Screening in Semiconductor

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Taur and Ning 2.1.4 Basic Equation for Device Operation

Topics

- Origin of Semiconductors vs. Metals (Informal Discussion)
- Bandgap, Fermi level & Equilibrium
- Screening :
  - Depletion
  - Free Carrier
- Depletion Approximation and its validity

- Transport topics

Band-gap, Fermi Level, Equilibrium

- In metals (conductivity $G = \infty$) and insulators ($G = 0$); no bandgap idea is needed

- For semiconductor, we need to acknowledge the existence of bandgap
  - Free carriers (majority, minority and dopants)
  - Fermi level

- Bandgap and Conduction vs Valence bands are described during the informal discussion

Equilibrium

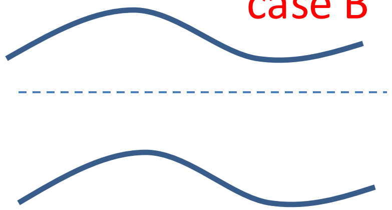
- $n*p=n_i^2$
  - No excess carriers
- Conduction and Valence bands are at equilibrium
  - Fermi level is common for n and p
- Conduction and Valence bands are shorted
  - Possibly by
    - fast recombination/generation
    - Metal semiconductor junction
- Question 1: If a band diagram below is given as such; how do we estimate n and p concentrations
- Question 2: If n & p concentration is given, how do we estimate band diagram
- Knowing n and assuming equilibrium (or Fermi level); we can get Ec and vice versa
- Which one is in equilibrium (case A or case B)
- If not in equilibrium, can we compute its evolution in time to equilibrium?
- We will see this next…

$$n(x) = N_C \exp\frac{E_F - E_C\,(x)}{kT}$$

E_F is constant ➔ equilibrium

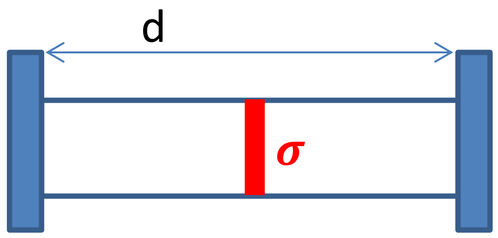
case A

case B



Screening by depletion vs. free carriers

- Background: We can solve dielectric with charge..
- Next step: Can we estimate for n-type semiconductor with $\boldsymbol{-\sigma(x=0)}$ sheet charge?



- Poisson Equation
- $\frac{d^2V}{dx^2} = -\frac{q\rho}{\varepsilon}$

Draw the charge, E, V, and Band Diagram

Case 1: $\rho = \sigma(x = 0)$=0 i.e. Dielectric capacitor w/ no charge

Case 2: $\rho = \sigma(x = 0)$>0 i.e. Dielectric capacitor w/ no charge

If dielectric was a semiconductor, make a band diagram to 'guess' the type of charges that will develop as a response from the semiconductor

Screening by depletion

Draw the charge, E, V, and Band Diagram

Case 3: Place a charge $\sigma(x=0) < 0$ in an n-type semiconductor

$$\rho = N_D + p(x) - n(x) + \sigma(x=0)$$

Steps:

