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ECE606: Solid State Devices
Lecture 25: Schottky Diode (I)

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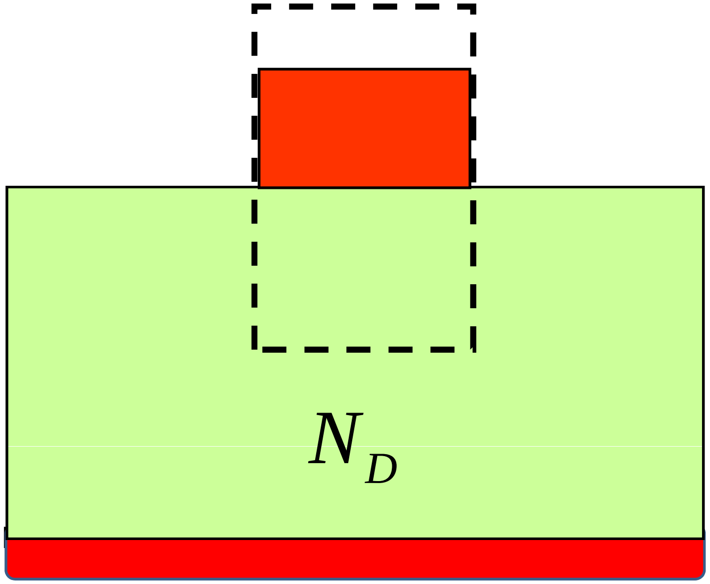
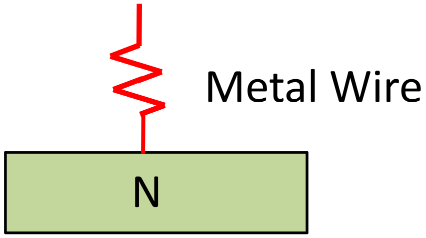
Outline

1) **Importance of metal-semiconductor junctions**
2) Equilibrium band-diagrams
3) DC Thermionic current (simple derivation)
4) Conclusions

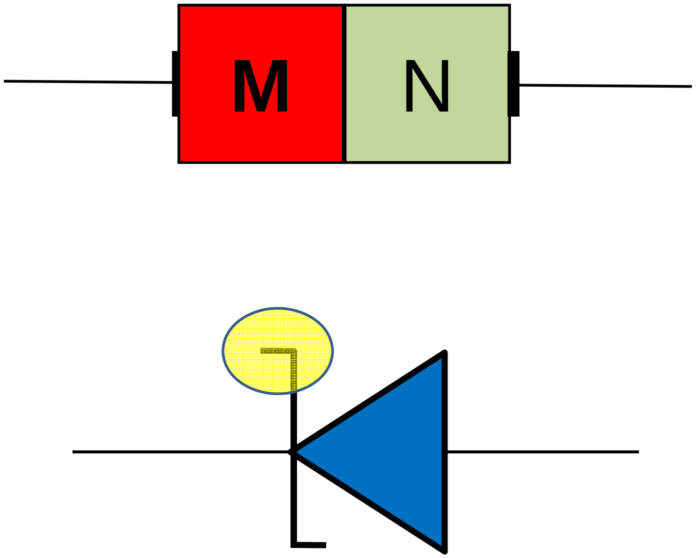
Ref. Semiconductor Device Fundamentals, Chapter 14, p. 477

Metal-semiconductor Diode

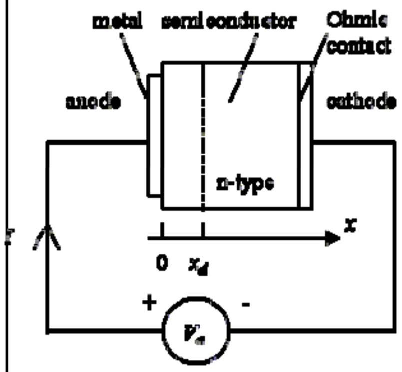




Symbols

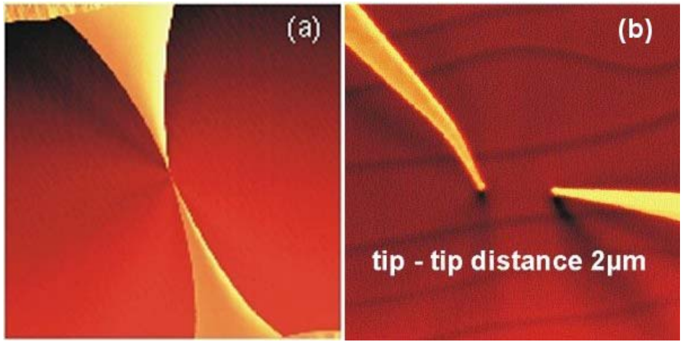


Applications of M-S Diode ….



