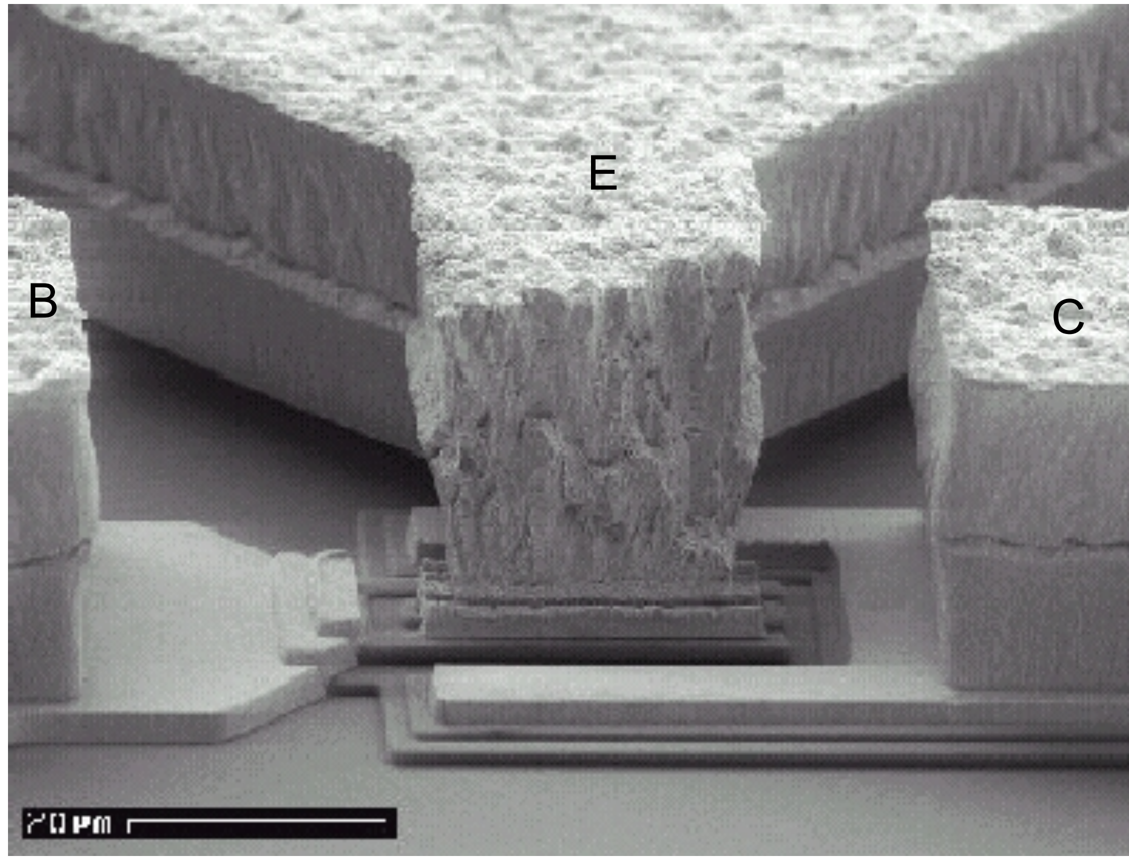
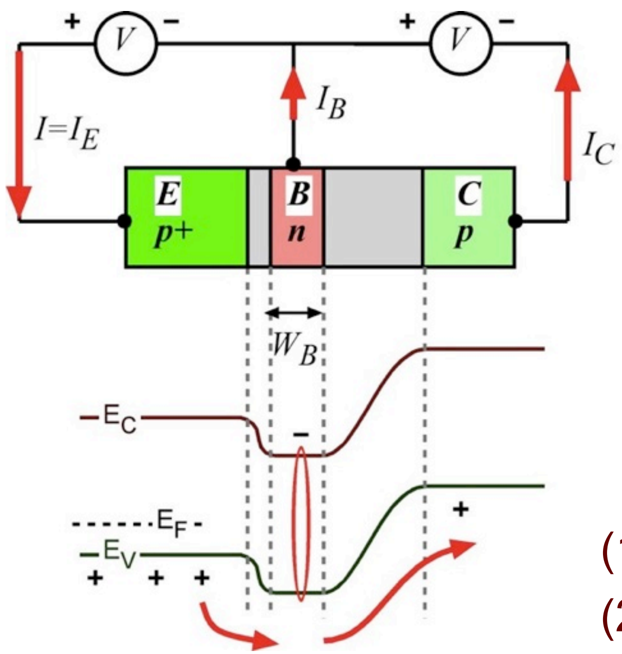
7.4, 7.9 – Currents in the BJT, HBTs

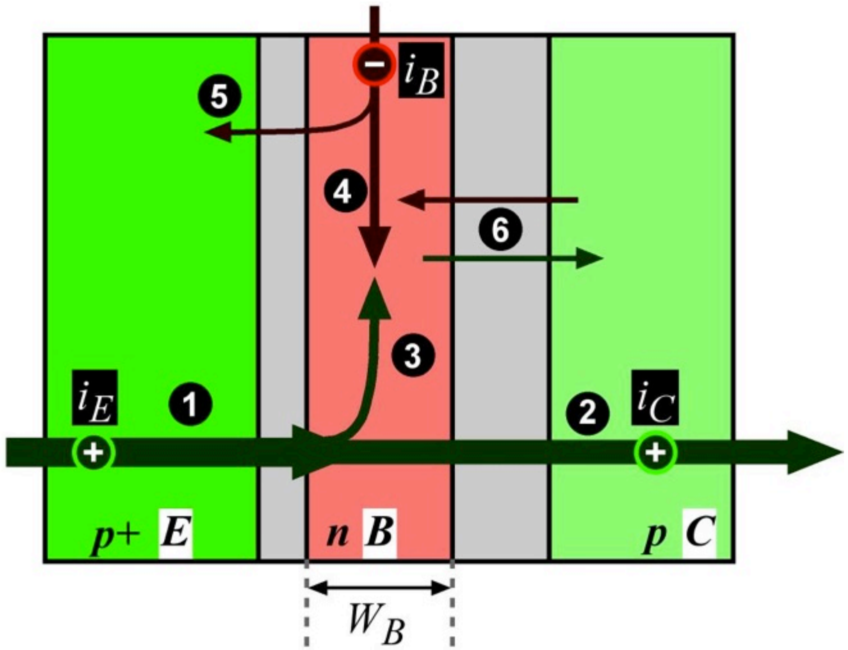


HBT fabrication more complicated than slapping together p+np materials…

What is different than CMOS here? Think **R=ρL/A (Ω)**

- Review this slide, and everything must make sense, else go back and review part A of the previous lecture!



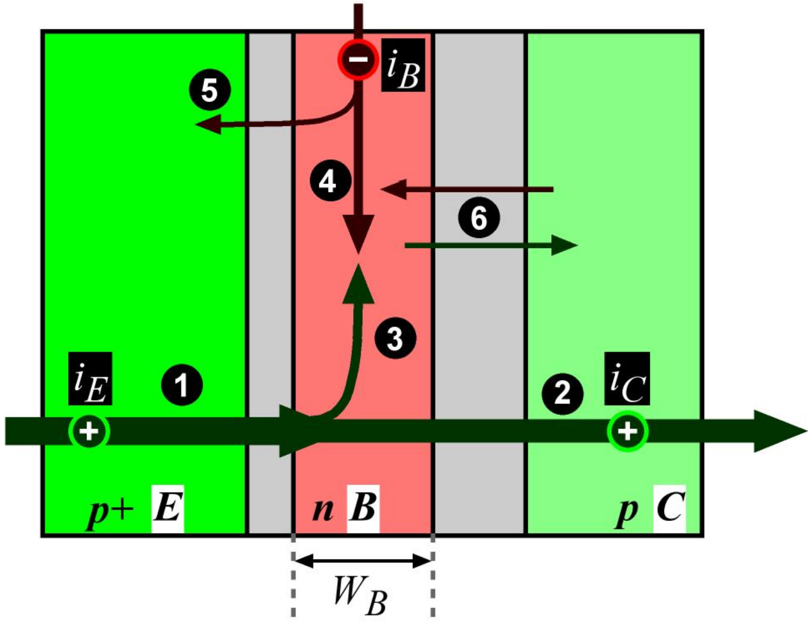


Emitter (inject holes)
Base (historical, Ge slab)
Collector (collect holes)
$I=I_E=I_B+I_C$

(1)	Holes injected do what?	**diffuse** across EB
(2)	Holes reach BC and do what?	**drift** to C
(3)	Holes injected do what?	**recombine** with B electrons
(4)	Electrons injected do what?	**recombine** with B holes
(5)	Electrons injected do what?	**diffuse** across EB
(6)	Reverse bias e or h do what?	**drift** across BC (small)

Remember: p+n for EB so (1) >> (5), $W_b << L_p$ so (2) >> (3), but (3)≠0

- Goal today, calculate currents for the BJT



- Key Assumptions…

Holes <u>diffuse</u> from emitter to collector, drift is negligible (no *E-field* in B).

$\gamma=1$ … (i_E is all holes).

No collector reverse saturation current (6).

EB and BC junctions have the same area in one dimension (i.e. all horiz. current in diagram…).

All current and voltages steady state.

Things will get VERY complicated, but hang on, I promise I will make them VERY simple in the end!

- Recall minority currents in a p+n junction (part of our p+np BJT).

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

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

- Review,

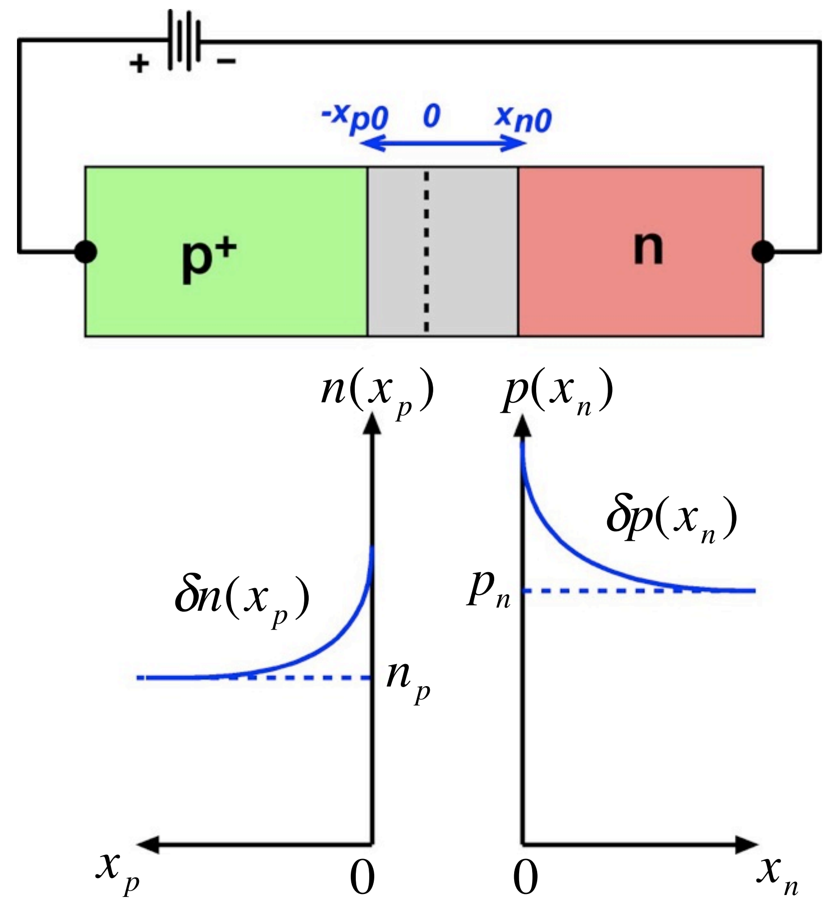
The diagram at right is if V is positive…

If V=0 it will look like what?

If V is negative, will look like what?

