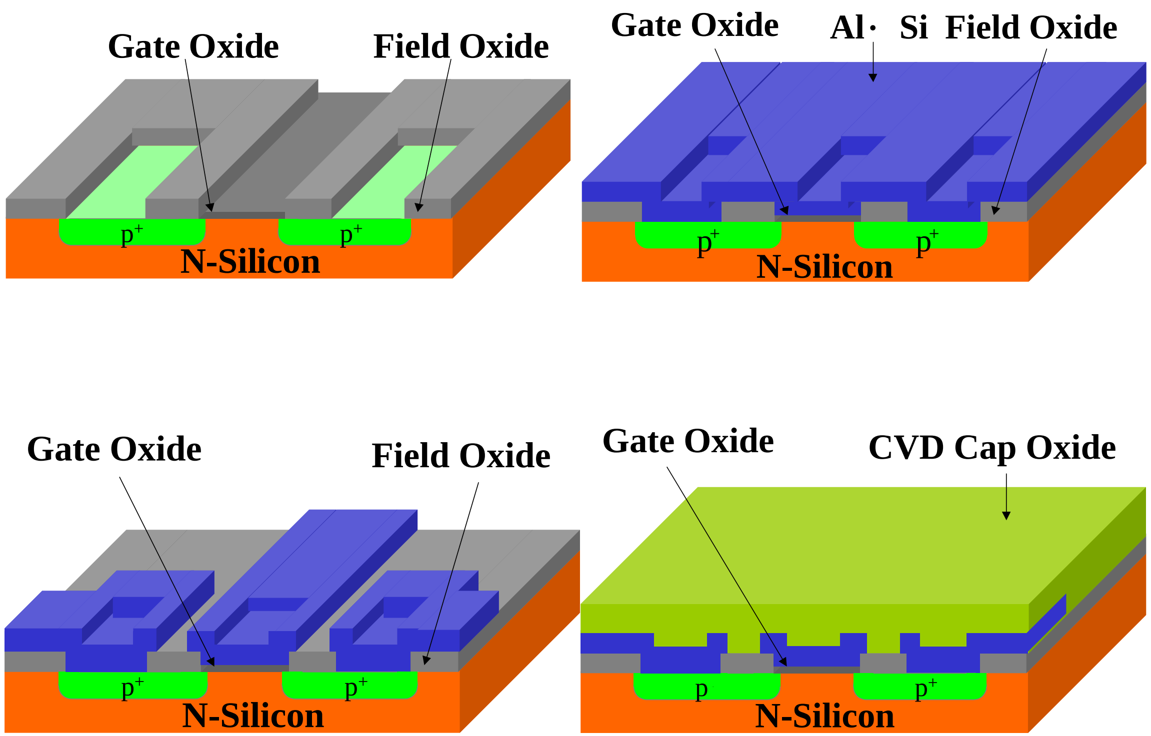
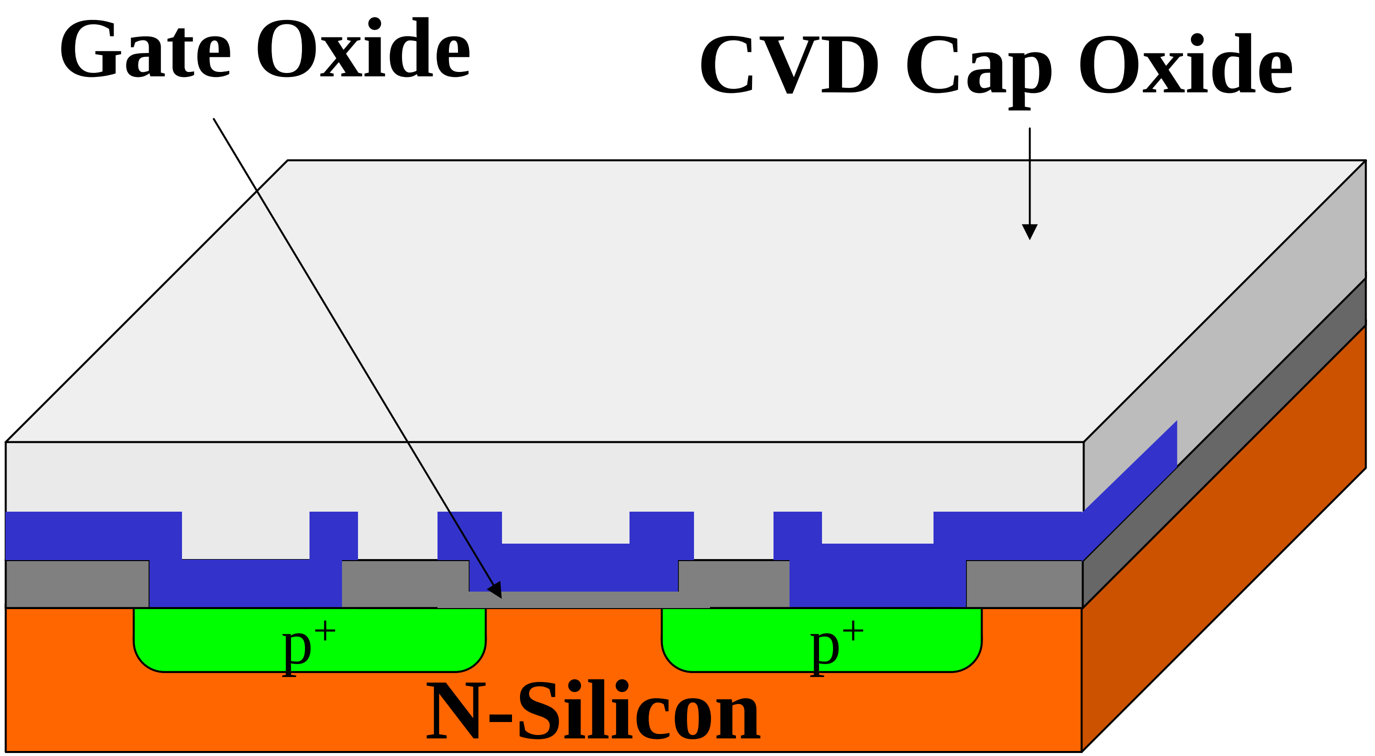