Detectors

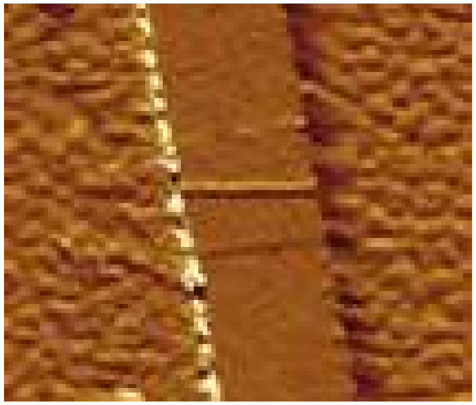
STM on semiconductor

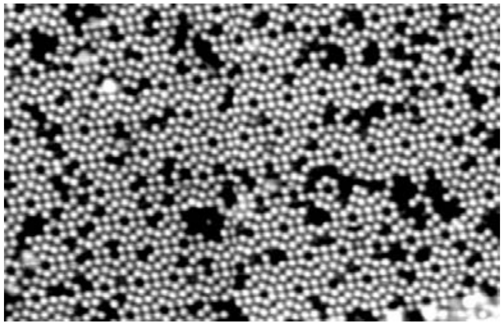


www.fz-juelich.de/ibn/index.php?index=674

Original Bipolar

CNT Transistors





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

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1) Importance of metal-semiconductor junctions
2) **Equilibrium band-diagrams**
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Topic Map