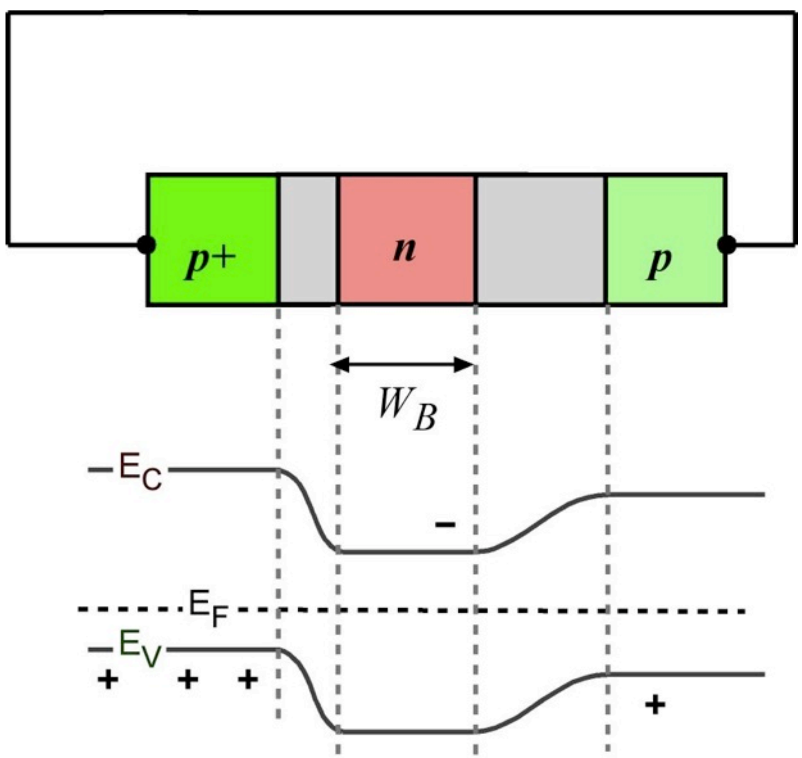
The equation above predicts the answer! See the drawing I do at right during the video.

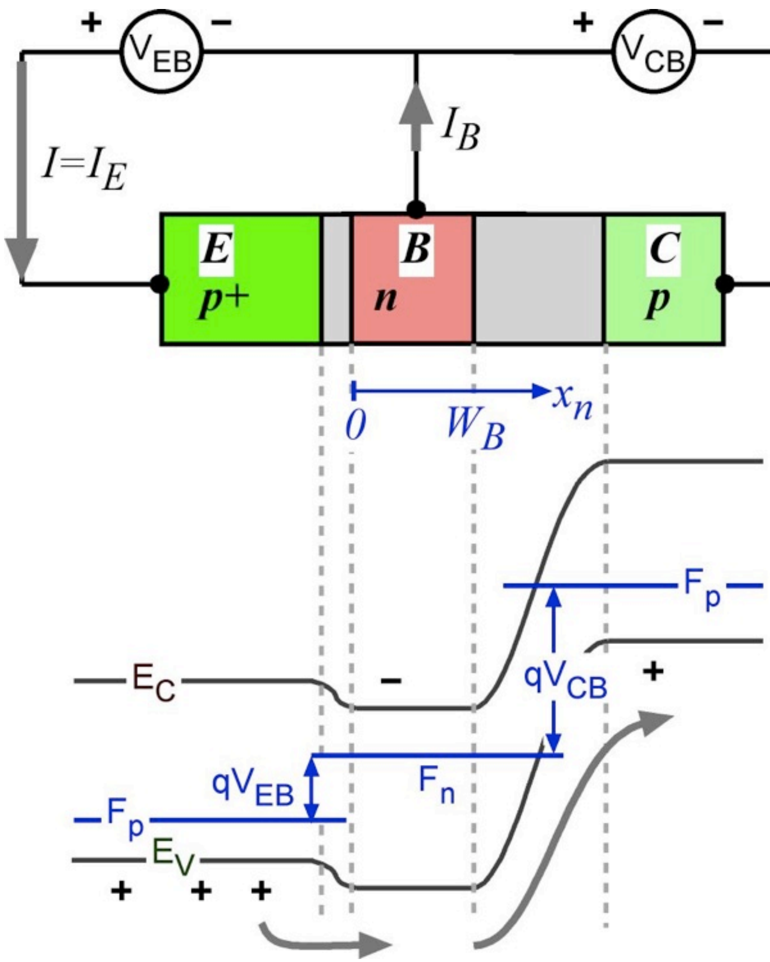
- Forward bias, diff dominates…



note above is a logarithmic scale…

- Note Fermi Levels shifts as voltage is applied…





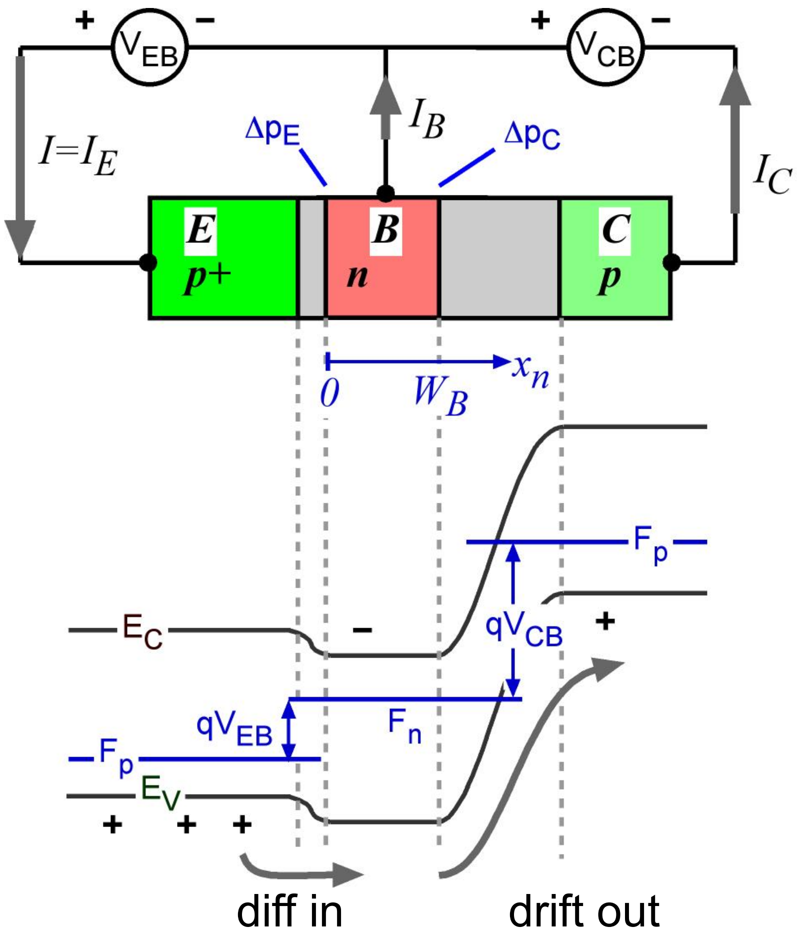
☆ Based on what we learned for the previous slide, where in the base, for the diagram at right should we see an excess of holes, or no (zero) holes at all?

- Apply the previous approach **to both** EB and BC junctions to get excess hole concentration at base edges:

$$\Delta p_E = p_n\left(e^{qV_{EB}/kT} - 1\right)$$

$$\Delta p_C = p_n\left(e^{qV_{CB}/kT} - 1\right)$$

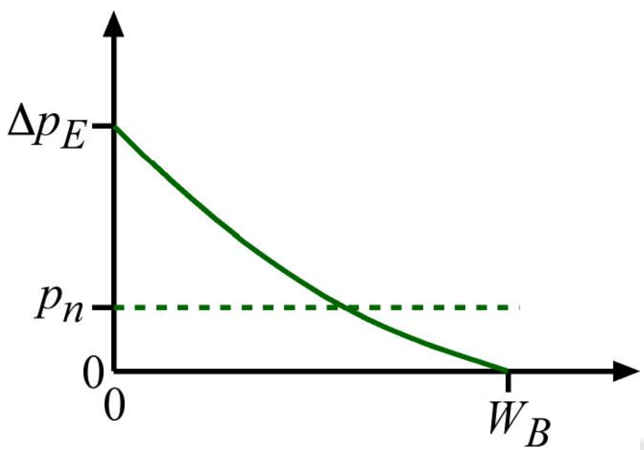
labeled at right



- Under normal conditions we can simplify these equations to the following, why? Answer based on equations and the diagram……

$$\Delta p_E \approx p_n e^{qV_{EB}/kT}$$

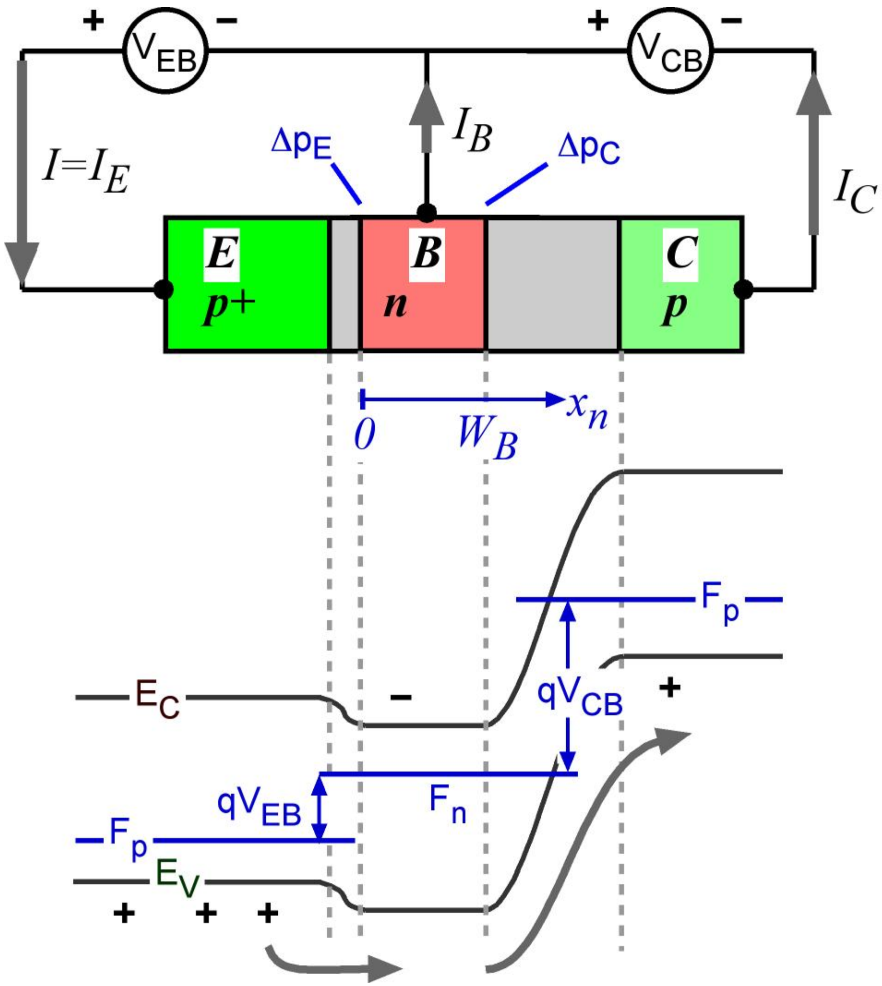
$$\Delta p_C \approx -p_n$$

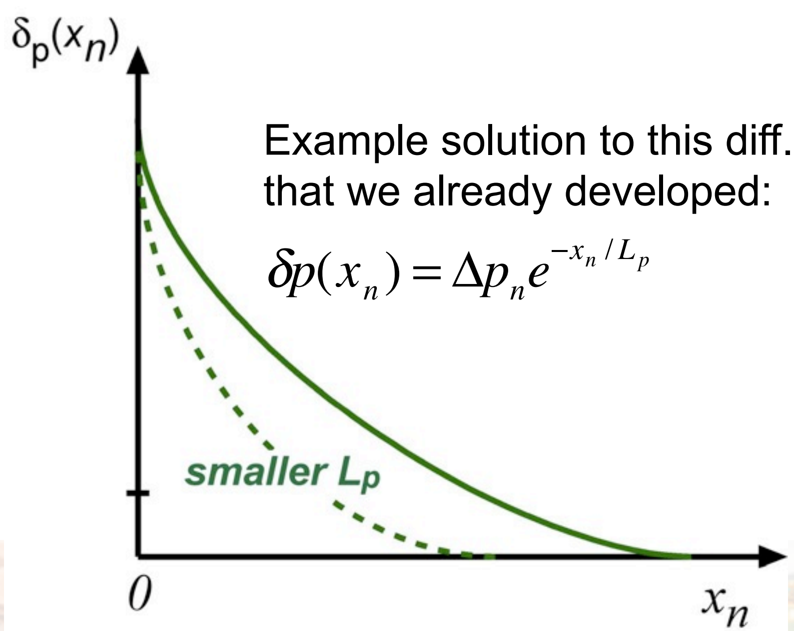


- Apply diffusion equation in ☆ the base… why?