Illustration of a PMOS

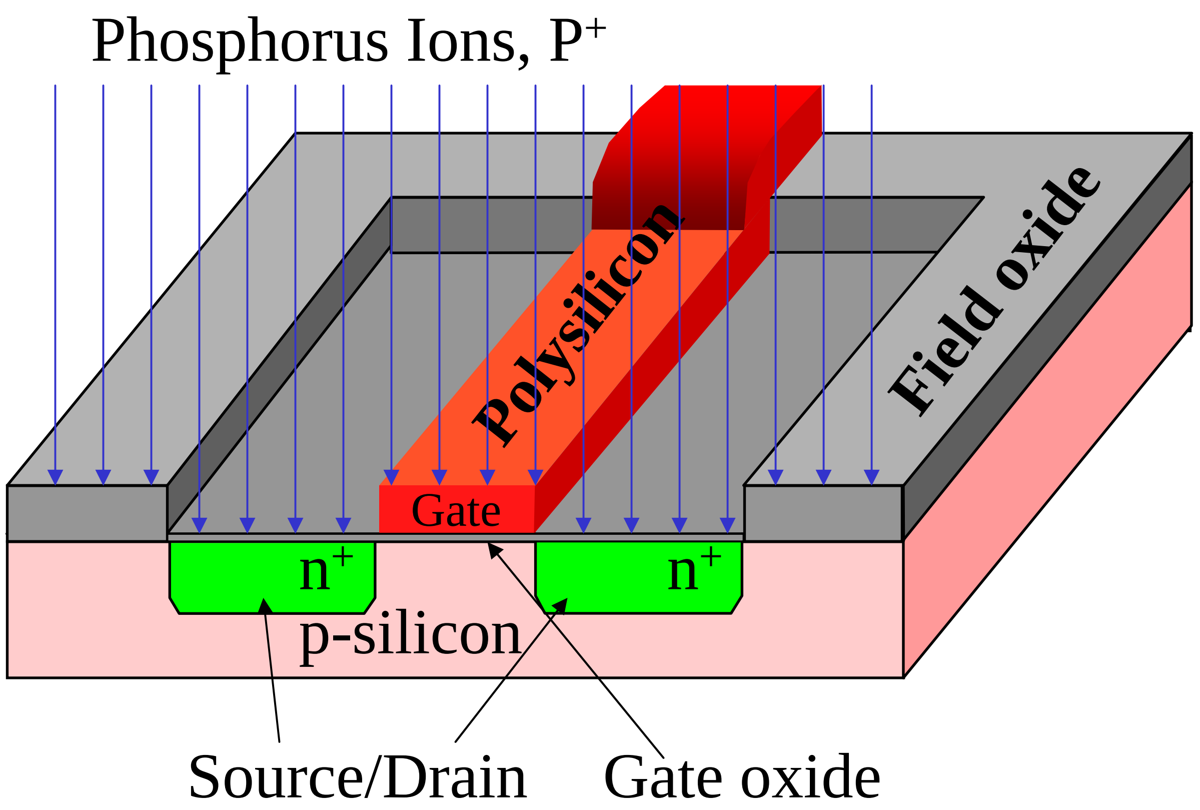


NMOS Process after mid-1970s

- Doping: ion implantation replaced diffusion
- NMOS replaced PMOS
  – NMOS is faster than PMOS
- Self-aligned source/drain

