EE 724 PN Junctions L1

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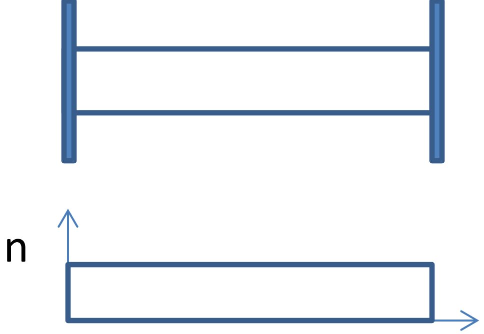
March 4, 2019

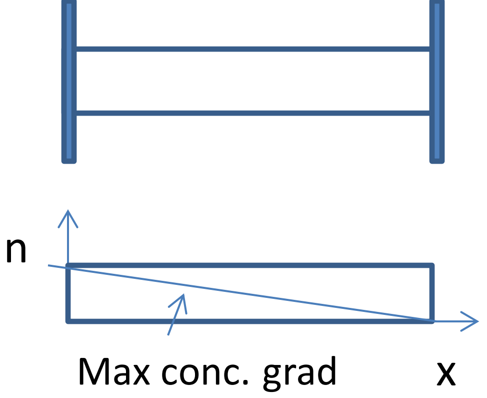
Read pn-junction chapter from Taur and Ning for reference!

Drift vs Diffusion



- A metal rod of length L has voltage V applied across it (assume electron density n /cm^3)
- Think:
  - Will we get a current through the device?
  - Will there be electric field inside a metal?
    - Will it be drift or diffusion
- Pair:
  - Estimate the drift and diffusion current magnitudes; when will drift or diffusion dominate?

Drift and Diffusion



Assume that max n(x)=n;

$$F = -\frac{d\psi}{dx} \qquad J_n = nq\mu_n F + qD_n \frac{dn}{dx}$$

Current has two components

$$J_{ndrift} = nq\mu_n F = nq\mu_n \frac{V}{L}$$

$$J_{ndiff} = qD_n \frac{dn}{dx} < qD_n \frac{n}{L} = qn\mu_n \frac{kT/q}{L} = qn\mu_n \frac{V_T}{L}$$

Max conc. grad

Using Einstein's relation $\frac{D}{\mu} = \frac{kT}{q}$

Bias V > V_T for drift to dominate;
Bias V < V_T for diffusion will dominate;

Solving both drift and diffusion together is always difficult; However if only one current is dominant, current is easy to solve.
Hence we will try to create a strategy such that we need to solve one to get current.
We will see examples of this.

Basics of pn-junction

Take 3 min to write this down by yourself.

- Based on Poisson's equation, draw the band diagram of uniform $N_D = N_A = 10^{15}/cc$ doped pn junction in
  - Equilibrium
  - Forward bias
  - Reverse bias
- Calculate the built-in potential

- Calculate depletion region at applied bias V (forward and reverse)

Deriving IV characteristics

Take 5 min to write this down in a group of 2-3.

- In equilibrium, show that if I=0 then show that E_F is flat.

$$F=-\frac{dV}{dx} \qquad J_n=0=nq\mu_n F+qD_n\frac{dn}{dx} \qquad F=-\frac{D_n}{\mu_n}\frac{dn/dx}{n}=-\frac{kT}{q}\frac{d\ln(n)}{dx}$$

Use MB distribution to show that the dE_F/dx=0

- In forward bias vs equilibrium (side by side),

1. Draw the carrier density profile what are the assumptions about Quasi Fermi Level- we will later check this!)
2. Set up diffusion equations
3. Solve for current
4. Using the carrier profile show that shape of E_{Fn} is consistent with your assumption

$$J_n=\underbrace{nq\mu_n F}_{\text{Drift }(F)}+\underbrace{qD_n\frac{dn}{dx}}_{\text{Diff}}=\underbrace{nq\mu_n F_{Fn}}_{\text{Drift }(F_{Fn})} \qquad qF_{Fn}=\frac{dE_{Fn}}{dx} \quad \text{QFL gradient}$$

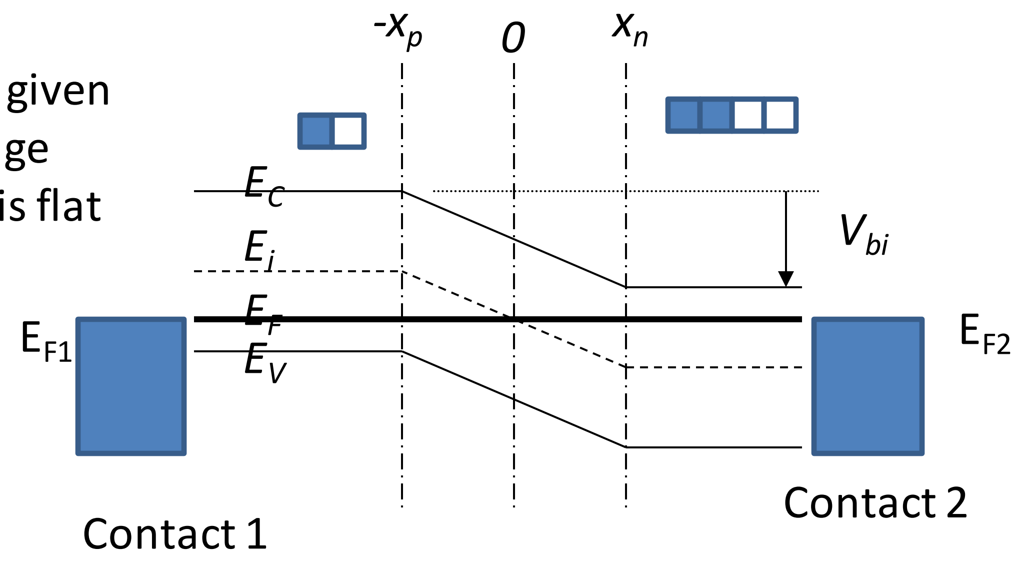
Why consider only diffusion regions? **What about current flow in other areas?**

Equilibrium

QFL description is simple: Do not need to account for diffusion /drift; see if there is a net QFL difference anywhere. If not, there is no current.

Equilibrium band diagram

Q: Show that states at given energy will not exchange particles if fermi level is flat



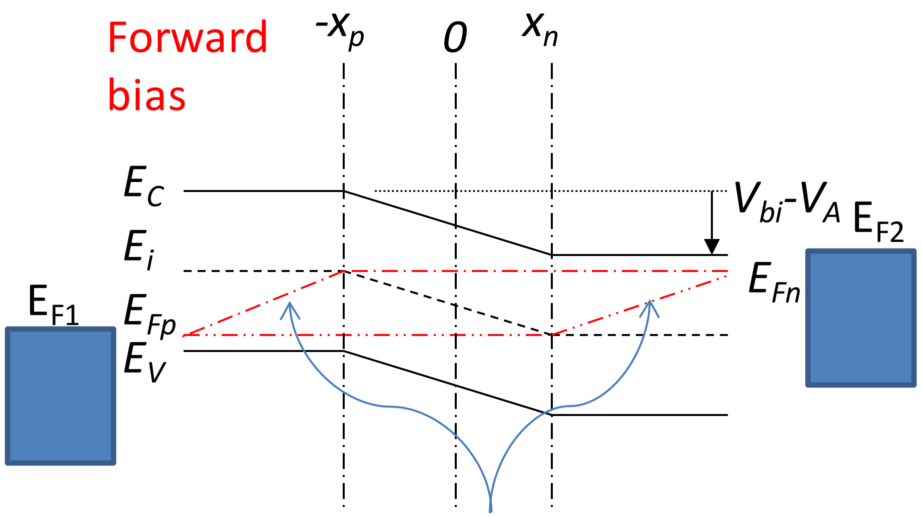
Net flux at given energy $= J_L - J_R = n_L p_L * n_R(1-p_R) - n_L(1-p_L) * n_R p_R$
$= n_L n_R (p_L - p_R - p_L p_R + p_R p_L) = 0$ if $p_L = p_R$

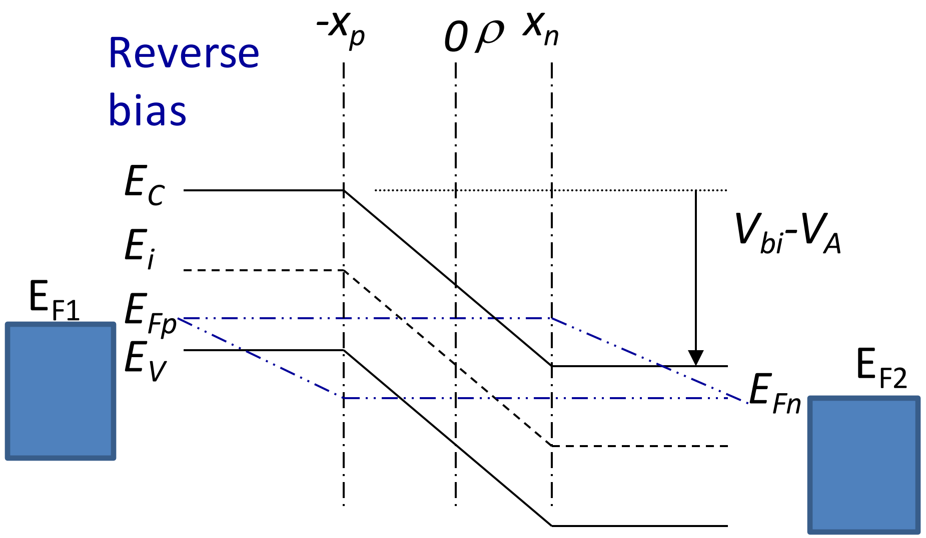
Equilibrium implies that all fermi levels are equal including those of contacts E_{F1} and E_{F2} ; ***All devices and contacts are in equilibrium.***

What is QFL? It describes electron distribution in energy. If there is a difference, current must flow.

