6.012 - Microelectronic Devices and Circuits

Lecture 8 - BJT Wrap-up, Solar Cells, LEDs - Outline

• Announcements
  First Hour Exam - Tomorrow, Wednesday, October 3, 7:30 pm, 54-100

• BJT Review
  History - 1948 to Today
  Wrapping up BJT (for now)

• p-n Diode review
  Reverse biased junctions - photodiodes and solar cells
    In the dark: no minority carriers, no current
    With illumination: superposition, \( i_D(v_{AB}, L) \); photodiodes
    The fourth quadrant: optical-to-electrical conversion; solar cells
    Video: "Solar cell electricity is better electricity - putting 6.012 to work improving our world (a true story)"

  Forward biased junctions - light emitting diodes, diode lasers
    Video: "The LEDs Around Us"
    Diode design for efficient light emission: materials, structure
    The LED renaissance: red, amber, yellow, green, blue, white
    Replacing incandescent lights – the US DOE L Prize winner!!
**BJT Modeling:** FAR models/characteristics

\[
\alpha_F \equiv -\frac{i_C}{i_E} = \frac{1 - \delta_B}{1 + \delta_E} \approx \frac{1}{1 + \delta_E}
\]

\[
\beta_F \equiv \frac{i_C}{i_B} = \frac{1 - \delta_B}{\delta_E + \delta_B} \approx \frac{1}{\delta_E}
\]

**Defects**

\[
\delta_E = \frac{D_h}{D_e} \cdot \frac{N_{AB}}{N_{DE}} \cdot \frac{w_{B,\text{eff}}}{w_{E,\text{eff}}}
\]

\[
\delta_B \approx \frac{w_{B,\text{eff}}^2}{2L_{eB}^2}
\]

**Design**

Doping: npn with \( N_{DE} \gg N_{AB} \)

\( w_{B,\text{eff}} \): very small

\( L_{eB} \): very large and \( \gg w_{B,\text{eff}} \)
Alloy junction BJT - Early 1950's

Grown junction BJT - mid-1950's

Diffused junction BJT - late-1950's

Early Bipolar Junction Transistors - the first 10 yrs.
Bipolar transistors in history: An early bipolar integrated circuit

Part of a series of US postage stamps commemorating the decade of the 1960's
Integrated circuit bipolar transistors: An early bipolar integrated circuit

A Fairchild Semiconductor DTL (digital) IC from 1964 (before most of us were born!)
Integrated Bipolar Junction Transistors
- integrated circuit processes.

Junction isolated integrated BJT - 1960's onward

Oxide isolated integrated BJT - a modern process
IBM Oxide
Isolated BJT with SiGe base

Color-enhanced cross-section photomicrograph

**pnp BJT's**: The other "flavor" of bipolar junction transistor

**pnp**

**Structure:**

- Symbol and FAR model:
  - Oriented with emitter down like npn:
  - Oriented as found in circuits:

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Clif Fonstad, 10/2/12

Lecture 8 - Slide 8
BJT's, cont.: What about the collector doping, $N_{DC}$?

An effect we didn't put into our large signal model

- **Base width modulation** - the Early effect and Early voltage:
  The width of the depletion region at the B-C junction increases as $v_{CE}$ increases and the effective base width, $w_{B,\text{eff}}$, gets smaller, thereby increasing $\beta$ and, in turn, $i_C$.

- **Punch through** - base width modulation taken to the limit
  When the depletion region at the B-C junction extends all the way through the base to the emitter, $i_C$ increases uncontrollably. Punch through has a similar effect on the characteristics to that of reverse breakdown of the B-C junction.

