Section 23
Schottky Diode

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PURDUE UNIVERSITY

School of Electrical and Computer Engineering

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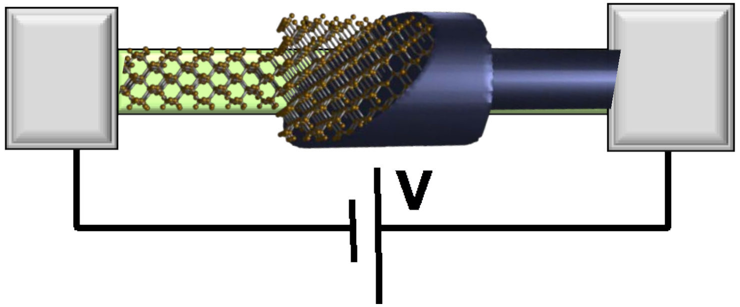
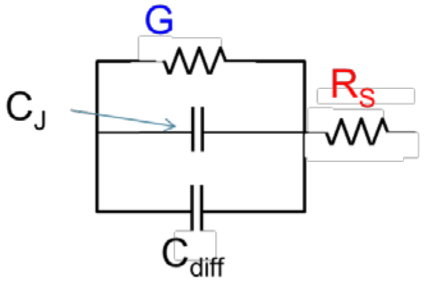
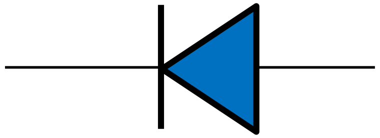


$I = G \times V$

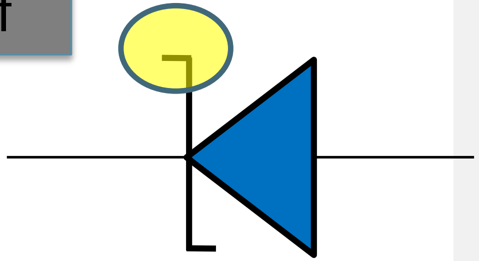
$= q \times n \times v \times A$

charge density velocity area





	Equilibrium	DC	Small signal	Large Signal	Circuits
PN Diode	Diode in **Non-**Equilibrium (External DC+AC voltage applied)				Digital Signals: switch on and off
Schottky Diode					
BJT/ HBT					
MOS					



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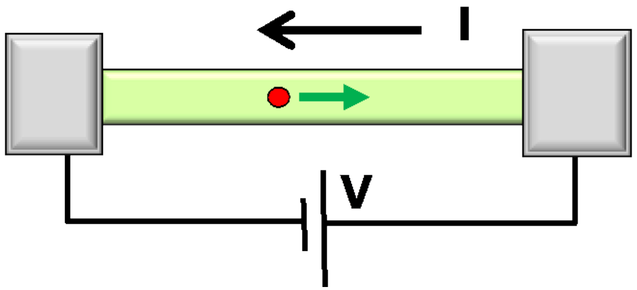
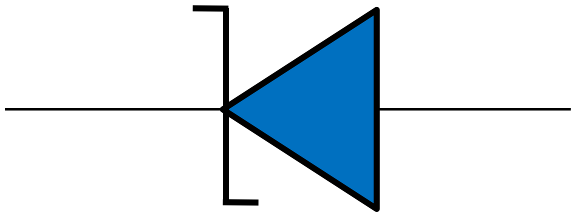


$$I = G \times V$$
$$= q \times n \times v \times A$$

charge density velocity area



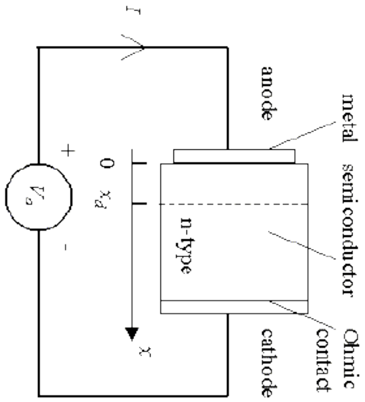
- 23.1 Basics
  - » Equilibrium band-diagram
  - » DC Thermionic current (simple derivation)
- 23.2 Physical Processes
  - » DC Thermionic current (detailed derivation)
  - » Recombination/Generation/Ionization
  - » AC and Large Signal Response
- 23.4 Practical Issues
  - » Ohmic vs. Schottky Contact
  - » Schottky Barrier Lowering – Image Charges
  - » Fermi Level Pinning

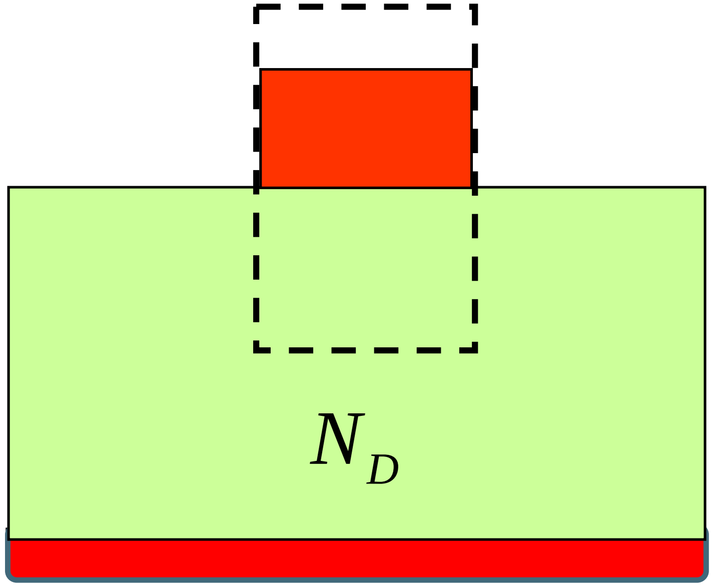
Video

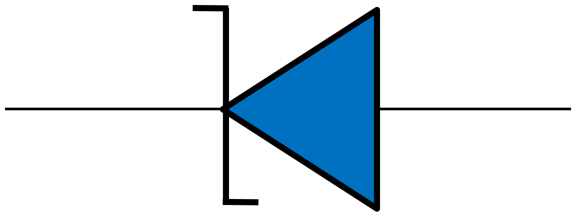
Video

Video

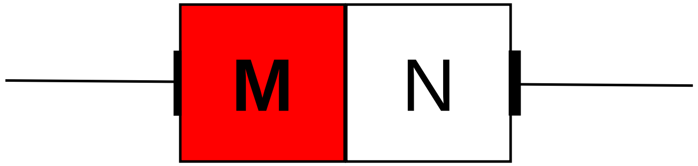
Metal-semiconductor Diode

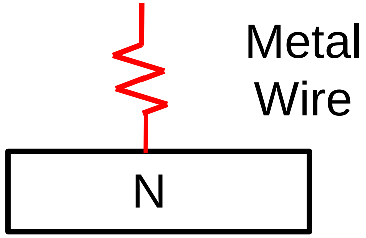




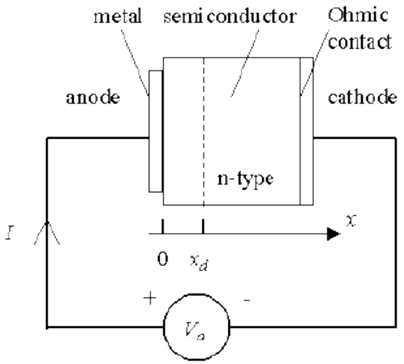


Symbols

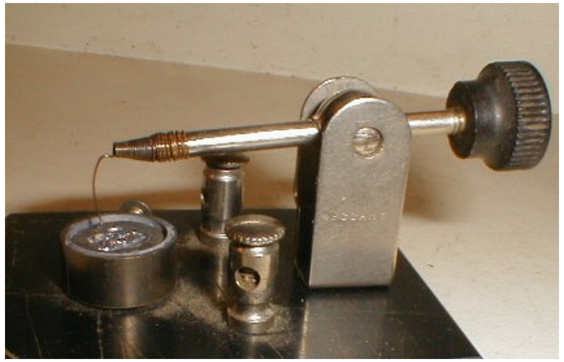




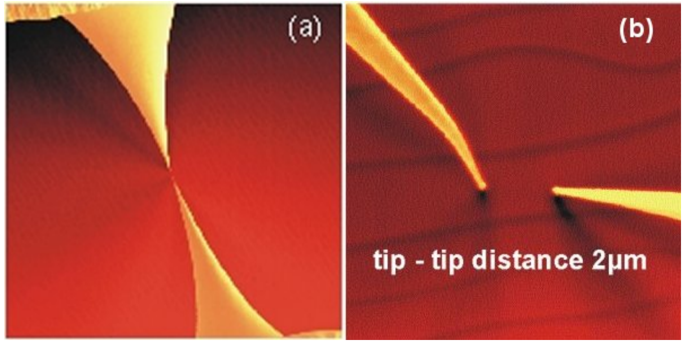
Applications of M-S Diode ....



