ECE 340
Solid State Electronic Devices

M,W,F 12:00-12:50 (X), 2015 ECEB
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E-mail: jdallesa@illinois.edu
Office Hours: Wednesday 13:00 – 14:00
# Final Exam Schedule

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<th>Course</th>
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<th>CRN</th>
<th>Date</th>
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<th>Start Time</th>
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<tr>
<td>ECE 340</td>
<td>ALL</td>
<td>ALL</td>
<td>05/04/2018</td>
<td>F</td>
<td>1:30 PM</td>
<td>4:30 PM</td>
<td>1002 Electrical &amp; Computer Eng Bldg</td>
<td>Combined</td>
</tr>
<tr>
<td>ECE 340</td>
<td>ALL</td>
<td>ALL</td>
<td>05/04/2018</td>
<td>F</td>
<td>7:00 PM</td>
<td>10:00 PM</td>
<td>2015 Electrical &amp; Computer Eng Bldg</td>
<td>Conflict</td>
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Announcements

• Anyone with a conflict for the final should contact Prof. Dallesasse before 4/27

• Students with accommodations through DRES must sign up with the TAC
## Tentative Schedule [3]

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<td>Metal-semiconductor junctions</td>
<td>MIS-FETs: Basic operation, ideal MOS capacitor</td>
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<th>APR 9</th>
<th>APR 11</th>
<th>APR 13</th>
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<tr>
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<td>Review, discussion, problems <em>(4/12 exam)</em></td>
<td>MOS capacitors: C-V analysis</td>
</tr>
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<tr>
<th>APR 16</th>
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<th>APR 20</th>
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<tbody>
<tr>
<td>MOSFETs: Output &amp; transfer characteristics</td>
<td>MOSFETs: small signal analysis, amps, inverters</td>
<td>Narrow-base diode</td>
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<th>APR 23</th>
<th>APR 25</th>
<th>APR 27</th>
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<tbody>
<tr>
<td>BJT fundamentals</td>
<td>BJT specifics</td>
<td>BJT normal mode operation</td>
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<thead>
<tr>
<th>APR 30</th>
<th>MAY 2 (LAST LECTURE)</th>
<th>FINAL EXAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>BJT common emitter amplifier and current gain</td>
<td>Review, discussion, problem solving</td>
<td><strong>Date &amp; time to be announced</strong></td>
</tr>
</tbody>
</table>

**Subject to Change**
Narrow Base Diode

(Class Website Material)
The Narrow-Base Junction

- The narrow-base junction is a p⁺-n-n⁺ structure
- Minority carrier holes in the n region are the dominant current carriers (large relative to minority carrier electrons in p⁺ region)
- Holes entering the n⁺ region are assumed to recombine instantly
  - $\tau$ is much shorter in the n⁺ region
- The “n” region is much smaller than the minority carrier diffusion length $L_p$ so the minority carrier concentration in the n region can be approximated by a straight line

Boundary Condition for Narrow-Base Diode:

$\delta p(x_n = 0) = \Delta p_n = p_n (e^{qV/kT} - 1)$

$\delta p(x_n = \ell) = 0$
Current Density Impact

Narrow Base Diode

Conventional $p^+n$ Junction

$J_{p\text{,diff}}(x) = -qD_p \frac{dp(x)}{dx}$

- The slope of the excess carrier concentration is much higher for the narrow base diode than the conventional junction
- The current density in the narrow base diode is therefore much higher (same voltage produces more current)
Why Examine the Narrow-Base Diode?

- The narrow-base diode resembles the emitter-base junction of a BJT.
- The point $x_n=0$ is at the n-edge of the emitter-base depletion region.
- The point $x_n=\ell$ is at the n-edge of the base-collector junction.
- Inject at low impedance, extract at high impedance.
Straight-Line Approximation

- If \( \ell \ll L_p \) the hole diffusion current at the “contact” \( x_n = \ell \) is almost as large as at the point of minority carrier injection \( x_n = 0 \)
- Most carriers diffuse across the base without recombining
- Key point: the diffusion current in the narrow-base diode is much larger than that in a standard p+n diode since \( \ell \) replaces \( L_p \) in the denominator of the diode equation
- Key point: from a physical perspective, any hole that random walks across the line \( x_n = \ell \) does not “come back” and reduce net current

The hole current in the n-region is approximately:

\[
J_p(x_n) \approx J_p \text{(diff)} = -qD_p \frac{dp(x_n)}{dx_n} \approx qD_p \frac{\Delta p_n}{\ell}
\]

The total hole current diffusing across the base is then:

\[
I_p(x_n) \approx AJ_p \text{(diff)} = qA \frac{D_p}{\ell} p_n \left( e^{qV/kT} - 1 \right)
\]

\( \ell \) typically much smaller than \( L_p \)
Total Current: Straight Line Model

\[ I = qA \left( \frac{D_n}{L_n} n_p + \frac{D_p}{l} p_n \right) \left( e^{qV/kT} - 1 \right) \]
Space Charge Neutrality

- When recombination occurs, an electron must flow in from the n⁺ “contact” to preserve space-charge neutrality (ionized donors)

\[ I_n(\text{recomb.}) = \frac{Q_p}{\tau_p} \approx \frac{1}{2} \frac{qA\ell\Delta p_n}{\tau_p} \approx \frac{qA\ell}{2\tau_p} p_n \left( e^{\eta V/kT} - 1 \right) \]

\[ I_p(x_n = 0) = I_p(x_n = \ell) + I_n(\text{recomb.}) \]

The majority electron current flowing into the n-region at \(x_n = \ell\) compensates the small decrease in hole diffusion current due to recombination within the "base" region:

\[ I_n(\text{recomb.}) = I_p(x_n = 0) - I_p(x_n = \ell) \approx I_p(x_n = 0) \left[ \frac{\ell^2}{2L_p^2} \right] \]
Exact Solution to the 1D Diffusion Equation

\[
\frac{d^2 \delta p}{dx^2} = \frac{\delta p}{L_p^2} \Rightarrow \delta p(x) = C_1 e^{x/L_p} + C_2 e^{-x/L_p}
\]

Subject to the boundary conditions:
\[
\delta p(x_n) = \Delta p_n \quad \text{for } x_n = 0
\]
\[
= 0 \quad \text{for } x_n = \ell
\]

so
\[
C_1 e^{x/L_p} + (\Delta p_n - C_1) e^{-x/L_p} = 0
\]
\[
C_1 + C_2 = \Delta p_n
\]
\[
C_1 e^{x/L_p} + C_2 e^{-x/L_p} = 0
\]

For constant cross-sectional area the solution to the 1-D diffusion equation is:
\[
\delta p(x_n) = \Delta p_n \left[ \frac{e^{(\ell-x_n)/L_p} - e^{(x_n-\ell)/L_p}}{e^{\ell/L_p} - e^{-\ell/L_p}} \right]
\]

The hole diffusion current at any point in the n-region is then given by:
\[
I_p(x_n) = -qA D_p \frac{d}{dx_n}(\delta p(x_n))
\]
\[
= qA \frac{D_p}{L_p} \Delta p_n \left[ \frac{e^{(\ell-x_n)/L_p} + e^{(x_n-\ell)/L_p}}{e^{\ell/L_p} - e^{-\ell/L_p}} \right]
\]
Hyperbolic Trig. Functions

\[ \sinh(x) = \frac{1}{2} (e^x - e^{-x}) \]
\[ \cosh(x) = \frac{1}{2} (e^x + e^{-x}) \]
\[ \tanh(x) = \frac{\sinh(x)}{\cosh(x)} \]
\[ \text{sech}(x) = \frac{1}{\cosh(x)} \]
\[ \text{csch}(x) = \frac{1}{\sinh(x)} \]
\[ \text{coth}(x) = \frac{1}{\tanh(x)} \]
Hole Current at \( x_n = 0 \)

\[
I_p(x_n) = qA \frac{D_p}{L_p} \Delta p_n \left[ e^{(\ell-x_n)/L_p} + e^{(x_n-\ell)/L_p} \right] \frac{e^{\ell/L_p} - e^{-\ell/L_p}}{e^{\ell/L_p} - e^{-\ell/L_p}}
\]

