EE130: Integrated Circuit Devices

(online at http://webcast.berkeley.edu)

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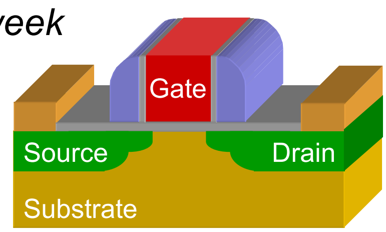
Course Outline

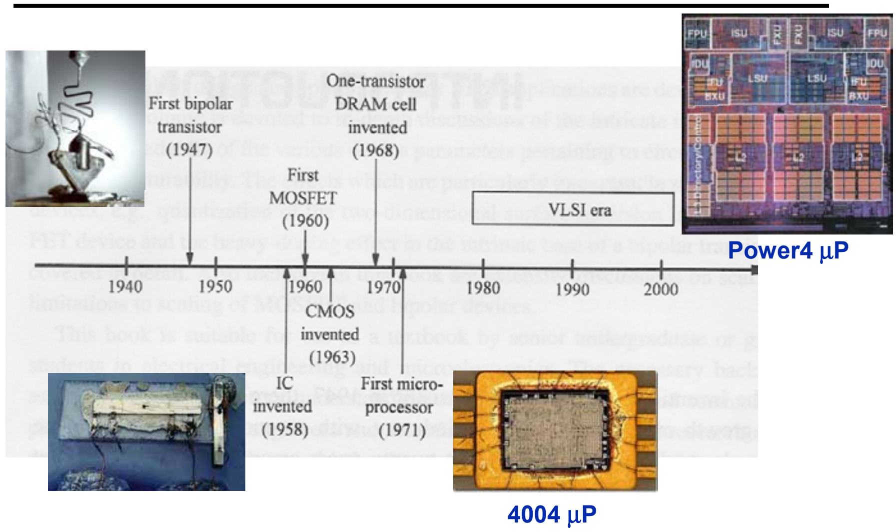
1. Semiconductor Fundamentals – *3 weeks*
2. Metal-Semiconductor Contacts – *1 week*
3. P-N Junction Diode – *3 weeks*
4. Bipolar Junction Transistor – *3 weeks*
5. MOS Capacitor – *1 week*
6. MOSFET – *4 weeks*



Spring 2003

Introduction

Integrated-Circuit Devices



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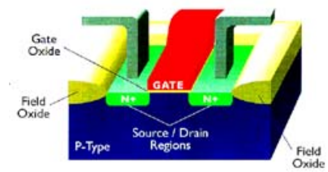
Planar Process Technology

starting substrate + *planar processing steps = multiple devices monolithically integrated

Si wafer ⇨



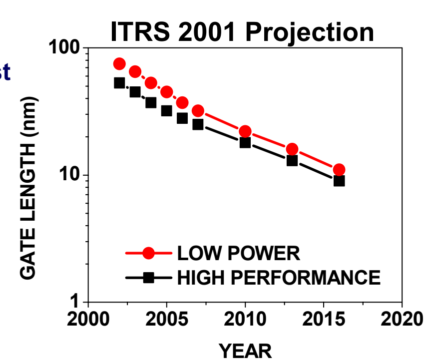
n-channel MOSFET

*sequence of **additive** and **subtractive** steps with **lateral patterning**

- additive ↓ **oxidation**, **deposition**, **ion implantation**
- subtractive ↓ **etching**
- lateral patterning ↓ **lithography**

IC Technology Advancement

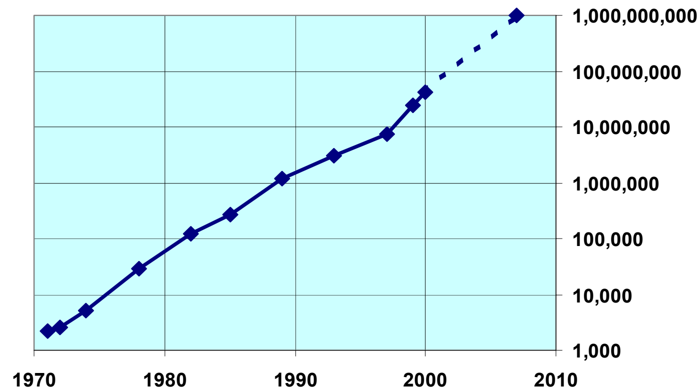
Rapid advances in IC technology have been achieved primarily by scaling down transistor lateral dimensions



Benefit of Transistor Scaling

"Moore's Law"