Detectors



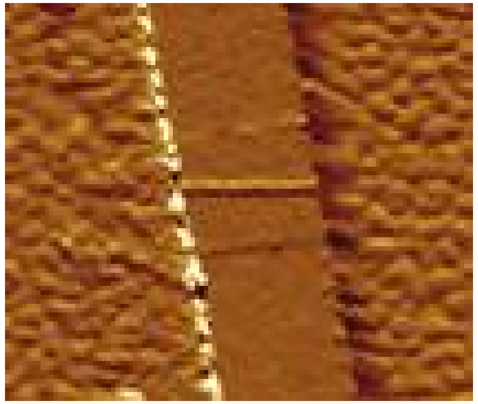
STM(scanning tunneling microscope) on semiconductor

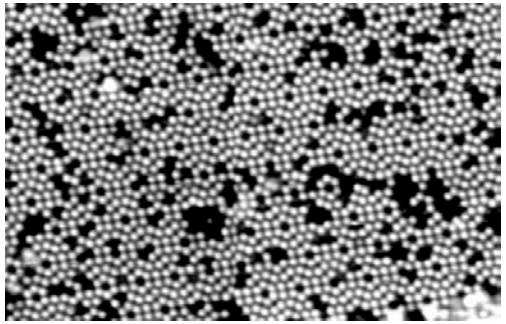


www.fz-juelich.de/ibn/index.php?index=674

Original Bipolar

CNT(carbon nanotube) Transistors

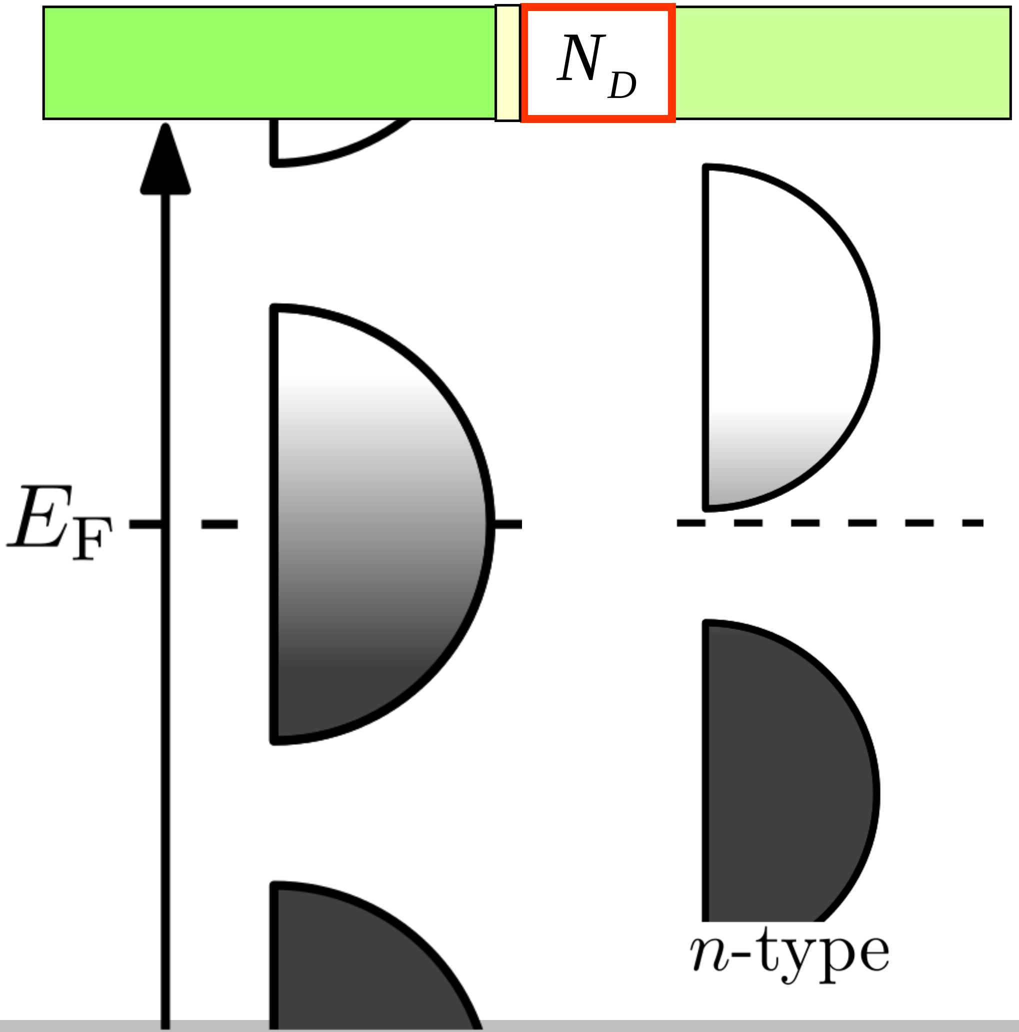




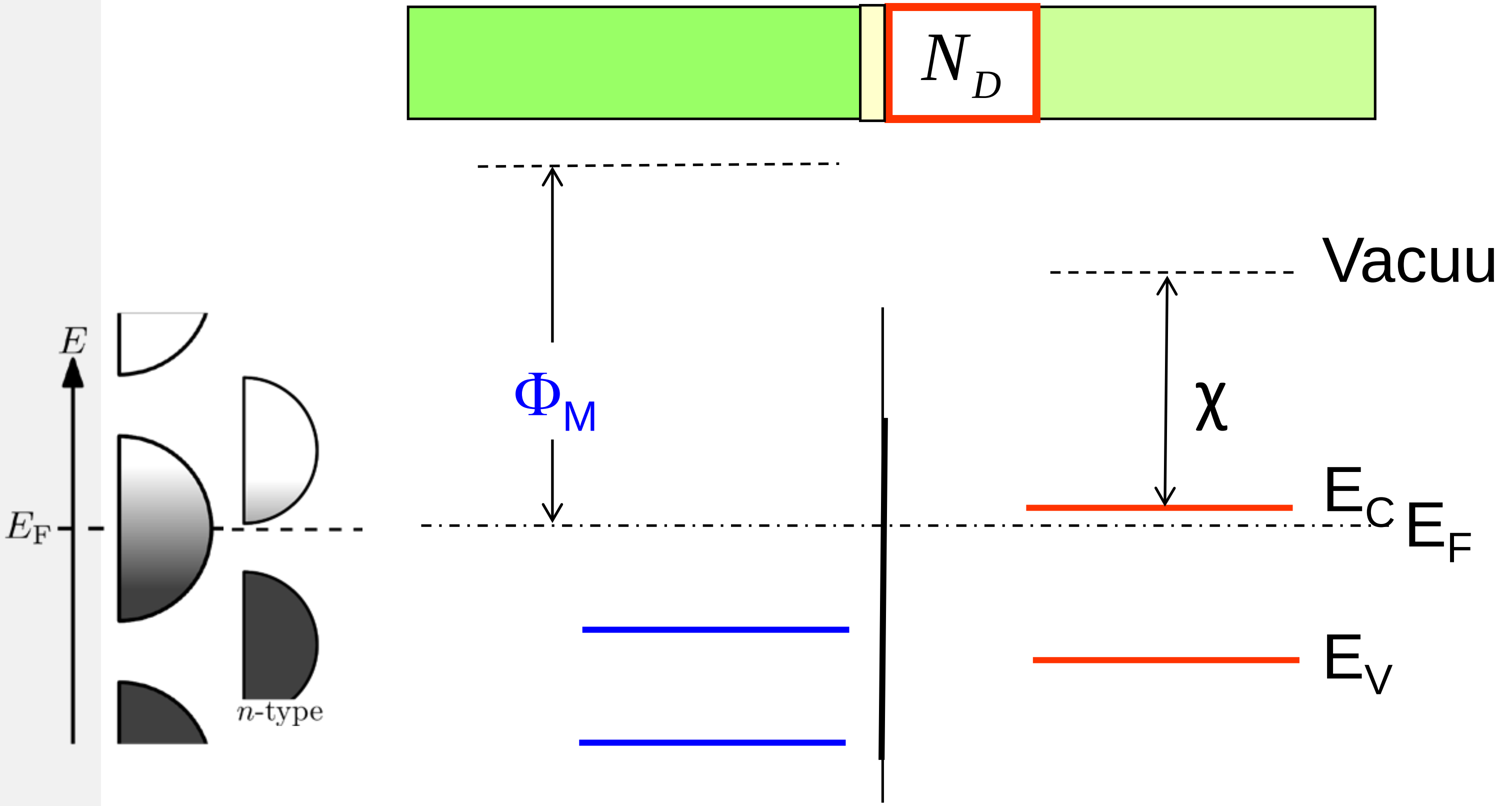
Originally, Gelena (PbS), Si as semiconductor and Phosphor Bronze for metal (cat's whisker)