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

general meaning of diffusion equation: smaller Lp, or larger Δp, results in more curvature (rate of change in slope, of the change in charge)…





Example solution to this diff. eq. that we already developed:

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

- How to solve a differential equation: ☆

(1) Here is the equation

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

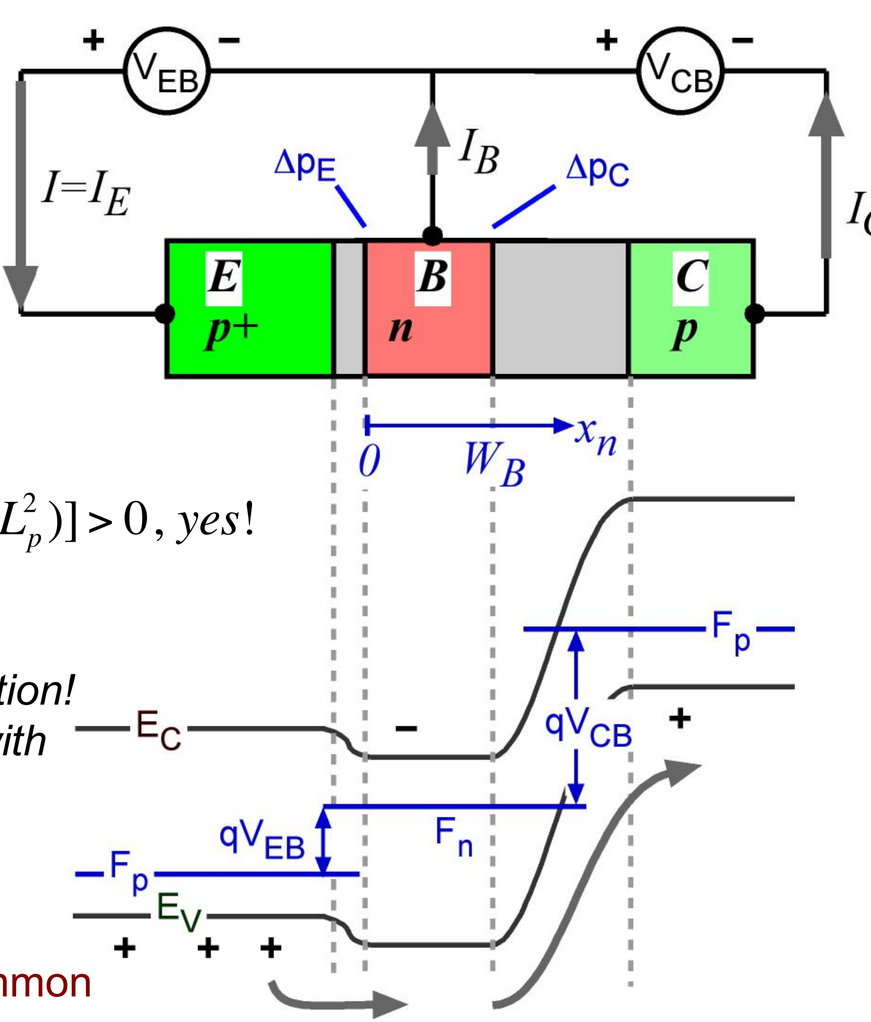
(2) Put derivatives in rank order

$$\frac{d^2\delta p(x_n)}{dx_n^2} - \frac{\delta p(x_n)}{L_p^2} + 0 = 0$$

(3) Look up online or in a math book what type of diff. equation it is.

$$y'' + ay' + by = 0$$

$$[a^2 - 4b] > 0\,? \Rightarrow [0^2 - 4(-1/L_p^2)] > 0,\ yes!$$



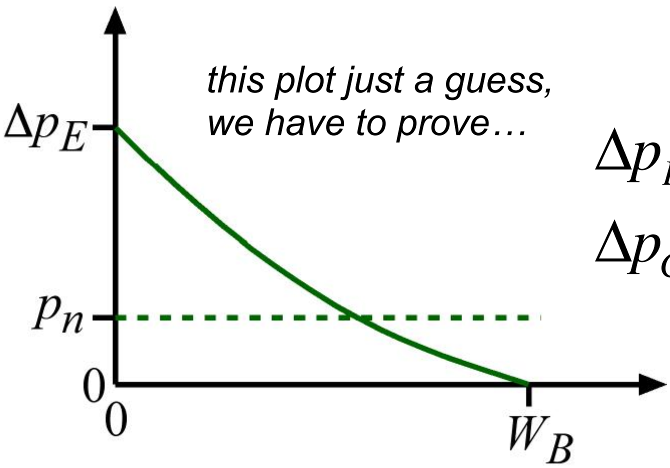
The book (Kreyszig, 2.2) tells you the general solution! Is a 2nd order homogeneous differential equation with constant coefficients and two real roots :

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

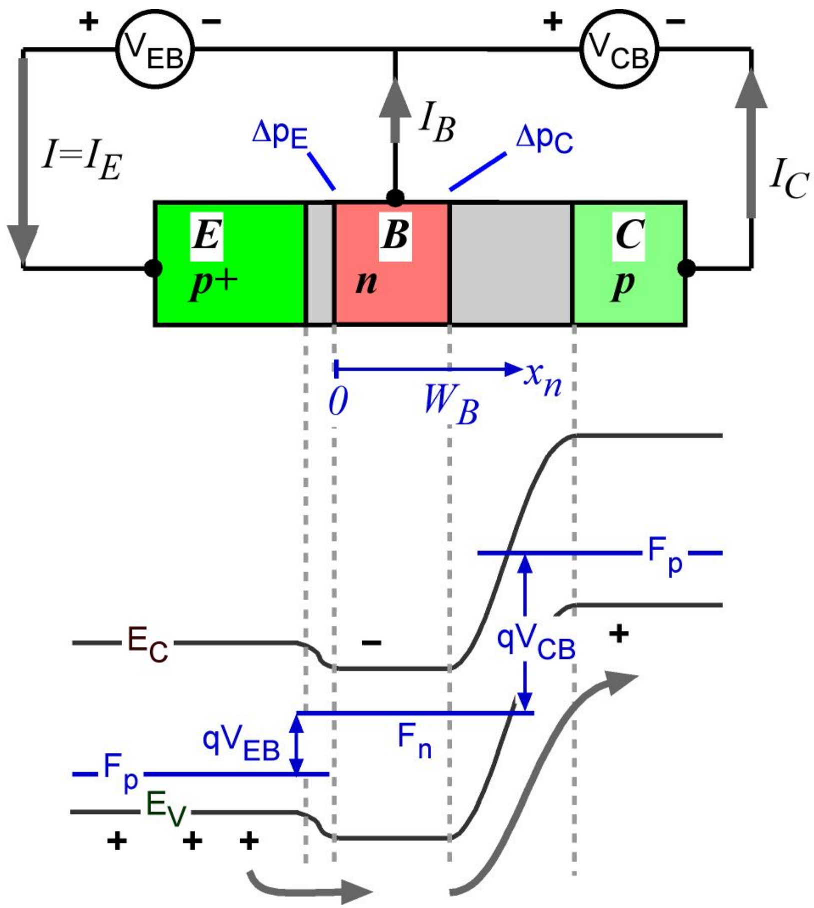
(4) Last step, apply boundary conditions (a.k.a. common sense) to solve for unknowns in the general solution.

In Chapter 4 we assumed one of the constants (C_1) was zero since excess holes disappeared at long distance (x) into n-type slab. Common sense! Hole concentration can't go to infinity!

But… we cannot do that here since $W_b \ll L_p$… Hmm… next slide!



$$\Delta p_E \approx p_n e^{qV_{EB}/kT}$$
$$\Delta p_C \approx -p_n$$



- Lets apply boundary conditions (this is easy!).

We know concentrations at edges (see above) and we have this equation now:

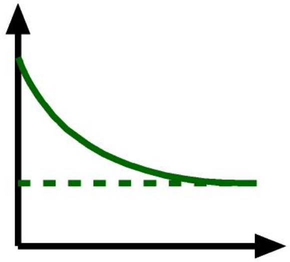
$$\delta p(x_n) = C_1 e^{x_n/L_p} + C_2 e^{-x_n/L_p}$$
$$\delta p(x_n = 0) = C_1 + C_2 = \Delta p_E$$
$$\delta p(x_n = W_b) = C_1 e^{W_b/L_p} + C_2 e^{-W_b/L_p} = \Delta p_C$$

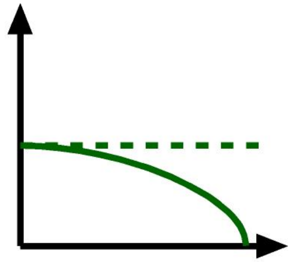
- For most differential equations, you would be done now… but for BJTs is more complex…
- 2 Eq. and 2 Variables, ICBST solving for C_1, C_2 we get:

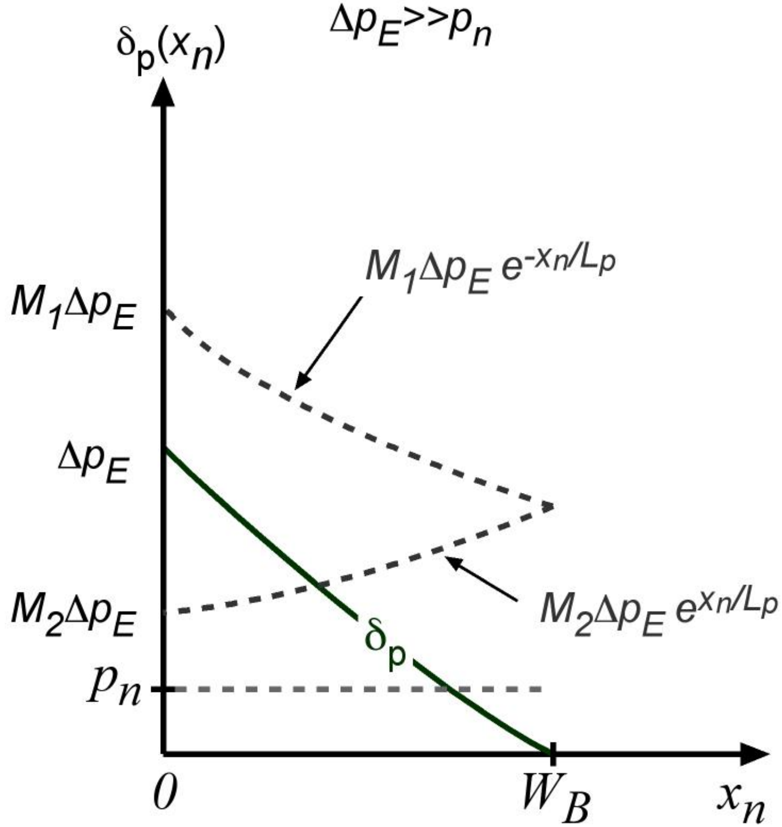
$$C_1 = \frac{\Delta p_C - \Delta p_E e^{-W_b/L_p}}{e^{W_b/L_p} - e^{-W_b/L_p}} \qquad C_2 = \frac{\Delta p_E e^{W_b/L_p} - \Delta p_C}{e^{W_b/L_p} - e^{-W_b/L_p}}$$

- Substitute newly found C_1, C_2 back in to: $$\delta p(x_n) = C_1 e^{x_n/L_p} + C_2 e^{-x_n/L_p}$$

- The two parts of the equation add up to a ~linear (nearly) hole distribution in base region:

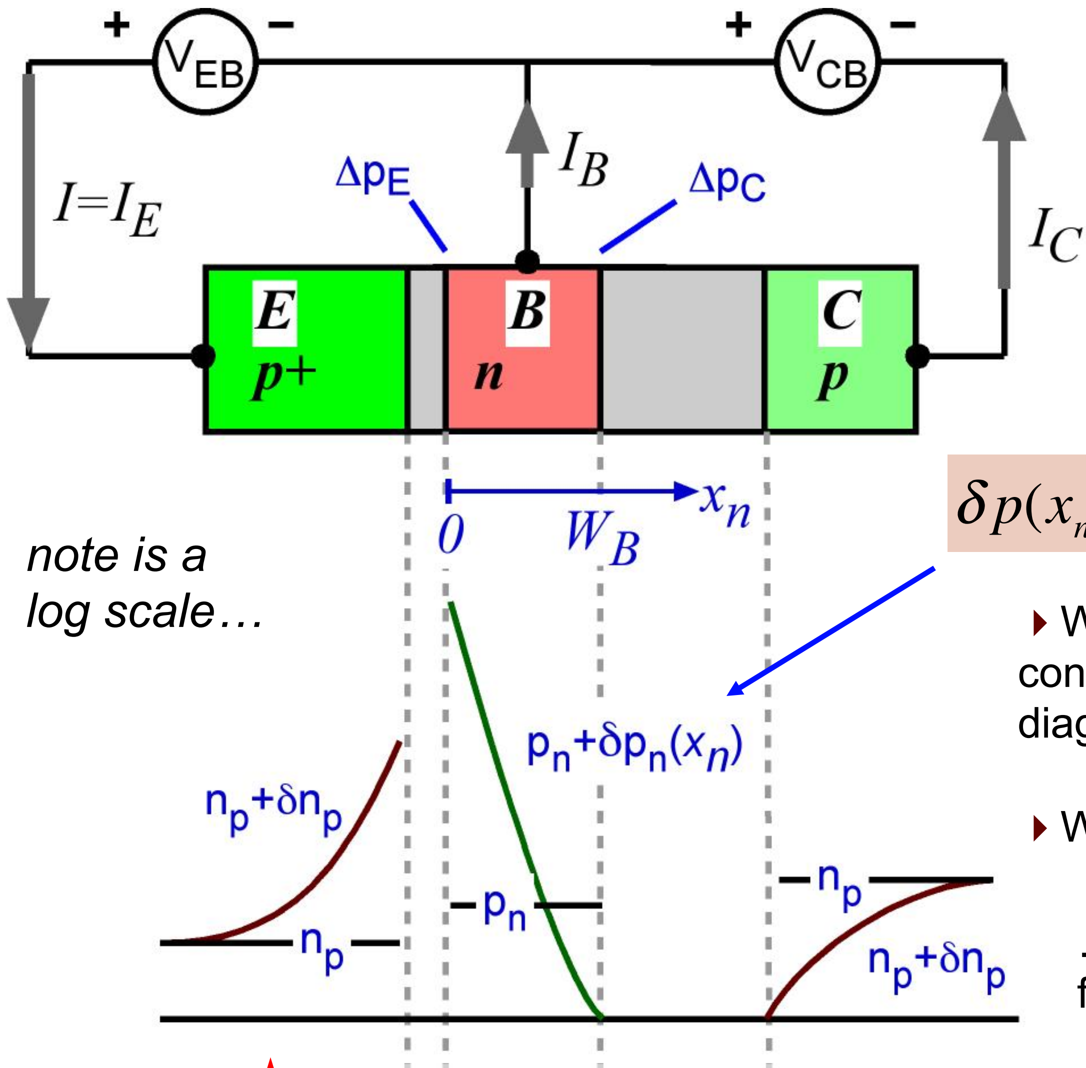






$$\delta p(x_n) = M_1 \Delta p_E e^{-x_n/L_p} - M_2 \Delta p_E e^{x_n/L_p}$$

$$M_1 = \frac{e^{W_b/L_p}}{e^{W_b/L_p} - e^{-W_b/L_p}} \qquad M_2 = \frac{e^{-W_b/L_p}}{e^{W_b/L_p} - e^{-W_b/L_p}}$$



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

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

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

- What causes each change in concentration of carriers? See below diagram…
- Why don't we show excess holes in C?

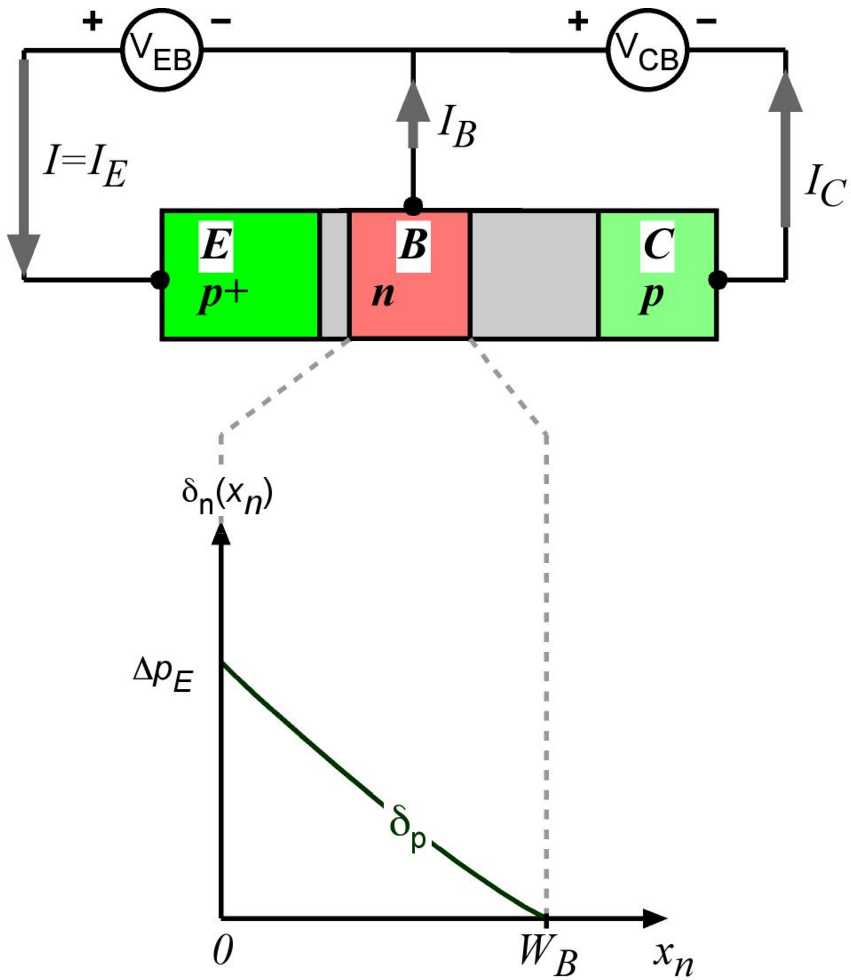
… because these are *minority carriers* for each region.

- Looks like two diodes! One forward bias, one reverse, and then with profiles joined at the base!

☆ *diffusion (PN forward)*

diffusion (base)

drift (PN reverse)



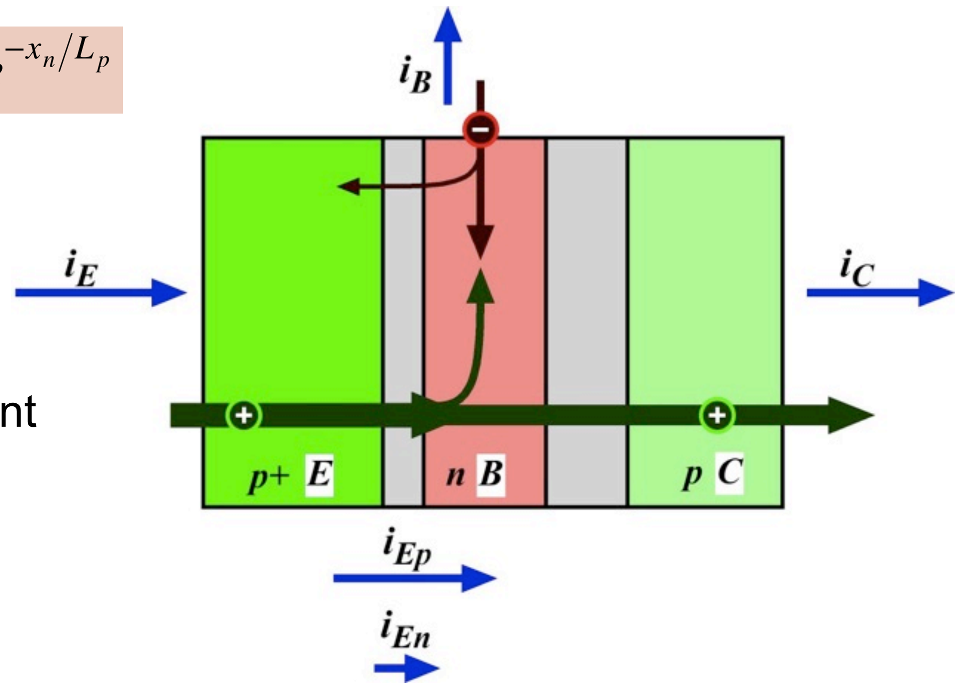
- We know at x_n=0 we have all I_{Ep} (we assumed γ=1)
- We know at x_n=W_b we have all I_C
- We now have an equation (δ_p) for hole density at each of these edges
- **We can then solve for I_{Ep} and I_C** using Eq. 4-22 from Ch. 4,

$$I_p(x_n) = -qAD_p \frac{d\delta p(x_n)}{dx_n}$$

- What is this equation and what does it tell us?

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

$$I_p(x_n) = -qAD_p \frac{d\delta p(x_n)}{dx_n}$$



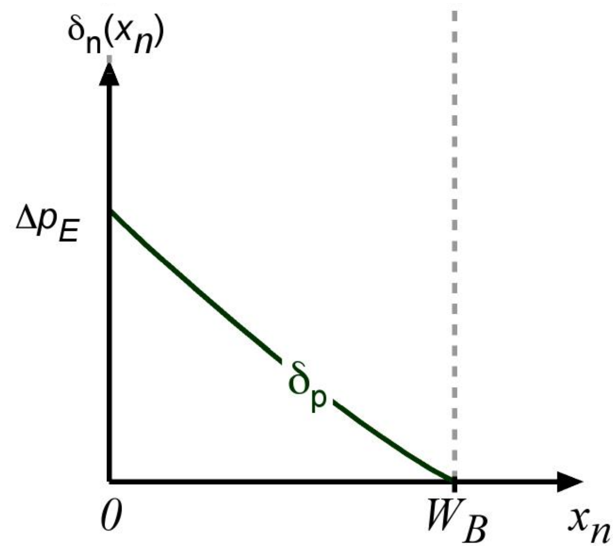
- We assumed γ=1, so at ***x_n=0*** our I_{Ep} current is equal to:

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

- We know at ***x_n=W_b*** our I_C current is equal to:

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

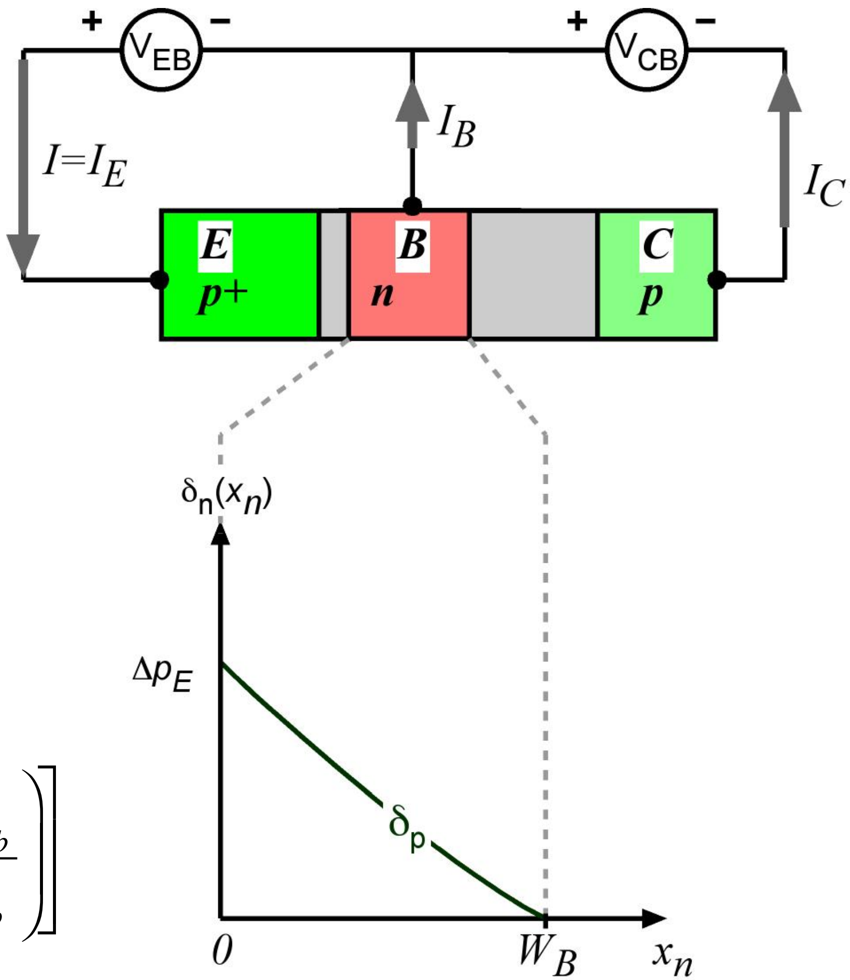
- So like before, we can solve for C_1 and C_2 with 2 eq. and 2 variables (but lets skip the math, you'll see why).



