EE 724 PN Junctions L3

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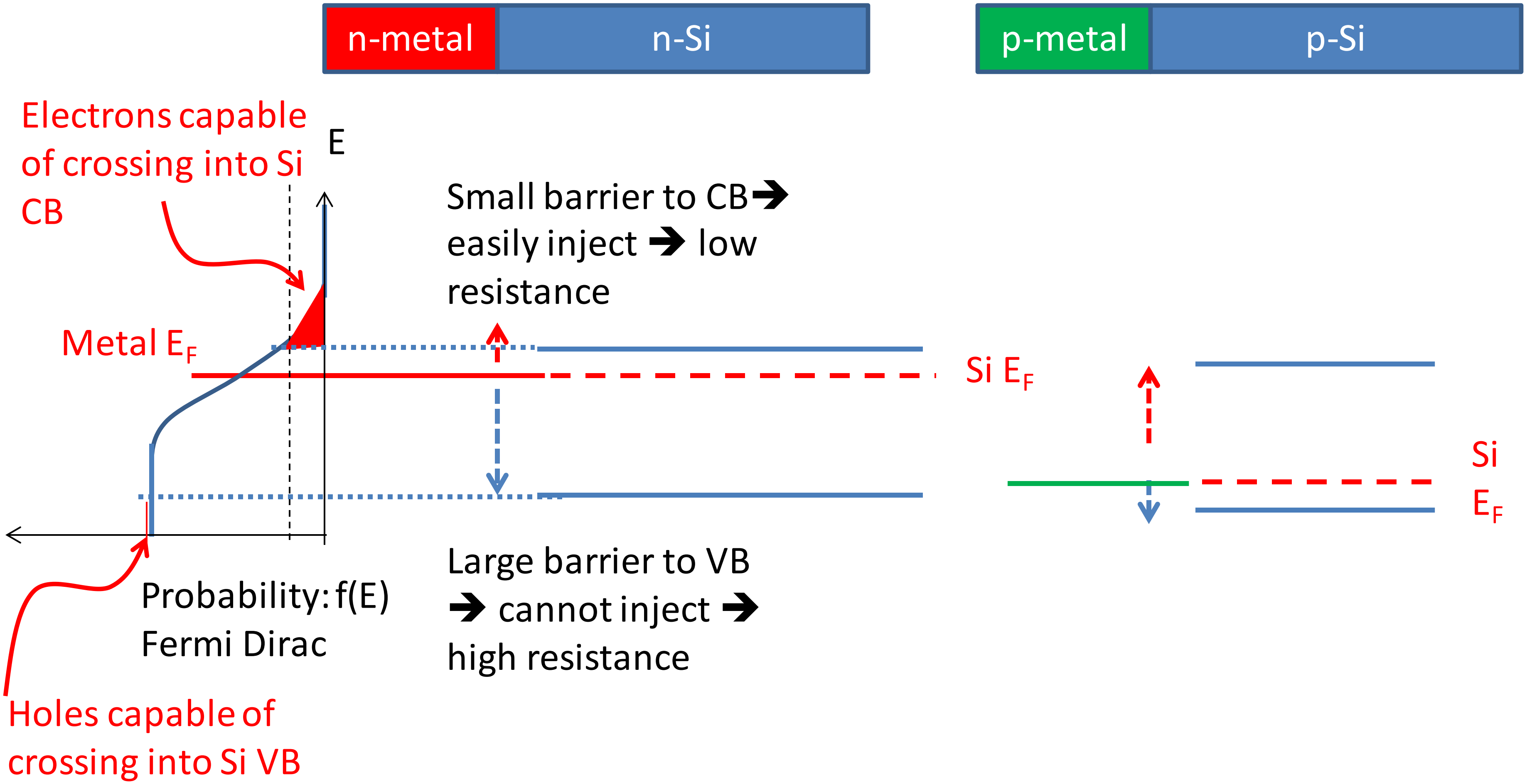
March 4, 2019

n/p-metal contact to semiconductor

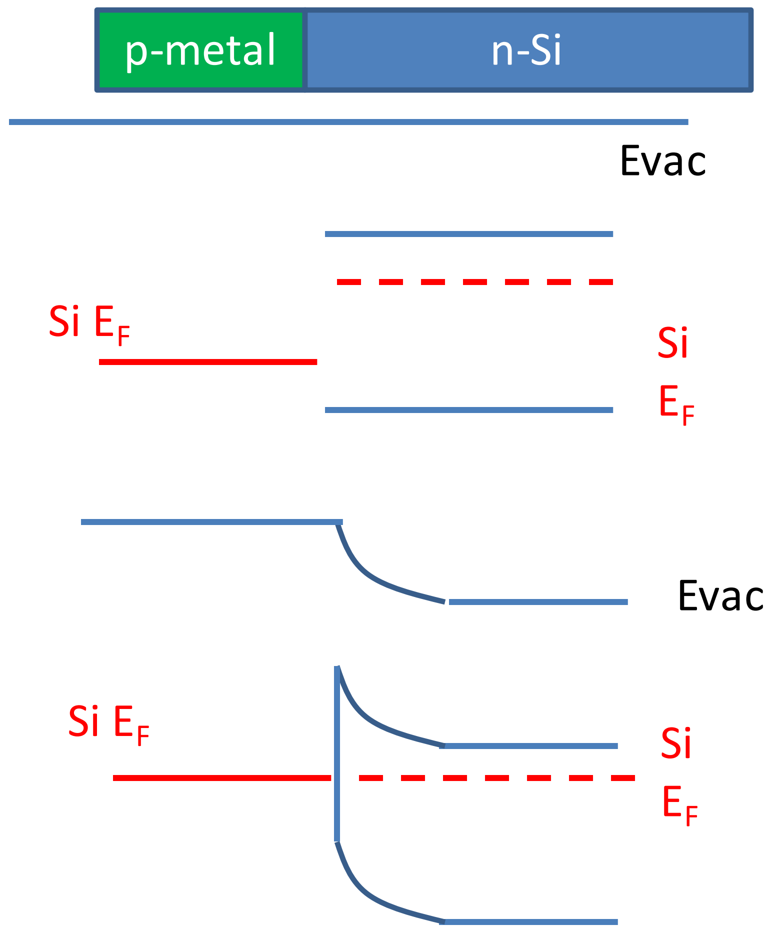


A metal work function closer to Si CB is able to inject electrons easily into CB but not holes into VB : n-type metal
Conversely p-metal may be defined.