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

Drawing Band Diagram in Equilibrium…

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

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

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

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

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

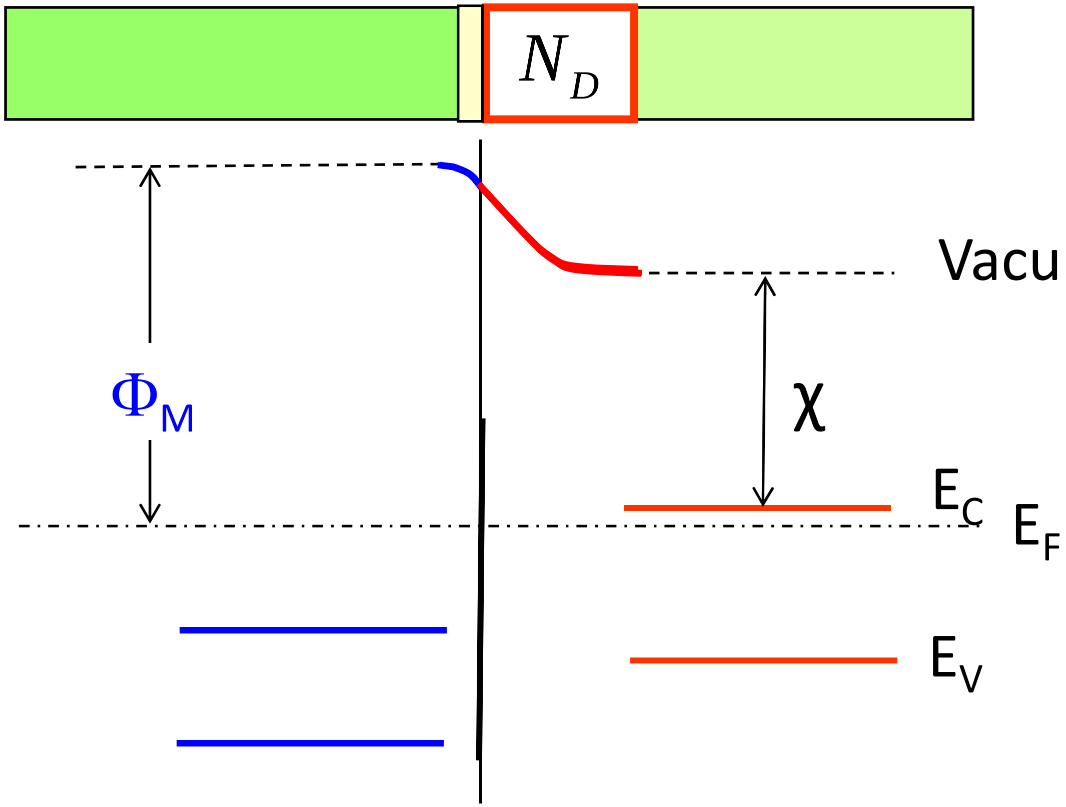
Equilibrium

DC dn/dt=0

Small signal dn/dt ~ jωtn

Transient --- full sol.

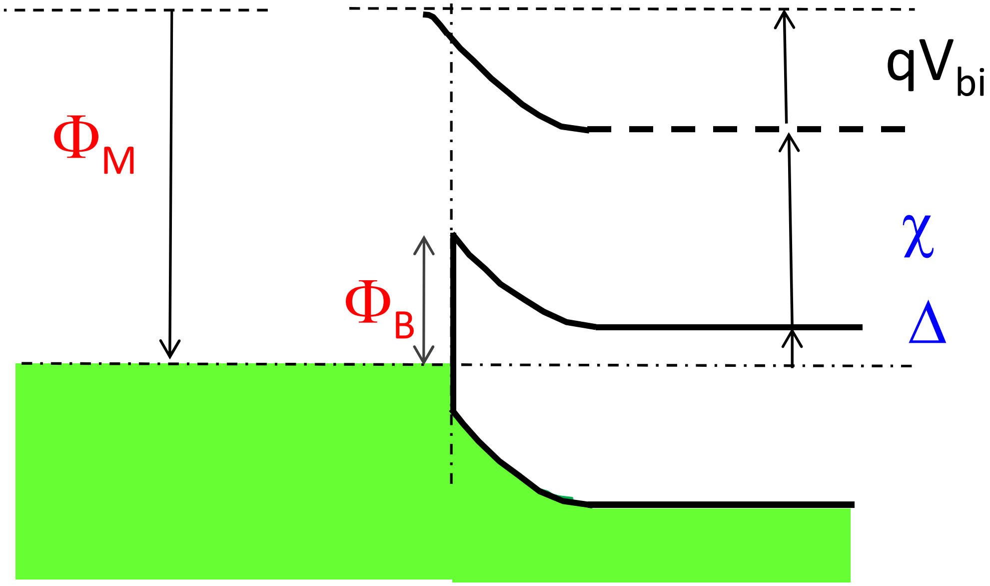
Band-Diagram



Negligible ..

$$N_A x_p = N_D x_n$$

Built-in Potential: bc @Infinity



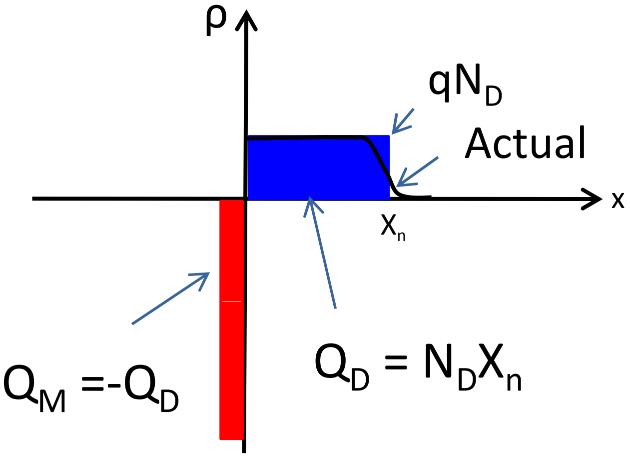
$$\Delta + \chi + qV_{bi} = \Phi_M$$

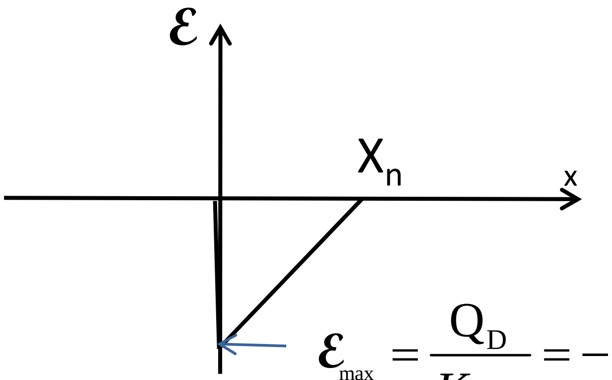
$$qV_{bi} = (\Phi_M - \chi) - \Delta \equiv \Phi_B - \Delta$$

