ECEN 3250
Microelectronics

Semiconductor Physics and P/N junctions

2/12/17

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Overview

• Energy bands
  – Atomic energy levels
  – Atoms to molecules to solids

• Metals, insulators, and semiconductors
  – Band structure
  – Current flow mechanism

• Carrier transport and concentration
  – Drift and diffusion
  – Ohm’s law
Periodic Table
Double slit experiment

http://abyss.uoregon.edu/~js/21st_century_science/lectures/lec13.html
Hydrogen energy levels

Lyman series

Balmer series

Paschen series
Hydrogen atom lines

Formation of Molecule

- When two hydrogen atoms are brought close together,
  - Standing wave for two electrons
  - Molecular orbitals
- Two different ways to form standing waves
  - Symmetric combination
    - Bonding orbital
    - Lower energy
  - Antisymmetric combination
    - Antibonding orbital
    - Higher energy

Kasap, Fig. 4.1
Formation of Molecule

- Electrons rearrange themselves in the newly formed molecular energy levels
- If the total energy of electrons in the molecule is lower than the sum of atomic energies
  - Stable molecule
  - For example, H₂
- If not, molecules are unstable and the species tend to stay in atoms
  - For example, He

Kasap, Fig. 4.3 & 4.5
Formation of Solid - Lithium

As more and more atoms are brought together, formation of bonding and anti-bonding orbitals continue.

Eventually energy bands are formed.

In the case of Li, one partially filled energy band is formed.
• Silicon has 4 valence electrons participating in the bonding
  – sp\(^3\) hybridization
• Splitting of 3s and 3p atomic orbitals overlap and produce
  – Two disjoint energy bands separated by a gap.
Silicon Crystal and Energy Band Structures

(a) Isolated Si
(b) Si preparing to bond

Si crystal in 2-D

Electron energy

$E_e + \chi$

Conduction Band (CB)
Empty of electrons at 0 K.

$E_v$

Valence Band (VB)
Full of electrons at 0 K.

Bandgap $= E_g$

In metals, electrons fill up to the middle of a band.
  - Partially filled band.
  - Good electrical conductors.

In insulators, electrons fill up to the band gap.
  - Completely full or completely empty bands.
  - Poor electrical conductors.
Rigorous definition of semiconductor:

The solids that are insulators at $T = 0 \, K$ but whose energy bandgap is of such a size that thermal excitation leads to observable conductivity at temperatures below its melting point are called the semiconductors.
Mobility

- Determined by collisions with lattice and impurities
Conductivity

- Now use the ohm’s law, $J = \sigma E$, to find the conductivity

$$\sigma = q(n\mu_n + p\mu_p)$$

- In extrinsic semiconductors, only one of the two currents, $J_n$ and $J_p$, are important,
  - because of the large difference between $n$ and $p$. 

![Graph showing conductivity versus resistivity with dopant density and resistivity values marked on the axes.](image)
Equilibrium Carrier Concentrations

\[ n(T) = \int_{E_c}^{\infty} dE \frac{1}{2\pi^2} \left( \frac{2m_n^*}{h^2} \right)^{3/2} \frac{(E - E_C)^{1/2}}{\exp[(E - E_F)/k_B T]} + 1 \]

See also
Semiconductor Applet Service: http://jas.eng.buffalo.edu/
3.3. Carrier concentrations

Kasap, Fig. 5.7
Impurity Energy Level

- Impurity with one extra electron: donor
- Impurity with one less electron: acceptor
- Treat the impurity as additional charge (+e for donors and −e for acceptors) distributed in a perfect crystal.
  - Hydrogen atom model
- Binding energy is drastically modified.
  - Consider, for example, an As donor in Ge crystal.
  - In free space, the bind energy would have been the first ionization energy of As atom, 9.81 eV!
  - In Ge crystal, the binding energy becomes 0.013 eV
  - Because of dielectric constant and effective mass.
Donors and Acceptors

- If the doping density is much greater than intrinsic carrier concentration, the total carrier concentration is roughly equal to the doping density.
  - Conductivity is engineered by doping.
Donor and Acceptor Energy Levels

