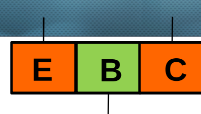
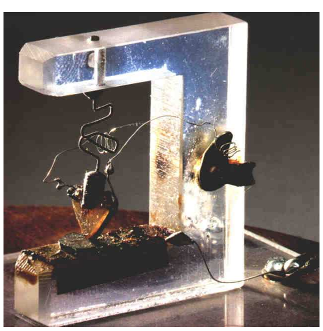
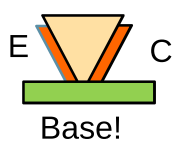
ECE606: Solid State Devices
Lecture 18

Bipolar Transistors
a) Introduction
b) Design (I)

Gerhard Klimeck
gekco@purdue.edu







Point contact **Germanium** transistor

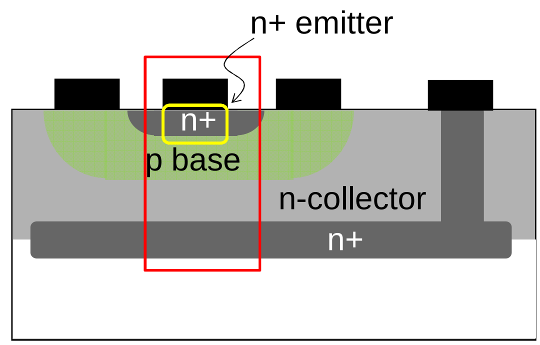
Ralph Bray from Purdue missed the invention of transistors.
http://www.electronicsweekly.com/blogs/david-manners-semiconductor-blog/2009/02/how-purdue-university-nearly-i.html
http://www.physics.purdue.edu/about_us/history/semi_conductor_research.shtml

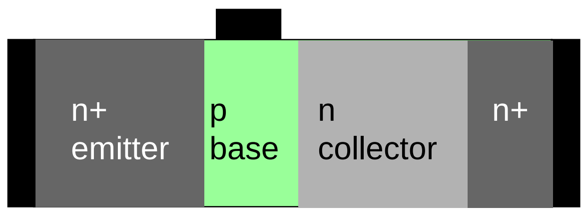
Transistor research was also in advanced stages in Europe (radar).

Shockley's Bipolar Transistors …

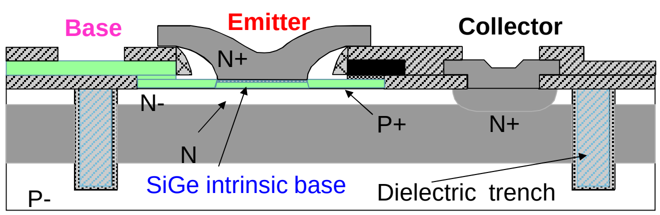
Double

Diffused BJT

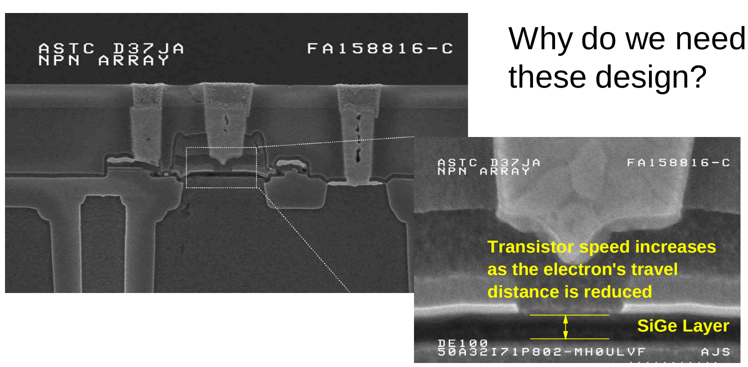




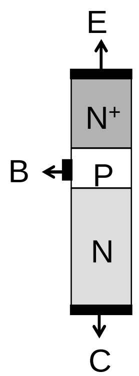
Modern Bipolar Junction Transistors (BJTs)



Why do we need all these design?



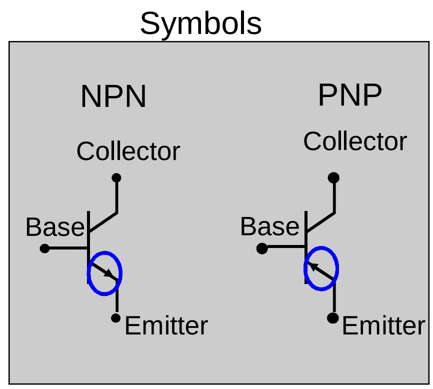
Symbols and Convention



Poly emitter

Low-doped base

Collector doping optimization



$I_C+I_B+I_E=0$ (DC)

$V_{EB}+V_{BC}+V_{CE}=0$

Outline

1) **Equilibrium and forward band-diagram**
2) Currents in bipolar junction transistors
3) Eber's Moll model
4) Intermediate Summary
5) Current gain in BJTs
6) Considerations for base doping
7) Considerations for collector doping
8) Conclusions

REF: SDF, Chapter 10

Topic Map

	Equilibrium	DC	Small signal	Large Signal	Circuit s
Diode					
Schottky					
BJT/HBT	◆				
MOS					

Band Diagram at Equilibrium

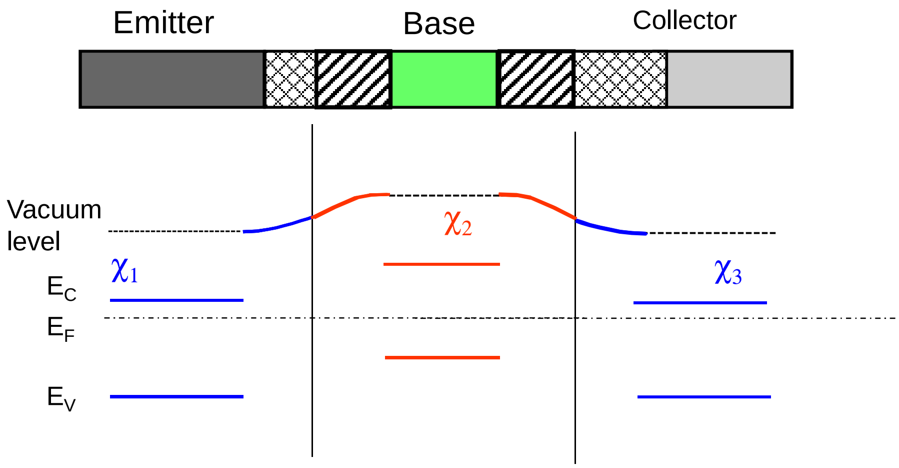
$$\nabla \bullet D = q\left(p - n + N_D^+ - N_A^-\right) \longleftarrow \textbf{Equilibrium}$$

$$\left.\begin{aligned}
\frac{\partial n}{\partial t} &= \frac{1}{q}\nabla \bullet \mathbf{J}_N - r_N + g_N \\
\mathbf{J}_N &= qn\mu_N E + qD_N \nabla n \\
\frac{\partial p}{\partial t} &= -\frac{1}{q}\nabla \bullet \mathbf{J}_P - r_P + g_P \\
\mathbf{J}_P &= qp\mu_P E - qD_P \nabla p
\end{aligned}\right\}$$