Evaluating this expression at the point \( x_n = 0 \)

yields the injected hole current:

\[
I_p(x_n = 0) = qA \frac{D_p}{L_p} \Delta p_n \left[ e^{\ell/L_p} + e^{-\ell/L_p} \right] = qA \frac{D_p}{L_p} \Delta p_n \coth \left( \frac{\ell}{L_p} \right)
\]

\[
\approx qA \frac{D_p}{\ell} \Delta p_n \left[ 1 + \frac{\ell^2}{3L_p^2} \right] \text{ for } \ell \ll L_p
\]

\[\uparrow \text{ lowest order correction to straight line model}\]
Aside: Hyperbolic Function Expansion

Hyperbolic Function Expansion:

\[
\text{sech } y = 1 - \frac{y^2}{2} + \frac{5y^4}{24} - \ldots
\]
\[
\text{ctnh } y = \frac{1}{y} + \frac{y^3}{3} - \frac{y^5}{45} + \ldots
\]
\[
\text{csch } y = \frac{1}{y} - \frac{y}{6} + \frac{7y^3}{360} - \ldots
\]
\[
\text{tanh } y = y - \frac{y^3}{3} + \frac{2y^5}{15} - \ldots
\]
\[
\text{coth } y = y^{-1} + \frac{y}{3} - \frac{y^3}{45} + \ldots
\]

Note Also:

\[
\text{coth } y = \frac{1}{y} \left(1 + \frac{y^2}{3} - \frac{y^4}{45} + \ldots\right)
\]

\[
I_p (x_n) = qA \frac{D_p}{L_p} \Delta p_n \left[\frac{e^{(\ell-x_n)/L_p} + e^{(x_n-\ell)/L_p}}{e^{\ell/L_p} - e^{-\ell/L_p}}\right]
\]
\[
I_p (x_n = 0) = qA \frac{D_p}{L_p} \Delta p_n \left[\frac{e^{(\ell)/L_p} + e^{-\ell)/L_p}}{e^{\ell/L_p} - e^{-\ell/L_p}}\right] = qA \frac{D_p}{L_p} \Delta p_n \text{coth} \left(\frac{\ell}{L_p}\right)
\]
\[
\approx qA \frac{D_p}{L_p} \Delta p_n \left(\frac{L_p}{\ell}\right) \left[1 + \frac{\ell^2}{3L_p^2}\right] = qA \frac{D_p}{\ell} \Delta p_n \left[1 + \frac{\ell^2}{3L_p^2}\right]
\]

\[
\uparrow \text{ lowest order correction to straight line model}
\]

for \( \ell \ll L_p \)
Hole Current at n-n\(^+\) Boundary

\[ I_p(x_n) = qA \frac{D_p}{L_p} \Delta p_n \left[ e^{(\ell-x_n)/L_p} + e^{(x_n-\ell)/L_p} \right] \]

At the point \( x_n = \ell \) the hole diffusion current at the n\(^+\) contact is given by:

\[ I_p(x_n = \ell) = qA \frac{D_p}{L_p} \Delta p_n \left[ e^{\ell/L_p} + e^{-\ell/L_p} \right] = qA \frac{D_p}{L_p} \Delta p_n \frac{2}{e^{\ell/L_p} - e^{-\ell/L_p}} \]

\[ = qA \frac{D_p}{L_p} \Delta p_n \text{csch} \left( \frac{\ell}{L_p} \right) \]

\[ \approx qA \frac{D_p}{\ell} \Delta p_n \left[ 1 - \frac{\ell^2}{6L_p^2} \right] \text{ for } \ell \ll L_p \]

The electron current due to hole recombination is therefore:

\[ I_n(\text{recomb.}) = I_p(x_n = 0) - I_p(x_n = \ell) \]

\[ = qA \frac{D_p}{L_p} \Delta p_n \tanh \left( \frac{\ell}{2L_p} \right) \approx qA \frac{D_p}{\ell} \Delta p_n \left[ \frac{\ell^2}{2L_p^2} \right] = qA \frac{\ell}{2 \tau_p} \Delta p_n \text{ for } \ell \ll L_p \]

\[ L_p^2 = D_p \tau_p \]

\[ I_n(\text{recomb.}) = \frac{Q_p}{\tau_p} \approx \frac{1}{2} qA \ell \Delta p_n \]

\[ \approx qA \ell p_n \left( e^{qV/kT} - 1 \right) \]
Narrow Base Diode Electron Current

• An exact solution would use the full expression for $I_n(\text{recomb.})$ with the hyperbolic tangent function (previous slide)

• The straight-line approximation, reasonably valid for $\ell < 0.5L_p$, provides adequate results

Stored Charge:
Under the straight-line model:
$$\frac{dp(x_n)}{dx_n} \approx -\frac{\Delta p_n}{\ell}$$
the stored minority charge (hole) is:
$$Q_p \approx \frac{1}{2} qA\ell\Delta p_n$$

Electron component of current crossing p-n junction:
$$I_n(\text{inj.}) = qA \frac{D_n}{L_n} n_p \left(e^{qV/kT} - 1\right)$$

The total electron current is therefore:
$$I_B = I_n(\text{recomb.}) + I_n(\text{inj.}) \approx qA \left(\frac{\ell}{2\tau_p} p_n + \frac{D_n}{L_n} n_p \right) \left(e^{qV/kT} - 1\right)$$

Aside: in a transistor, a small base current $I_B$ can be used to control a much larger current due to holes crossing the n-region from the emitter to the collector. The result is current amplification (gain).

The narrow-base diode electron current is analogous to the p-n-p transistor base current!
Narrow Base Diode Total Current

\[ I_{tot} = I_p(x_n = \ell) + I_n(recomb.) + I_n(inj.) \]

\[ = qA \frac{D_p}{L_p} \Delta p_n \text{csch} \left( \frac{\ell}{L_p} \right) + qA \frac{D_p}{L_p} \Delta p_n \tanh \left( \frac{\ell}{2L_p} \right) + qA \frac{D_n}{L_n} \Delta n_p \]

\[ = \left( qA \frac{D_p}{L_p} p_n \text{csch} \left( \frac{\ell}{L_p} \right) + qA \frac{D_p}{L_p} p_n \tanh \left( \frac{\ell}{2L_p} \right) + qA \frac{D_n}{L_n} n_p \right) \left( e^{qV/kT} - 1 \right) \]
BJT Fundamentals
Some Definitions

• FET: Field Effect Transistor
  – JFET (Junction FET): The control (gate) voltage varies the depletion width of a reverse-biased p-n junction
  – MESFET (MEmtal-Semiconductor FET): The p-n junction is replaced by a Schottky barrier diode in reverse bias
  – MISFET (Metal-Insulator-Semiconductor FET): The metal electrode is separated from the semiconductor by an insulator
  – MOSFET (Metal-Oxide-Semiconductor FET): The insulator is an oxide
  – FETs are majority carrier, unipolar devices
  – FETs are voltage-controlled devices

• BJT: Bipolar Junction Transistor
  – The action of both majority carriers and minority carriers is important
    • Bipolar device
      – BJTs are current-controlled devices

• Key Applications: amplification and switching
John Bardeen and Walter Brattain
Discovery of Transistor by Bardeen and Brattain (1947)

Identification of minority carrier injection, recombination in the base and collection underlying bipolar transistor operation
How do you make a pnp transistor using only n-type Ge?

Band Bending!