- Solving for C_1 and C_2 (skip this fun math) we can obtain:

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

$$I_C = qA\frac{D_p}{L_p}\left(\Delta p_E \ \mathbf{csch}\frac{W_b}{L_p} - \Delta p_C \ \mathbf{ctnh}\frac{W_b}{L_p}\right)$$



- But how will I get I_B? Is easy… think networks.

$$I_B = I_{Ep} - I_C$$

$$= qA\frac{D_p}{L_p}\left[(\Delta p_E + \Delta p_C)\left(\mathbf{ctnh}\frac{W_b}{L_p} - \ \mathbf{csch}\frac{W_b}{L_p}\right)\right]$$

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

That's it, here are the equations to predict currents for each terminal of a BJT! Hang on… in next lecture I will make them elegantly simple for you!

- How do you solve a differential equation? (Just tell me the four general steps).

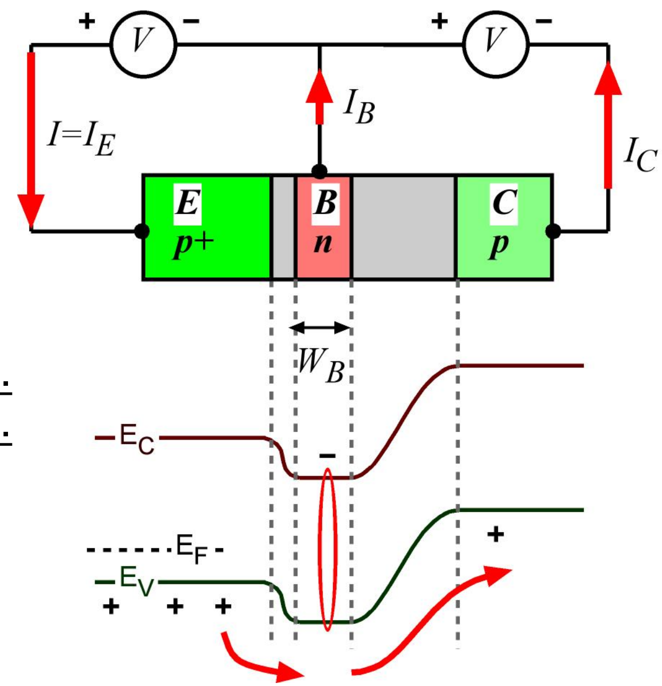
- The hole concentration across the base, what does it look like?
  - Is zero everywhere.
  - Is excess on the emitter-side and zero at the collector-side.
  - Is zero on the emitter-side and excess at the collector-side.
  - I am tired and am going to bed...

- Current is driven from emitter into the base by: *drift, diffusion, neither, both.*

- Current is driven across the base by: *drift, diffusion, neither, both.*

- Current is driven from base into the collector by: *drift, diffusion, neither, both.*

- Lastly, peak ahead, notice how in the equations we derived, they all share a blue-highlighted term such that all current increase or decrease at the SAME rate (but are obviously not equal). You should have expected this already based on what we know about BJTs…



$$\Delta p_E = p_n(e^{qV_{EB}/kT} - 1)$$

$$I_{Ep} \approx qA\frac{D_p}{L_p}\Delta p_E \,\mathbf{ctnh}\frac{W_b}{L_p}$$

$$I_C \approx qA\frac{D_p}{L_p}\Delta p_E \,\mathbf{csch}\frac{W_b}{L_p}$$

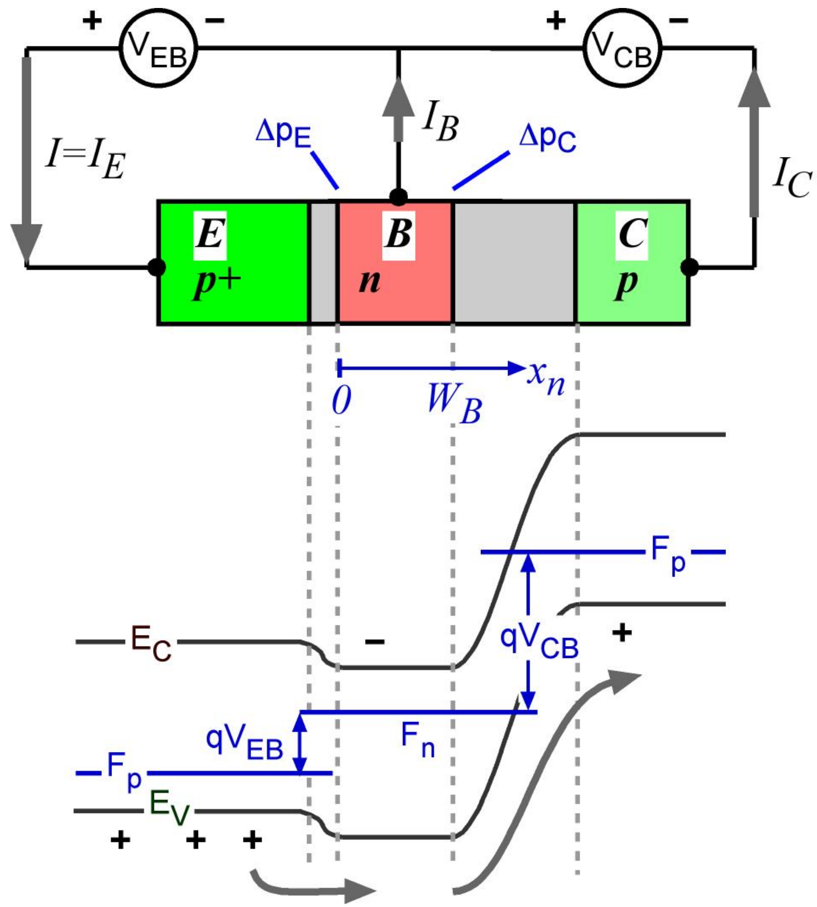
$$I_B \approx qA\frac{D_p}{L_p}\Delta p_E \,\mathbf{tanh}\frac{W_b}{2L_p}$$

- With a bit more work, I can get to the following ***simplified*** equations:

$$I_{Ep} \approx qA\frac{D_p}{L_p}\Delta p_E \,\mathbf{ctnh}\frac{W_b}{L_p}$$

$$I_C \approx qA\frac{D_p}{L_p}\Delta p_E \,\mathbf{csch}\frac{W_b}{L_p}$$

$$I_B \approx qA\frac{D_p}{L_p}\Delta p_E \,\mathbf{tanh}\frac{W_b}{2L_p}$$



- Remember, this is the equation for $\Delta p_E (V_{EB})$ but what does this mean?

$$\Delta p_E = p_n(e^{qV_{EB}/kT} - 1)$$

V_{EB}↑ I_{Ep} & I_C & I_B↑

But what is the other 'stuff' …

They ALL INCREASE the same with V_{EB}, diode forward bias, which makes perfect sense!

$$\Delta p_E = p_n(e^{qV_{EB}/kT} - 1)$$

$$I_{Ep} \approx qA\frac{D_p}{L_p}\Delta p_E \,\mathbf{ctnh}\frac{W_b}{L_p}$$

$$I_C \approx qA\frac{D_p}{L_p}\Delta p_E \,\mathbf{csch}\frac{W_b}{L_p}$$

$$I_B \approx qA\frac{D_p}{L_p}\Delta p_E \,\mathbf{tanh}\frac{W_b}{2L_p}$$

- How about this term in front? *Steal the p_n from Δp_E… recognize it?*

$$qA\frac{D_p}{L_p}p_n$$

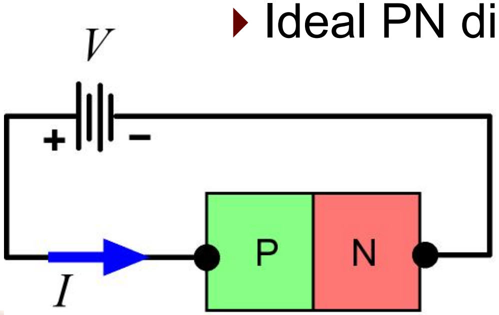
- Why does it only deal with the base (p_n)?

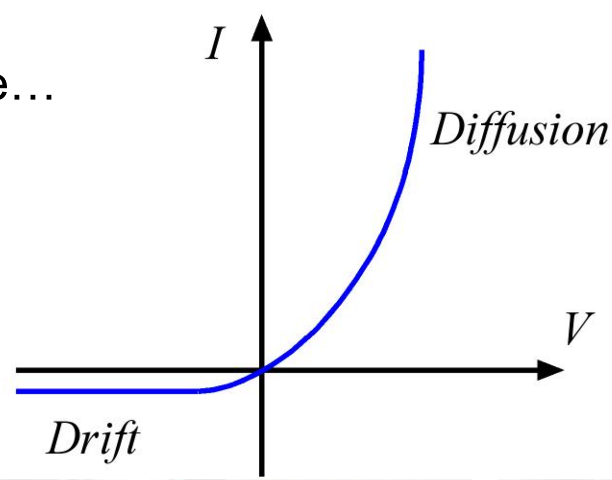
is p+n diode, and also that is the whole point of why we derived these by solving the diff. eq. in the base only!

… this is getting simpler!

… last thing we need is a way to differentiate between the three components…

- Ideal PN diode…





$$I = I_0(e^{qV/kT} - 1)$$

n-side p-side

$$I_0 = qA\left(\frac{D_p}{L_p}p_n - \frac{D_n}{L_n}n_p\right)$$

$$\Delta p_E = p_n(e^{qV_{EB}/kT} - 1)$$

$W_b/L_p = x = 0.01$

$$I_{Ep} \approx qA\frac{D_p}{L_p}\Delta p_E \,\mathbf{ctnh}\frac{W_b}{L_p} \longrightarrow \mathbf{ctnh} = \frac{1}{\tanh} = \frac{e^{2x}+1}{e^{2x}-1} \longrightarrow \sim 100$$

$$I_C \approx qA\frac{D_p}{L_p}\Delta p_E \,\mathbf{csch}\frac{W_b}{L_p} \longrightarrow \mathbf{csch} = \frac{1}{\sinh} = \frac{2}{e^{x}-e^{-x}} \longrightarrow \sim 100$$

$$I_B \approx qA\frac{D_p}{L_p}\Delta p_E \,\mathbf{tanh}\frac{W_b}{2L_p} \longrightarrow \mathbf{tanh} = \frac{\sinh}{\cosh} = \frac{e^{2x}-1}{e^{2x}+1} \longrightarrow \sim 0.005$$

- Lastly, what do these hyperbolic trig functions do?