Sze, p.21
P-N junction formation

\[ p \gtrsim N_a \quad \text{and} \quad n \gtrsim N_d \]

(a) Bound charges

(b) Potential

Barrier voltage \( V_0 \)
P-N junction at equilibrium
P-N junction under bias

(a) Open-circuit (Equilibrium)

(b) Reverse Bias

(c) Forward Bias
Forward bias
Reverse bias

1. Electron acceleration
2. Impact ionization

Avalanche

Zener

Breakdown field (V cm⁻¹)

Concentration N (cm⁻³)

$E_c$

$E_v$

$E_{fp}$

$p$-type

$n$-type

$E_c$

$E_{fn}$

Avalanche

Zener
Carrier Distribution under Forward Bias

- Under forward bias, carriers are injected across the junction
  - Minority carrier concentration increases exponentially.
-Injected minority carriers then diffuse further into the semiconductor
  - Creating an exponentially decaying function

\[ n_p(-x_p) = n_{po} \exp\left(\frac{V_a}{V_T}\right) = \frac{n_i^2}{N_A} \exp\left(\frac{V_a}{V_T}\right) \]
\[ n_p(x) = n_{po} + n_{po} \left[ \exp\left(\frac{V_a}{V_T}\right) - 1 \right] \exp\left(\frac{x + x_p}{L_n}\right) \]

\[ p_n(x_n) = p_{no} \exp\left(\frac{V_a}{V_T}\right) = \frac{n_i^2}{N_D} \exp\left(\frac{V_a}{V_T}\right) \]
\[ p_n(x) = p_{no} + p_{no} \left[ \exp\left(\frac{V_a}{V_T}\right) - 1 \right] \exp\left(-\frac{x - x_n}{L_p}\right) \]
Current in $pn$ Junction

- Exponentially decaying carrier profile leads to exponential diffusion current.
- Current in $pn$ junction is minority carrier diffusion current.

\[
J_p(x) = -qD_p \frac{dp_n}{dx} = \frac{qD_p}{L_p} \frac{n_i^2}{N_D} \left[ \exp \left( \frac{V_a}{V_T} \right) - 1 \right] \exp \left( -\frac{x-x_n}{L_p} \right)
\]

\[
J_n(x) = \frac{qD_n}{L_n} \frac{n_i^2}{N_A} \left[ \exp \left( \frac{V_a}{V_T} \right) - 1 \right] \exp \left( \frac{x+x_p}{L_n} \right)
\]

\[
J_t = J_n(-x_p) + J_p(x_n) = qn_i^2 \left( \frac{D_p}{L_p N_D} + \frac{D_n}{L_n N_A} \right) \left[ \exp \left( \frac{V_a}{V_T} \right) - 1 \right] = J_o \left[ \exp \left( \frac{V_a}{V_T} \right) - 1 \right]
\]
Avalanche Breakdown

- At large reverse bias, current begins to increase rapidly: breakdown
  - Non-destructive, reversible process
  - Avalanche breakdown & Zener breakdown
- Avalanche breakdown occurs when electrons gain high enough kinetic energy to knock electrons out of valence band – impact ionization.

  - Consider a single electron entering the depletion region.
    - Goes through one impact ionization event, generating an electron-hole pair.
    - The two electrons exit but the generated hole travel in the opposite direction,
    - And goes through another impact ionization,
    - This process repeats indefinitely → breakdown.

1. Electron acceleration
2. Impact ionization
Zener Breakdown

- A different kind of breakdown occurs when the carriers gain enough energy to tunnel through the energy barrier of the junction. - Zener breakdown.
- Zener breakdown occurs when the electric field is high enough to rip a covalent electron from a bonding, creating an electron-hole pair.
- In energy band diagram, this process may be described as an electron in the valence band in the p-side tunnels through the energy barrier at the junction and reaches the conduction band in the n-side.
- When dopant concentration is high, the depletion width is small and the critical field required for avalanche breakdown is high.
  - In this case, Zener breakdown dominates.
Breakdown mechanism is distinguished by their temperature dependence.

- With increasing temperature, tunneling current increases due to the increase of influx of valence band electrons.