Figure From:
J.W. Mayer, “Gold Contacts to Semiconductor Devices”
The Load Line: 2-Terminal Case

- Loop equation: $E = R i_D + v_D$
- Device i-v relationship: $i_D = f(v_D)$
- The load line is used to find the simultaneous solution to both equations
3-Terminal Case

- Loop equation: \( E = R i_D + v_D \)
- Device i-v relationship: \( i_D = f(v_D, v_G) \) or \( i_D = f(v_D, i_B) \)
- The load line is used to find the simultaneous solution to both equations
Amplification and Switching

- Small changes in $v_G$ (FET) or $i_B$ (BJT) effect large changes in $I_D$
- This feature makes FETs and BJTs useful for amplification and switching
Minority Carrier Injection in Reverse-Biased Junctions

- The optical generation of carriers for a reverse-biased pn junction causes $I_o$ to increase, shifting the I-V downward as the generation term increases.
- Current is essentially independent of voltage in the 3\textsuperscript{rd} quadrant.
- The diode under illumination essentially acts like an ideal current source.
Emitter-Base Junction as Hole Injector

- The base-collector junction corresponds to the isolated pn junction on the previous page.
- Minority carriers are injected electrically by the forward biased emitter-base junction.
- This acts as the “hole injection device” depicted on the previous page.
- For the greatest change in $I_C$ with increasing $I_E$, hole recombination in the base needs to be minimized:
  - Hole lifetime long
  - $W_b << L_p$
  - $I_E$ is mostly hole current.
Current Flow in a pnp Transistor

Transistor Current Components

- Hole recombination in base (1)
- Holes injected into reverse-biased base-collector junction (2)
- Thermal generation-recombination current in reverse-biased base-collector junction (3)
- Electron flow into base to compensate for electrons lost due to recombination with injected holes (4)
- Electron flow from n-type base to p⁺ emitter under forward bias (5)

Components of electron (particle) flow into base:

- Recombination (-)
- Forward injection into p⁺ region (-)
- Thermal generation flow from collector (+)
nnpn Transistor

- n-type emitter
- p-type base
- n-type collector

- Forward Bias
  - Injected holes
  - Hole flow
  - Leakage current

- Reverse Bias
  - Injected electrons

- Electron flow
- Hole flow

- $I_{E,e}$
- $I_{E,p}$
- $I_{B,p}$
- $I_{C,e}$
Key Definitions

$I_C \approx Bi_{Ep}$

$B \equiv$ fraction of injected holes that make it to the collector

[Note: $(1 - B)$ is the fraction of holes that recombine in the base]

B is called the "Base Transport Factor"

**Emitter injection efficiency:** $\gamma = \frac{i_{Ep}}{i_{En} + i_{Ep}}$

Ideally, B and $\gamma$ approach unity for an efficient transistor.

Note also: $\frac{i_C}{i_E} = \frac{Bi_{Ep}}{i_{En} + i_{Ep}} = B\gamma \equiv \alpha$

$\alpha$ is the "current transfer ratio"

Base Current: $i_B = i_{En} + (1 - B)i_{Ep}$

and so, neglecting $I_o$ in the base-collector junction:

$$\frac{i_C}{i_B} = \frac{Bi_{Ep}}{i_{En} + (1 - B)i_{Ep}} = \frac{B}{1 - B} \frac{i_{Ep}}{i_{En} + i_{Ep}} = \frac{B\gamma}{1 - B\gamma} = \frac{\alpha}{1 - \alpha} \equiv \beta$$

$\beta$ is the "base to collector current amplification factor"

Typical values of $\alpha$ are $\sim 0.99$ and $\beta$ are $\sim 100$

$\tau_p = 10 \mu$s

$\tau_i = 0.1 \mu$s

$\frac{i_C}{i_B} = \beta = \frac{\tau_p}{\tau_i} = 100$

Neglecting $v_{BE}$

$I_B = \frac{5V}{50 \, \text{k}\Omega} = 0.1 \, \text{mA}$

$I_C = \beta I_B = 10 \, \text{mA}$
BJT Current Gain

- A small base current is used to control a large emitter and collector current
- A simplified analysis can be performed by assuming DC or small-signal AC at low frequency
- Generation-recombination term in reverse-biased base-collector junction is also neglected in the simplified analysis
  - Note: just because we neglect it mathematically doesn’t mean it’s not important

\[
i_E = i_B + i_C
\]

\[
i_C = \beta i_B
\]
Biasing Configurations

- Various BJT biasing methods are possible
  - “Common emitter”
  - “Common base”
  - “Common collector”
- Preferred biasing method depends upon intended application
  - Input and output impedance
  - Voltage/current/power gain
  - Input/output phase relationship
### Transistor Configuration Comparison Chart

(see Sedra & Smith and "Detailed Analysis" below)

<table>
<thead>
<tr>
<th>AMPLIFIER TYPE</th>
<th>COMMON BASE</th>
<th>COMMON EMITTER</th>
<th>COMMON EMITTER (Emitter Resistor)</th>
<th>COMMON COLLECTOR (Emitter Follower)</th>
</tr>
</thead>
<tbody>
<tr>
<td>INPUT/OUTPUT PHASE RELATIONSHIP</td>
<td>$0^\circ$</td>
<td>$180^\circ$</td>
<td>$180^\circ$</td>
<td>$0^\circ$</td>
</tr>
<tr>
<td>VOLTAGE GAIN</td>
<td>HIGH</td>
<td>MEDIUM</td>
<td>MEDIUM</td>
<td>LOW</td>
</tr>
<tr>
<td></td>
<td>$\frac{\alpha R_C}{R_s + r_e}$</td>
<td>$\frac{\beta (R_C \parallel r_e)}{R_s + r_e}$</td>
<td>$\frac{\beta R_C}{R_s + (\beta + 1)(r_e + R_C)}$</td>
<td>$\frac{(\beta + 1)(R_C \parallel r_e)}{R_s + (\beta + 1)[r_e + (R_L \parallel R_C)]}$</td>
</tr>
<tr>
<td>CURRENT GAIN</td>
<td>LOW</td>
<td>MEDIUM</td>
<td>MEDIUM</td>
<td>HIGH</td>
</tr>
<tr>
<td></td>
<td>$a$</td>
<td>$\frac{\beta r_e}{R_C + r_e}$</td>
<td>$b$</td>
<td>$\frac{(\beta + 1)}{r_e + R_L}$</td>
</tr>
<tr>
<td>POWER GAIN</td>
<td>LOW</td>
<td>HIGH</td>
<td>HIGH</td>
<td>MEDIUM</td>
</tr>
<tr>
<td>INPUT RESISTANCE</td>
<td>LOW</td>
<td>MEDIUM</td>
<td>MEDIUM</td>
<td>HIGH</td>
</tr>
<tr>
<td></td>
<td>$r_e$</td>
<td>$r_e = (\beta + 1) r_e$</td>
<td>$(\beta + 1)(r_e + R_C)$</td>
<td>$(\beta + 1)[r_e + (R_L \parallel R_C)]$</td>
</tr>
<tr>
<td>OUTPUT RESISTANCE</td>
<td>HIGH</td>
<td>MEDIUM</td>
<td>MEDIUM</td>
<td>LOW</td>
</tr>
<tr>
<td></td>
<td>$R_C$</td>
<td>$R_C \parallel r_e$</td>
<td>$R_C$</td>
<td>$r_e \parallel \left[ r_e + \frac{R_C}{(\beta + 1)} \right]$</td>
</tr>
</tbody>
</table>

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**Bonus Material**

Space Charge Neutrality
Space-Charge Neutrality in the Base

- The base region between the emitter-base and base-collector depletion regions is electrostatically neutral
- In an n-type base, electrons enter from the base contact and the reverse-biased base-collector junction
- In an n-type base, electrons leave through recombination with injected minority carrier holes and through injection into the p-type emitter across the forward-biased emitter-base junction
- In a p-n-p device holes enter the base through injection by the p-type emitter
- In a p-n-p device holes leave through recombination with electrons in the base or by diffusing into the field region of the reverse-biased base-collector junction

\[
I_{Ep} (x = 0) = \frac{Q_p}{\tau_p} + \frac{Q_p}{\tau_t} \approx \frac{Q_p}{\tau_t} \approx \frac{qAW_B\Delta p_n}{2\tau_t} \\
\approx \frac{qAW_B p_n e^{qV_{EB}/kT}}{2\tau_t} \approx I_o e^{qV_{EB}/kT} \approx I_C
\]
Space-Charge Neutrality in the Base