DC dn/dt=0
Small signal dn/dt ~ jωtn
Transient --- Charge control model

Band Diagram at Equilibrium

NPN homojunction BJT



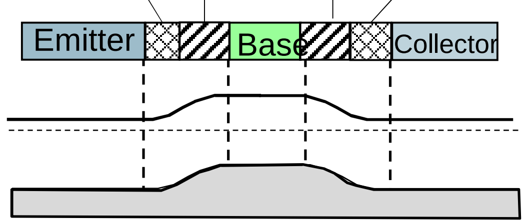
Electrostatics in Equilibrium

$$x_{p,BE}=\sqrt{\frac{2k_s\varepsilon_0}{q}\frac{N_E}{N_B\left(N_E+N_B\right)}V_{bi}}$$

$$x_{p,BC}=\sqrt{\frac{2k_s\varepsilon_0}{q}\frac{N_C}{N_B\left(N_C+N_B\right)}V_{bi}}$$

$$x_{n,E}=\sqrt{\frac{2k_s\varepsilon_0}{q}\frac{N_B}{N_E\left(N_B+N_E\right)}V_{bi}}$$

$$x_{n,C}=\sqrt{\frac{2k_s\varepsilon_0}{q}\frac{N_B}{N_C\left(N_C+N_B\right)}V_{bi}}$$



Two back to back p-n junction

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Topic Map

	Equilibrium	DC	Small signal	Large Signal	Circuits
Diode					
Schottky					
BJT/HBT		◆			
MOS					

Band Diagram with Bias

$$\nabla \bullet D = q\left(p - n + N_D^+ - N_A^-\right)$$

Non-equilibrium

$$\frac{\partial n}{\partial t} = \frac{1}{q}\nabla \bullet \mathbf{J}_N - r_N + g_N$$

$$\mathbf{J}_N = qn\mu_N E + qD_N \nabla n$$

$$\frac{\partial p}{\partial t} = \frac{1}{q}\nabla \bullet \mathbf{J}_P - r_P + g_P$$

$$\mathbf{J}_P = qp\mu_P E - qD_P \nabla p$$

DC dn/dt=0

Small signal dn/dt ~ jωtn

Transient --- Charge control model

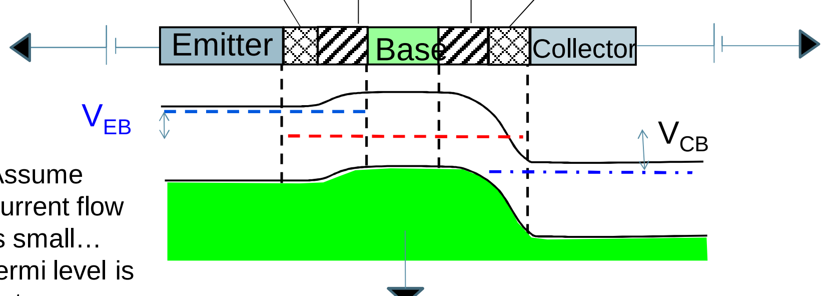
Electrostatics in Equilibrium

$$x_{p,BE} = \sqrt{\frac{2k_s\varepsilon_0}{q}\frac{N_E}{N_B\left(N_E+N_B\right)}\left(V_{bi}-V_{EB}\right)}$$

$$x_{p,BC} = \sqrt{\frac{2k_s\varepsilon_0}{q}\frac{N_C}{N_B\left(N_C+N_B\right)}\left(V_{bi}-V_{CB}\right)}$$

$$x_{n,E} = \sqrt{\frac{2k_s\varepsilon_0}{q}\frac{N_B}{N_E\left(N_B+N_E\right)}\left(V_{bi}-V_{EB}\right)}$$

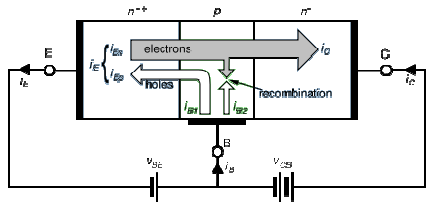
$$x_{n,C} = \sqrt{\frac{2k_s\varepsilon_0}{q}\frac{N_B}{N_C\left(N_C+N_B\right)}\left(V_{bi}-V_{CB}\right)}$$

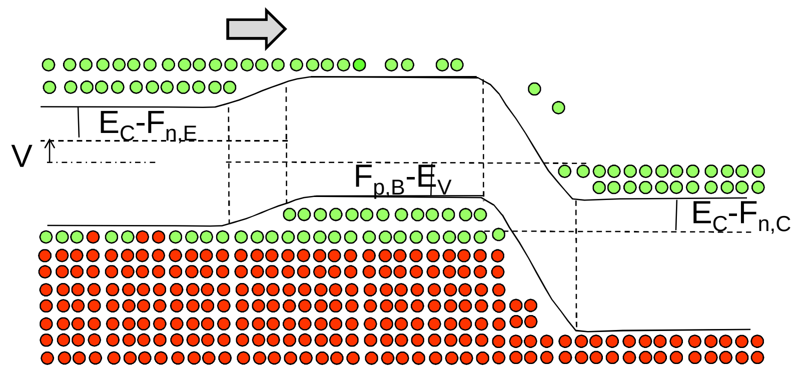


Assume current flow is small… fermi level is flat

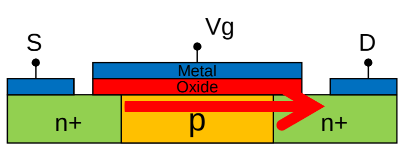
Current flow with Bias

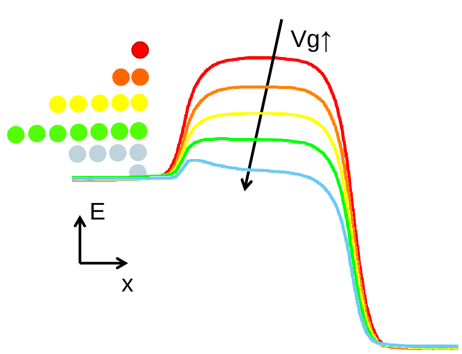
Input small amount of holes results in large amount of electron output

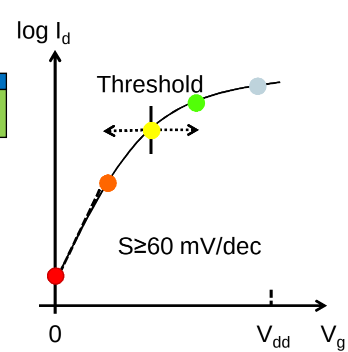




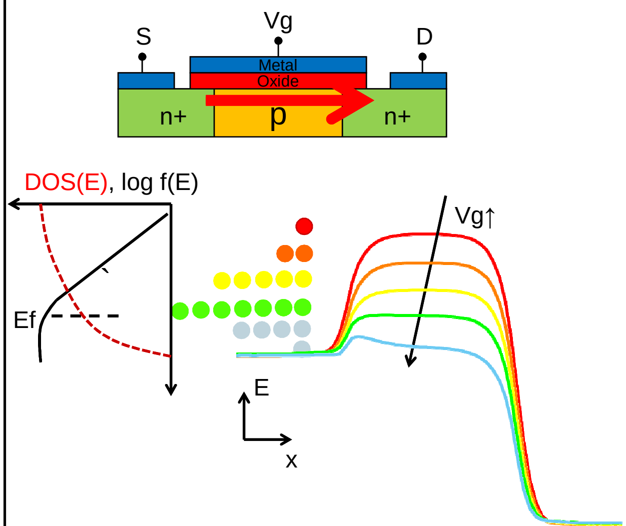
Modern MOSFET – "Fundamental" Limit looks similar to BJT