0. Draw potential for dielectric case as initial guess. We now know E_F and E_C to <u>guess</u> charge response

1. near x=0 $\rho \approx N_D$; ➔ depletion

2. far from x=0; $\rho = 0$; ➔ σ screened out

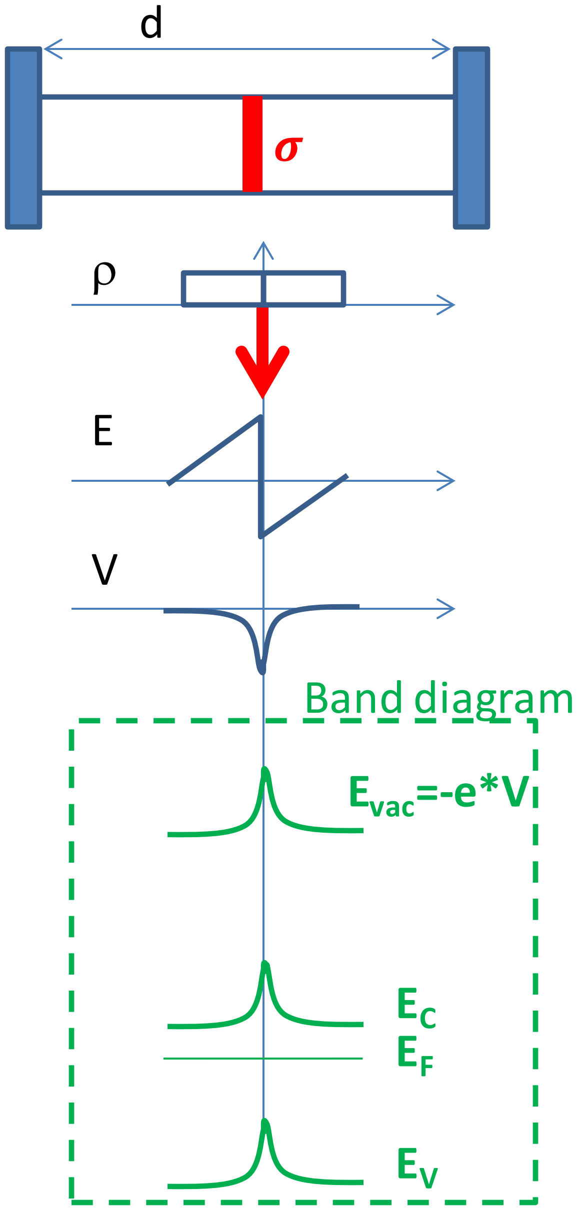
3. Use depletion approximation to find charge,

4. Depletion length comes from charge neutrality i.e. $\sigma = N_D * L_{Depletion}$ ➔then find E, V and band diagram

If $L_{Depletion} << D$, does the electrode participate in screening i.e. does electrode feel the presence of the charge?

Under what condition will electrode participate in screening?

$L_{Depletion} >> D$



Screening by Free Carriers

Draw the charge, E, V, and Band Diagram

Case 3: Place a charge $\sigma(x=0)>0$ in an n-type semiconductor

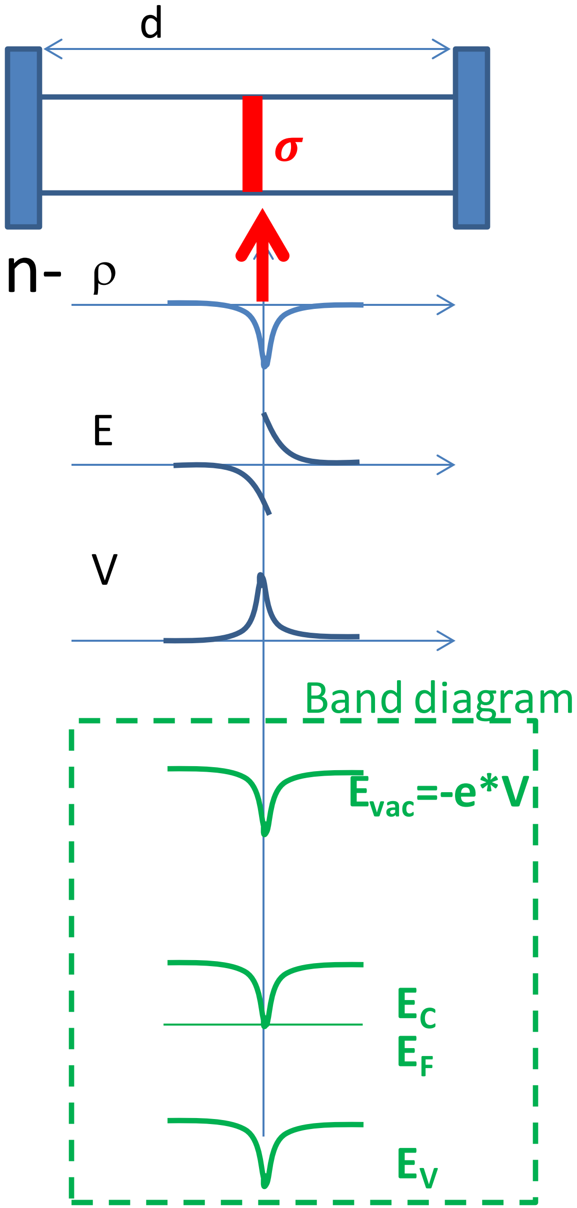
$$\rho = N_D + p(x) - n(x) + \sigma(x=0)$$