- The average hole spends a time equal to the transit time $\tau_t$ in the base, and $\tau_t$ is significantly less than the carrier lifetime $\tau_p$.
- The average electron spends a time equal to the hole minority carrier lifetime $\tau_p$ waiting to recombine in the base.
- Each electron can provide space charge compensation for $(\tau_p/\tau_t)$ holes!
- The rate of flow of electrons (base current) determines how many holes can flow (emitter/collector current).
  - A small base current can control much larger currents in the emitter and collector.

\[
\beta = \frac{i_C}{i_B} = \frac{Q_p}{\tau_p} \left( \frac{\tau_t}{\tau} \right) = \frac{\tau_p}{\tau_t}
\]
BJT Fabrication
Figure 7.5

Process flow for double polysilicon, self-aligned n-p-n BJT: (a) n+ buried layer formation; (b) n epitaxy followed by LOCOS isolation; (c) base-emitter window definition and (optional) masked “sinker” implant (P) into collector contact region; (d) intrinsic base implant using self-aligned oxide sidewall spacers; (e) self-aligned formation of n+ emitter, as well as n+ collector contact.
Diffusion Equation in the Base
Simplified Analysis of the BJT

Assumptions in the Simplified Analysis:
• Holes diffuse from the emitter to collector – drift is negligible in the base
• The active area of the base, emitter-base junction, and base-collector junction have the same area
• All currents and voltages are steady state
• Recombination in depletion regions is neglected

Other (Initial) Assumptions:
• The emitter current is composed only of holes – the emitter injection efficiency is unity (γ=1)
• The collector saturation current $I_o$ is negligible
Diffusion Equation in the Base

Excess Hole Concentration:

\[ \Delta p_E = p_n \left( e^{qV_{EB}/kT} - 1 \right) \quad \text{and} \quad \Delta p_C = p_n \left( e^{qV_{CB}/kT} - 1 \right) \]

If \( V_{EB} \gg kT / q \) and \( V_{CB} \ll 0 \):

\[ \Delta p_E = p_n e^{qV_{EB}/kT} \quad \text{and} \quad \Delta p_C = -p_n \]

Using the diffusion equation:

\[ \frac{d^2 \delta p(x_n)}{dx_n^2} = \frac{\delta p(x_n)}{L_p^2} \]

Solution: \( \delta p(x_n) = C_1 e^{x_n/L_p} + C_2 e^{-x_n/L_p} \)
Diffusion Equation in the Base

Apply Boundary Conditions:
\[ \delta p(x_n = 0) = C_1 + C_2 = \Delta p_E \] and
\[ \delta p(x_n = W_b) = C_1 e^{W_b / L_p} + C_2 e^{-W_b / L_p} = \Delta p_C \]

Solving for \( C_1 \) and \( C_2 \):
\[ C_1 = \frac{\Delta p_C - \Delta p_E e^{-W_b / L_p}}{e^{W_b / L_p} - e^{-W_b / L_p}} \quad \text{and} \quad C_2 = \frac{\Delta p_E e^{W_b / L_p} - \Delta p_C}{e^{W_b / L_p} - e^{-W_b / L_p}} \]

For a strongly reverse-biased collector and \( \Delta p_E \gg p_n \):
\[ \delta p(x_n) = C_1 e^{x_n / L_p} + C_2 e^{-x_n / L_p} = \Delta p_E \frac{e^{x_n / L_p} - e^{x_n / L_p} e^{-W_b / L_p}}{e^{W_b / L_p} - e^{-W_b / L_p}} \quad \text{for} \quad \Delta p_C \approx 0 \]
Band Diagram Under Normal Bias

\[ p(x_n = 0) = p_n e^{-\frac{q V_{EB}}{kT}} \]

\[ p(x_n = W_b) = p_n e^{-\frac{q V_{CB}}{kT}} \approx 0 \text{ for } V_{CB} \leq 0 \]
Minority Carrier Distributions

- Graphical representation of minority carrier distributions based upon the solution to the diffusion equation (normal biasing)
- Assumes moderate base width
- Assumes “long diode” such that minority carrier electrons in p-emitter decay to ~0
Diffusion Equation: General Solution

Excess Hole Concentration:
$$\Delta p_E = p_n \left( e^{qV_{EB}/kT} - 1 \right) \text{ and } \Delta p_C = p_n \left( e^{qV_{CB}/kT} - 1 \right)$$

Using the diffusion equation:
$$\frac{d^2 \delta p(x_n)}{dx_n^2} = \frac{\delta p(x_n)}{L_p^2}$$

Solution: $$\delta p(x_n) = C_1 e^{x_n/L_p} + C_2 e^{-x_n/L_p}$$

Apply Boundary Conditions:
$$\delta p(x_n = 0) = C_1 + C_2 = \Delta p_E \text{ and } \delta p(x_n = W_b) = C_1 e^{W_b/L_p} + C_2 e^{-W_b/L_p} = \Delta p_C$$

Solving for $C_1$ and $C_2$:
$$C_1 = \frac{\Delta p_C - \Delta p_E e^{-W_b/L_p}}{e^{W_b/L_p} - e^{-W_b/L_p}} \text{ and } C_2 = \frac{\Delta p_E e^{W_b/L_p} - \Delta p_C}{e^{W_b/L_p} - e^{-W_b/L_p}}$$
Hyperbolic Trig. Functions

\[
\sinh(x) = \frac{1}{2} \left( e^x - e^{-x} \right)
\]

\[
\cosh(x) = \frac{1}{2} \left( e^x + e^{-x} \right)
\]

\[
\tanh(x) = \frac{\sinh(x)}{\cosh(x)}
\]

\[
\text{sech}(x) = \frac{1}{\cosh(x)}
\]

\[
\text{csch}(x) = \frac{1}{\sinh(x)}
\]

\[
\coth(x) = \frac{1}{\tanh(x)}
\]
Evaluation of the Terminal Currents
Review: Minority Carrier Distributions

$$\delta p(x_n) = M_1 \Delta p_E e^{-x_n/L_p} - M_2 \Delta p_E e^{x_n/L_p}$$

where

$$M_1 = \frac{e^{W_b/L_p}}{e^{W_b/L_p} - e^{-W_b/L_p}}$$

$$M_2 = \frac{e^{-W_b/L_p}}{e^{W_b/L_p} - e^{-W_b/L_p}}$$

$$\delta p(x_n = 0) = C_1 + C_2 = \Delta p_E$$ and

$$\delta p(x_n = W_b) = C_1 e^{W_b/L_p} + C_2 e^{-W_b/L_p} = \Delta p_C$$

So:

$$C_1 = \frac{\Delta p_C - \Delta p_E e^{-W_b/L_p}}{e^{W_b/L_p} - e^{-W_b/L_p}}$$ and

$$C_2 = \frac{\Delta p_E e^{W_b/L_p} - \Delta p_C}{e^{W_b/L_p} - e^{-W_b/L_p}}$$

For General Biasing:  $$\delta p(x_n) = C_1 e^{x_n/L_p} + C_2 e^{-x_n/L_p}$$

For a strongly reverse-biased collector and $$\Delta p_E \gg p_n$$:

$$\delta p(x_n) = \Delta p_E \frac{e^{W_b/L_p} e^{-x_n/L_p} - e^{-W_b/L_p} e^{x_n/L_p}}{e^{W_b/L_p} - e^{-W_b/L_p}}$$ for $$\Delta p_C = 0$$
Terminal Currents

Emitter and collector currents are calculated at the edge of each depletion region from the minority carrier (hole) concentration gradient:

\[ I_p(x_n) = -qAD_p \frac{d\delta p(x_n)}{dx_n} = -qAD_p \frac{d}{dx_n} \left[ C_1 e^{x_n/L_p} + C_2 e^{-x_n/L_p} \right] \]

therefore, at \( x_n = 0 \):

\[ I_{Ep} = I_p(x_n = 0) = qA \frac{D_p}{L_p} (C_2 - C_1) \]