Applied Bias and Fermi-Level Split

Now a bias V_A is applied on the N and P sides (Fermi level splits): $\psi_m = V_{bi} \pm V_A$





The E_{Fn} and E_{Fp} part is is approx.

When some bias is applied i.e. the contact $E_{F1} \neq E_{F2}$ the device is out of equilibrium

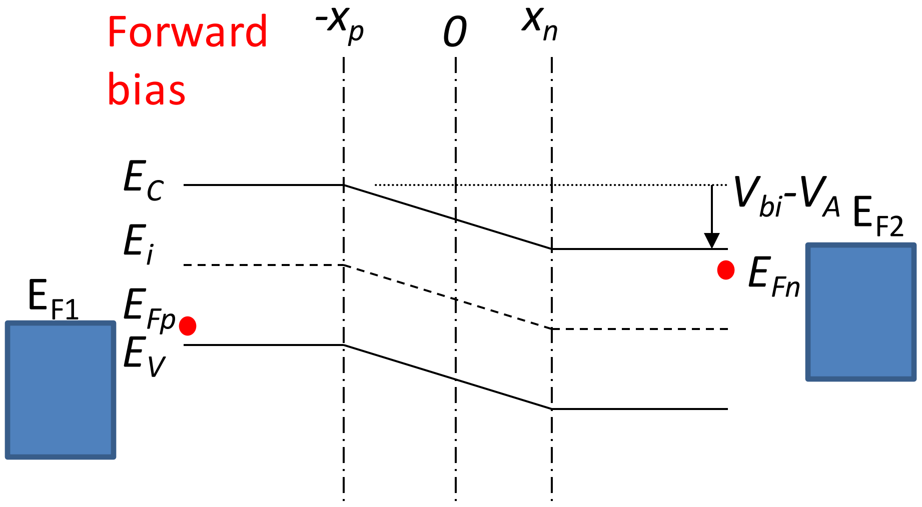
The question is to ask/understand

a) Which part of the device (i.e. n vs p band and position) will be in equilibrium with left contact E_{F1}?
b) Which part of the device will be in equilibrium with right contact E_{F2}?
c) Hence where is the device out of equilibrium with either contacts? i.e. where will the Quasi Fermi level (potential) drop?

Step 1

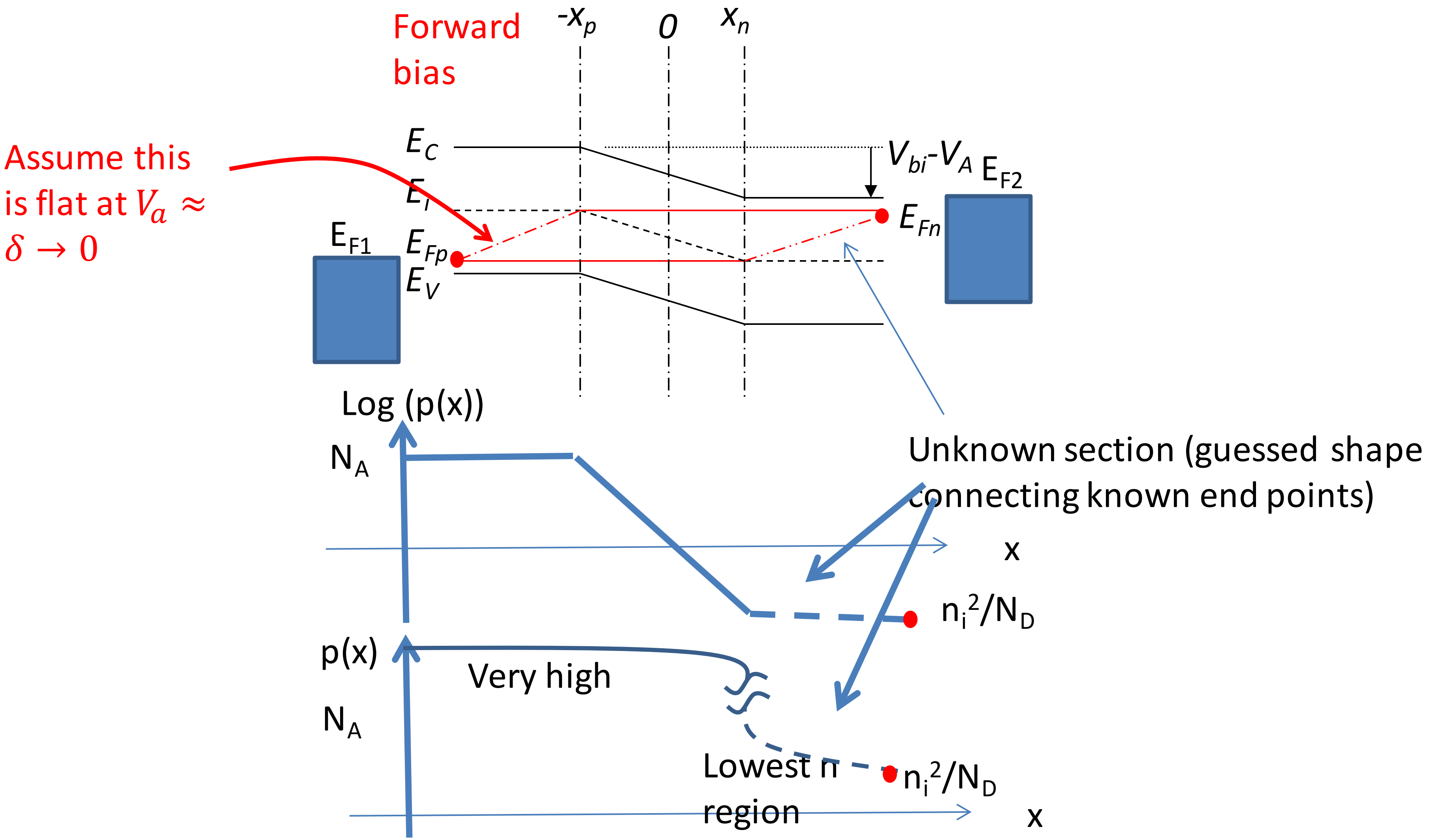
Step 0: Assume a very small potential is applied $V_A = \delta$ to produce a very small forward bias. The electron concentration can be well approximated by the equilibrium profile

Step 1. Contacts are at equilibrium with respective sources



Step 2

Step 2. For small bias $V_a \approx \delta$; we know $E_{Fn} = E_{Fp} = E_F$ is flat then plot n(x) and p(x) in log-lin and then lin-lin scale;
For high bias, we can start from Equilibrium and add small bias and test