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

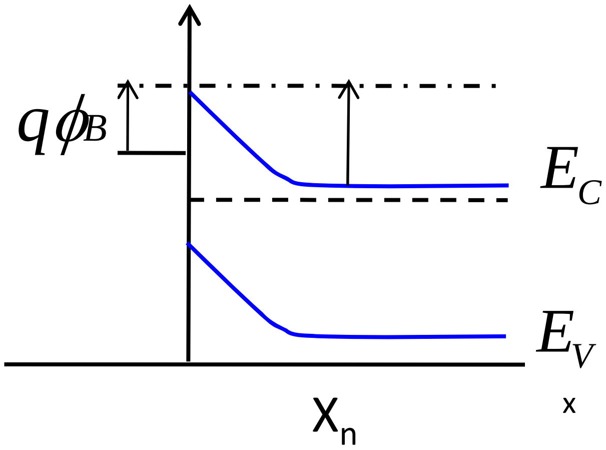
Complete Analytical Solution

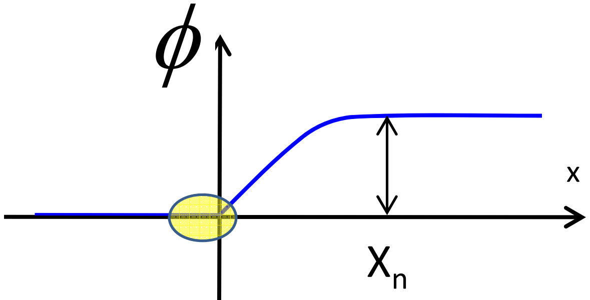
Depletion Approximation





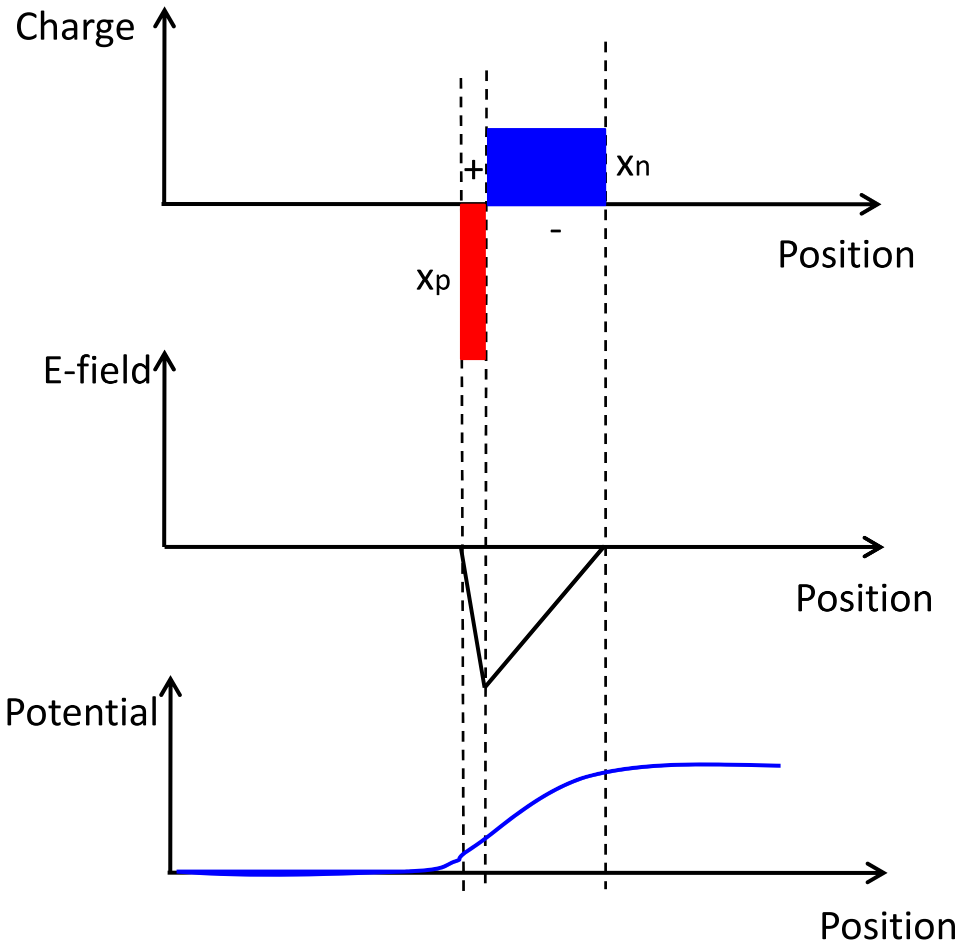
$$\mathcal{E}_{\max} = \frac{Q_D}{K_s \varepsilon_0} = -\frac{qN_D x_n}{K_s \varepsilon_0}$$





