Chapter 3
Basics Semiconductor Devices and Processing

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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

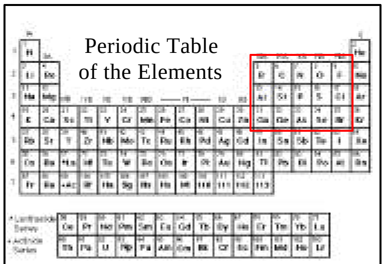
Topics

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

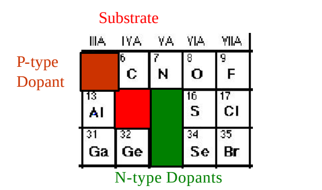
What is Semiconductor

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

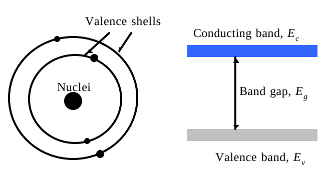
Periodic Table of the Elements



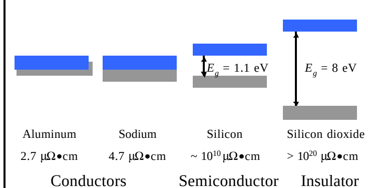
Semiconductor Substrate and Dopants



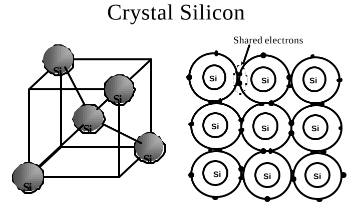
Orbital and Energy Band Structure of an Atom



Band Gap and Resistivity



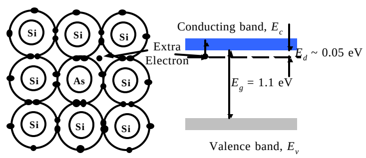
Crystal Structure of Single Crystal Silicon



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

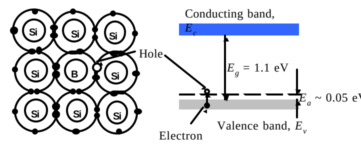
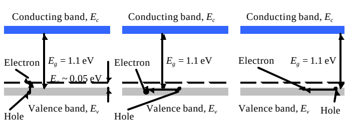
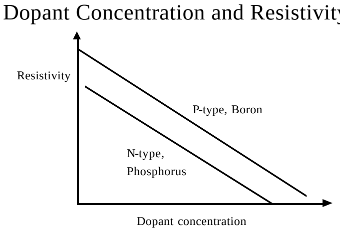


Illustration of Hole Movement



Dopant Concentration and Resistivity



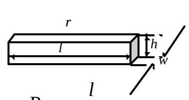
Dopant Concentration and Resistivity

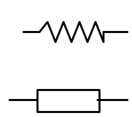
- Higher dopant concentration, more carriers (electrons or holes)
- Higher conductivity, lower resistivity
- Electrons move faster than holes
- N-type silicon has lower resistivity than p-type silicon at the same dopant concentration

Basic Devices

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

Resistor





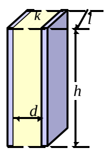
$$R = r\frac{l}{wh}$$

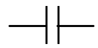
r: Resistivity

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





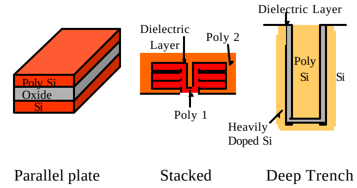
$$C = k\frac{hl}{d}$$

k: Dielectric Constant

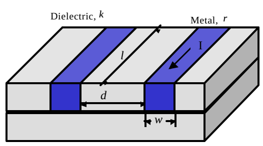
Capacitors

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

Capacitors



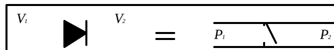
Metal Interconnection and RC Delay



Diode

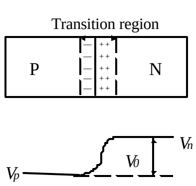
- P-N Junction
- Allows electric current go through only when it is positively biased.