Note: band bending is small because metal / Si Fermi levels are initially aligned.

Schottky barrier

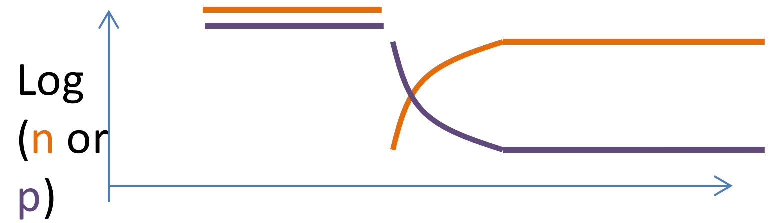
1. Electrostatics

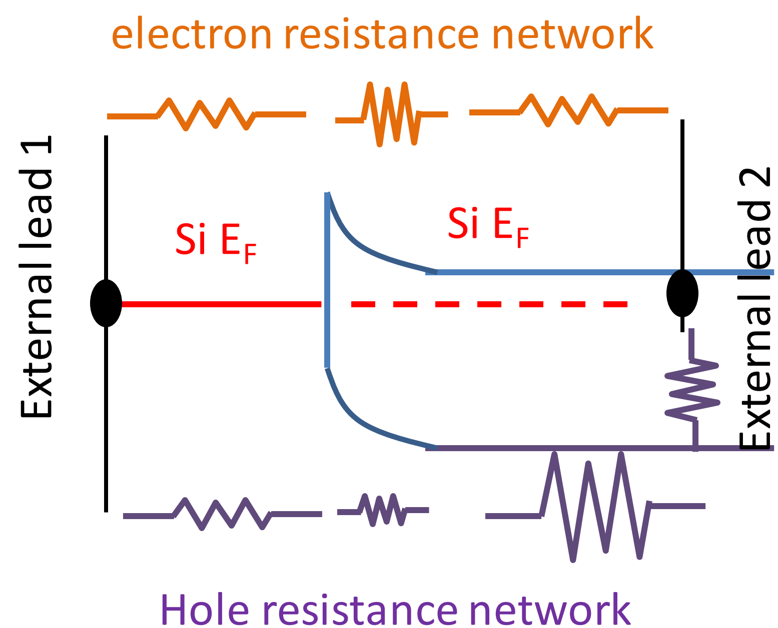


Band bending can be calculated by depletion approximation

2. Transport

To make resistor network, (1) plot free carrier profile (2) convert $R=1/q\mu n$





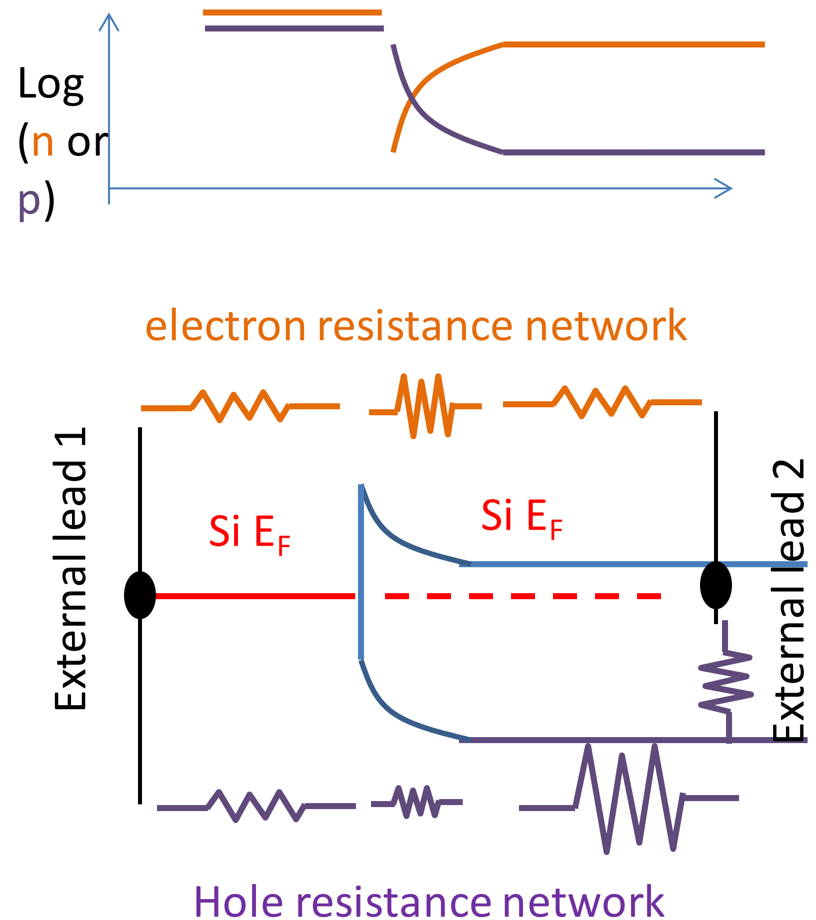
Based on the resistor network, electron current will dominate.

PS: External lead 2 must be an n-contact; so there may be addition resistance to VB

Method

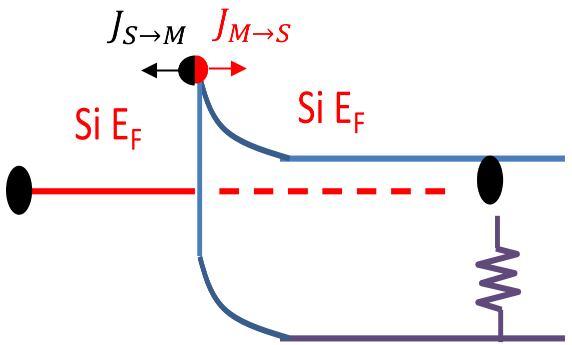
1. Choose Equilibrium band diagram
2. Plot n(x) and p(x)
3. If there was a small bias applied, where will the Fermi level bend?
4. If larger bias was applied where will it bend?