- Remember, we want Wb smaller than Lp for good design (so holes get across without recombining)!

$$\frac{W_b}{L_p} \approx 0.1 \quad to \quad 0.001 \qquad e^{0.01} = 1.01$$

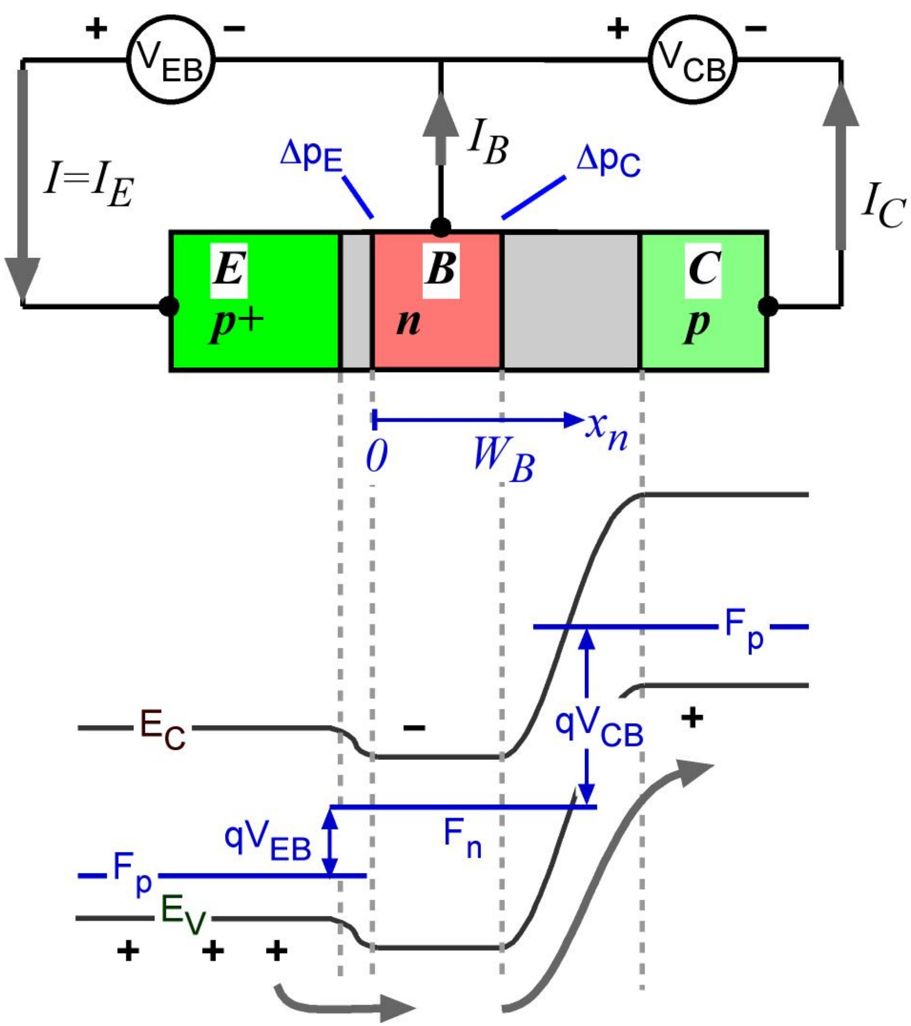
Example 7-4 in book:
$N_D = 10^{15}$/cc
L_P = 108 μm
W_B = 1 μm
β = 832

$$\Delta p_E = p_n(e^{qV_{EB}/kT} - 1)$$

$$I_{Ep} \approx qA\frac{D_p}{L_p}\Delta p_E \,\text{ctnh}\frac{W_b}{L_p}$$

$$I_C \approx qA\frac{D_p}{L_p}\Delta p_E \,\text{csch}\frac{W_b}{L_p}$$

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



- Review 'parts' one last time…

Reverse sat. current (constant)!

Effect of V_{EB}! ALL scale together!

Current magnitudes must be different, and the effect of W_b and L_p!

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

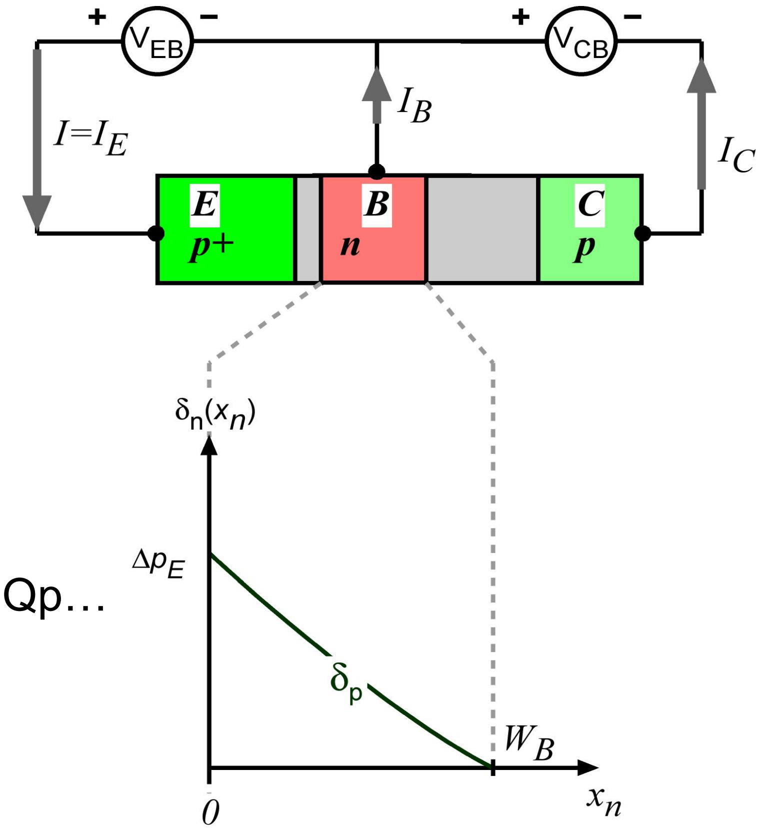
for small W_b/L_p (good design)
via series expansion it can be shown that…

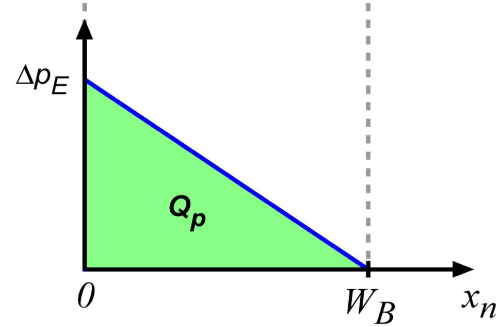
$$I_B \approx \frac{qAW_b\Delta p_E}{2\tau_p}$$

- What does this equation say? Look at geometry for Qp…

$$Q_p = \tfrac{1}{2} qA\Delta p_E W_b$$

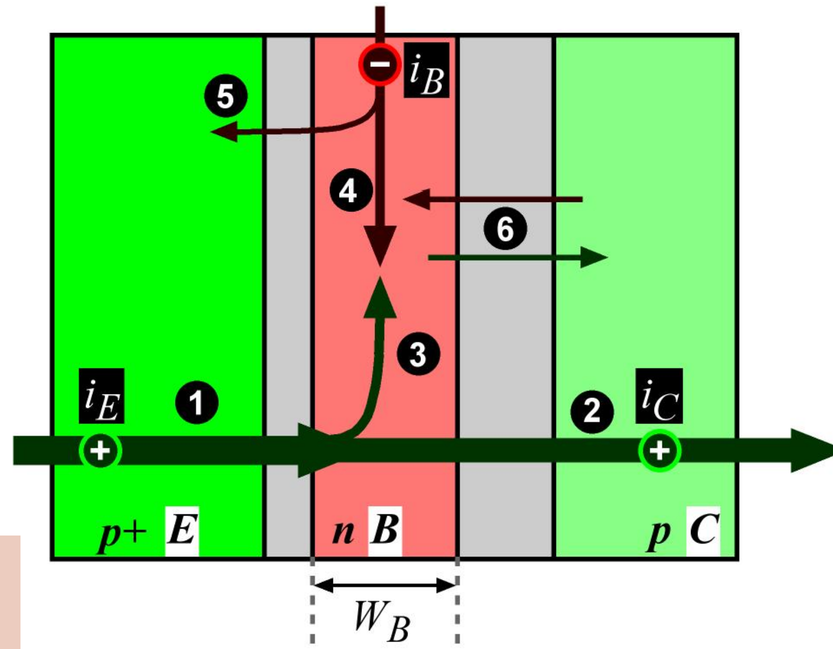
$$I_B \approx \frac{Q_p}{\tau_p}$$





- To simplify our calculations we assumed $\delta = 1$ (which is a safe assumption).

- However, if you are a designer, you know in practice it is not unity, and would like to know how to get it as close to unity as possible…



$$\gamma = \frac{i_{Ep}}{i_{En} + i_{Ep}}$$

$$\gamma = \left[1 + \frac{L_p^n n_n \mu_n^p}{L_n^p p_p \mu_p^n} \tanh \frac{W_b}{L_p^n}\right]^{-1} \approx \left[1 + \frac{W_b n_n \mu_n^p}{L_n^p p_p \mu_p^n}\right]^{-1}$$

L_p^n = *hole diffusion length in n-type base*

μ_n^p = *electron mobility in p-type emitter*

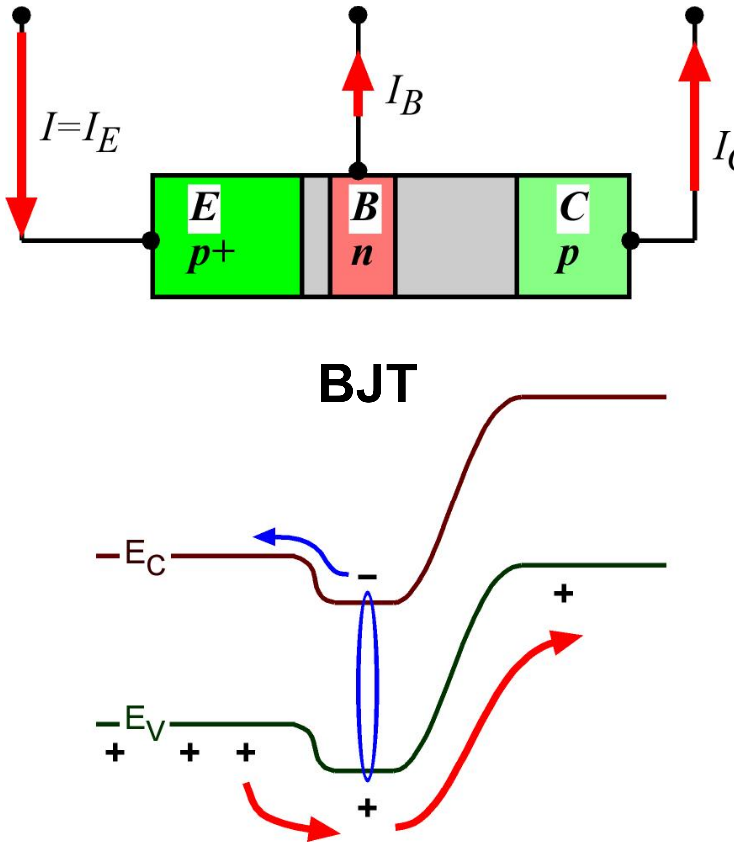
$\mathrm{sech}(z) = 1/\cosh(z)$

- Also base transport should be as close to unity as possible for good design

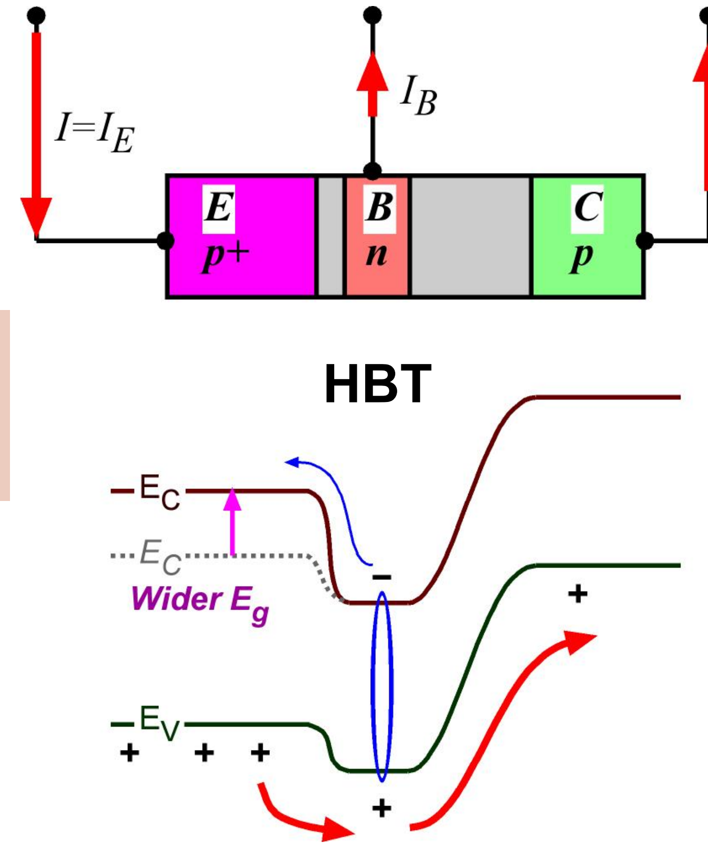
$$i_c = B i_{Ep}$$

$$B = \frac{I_C}{I_E} = \frac{qA \frac{D_p}{L_p} \Delta p_E \ \mathrm{csch}\ W_b/L_p}{qA \frac{D_p}{L_p} \Delta p_E \ \mathrm{ctnh}\ W_b/L_p} = \mathrm{sech}\ \frac{W_b}{L_p}$$

- It should be noted that the highest performance BJTs are Heterojunction BTs (HBTs) using a wider-band-gap material for the emitter, why?



$$\gamma = \frac{i_{Ep}}{i_{En} + i_{Ep}}$$



ΔEg effects exponential Fermi distribution of electrons that can diffuse over the barrier!

$$\frac{I_p}{I_n} \propto \frac{N_A^E}{N_D^B} e^{\Delta E_g / kT}$$

- HBTs use materials such as AlGaAs/GaAs (which is AlGaAs)?