Neglecting collector reverse saturation current, \( I_C \) is dominated by holes:

\[ I_C = I_p(x_n = W_b) = qA \frac{D_p}{L_p} \left( C_2 e^{-W_b/L_p} - C_1 e^{W_b/L_p} \right) \]

Substituting in the previously determined values for \( C_1 \) and \( C_2 \):

\[ I_{Ep} = qA \frac{D_p}{L_p} \left[ \Delta p_E \left( e^{W_b/L_p} + e^{-W_b/L_p} \right) - 2\Delta p_C \right] \]

or, expressing as hyperbolic functions:

\[ I_{Ep} = qA \frac{D_p}{L_p} \left( \Delta p_E \tanh \frac{W_b}{L_p} - \Delta p_C \operatorname{csch} \frac{W_b}{L_p} \right) \]

and \( I_C = qA \frac{D_p}{L_p} \left( \Delta p_E \operatorname{csch} \frac{W_b}{L_p} - \Delta p_C \tanh \frac{W_b}{L_p} \right) \)

The value of \( I_B \) is obtained via node analysis: \( I_B = I_E - I_C \)

\[ I_B = qA \frac{D_p}{L_p} \left[ (\Delta p_E + \Delta p_C) \left( \tanh \frac{W_b}{L_p} - \operatorname{csch} \frac{W_b}{L_p} \right) \right] = qA \frac{D_p}{L_p} \left[ (\Delta p_E + \Delta p_C) \tanh \frac{W_b}{2L_p} \right] \]
Visualizing the Terminal Currents

\[ I_{Ep} = qA \frac{D_p}{L_p} \left( \Delta p_E \cosh \frac{W_b}{L_p} - \Delta p_C \sinh \frac{W_b}{L_p} \right) \]

\[ I_{Cp} = qA \frac{D_p}{L_p} \left( \Delta p_E \sinh \frac{W_b}{L_p} - \Delta p_C \cosh \frac{W_b}{L_p} \right) \]

\[ I_B = qA \frac{D_p}{L_p} \left[ \left( \Delta p_E + \Delta p_C \right) \tanh \frac{W_b}{2L_p} \right] \]

Hyperbolic Function Expansion:

\[ \cosh y = \frac{1}{2} \left( e^y + e^{-y} \right) \]

\[ \sinh y = \frac{1}{2} \left( e^y - e^{-y} \right) \]

\[ \tanh y = \frac{e^y - e^{-y}}{e^y + e^{-y}} = \frac{\sinh y}{\cosh y} \]

\[ \csc y = \frac{1}{y} \left( 1 - \frac{y^2}{3} + \frac{y^4}{45} - \ldots \right) \]

\[ \tanh y = y - \frac{y^3}{3} + \ldots \]
Terminal Currents: General Case

Terminal Currents for Arbitrary Transistor Biasing:

\[ I_{Ep} = qA \frac{D_p}{L_p} \left( \Delta p_E \text{ctnh} \frac{W_b}{L_p} - \Delta p_C \text{csch} \frac{W_b}{L_p} \right) \]

\[ I_{Cp} = qA \frac{D_p}{L_p} \left( \Delta p_E \text{csch} \frac{W_b}{L_p} - \Delta p_C \text{ctnh} \frac{W_b}{L_p} \right) \]

\[ I_B = qA \frac{D_p}{L_p} \left[ \left( \Delta p_E + \Delta p_C \right) \text{tanh} \frac{W_b}{2L_p} \right] \]

Note: These do not include the electron component across the emitter and collector junctions.
Approximation of the Terminal Currents
Simplification of the Current Equations

General Expressions:

\[ I_{E_p} = qA \frac{D_p}{L_p} \left( \Delta p_E \text{ctnh} \frac{W_b}{L_p} - \Delta p_c \text{csch} \frac{W_b}{L_p} \right) \]

\[ I_{C} = qA \frac{D_p}{L_p} \left( \Delta p_E \text{csch} \frac{W_b}{L_p} - \Delta p_c \text{ctnh} \frac{W_b}{L_p} \right) \]

\[ I_{B} = qA \frac{D_p}{L_p} \left[ (\Delta p_E + \Delta p_C) \tanh \frac{W_b}{2L_p} \right] \]

Under normal bias, the generalized expressions can be simplified

If the collector is reverse biased, \( \Delta p_C = -p_n \)

If \( p_n \) is small, \( \Delta p_C \) can be neglected

If \( \gamma \approx 1 \), \( I_E \approx I_{E_p} \) therefore:

\[ I_{E} \approx qA \frac{D_p}{L_p} \Delta p_E \text{ctnh} \frac{W_b}{L_p} \]

\[ I_{C} \approx qA \frac{D_p}{L_p} \Delta p_E \text{csch} \frac{W_b}{L_p} \]

\[ I_{B} \approx qA \frac{D_p}{L_p} \Delta p_E \tanh \frac{W_b}{2L_p} \]
Hyperbolic Function Expansion

Using the series expansions of the hyperbolic functions, and assuming that \( \frac{W_b}{L_p} \) is small such that terms above the first order can be neglected:

\[
I_B = qA \frac{D_p}{L_p} \Delta p_E \tanh \left( \frac{W_b}{2L_p} \right) = qA \frac{D_p}{L_p} \Delta p_E \frac{W_b}{2L_p} = \frac{qAW_b \Delta p_E}{2\tau_p}
\]

This can also be obtained from the expanded emitter and collector current expressions:

\[
I_B = I_E - I_C = qA \frac{D_p}{L_p} \Delta p_E \left[ \left( \frac{1}{W_b / L_p} + \frac{W_b / L_p}{3} \right) - \left( \frac{1}{W_b / L_p} - \frac{W_b / L_p}{6} \right) \right]
\]

\[
\approx \frac{qAD_p W_b \Delta p_E}{2L_p^2} = \frac{qAW_b \Delta p_E}{2\tau_p} \quad \iff \quad L_p^2 = D_p \tau_p
\]

Using the straight-line model, the charge in the base is: \( Q_p = \frac{1}{2} qA \Delta p_E W_b \)

If recombination dominates the base current, the charge control model gives:

\[
I_B = \frac{Q_p}{\tau_p} = \frac{qA \Delta p_E W_b}{2\tau_p}
\]

Hyperbolic Function Expansion:

\[
\text{sech } y = 1 - \frac{y^2}{2} + \frac{5y^4}{24} - ...
\]

\[
\text{ctnh } y = \frac{1}{y} + \frac{y}{3} - \frac{y^3}{45} + ...
\]

\[
\text{csch } y = \frac{1}{y} - \frac{y}{6} + \frac{7y^3}{360} - ...
\]

\[
\tanh y = y - \frac{y^3}{3} + ...
\]
Terminal Currents: Normal Biasing

General Expressions:

\[ I_{E_p} = qA \frac{D_p}{L_p} \left( \Delta p_E \coth \frac{W_b}{L_p} - \Delta p_C \csch \frac{W_b}{L_p} \right) \]

\[ I_{C_p} = qA \frac{D_p}{L_p} \left( \Delta p_E \csch \frac{W_b}{L_p} - \Delta p_C \coth \frac{W_b}{L_p} \right) \]

\[ I_B = qA \frac{D_p}{L_p} \left( (\Delta p_E + \Delta p_C) \tanh \frac{W_b}{2L_p} \right) \]

If the collector is reverse biased, \( \Delta p_C = -p_n \)

If \( p_n \) is small, \( \Delta p_C \) can be neglected

If \( \gamma \approx 1 \), \( I_E \approx I_{E_p} \) therefore:

\[ I_{E_p} \approx qA \frac{D_p}{L_p} \Delta p_E \coth \frac{W_b}{L_p} \]

\[ I_{C_p} \approx qA \frac{D_p}{L_p} \Delta p_E \csch \frac{W_b}{L_p} \]

\[ I_B \approx qA \frac{D_p}{L_p} \Delta p_E \tanh \frac{W_b}{2L_p} \]