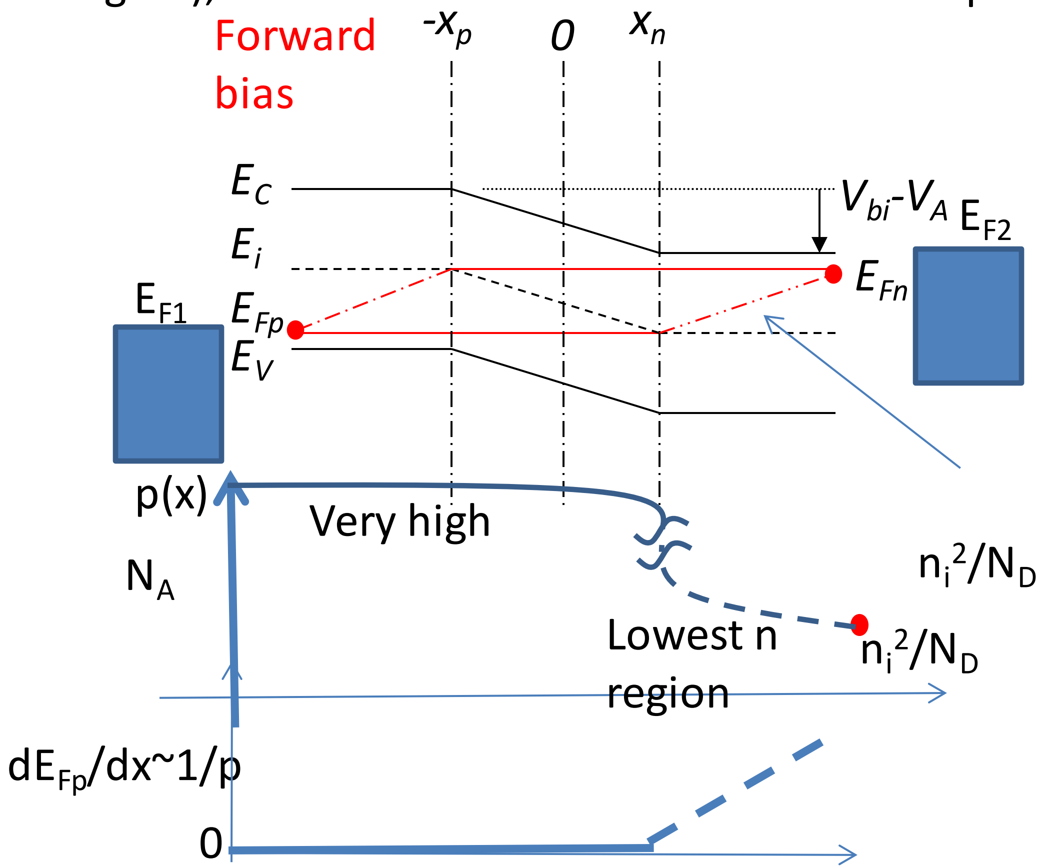


Step 3

Step 3. based on current continuity in steady state $J(x)=J=q\mu\ n(x)\ dE_{Fn}/dx$; Current is position independent as any current mismatch into and out of a position will cause charge pile up ➔ not steady state (pile up increases potential with time); No RG implies that current in conduction or valence bands are independent

So slope of Quasi Fermi Level $\mathbf{dE_{Fn}/dx\sim 1/n(x)}$;

n(x) produces the same Fermi level shape as we had assumed (Flat from n-contact to right across depletion region); hence consistent i.e. the assumed shape of E_{Fn} is correct

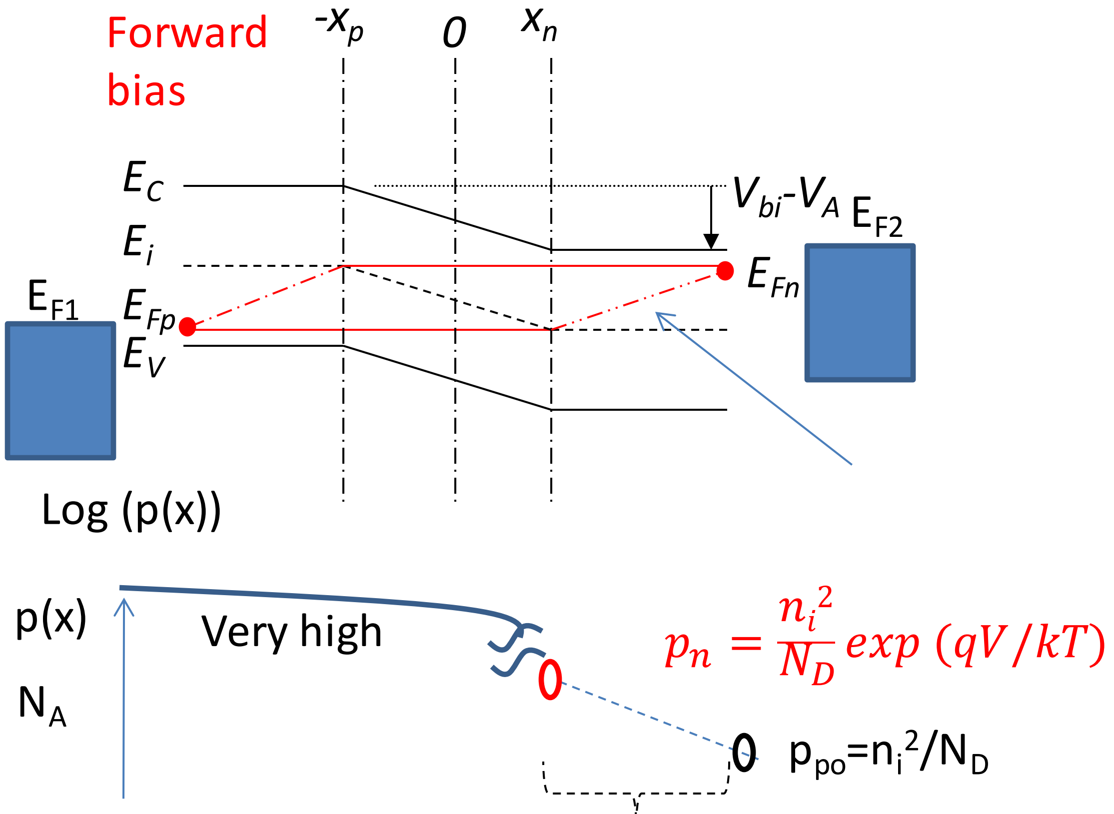


From p(x) ➔ we derive $E_{fp}(x)$

For higher bias; keep doing this with increasing V_a starting from equilibrium (known E_F is flat) and then update the $E_{Fn}(x)$

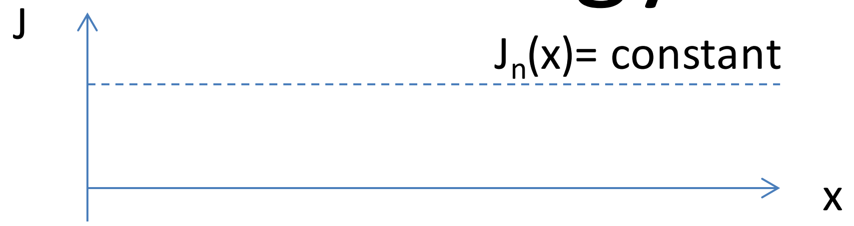
Step 4

Step 4. Set up current calculation where current is being blocked (details of $E_{Fn}(x)$ is most sensitive to current). In this case, in the quasi neutral region, E-field is zero ➔ drift is negligible. Knowing n(x) current can be calculated. This current in steady state is position independent but complicated in other places to calculate due to (a) the need to balance drift and diffusion (b) insensitivity to that place (like a wire connecting a battery to diode. Calculating the current as only defined by the wire makes no sense. It is a short; need to calculate at diode).

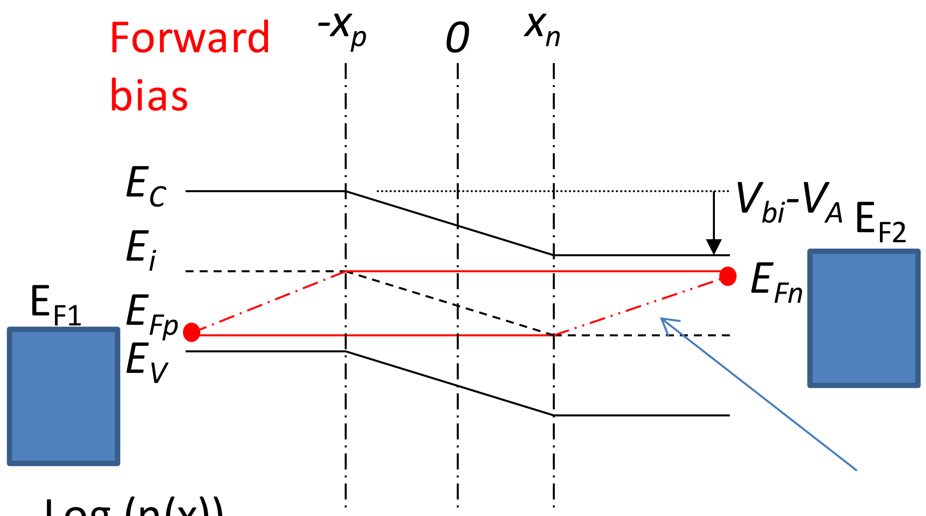


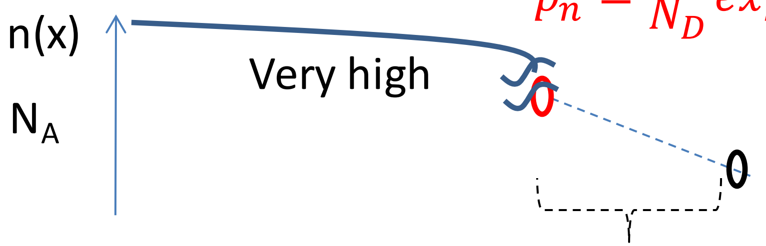
Set up diffusion only current calculation here

Strategy to evaluate J_n (x)



If RG is negligible everywhere; bands do no exchange carriers hence J_n (x)=J_n independent position





$$p_n = \frac{n_i^2}{N_D} exp\ (qV/kT)$$

$$p_{no} = \frac{n_i^2}{N_D}$$

To evaluate in J_n in various regions

1. In p region Quasi Neutral Region (QNR): Jn is given by diffusion current only hence it is easy to evaluate knowing n(x);
2. In depletion and n-region QNR Jn should still be constant; how can we evaluate this?