Band-Diagram

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



Band-Diagram



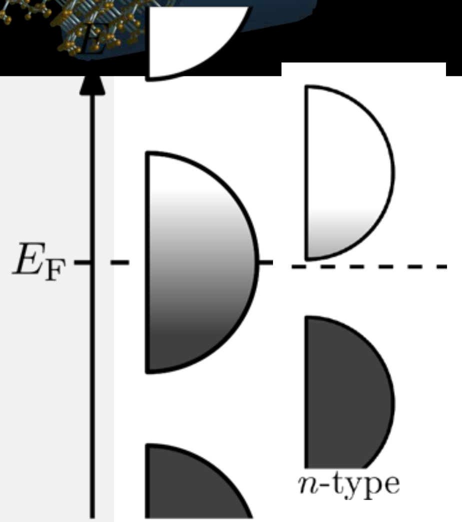
1. E_F flat in equilibrium
2. E_C/E_V in Metal
3. Vacuum level in Metal
4. Ec/Ev in semiconductor
5. Vacuum level in semiconductor
6. Connect vacuum levels
7. duplicate the connections down to Ec/Ev

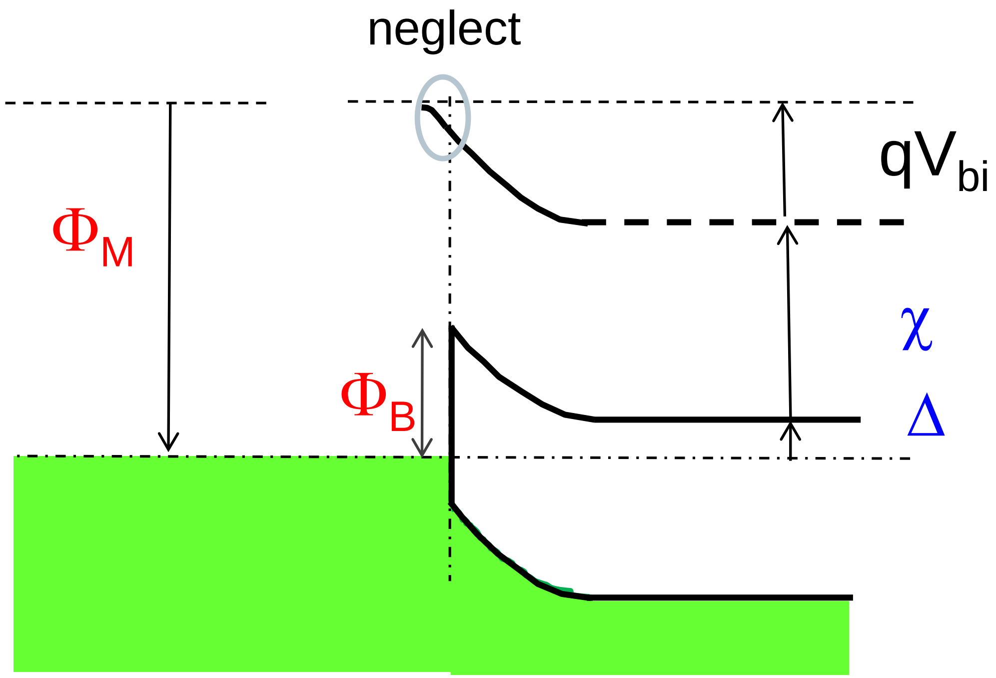
Since N_A is large, x_p is negligible ..

$$N_A x_p = N_D x_n$$

Charge(metal) = charge(semiconductor)

Built-in Potential: bc @Infinity



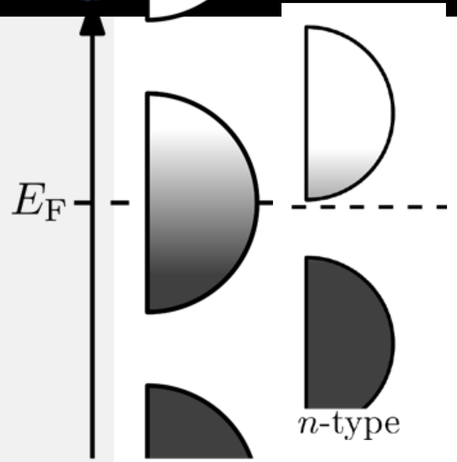


$$\Delta + \chi + qV_{bi} = \Phi_M$$

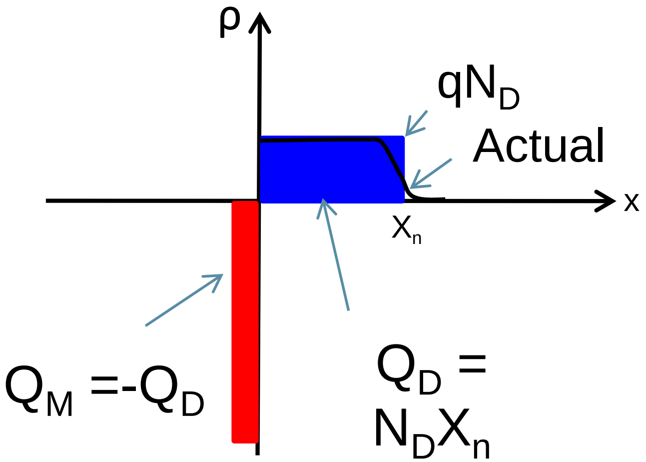
$$qV_{bi} = (\Phi_M - \chi) - \Delta \equiv \Phi_B - \Delta$$

$$= \Phi_B - k_B T \ln \frac{N_D}{N_C}$$ non-degenerate

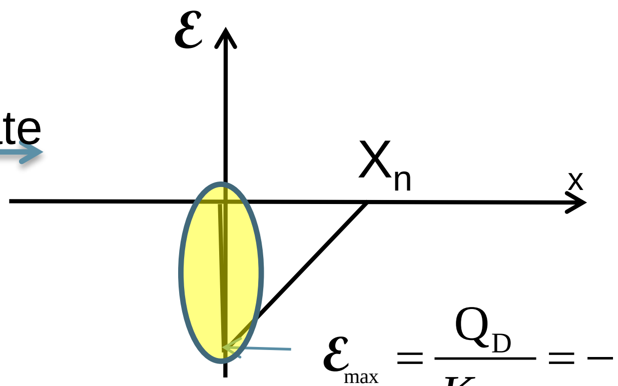
Analytical Solution (Simple Approach)



Depletion Approximation

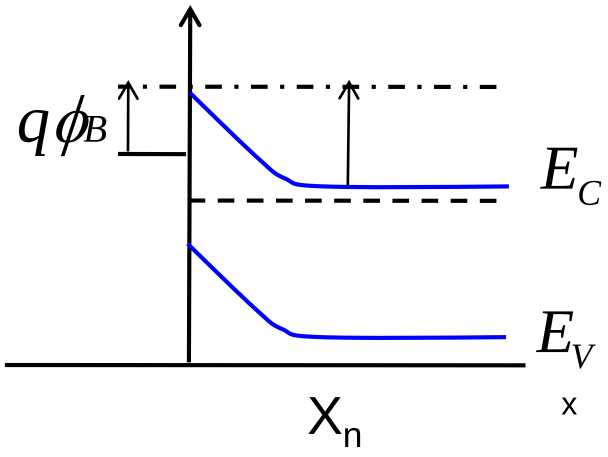


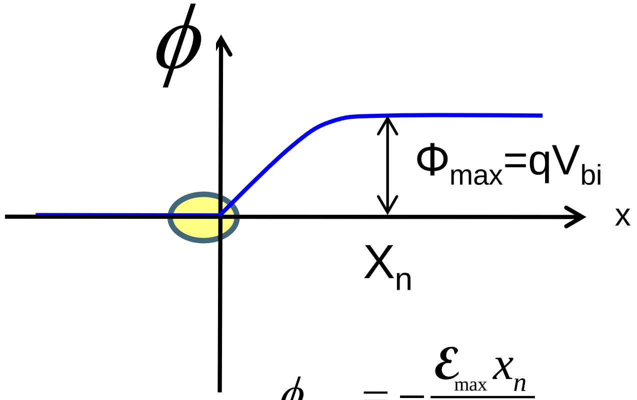
integrate



$$\mathcal{E}_{\max} = \frac{Q_D}{K_s\varepsilon_0} = -\frac{qN_D x_n}{K_s\varepsilon_0}$$