**To minimize the Early effect we make $N_{DC} < N_{AB}$**

- We will take this effect into account in our small signal LEC modeling.
Photodiodes - *illuminated p-n junction diodes*

Consider a p-n diode illuminated at \( x = x_n + a(w_n-x_n), \ 0 \leq a \leq 1. \)

What is \( i_D(v_{AB}, M) \)? Use superposition to find the answer:

\[
i_D(v_{AB}, M) = i_D(v_{AB}, 0) + i_D(0, M)
\]

We know \( i_D(v_{AB}, 0) \) already...

\[
i_D(v_{AB}, 0) = I_S(e^{qv_{AB}/kT} - 1)
\]

The question is, "What is \( i_D(0, M) \)."

\[
i_D(0, M) = ?
\]
Photodiodes - cont.: the photocurrent, $i_D(0,M)$

The excess minority carriers:

\[ n'(x) = \begin{cases} 0 & \text{for } -w_p \leq x \leq -x_p \\ p'(x_L) & x = x_L \\ 0 & x = x_n \\ -w_p & x = -w_p \end{cases} \]

\[ p'(w_n) = 0 \]

The minority carrier currents:

\[ J_e(-w_p \leq x \leq -x_p) = 0 \]

\[ \{qM \} \]

\[ -(1-a)qM \]

The photocurrent, $i_D(0,M)$:

\[ i_D(0,M) = -AqM(1-a) \]
Photodiodes - cont.: The i-v characteristic and what it means.

The total current: \( i_D(v_{AB}, M) = i_D(v_{AB}, 0) + i_D(0, M) \)

\[
= I_S \left( e^{qv_{AB}/kT} - 1 \right) - AqM \left( 1 - a \right)
\]

The illumination shifts the ideal diode curve vertically down.
Solar cell electricity is better electricity - putting 6.012 to work improving our world - a true story -
Photovoltaic Energy Conversion: Solar cells and TPV, cont.

Efficiency issues: 1. $h\nu : E_g$ mismatch
2. $V_{oc}$ and fill factor
3. Intensity (concentrator) effect

1. $h\nu \begin{cases} < E_g & \text{not absorbed; energy lost} \\ > E_g & \text{excess energy, } (h\nu - E_g), \text{ lost} \end{cases}$

2. $V_{oc} = \frac{kT}{q} \ln \left( \frac{q\eta_i L}{I_s} \right)$ \hspace{1cm} $P_{out \ max} < -i_{SC} V_{oc} = \eta_i L \cdot kT \ln \left( \frac{q\eta_i L}{I_s} \right)$

3. $L \uparrow \Rightarrow \eta \uparrow$

Skyline Solar parabolic reflector/concentrator multi-junction cell installation photo-illustration from website.
Multi-junction cells - efficiency improvement with number

"Photovoltaics take a load off soldiers," Oct. 27, 2006, online at: http://compoundsemiconductor.net/cws/article/magazine/26146
### Multi-junction cells, cont. - 2 designs

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<th>Cell</th>
<th>Bandgap ($E_g$)</th>
<th>Thickness (µm)</th>
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<td>InGaP cell</td>
<td>1.84 eV</td>
<td>0.67</td>
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<td>GaAs cell</td>
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<td>Ge cell</td>
<td>0.7 eV</td>
<td>1.75</td>
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#### A 3-junction design
(3 lattice-matched cells connected in series by tunnel diodes)

#### A 6-junction design*
(3-tandem multi-junction cells set side-by-side)

* "Photovoltaics take a load off soldiers," Oct. 27, 2006, online at: [http://compoundsemiconductor.net/cws/article/magazine/26146](http://compoundsemiconductor.net/cws/article/magazine/26146)
Concentrator installations

Light emitting diodes: what they are all about

The basic idea

In Si p-n diodes and BJTs we make heavy use of the very long minority carrier lifetimes in silicon, but in LEDs we want all the excess carriers to recombination, and to do so creating a photon of light. We want asymmetrical long-base operation:

Why have people cared so much about LEDs?

a cool, efficient source of light
rugged with extremely long lifetimes
can be turned on and off very quickly,
and modulated at very high data rates
Light emitting diodes -
typical spectra

- LED emission - typ. 20 nm wide

- Important spectra to compare with LED emission spectra
**Light emitting diodes: historical perspective**

LEDs are a very old device, and were the first commercial compound semiconductor devices in the marketplace. Red, amber, and green LEDs (but not blue) were sold in the 1960's, but the main opto research focus was on laser diodes; little LED research in universities was done for many years.

Then...things changed dramatically in the mid-1990's:

In part because of **new materials** developed for red and blue lasers
(AlInGaP/GaAs, GaInAlN/GaN)

In part because of **packaging innovations**
(Improved heat sinking and advanced reflector designs)

In part due to advances in **wafer bonding**
(Transparent substrates for improved light extraction)

In part due to the **diligence** of LED researchers
(Taking advantage of advances in other fields)
The LEDs around us.