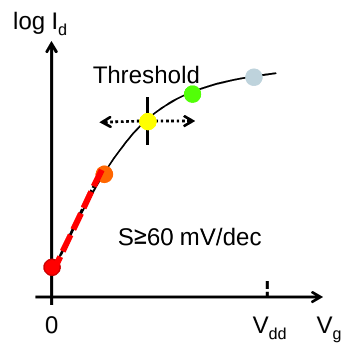






Modern MOSFET - "Fundamental" Limit looks similar to BJT

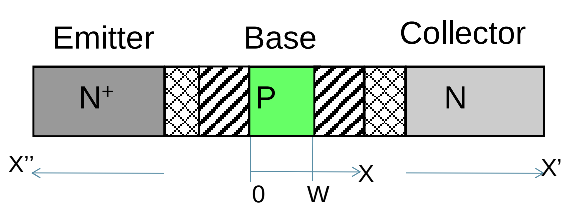




$$S = 2.3m\left(k_BT/q\right)\ \frac{\text{mV}}{\text{dec}}$$

$$m = \left(1 + C_D/C_{OX}\right) \geq 1$$

Coordinates and Convention



$$N_E = N_{D,E}, \ldots. N_B = N_{A,B}, \ldots. N_C = N_{D,C}$$ Doping

$$D_E = D_P, \ldots\ldots. D_B = D_N, \ldots\ldots D_C = D_P$$ Minority carrier diffusion

$$n_{E0} = n_{p0}, \ldots\ldots. p_{B0} = p_{n0}, \ldots\ldots n_{C0} = n_{p0}$$ Majority carriers

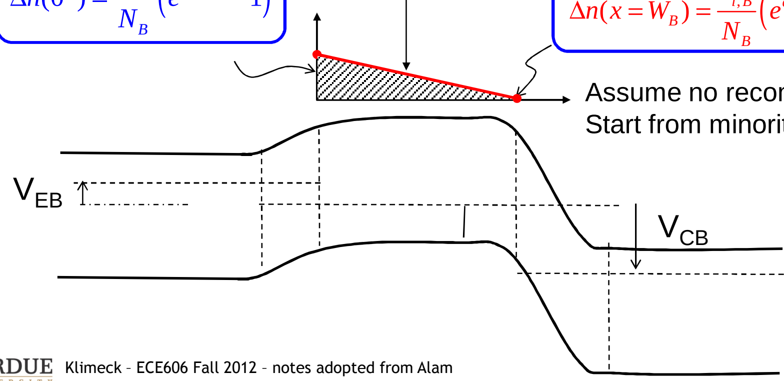
Carrier Distribution in Base

$$\Delta n(x) = Ax + B = C\left(1-\frac{x}{W_B}\right) + D\left(\frac{x}{W_B}\right)$$

$$\Delta n(x) = \frac{n_{i,B}^2}{N_B}\left(e^{qV_{BE}\beta}-1\right)\left(1-\frac{x}{W_B}\right) + \frac{n_{i,B}^2}{N_B}\left(e^{qV_{BC}\beta}-1\right)\left(\frac{x}{W_B}\right)$$

C: $\Delta n(0^+) = \frac{n_{i,B}^2}{N_B}\left(e^{qV_{BE}\beta}-1\right)$

D: $\Delta n(x = W_B) = \frac{n_{i,B}^2}{N_B}\left(e^{qV_{BC}\beta}-1\right)$

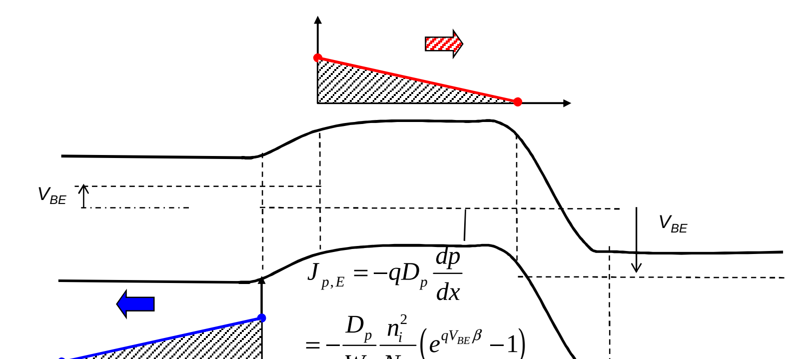


Assume no recombination.
Start from minority carrier

Collector and Emitter Electron Current

$$\Delta n(x) = \frac{n_{i,B}^2}{N_B}\left(e^{qV_{BE}\beta}-1\right)\left(1-\frac{x}{W_B}\right) + \frac{n_{i,B}^2}{N_B}\left(e^{qV_{BC}\beta}-1\right)\left(\frac{x}{W_B}\right)$$

$$J_{n,C} = qD_n \left.\frac{dn}{dx}\right|_{W_B} = -\frac{qD_n}{W_B}\frac{n_{i,B}^2}{N_B}\left(e^{qV_{BE}\beta}-1\right) + \frac{qD_n}{W_B}\frac{n_{i,B}^2}{N_B}\left(e^{qV_{BC}\beta}-1\right)$$

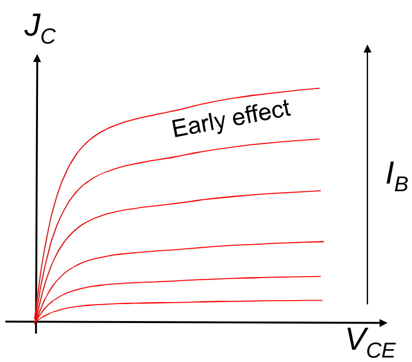


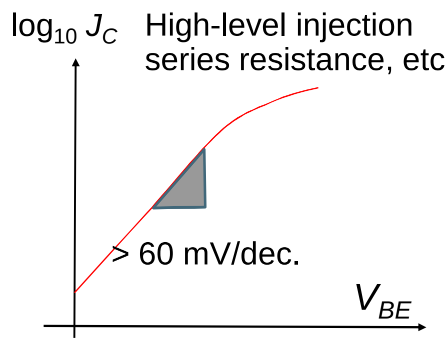
$$J_{p,E} = -qD_p\frac{dp}{dx} = -\frac{D_p}{W_n}\frac{n_i^2}{N_D}\left(e^{qV_{BE}\beta}-1\right)$$

Current-Voltage Characteristics

Normal, Active Region
EB: Forward biased
BC: Reverse biased

$$J_{n,C} = -\frac{qD_n}{W_B}\frac{n_{i,B}^2}{N_B}\left(e^{qV_{BE}\beta}-1\right)+\frac{qD_n}{W_B}\frac{n_{i,B}^2}{N_B}\left(e^{qV_{BC}\beta}-1\right)$$





W_B is not independent of bias => Early Effect

same physics of diode , rollover

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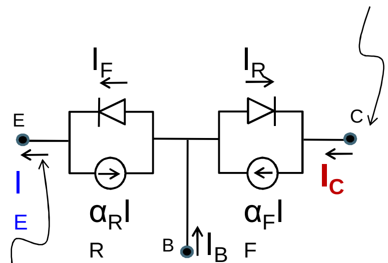
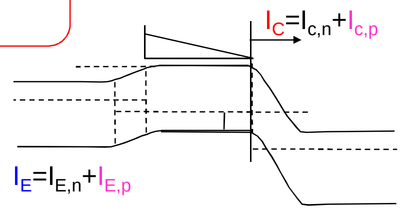
Ebers Moll Model

