Principles of Micro- and Nanofabrication for Electronic and Photonic Devices

Materials: Structures and Synthesis

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Raw Materials

MOS: Metal-Oxide-Semiconductor

Silicon

SiO₂

Metal
Crystal Structures

Video
It is all about **energy**

**Lennard-Jones Potential**

\[
V(r) = \frac{A}{r^{12}} - \frac{B}{r^{6}}
\]
Crystal Structures

- **3D:**
  - 14 Bravais lattices
  - 32 point groups
  - 230 space groups

Li, Na, Cr,...  Al, Cu, Au,...  Mg, Zn, Ti,...

https://en.wikipedia.org/wiki/Crystal_structure
Miller Indices

(\(lmn\)) plane

intercepts at

\(a_1/l, a_2/m, a_3/n\)

https://en.wikipedia.org/wiki/Crystal_structure
Crystals

![Image of crystals](image-url)
Defects in Crystals

Q: why?

- 0D point defect
- 1D dislocation
- 2D grain boundary
Single Crystal (Mono Crystal)

Silicon wafers, GaAs, GaN, sapphire, ...

Quartz

Sugar

turbine blade

Increasing Resistance to Creep Deformation
Polycrystal

Q: why blue?

grain boundary

Poly-Crystalline Solar Cell
Mono-Crystalline Solar Cell

ceramics
Amorphous Materials

- Defects are everywhere ...

Q: why is glass transparent?
Carbon

Q: which one is electrically conductive, diamond or graphite?
Carbon

H. Kroto, R. Curl, R. Smalley
1996 Nobel Prize in Chemistry


graphene

A. Geim, K. Novoselov
2010 Nobel Prize in Physics
2D Materials

- Single atomic layer crystal

Graphene

A. Geim, K. Novoselov
2010 Nobel Prize in Physics

Transition metal dichalcogenide (TMDC)
MoS$_2$, WSe$_2$, ...
Liquid Crystals

Liquid crystal display (LCD)

P. de Gennes
1991 Nobel Prize in Physics
Organic Materials

- Small Molecules
Organic Materials

**LCD vs. OLED**

- Complex Structure
- BLU (Backlight Unit) CCFL, LED
- Lighting Unit = Pixel Unit

- Simple Structure
- Self-emissive
- Lighting Unit = Pixel Unit
Organic Materials

- Polymers

```
\begin{array}{c}
\text{H} & \text{H} & \text{H} & \text{H} & \text{H} & \text{H} & \text{H} & \text{H} \\
\text{C} & \text{C} & \text{C} & \text{C} & \text{C} & \text{C} & \text{C} & \text{C} \\
\text{H} & \text{H} & \text{H} & \text{H} & \text{H} & \text{H} & \text{H} & \text{H} \\
\end{array}
```

Linear  Branched  Cross-linked

Amorphous  Crystalline  Amorphous region  Crystalline region
Quasi-Crystal

- Neither crystalline nor amorphous
  - 5, 8, 10, or 12-fold symmetry

Penrose tiling

A Ho-Mg-Zn quasicrystal

D. Shechtman
2011 Nobel Prize in Chemistry
Optical Disc

- Phase Change Memory
Materials Characterization

- **SEM / TEM**
  - Scanning / Transmission Electron Microscope

- **HRTEM**
  - High Resolution Transmission Electron Microscope

- **XRD**
  - X-ray Diffraction

- **DSC**
  - Differential Scanning Calorimetry
Materials Characterization

- **HRTEM**
  - High Resolution Transmission Electron Microscope

![Image of HRTEM with labels: amorphous, single crystal, quantum dot]
Materials Characterization

- HRTEM
  - High Resolution Transmission Electron Microscope

**diffraction patterns**

- single crystal
- polycrystal
- amorphous
Materials Characterization

- XRD
  - X-ray Diffraction

![Graph showing intensity vs 2 theta degrees for Crystalline and Amorphous materials.](image)

![Diagram illustrating X-ray diffraction geometry.](image)
Materials Characterization

- DSC
  - Differential Scanning Calorimetry

![Diagram showing DSC graph with Glass Transition, Crystallization, and Melting points labeled with temperatures $T_g$, $T_c$, and $T_m$.]
CMOS Device

polycrystalline → Al
amorphous → SiO₂
single crystalline → Si

Silicon  |  SiO₂  |  Metal
Substrates for Devices

- Usually single crystals

diamond structure:
Si, Ge, C, ...

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Substrates for Devices

- quartz (SiO$_2$)
- single crystalline
- amorphous glass
Substrates for Devices

zinc blende structure: GaAs, InP, β-SiC, ...