\# transistors/chip doubles every 1.5 to 2 years



Example: Microprocessor Evolution

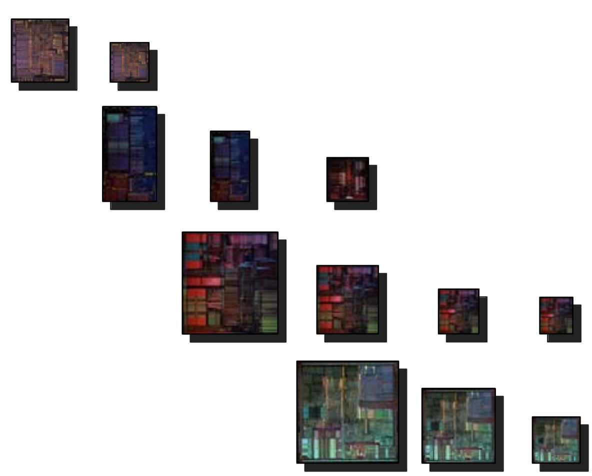
Generation: **1.5µ** **1.0µ** **0.8µ** **0.6µ** **0.35µ** **0.25µ**

Intel386™ DX Processor

Intel486™ DX Processor

Pentium® Processor

Pentium® II Processor



Semiconductor Fundamentals

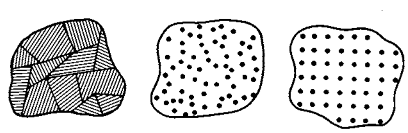
OUTLINE

- General material properties
- Crystal structure
- Bond model

Read: Chapter 1

What is a Semiconductor?

- Low resistivity => "conductor"
- High resistivity => "insulator"
- Intermediate resistivity => "semiconductor"
  - conductivity lies between that of conductors and insulators
  - generally crystalline in structure for IC devices
    - In recent years, however, non-crystalline semiconductors have become commercially very important



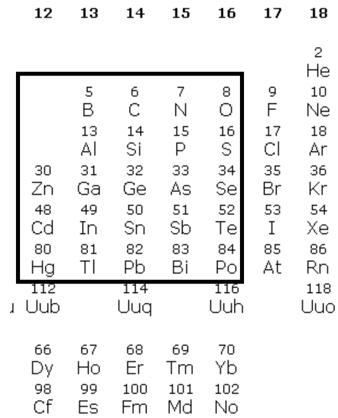
polycrystalline amorphous crystalline

Semiconductor Materials

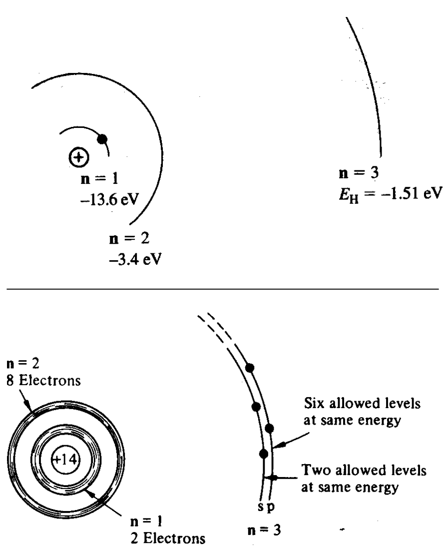
Elemental:

Compound:

Alloy:



From Hydrogen to Silicon



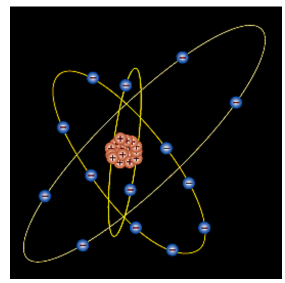
Z	Name	# of Electrons						Notation
		1	2		3			
		1s	2s	2p	3s	3p	3d	
1	H	1						$1s^1$
2	He	2						$1s^2$
3	Li	2	1					$1s^2 2s^1$
4	Be	2	2					$1s^2 2s^2$
5	B	2	2	1				$1s^2 2s^2 2p^1$
6	C	2	2	2				$1s^2 2s^2 2p^2$
7	N	2	2	3				$1s^2 2s^2 2p^3$
8	O	2	2	4				$1s^2 2s^2 2p^4$
9	F	2	2	5				$1s^2 2s^2 2p^5$
10	Ne	2	2	6				$1s^2 2s^2 2p^6$
11	Na	2	2	6	1			$1s^2 2s^2 2p^6 3s^1$
12	Mg	2	2	6	2			$1s^2 2s^2 2p^6 3s^2$
13	Al	2	2	6	2	1		$1s^2 2s^2 2p^6 3s^2 3p^1$
14	Si	2	2	6	2	2		$1s^2 2s^2 2p^6 3s^2 3p^2$
15	P	2	2	6	2	3		$1s^2 2s^2 2p^6 3s^2 3p^3$
16	S	2	2	6	2	4		$1s^2 2s^2 2p^6 3s^2 3p^4$
17	Cl	2	2	6	2	5		$1s^2 2s^2 2p^6 3s^2 3p^5$
18	Ar	2	2	6	2	6		$1s^2 2s^2 2p^6 3s^2 3p^6$