Hole diffusion in collector

$$I_C = -A\frac{qD_n}{W_B}\frac{n_{i,B}^2}{N_B}\left(e^{qV_{BE}\beta}-1\right) + A\left[\frac{qD_n}{W_B}\frac{n_{i,B}^2}{N_B} + \frac{qD_p}{W_C}\frac{n_{i,C}^2}{N_C}\right]\left(e^{qV_{BC}\beta}-1\right)$$

$$\equiv \alpha_F I_{F0}\left(e^{qV_{BE}\beta}-1\right) - I_{R0}\left(e^{qV_{BC}\beta}-1\right)$$





$$I_F = I_{F0}\left(e^{qV_{BE}\beta}-1\right)$$

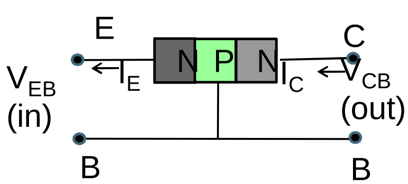
$$I_R = I_{R0}\left(e^{qV_{BC}\beta}-1\right)$$

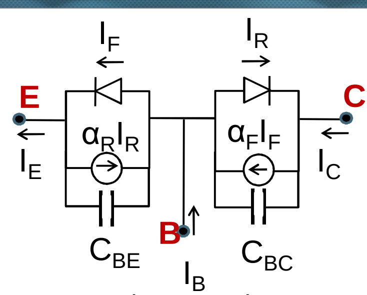
Temperature dependent

$$I_E = -A\left[\frac{qD_p}{W_E}\frac{n_{i,E}^2}{N_E} + \frac{qD_n}{W_B}\frac{n_{i,B}^2}{N_B}\right]\left(e^{qV_{BE}\beta}-1\right) + A\frac{qD_n}{W_E}\frac{n_{i,B}^2}{N_B}\left(e^{qV_{BC}\beta}-1\right)$$

$$\equiv I_{F0}\left(e^{qV_{BE}\beta}-1\right) - \alpha_R I_{R0}\left(e^{qV_{BC}\beta}-1\right)$$

Common Base Configuration





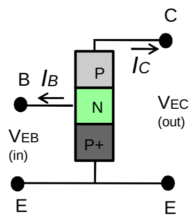
Junction capacitance and diffusion capacitance

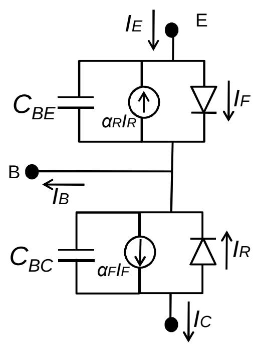
How would the model change if this was a Schottky barrier BJT?

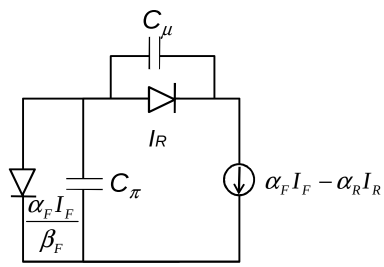
The original transistor was a metal/ semicond / metal device
No minority carriers, no diffusion capacitance but the "rest" about the same.

Common base configuration provides power gain, but no current gain.
=> Emitter and collector current are identical => no current gain
=> Collector current I_C can be driven through large resistor => power gain
Is there another configuration that can deliver current gain?

Common Emitter Configuration







$$\frac{\alpha_F I_F}{\beta_F} = \frac{\alpha_F I_F}{\frac{\alpha_F}{1-\alpha_F}} = (1-\alpha_F) I_F = I_B$$

This is a practice problem …

Intermediate Summary

- The physics of BJT is most easily understood with reference to the physics of junction diodes.
- The equations can be encapsulated in simple equivalent circuit appropriate for dc, ac, and large signal applications.
- Design of transistors is far more complicated than this simple model suggests => the next lecture elements
- For a terrific and interesting history of invention of the bipolar transistor, read the book “Crystal Fire”.

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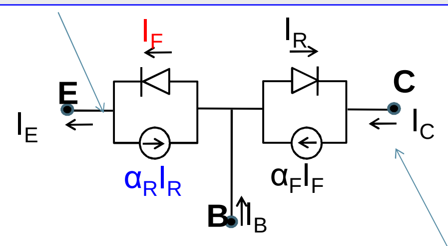
Ebers Moll Model

$$I_B = A\frac{qD_p}{W_E}\frac{n_{i,E}^2}{N_E}\left(e^{qV_{BE}\beta}-1\right)+A\frac{qD_p}{W_C}\frac{n_{i,C}^2}{N_C}\left(e^{qV_{BC}\beta}-1\right)$$

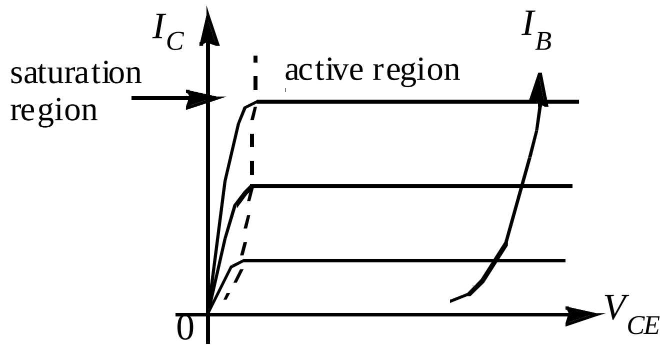
$$I_E = -A_E\left(\frac{qD_n}{W_B}\frac{n_{i,B}^2}{N_B}+\frac{qD_p}{W_E}\frac{n_{i,E}^2}{N_E}\right)\left(e^{qV_{BE}\beta}-1\right)+A_E\frac{qD_n}{W_B}\frac{n_{i,B}^2}{N_B}\left(e^{qV_{BC}\beta}-1\right)$$
$$= I_{F0}\left(e^{qV_{BE}\beta}-1\right)-\alpha_R I_{R0}\left(e^{qV_{BC}\beta}-1\right)$$



$$I_F = I_{F0}\left(e^{qV_{BE}\beta}-1\right)$$
$$I_R = I_{R0}\left(e^{qV_{BC}\beta}-1\right)$$

$$I_C = -A_C\frac{qD_n}{W_B}\frac{n_{i,B}^2}{N_B}\left(e^{qV_{BE}\beta}-1\right)+A_C\left[\frac{qD_n}{W_B}\frac{n_{i,B}^2}{N_B}+\frac{qD_n}{W_C}\frac{n_{i,C}^2}{N_C}\right]\left(e^{qV_{BC}\beta}-1\right)$$
$$= \alpha_F I_{F0}\left(e^{qV_{BE}\beta}-1\right)-I_{R0}\left(e^{qV_{BC}\beta}-1\right)$$

Ebers Moll Model (Basic definition)



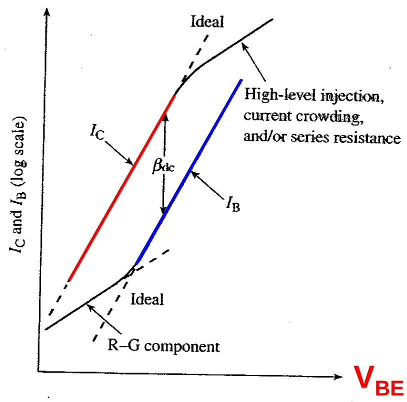
The Ebers-Moll model describes both the active and the saturation regions of BJT operation.