integrate

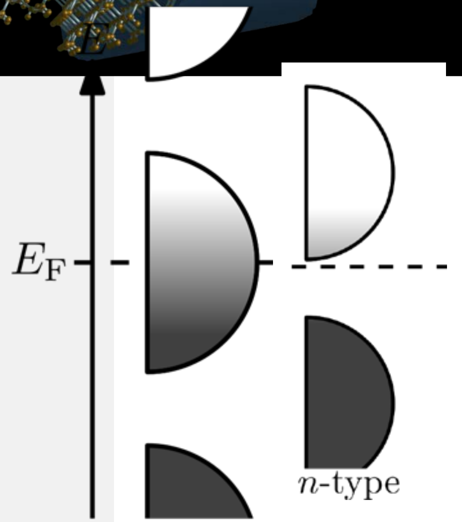


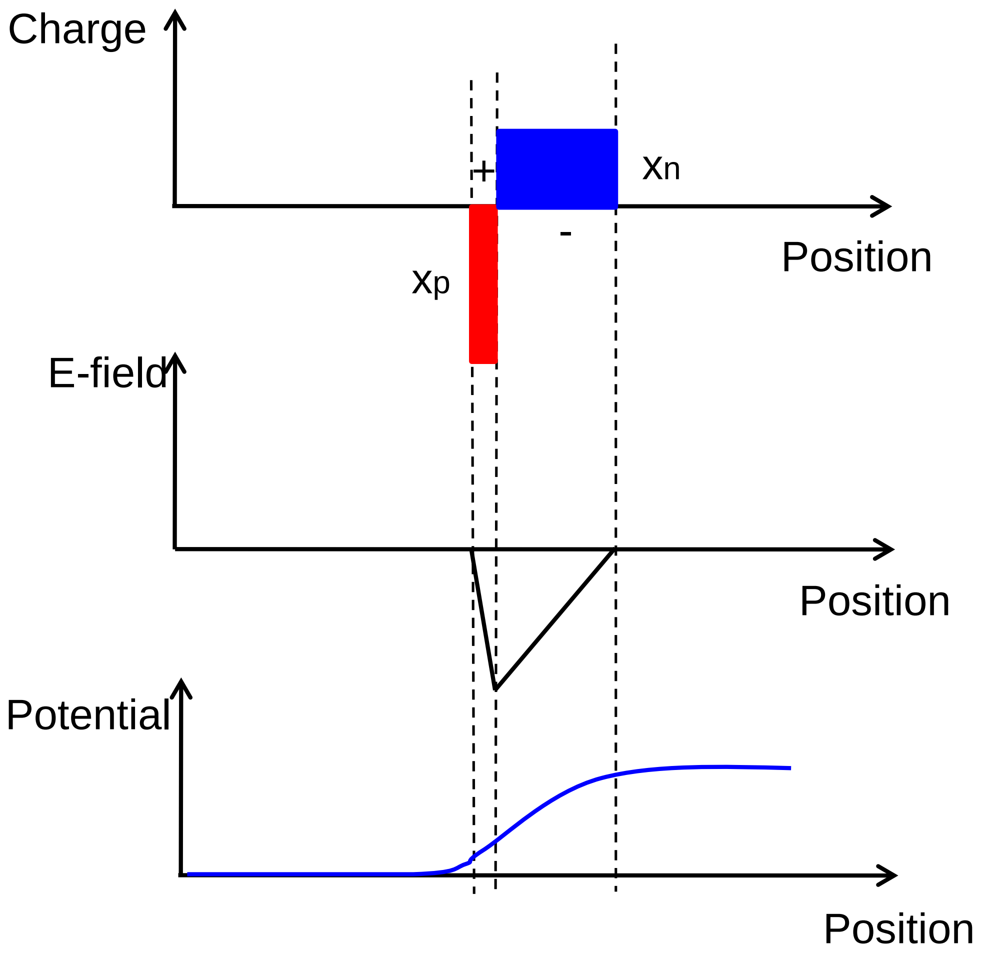


$$\phi_{\max} = -\frac{\mathcal{E}_{\max} x_n}{2}$$

Notice how we neglect x_p here, is there a proof?

Complete Analytical Solution





$$\mathcal{E}(0^+) = \frac{qN_D x_n}{k_s \varepsilon_0}$$

$$\mathcal{E}(0^-) = \frac{qN_M x_p}{k_s \varepsilon_0} \; ?$$

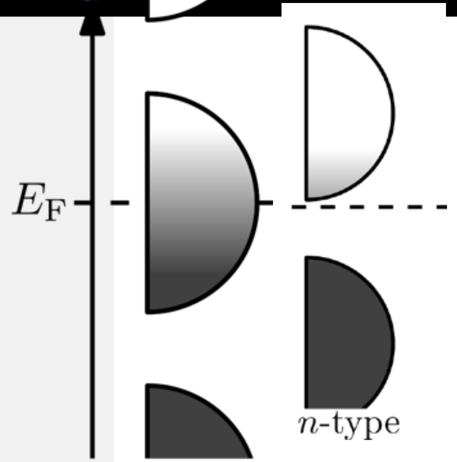
$$\Rightarrow N_D x_n = N_M x_p$$

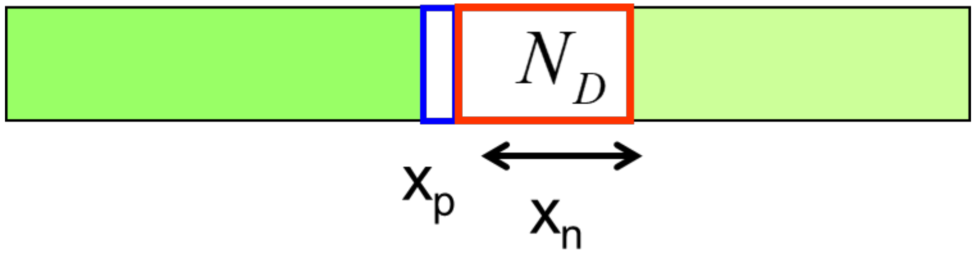
$$qV_{bi} = \frac{\mathcal{E}(0^-) x_n}{2} + \frac{\mathcal{E}(0^+) x_p}{2}$$

$$= \frac{qN_D x_n^{\,2}}{2k_s \varepsilon_0} + \frac{qN_M x_p^{\,2}}{2k_s \varepsilon_0}$$

$$qV_{bi} = \frac{qN_D x_n^{\,2}}{2k_s \varepsilon_0} + \frac{qN_M x_p^{\,2}}{2k_s \varepsilon_0}$$

Depletion Regions





$$N_D x_n = N_M x_p$$

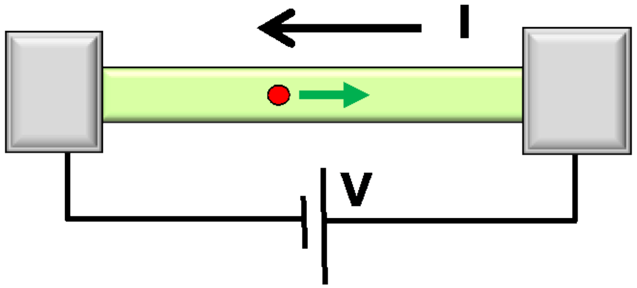
$$qV_{bi} = \frac{qN_D x_n^2}{2k_s\varepsilon_0} + \frac{qN_M x_p^2}{2k_s\varepsilon_0}$$

$$x_n = \sqrt{\frac{2k_s\varepsilon_0}{q}\frac{N_M}{N_D\left(N_M+N_D\right)}V_{bi}} \rightarrow \sqrt{\frac{2k_s\varepsilon_0}{q}\frac{1}{N_D}V_{bi}}$$

$N_M \rightarrow \infty$

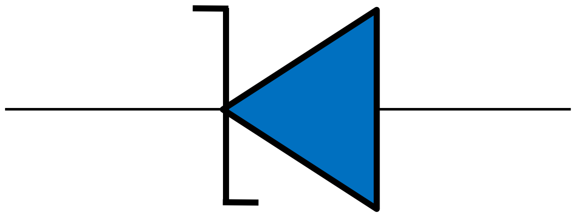
$$x_p = \sqrt{\frac{2k_s\varepsilon_0}{q}\frac{N_D}{N_M\left(N_M+N_D\right)}V_{bi}} \rightarrow 0$$

This is why we can neglect x_p



$$I = G \times V$$
$$= q \times n \times v \times A$$

charge density velocity area



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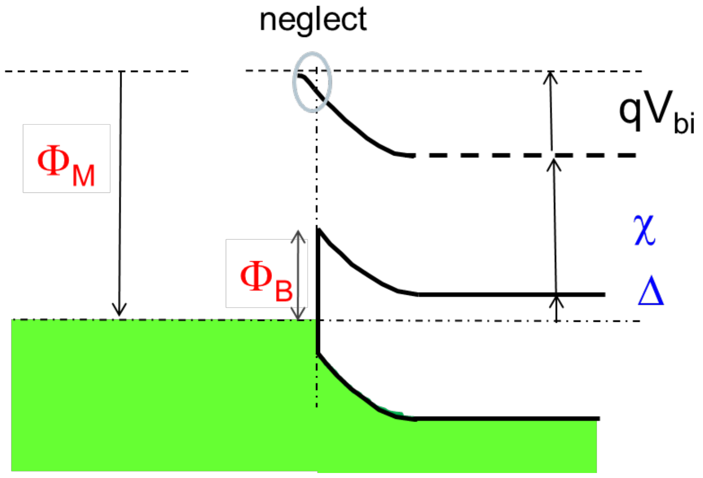
status



Video

Video

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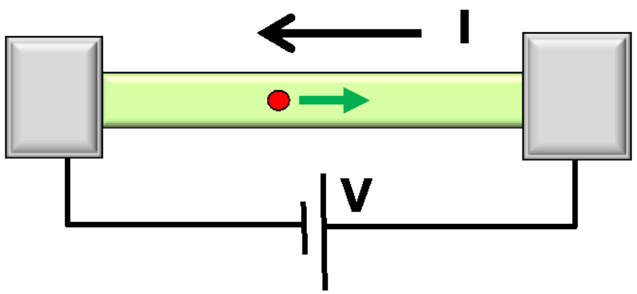