Hyperbolic Function Expansion:

\[ \text{sech } y = 1 - \frac{y^2}{2} + \frac{5y^4}{24} - ... \]

\[ \coth y = \frac{1}{y} + \frac{y}{3} - \frac{y^3}{45} + ... \]

\[ \text{csch } y = \frac{1}{y} - \frac{y}{6} + \frac{7y^3}{360} - ... \]

\[ \tanh y = y - \frac{y^3}{3} + ... \]

Using \( L_p = \sqrt{D_p \tau_p} \).
Emitter Injection Efficiency, Base Transport Factor, and Current Transfer Ratio

Analytical Expressions
Emitter Injection Efficiency ($\gamma < 1$)

In the case where $\gamma < 1$, we need to include $I_{En}$ in the total emitter current. Assuming the emitter region is long compared to the electron diffusion length, normal biasing, and $V_{EB} \gg kT / q$:

$$I_E = I_{Ep} + I_{En} \quad \text{using} \quad I_{En} = \frac{qAD_n^p}{L_n^p} n_p e^{qV_{EB}/kT} \quad \text{and} \quad I_{Ep} = \frac{qAD_p^n}{L_p^n} (p_n e^{qV_{EB}/kT}) \tanh \frac{W_b}{L_p^n}$$

$$I_E = qA \left[ \frac{D_p^n}{L_p^n} p_n \tanh \frac{W_b}{L_p^n} + \frac{D_n^p}{L_n^p} n_p \right] e^{qV_{EB}/kT} \quad \text{and so:}$$

$$\gamma = \frac{I_{Ep}}{I_E} = \left[ \frac{I_{Ep} + I_{En}}{I_{Ep}} \right]^{-1} = \left[ 1 + \frac{I_{En}}{I_{Ep}} \right]^{-1} = \left[ 1 + \frac{D_n^p}{L_n^p} \frac{n_p}{p_n} \tanh \frac{W_b}{L_p^n} \right]^{-1}$$

But $\frac{n_p}{p_n} = \frac{n_n}{p_p}$, $\frac{D_n^p}{D_p^n} = \frac{\mu_n^p}{\mu_p^n}$, and $\frac{D}{\mu} = \frac{kT}{q}$. Therefore:

$$\gamma = \left[ 1 + \frac{L_n^p n_n \mu_n^p}{L_p^n P_p \mu_p^n} \tanh \frac{W_b}{L_p^n} \right]^{-1} \approx \left[ 1 + \frac{W_b n_n \mu_n^p}{L_p^n P_p \mu_p^n} \right]^{-1}$$
Base Transport Factor and Current Transfer Ratio

Assuming the emitter region is long compared to the electron diffusion length, normal biasing, and $V_{EB} \gg kT / q$.

The base transport factor $B$ is:

$$
B = \frac{I_C}{I_{Ep}} = \frac{qA \frac{D_p}{L_p} \Delta p_E \text{csch} \frac{W_b}{L_p}}{\frac{D_p}{L_p} \Delta p_E \text{ctnh} \frac{W_b}{L_p}} = \frac{\text{csch} \frac{W_b}{L_p}}{\text{ctnh} \frac{W_b}{L_p}} = \text{sech} \frac{W_b}{L_p}
$$

The current transfer ratio $\alpha$ is the product of $B$ and $\gamma$:

$$
\alpha = \gamma B \equiv \left[1 + \frac{W_b n_n \mu_n}{L_p p_p \mu_p} \right]^{-1} \text{sech} \frac{W_b}{L_p}
$$

Recall Also:

$$
\beta = \frac{\alpha}{1 - \alpha}
$$
Ebers-Moll Equations
Coupled Diode Model

(a) 

(b) 

(c)
Ebers-Moll Equations

It can be shown that:

\[ I_E = I_{ES} \left( e^{\frac{qV_{EB}}{kT}} - 1 \right) - \alpha_I I_{CS} \left( e^{\frac{qV_{CB}}{kT}} - 1 \right) \]

\[ I_C = \alpha_N I_{ES} \left( e^{\frac{qV_{EB}}{kT}} - 1 \right) - I_{CS} \left( e^{\frac{qV_{CB}}{kT}} - 1 \right) \]

where

\( \alpha_N \) and \( \alpha_I \) are the normal and inverted current transfer ratios

\( I_{ES} \) and \( I_{CS} \) are the diode saturation current with the other junction shorted

Note For Example:

\[ I_{ES} \approx qA \left( \frac{D_p}{W_b} p_n + \frac{D_n^E}{L_n} n_p^E \right) \text{ for } W_b \ll L_p \]
Common Emitter Amplifier

Large Signal Model
Common-Emitter Amplifier

- Coupling capacitors on the input and output
  - Block DC, pass AC
- Emitter identified by an arrow that points in the direction of emitter **current** flow
  - pnp, arrow points into base, holes injected into base
  - npn, arrow points away from base, electrons injected into base (but current is in the opposite direction)
For the common-emitter amplifier, input is applied to the base and taken from the collector.

\[ I_E = I_B + I_C \]
Common-Emitter Input Characteristic

• Transistor biased in normal mode:
  – Collector and base currents independent of the reverse bias voltage across the collector junction

• Operating point determined using load line

Ideal Diode Equation:

\[ I_C = \beta I_B \approx I_{ES} \left( e^{qV_{EB}/kT} - 1 \right) \]

where

\[ I_{ES} = qA \left( \frac{D_p}{W_b} p_n + \frac{D_n^E}{L_n} n_p^E \right) \]

so:

\[ I_B \approx \frac{I_{ES}}{\beta} \left( e^{qV_{EB}/kT} - 1 \right) \]

Since \( V_{EB} \) is small, \( I_B \approx \frac{V_{BB}}{R_B} = \frac{5V}{50k\Omega} = 0.10 \text{ mA} \)

Loop Analysis on Input Loop:

\[ V_{BB} = V_{EB} + I_B R_B \]

so:

\[ I_B = \frac{V_{BB} - V_{EB}}{R_B} \]
Common-Emitter Output Characteristic

- $I_C$ is plotted as a function of $V_{EC}$ for increasing base current $I_B$
- The collector load line is plotted to determine operating points
- Except for $V_{EC} \approx 1V$, $I_C = \beta I_B$
  - As $V_{EC}$ approaches 0, $V_{CB}$ approaches $V_{EB}$ and reverse bias on the collector is lost and $I_C$ falls toward zero
- Positioning the operating point midway on the family of curves helps to preserve normal mode operation over a larger range

$$V_{EC} = V_{EB} + V_{BC}$$
$$= V_{EB} - V_{CB}$$

**Load Line:**

$$I_C R_C - V_{CC} + V_{EC} = 0$$

so

$$I_C = \frac{V_{CC} - V_{EC}}{R_C}$$
Small Signal Current Gain
Common-Emitter AC Equivalent Circuit

- AC equivalent circuit model treats coupling capacitor and DC voltage source as short circuits.
- A positive voltage applied to the input $v_{in}$ opposes the bias voltage (output phase shift).
- Junction resistance $r_{\pi}$ is differential resistance of forward-biased junction.
Differential conductance for small AC signal $v_{in} < kT / q \approx 26mV$:

$$\frac{1}{r_{\pi}} = \frac{dI_B}{dV_{EB}} \approx \frac{q}{kT} I_B$$

so, an input voltage $v_{in}$ produces a small AC modulation on the base current:

$$i_B = -\frac{v_{in}}{r_{\pi}}$$

For the example in the handout: $r_{\pi} = \frac{kT / q}{I_B} \approx \frac{0.026V}{0.1mA} \approx 260\Omega$

Why “−”??
Why “-”? 