- Main driving force: watches and calculators

Self-aligned S/D Implantation

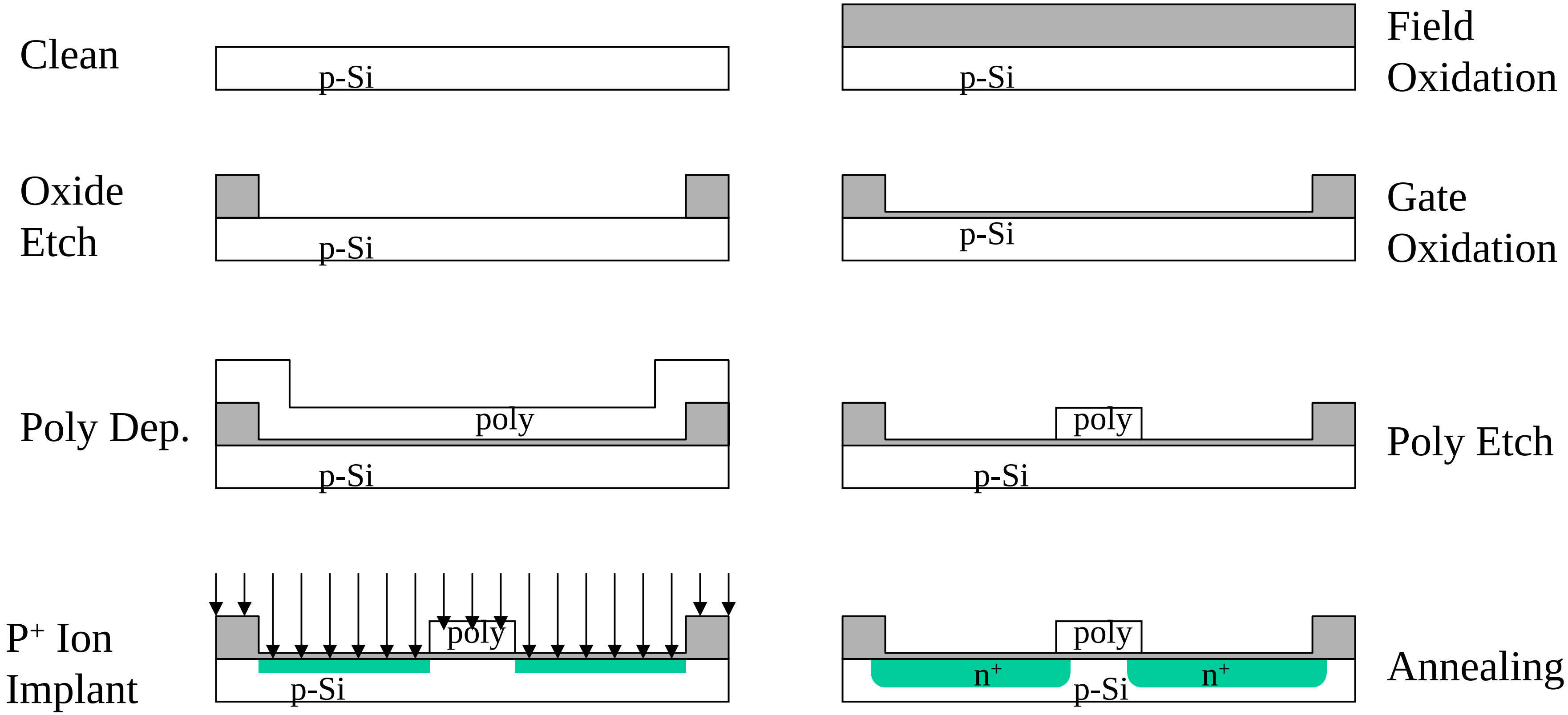


NMOS Process Sequence (1970s)

Wafer clean
Grow field oxide
Mask 1. Active Area
Etch oxide
Strip photo resist/Clean
Grow gate oxide
Deposit polysilicon
Mask 2. Gate
Etch polysilicon
Strip photo resist/Clean
S/D and poly dope implant
Anneal and poly reoxidation
CVD USG/PSG

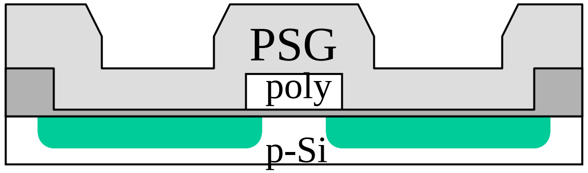
PSG reflow
Mask 3. Contact
Etch PSG/USG
