Cluster 5 Light at Work

Lecture 2
7/2/2017

- Semiconductor
- Bending light
• On a scale of 1 (elementary) to 5 (difficult), is the lab on prism on Monday

• A. 1
• B. 2
• C. 3
• D. 4
• E. 5
Prism and Grating Spectrometer

• On a scale of 1 (elementary) to 5 (difficult), is the spectrometer lab
  • A. 1
  • B. 2
  • C. 3
  • D. 4
  • E. 5
Outline

• **Semiconductors**: band gap, electrons, holes

• **Applications**
  – Electronic: transistors
  – Optoelectronic:
    light-emitting diodes (LEDs), lasers, photodetectors
  – Photovoltaic: Solar cells

• **Refraction**
  – Snell’s Law
Two Hydrogen Atoms Form A Hydrogen Molecule

The two 1s energy levels of two hydrogen atoms become two different energy levels in a hydrogen molecule.

http://www.sparknotes.com/chemistry/bonding/molecularorbital/section1.rhtml
As more atoms come close together, separation of energy levels becomes smaller, and the energy levels form energy bands.

Suppose an atom has 5 electrons, can all 5 go into 1s energy level?

http://www.chembio.uoguelph.ca/educmat/chm729/band/detail1.htm
Energy Band Gap
A solid has 100…21 more 0’s atoms → energy bands → energy band gap.

http://micro.magnet.fsu.edu/primer/java/lasers/diodelasers/
Can you find where the most common semiconductor is?

**Periodic Table of the Elements**

<table>
<thead>
<tr>
<th>Element</th>
<th>Atomic Number</th>
<th>Atomic Mass</th>
<th>Symbol</th>
<th>Name</th>
<th>Electron Shells</th>
<th>Electron Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>1</td>
<td>1.008</td>
<td>H</td>
<td>Hydrogen</td>
<td>1s1</td>
<td>1s1</td>
</tr>
<tr>
<td>He</td>
<td>2</td>
<td>4.003</td>
<td>He</td>
<td>Helium</td>
<td>1s2</td>
<td>1s2</td>
</tr>
<tr>
<td>Li</td>
<td>3</td>
<td>6.94</td>
<td>Li</td>
<td>Lithium</td>
<td>1s22s1</td>
<td>1s22s1</td>
</tr>
<tr>
<td>Be</td>
<td>4</td>
<td>9.012</td>
<td>Be</td>
<td>Beryllium</td>
<td>1s22s22p1</td>
<td>1s22s22p1</td>
</tr>
<tr>
<td>B</td>
<td>5</td>
<td>10.81</td>
<td>B</td>
<td>Boron</td>
<td>1s22s22p3</td>
<td>1s22s22p3</td>
</tr>
<tr>
<td>C</td>
<td>6</td>
<td>12.01</td>
<td>C</td>
<td>Carbon</td>
<td>1s22s22p4</td>
<td>1s22s22p4</td>
</tr>
<tr>
<td>N</td>
<td>7</td>
<td>14.01</td>
<td>N</td>
<td>Nitrogen</td>
<td>1s22s22p5</td>
<td>1s22s22p5</td>
</tr>
<tr>
<td>O</td>
<td>8</td>
<td>15.99</td>
<td>O</td>
<td>Oxygen</td>
<td>1s22s22p6</td>
<td>1s22s22p6</td>
</tr>
<tr>
<td>F</td>
<td>9</td>
<td>18.99</td>
<td>F</td>
<td>Fluorine</td>
<td>1s22s22p7</td>
<td>1s22s22p7</td>
</tr>
<tr>
<td>Ne</td>
<td>10</td>
<td>20.18</td>
<td>Ne</td>
<td>Neon</td>
<td>1s22s22p6</td>
<td>1s22s22p6</td>
</tr>
</tbody>
</table>

**Solid, Liquid or Gas**

- **Solid**
  - K (Potassium)
  - Ca (Calcium)
  - Sc (Scandium)
  - Ti (Titanium)
  - V (Vanadium)
  - Cr (Chromium)
  - Mn (Manganese)
  - Fe (Iron)
  - Co (Cobalt)
  - Ni (Nickel)
  - Cu (Copper)
  - Zn (Zinc)
  - Ga (Gallium)
  - Ge (Germanium)
  - As (Arsenic)
  - Se (Selenium)
  - Br (Bromine)
  - Kr (Krypton)
  - Xe (Xenon)
  - Ba (Barium)
  - Ra (Radium)
  - Ac (Actinium)
  - Th (Thorium)
  - Pa (Protactinium)
  - U (Uranium)
  - Np (Neptunium)
  - Pu (Plutonium)
  - Am (Americium)
  - Cm (Curium)
  - Bk (Berkelium)
  - Cf (Californium)
  - Es (Einsteinium)
  - Fm (Fermium)
  - Md (Mendelevium)
  - No (Nobelium)
  - Lr (Lawrencium)