- To get the current equations, we solved for what in the base? *Drift current equation, or diffusion current equation, neither, or both?*

- For our equations, what is the yellow? How does it effect currents as voltage changes?

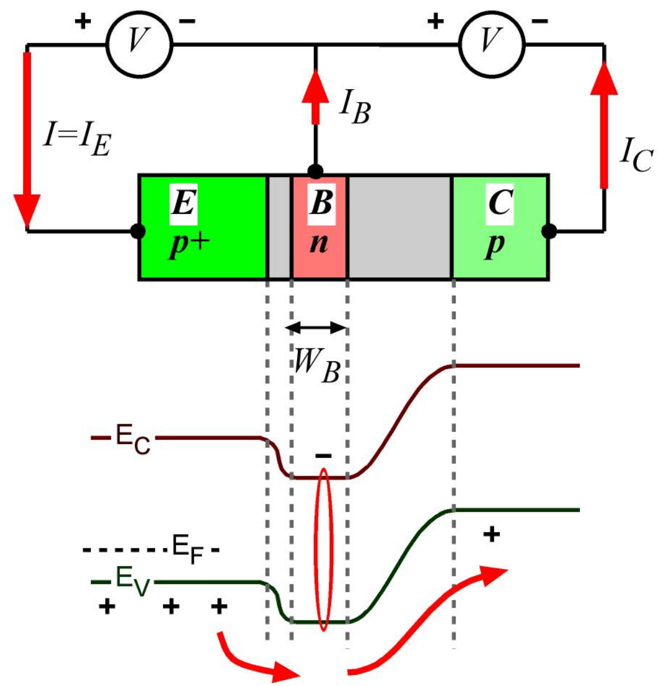
- Is it good that all currents respond linearly to base current? *Not that I can think of, or wow I now have a single device that linearly amplifies current!*

- For our equations, what is the blue? *Hint, the BJT is just diodes, and this is a key part of the diode equation…*

- For our equations, what is the pink? How does it effect currents? *Hint, I need these, without these would I still have an amplifier?*

- If we made W_b really large, what would our circuit and equations reduce to? *You can do the math, but to make this easier just trust your instincts, if Wb becomes large, you basically get two separate diodes, not a BJT. Does that give you amplification then?*

- Why do we make HBTs? *Improves emitter injection efficiency, but how?*



$$\Delta p_E = p_n(e^{qV_{EB}/kT} - 1)$$

$$I_{Ep} \approx qA\frac{D_p}{L_p}\Delta p_E \,\mathbf{ctnh}\frac{W_b}{L_p}$$

$$I_C \approx qA\frac{D_p}{L_p}\Delta p_E \,\mathbf{csch}\frac{W_b}{L_p}$$

$$I_B \approx qA\frac{D_p}{L_p}\Delta p_E \,\mathbf{tanh}\frac{W_b}{2L_p}$$

- If time allows, let's run through an example HBT fabrication process…

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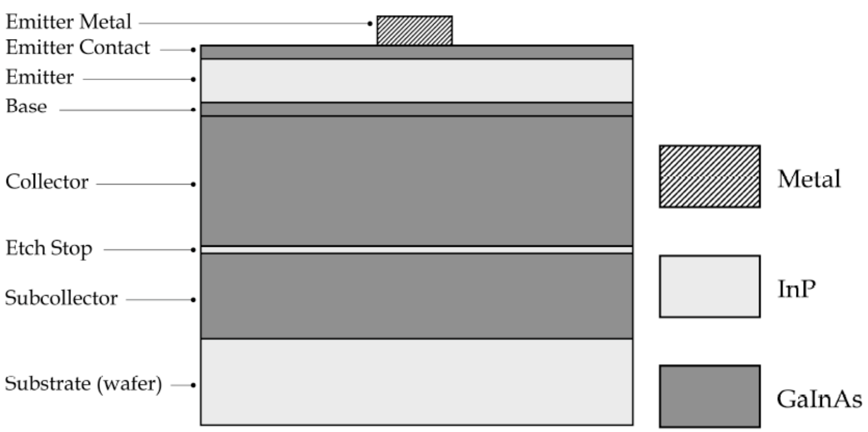
Master of Science in Electrical Engineering Research Thesis

Shraga Kraus
Submitted to the Senate of the Technion - Israel Institute of Technology
Iyar 5766 Haifa May 2006



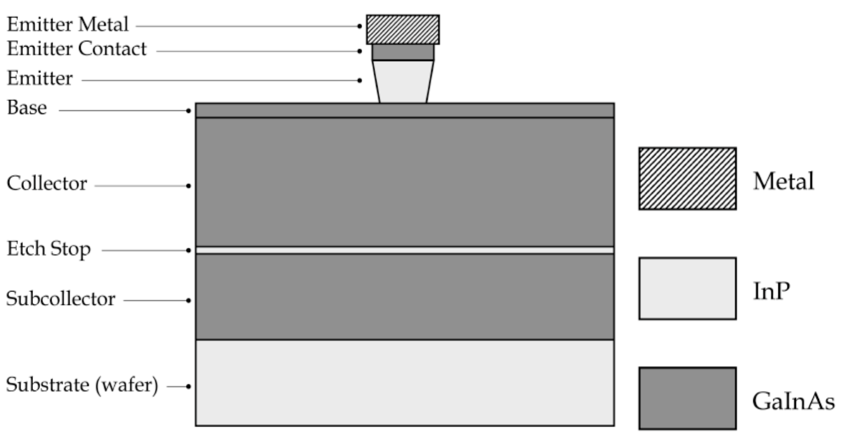


Figure 2.10: Wafer layers after emitter etch

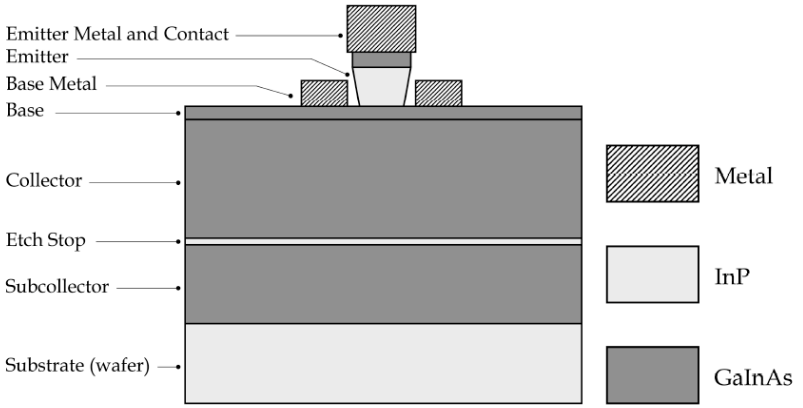


Figure 2.11: Wafer layers after base metal mask

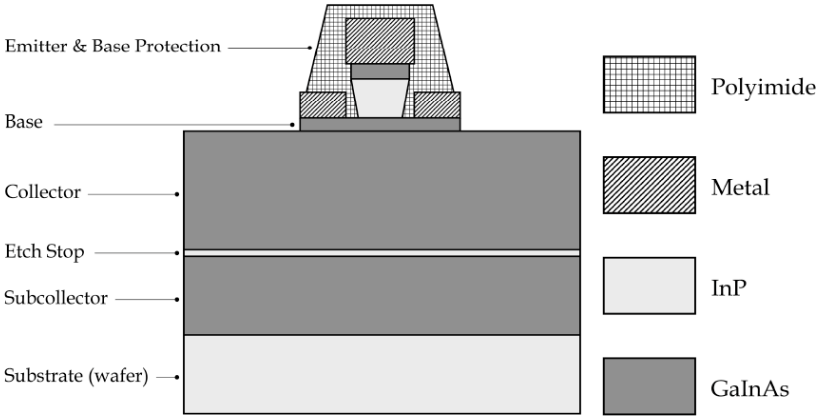


Figure 2.12: Wafer layers after base etch

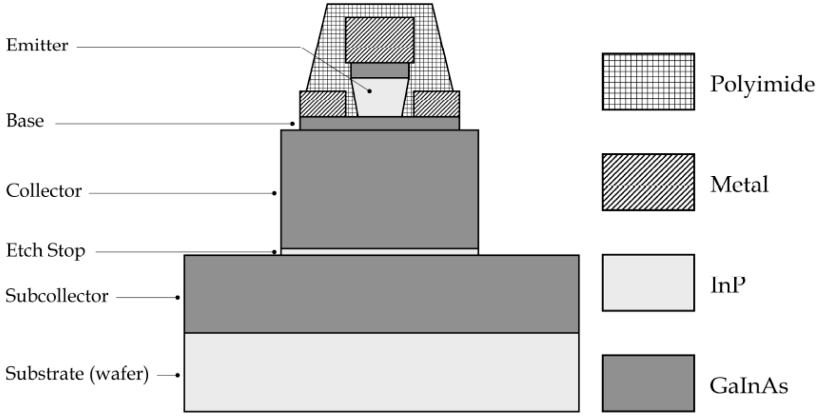


Figure 2.13: Wafer layers after collector etch

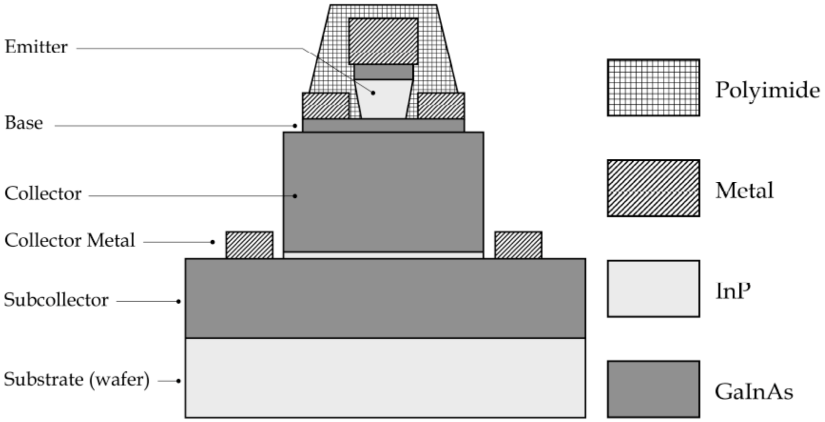


Figure 2.14: Wafer layers after collector metal implementation

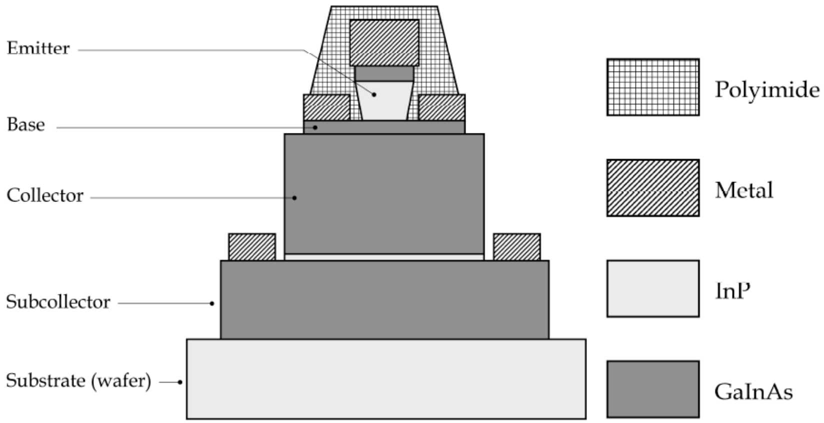


Figure 2.15: Wafer layers after subcollector etch

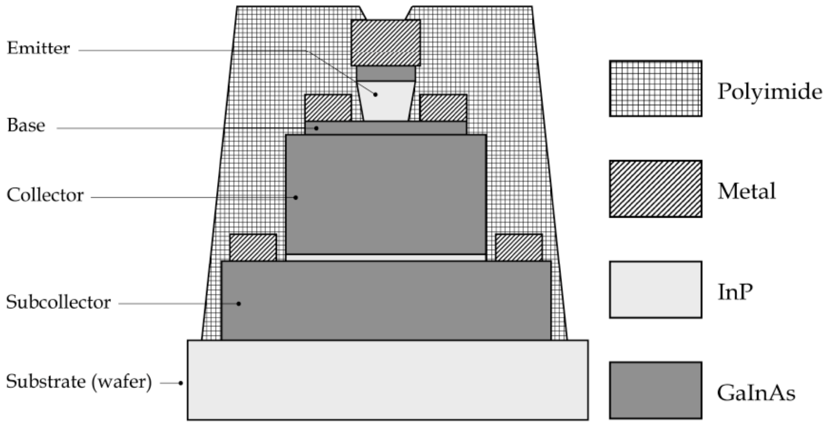


Figure 2.16: Wafer layers after transistor passivation. Only emitter via is shown in this cross–section