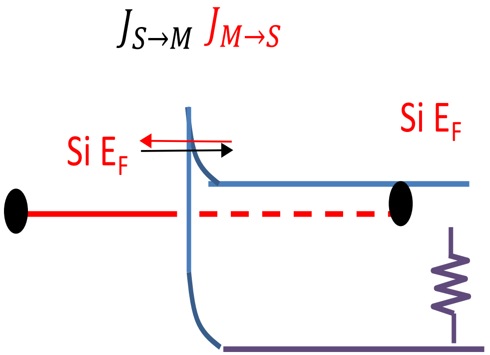
- Think – if Q4 was asked before Q3, what would be the trouble in answering Q4 directly? Would it be easier if you asked yourself Q3 first?



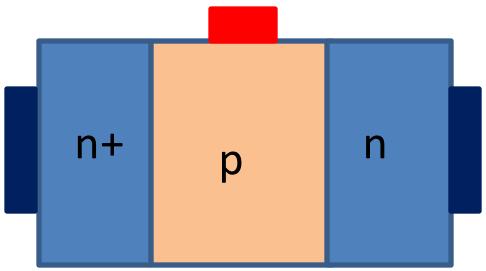
Three limiting cases

- Over-the-Barrier-Current
  - only T dependent in reverse bias
- Tunneling
  - No T dependence but strong V dependence in reverse bias
- Mixed
  - Both T and V dependence

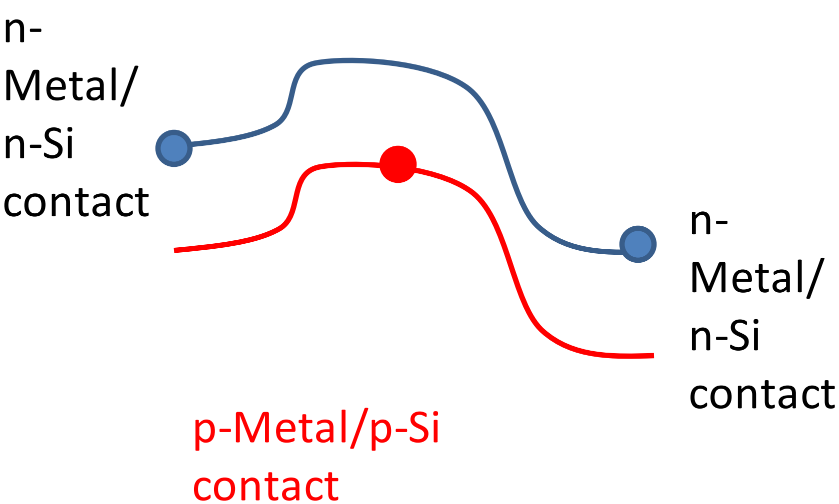




Application1: Band Transport in a BJT



Question 1: Stepwise show how far the current may be calculated using QFL arguments.

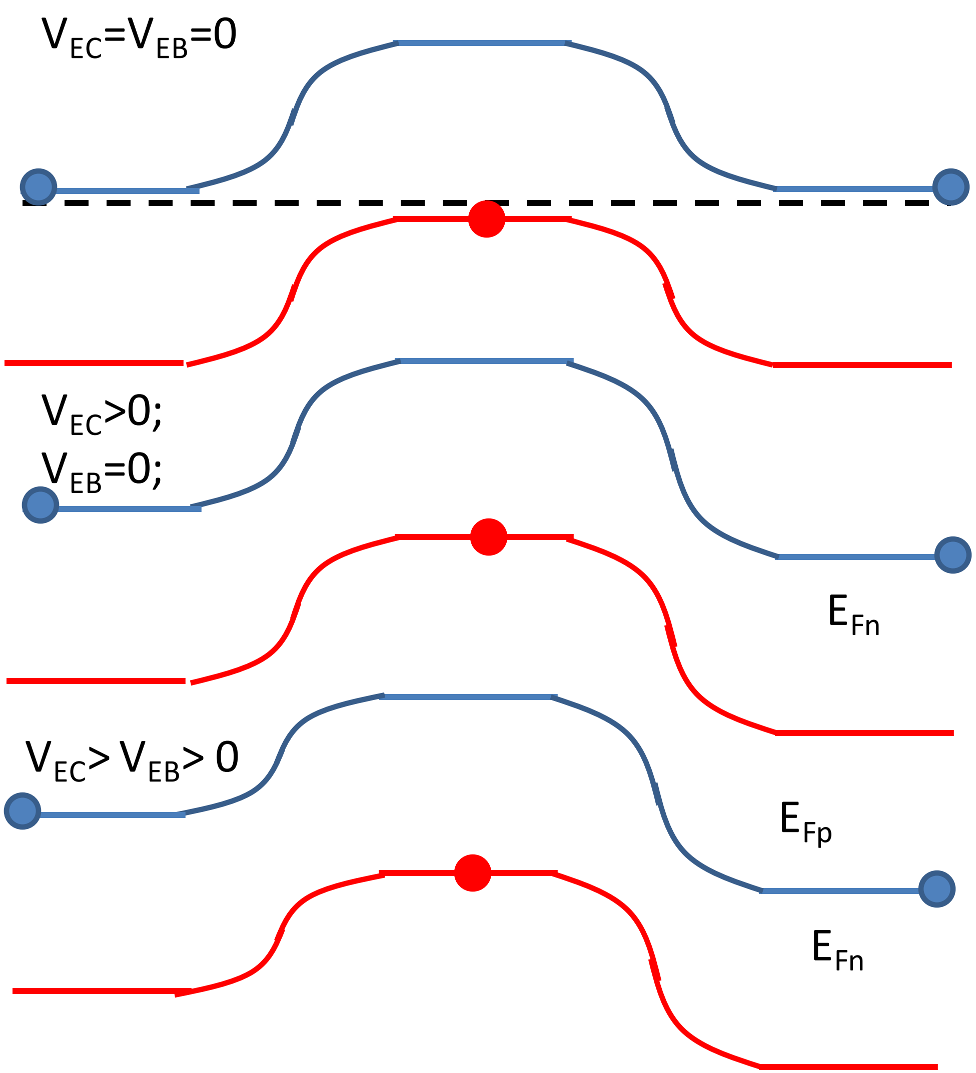


Assume depletion regions are not merged (i.e. not punch-through).

