ECE-305: Spring 2015

Material Properties: I

Pierret, Semiconductor Device Fundamentals (SDF) pp. 3-19

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1/14/15

ECE 305 Fall 2014 Week by Week Course Schedule

All reading assignments are from: Semiconductor Device Fundamentals, 2nd ed., R.F. Pierret (which is referred to below as SDF)

Aug. 25: Week 1: Material properties
Reading Assignment: SDF, pp. 3-19, 23-32
Topics: General material properties, crystal lattices, crystal growth, quantization, semiconductor models
Week 1 Quiz 1
Week 1 Quiz 2
Week 1 Quiz Answers
Week 1 Homework Assignment
Week 1 Homework Solutions
Week 1: References and Supplementary Information
Introduction to ECE 305 Fall 2014 Material Properties 1

Sept. 1: Week 2: Carrier properties
Reading Assignment: SDF, pp. 32-49
Topics: Carrier properties (charge, effective mass, intrinsic and extrinsic carrier densities), density of states, carrier distributions.
Week 2 Quiz 1
Week 2 Quiz 2
Week 2 Quiz Answers
Week 2 Homework Assignment
Week 2 Homework Solutions
Exam 1 Goals
ECE 305 Key Equations
Exam 1
Exam 1 Solutions
Exam 1 Results

https://nanohub.org/groups/ece305lundstrom
semiconductors

“One shouldn’t work on semiconductors, that is a filthy mess; who knows whether any semiconductors exist.”

Wolfgang Pauli, 1931

outline

1. Silicon
2. Crystals
3. Miller indices
semiconductors

http://en.wikipedia.org/wiki/Periodic_table

column IV

silicon energy levels

Si atom (At. no. 14)

4S^0

3P^2

3S^2

2P^6

2S^2

1S^2

4 valence electrons

8 valence states

“core levels”

Lundstrom ECE-305 S15
Si atoms in a solid

1) In a Si crystal, each atom occupies a specific location in a crystal lattice.

2) Polycrystalline Si consists of many crystalline “grains” with different orientations.

3) In amorphous Si, the atoms are more or less randomly distributed throughout the solid.

a 2D crystal

[Diagram of a 2D crystal with labeled axes a and b]
Graphene: 2011 Nobel Prize in Physics

Graphene is a one-atom-thick planar carbon sheet with a honeycomb lattice.

source: CNTBands 2.0 on nanoHUB.org

unit cells
lattice plus basis

3D crystal structure

http://en.wikipedia.org/wiki/Bravais_lattice
semiconductors

<table>
<thead>
<tr>
<th>Periodic Table</th>
<th>Column IV</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Lanthanoids</strong></td>
<td><strong>Actinoids</strong></td>
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<td><em>Pr</em></td>
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<td><em>Tb</em></td>
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<td><em>Dy</em></td>
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<td><em>Ho</em></td>
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<td><em>Yb</em></td>
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<td><em>Lu</em></td>
<td>71</td>
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</tbody>
</table>

http://en.wikipedia.org/wiki/Periodic_table

Lundstrom ECE-305 S15
Si crystal structure (diamond lattice)

4 nearest neighbors

$N_{\text{atom}} = 5 \times 10^{22} \text{ cm}^{-3}$

diamond lattice

https://nanohub.org/tools/crystal_viewer
The diamond lattice

Atoms per unit cell
8 times $1/8$ + 6 times $\frac{1}{2}$ + 4
8 atoms per unit cell

https://nanohub.org/tools/crystal_viewer

Silicon: density

Lattice constant: $a = 5.4307$ Ang
Density = total mass/vol. of unit cell.
Atomic mass of Si: 28.0855 amu
1 amu = $1.6605 \times 10^{-27}$ kg

$$\rho = \frac{8 \times 28.0855 \times 1.6605 \times 10^{-27}}{(5.4307 \times 10^{-10})^3} \text{ kg/m}^3$$

$$\rho = 2.3296 \text{ g/cm}^3$$

https://nanohub.org/tools/crystal_viewer
Silicon: NN spacing

Lattice constant: $a = 5.4307$ Ang

Body diagonal = $\sqrt{3} \ a$.