The impact ionization rate, however, decreases with increasing temperature.

- This is due to the decrease of $\lambda$, the mean free path for phonon scattering.
- The electrons are more likely to lose energy by phonon scattering and consequently less likely to acquire enough energy to initiate impact ionization.
Other P-N junction devices

• LEDs
  – Forward biased radiative recombination
  – Use blue LEDs and phosphor to make white
Light Emitting Diode (LED)

- Some semiconductor has very strong radiative recombination of carriers
- Under forward bias, current is converted to light.
  - Light emitting diode
When LED is driven very hard, population inversion may be reached. Laser facets act as mirrors and lead to laser oscillation. Injection level is high $\rightarrow$ population inversion $\rightarrow$ stimulated emission $\rightarrow$ laser oscillation.

Semiconductor Laser

- Edge emitting LD
- Vertical cavity surface emitting laser (VCSEL)

http://www.fi.isc.cnr.it/users/giovanni.giacomelli/Semic/Samples/samples.html
Semiconductor Laser

- Population inversion reached at very high injection level
- Output power increases rapidly and linewidth collapses.

Photodiode

- Photodiode: a reverse-biased pn diode.
  1. light absorption $\rightarrow$ e-h pair generation
  2. E-field in the depletion region sweeps carriers out of the depletion region.

$\rightarrow$ generation current

- Compact, solid-state detector
- High quantum efficiency and large bandwidth
- Speed is determined by
  - Carrier diffusion
  - Junction capacitance
Avalanche Photodiode

• When reverse bias is large, the photodiode may experience impact ionization and avalanche breakdown.
• Single electron generated by a photon can produce many electrons and holes through avalanche breakdown process
  – Produces gain
  – Effective low light level detector
Solar Cell

- Solar cell is also a p-n diode.
  - Operating mechanism is the same as the photodiode.
  - Photogenerated current (reverse current) is used to power a load.

Fig 6.49

• Short circuit current = photogenerated current
• When there is a load, photocurrent produces a voltage drop
  • Which is consequently imposed on the diode
  • And therefore produces diode current
  • Total current = diode current - photocurrent
Solar cell I-V characteristic:

\[ I = -I_{ph} + I_o \left[ \exp \left( \frac{qV}{nkT'} \right) - 1 \right] \]

Delivered power:

\[ P = V'I' \]

Fig 6.53

Under reverse bias, p-n junction exhibits little current because the current arises from the flow of minority carriers.

- Can be enhanced if the minority carrier supply is somehow increased.
  - e.g. photons or forward-biased p-n junction

Control of reverse-biased p-n junction current with a nearby forward-biased p-n junction: transistor action.

Consider a structure consisting of two back-to-back p-n junctions.

- Bipolar junction transistor (BJT)

**npn bipolar junction transistor**

- back-to-back *np* and *pn* junctions

The *n*, *p*, *n* regions are called emitter, base and collector.

**Applied bias**

- $V_{BE}$, $V_{BC}$
Carrier Concentration

equilibrium  cut-off  saturation  active mode
Transistor Switching

- Forward active bias: \( V_{BE} > 0 \) and \( V_{BC} < 0 \).
- Reverse active bias: \( V_{BE} < 0 \) and \( V_{BC} > 0 \).
- In a prototype device which is perfectly symmetrical, reverse active bias is identical to forward active bias, except the reversal of current.
- In real transistors where the base is doped non-uniformly and emitter region is much narrower than collector, the current behaviors under the two bias conditions could be markedly different.
- In the saturation region, both junctions are forward biased.
  - This state represents the transistor switched “on”.
- Under this condition, both junctions inject minority carriers into the base region and at the same time both junctions are collecting electrons as well.
Extra slides
### Table 6.2  Selected LED semiconductor materials