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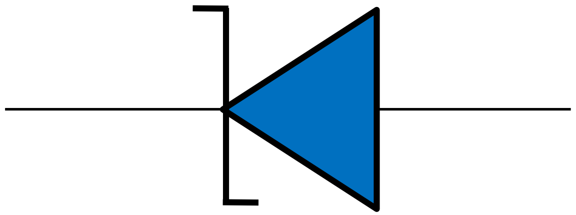

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status

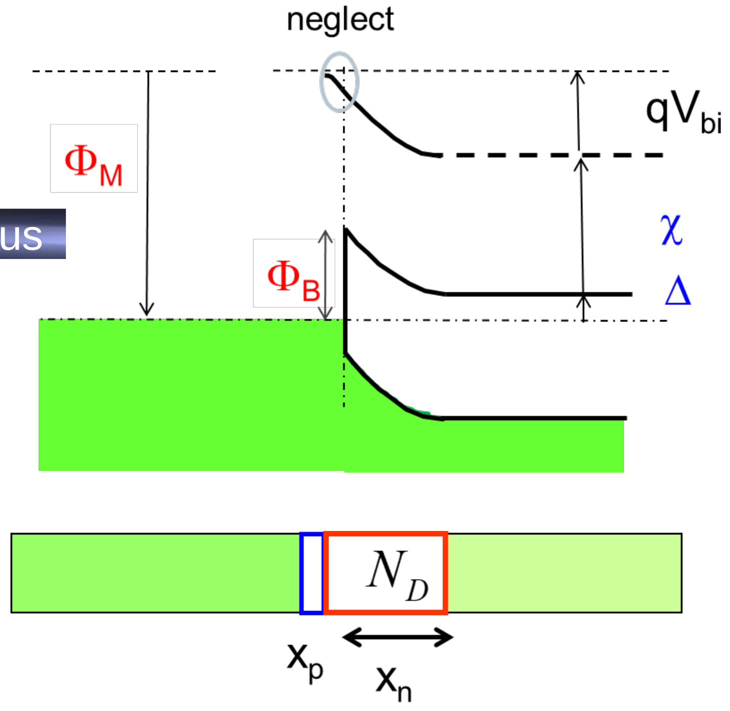
$$\nabla \bullet D = q\left(p - n + N_D^+ - N_A^-\right)$$

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

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

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

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

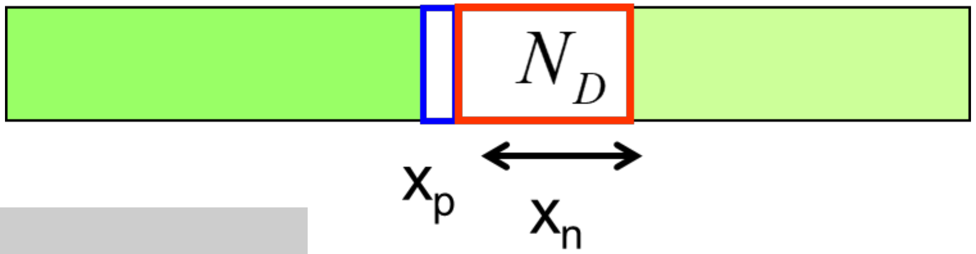


Video

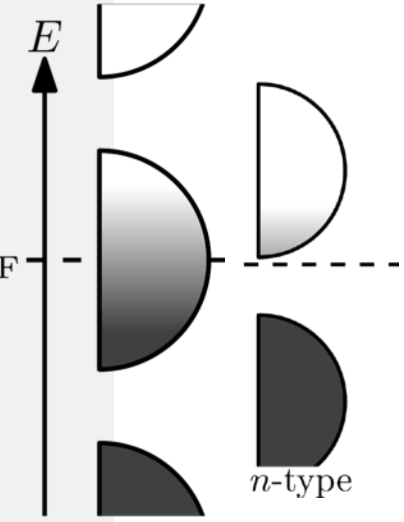
Video

Video

Band Diagram with Applied Bias…



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



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

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

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

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

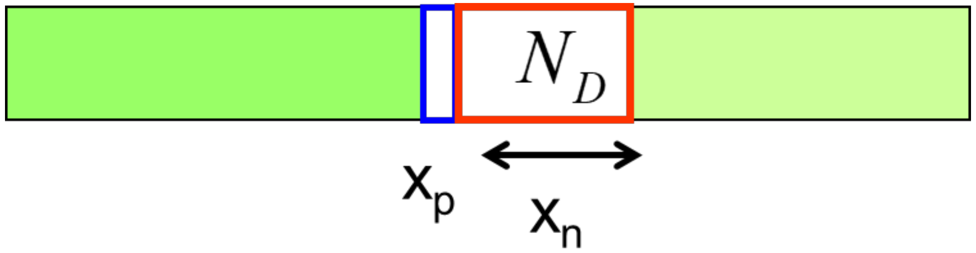
This works for doping-modulated Semiconductors.

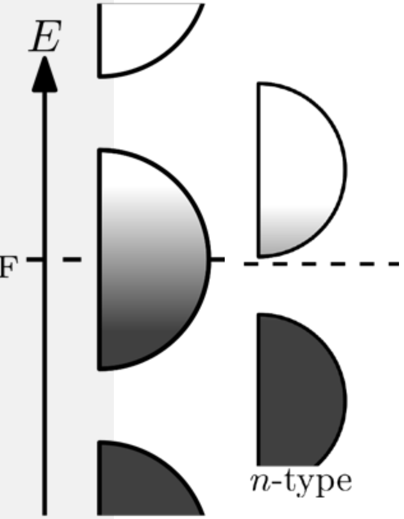
Does not work for heterostructures
(when the conduction band is not continuous)

Metal-Semiconductor is a HS

Need theory of thermionic emission

Depletion Regions with Bias



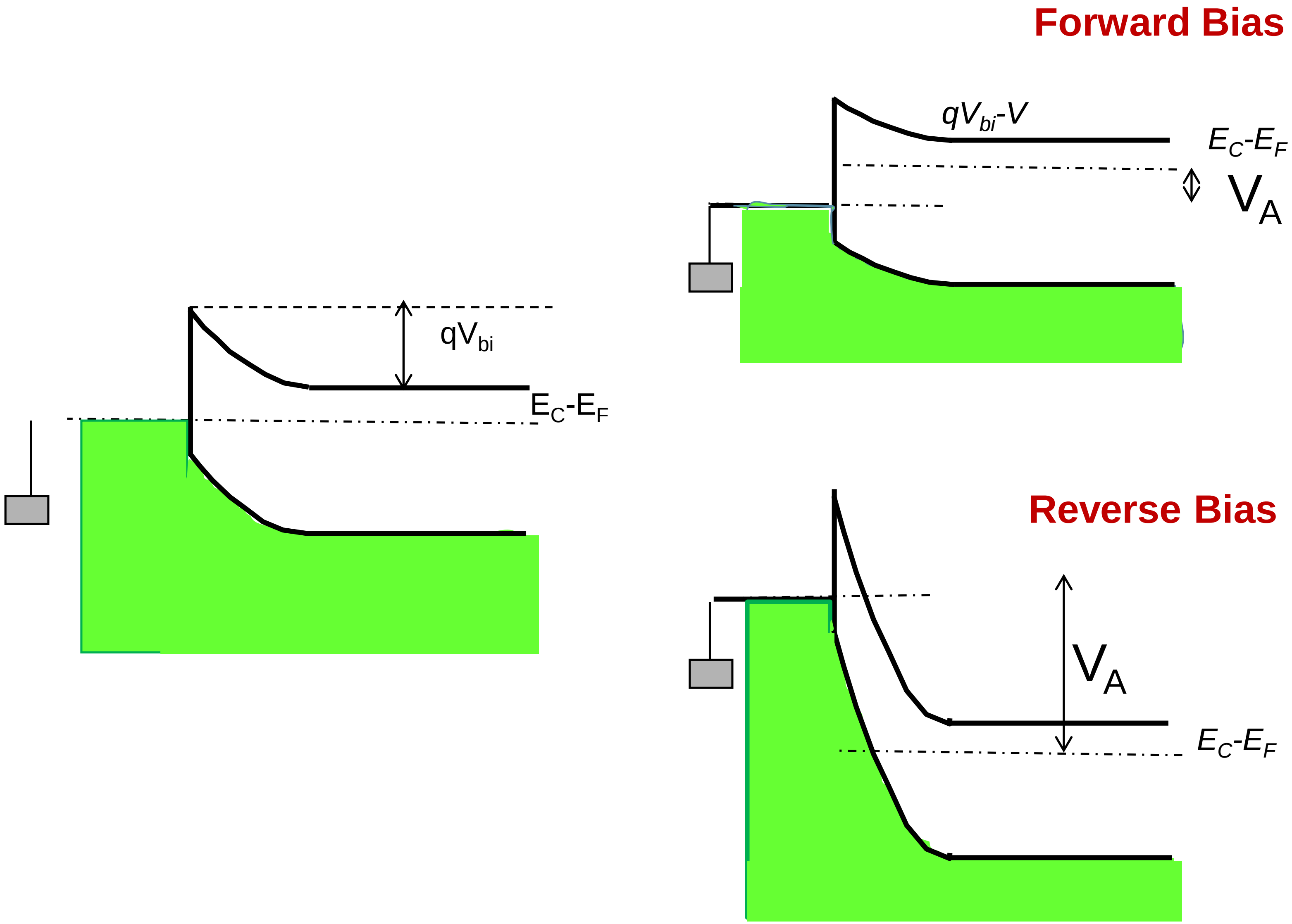


$$x_n = \sqrt{\frac{2k_s\varepsilon_0}{q}\frac{N_M}{N_D\left(N_M+N_D\right)}V_{bi}} \rightarrow \sqrt{\frac{2k_s\varepsilon_0}{q}\frac{1}{N_D}\left(V_{bi}-V_A\right)}$$