Wurtzite structure: α-SiC, GaN, ZnO, ...

sapphire (Al₂O₃)
Lattice Constants vs. Bandgap

![Graph showing lattice constants vs. bandgap for various compounds such as AlN, GaN, InN, ZnS, ZnSe, MgSe, MgTe, CdS, ZnTe, CdSe, AlSb, CdTe, Si, Ge, GaAs, InSb, and InP. The graph plots gap energy (eV) against lattice constant (Å) on a logarithmic scale, with wavelength (nm) on the secondary y-axis.]
Requirement for Electronics

- low cost
- single crystal
- p-doping and n-doping
- low defect level
  - purity > 99.99999....%
  - dislocation < 1000 /cm²
- suitable bandgap
  - too large -> high voltage, power, ...
  - too small -> thermal noise, leakage, defects, ...
- semiconductor/oxide interface quality
- mobility, surface uniformity, ...
Silicon vs. Germanium

Silicon

- earth abundant
  - > 25% on earth
- perfect Si/SiO₂ interface
- bandgap 1.1 eV

Germanium

- expensive
- GeO₂ is not stable
- bandgap 0.67 eV

Silicon wins
and will always win (?)
Properties of Silicon

- **Structural**
  - diamond structure (FCC)
  - lattice constant $a = 5.431 \text{ Å}$
  - atomic density $= 5 \times 10^{22} /\text{cm}^3$
  - melting point $= 1417 \, ^\circ\text{C}$

- **Electronic**
  - bandgap $E_g = 1.12 \, \text{eV}$
  - dielectric constant $\varepsilon_r = 11.9$
  - mobility: electron $\mu_e = 1500 \, \text{cm}^2/\text{V}\cdot\text{s}$, hole $\mu_h = 450 \, \text{cm}^2/\text{V}\cdot\text{s}$
  - intrinsic carrier density $n_i = 1.45 \times 10^{10} /\text{cm}^3$

- **Optical**
  - refractive index $n = 3.6$
  - absorbs $< 1100 \, \text{nm}$, transparent $> 1100 \, \text{nm}$
How to Make Silicon Wafers?

1. SiO$_2$
2. raw Si
3. IC chips
4. Si ingots and wafers
How to Make Silicon Wafers?

SiO$_2$ + 2C = Si + 2CO  

at 2000 °C

Metallurgical Grade Silicon, purity ~ 98%
Applications: aluminum, silicone, ...
How to Make Silicon Wafers?

SiO$_2$ → raw Si

Si + 4HCl = SiCl$_4$ + 2H$_2$

SiCl$_4$ + 2H$_2$ = Si + 4HCl

Purification (Siemens process)

Polycrystalline Silicon, purity > 99.99%
Applications: solar cells, ...
How to Make Silicon Wafers?

poly crystal -> single crystal

Czochralski process (CZ)

Float-zone process (FZ)
How to Make Silicon Wafers?

Czochralski process (CZ)  Float-zone process (FZ)
How to Make Silicon Wafers?

- wafer slicing
- wafer polishing
Silicon wafers: size

18 inch wafer
Silicon wafers: purity

- **Metallurgical grade**
  - polycrystalline
  - purity > 98%
  - application: aluminum alloy, silicone

- **Solar grade**
  - polycrystalline
  - purity > 99.99% (4N)
  - application: solar cells

- **Electronic grade**
  - single crystalline
  - purity > 99.9999999% (9N)
  - application: IC industry, high efficiency solar cells
Silicon wafers: defects

- **Point Defects** e.g. Vacancies (V), Interstitials (I)
- **Line Defects** e.g. Dislocations
- **Area Defects** e.g. Stacking Faults ("extrinsic" or "intrinsic" form along {111} planes)
- **Volume Defects** e.g. Precipitates, Collection of Vacancies
Silicon wafers: doping
Silicon wafers: orientation

{111} p-Type
{111} n-Type

<110>
<110>
<110>
<110>

45°

cleavage direction

why ???
Breaking Amorphous Materials
Silicon-on-Insulator (SOI)

- Thin or Ultra-Thin Top Silicon
- Buried Oxide
- Base Silicon

Bulk Device

The fully depleted SOI transistor at 20 nm is significantly simpler than even a simplified version of the bulk CMOS transistor.

FD-SOI Device
Silicon-on-Insulator (SOI)

Thin or Ultra-Thin Top Silicon

Buried Oxide

Base Silicon

Silicon waveguide

Ring resonator
Other single crystals

Ge

GaAs

sapphire

Q: Can we make diamond crystals?
Optical Fibers

silica (\(\text{SiO}_2\))

K. Kao (1933–2018)
2009 Nobel Prize in Physics

Absorption of Silica (SiO$_2$)

- Minimum loss at 1550 nm, 0.2 dB/km
- ~ 2% loss every kilometer
Optical Fiber Drawing

preform

fibers

Video
Glass Transition

吹玻璃

1st order transition

2nd order transition

glassy / plastic state

viscous / rubbery state
Optical Fibers