Show I_C, I_b vs V_B @ constant V_C and V_C @ constant V_B

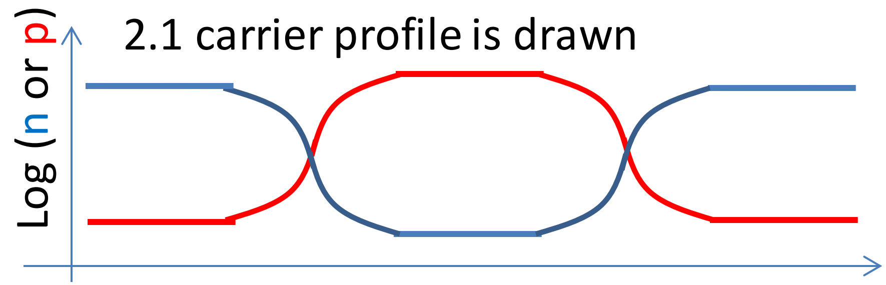
Electrostatics & Transport in BJT

1. Electrostatics: Use Depletion approximation

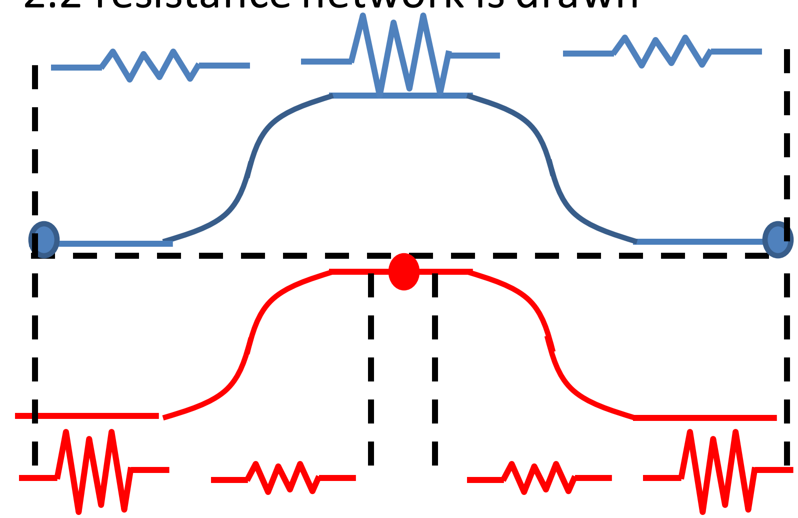


2 Transport (use previous algorithm

2.1 carrier profile is drawn

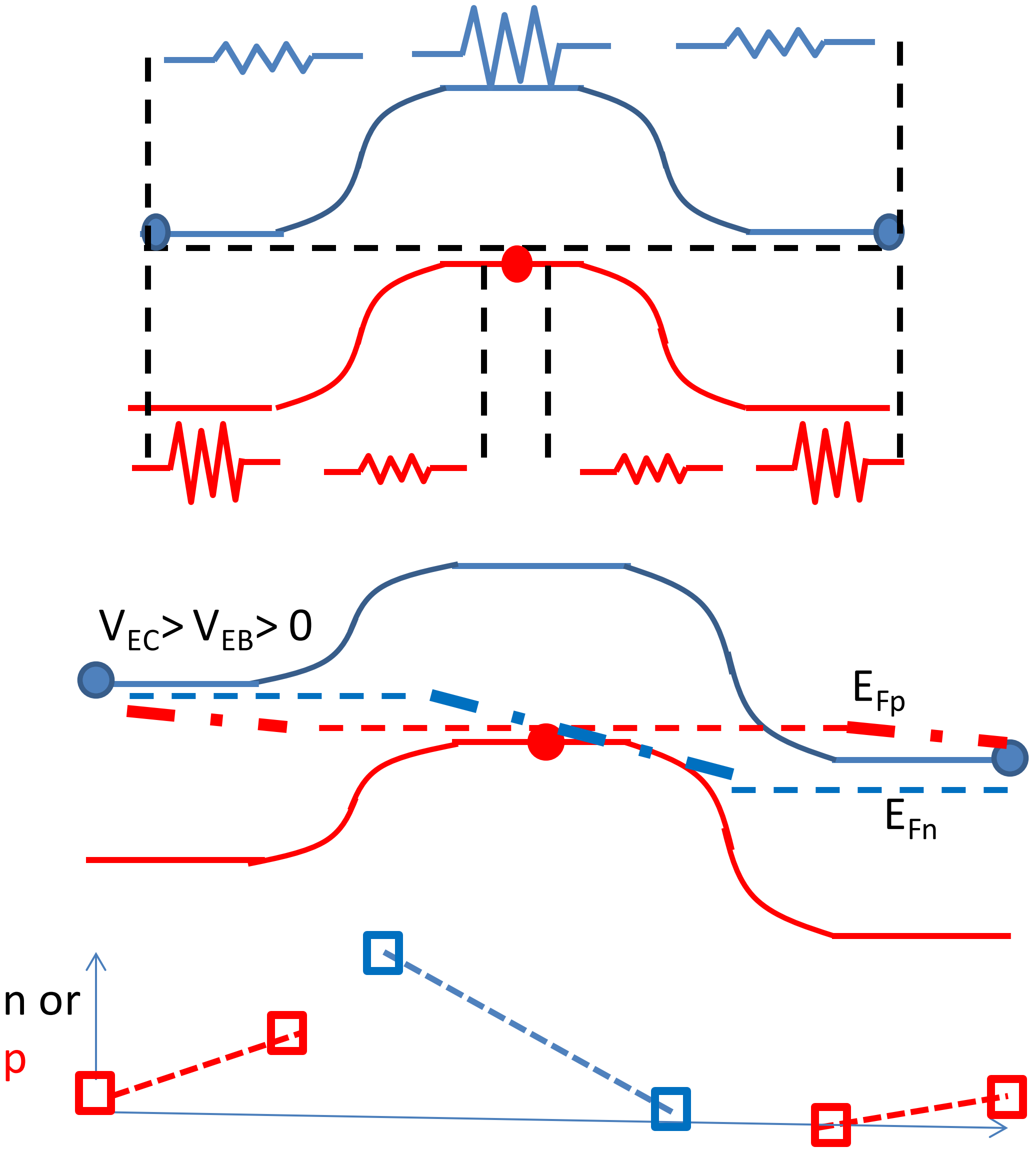


2.2 resistance network is drawn



So we know where the E_{Fn} and E_{Fp} will bend. Or conversely where is it flat. Can we draw this? See in the next page!