near x=0 $\rho \approx n(x)$; ➔ accumulated

far from x=0; $\rho = 0$; ➔ σ screened out

To find accumulated charge, from charge neutrality i.e. σ= $2\int n(x)dx$

n(x) must be known ➔then find E, V and band diagram can be drawn

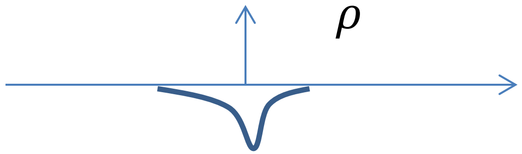


Guess/Approximate crudely the shape of n(x) and predict the approx. E V profiles and band diagrams.

➔ The basic form of n(x) and V(x) is not known; can we calculate?

Derivation of Debye Length

- $\frac{d^2V}{dx^2} = -\frac{q\rho}{\varepsilon}$ where $\rho = N_D + p(x) - n(x) + \sigma(x=0)$
- To get the general solution we solve for the case when $\sigma = 0$ i.e. at $x \neq 0$; then we can find particular solution
- Guess that at most places V=0 ➔ ρ =0; so lets calculate ΔV instead which comes from the excess charge compared to net ρ =0
- $\rho = N_D + \cancel{\frac{n_i^{\ 2}}{n(x)}} - n(x) = N_D\left(1 - \exp\left(\frac{qV}{kT}\right)\right)$



- where $qV = E_c - E_{co}$ (i.e. the E_C bending)
- If $V(x) \to 0$(small bending), we can do Taylor series expansion of the exponent
- $\rho = N_D + \frac{n_i^{\ 2}}{n(x)} - n(x) = -N_D\left(\frac{qV}{kT}\right)$
- $\frac{d^2V}{dx^2} = -\frac{q\rho}{\varepsilon} = \frac{q^2 N_D V}{\varepsilon kT} = \frac{V}{L_D^{\ 2}}$
- Where the solution is of the nature V(x)~ exp (x/L_D) for small charge perturbation

What is the screening length?

Free carrier screening or Debye Length screening is exponential with screening length. This is very effective screening cf. depletions;

Exact solution is not easy. Numerical solution OK.

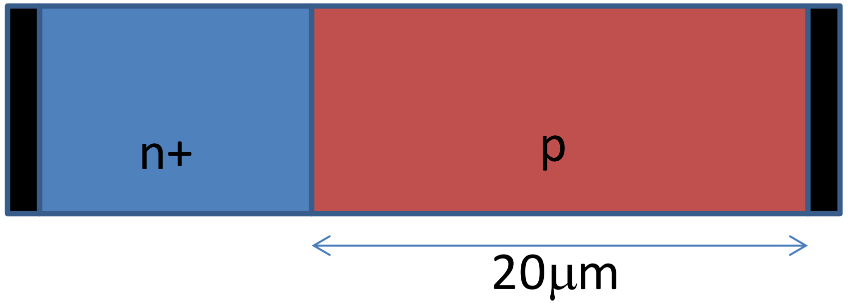
Difference between Debye and Depletion Length