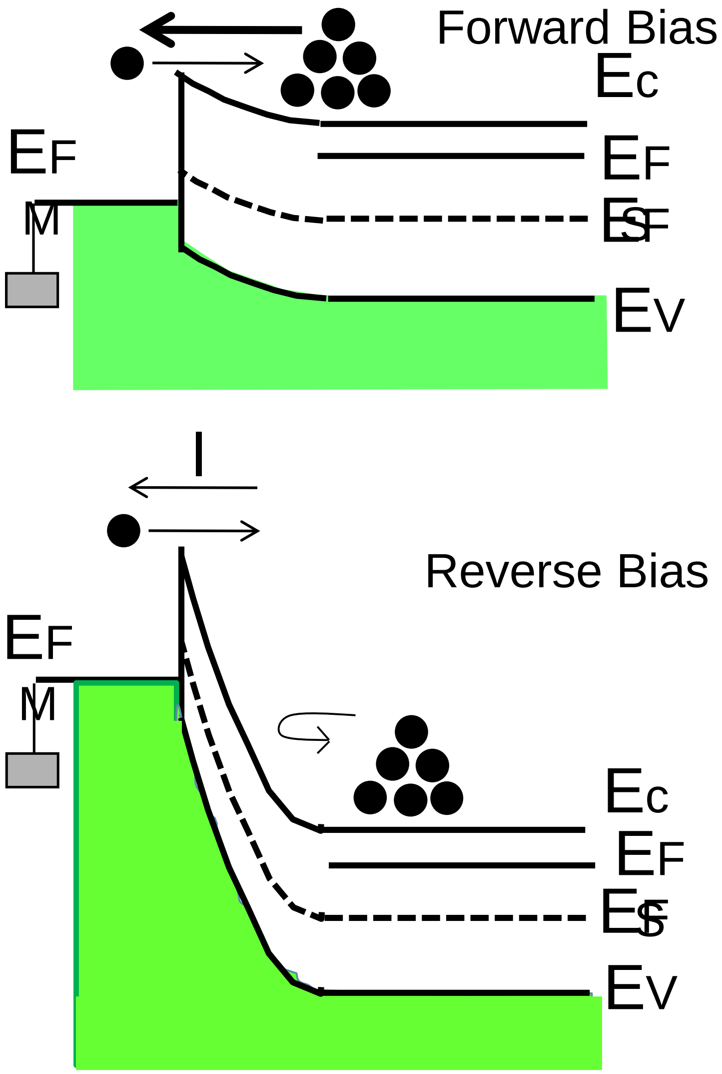
$$x_p = \sqrt{\frac{2k_s\varepsilon_0}{q}\frac{N_D}{N_M\left(N_M+N_D\right)}V_{bi}} \rightarrow 0$$

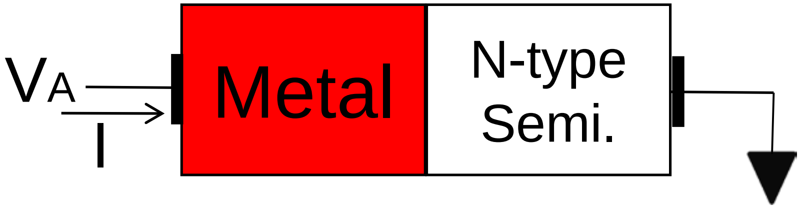
Forward bias: x_n decrease
Reverse bias: x_n increase

Band-diagram with Bias

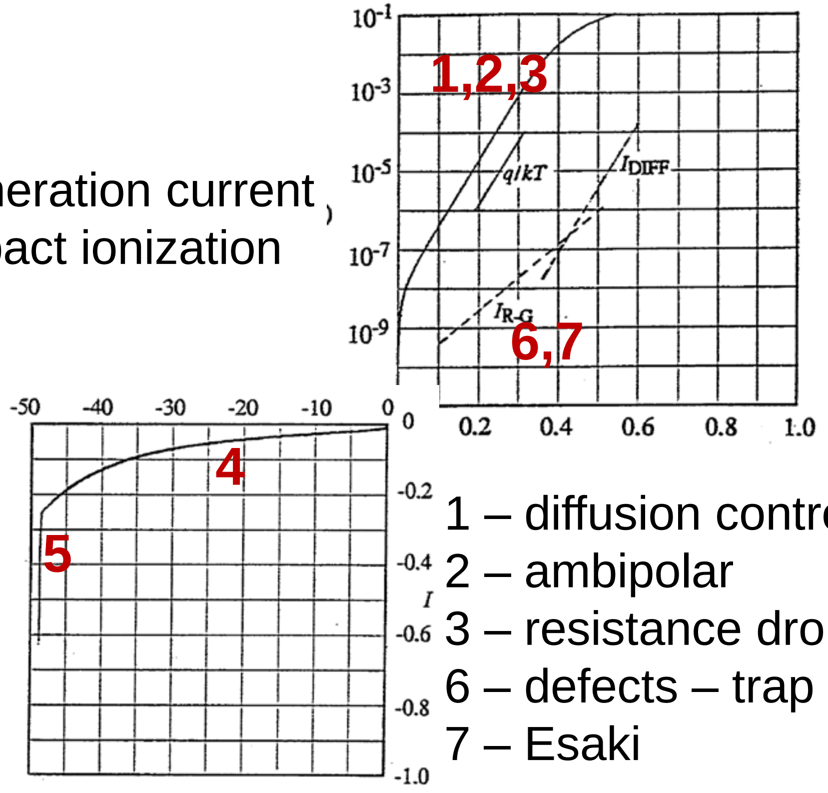


I-V Characteristics





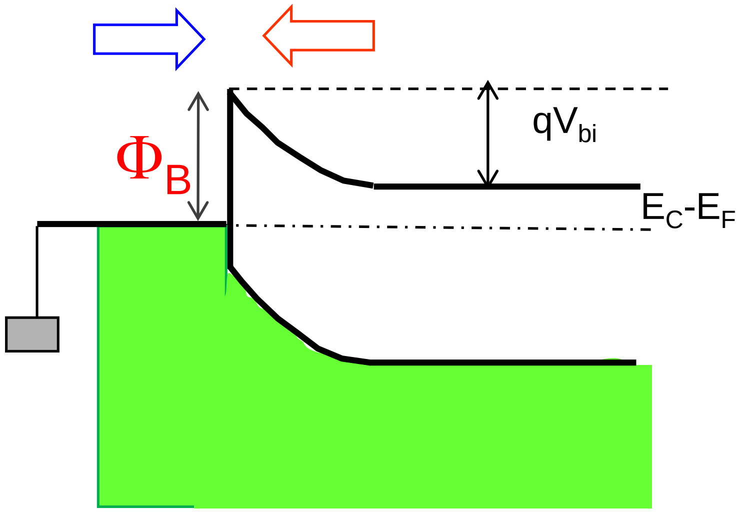
4 – generation current
5 – impact ionization



1 – diffusion control
2 – ambipolar
3 – resistance drop
6 – defects – trap assist
7 – Esaki

Current Flow Concept

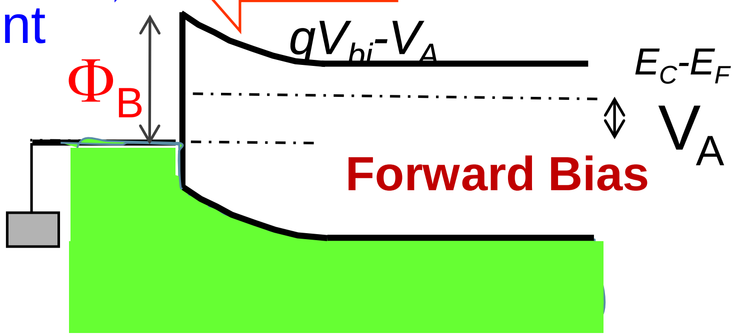
Partition problem in 2 currents
M=>S S<=M



In Equilibrium:
→ and ← are equal

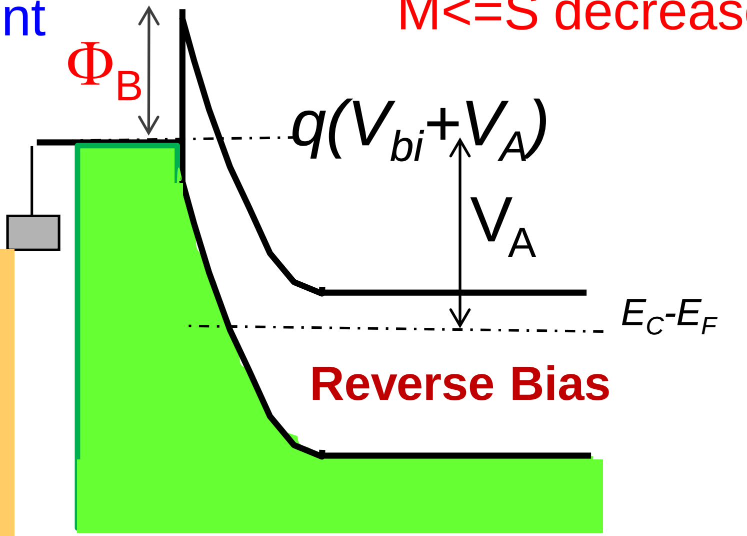
Barrier
The same!
M=>S current
unchanged!