BJT transport calculation



2.3 Based on resistor network, we know where E_{Fn} and E_{Fp} is flat Electron and hole conc at edges of diffusion calculation zones known electron ☐ hole. ☐

2.4 Electron ---- and hole ---- profiles are drawn based on transport e.g. diffusion in this case. Other mechanisms will be shown later

2.5 E_{Fn} and E_{Fp} profiles in diffusion calculation regions (where there is gradient) are created based on n and p profiles

Calculating current

Electron current calculated in p-region

$$\frac{dn}{dt} = \nabla J + R = D\frac{d^2n}{dx^2} + \cancel{\frac{n-n_o}{\tau}}=0$$

Assume no recombination $\tau \rightarrow \infty$

e-Current from E to C

$$J_o = J(x) = qD\frac{dn}{dx}= \text{constant}$$

$$\Rightarrow \frac{dn}{dx}= \text{constant}=\frac{n_L-n_R}{l_p}$$

Where $n_L = \frac{n_i2}{N_A}\exp(\frac{V_{EB}}{V_T})$; forward biased

$n_R = \frac{n_i2}{N_A}\exp(-\frac{V_{BC}}{V_T})$; reverse biased

l_p: quazi neutral p-region (which also has a V_{BE} and V_{BC} dependence based on depletion approximation)

Similarly ; you may calculate hole current at the various junctions
Which hole current dominated EB or CB?

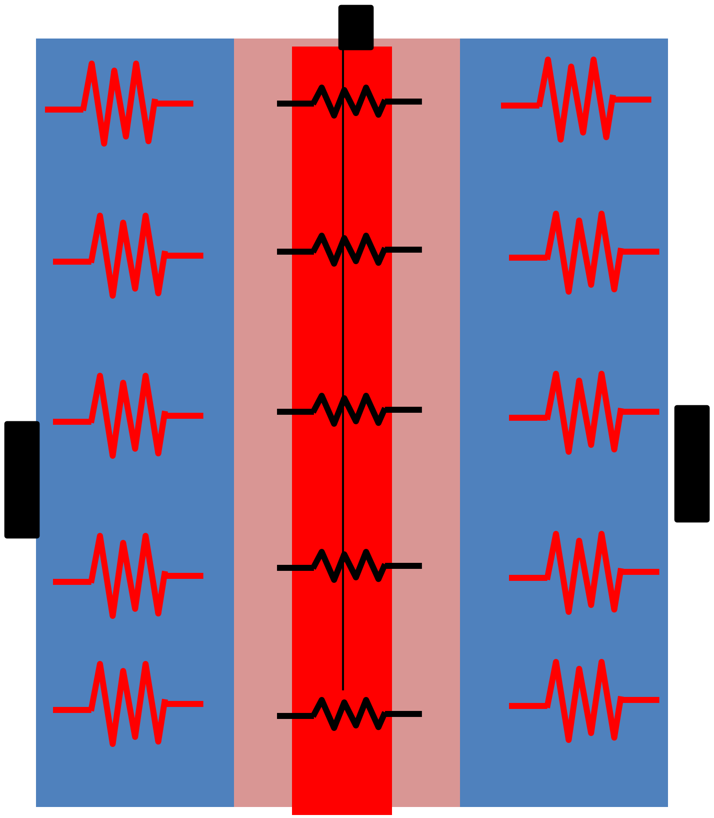
h-Current from E to C

$$J_o = \frac{qD}{l_{nE}}\frac{n_i2}{N_{DE}}(\exp(\frac{V_{EB}}{V_T})\text{-}1)$$

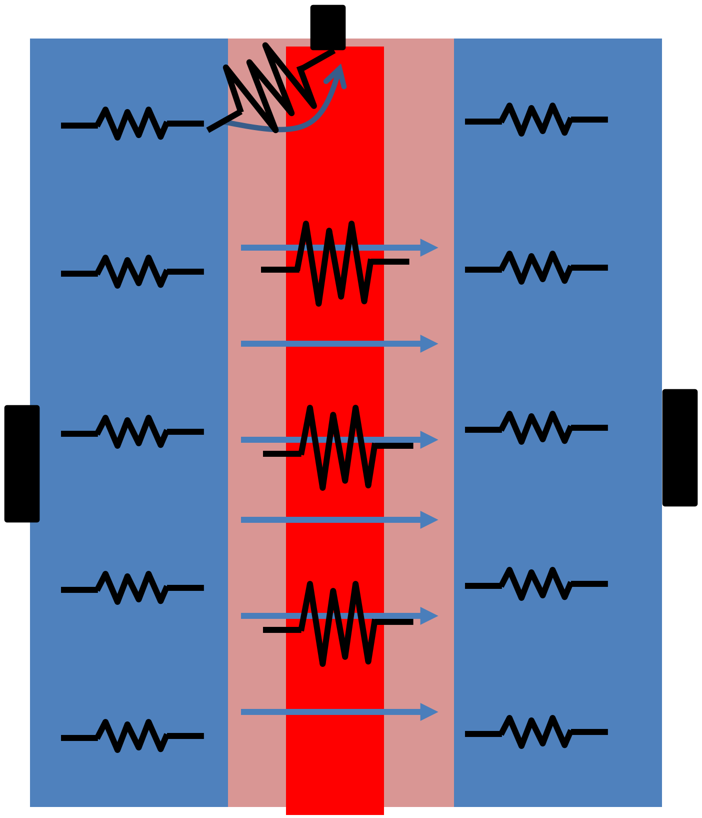
e-Current from E to C

$$J_o = \frac{qD}{l_p}\frac{n_i2}{N_A}(\exp(\frac{V_{EB}}{V_T})\text{-}\exp(-\frac{V_{BC}}{V_T}))$$

Difference between base contact effect to control base potential vs. current sink