Gummel Plot and Output Characteristics

- The simultaneous plot of collector and base current vs. the base-emitter voltage on a semi-logarithmic scale is known as a Gummel Plot.
- This plot is extremely useful in device characterization because it reflects on the quality of the emitter-base junction while the base-collector bias is kept at a constant.
- A number of other device parameters can be ascertained either quantitatively or qualitatively directly from the Gummel plot because of its semi-logarithmic nature
  - For example the d.c gain β, base and collector ideality factors, series resistances and leakage currents.

Gummel Plot and Output Characteristics

$$\frac{I_C}{A} \simeq -\frac{qD_n}{W_B}\frac{n_{i,B}^2}{N_B}\left(e^{qV_{BE}/kT}-1\right)+\cancel{\frac{qD_n}{W_B}\frac{n_{i,B}^2}{N_B}\left(e^{qV_{BC}/kT}-1\right)}$$

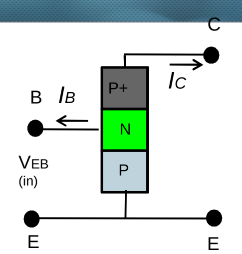


$$\frac{I_B}{A} = \frac{qD_p}{W_E}\frac{n_{i,E}^2}{N_E}\left(e^{qV_{BE}/kT}-1\right)$$

$$\beta_{DC} = \frac{I_C}{I_B}$$

$\beta_{DC} \longrightarrow$ Common emitter Current Gain

Current Gain



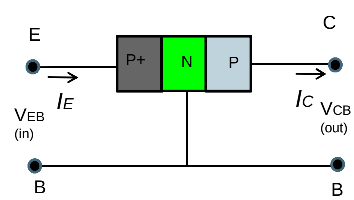
Common Emitter current gain ..

$$\beta_{DC} = \frac{I_C}{I_B}$$

$$= \frac{\frac{qD_n}{W_B}\frac{n_{i,B}^2}{N_B}\left(e^{qV_{BE}/kT}-1\right)+\cancel{\frac{qD_n}{W_B}\frac{n_{i,B}^2}{N_B}\left(e^{(qV_{BC}/kT)}-1\right)}}{\frac{qD_n}{W_E}\frac{n_{i,E}^2}{N_E}\left(e^{qV_{BE}/kT}-1\right)} \approx \frac{D_n}{W_B}\frac{W_E}{D_p}\frac{n_{i,B}^2}{n_{i,E}^2}\frac{N_E}{N_B}$$

Will examine

Common Base current gain ..



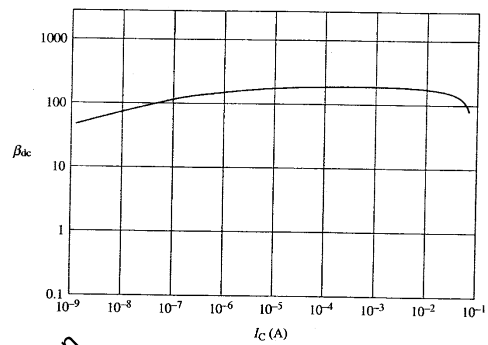
$$\alpha_{DC} = \frac{I_C}{I_E} \Rightarrow \beta_{DC} = \frac{I_C}{I_B} = \frac{I_C}{I_E - I_C} = \frac{\alpha_{DC}}{1-\alpha_{DC}}$$

DC transfer gain

Properties are related – (transistor did not change ☺)

Current Gain

$$\beta_{DC} \approx \frac{D_n}{W_B}\frac{W_E}{D_p}\frac{n_{i,B}^2}{n_{i,E}^2}\frac{N_E}{N_B}$$



Base recombination
=> roll-off

High injection
collector current
=>roll-off
Base current
does not roll off

How to make a Good Silicon Transistor

For a given Emitter length

~1, same material
primarily determined
by bandgap

$$\beta_{DC} \approx \frac{D_n}{W_B}\frac{W_E}{D_p}\frac{n_{i,B}^2}{n_{i,E}^2}\frac{N_E}{N_B}$$

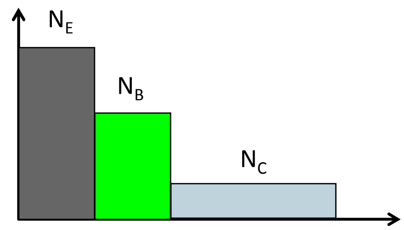
Make-Base short …
(few mm in 1950s, 200 A now)
Want high gradient of carrier density

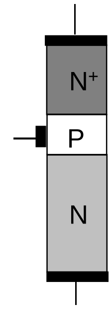
Emitter doping higher
than Base doping

Base doping hard to control
Emitter doping easier

Doping for Gain …

$$\beta_{DC} \approx \frac{D_n}{W_B}\frac{W_E}{D_p}\cancel{\frac{n_{i,B}^2}{n_{i,E}^2}}\frac{N_E}{N_B}$$



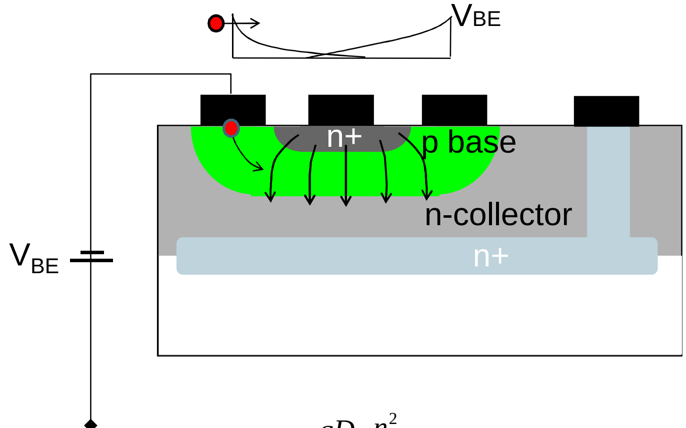


Outline

1) Equilibrium and forward band-diagram
2) Currents in bipolar junction transistors
3) Eber's Moll model
4) Intermediate Summary
5) Current gain in BJTs
6) **Considerations for base doping**
   what's wrong with the previous recipe?
7) Considerations for collector doping
8) Conclusions

REF: SDF, Chapter 10

Problem of Low Base Doping: Current Crowding



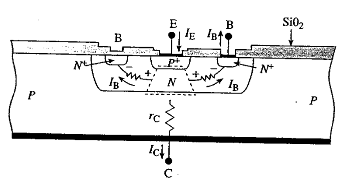
$$\beta = \frac{I_C}{I_B} = \frac{\int J_C(x)dx}{\int J_B(x)dx} = \frac{\int \frac{qD_n}{W_B}\frac{n_{i,B}^2}{N_B}\left(e^{qV'_{BE}(x)\beta}-1\right)dx}{\int \frac{qD_p}{W_E}\frac{n_{i,E}^2}{N_E}\left(e^{qV'_{BE}(x)\beta}-1\right)dx}$$

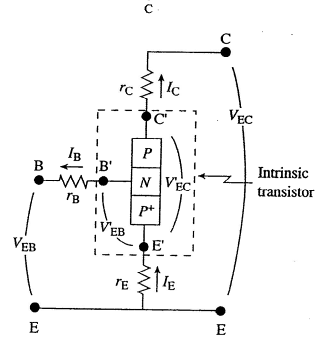
Double diffused junction configuration: Emitter doping must compensate / overcome the base doping