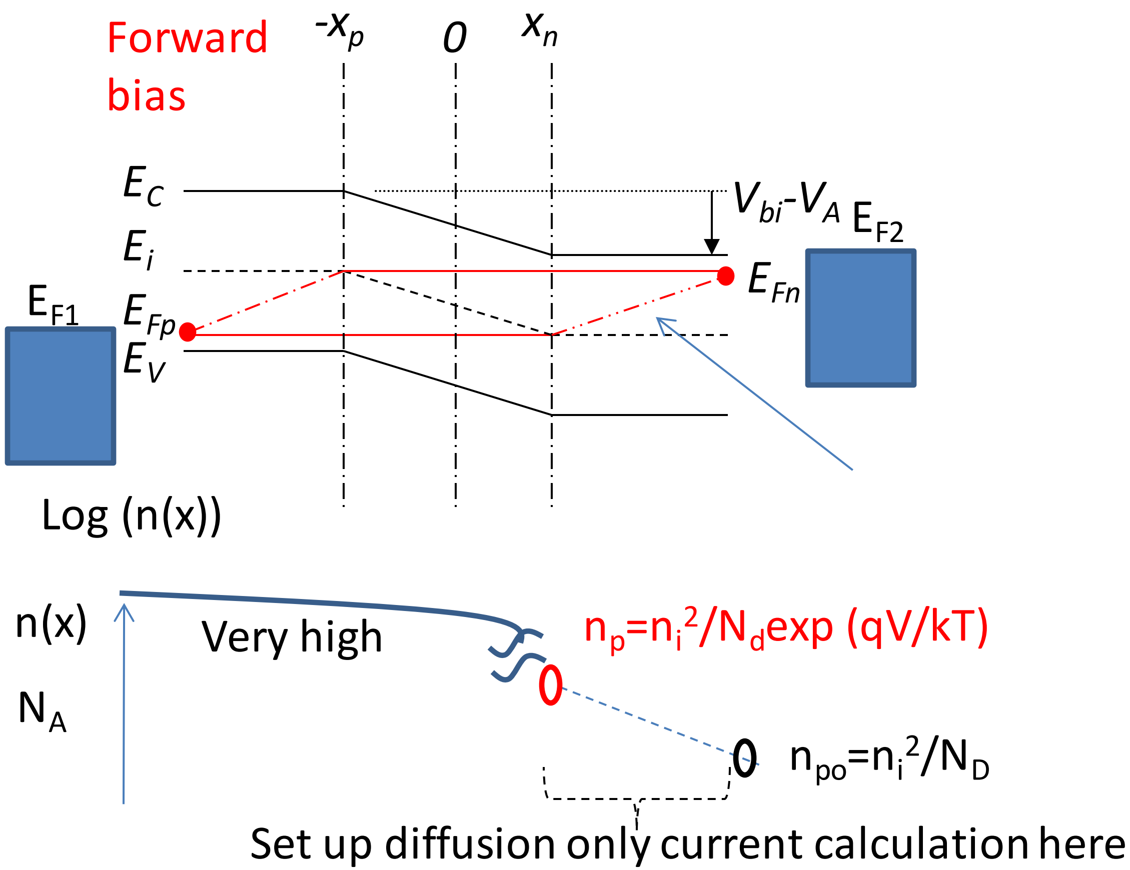
We need to know n(x) and V(x) to calculate drift and diffusion

$$J_n = nq\mu_n F + qD_n \frac{dn}{dx} = nq\mu_n F_{Fn}$$

Or we can use QFL description of current. (we will continue in next part)

Activity

- Think: Where is only diffusion occurring? Where is only drift occurring?
- Pair: Where are both drift and diffusion occurring? How to simplify that? Does QFL help?What does current depend upon (drift/diffusion) in depletion region?
- Why does potential and QFL drop at different places?

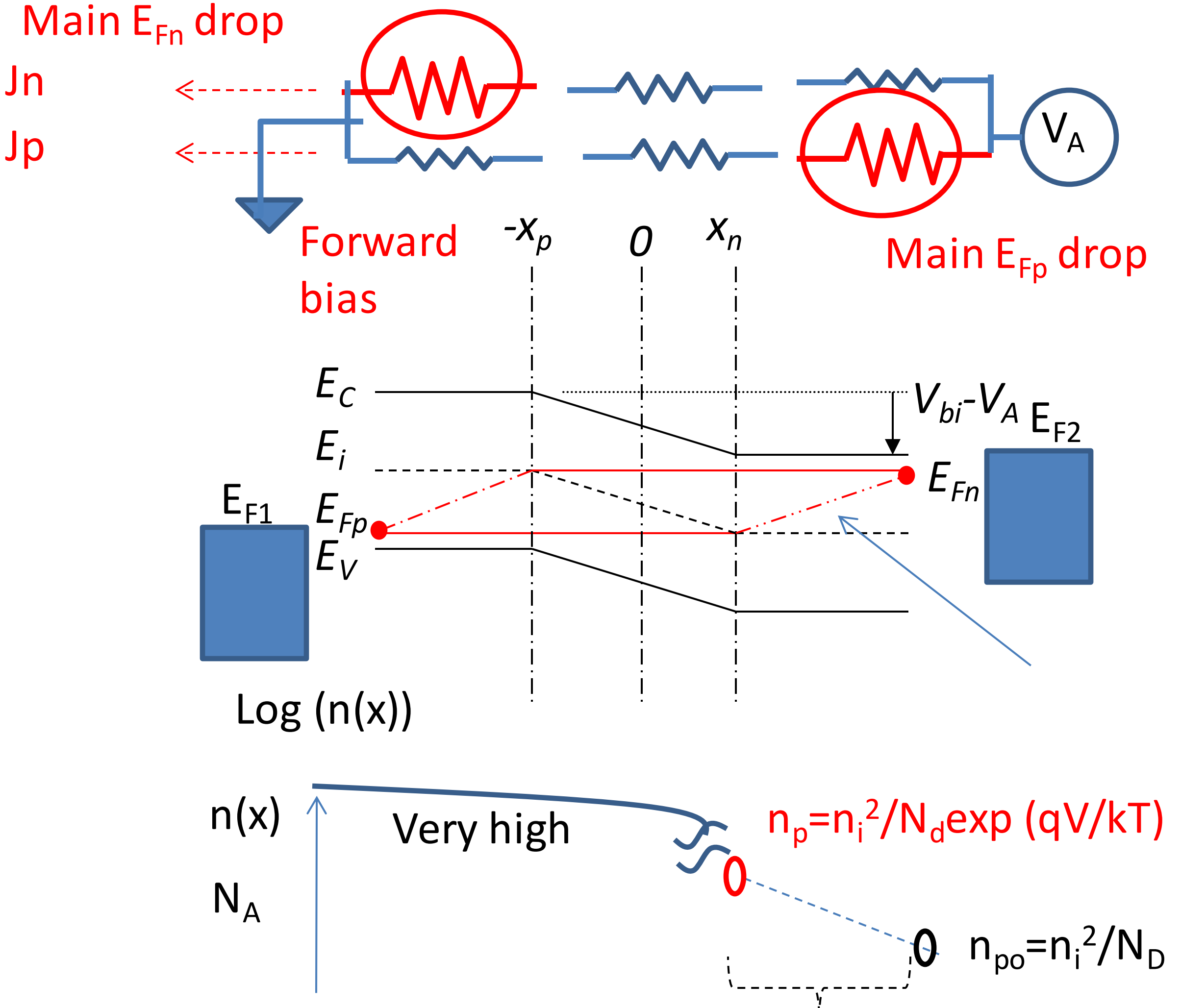


QFL based IV ➔ Resistive Network Model

- The QFL description
  - reduces the Drift Diffusion Competitive model
  - to a Drift only Model by QFL gradient
- Model: QFL is equal to potential which drops across the circuit : Equivalent to R network
- Draw the resistive network model for a pn junction
  - Where will QFL drop?
  - Does it drop at different places for electrons vs. holes?
  - If RG is negligible, do these circuits interact?
  - If there is finite RG, where will the circuits interact.