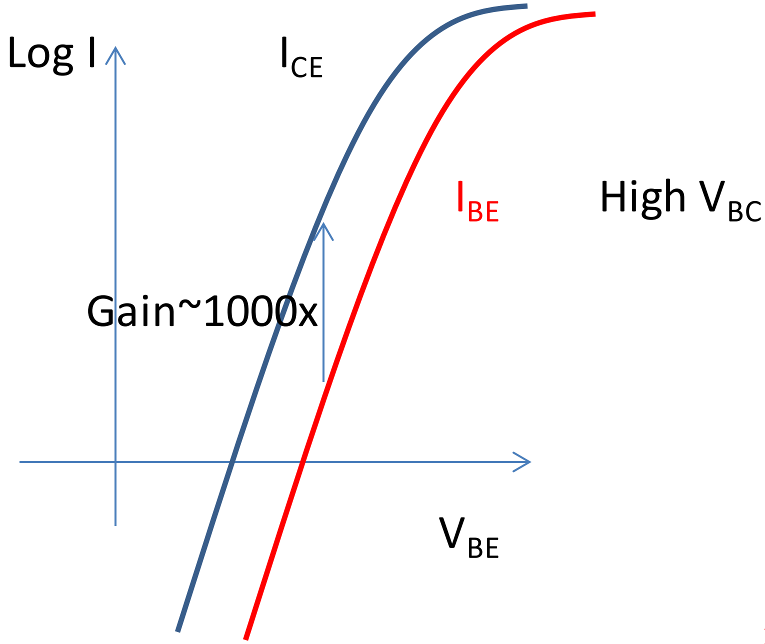


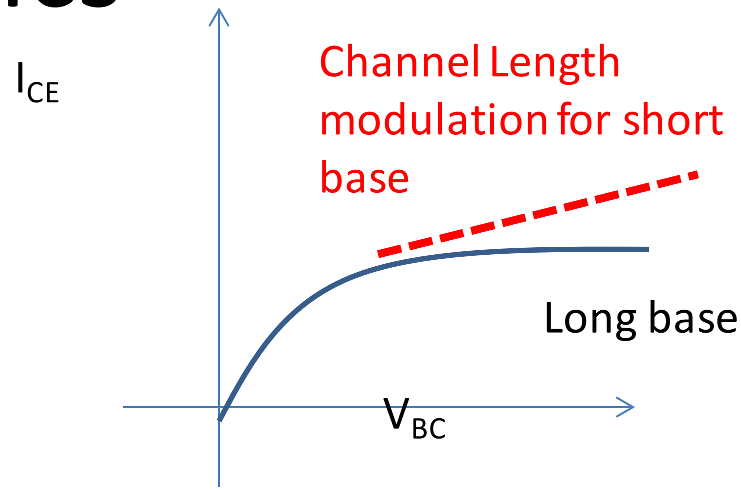
Base contact is strongly electrically coupled (potential divider model) to entire base



Fraction of e-current makes it to base contact due to geometry effect;
Only a small fraction (local) electrons reach base; rest majority reach S/D

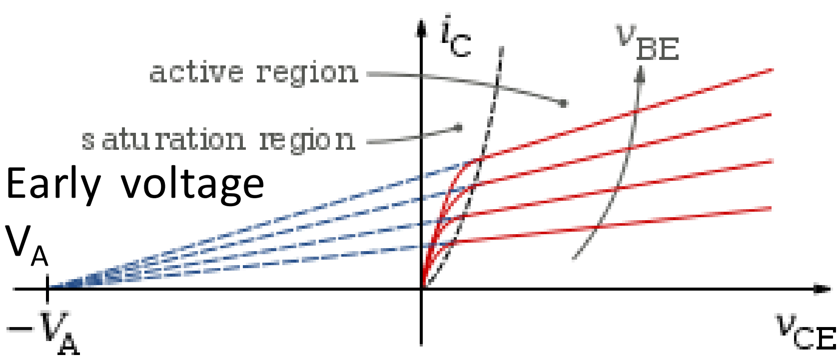
BJT IV characteristics





e-Current from E to C

$$J_o = \frac{qD}{\boldsymbol{l_p}}\frac{n_i 2}{N_A}(\exp(\frac{V_{EB}}{V_T})\text{-}\exp(-\frac{V_{BC}}{V_T}))$$

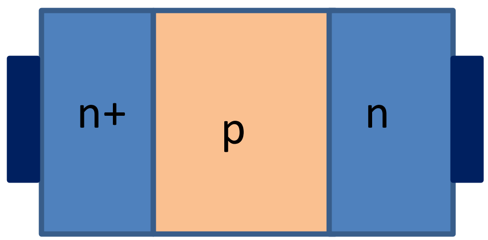


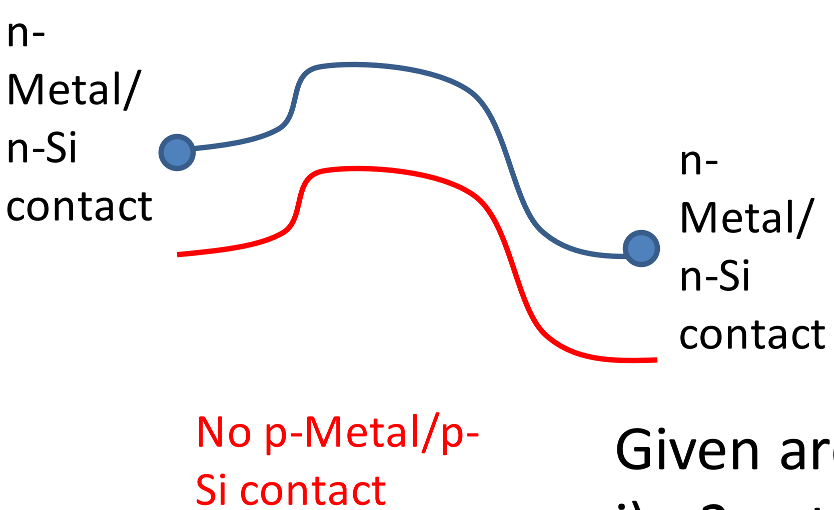
l_p: quazi neutral p-region (which also has a V_{BE} and V_{BC} dependence based on depletion approximation)

For long base, *lp* % change due to V_{BC} is low but high for short base

Application 2: Transport in punch-through diode

Punch-through diodes are used for (i) ESD protection (b) RRAM selector devices





Question 1: Show how far the current may be calculated using QFL arguments;

a) With punch-through of depletions at V=0 b) With punch-through of depletions at V=V+ ? Guess the IV characteristics and band profile.