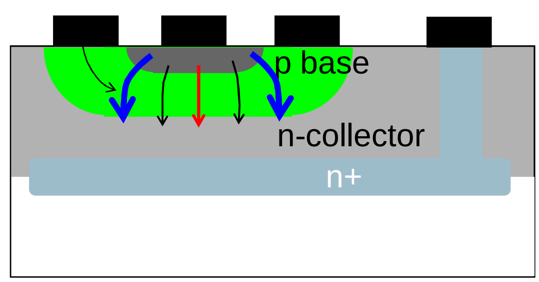
Low doping in base
=> resistance along the current path
=> potential drop
=> Determines the injection
=> Spatially dependent
=> More current in the corners

Low Base Doping: Non-uniform Turn-on

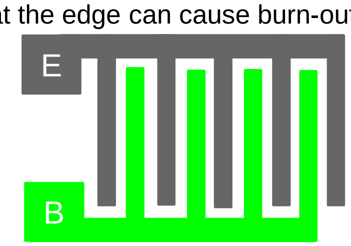
Sketches from text book





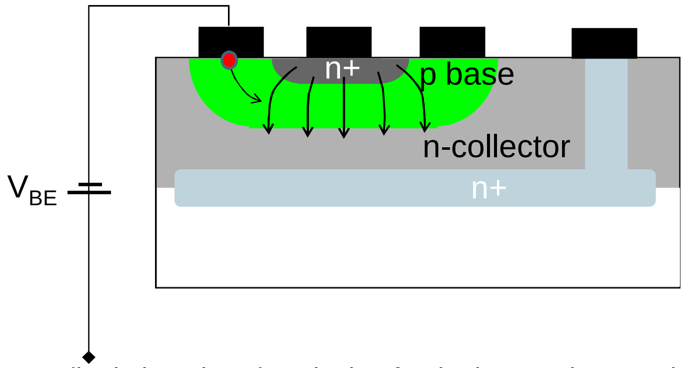


Non-uniform current inefficient
High current at the edge can cause burn-out



Interdigitated designs for almost all high power transistors (E-B distance minimized)

Low Base Doping: Current Crowding

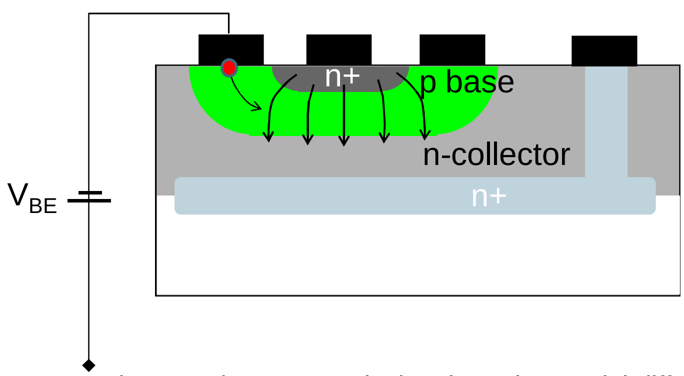


We talked about how low doping for the base enhances the current gain.

But there is a potential downside to this approach

If the base doping is kept to small values, it will have a high resistance: Lesser ability to conduct means higher resistance

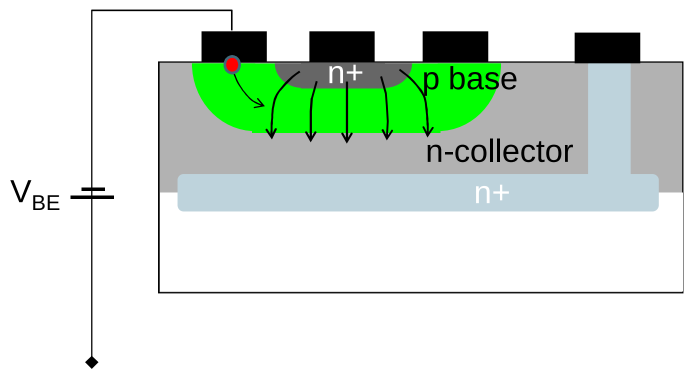
Low Base Doping: Current Crowding



Non-zero base resistance results in a lateral potential difference under the emitter region

For an n-p-n transistor as shown, the potential decreases from edge of the emitter towards the centre (the emitter is highly doped and can be considered an equipotential region)

Low Base Doping: Current Crowding



The number of electrons injected from emitter to base is exponentially dependent on base-emitter voltage

With the lateral drop in the voltage in the base between the edge and centre of emitter, more carriers will be injected at the edge than the emitter centre.

Low Base Doping: Current Crowding

Key facts:

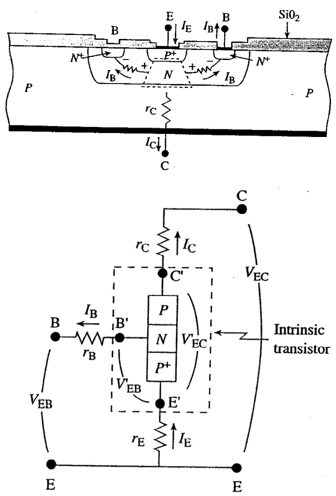
1. Current crowding is due to 2D nature of BJTs
2. It is a function of the doping concentration
3. As doping concentration increases, resistivity decreases
   - Consequence: Current gain goes smaller → Emitter current injection efficiency decreases

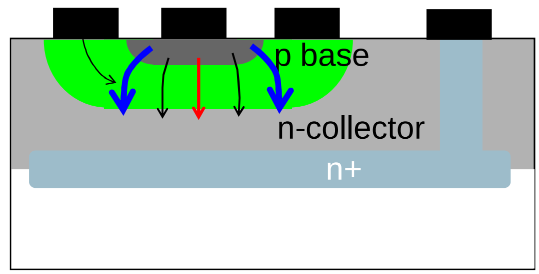
The larger current density near the emitter may cause localized heating and high injection effects

Possible Solution: Emitter widths are fabricated with an inter-digitated design → Many narrow emitters connected in parallel to achieve the required emitter area

Low Base Doping: Non-uniform Turn-on

Sketches from text book





Non-uniform current inefficient
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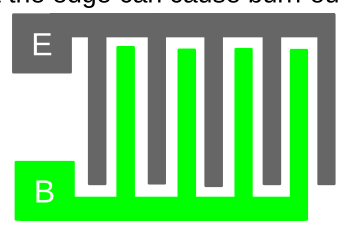
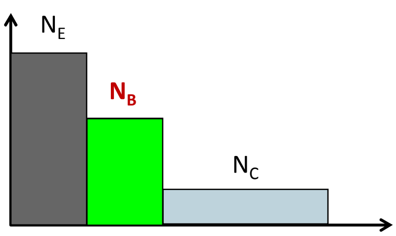
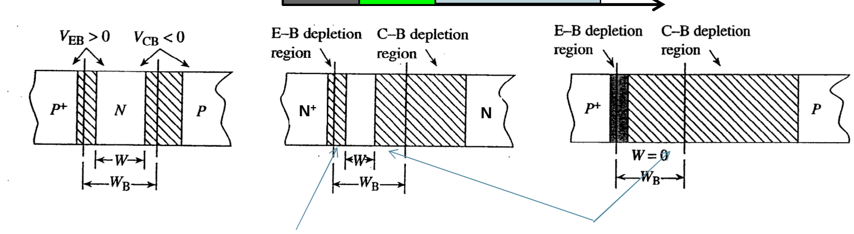


Interdigitated designs for almost all high power transistors (E-B distance minimized)

Problem of Low Base Doping: Punch-through





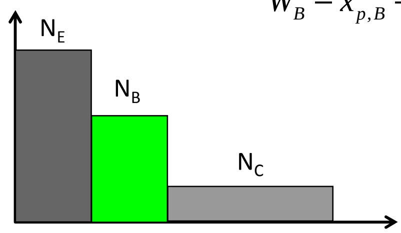
$$x_{p,BE} = \sqrt{\frac{2k_s\varepsilon_0}{q}\frac{N_E}{N_B\left(N_E+N_B\right)}\left(V_{bi}-V_{BE}\right)} \qquad x_{p,BC} = \sqrt{\frac{2k_s\varepsilon_0}{q}\frac{N_C}{N_B\left(N_C+N_B\right)}\left(V_{bi}-V_{BC}\right)}$$

Low base doping is not a good idea!