- Debye Length is ${L_D}^2 = \frac{\varepsilon}{qN_D}\frac{kT}{q} = \frac{\varepsilon}{qN_D}V_T$
- Depletion Length is ${L_{Dep}}^2 = \frac{2\varepsilon}{qN_D}V_{bending}$
- $\frac{L_{Dep}}{L_D} = (2\frac{V_{bend}}{V_T})^{1/2}$ at the same doping
- Hence Debye length is smaller
- Its dependence is exponential
- Note the temperature dependence…
- At T=0 $L_D \rightarrow 0$; but L_{dep} remains finite; physically why?
- Electrons are confined by well easily at T=0; No spread (diffusion) is needed.

Example

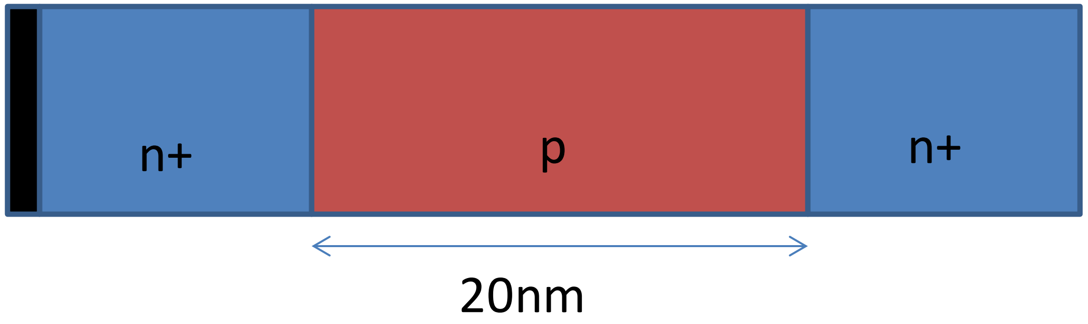
p: doping in 10^{17}/cm3
n+ doping is $10^{20}/cm^3$

Given a n+/p device, what is the depletion length?



Write down the steps including assumptions to draw the band diagram. Explicitly draw all charge profiles – free and bound.

Given a n+/p/n+ device (consider it a planar MOSFET without a gate electrode), there should be an barrier between S/D;



q	1.60E-19	C
eo	8.84E-14	F/cm
Nd	1.00E+17	per cc
V	1.00E+00	V
epsilon_S	1.19E+01	
L	1.15E-05	cm
	115	nm

Write down the steps including assumptions to draw the band diagram. Explicitly draw all charge profiles – free and bound.