Strip photo resist/Clean
Al deposition
Mask 4. Metal
Etch Aluminum
Strip photo resist
Metal anneal
CVD oxide
Mask 5. Bonding pad
Etch oxide
Test and packaging

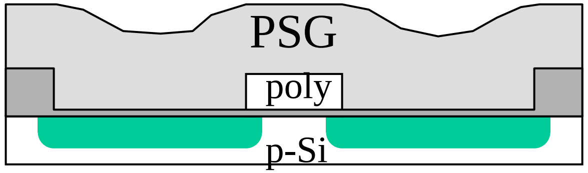
NMOS Process Sequence



NMOS Process Sequence

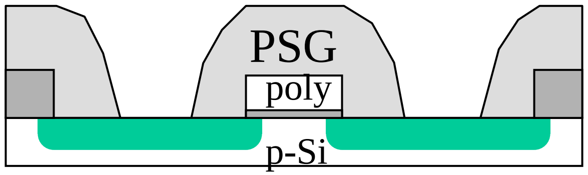
PSG Dep.

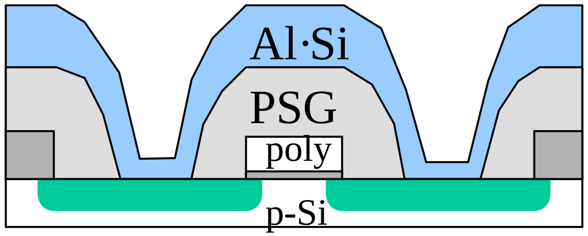




PSG Reflow

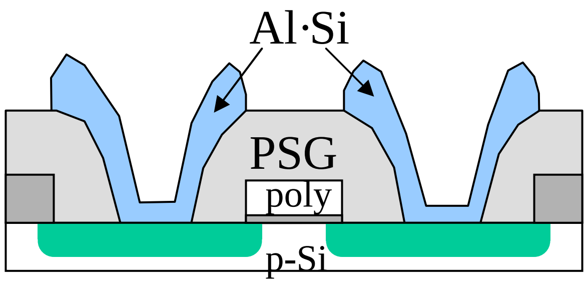
PSG Etch

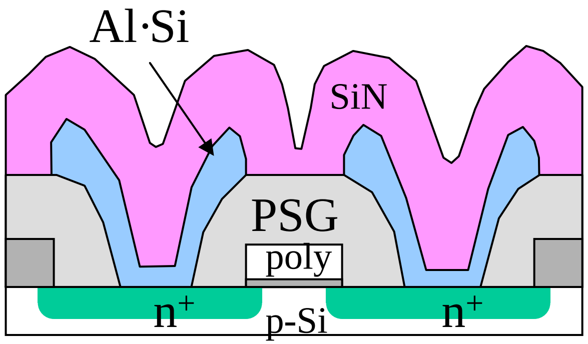




Metal Dep.