Barrier smaller
M<=S increased



Barrier
The same!
M=>S current
unchanged!

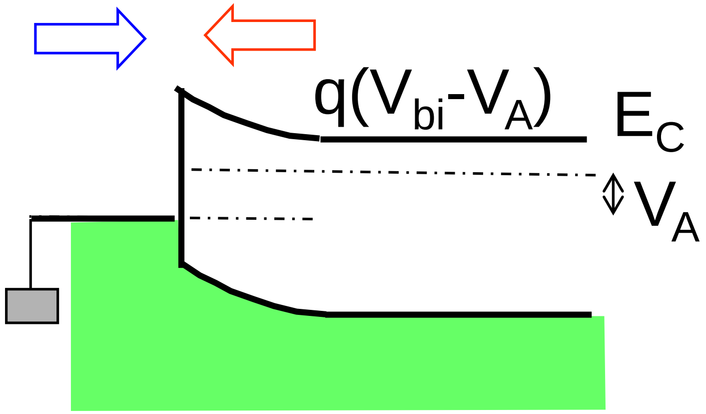
Barrier bigger
M<=S decreased



M=>S current Independent of bias!

We use thermionic emission because:

1. E_C is not continuous here
2. There's no minority carriers!



$$J_T(V_A=0)=0=J_{m\rightarrow s}(0)-J_{s\rightarrow m}(0)$$

(detailed balance)

$$\Rightarrow J_{m\rightarrow s}(0)=J_{s\rightarrow m}(0)$$

$$J_T(V_A)=J_{m\rightarrow s}(V_A)-J_{s\rightarrow m}(V_A)$$
$$=J_{m\rightarrow s}(0)-J_{s\rightarrow m}(V_A)$$

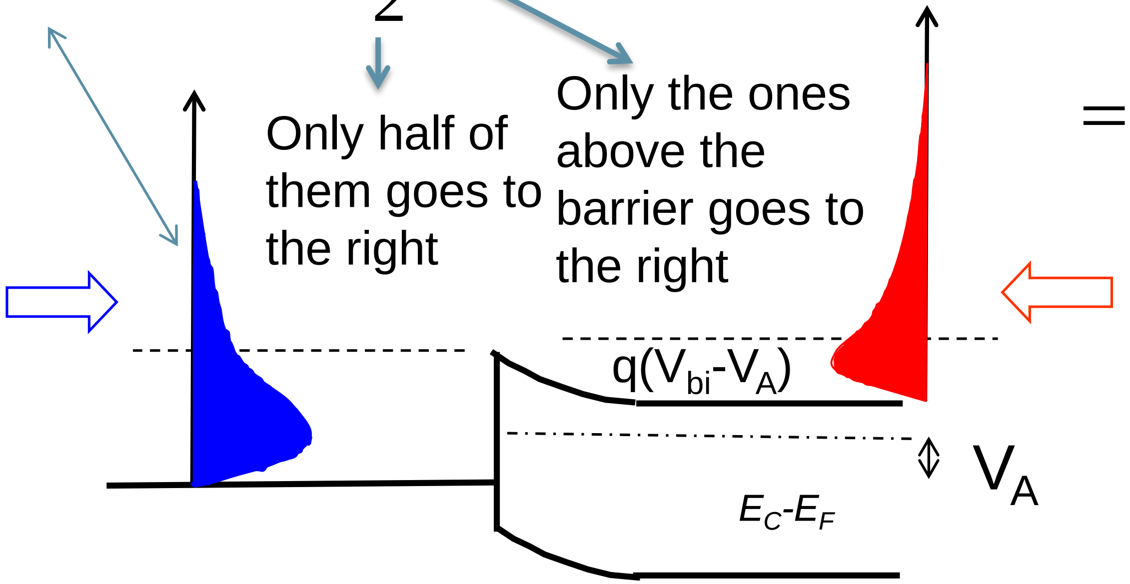
M=>S current independent of bias

$$J_T(V_A)=J_{s\rightarrow m}(0)-J_{s\rightarrow m}(V_A)$$

Semiconductor to Metal Flux

$$J_{m\to s}(0) =$$

$$J_{m\to s}(V_A) = -q\frac{n_m}{2} e^{-\frac{q\Phi_B}{kT}} \upsilon_{thM}$$



$$J_{s\to m}(0) = -q\frac{n_s}{2} e^{-q\frac{V_{bi}}{kT}} \upsilon_{th} = J_{m\to s}(0)$$

$$J_{s\to m}(V_A) = -q\frac{n_s}{2} e^{-q\frac{V_{bi}-V_A}{kT}} \upsilon_{th}$$

$$= -q\frac{n_s \upsilon_{th}}{2} e^{-\frac{qV_{bi}}{kT}} \times e^{\frac{qV_A}{kT}}$$

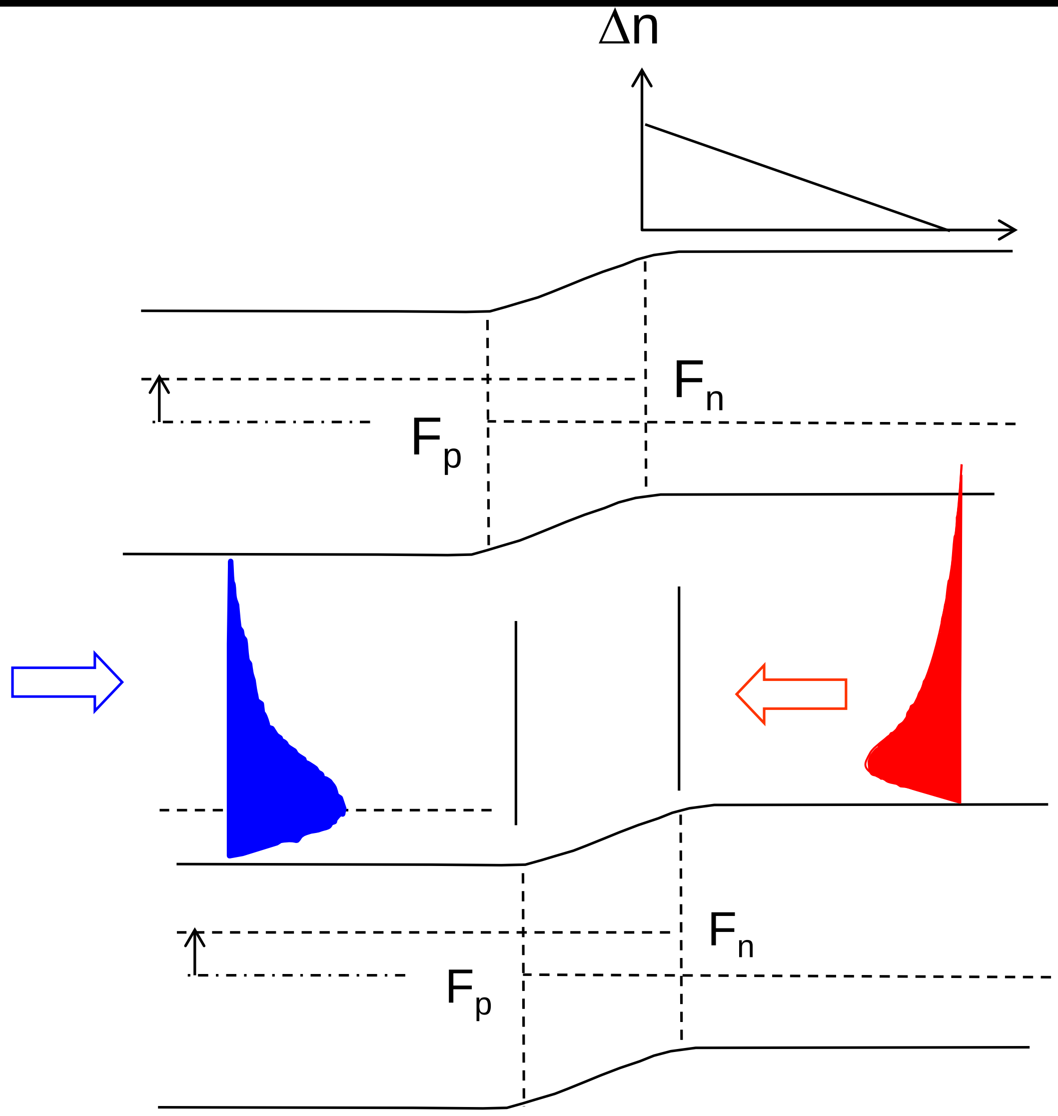
$$= J_{s\to m}(0) e^{\frac{qV_A}{kT}}$$

$$= J_{m\to s}(0) e^{\frac{qV_A}{kT}}$$

$$= -q\frac{n_m \upsilon_{thM}}{2} e^{-\frac{q\Phi_B}{kT}} e^{\frac{qV_A}{kT}}$$

$$J_T = J_{s\to m}(0) - J_{s\to m}(V_A) = \frac{q n_m \upsilon_{thM}}{2} e^{\frac{-q\Phi_B}{kT}} \left[e^{\frac{qV_A}{kT}} - 1 \right]$$