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

Analytical Solution (Simple Approach)



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

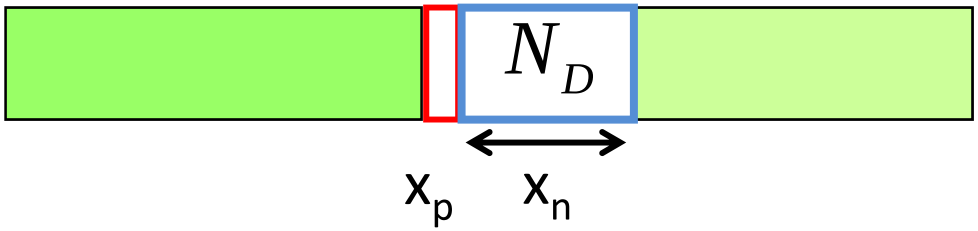
$$\mathcal{E}(0^-) = \frac{qN_M x_p}{k_s \varepsilon_0} \; ?$$

$$\Rightarrow N_D x_n = N_M x_p$$

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

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

Depletion Regions



$$\left.\begin{aligned} N_D x_n &= N_M x_p \\ qV_{bi} &= \frac{qN_D x_n^{\,2}}{2k_s\varepsilon_0} + \frac{qN_M x_p^{\,2}}{2k_s\varepsilon_0} \end{aligned}\right\}$$

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

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

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

Band Diagram with Applied Bias…

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

Band diagram …

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

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

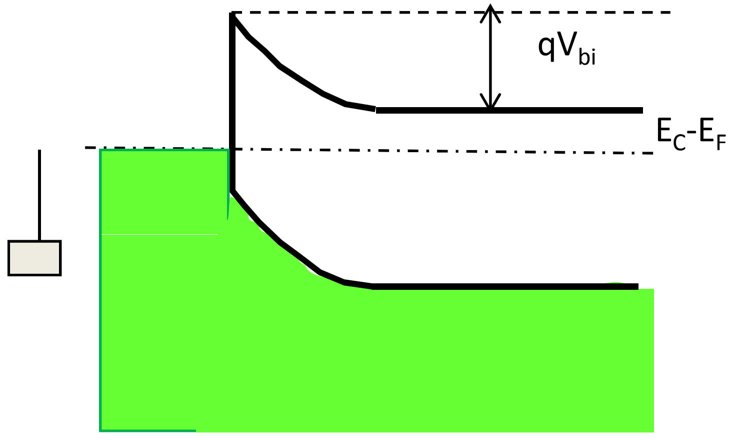
This will not work

Need theory of thermionic emission

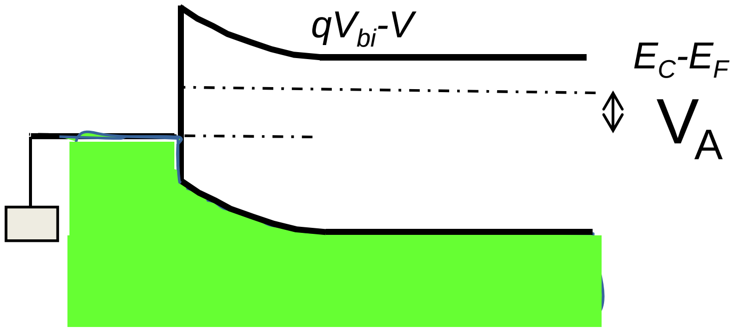
$$\frac{\partial p}{\partial t} = -\frac{1}{q}\nabla \bullet \mathbf{J}_P - r_P + g_P$$