\[ i_B = -\frac{v_{in}}{r_{\pi}} \]
Input Impedance $r_{\pi}$

Input Characteristic

$I_B \approx \frac{I_{ES}}{\beta} \left( e^{\frac{qV_{EB}}{kT}} - 1 \right)$

$(V_{CB} \leq 0)$

$I_B (mA)$

$V_{BB} \div R_B = 0.10$

$V_0 \sim 0.8 \text{ V}$

$V_{BB} = 5.0 \text{ V}$

$V_{EB}$
For this input current $i_B$, the resultant AC component of the collector current is:

$$i_C = \beta i_B = -\beta \frac{v_{in}}{r_\pi}$$

For the simplified case of no load resistance, the output voltage is therefore:

$$v_{out} = i_C R_C = -\beta \frac{R_C}{r_\pi} v_{in}$$

The **open-circuit voltage gain** is therefore:

$$\frac{v_{out}}{v_{in}} = -\beta \frac{R_C}{r_\pi} \approx -100 \times \frac{500\Omega}{260\Omega} \approx -192$$
For an $I_B$ swing of $\pm 0.05$ mA, there is an $I_C$ swing of $\pm 5$ mA
Exam II Statistics

• Average (All Sections): 61.85
• Standard Deviation (All Sections): 14.18
Assignments
Assignments

• Homework assigned every Friday, due following Friday

• Reading from Streetman’s book:
  – Mon 4/16: §'s 6.5.1, 6.5.2
  – Wed 4/18: §'s 6.5.8, 9.3.1, 9.5.1
  – Fri 4/20: Handout on BJT (Posted on Website)
  – Mon 4/23: §'s 6.1.1, 6.1.2, 7.1, 7.2, 7.3, and handout
  – Wed 4/25: §'s 7.3, 7.4.1, 7.4.2, 7.4.3, 7.4.4, and handout
  – Fri 4/27: §'s 7.3, 7.4.1, 7.4.2, 7.4.3, 7.4.4, and handout
  – Mon 4/30: §'s 7.4.1, 7.4.2, 7.4.3, 7.4.4, and handout

• Chapters 16, 17, 18, 10, 11, and 12 in Pierret cover similar material
Topics for Next Lecture
• Continue BJT
Thank You for Listening!
Instructional Objectives (1)

By the time of exam No. 1 (after 17 lectures), the students should be able to do the following:
1. Outline the classification of solids as metals, semiconductors, and insulators and distinguish direct and indirect semiconductors.
2. Determine relative magnitudes of the effective mass of electrons and holes from an E(k) diagram.
3. Calculate the carrier concentration in intrinsic semiconductors.
4. Apply the Fermi-Dirac distribution function to determine the occupation of electron and hole states in a semiconductor.
5. Calculate the electron and hole concentrations if the Fermi level is given; determine the Fermi level in a semiconductor if the carrier concentration is given.
6. Determine the variation of electron and hole mobility in a semiconductor with temperature, impurity concentration, and electrical field.
7. Apply the concept of compensation and space charge neutrality to calculate the electron and hole concentrations in compensated semiconductor samples.
8. Determine the current density and resistivity from given carrier densities and mobilities.
9. Calculate the recombination characteristics and excess carrier concentrations as a function of time for both low level and high level injection conditions in a semiconductor.
10. Use quasi-Fermi levels to calculate the non-equilibrium concentrations of electrons and holes in a semiconductor under uniform photoexcitation.
11. Calculate the drift and diffusion components of electron and hole currents.
12. Calculate the diffusion coefficients from given values of carrier mobility through the Einstein’s relationship and determine the built-in field in a non-uniformly doped sample.
Instructional Objectives (2)

By the time of Exam No.2 (after 32 lectures), the students should be able to do all of the items listed under A, plus the following:

13. Calculate the contact potential of a p-n junction.
14. Estimate the actual carrier concentration in the depletion region of a p-n junction in equilibrium.
15. Calculate the maximum electrical field in a p-n junction in equilibrium.
16. Distinguish between the current conduction mechanisms in forward and reverse biased diodes.
17. Calculate the minority and majority carrier currents in a forward or reverse biased p-n junction diode.
18. Predict the breakdown voltage of a p+-n junction and distinguish whether it is due to avalanche breakdown or Zener tunneling.
19. Calculate the charge storage delay time in switching p-n junction diodes.
20. Calculate the capacitance of a reverse biased p-n junction diode.
21. Calculate the capacitance of a forward biased p-n junction diode.
22. Predict whether a metal-semiconductor contact will be a rectifying contact or an ohmic contact based on the metal work function and the semiconductor electron affinity and doping.
23. Calculate the electrical field and potential drop across the neutral regions of wide base, forward biased p+-n junction diode.
24. Calculate the voltage drop across the quasi-neutral base of a forward biased narrow base p+-n junction diode.
25. Calculate the excess carrier concentrations at the boundaries between the space-charge region and the neutral n- and p-type regions of a p-n junction for either forward or reverse bias.
Instructional Objectives (3)

By the time of the Final Exam, after 44 class periods, the students should be able to do all of the items listed under A and B, plus the following:

26. Calculate the terminal parameters of a BJT in terms of the material properties and device structure.
27. Estimate the base transport factor “B” of a BJT and rank-order the internal currents which limit the gain of the transistor.
28. Determine the rank order of the electrical fields in the different regions of a BJT in forward active bias.
29. Calculate the threshold voltage of an ideal MOS capacitor.
30. Predict the C-V characteristics of an MOS capacitor.
31. Calculate the inversion charge in an MOS capacitor as a function of gate and drain bias voltage.
32. Estimate the drain current of an MOS transistor above threshold for low drain voltage.
33. Estimate the drain current of an MOS transistor at pinch-off.
34. Distinguish whether a MOSFET with a particular structure will operate as an enhancement or depletion mode device.
35. Determine the short-circuit current and open-circuit voltage for an illuminated p/n junction solar cell.
Course Purpose & Objectives

- Introduce key concepts in semiconductor materials
- Provide a basic understanding of p-n junctions
- Provide a basic understanding of light-emitting diodes and photodetectors
- Provide a basic understanding of field effect transistors
- Provide a basic understanding of bipolar junction transistors
## Tentative Schedule [1]

<table>
<thead>
<tr>
<th>JAN 17</th>
<th>JAN 19</th>
</tr>
</thead>
<tbody>
<tr>
<td>Course overview</td>
<td>Intro to semiconductor electronics</td>
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</table>

<table>
<thead>
<tr>
<th>JAN 22</th>
<th>JAN 24</th>
<th>JAN 26</th>
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<tbody>
<tr>
<td>Materials and crystal structures</td>
<td>Bonding forces and energy bands in solids</td>
<td>Metals, semiconductors, insulators, electrons, holes</td>
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<table>
<thead>
<tr>
<th>JAN 29</th>
<th>JAN 31</th>
<th>FEB 2</th>
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<tbody>
<tr>
<td>Intrinsic and extrinsic material</td>
<td>Distribution functions and carrier concentrations</td>
<td>Distribution functions and carrier concentrations</td>
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<table>
<thead>
<tr>
<th>FEB 5</th>
<th>FEB 7</th>
<th>FEB 9</th>
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</thead>
<tbody>
<tr>
<td>Temperature dependence, compensation</td>
<td>Conductivity and mobility</td>
<td>Resistance, temperature, impurity concentration</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>FEB 12</th>
<th>FEB 14</th>
<th>FEB 16</th>
</tr>
</thead>
<tbody>
<tr>
<td>Invariance of Fermi level at equilibrium</td>
<td>Optical absorption and luminescence</td>
<td>Generation and recombination</td>
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</table>

**Subject to Change**
<table>
<thead>
<tr>
<th>Date</th>
<th>Topic</th>
<th>Date</th>
<th>Topic</th>
<th>Date</th>
<th>Topic</th>
</tr>
</thead>
<tbody>
<tr>
<td>FEB 19</td>
<td>Quasi-Fermi levels and photoconductive devices</td>
<td>FEB 21</td>
<td>Carrier diffusion</td>
<td>FEB 23</td>
<td>Built-in fields, diffusion and recombination</td>
</tr>
<tr>
<td>Feb 26</td>
<td>Review, discussion, problems (2/27 exam)</td>
<td>FEB 28</td>
<td>Steady state carrier injection, diffusion length</td>
<td>MAR 2</td>
<td>p-n junctions in equilibrium &amp; contact potential</td>
</tr>
<tr>
<td>MAR 5</td>
<td>p-n junction Fermi levels and space charge</td>
<td>MAR 7</td>
<td>Continue p-n junction space charge</td>
<td>MAR 9</td>
<td>NO CLASS (EOH)</td>
</tr>
<tr>
<td>MAR 12</td>
<td>p-n junction current flow</td>
<td>MAR 14</td>
<td>Carrier injection and the diode equation</td>
<td>MAR 16</td>
<td>Minority and majority carrier currents</td>
</tr>
<tr>
<td>3/19-3/23 Spring Break</td>
<td>Reverse-bias breakdown</td>
<td>MAR 28</td>
<td>Stored charge, diffusion and junction capacitance</td>
<td>MAR 30</td>
<td>Photodiodes, I-V under illumination</td>
</tr>
</tbody>
</table>

**Subject to Change**
Schedule & Policies
Important Information

• Course Website:
  – [http://courses.engr.illinois.edu/ece340/](http://courses.engr.illinois.edu/ece340/)

• Download and Review Syllabus / Course Information from Website!