what should be the doping for a 0.6V barrier

Steps

1. Assume depletion approx. to create $\rho_{assume}(x)$

2. Show that V(x) is a parabola (calc E(x))

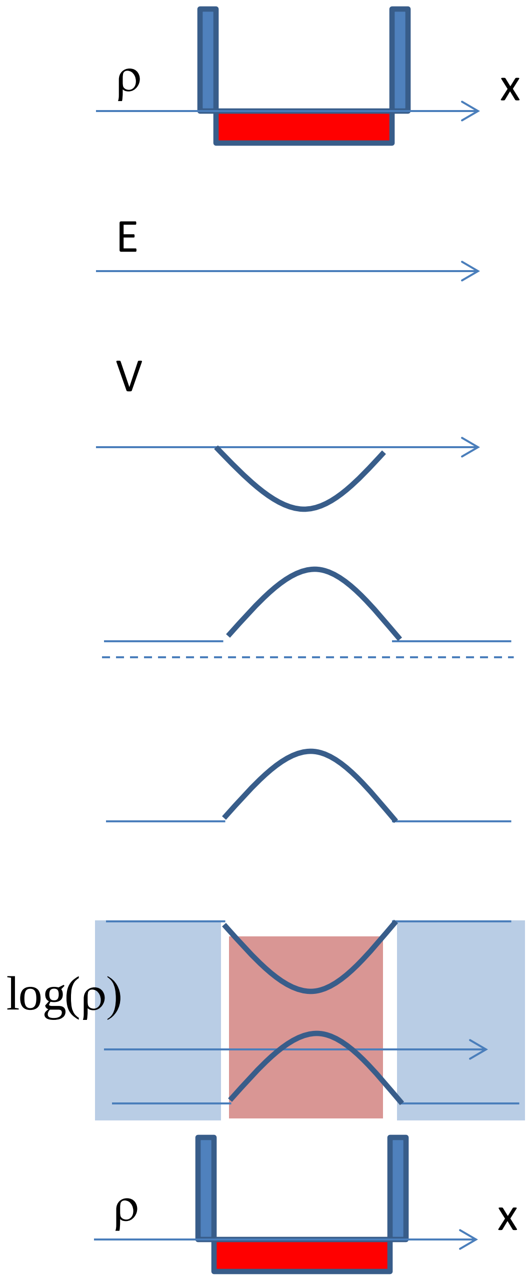
3. Band diagram is obtained

4. Charge profile is obtained log ($\rho_{\mathrm{calc}}(\mathrm{x})$) write down y-axis values

5. Compare: $\rho_{calc}(x) = \rho_{assume}(x)$

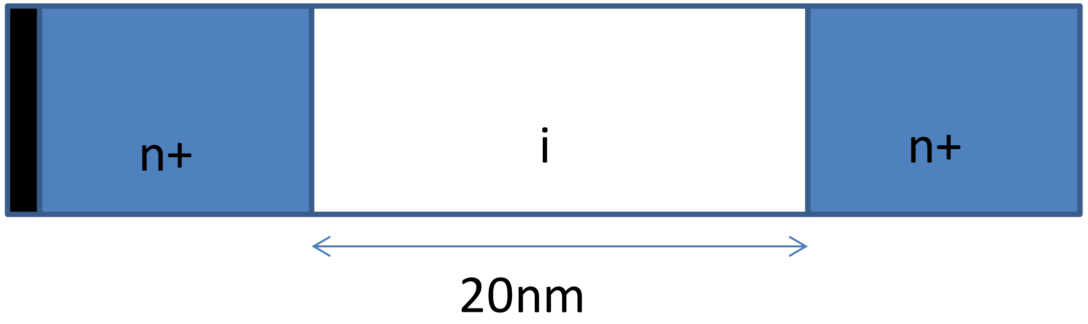
➔ Solution is self-consistent

Essentially, free carrier does not disturb the $\rho_{assume}(x)$



Example

Given a n+/p/n+ device (consider it a FinFET without a gate electrode), how much is the barrier between S/D;



n+ doping is $10^{20}/cm^3$

Write down the steps including assumptions to draw the band diagram.