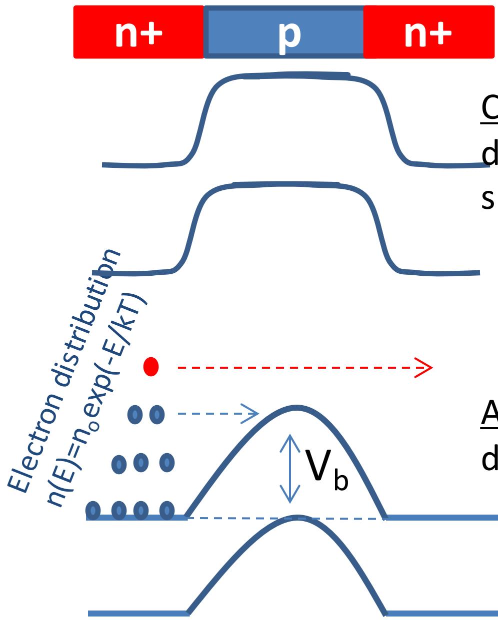
Given are other device options;

i) 2 antiparallel diodes
ii) Two anti-serial Schottky diodes

What are the advantages vs. disadvantages

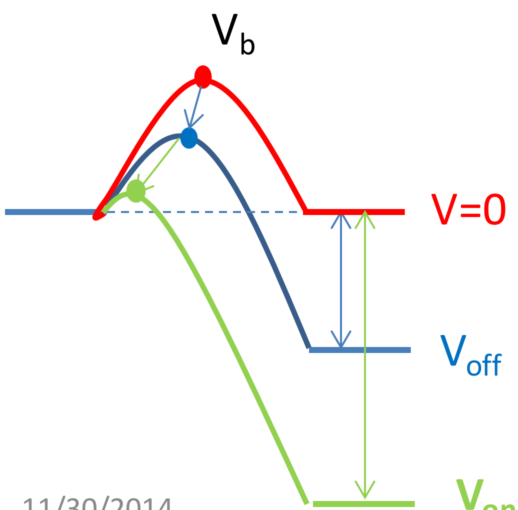
[13]S Lashkare, ICEE 2012

Punch-through diode as Selector



Conventional n+pn+ junction: depletion regions are separate (e.g. BJT, MOSFET)

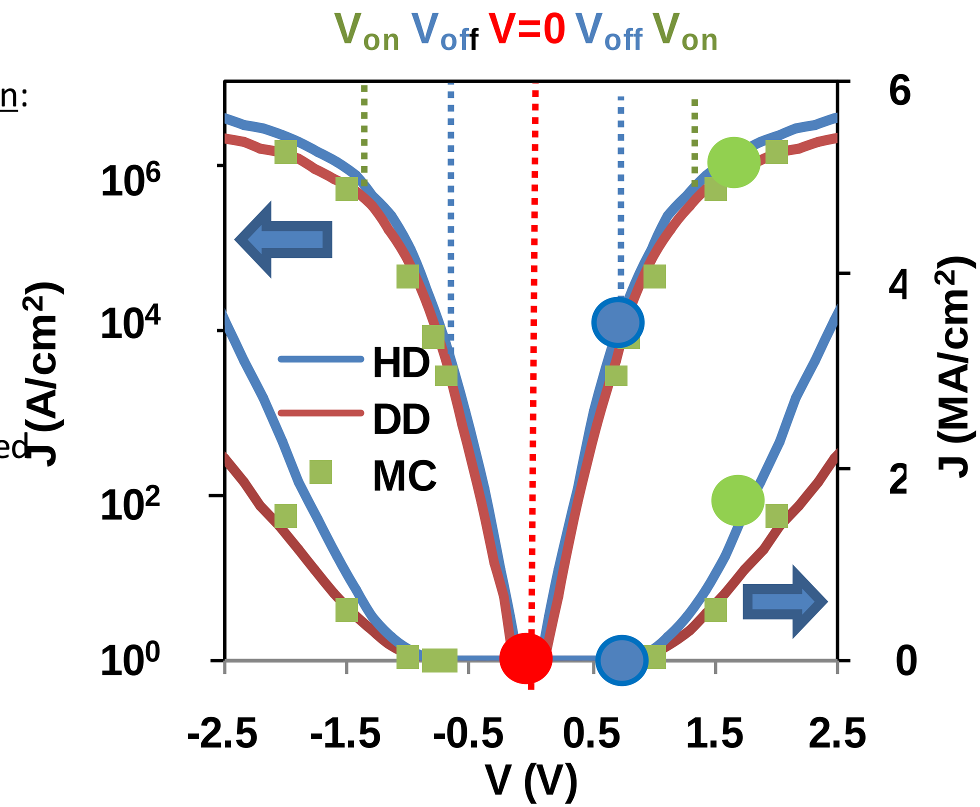
A punch-through diode: depletion regions are merged



Punch-through

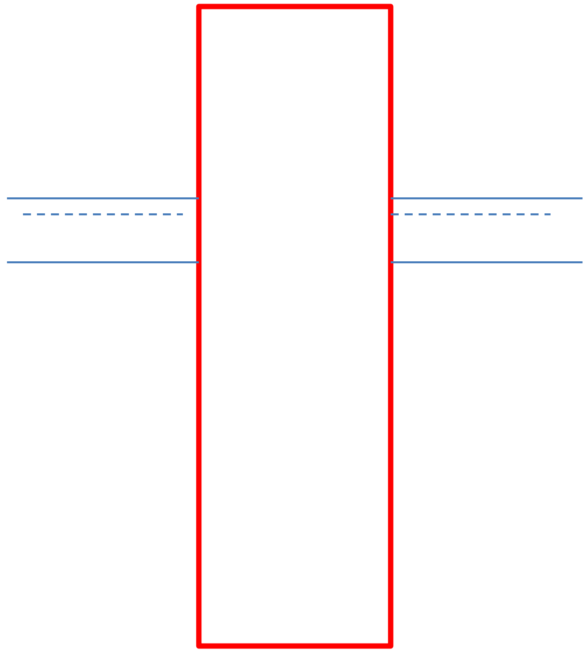
Barrier modulated (I~exp(V))

SCLC (I~V, V²)



Ambipolar operation (turns on in both polarity) based on punch-through

Application 3a: A case of Si n+/insulator/n+ junction

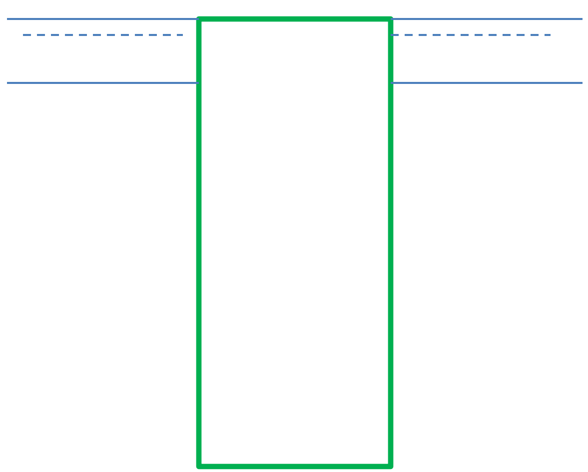


- Plot carrier profiles; Where is the maximum resistance?