Resistive network

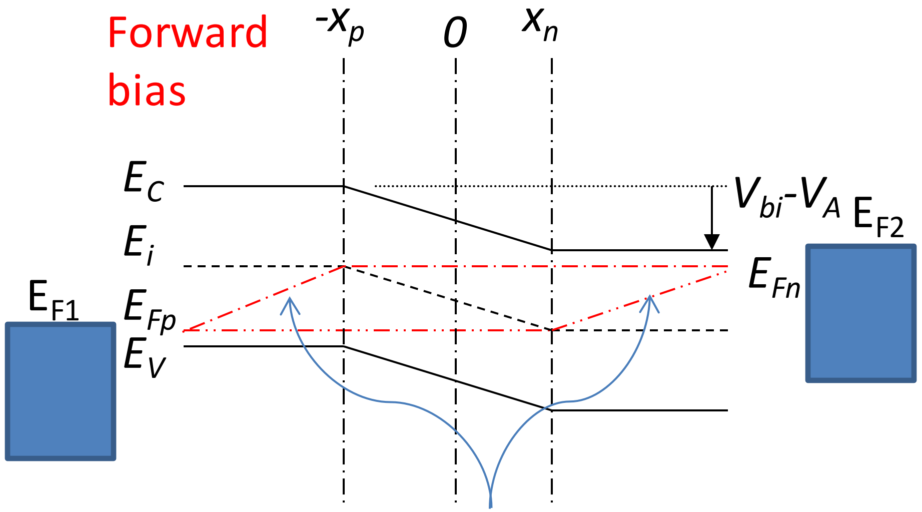
Resistivity depends upon $R = \frac{1}{q\mu n(x)}$

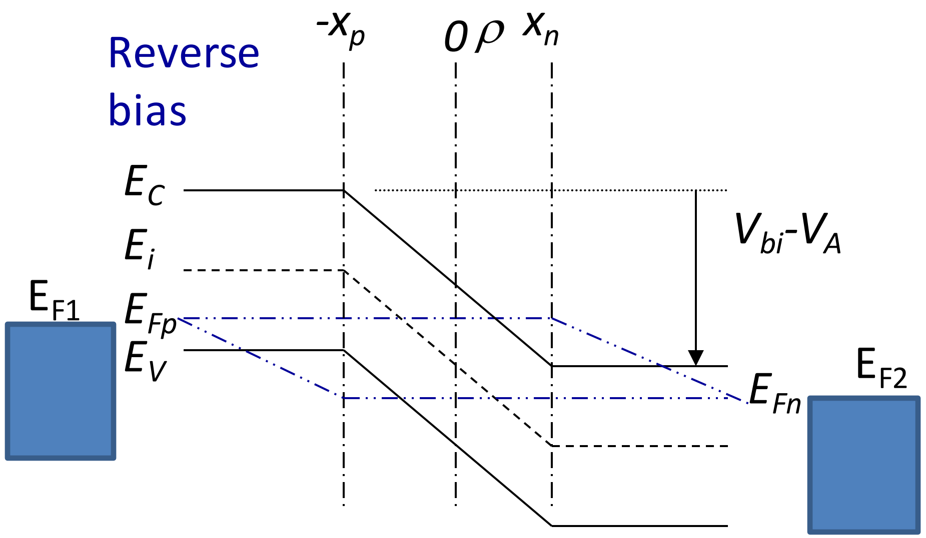


Set up diffusion only current calculation here

Applied Bias and Fermi-Level Split

Now a bias V_A is applied on the N and P sides (Fermi level splits): $$\psi_m = V_{bi} \pm V_A$$





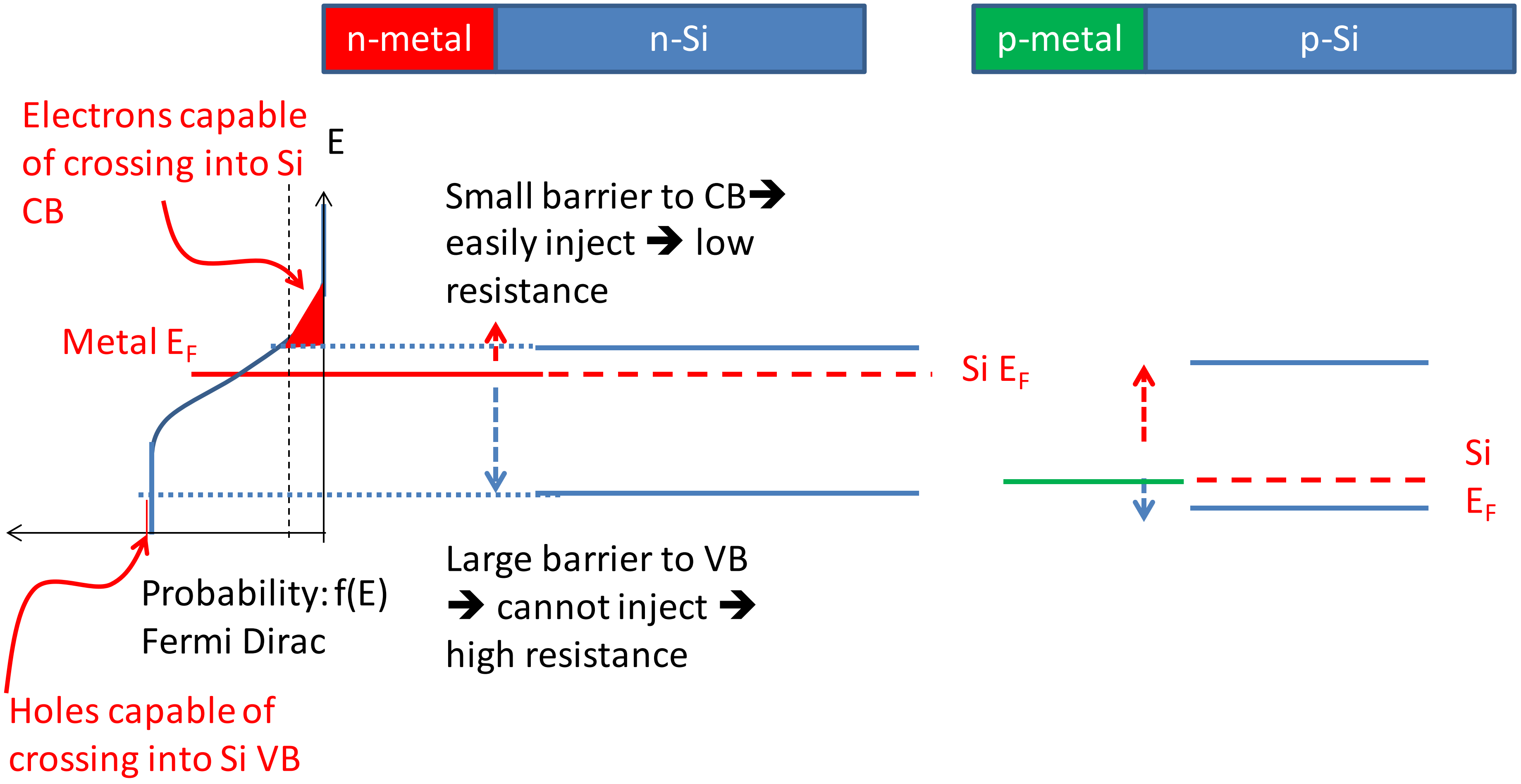
The E_{Fn} and E_{Fp} part is is approx.

When some bias is applied i.e. the contact $E_{F1} \neq E_{F2}$ the device is out of equilibrium

Activity: Based on the assumed QFL profile.

1. Draw the electron and hole density in Eqm (Solid) , Forward (dot) and Reverse Bias (dash) on the same Figure.
2. Where will the QFL bend?
3. Verify the above <u>assumed</u> Quasi Fermi Level profiles.