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

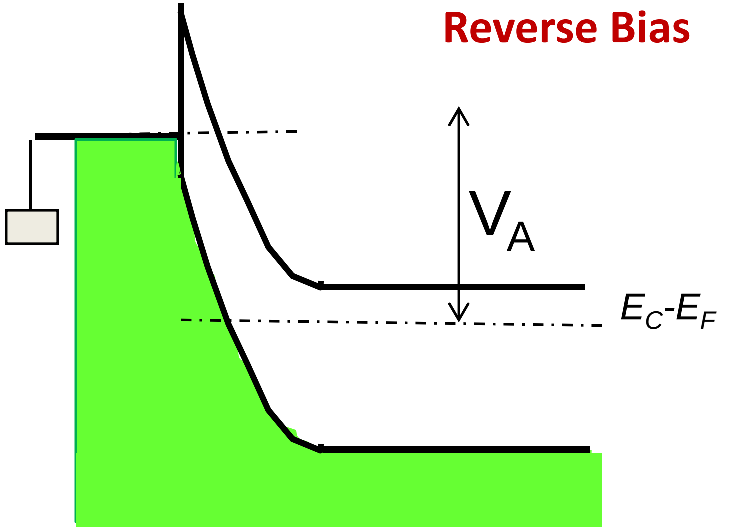
Band-diagram with Bias



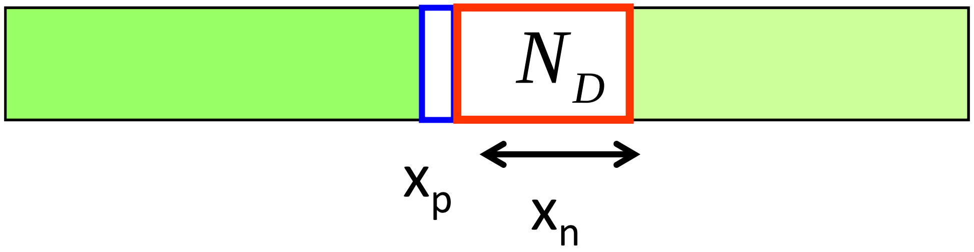
Forward Bias



Reverse Bias



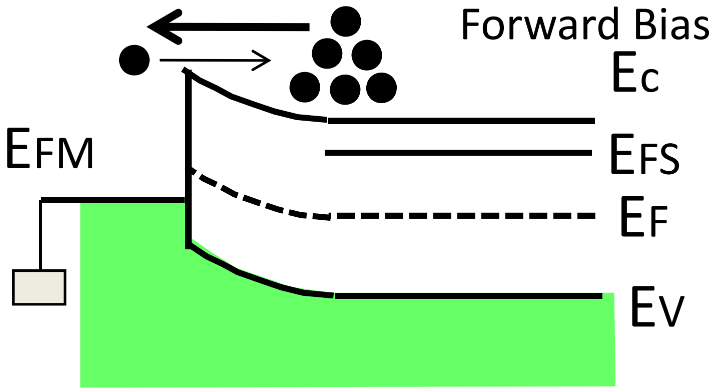
Depletion Regions with Bias

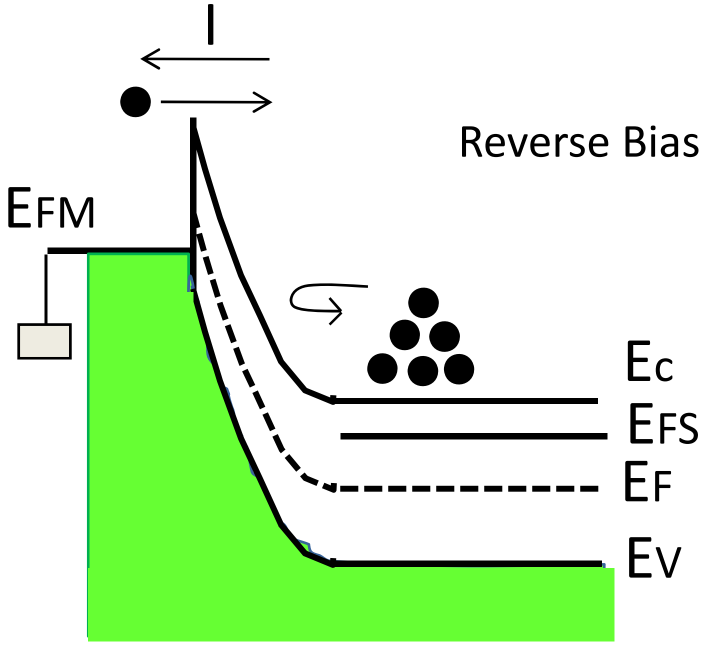


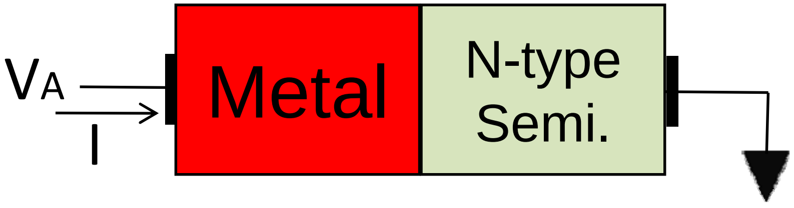