- Does it matter
  - if the contacts are metals or highly doped semiconductors? Draw band diagram & derive current. What type of device is this?

Application 3b: A case of Si n+/insulator/n+ junction

Contact resistance is defined by Fermi level pinning:

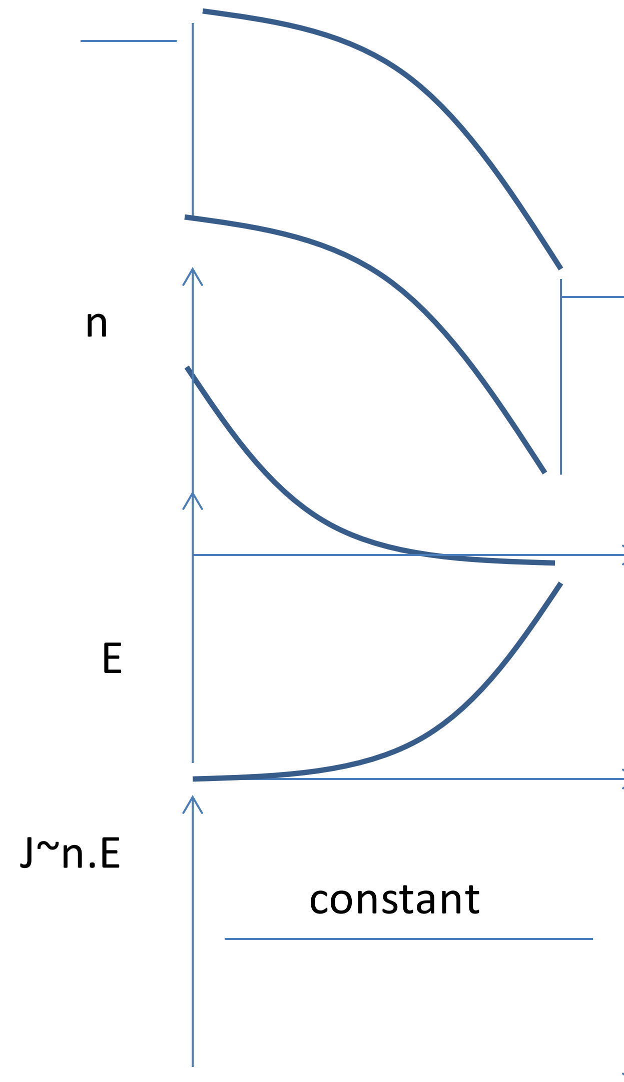


- What happens when the conduction band offset is zero with a fine valance band offset? What type of device is this?

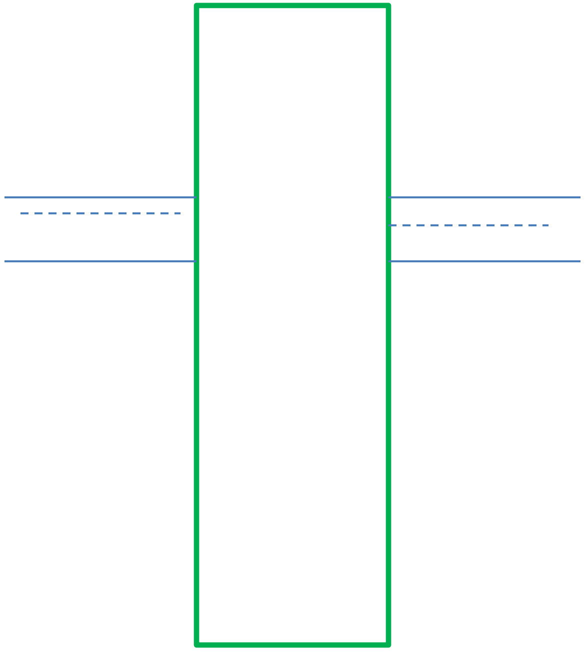
Space Charge Limited Current

- In Ohmic conduction: V only adds electric field that moves intrinsic Carriers
- In insulators; intrinsic charge is low, injected charged is voltage depend (like charging up a capacitor);
- $J(x) = q\mu n(V)E(V) = \mu\left(\frac{CV}{L}\right)\left(\frac{V}{L}\right) = \mu\left(\frac{\epsilon V}{L^2}\right)\left(\frac{V}{L}\right) = \frac{\epsilon\mu V^2}{L^3}$

- More accurate derivation: Drift is dominant
- $J(x) = q\mu n(x)E(x) = Jo$ as there is no recombination
- $n(x) = \frac{J_o}{q\mu E}$... from Drift based transport
- $\frac{dE}{dx} = -\frac{qn(x)}{\epsilon}$ from Poisson
- $\frac{dE}{dx} = -\frac{q}{\epsilon}\frac{J_o}{q\mu E}$
- $E^2 = \frac{2q}{\epsilon}\frac{J_o}{q\mu}x \Rightarrow \frac{dV}{dx} = (2\frac{q}{\epsilon}\frac{J_o}{q\mu}x)^{1/2}$
- $V = \frac{2}{3}(\frac{2q}{\epsilon}\frac{J_o}{q\mu})^{1/2}\,(x)^{3/2} \Rightarrow J_o = \frac{9}{8}\frac{\epsilon\mu V^2}{L^3}$



Application 3c: A case of Si n+/insulator/n+ junction



- What if one side is low doped semiconductors? Draw band diagram & derive current. What type of device is this?