Exercise: Use same steps as before but for new case

Steps

1. Assume depletion approx. to create $\rho_{assume}(x)$

2. Show that V(x) is a parabola (calc E(x))

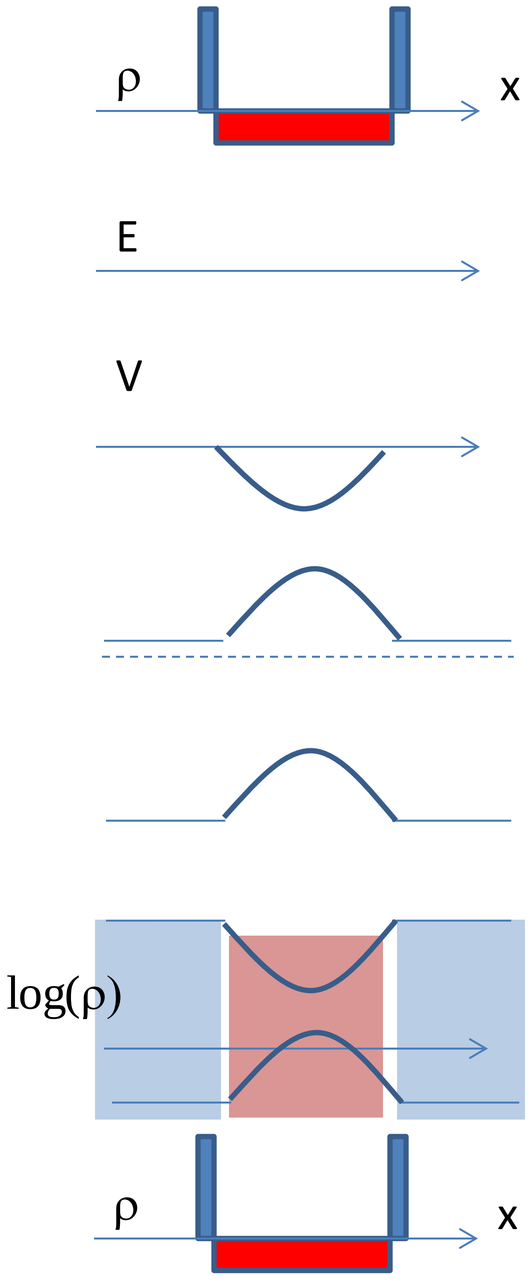
3. Band diagram is obtained

4. Charge profile is obtained log $(\rho_{\text{calc}}(\mathrm{x}))$ write down y-axis values

5. Compare: $\rho_{calc}(x) = \rho_{assume}(x)$

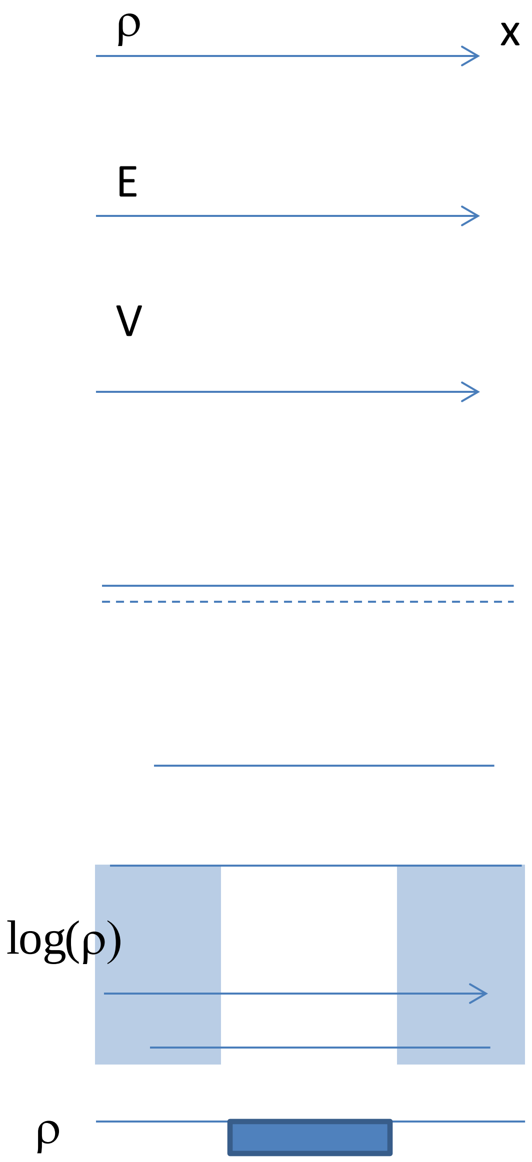
➔ Solution is self-consistent

Essentially, free carrier does not disturb the $\rho_{assume}(x)$



Steps

No doping ➔ no depletion

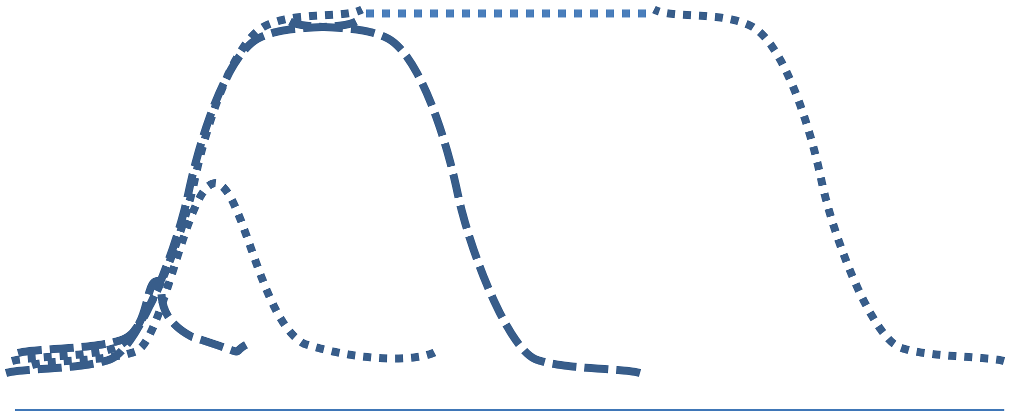