n/p-metal contact to semiconductor

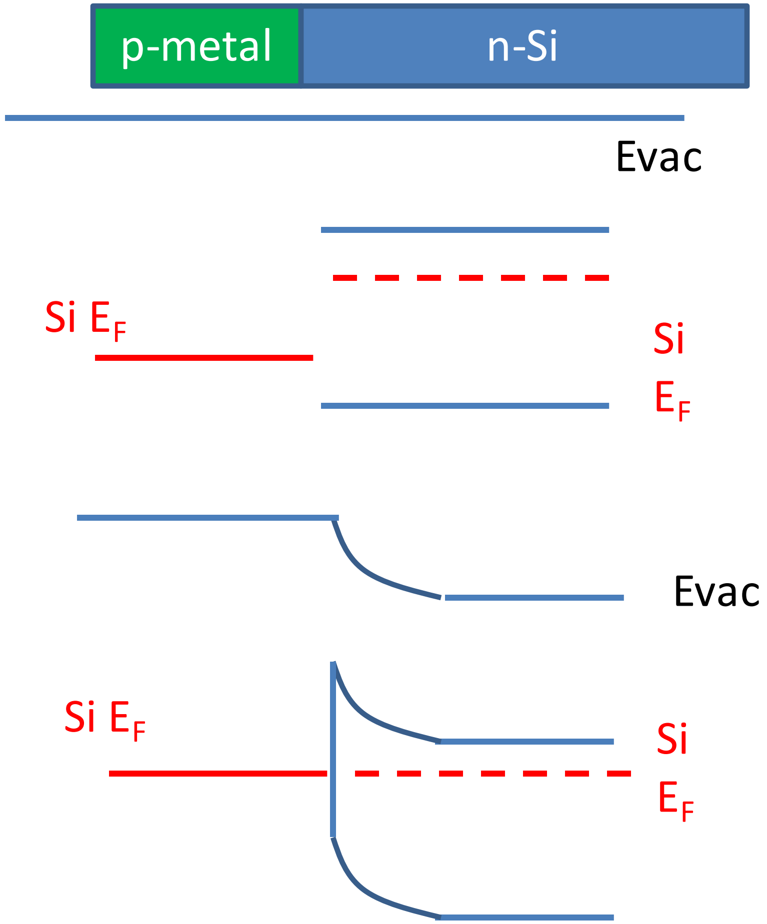


A metal work function closer to Si CB is able to inject electrons easily into CB but not holes into VB : n-type metal
Conversely p-metal may be defined.

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

Schottky barrier

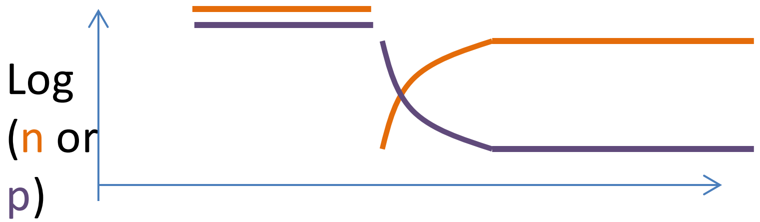
1. Electrostatics

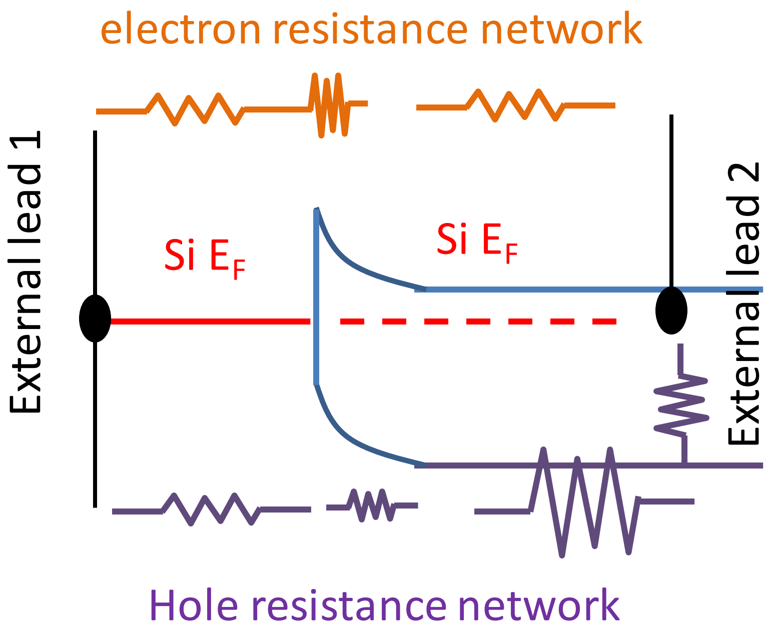


Band bending can be calculated by depletion approximation

2. Transport

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





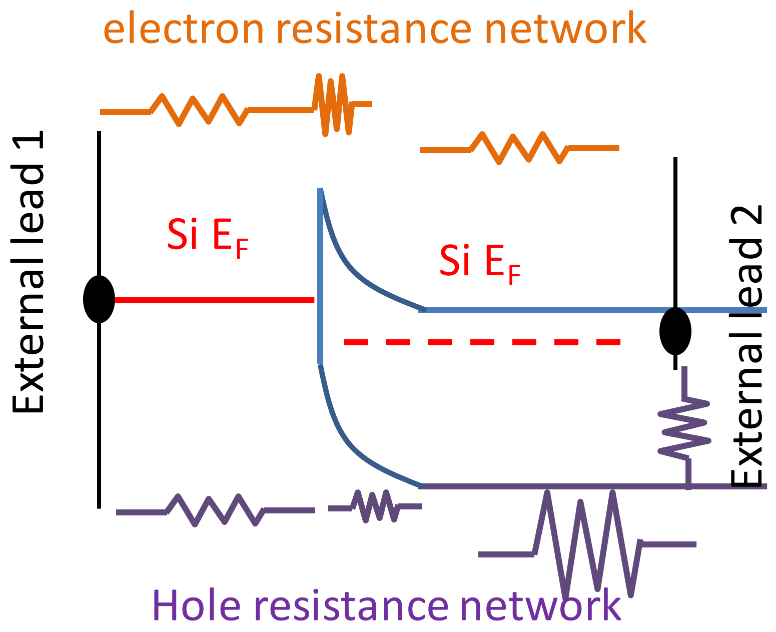
Based on the resistor network, electron current will dominate.

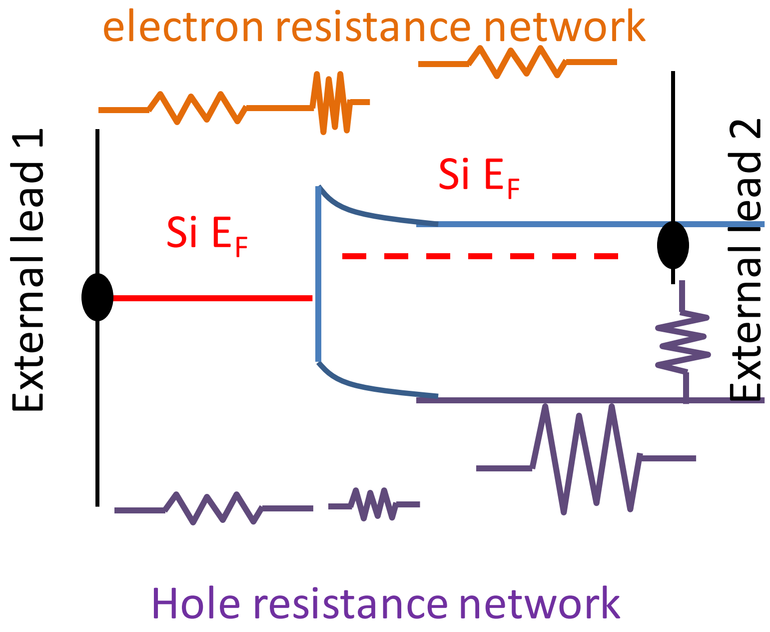
PS: External lead 2 must be an n-contact; so there may be addition resistance to VB

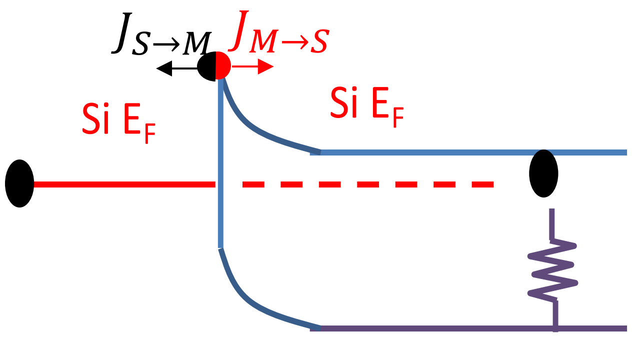
Methodology

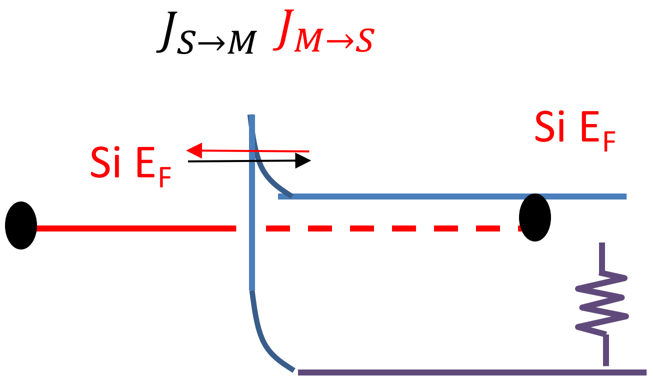
- Step 1: How does electrostatics change with bias?
- Step 2: Where does QFL bend? This is the most “resistive” part of the device; The current limiter.
- Step 3: Calculate current where QFL bends. What is the exact transport physics?
  - Can be any.. DD, Thermal (over the barrier), Tunnel