<table>
<thead>
<tr>
<th>Semiconductor Active Layer</th>
<th>Structure</th>
<th>D or I</th>
<th>$\lambda$ (nm)</th>
<th>$\eta_{\text{external}}$ (%)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>GaAs</td>
<td>DH</td>
<td>D</td>
<td>870–900</td>
<td>10</td>
<td>Infrared (IR)</td>
</tr>
<tr>
<td>$\text{Al}<em>{x}\text{Ga}</em>{1-x}\text{As}$ ($0 &lt; x &lt; 0.4$)</td>
<td>DH</td>
<td>D</td>
<td>640–870</td>
<td>3–20</td>
<td>Red to IR</td>
</tr>
<tr>
<td>$\text{In}_{1-x}\text{Ga}_x\text{As}<em>y\text{P}</em>{1-y}$ ($y \approx 2.20x$, $0 &lt; x &lt; 0.47$)</td>
<td>DH</td>
<td>D</td>
<td>1–1.6 $\mu$m</td>
<td>$&gt;10$</td>
<td>LEDs in communications</td>
</tr>
<tr>
<td>$\text{In}<em>{0.49}\text{Al}</em>{x}\text{Ga}_{0.51-x}\text{P}$</td>
<td>DH</td>
<td>D</td>
<td>590–630</td>
<td>$&gt;10$</td>
<td>Amber, green, red; high luminous intensity</td>
</tr>
<tr>
<td>$\text{InGaN/GaN quantum well}$</td>
<td>QW</td>
<td>D</td>
<td>450–530</td>
<td>5–20</td>
<td>Blue to green</td>
</tr>
<tr>
<td>$\text{GaAs}_{1-y}\text{P}_y$ ($y &lt; 0.45$)</td>
<td>HJ</td>
<td>D</td>
<td>630–870</td>
<td>$&lt; 1$</td>
<td>Red to IR</td>
</tr>
<tr>
<td>$\text{GaAs}_{1-y}\text{P}_y$ ($y &gt; 0.45$) (N or Zn, O doping)</td>
<td>HJ</td>
<td>I</td>
<td>560–700</td>
<td>$&lt; 1$</td>
<td>Red, orange, yellow</td>
</tr>
<tr>
<td>SiC</td>
<td>HJ</td>
<td>I</td>
<td>460–470</td>
<td>0.02</td>
<td>Blue, low efficiency</td>
</tr>
<tr>
<td>GaP (Zn)</td>
<td>HJ</td>
<td>I</td>
<td>700</td>
<td>2–3</td>
<td>Red</td>
</tr>
<tr>
<td>GaP (N)</td>
<td>HJ</td>
<td>I</td>
<td>565</td>
<td>$&lt; 1$</td>
<td>Green</td>
</tr>
</tbody>
</table>

**NOTE:** Optical communication channels are at 850 nm (local network) and at 1.3 and 1.55 $\mu$m (long distance). $D = $ direct bandgap, $I = $ indirect bandgap. $\eta_{\text{external}}$ is typical and may vary substantially depending on the device structure. $\text{DH} = $ double heterostructure, $\text{HJ} = $ homojunction, $\text{QW} = $ quantum well.
Blue LED – Why Blue?

- LED is an excellent light source due to its high efficiency, fast response time, and long device life.
  - Compared to fluorescent and incandescent lamps
  - Solid-state light source
- Applications include:
  - Traffic lights, color displays, lighting, etc.
- Efficient AlGaAs red LEDs are available.
- Reasonably efficient GaP green LEDs are also available.
- But full color displays and white light sources were unable to achieve due to the lack of blue LED.
  - That was until the emergence of GaN blue LEDs.
- Furthermore, GaN-based blue-violet (405nm) laser diodes can dramatically improve the data storage capacity of CD and DVD since data density is primarily limited by the operating wavelength. Conventional CD players use laser diodes operating at 780 nm. – Blu-ray DVD
Applications of LED
LED Spectral Characteristics

- Emitted light color is determined by the bandgap energy, $E_g$.
- Spectral width is determined by the broadening of electron-hole distribution, which is typically $\sim 3k_B T$.

• Light output is proportional to the current.
• I-V characteristics follow the typical pn junction behavior.
Phosphor-Converted White LED

- Yellow phosphors are coated on the surface of blue LED.
  - Yellow emission by phosphors plus blue LED emission produces white.
- Color can be improved by having two color phosphors excited with blue LED or three color phosphors excited by UV LED.