• Course Coordinator: Prof. John Dallesasse
  – [jdallesa@illinois.edu](mailto:jdallesa@illinois.edu)
  – Coordinates schedule, policies, absence issues, homework, quizzes, exams, etc.

• Contact Information and Office Hours for All ECE340 Professors & TAs in Syllabus

• Lecture Slides: Click on “(Sec. X)” next to my name in instructor list

• DRES Students: Contact Prof. Dallesasse ASAP

• Textbook:
  – Additional reference texts listed in syllabus
Key Points

• Attend Class!
  – 3 unannounced quizzes, each worth 5% of your grade
  – You must take the quiz in your section
  – Excused absences must be pre-arranged with the course director
  – Absences for illness, etc. need a note from the Dean
    • See policy on absences in the syllabus

• No Late Homework
  – Homework due on the date of an excused absence must be turned in ahead of time
  – You must turn in homework in your section
  – No excused absences for homework assignments
  – Top 10 of 11 homework assignments used in calculation of course grade
    • Do all of them to best prepare for the exams!

• No Cheating
  – Penalties are severe and will be enforced

• Turn Off Your Phone
  – No video recording, audio recording, or photography
Homework

• Assigned Friday, Due Following Friday
  – Due dates shown in syllabus
• Due at Start of Class
• Follow Guidelines in Syllabus
• Peer Discussions Related to Homework are Acceptable and Encouraged
• Directly Copying Someone Else’s Homework is Not Acceptable
  – Graders have been instructed to watch for evidence of plagiarism
  – Both parties will receive a “0” on the problem or assignment
Absences

• The absence policy in the syllabus will be strictly enforced
• To receive an excused absence (quiz), you must:
  – Pre-arrange the absence with the course director (valid reason and proof required)
  – Complete an Excused Absence Form at the Undergraduate College Office, Room 207 Engineering Hall (333-0050)
    • The form must be signed by a physician, medical official, or the Emergency Dean (Office of the Dean of Students)
    • The Dean’s Office has recently put a strict policy in place (3 documented days of illness)
  – Excused quiz score will be prorated based upon average of completed scores
  – No excused absences are given for homework, but only the best 10 of 11 are used to calculate your final grade
  – Excused absences are not given for exams, except in accordance with the UIUC Student Code
    – Unexcused work will receive a “0”
• Failure to take the final will result in an “incomplete” grade (if excused) or a “0” (if unexcused)
Exams

• Exam I: Tuesday February 27\textsuperscript{th}, 7:30-8:30 pm
• Exam II: Thursday April 12\textsuperscript{th}, 7:30-8:30 pm
• Final Exam: Date/Time To Be Announced
  – Determined by University F&S
## Grading

<table>
<thead>
<tr>
<th>Grading Criterion</th>
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<tbody>
<tr>
<td>Homework</td>
<td>10 %</td>
</tr>
<tr>
<td>Quizzes</td>
<td>15 %</td>
</tr>
<tr>
<td>Hour Exam I</td>
<td>20 %</td>
</tr>
<tr>
<td>Hour Exam II</td>
<td>20 %</td>
</tr>
<tr>
<td>Final Exam</td>
<td>35 %</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>100 %</strong></td>
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</table>

### Historical Grade Trends*

<table>
<thead>
<tr>
<th></th>
<th>Spring 2016</th>
<th>Fall 2016</th>
<th>Spring 2017</th>
</tr>
</thead>
<tbody>
<tr>
<td>A’s</td>
<td>27 %</td>
<td>28 %</td>
<td>27 %</td>
</tr>
<tr>
<td>B’s</td>
<td>37 %</td>
<td>26 %</td>
<td>38 %</td>
</tr>
<tr>
<td>C’s</td>
<td>27 %</td>
<td>25 %</td>
<td>27 %</td>
</tr>
<tr>
<td>D’s</td>
<td>6 %</td>
<td>16 %</td>
<td>4 %</td>
</tr>
<tr>
<td>F’s</td>
<td>3 %</td>
<td>5 %</td>
<td>4 %</td>
</tr>
</tbody>
</table>

*Past performance is not necessarily indicative of future results
My Recommendations

• Read the syllabus and information posted on the course website
• **Attend class** & participate
• Attend office hours (TA and Professors)
• **Read the book**
• Re-read the book
• Look at and read selected portions of the supplemental texts
• Form study groups to review concepts and discuss high-level approaches for solving homework problems
  – Don’t form study groups to copy homework solutions
• **Don’t miss any homework, quizzes, or exams**
  • It’s hard to overcome a zero
• Ask questions in class!
Instructional Objectives (1)

By the time of exam No. 1 (after 17 lectures), the students should be able to do the following:

✔ 1. Outline the classification of solids as metals, semiconductors, and insulators and distinguish direct and indirect semiconductors.

✔ 2. Determine relative magnitudes of the effective mass of electrons and holes from an E(k) diagram.

✔ 3. Calculate the carrier concentration in intrinsic semiconductors.

✔ 4. Apply the Fermi-Dirac distribution function to determine the occupation of electron and hole states in a semiconductor.

✔ 5. Calculate the electron and hole concentrations if the Fermi level is given; determine the Fermi level in a semiconductor if the carrier concentration is given.

✔ 6. Determine the variation of electron and hole mobility in a semiconductor with temperature, impurity concentration, and electrical field.

✔ 7. Apply the concept of compensation and space charge neutrality to calculate the electron and hole concentrations in compensated semiconductor samples.

✔ 8. Determine the current density and resistivity from given carrier densities and mobilities.

✔ 9. Calculate the recombination characteristics and excess carrier concentrations as a function of time for both low level and high level injection conditions in a semiconductor.

✔ 10. Use quasi-Fermi levels to calculate the non-equilibrium concentrations of electrons and holes in a semiconductor under uniform photoexcitation.

✔ 11. Calculate the drift and diffusion components of electron and hole currents.

✔ 12. Calculate the diffusion coefficients from given values of carrier mobility through the Einstein’s relationship and determine the built-in field in a non-uniformly doped sample.

Plus continuity equation, steady-state carrier injection, and diffusion length

https://my.ece.illinois.edu/courses.description.asp?ECE340
Quiz 1 Statistics

- Average: 8.65
- Standard Deviation: 1.49
Quiz 2 Statistics

- Average: 4.59
- Standard Deviation: 1.86
Exam I Statistics

- Average (All Sections): 71.88
- Standard Deviation (All Sections): 15.44
Streetman Errata (6th Edition)

• Equation 4-30: “ΔxA” not δxA
• Equation 4-33b: “τ_p” not “τ_n”
Streetman Errata

• Equation 6-35 in Streetman’s “Solid State Electronic Devices” 6th edition has a typo:

  Equation in Streetman:

  \[ C_i = \frac{\varepsilon_s}{W} \]

  Corrected Version:

  \[ C_d = \frac{\varepsilon_s}{W} \]