Forward and Reverse Bias

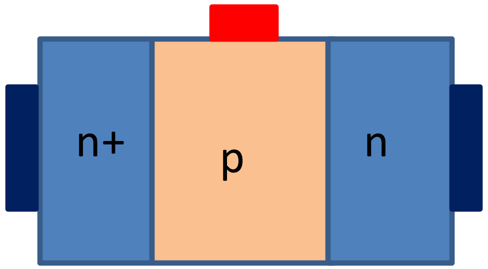


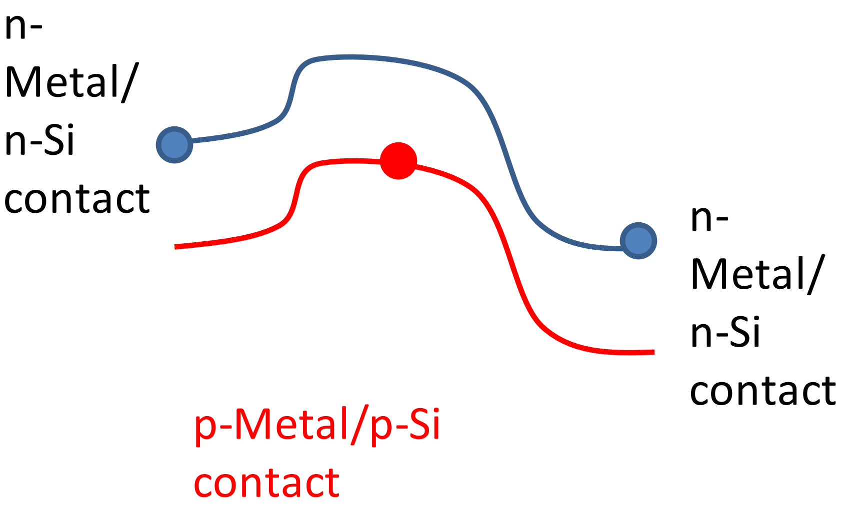






Application1: Band Transport in a BJT





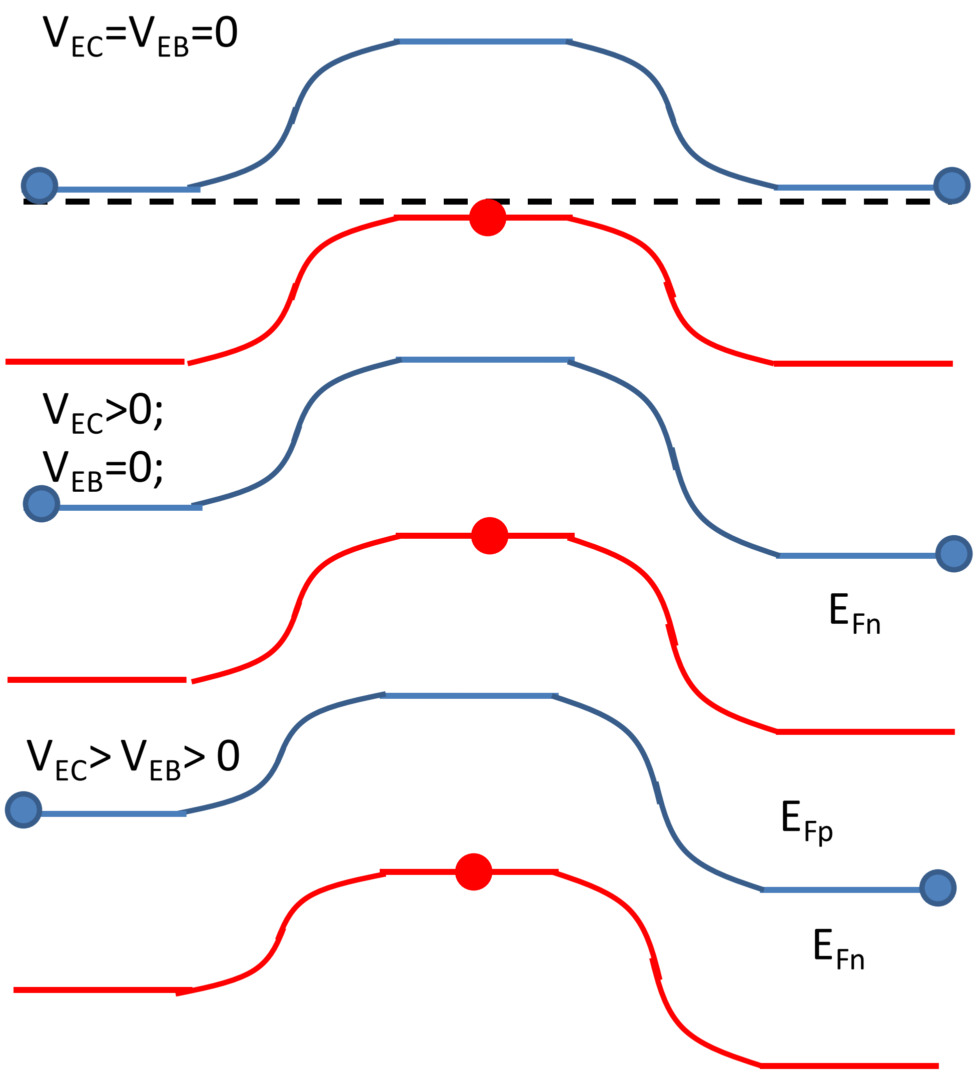
Question 1: Stepwise show how far the current may be calculated using QFL arguments.