NN spacing = $\sqrt{3}a/4$

https://nanohub.org/tools/crystal_viewer

“cartoon” Si crystal

Line represents a shared valence electron

Circle represents the core of a semiconductor (e.g., Si) atom
1. Silicon ✔
2. Crystals ✔
3. Miller indices

Miller index prescription for describing planes

x, y, and z-axis intercepts:
2a, 1a, 2a
2, 1, 2

invert:
½, 1, ½

Rationalize:
1, 2, 1
question

Where does this prescription come from?

Answer: If we remember the equation for a plane, we can figure it out.

where it comes from

(1, 2, 1) plane

equation of a plane:

\[
\frac{x}{x_{int}} + \frac{y}{y_{int}} + \frac{z}{z_{int}} = 1
\]

describe with the numbers:

\[
\frac{1}{x_{int}}, \frac{1}{y_{int}}, \frac{1}{z_{int}}
\]

equivalent to:

\[
\frac{1}{x_{int}/a}, \frac{1}{y_{int}/a}, \frac{1}{z_{int}/a}
\]
prescription for describing directions

$$\vec{v} = [2, 2, 3]$$

- equation of a vector:
  $$\vec{v} = 2a\hat{x} + 2a\hat{y} + 3a\hat{z}$$

- describe with components:
  $$2a, 2a, 3a$$

- equivalent to:
  $$2, 2, 3$$

direction normal to a plane

$$\vec{v} = [1, 2, 1]$$

Why is $[1, 2, 1]$ normal to $(1, 2, 1)$?
where it comes from

equation of a plane:
\[ f(x, y, z) = \frac{x}{x_{\text{int}}} + \frac{y}{y_{\text{int}}} + \frac{z}{z_{\text{int}}} = 1 \]

normal to a plane:
\[
\hat{N} = \nabla f(x, y, z) = \frac{\partial f}{\partial x} \hat{x} + \frac{\partial f}{\partial y} \hat{y} + \frac{\partial f}{\partial z} \hat{z}
\]

(gradient)
\[
\hat{N} = \frac{1}{x_{\text{int}}} \hat{x} + \frac{1}{y_{\text{int}}} \hat{y} + \frac{1}{z_{\text{int}}} \hat{z}
\]

angle between planes

\[
\hat{N}_1 = [1, 0, 0] \\
\hat{N}_2 = [1, 1, 1]
\]

\[
\hat{N}_1 \cdot \hat{N}_2 = N_1 N_2 \cos \theta
\]
angle between planes

\[ \cos \theta = \frac{\mathbf{N}_1 \cdot \mathbf{N}_2}{N_1 N_2} \]

\[ \mathbf{N}_1 = [h_1, k_1, l_1] \]
\[ \mathbf{N}_2 = [h_2, k_2, l_2] \]

\[ \cos \theta = \frac{h_1 h_2 + k_1 k_2 + l_1 l_2}{\sqrt{h_1^2 + k_1^2 + l_1^2} \sqrt{h_2^2 + k_2^2 + l_2^2}} \]

\[ \mathbf{N}_1 = [1, 0, 0] \]
\[ \mathbf{N}_2 = [1, 1, 1] \]

\[ \cos \theta = \frac{1 + 0 + 0}{\sqrt{1^2 + 0^2 + 0^2} \sqrt{1^2 + 1^2 + 1^2}} \]

\[ \cos \theta = \frac{1}{\sqrt{3}} \]
\[ \theta = 54.7^\circ \]

summary

\( (h \; k \; l) \) A specific plane.

\([h \; k \; l]\) A direction normal to the plane above.

\( \mathbf{N} = h \mathbf{\hat{x}} + k \mathbf{\hat{y}} + l \mathbf{\hat{z}} \)

\( \{h \; k \; l\} \) A set of equivalent planes.

\( \langle h \; k \; l \rangle \) A set of equivalent directions.
what plane is this?
Silicon: atoms / cm$^2$ on (100)

Lattice constant: 5.4307 Ang

Atoms on face = 4 times $\frac{1}{4} + 1 = 2$

$N_s = \frac{2}{a^2}$

$N_s = 6.81 \times 10^{14}$ /cm$^2$

https://nanohub.org/tools/crystal_viewer

outline

1. Silicon
2. Crystals
3. Miller indices

Online tool: https://nanohub.org/tools/crystal_viewer