- **Liquid**
  - Na (Sodium)
  - Mg (Magnesium)
  - Al (Aluminium)
  - Si (Silicon)
  - P (Phosphorus)
  - S (Sulphur)
  - Cl (Chlorine)
  - Ar (Argon)
  - Rb (Rubidium)
  - Sr (Strontium)
  - Cs (Cesium)
  - Ba (Barium)
  - La (Lanthanum)
  - Ce (Cerium)
  - Pr (Praseodymium)
  - Nd (Neodymium)
  - Pm (Promethium)
  - Sm (Samarium)
  - Eu (Euridyine)
  - Gd (Gadolinium)
  - Tb (Terbium)
  - Dy (Dysprosium)
  - Ho (Holmium)
  - Er (Erbium)
  - Tm (Thulium)
  - Yb (Ytterbium)
  - Lu (Lutetium)

- **Gas**
  - He (Helium)
  - Ne (Neon)
  - Ar (Argon)
  - Kr (Krypton)
  - Xe (Xenon)
  - Rn (Radon)
  - Po (Polonium)
  - At (Astatine)
  - Tl (Thallium)
  - Pb (Lead)
  - Bi (Bismuth)
  - Po (Polonium)
  - At (Astatine)
  - Rn (Radon)

The most common semiconductor is Silicon (Si), represented by the element number 14 and atomic mass 28.085.
Electrons and Holes

Thermal radiation


If a positive terminal of a battery is applied to the right, electrons—negatively charged—move to the right.

$e^-$ in the valence band (VB) moves to the empty state on the right $\rightarrow$ as though the empty state—hole—moves to the left.

$\rightarrow$ As though the hole is positively charged, $h^+$. 

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N- and P-type Doping

We can change the conductivity of a semiconductor by intentionally introducing impurity atoms—doping.

Undoped

Arsenic (As) atom has 5 valence electrons—4 are used to bond with 4 neighbors and 1 is free to move around.

n-type doping

p-type doping

Boron (B) atom has 3 valence electrons, but 4 are needed to bond with 4 neighbors → 1 hole

http://britneyspears.ac/physics/basics/basics.htm
Conductivities

![Graph showing conductivities of different materials.](Image)
Types of Solids

Single-crystalline   Polycrystalline        Amorphous

Which type of solids do you think gives the highest performance, A, B, or C? And Why?
Crystal Puller

- High purity polycrystalline Si in crucible
- Heated to melting point of Si (1412°C)
- Crucible rotates for uniform temp
- A “seed” crystal is placed into the melt and then pulled out
- Molten Si crystallizes in the appropriate orientation and forms an ingot
Silicon Wafer Production
Evolution of Si Substrate Wafer Size

National Sun Yet-Sen University, Kaohsiung, Taiwan
Q. What do the electron and hole concentrations look like after the P and N sections are joined together?

\[ E_c \quad P \quad E_v \quad E_F \quad N \quad E_F \]

\[ E_{applied} = 0 \]

\[ N_a = N_d \]

a) \[ p(x) \quad n(x) \]

b) \[ p(x) = n(x) \]

c) \[ p(x) \quad n(x) \]

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Q. If the carrier concentration is as shown below what happens?

\[ n(x) \quad p(x) \]

- \[ V_{\text{applied}} = 0 \]
- \[ N_a = N_d \]

a) Holes diffuse to the left, electrons diffuse to the right
b) Holes and electrons stay fixed
c) Holes diffuse to the right and electrons diffuse to the left
d) Holes diffuse to the right and electrons diffuse to the right
Q. When holes diffuse to the right and electrons diffuse to the left, they leave behind ionized acceptors and donors respectively, what happens?

a) Ionized donors are negatively charged and thus attract more holes to the n side
b) Ionized donors are positively charged and thus attract more electrons to the n side
c) Ionized acceptors are negatively charged and thus attract holes to the p side
d) b + c

\[ V_{app} = 0 \]
\[ N_a = N_d \]
Biasing a pn Junction

- **Bias** = Connecting a battery to a pn junction
- **Forward bias** (producing current)
  - **A.** p side to negative terminal
  - **B.** p side to positive terminal
(a) Equilibrium ($V_A = 0$)

(b) Forward bias ($V_A > 0$)

(c) Reverse bias ($V_A < 0$)

Pierret’s book, Fig. 6.1
(a) The energy band diagram of a p-n⁺ (heavily n-type doped) junction without any bias. Built-in potential $V_o$ prevents electrons from diffusing from $n⁺$ to $p$ side. (b) The applied bias reduces $V_o$ and thereby allows electrons to diffuse, be injected, into the $p$-side. Recombination around the junction and within the diffusion length of the electrons in the $p$-side leads to photon emission.

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LED
Solar Cell

pn Junction Solar Cell
Light is an electromagnetic wave

http://micro.magnet.fsu.edu/primer/java/electromagnetic/
The Easiest Way to Bend Light

A Mirror!