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

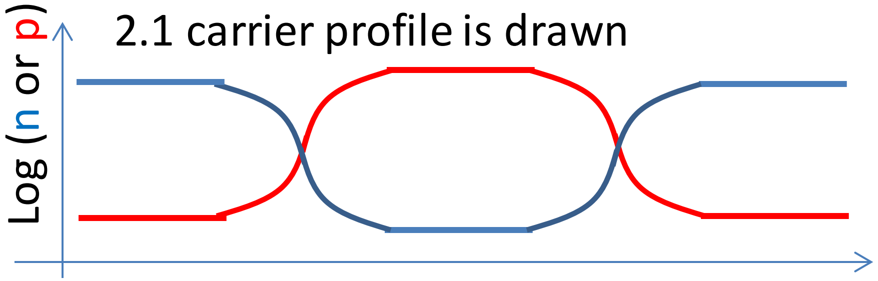
Electrostatics & Transport in BJT

1. Electrostatics: Use Depletion approximation

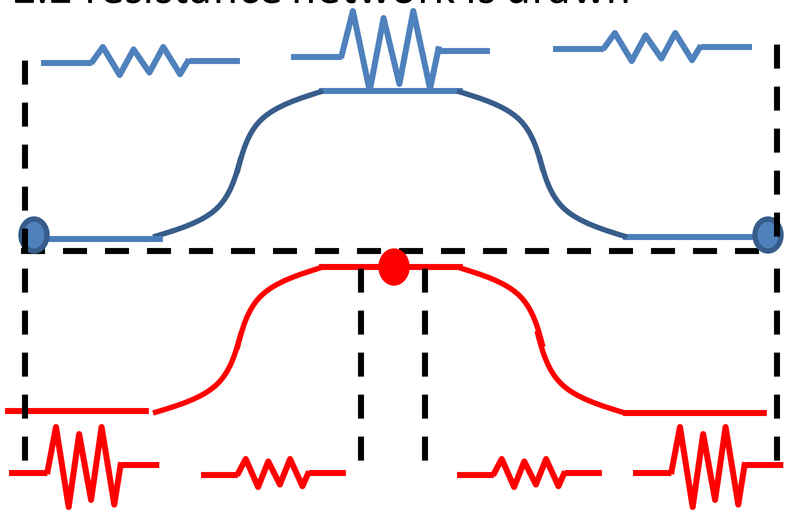


2 Transport (use previous algorithm)

2.1 carrier profile is drawn

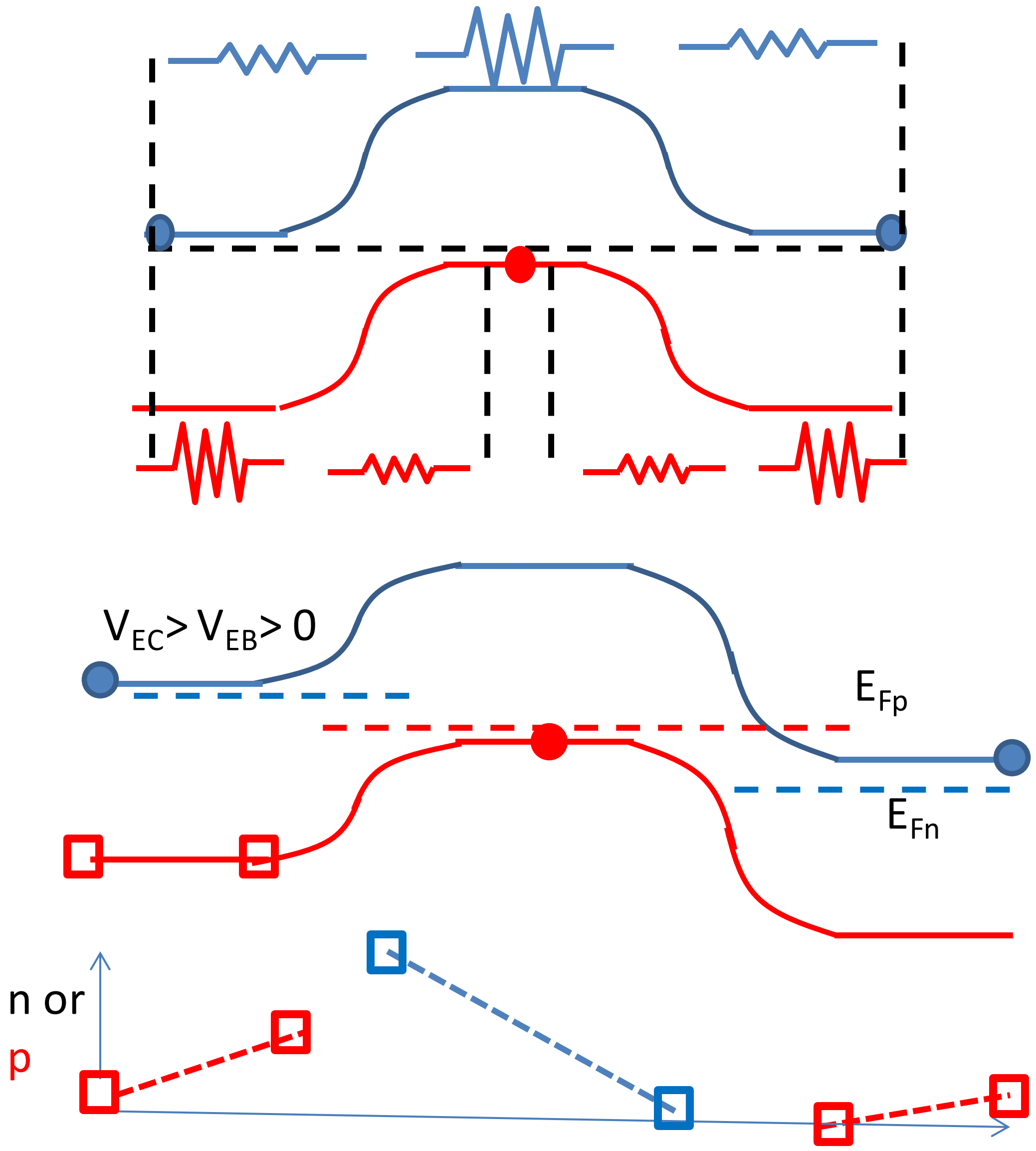


2.2 resistance network is drawn



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

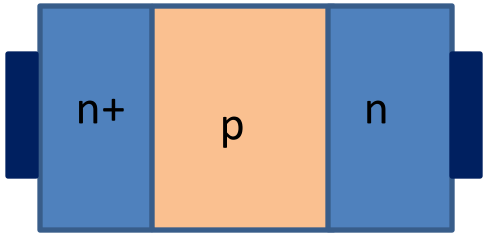


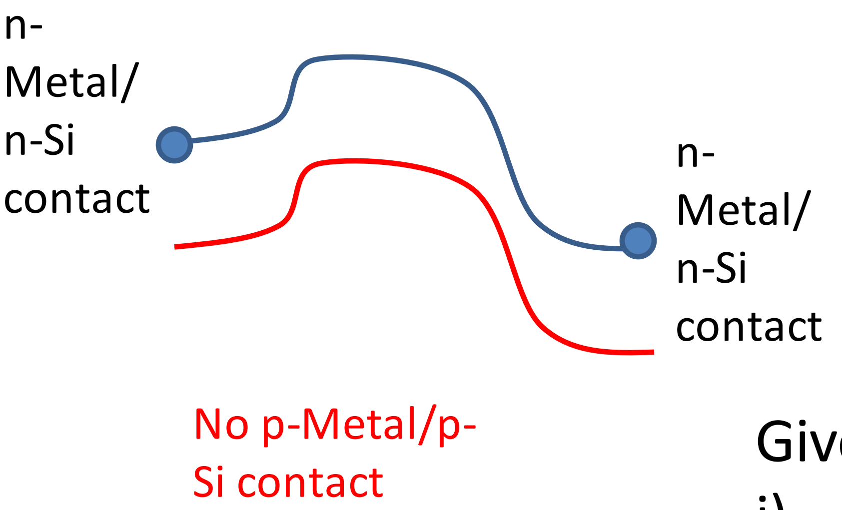
2.3 Based on resistor network, we know where E_{Fn} and E_{Fp} is flat
Electron and hole conc at edges of diffusion calculation zones known
electron □ hole. □

2.4 Profiles are drawn based on transport e.g. diffusion in this case.
Other mechanisms will be shown later

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;

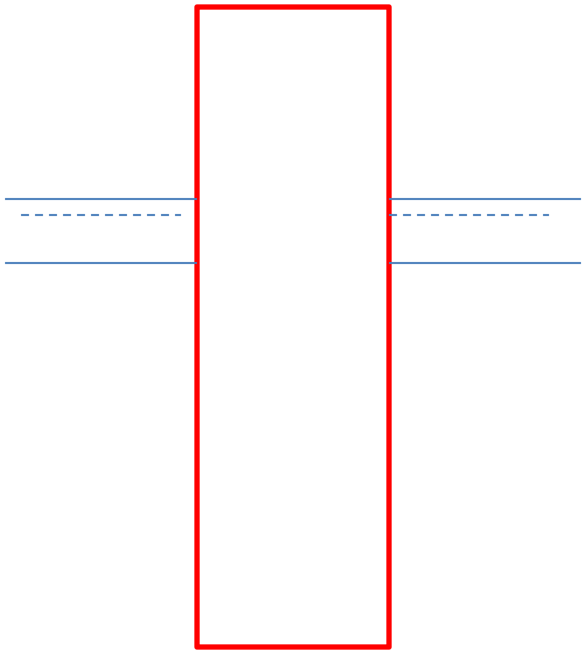
a) With punch-through of depletions at V=0 b) With punch-through of depletions at V=V+ ? Guess the IV characteristics and band profile.

Given are other device options;

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

What are the advances vs. disadvantages

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

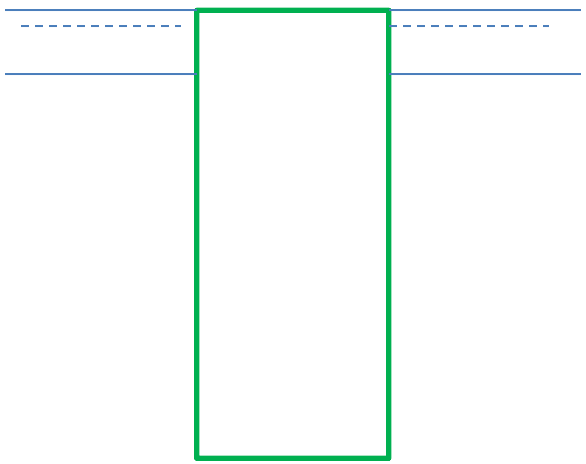


- Plot carrier profiles; Where is the maximum resistance?

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

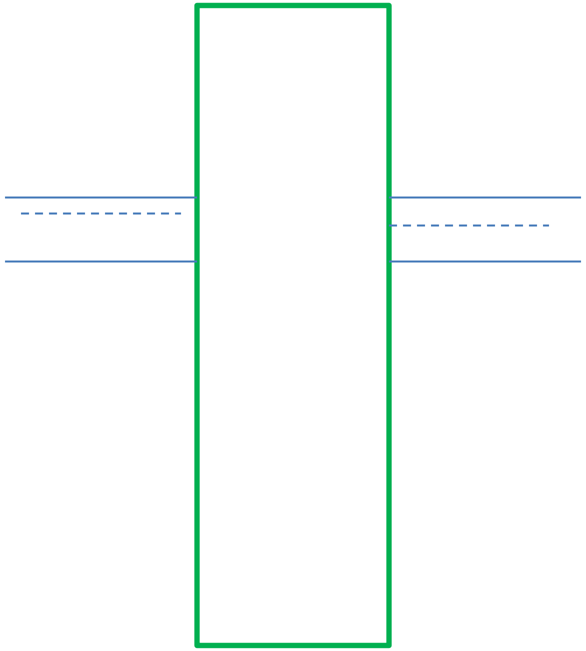
Application 3b: A case of Si n+/insulator/n+ junction

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?

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?