Problem of low Base-doping: Base Width Modulation

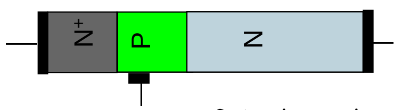
Electrical base region is smaller than the metallurgical region!

$$\beta_{DC} \approx \frac{D_n}{W_B - x_{p,B} - x_{p,c}} \frac{W_E}{D_p} \cancel{\frac{n^2_{i,B}}{n^2_{i,E}}} \frac{N_E}{N_B}$$



$$x_{p,BE} = \sqrt{\frac{2k_s\varepsilon_0}{q} \frac{N_E}{N_B(N_E+N_B)} (V_{bi} - V_{BE})}$$

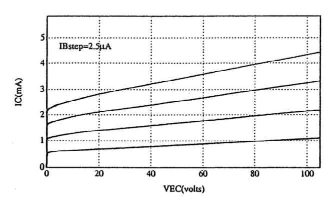
$$x_{p,BC} = \sqrt{\frac{2k_s\varepsilon_0}{q} \frac{N_C}{N_B(N_C+N_B)} (V_{bi} - V_{BC})}$$



Gain depends on collector voltage (bad) …
Depletion region width modulation

Problem of Low Base-doping: Early Voltage

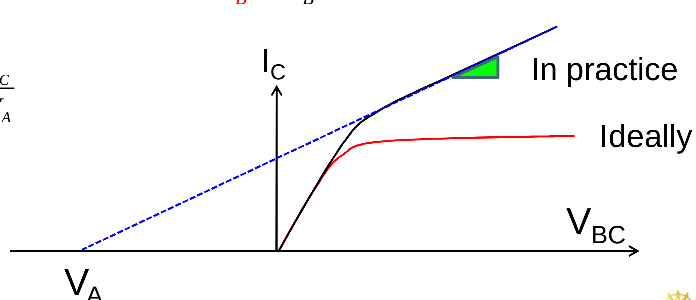
$$\beta_{DC} \approx \frac{D_n}{W_B - x_{p.B} - x_{p.C}} \frac{W_E}{D_p} \cancel{\frac{n^2_{i,B}}{n^2_{i,E}}} \frac{N_E}{N_B}$$



$$I_{n,C} = -\frac{qD_n}{W_B'} \frac{n^2_{i,B}}{N_B}(e^{(qV_{BE}/kT)} - 1) + \frac{qD_n}{W_B'} \frac{n^2_{i,B}}{N_B}(e^{(qV_{BC}/kT)} - 1)$$

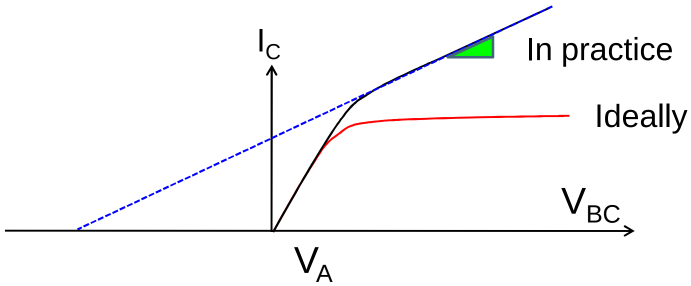
$$\frac{dI_C}{dV_{BC}} = \frac{I_C}{V_{BC} + V_A} \approx \frac{I_C}{V_A}$$

V_{BC} about 1V
V_A ideally infinity



Jim Early
device pioneer

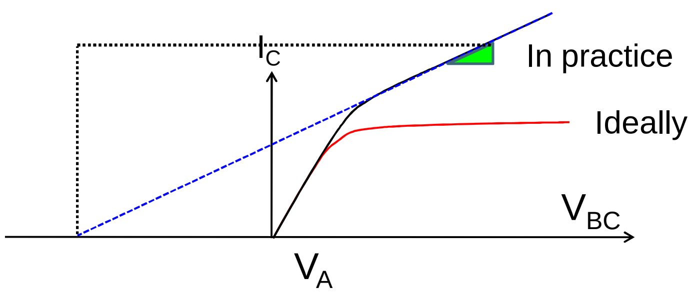
The Early Voltage PS1



- The collector current depends on V_{CE}:
- For a fixed value of V_{BE}, as V_{CE} increases, the reverse bias on the collector-base junction increases, hence the width of the depletion region increases.
  - The quasi-neutral base width decreases → collector current increases.

Due to the Early effect, collector current increases with increasing V_{CE}, for a fixed value of V_{BE}.

The Early Voltage PS2



- The Early voltage is obtained by drawing a line tangential to the transistor *I-V* characteristic at the point of interest.
- The Early voltage equals the horizontal distance between the point chosen on the *I-V* characteristics and the intersection between the tangential line and the horizontal axis.
- Early voltage is indicated on the figure by the horizontal dotted line

Punch-through and Early Voltage

$$\frac{dI_C}{dV_{BC}} = \frac{I_C}{V_{BC}+V_A} \approx \frac{I_C}{V_A}$$

$$\frac{dI_C}{dV_{BC}} = \frac{dI_C}{d(qN_BW_B)}\frac{d(qN_BW_B)}{dV_{BC}}$$

$$= \frac{1}{qN_B}\left(\frac{dI_C}{dW_B}\right)\left[\frac{dQ_B}{dV_{BC}}\right]$$

$$= -\frac{1}{qN_B}\left(\frac{I_C}{W_B}\right)C_{CB}$$

$$-\frac{C_{CB}}{qN_B}\frac{I_C}{W_B} \approx \frac{I_C}{V_A}$$

$$\Rightarrow V_A = -\frac{qN_BW_B}{C_{CB}} \quad \rightarrow \infty$$

Need higher N_B and W_B or …

$$I_C = \frac{qD_n}{W_B}\frac{n_{i,B}^2}{N_B}\left(e^{qV_{BE}\beta}-1\right) + \frac{qD_n}{W_B}\frac{n_{i,B}^2}{N_B}\left(e^{qV_{BC}\beta}-1\right)$$

$$= \frac{\xi}{W_B}$$

$$\frac{dI_C}{dW_B} = \frac{d}{dW_B}\left(\frac{\xi}{W_B}\right) = -\frac{\zeta}{W_B^{\;2}}$$

$$= -\frac{I_C}{W_B}$$

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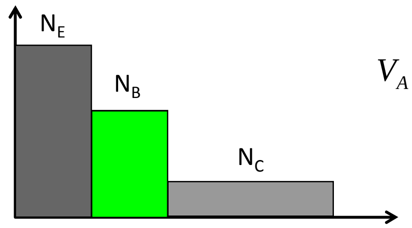
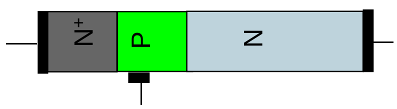
Collector Doping

$$\beta \approx \frac{D_n}{W_B - x_{p,B} - x_{p,C}} \frac{W_E}{D_p} \cancel{\frac{n_{i,B}^2}{n_{i,E}^2}} \frac{N_E}{N_B}$$