Metal Etch





Nitride Dep.

CMOS

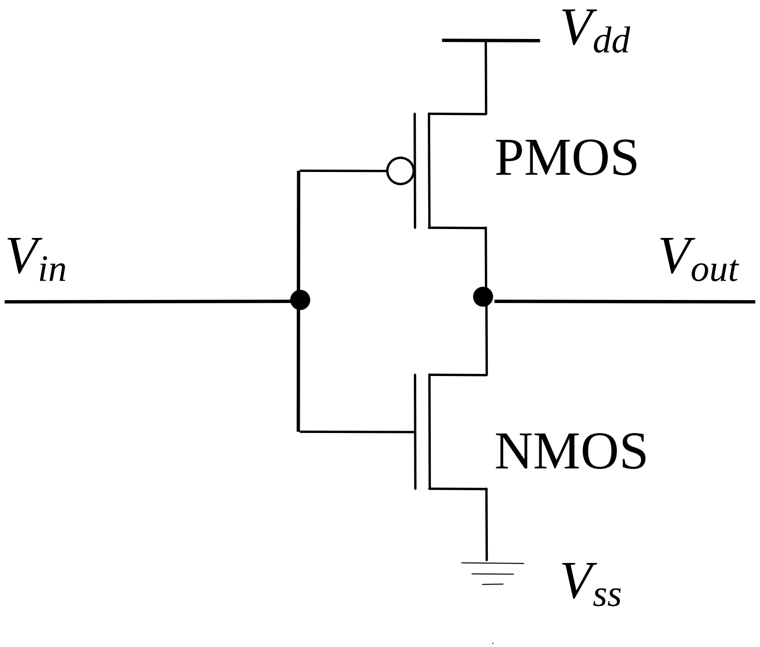
- In the 1980s MOSFET IC surpassed bipolar
- LCD replaced LED
- Power consumption of circuit
- CMOS replaced NMOS
- Still dominates the IC market