Diode



- $V_1 > V_2$, current →
- $V_1 < V_2$, no current
- $P_1 > P_2$, current →
- $P_1 < P_2$, no current

Figure 3.14

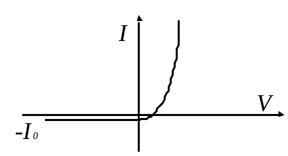


Intrinsic Potential

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

- For silicon $V_0 \sim 0.7$ V

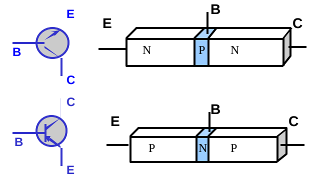
I-V Curve of Diode



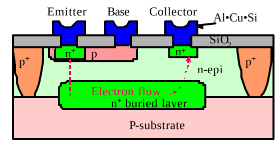
Bipolar Transistor

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

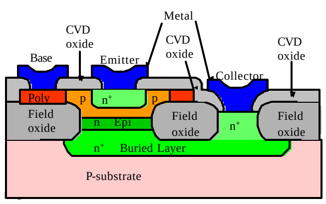
NPN and PNP Transistors



NPN Bipolar Transistor



Sidewall Base Contact NPN Bipolar Transistor

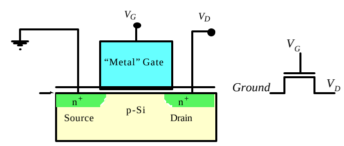


MOS Transistor

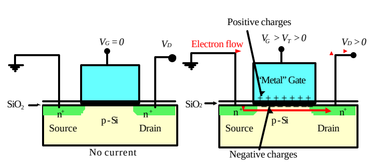
- Metal-oxide-semiconductor
- Also called MOSFET (MOS Field Effect Transistor)
- Simple, symmetric structure
- Switch, good for digital, logic circuit
- Most commonly used devices in the semiconductor industry

NMOS Device

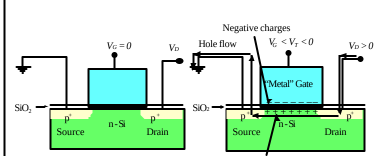
Basic Structure



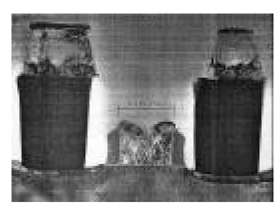
NMOS Device



PMOS Device



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

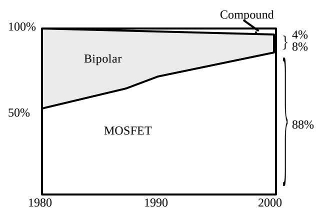
Basic Circuits

- 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

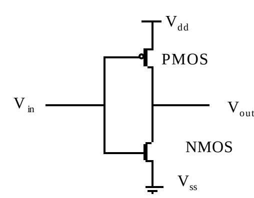
NMOS

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

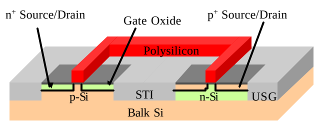
CMOS

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

CMOS Inverter



CMOS IC



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)