Diffusion vs. Thermionic Emission



Check that both gives the same result for a diode…

Thermionic Emission theory is a more general approach, can be used for device so small that no scattering occur (can't use diffusion!).

$$J_T = J_{s\to m}(0) - J_{s\to m}(V_A) = \frac{q n_m \upsilon_{th}}{2} e^{\frac{-q\Phi_B}{kT}} \left[e^{\frac{qV_A}{kT}} - 1 \right]$$

Intermediate Summary

Schottky barrier diode is a majority carrier device of great historical importance.

There are similarities and differences with p-n junction diode: for electrostatics, it behaves like a one-sided diode, but current, the drift-diffusion approach requires modification.

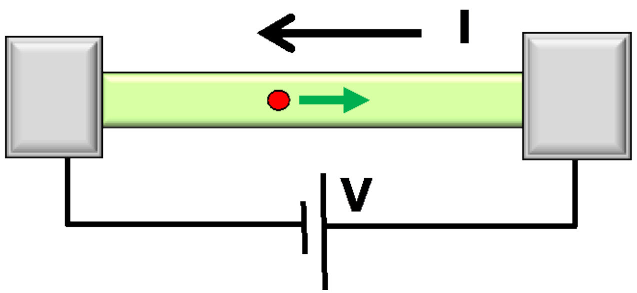
The trap-assisted current, avalanche breakdown, Zener tunneling all could be calculated in a manner very similar to junction diode.

$$J_T = J_{s\rightarrow m}(0) - J_{s\rightarrow m}(V_A) = \frac{q n_m \upsilon_{th}}{2} e^{\frac{-q\Phi_B}{kT}} \left[e^{\frac{qV_A}{kT}} - 1 \right]$$

Video

Video

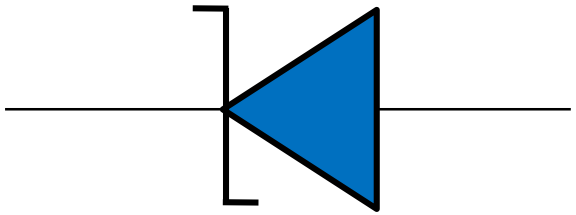
Video



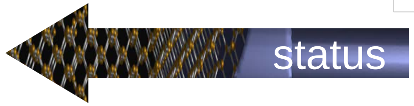
$I = G \times V$

$= q \times n \times v \times A$

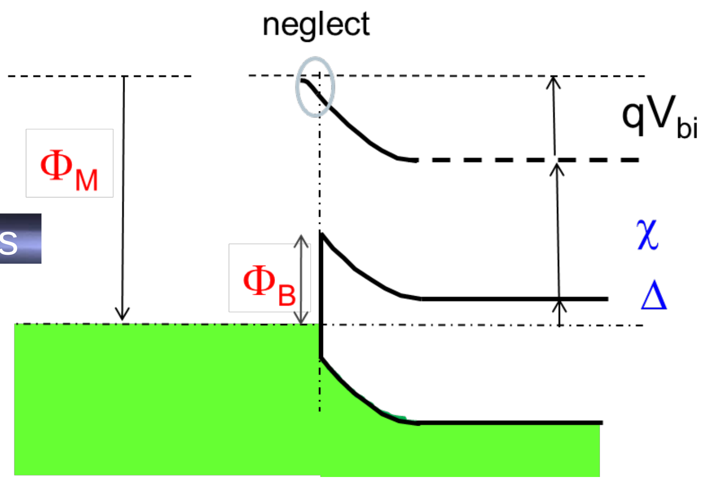
charge density velocity area

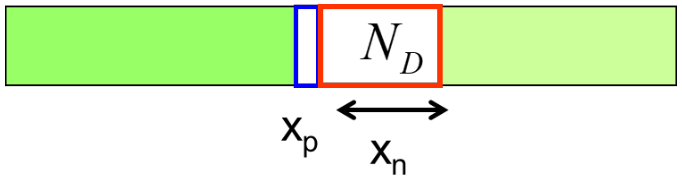


- 23.1 Basics
  - »Equilibrium band-diagram
  - »DC Thermionic current (simple derivation)



- 23.2 Physical Processes

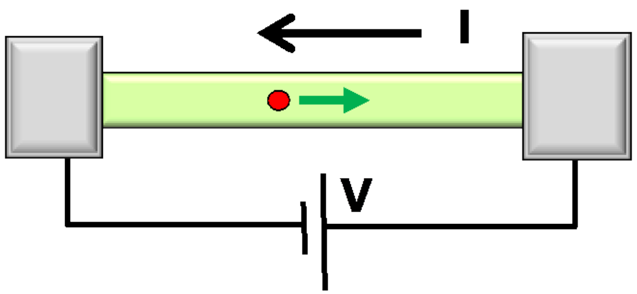




- 23.4 Practical Issues

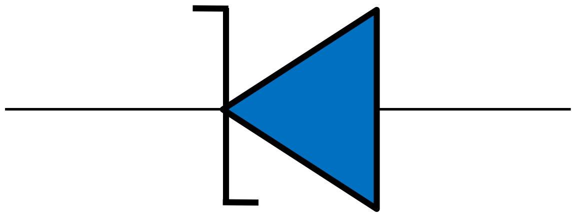
$$J_T = J_{s\to m}(0) - J_{s\to m}(V_A) = \frac{q n_m \upsilon_{th}}{2} e^{\frac{-q\Phi_B}{kT}} \left[e^{\frac{qV_A}{kT}} - 1 \right]$$

Section 23
Schottky Diode

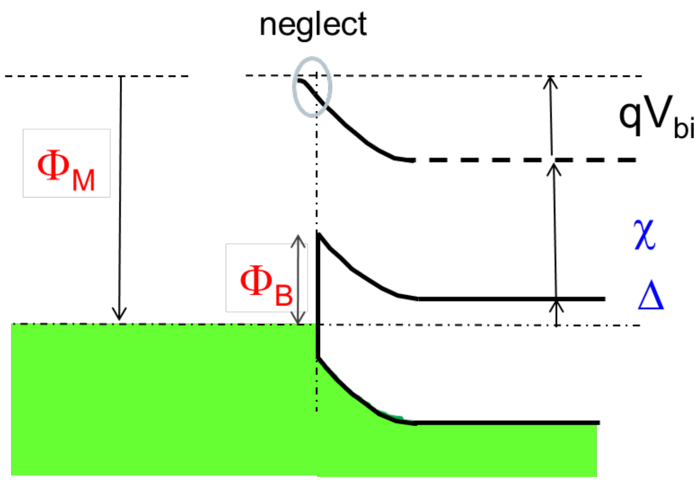


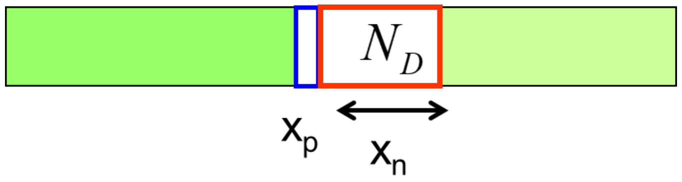
$$I = G \times V$$
$$= q \times n \times v \times A$$

charge density velocity area



- 23.1 Basics
  - »Equilibrium band-diagram
  - »DC Thermionic current (simple derivation)
- 23.2 Physical Processes ← status
  - »DC Thermionic current (detailed derivation)
  - »Recombination/Generation/Ionization
  - »AC and Large Signal Response
- 23.4 Practical Issues





Video

Video

Video

$$J_T = J_{s\to m}(0) - J_{s\to m}(V_A) = \frac{q n_m \upsilon_{th}}{2} e^{\frac{-q\Phi_B}{kT}} \left[e^{\frac{qV_A}{kT}} - 1 \right]$$