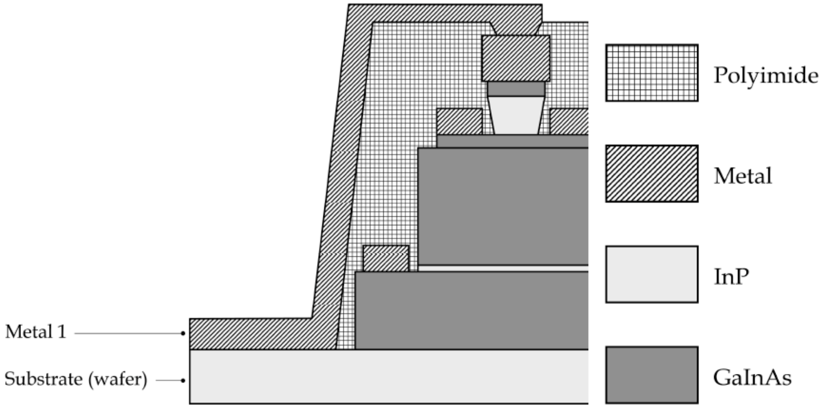


Figure 2.17: Metal 1 as connected to transistor contacts. Only emitter connection is shown in this cross–section

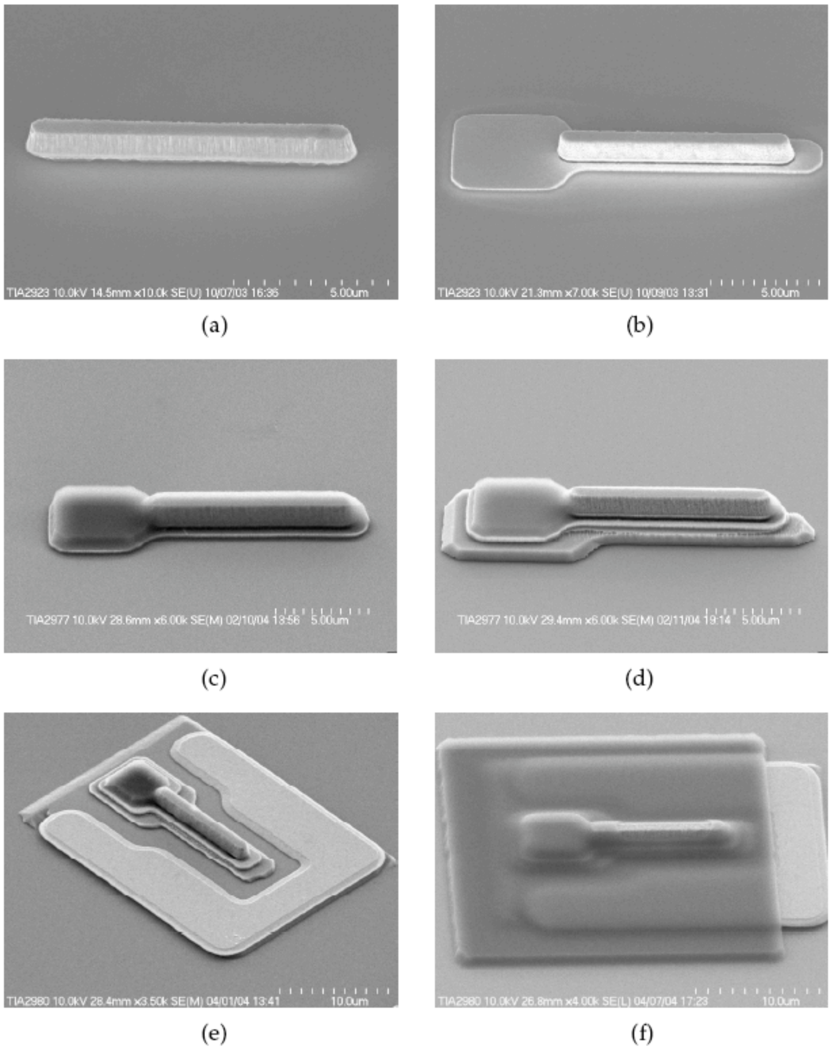


Figure 2.19: SEM images of a transistor at various fabrication process steps: (a) emitter etch (b) base metal deposition and liftoff (c) emitter protect (d) collector protect (e) isolation (f) emitter expose

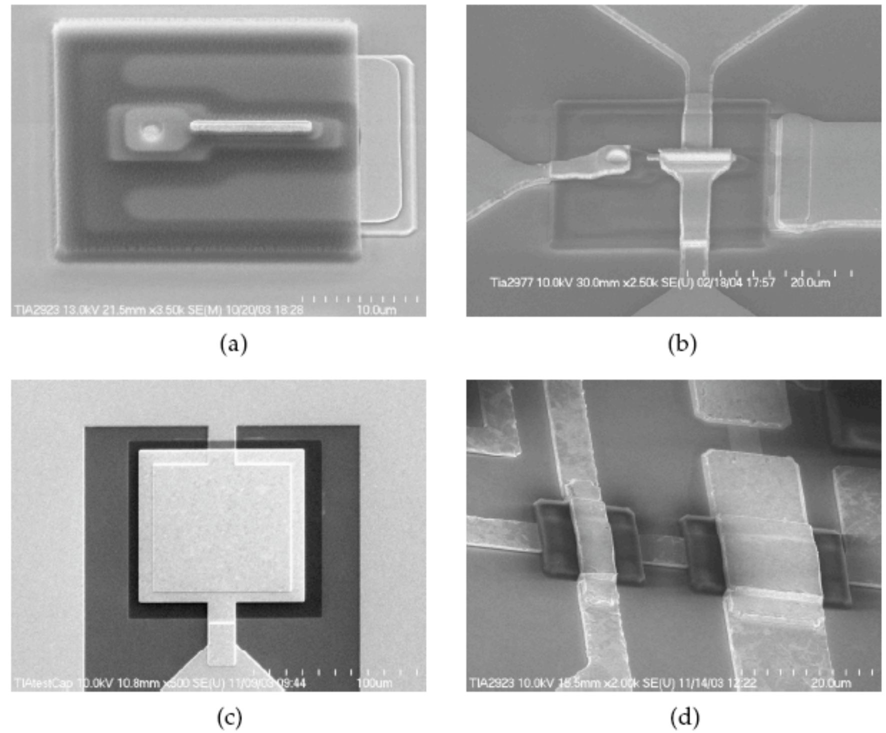


Figure 2.20: SEM images of a transistor and circuit at various fabrication process steps: (a) base–collector via (b) metal 1 deposition and liftoff (c) completed capacitor (d) completed interconnects with crossovers and a resistor

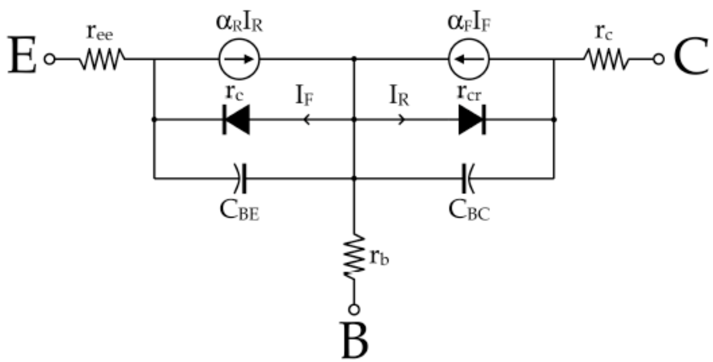


Figure 2.46: Ebers–Moll model (injection version)

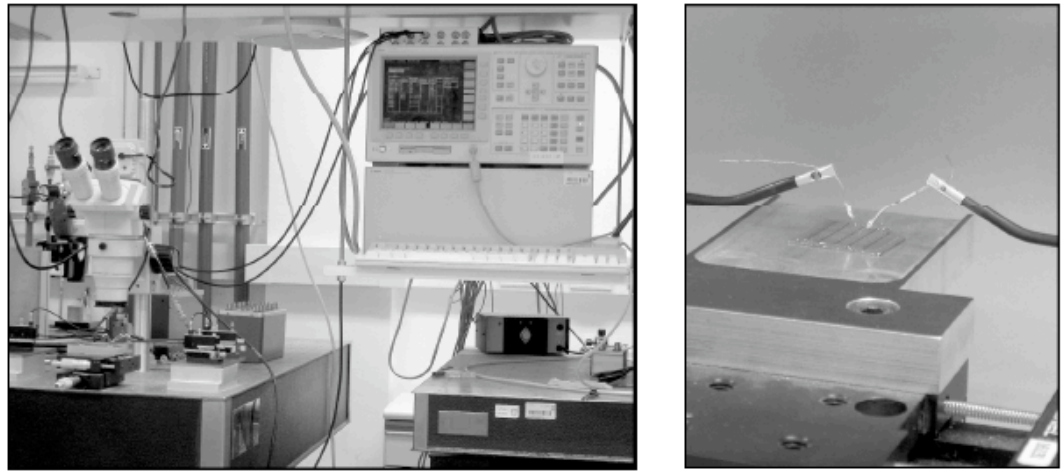

(a)
(b)

Figure 2.21: DC measurement setup: (a) measurement system (b) handmade probes

- Amplification factor is 15 mA/200 μA= 75
- We will talk about the circuit model above next time… looks simple right?

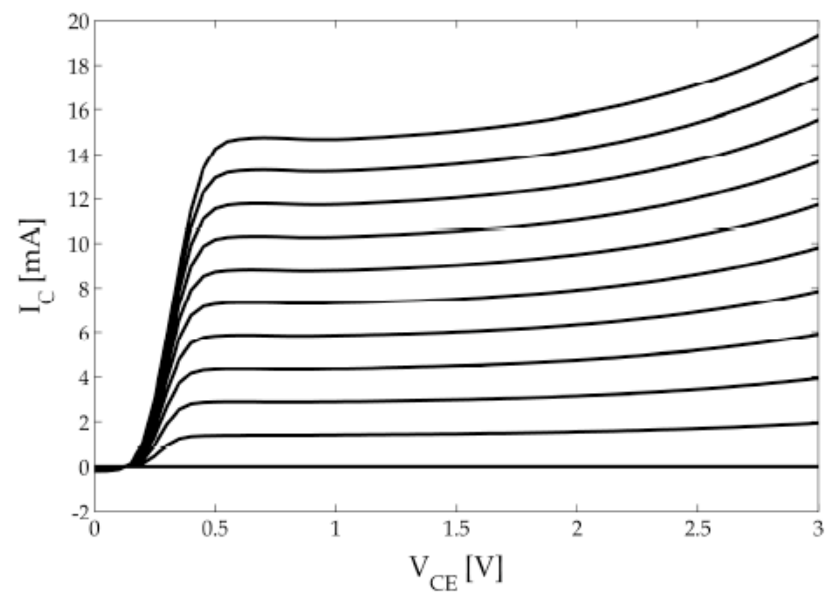


Figure 2.23: Common emitter measurement curves (measured on a large area device). I_B varies from 0 to 200 μA in 20 μA steps