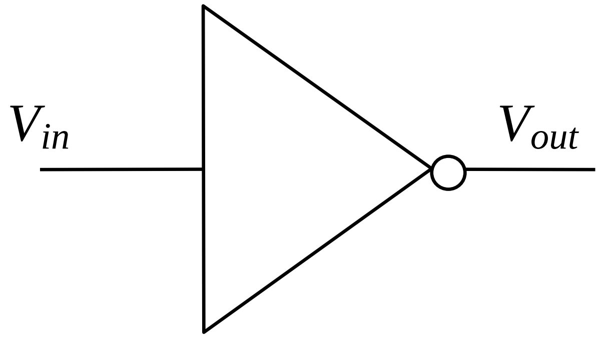
- Backbone of information revolution

Advantages of CMOS

- Low power consumption
- High temperature stability
- High noise immunity

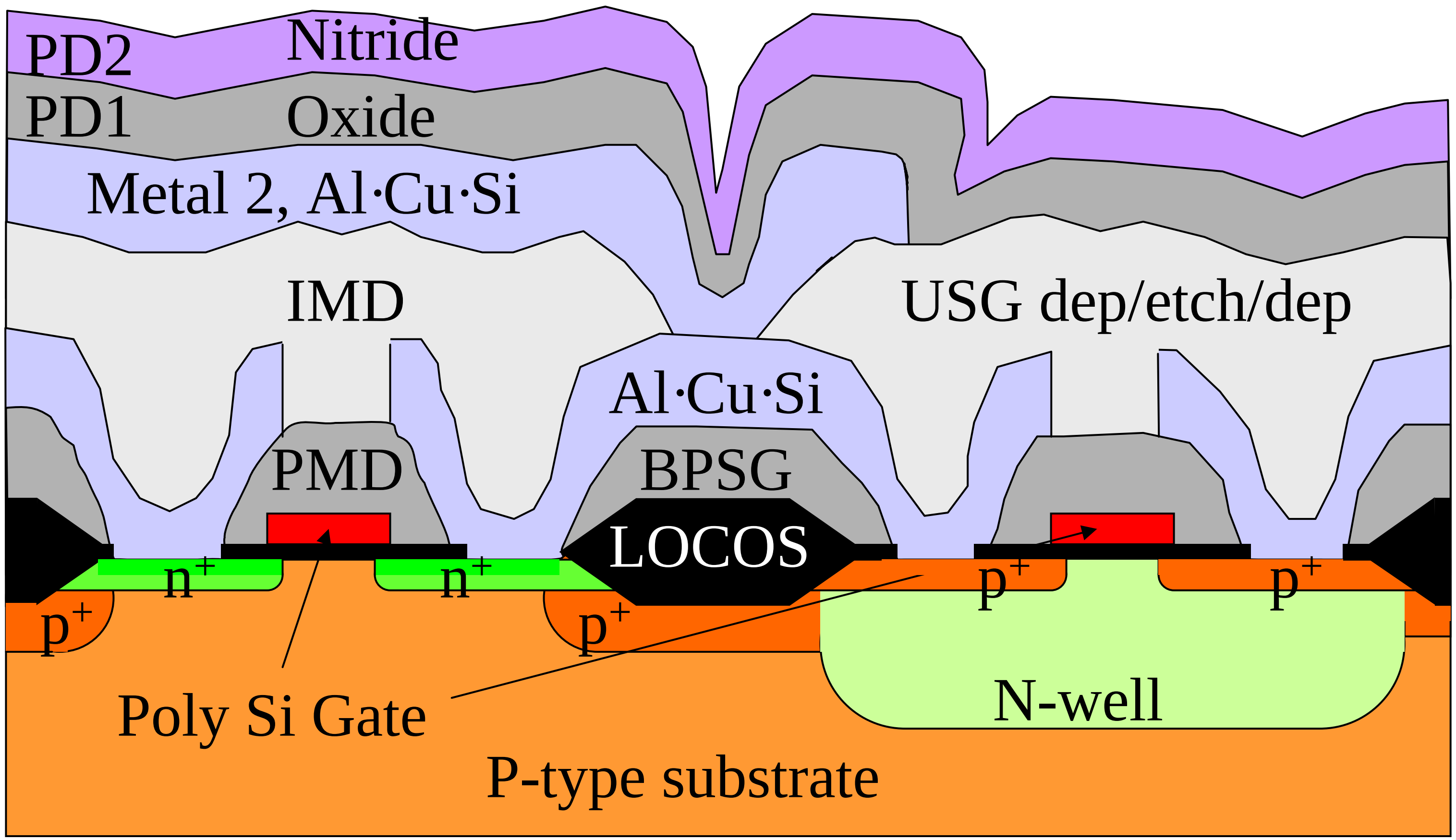
CMOS Inverter, Its Logic Symbol and Logic Table