The Silicon Atom

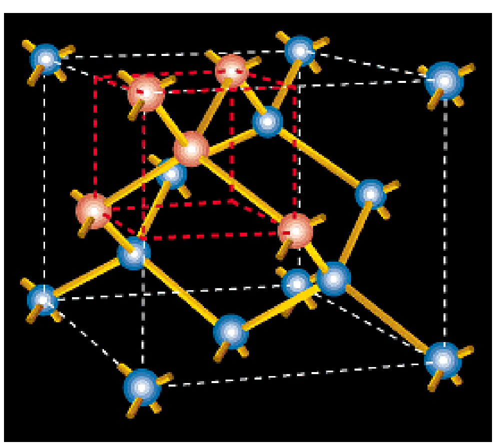
- 14 electrons occupying the 1st 3 energy levels:
  - 1s, 2s, 2p orbitals filled by 10 electrons
  - 3s, 3p orbitals filled by 4 electrons

To minimize the overall energy, the 3s and 3p orbitals hybridize to form 4 tetrahedral 3sp orbitals

Each has one electron and is capable of forming a bond with a neighboring atom



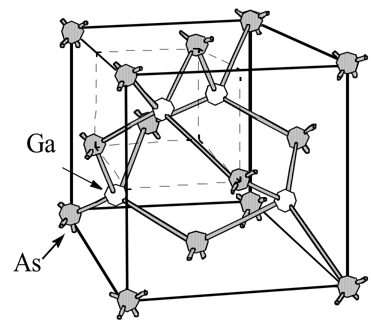
The Si Crystal



"diamond cubic" lattice

- **Each Si atom has 4 nearest neighbors**
- **lattice constant = 5.431Å**

Compound Semiconductors



- "zincblende" structure
- III-V compound semiconductors: GaAs, GaP, GaN, *etc.*
  - ✓ important for optoelectronics and high-speed ICs

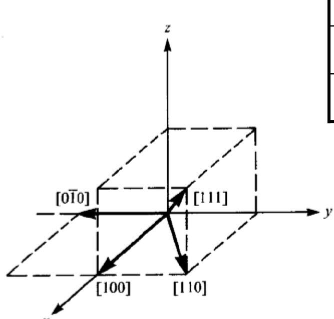
Crystallographic Notation

Miller Indices:

Notation	Interpretation
(***h k l***)	crystal plane
{ ***h k l*** }	equivalent planes
[***h k l***]	crystal direction
< ***h k l*** >	equivalent directions

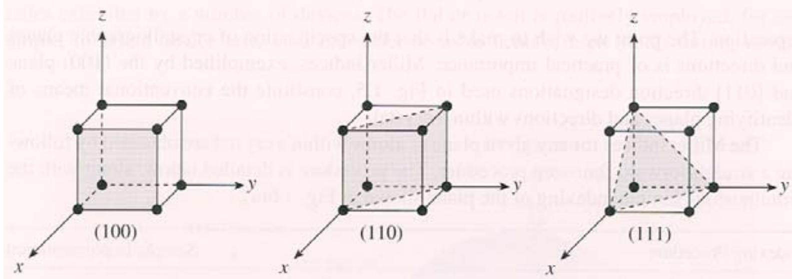
***h*: inverse *x*-intercept of plane**
***k*: inverse *y*-intercept of plane**
***l*: inverse *z*-intercept of plane**

(Intercept values are in multiples of the lattice constant; *h*, *k* and *l* are reduced to 3 integers having the same ratio.)

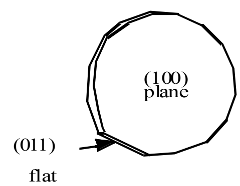


Sample direction vectors and their corresponding Miller indices.