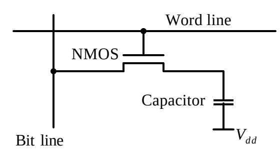
Memory Chips

- 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



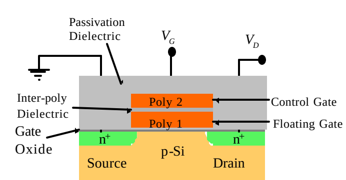
SRAM

- 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

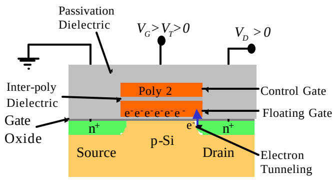
EPROM

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

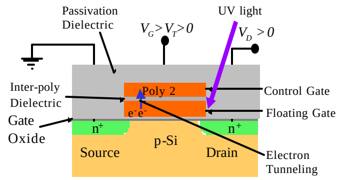
EPROM



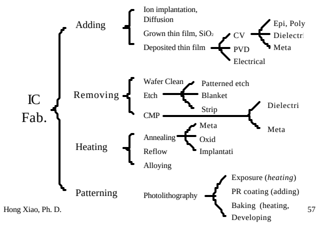
EPROM Programming



EPROM Programming



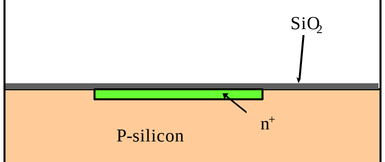
IC Fabrication Processes



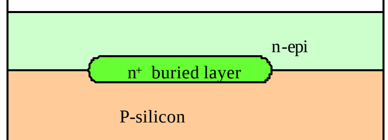
Basic Bipolar Process Steps

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

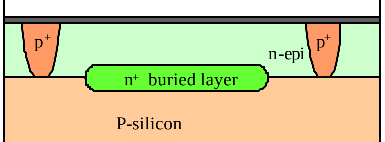
Buried Layer Implantation



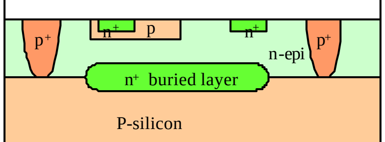
Epitaxy Grow



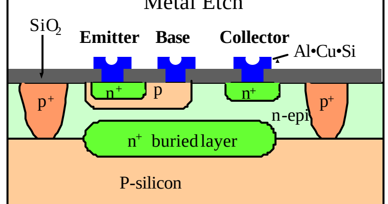
Isolation Implantation



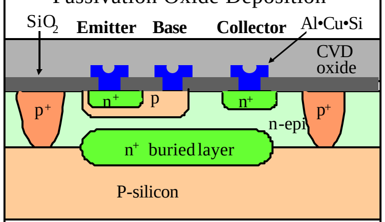
Emitter/Collector and Base Implantation



Metal Etch



Passivation Oxide Deposition



MOSFET

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

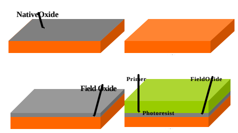
1960s: PMOS Process

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

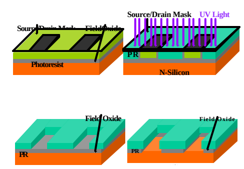
PMOS Process Sequence (1960s)

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

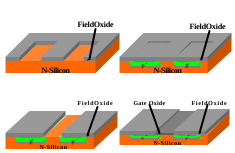
Wafer clean, field oxidation, and photoresist coating



Photolithography and etch



Source/drain doping and gate oxidation



Contact, Metallization, and Passivation

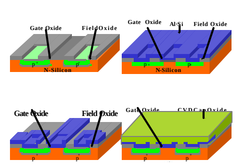
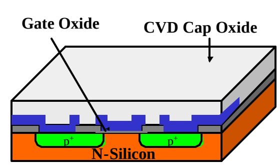


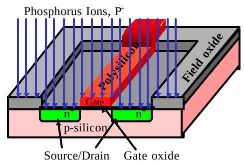
Illustration of a PMOS



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

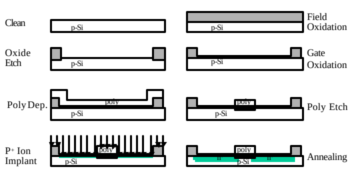
Self-aligned S/D Implantation



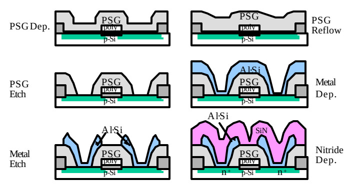
NMOS Process Sequence (1970s)

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. Bondingpad
Etch oxide
Test and packaging

NMOS Process Sequence



NMOS Process Sequence



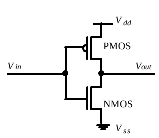
CMOS

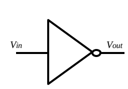
- In the 1980s MOSFET IC surpassed bipolar
- LCD replaced LED
- Power consumption of circuit
- CMOS replaced NMOS
- Still dominates the IC market
- Backbone of information revolution

Advantages of CMOS

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

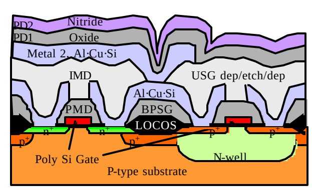
CMOS Inverter, Its Logic Symbol and Logic Table



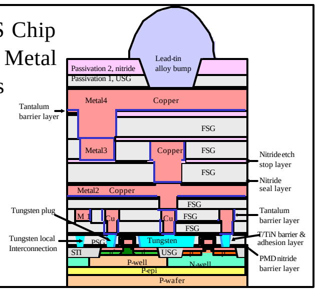


In	Out
0	1
1	0

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

- $R = r\, l/A$
- $C = k\, A/d$
- 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.