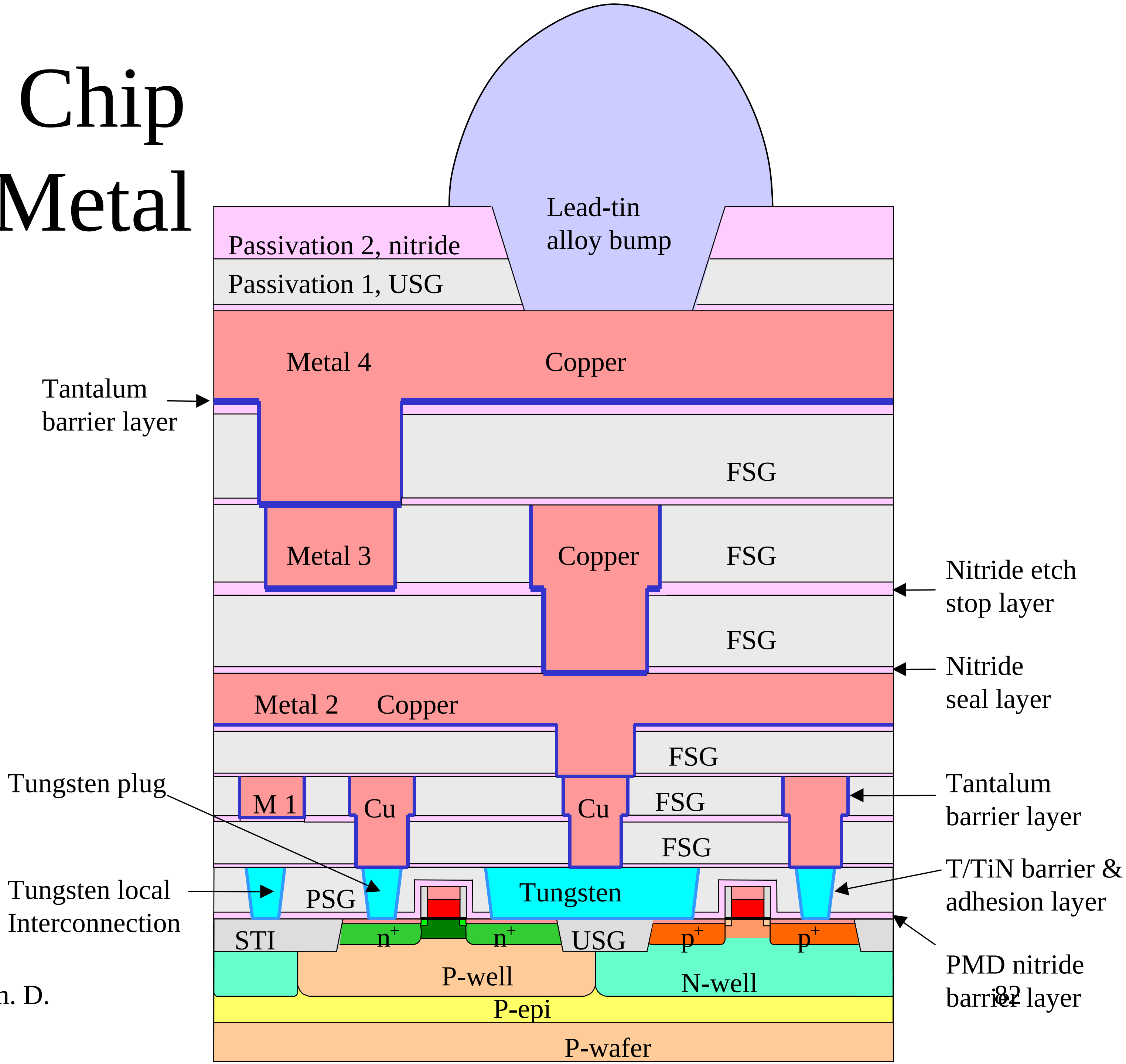


In	Out
0	1
1	0

CMOS Chip with 2 Metal Layers



CMOS Chip with 4 Metal Layers



Summary

- Semiconductors are the materials with conductivity between conductor and insulator
- Its conductivity can be controlled by dopant concentration and applied voltage
- Silicon, germanium, and gallium arsenate
- Silicon most popular: abundant and stable oxide

Summary

- Boron doped semiconductor is p-type, majority carriers are holes
- P, As, or Sb doped semiconductor is p-type, the majority carriers are electrons
- Higher dopant concentration, lower resistivity
- At the same dopant concentration, n-type has lower resistivity than p-type

Summary

- $R = \rho\, l/A$
- $C = \kappa\, A/d$
- Capacitors are mainly used in DRAM
- Bipolar transistors can amplify electric signal, mainly used for analog systems
- MOSFET electric controlled switch, mainly used for digital systems

Summary

- MOSFETs dominated IC industry since 1980s
- Three kinds IC chips microprocessor, memory, and ASIC
- Advantages of CMOS: low power, high temperature stability, high noise immunity, and clocking simplicity

Summary

- The basic CMOS process steps are transistor making (front-end) and interconnection/passivation (back-end)
- The most basic semiconductor processes are adding, removing, heating, and patterning processes.