Crystallographic Planes and Si Wafers

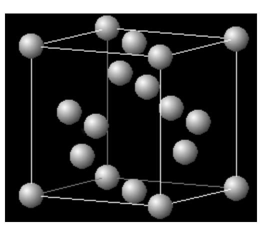


Silicon wafers are usually cut along the (100) plane with a flat or notch to orient the wafer during IC fabrication:



Crystallographic Planes in Si

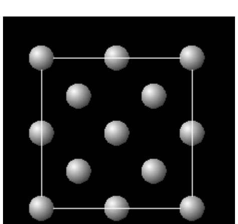
Unit cell:



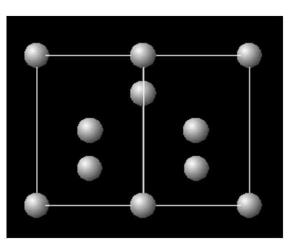
lattice constant = 5.431Å

→ 5 x 10^{22} atoms/cm^3

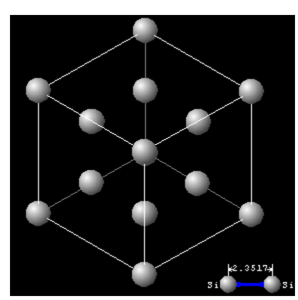
View in <100> direction



View in <110> direction



View in <111> direction



Electronic Properties of Si

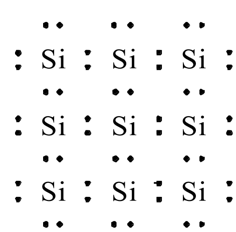
- **Silicon is a semiconductor material.**
  - Pure Si has a relatively high electrical resistivity at room temperature.

- **There are 2 types of mobile charge-carriers in Si:**
  - ***Conduction electrons*** are negatively charged;
  - ***Holes*** are positively charged.

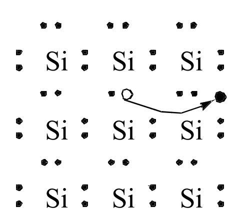
- **The concentration (#/cm^3) of conduction electrons & holes in a semiconductor can be modulated in several ways:**
  1. **by adding special impurity atoms (*dopants*)**
  2. **by applying an electric field**
  3. **by changing the temperature**
  4. **by irradiation**

Bond Model of Electrons and Holes

2-D representation:

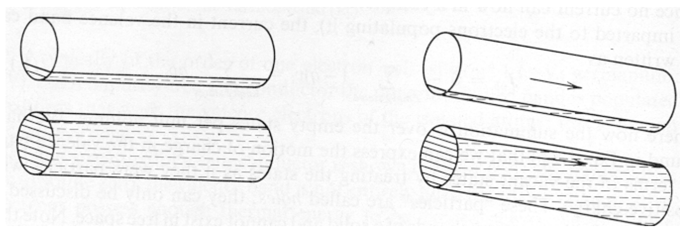


When an electron breaks loose and becomes a ***conduction electron***, a ***hole*** is also created.



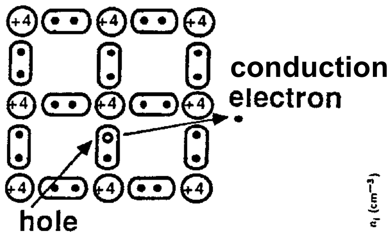
What is a Hole?

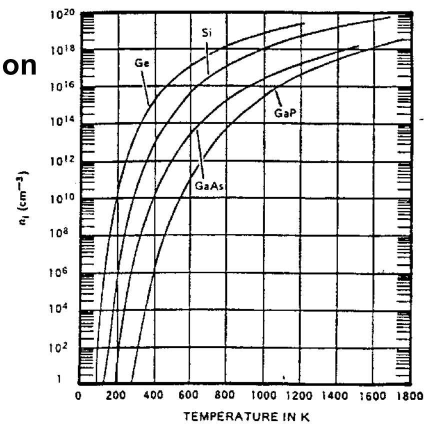
- Mobile positive charge associated with a half-filled covalent bond
  - Treat as positively charged mobile particle in the semiconductor
- Fluid analogy:



The Hole as a Positive Mobile Charge

Pure Si





Covalent (shared e⁻) bonds exists between Si atoms in a crystal. Since the e⁻ are loosely bound, some will be free at any T, creating hole electron pairs.

Si:

$$n_i = 3.9 \times 10^{16} T^{3/2} e^{-\frac{0.605eV}{kT}} /cm^3$$

$n_i \cong 10^{10}$ cm^{-3} at room temperature

Summary

- Crystalline Si:
  - 4 valence electrons per atom
  - diamond lattice: each atom has 4 nearest neighbors
  - 5 x 10^{22} atoms/cm^3
- In a pure Si crystal, conduction electrons and holes are formed in pairs.
  - Holes can be considered as positively charged mobile particles which exist inside a semiconductor.
  - Both holes and electrons can conduct current.