1. Assume depletion approx. to create $\rho_{assume}(x)$
2. Show that V(x) is a parabola (calc E(x))
3. Band diagram is obtained
4. Charge profile is obtained log ($\rho_{\text{calc}}(\text{x})$) write down y-axis values
5. Compare: $\rho_{calc}(x) = \rho_{assume}(x)$

➔ Solution is NOT self-consistent

Essentially, free carrier highly disturbs the $\rho_{assume}(x)$

Changing Lp in npn structure

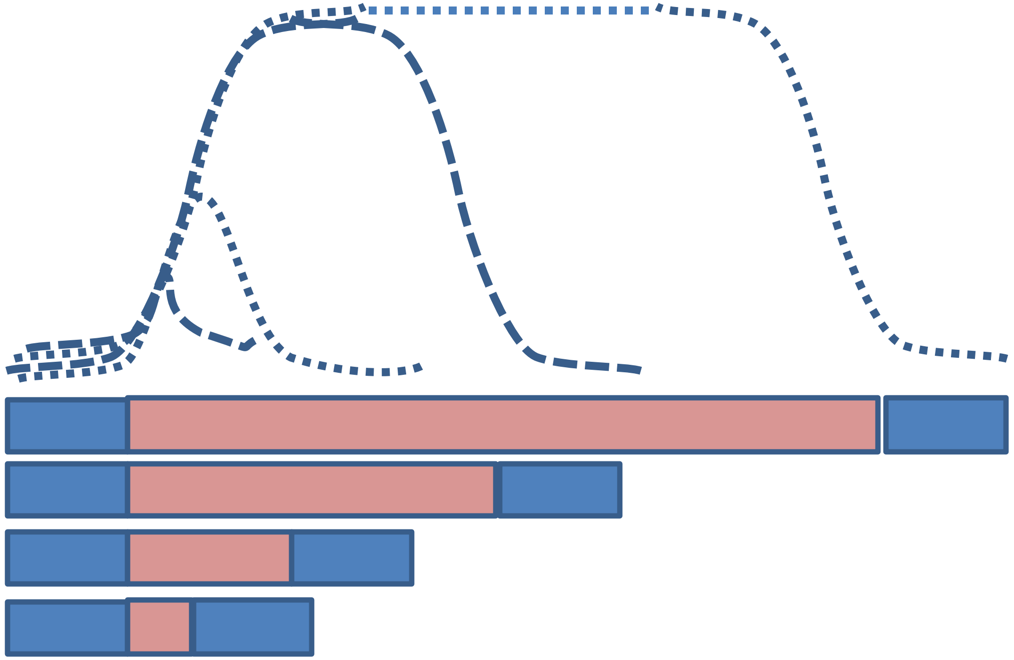


Q: Plot V_{bi} vs. L_p

Only doping dependent built-in barrier or potential is the max potential possible. ***Here $\mathbf{V_{bi}}$ is Lp independent when Lp $\gg$ $\mathbf{L_{dep}}$...***