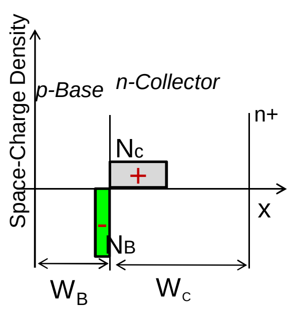
$$V_A = -\frac{qN_B W_B}{C_{CB}} \qquad C_{CB} = \frac{\kappa_s \varepsilon_0}{x_{n,C} + x_{p,B}}$$

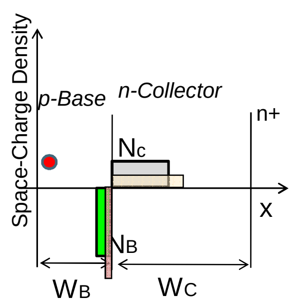
Base-Collector in reverse bias
⇒Majority carriers only
⇒No diffusion capacitance

⇒Reduce capacitance
⇒Increase x_{nC}

If you want low base doping then reduce collector doping even more to increase Collector depletion.....

... but (!) Kirk Effect and Base Pushout





$$J_C = qv_{sat}n$$

Additional charge! Can be large compared to low doping

$$N_B x_B = N_C x_C$$

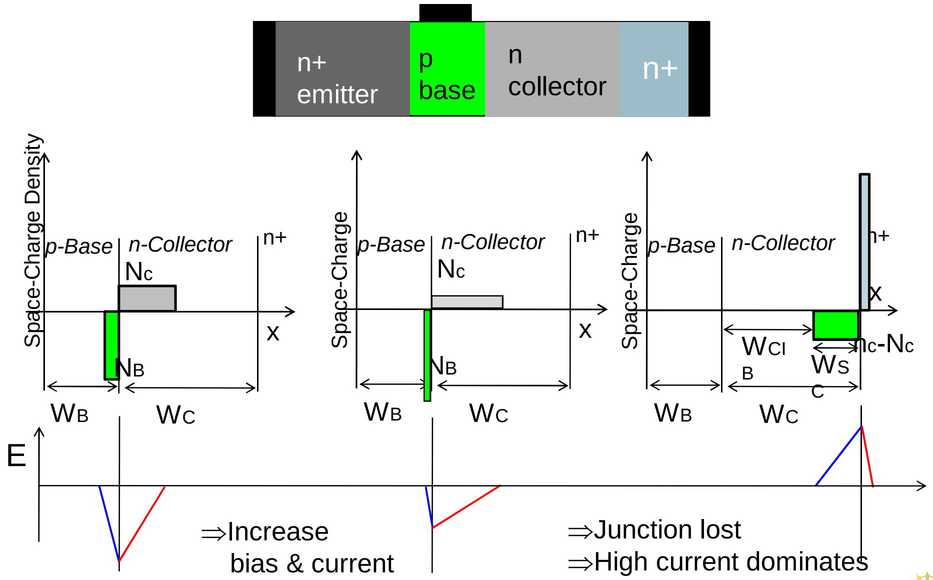
$$V_{bi} - V_{BC} = \frac{q}{2\kappa_s \varepsilon_0}\left[N_B x_B^2 + N_C x_C^2\right]$$

$$(N_B + n)x_B' = (N_C - n)x_C'$$

$$V_{bi} - V_{BC} = \frac{q}{2\kappa_s \varepsilon_0}\left[(N_B + n)x_B^2{}' + (N_C - n)x_C^2{}'\right]$$

$$x_C' = x_C\sqrt{\frac{1+\frac{n}{N_B}}{1-\frac{n}{N_C}}} = x_C\sqrt{\frac{1+\frac{J_C}{qv_{sat}N_B}}{1-\frac{J_C}{qv_{sat}N_C}}}$$

Kirk Effect and Base Pushout



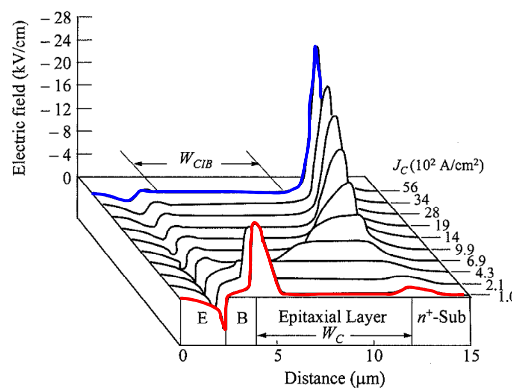
⇒Increase
bias & current

⇒Junction lost
⇒High current dominates collector doping

Kirk Effect and Base Pushout

$$x_C' = x_C \sqrt{\frac{1+\frac{J_C}{qv_{sat}N_B}}{1-\frac{J_C}{qv_{sat}N_C}}}$$

$$J_{C,crit} = qv_{sat}N_C \equiv J_K$$



Can not reduce collector doping
arbitrarily without causing base pushout

Kirk Effect

The Kirk effect occurs at high current densities in a bipolar transistor. The effect is due to the charge density associated with the current passing through the base-collector region. As this charge density exceeds the charge density in the depletion region the depletion region ceases to exist. Instead, there will be a build-up of majority carriers from the base in the base-collector depletion region. The dipole formed by the positively and negatively charged ionized donors and acceptors is pushed into the collector and replaced by positively charged ionized donors and a negatively charged electron accumulation layer, which is referred to as base push out. This effect occurs if the charge density associated with the current is larger than the ionized impurity density in the base-collector depletion region. Assuming full ionization, this translates into the following condition on the collector current density.

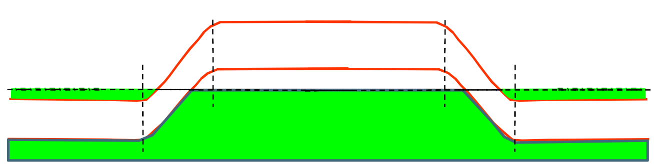
Key point : Under high current and low collector doping the depletion approximation is invalid in the C-B junction!

Perhaps High Doping in Emitter?

Band-gap narrowing reduces gain significantly …

$$\beta \approx \frac{D_n}{W_B}\frac{W_E}{D_p}\frac{n_{i,B}^2}{n_{i,E}^2}\frac{N_E}{N_B} = \frac{D_n}{W_B}\frac{W_E}{D_p}\frac{N_C N_V e^{-E_{g,B}/kT}}{N_C N_V e^{-E_{g,E}/kT}}\frac{N_E}{N_B} \approx e^{-\Delta E_g/kT}\frac{N_E}{N_B}$$

(Easki-like) Tunneling cause loss of base control …



While basic transistor operation is simple, its optimum design is not.

In general, good transistor gain requires that the emitter doping be larger than base doping, which in turn should be larger than collector doping.

If the base doping is too low, however, the transistor suffers from current crowding, Early effects. If the collector doping is too low, then we have Kirk effect (base push out) with reduced high-frequency operation and if the emitter doping is too high then the gain is reduced.