Angle of Incidence

\[ \theta_1 \]

Angle of Reflection

\[ \theta_2 \]

\[ \theta_1 = \theta_2 \]

Glass

Metal coating

Protective paint
Special Mirrors

- Front surface mirror
- Metal coating
- Corner cube reflector
- Glass
- Reversing mirror
Some Natural Mirrors

Water

Glass

Metal
Slowing Light Down

- The speed of light is $3 \times 10^8$ m/s, except...
- when it's traveling through something that's not free space (a vacuum).
- Air (and most other gases) are so close to free space, there's no significant difference.
- But if light travels through a transparent liquid or solid (e.g. water or glass) it slows down quite a bit. Why?
The index of refraction (n) of a material measures how much it slows light down.

<table>
<thead>
<tr>
<th>Material</th>
<th>Index n</th>
<th>c/n (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vacuum or air</td>
<td>1</td>
<td>3E+8</td>
</tr>
<tr>
<td>Water</td>
<td>1.33</td>
<td>2.26E+8</td>
</tr>
<tr>
<td>Glass</td>
<td>1.5</td>
<td>2E+8</td>
</tr>
<tr>
<td>Diamond</td>
<td>2.42</td>
<td>1.24E+8</td>
</tr>
</tbody>
</table>

Just recently, scientists have been able to slow light to just a few meters per second, using super-cold cesium vapor.
When Light Slows Down...

- Speed = Frequency • Wavelength is always true
- Frequency cannot change; property of the source
- So, if light slows down, what happens?
- Wavelength has to decrease.

\[ v = \frac{c}{n} \]

\[ \lambda = \frac{\lambda_0}{n} \]

Notice the continuity of waves across the interface.
Snell's Law – The Law of Refraction

From Fermat’s Principle:
Light follows the path of least time

\[ t = \frac{\sqrt{x^2 + h_1^2}}{c/n_1} + \frac{\sqrt{(1-x)^2 + h_2^2}}{c/n_2} \]

\[ \frac{d}{dx} \left( \frac{n_1 x}{c\sqrt{x^2 + h_1^2}} + \frac{-n_2 (1-x)}{c\sqrt{(1-x)^2 + h_2^2}} \right) = \frac{n_1 x}{\sqrt{x^2 + h_1^2}} + \frac{n_2 (1-x)}{\sqrt{(1-x)^2 + h_2^2}} \]

\[ n_1 \sin(\theta_1) = n_2 \sin(\theta_2) \]

or

\[ \theta_2 = \arcsin\left(\frac{n_1}{n_2} \cdot \sin(\theta_1)\right) \]
Car Analogy
What is Dispersion?

Why? Index of refraction depends on wavelength.
But, How Much Light Is Reflected vs Transmitted?

- If the light is perpendicular to the surface:
  - \( \frac{P_r}{P_i} = R = \frac{(n_1 - n_2)^2}{(n_1 + n_2)^2} \)
  - \( \frac{P_t}{P_i} = T = \frac{4n_1n_2}{(n_1 + n_2)^2} \)

Also called "normal" incidence
Critical Angle for Total Internal Reflection

- Occurs only going from higher $n$ to lower $n$
- Total internal reflection
- $\theta_C = \arcsin(n_1/n_2)$
Another Way to Bend Light: Diffraction

Wave nature
Interference
Huygen’s Principle

The diffracted wave can be found as the sum of all the point sources in the open aperture.

Easy to say, but the math is hard
The Pattern of Diffracted Light Depends on the Mask

Sinusoidal

Sawtooth

Rectangle
Diffraction from Two Slits

http://pe2bz.philpem.me.uk/Lights/-%20Laser/Info-999-LaserCourse/C06-M09-Gratings/mod06_09.htm
Angle of Diffracted Wave

\[
\sin(\theta) = \frac{\lambda}{L}
\]

\[
\theta = \arcsin\left(\frac{\lambda}{L}\right)
\]
Diffraction from Many Slits (Diffraction Grating)

http://pe2bz.philpem.me.uk/Lights/-%20Laser/Info-999-LaserCourse/C06-M09-Gratings/mod06_09.htm

http://hyperphysics.phy-astr.gsu.edu/hbase/phyopt/imgpho/diffgrat.gif
Surface Relief Creates Diffraction Too

Sinusoidal

Rectangle

Sawtooth
What Have We Learned?

- Mirrors: Angle of incidence = Angle of reflection
- Corner cubes
- Index of refraction: $n$
- Snell's Law: $n_1 \sin(\theta_1) = n_2 \sin(\theta_2)$
- Brewster angle; Critical angle
- Diffraction
Is the content on semiconductors

A. Too elementary (I know the materials already)

B. About right

C. Too difficult (you talked over my heads)

D. Don’t know (I was dozing off)
Is the content on bending light

A. Too elementary (I know the materials already)

B. About right

C. Too difficult (you talked over my heads)

D. Don’t know (I was dozing off)