$$V_{bio} = V_T \ln N_D/N_A$$

When $Lp \le L_{dep}$, then V_{bi} reduces with Lp i.e. Lp dependent



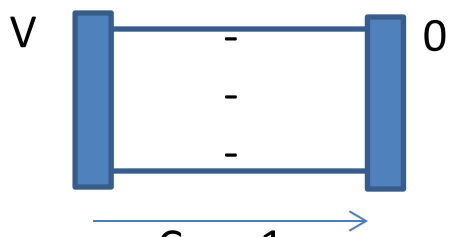
Q: Can I keep Lp constant but reduce V_{bi}

Yes. By increasing L_{dep} which depends upon doping.

Q: Verify this with FEM simulation

Lp>>Ldep	$V_{bi} = V_{bio}$
Lp≈Ldep	$V_{bi} = V_{bio}$
Lp<Ldep	$V_{bi} = f(L_p) < V_{bio}$
Lp≪Ldep	$V_{bi} = f(L_p) << V_{bio}$

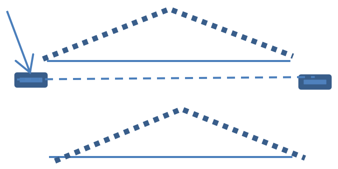
Case 3: $\sigma=\sigma'$; V=0



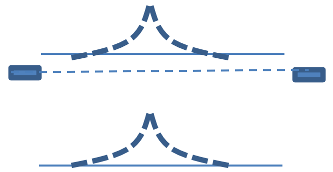
3 Types of screening

Compare length-scales of screening

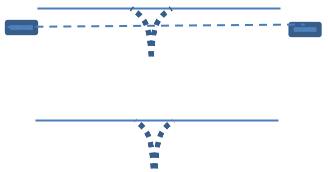
Metal WF



Case 1



Case 2



Case 3

- Case 1: assume that a dielectric is between metals and σ is sheet charge at L/2. ***The field lines will go all the way to the electrode i.e. L/2 (device geometry);*** Screening by dipoles will only reduce the electric field. This screening is by **dielectric polarization.**
- Case 2: Assume that the dielectric is n-type semiconductor; In addition to dielectric polarization, free carrier (electrons) will be repelled to cause local depletion; ***ionic cores will screen out potential in depletion length, $L_{depletion}$ (materials lengthscale)***. V(x) is quadratic;
- Case 3. Assume the σ is positive; then electrons are attracted causing accumulation. ***Free carrier screening will screen out electric field by debye length L_{Debye} (materials/local free carrier based length-scale)***. V(x) is approx. exponential decay.
- In case of all phenomenon acting together, the effective screening is by the shortest length scale.

Question 1 : In quiz question, we assumed that a 20 nm gate length FinFET is practically undoped. Think about at what doping value, this assumption is violated in off-state qualitatively and if possibly a method to quantitatively estimate this doping.
In inversion, the free carrier concentration rises, at what gate voltage (assume V_{SD} = 0; and undoped channel) will debye length modify the electrostatics estimated by Laplace Equation;

3 Lessons

- $n(x) = Nc * \exp \frac{-(Ec - Ef)}{kT}$; Under Boltzmann Distribution and Equilibrium (E_F is flat) $\log\left(n(x)\right)$ has the same shape as E_c
- There are two kinds of screening
  - Bound Charges i.e. ionized Dopants
    - Characterized by Depletion Length)
    - Can be solved more easily
  - Free Carrier
    - Characterized by Debye Length)
    - needs numerical solution mostly for self consistency of potential and charge density.