(≈ 2 min)
Light emitting diodes - design issues

Significant challenges in making LEDs include:

1. Choosing the right semiconductor(s)
   - efficient radiative recombination of excess carriers
   - emission at the right wavelength (color)

2. Getting the light out of the semiconductor
   - overcoming total internal reflection and reabsorption

3. Packaging the diode
   - good light extraction and beam shaping
   - good heat sinking (for high intensity applications)
Compound Semiconductors:

Diamond lattice (Si, Ge, C)

Zinc blende lattice (GaAs shown)

A wide variety of bandgaps. The majority are "direct gap" (a must for efficient optical emission).

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Materials for Red LEDs: GaAsP and AlInGaP

Modern AlInGaP red LEDs grown lattice-matched on GaAs, and then transferred to GaP substrates

GaP red LEDs grown GaP and based on Zn-O pair transitions

Early GaAsP red LEDs grown on a linearly graded buffer on GaAs
- Holonyak and Bevacqua, APL 1 (1962) 82.
Materials for **Amber LEDs**: GaAsP, AlInGaP, and GaP

**Modern AlInGaP amber LEDs** grown lattice-matched on GaAs, and then transferred to GaP substrates


**Early GaAsP amber LEDs** grown on a linearly graded buffer on GaAs

- Holonyak and Bevacqua, APL 1 (1962) 82.
Materials for **Green LEDs**: GaP, InGaAlP

The first green LEDs were GaP grown by liquid phase epitaxy on GaP substrates and based on N doping. N is an "isoelectronic" donor, with a very small $E_d$.

InGaAlP grown by MOCVD on GaAs substrates provide modern high brightness LEDs.
A material covering the spectrum:

The III-V wurtzite quarternary: GaInAlN

Good for UV (unique)

Great for blue (the best)

Good for green

Not so good for red yet.
Light emitting diodes: fighting total internal reflection

With an index of refraction $\approx 3.5$, the angle for total internal reflection is only $16^\circ$. (Only 2% gets out the top!)

Total internal reflection can be alleviated somewhat if the device is packaged in a domed shaped, high index plastic package:

(With $n_{dome} = 2.2$, 10% gets out the top!)

If the device is fabricated with a substrate that is transparent to the emitted radiation, then light can be extracted from the 4 sides and bottom of the device, as well as the top. Increases the extraction efficiency by a factor of 6!

* Critical angle, $\theta_c = \sin^{-1}(n_{out}/n_{in})$,
** Fraction $\approx (\sin \theta_c)^2/4 = (n_{out}/2n_{in})^2$
Light emitting diodes: fighting total internal reflection, and keeping it cool (getting the light and the heat both out).

Taking heat extraction seriously
(a) Old wimpy plastic packages  (b) A real package
Light emitting diodes: the latest wrinkles
Surface texturing, Super-thin (~ 5 µm) devices

White Light from LEDs

Three methods of Generating LED White Light

- Each method has potential strengths!

Red + Green + Blue LEDs
UV LED + RGB Phosphor
Binary Complimentary

RGB LEDs
UV LED + RGB phosphor
Blue LED + Yellow phosphor
Photodiodes and solar cells

**Characteristic:**
\[ i_D(v_{AB}, L) = I_S(e^{qv_{AB}/kT} - 1) - I_L \]

- Reverse or zero bias: \( i_D(v_{AB} < 0) \approx - I_L \) (detects the presence of light)
- In fourth quadrant: \( i_D \times v_{AB} < 0 \) (power is being produced!!)

Light emitting diodes; laser diodes

**Materials:**
- red: GaAlAs, GaAsP, GaP
- amber: GaAsP
- yellow: GaInN
- green: GaP, GaN
- blue: GaN
- white: GaN w. a phosphor

**The LED renaissance:**
- new materials (phosphides, nitrides)
- new applications (fibers, lighting, displays, etc)

**Laser diodes:**
- CD players, fiber optics, pointers

**Check out:**
http://www.britneyspears.ac/lasers.htm