$$x_n = \sqrt{\frac{2k_s\varepsilon_0}{q}\frac{N_M}{N_D\left(N_M+N_D\right)}V_{bi}} \rightarrow \sqrt{\frac{2k_s\varepsilon_0}{q}\frac{1}{N_D}\left(V_{bi}-V_A\right)}$$

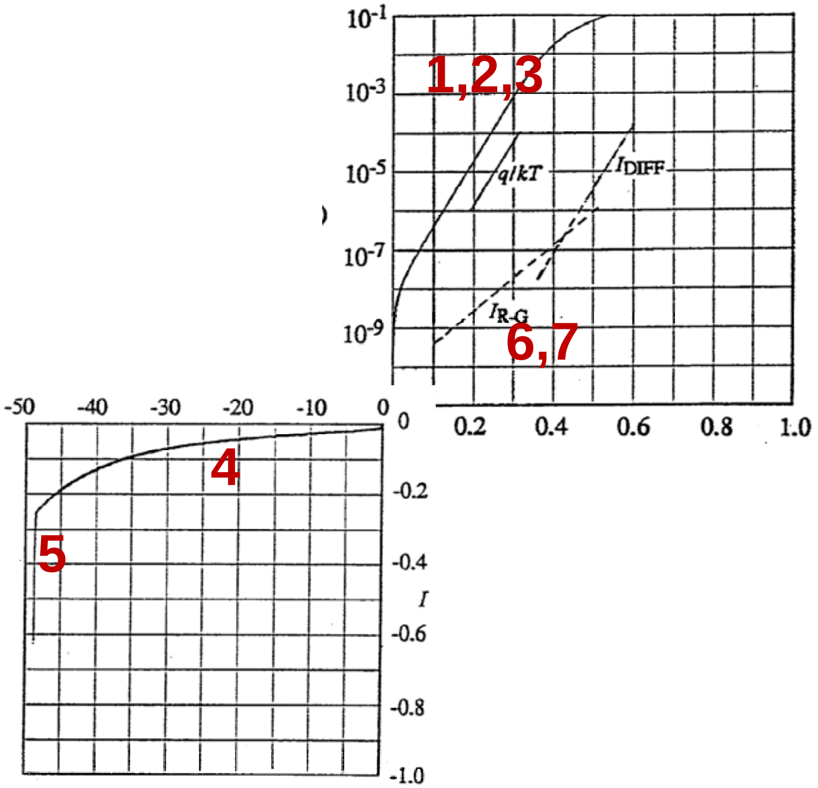
$$x_p = \sqrt{\frac{2k_s\varepsilon_0}{q}\frac{N_D}{N_M\left(N_M+N_D\right)}V_{bi}} \rightarrow 0$$

I-V Characteristics

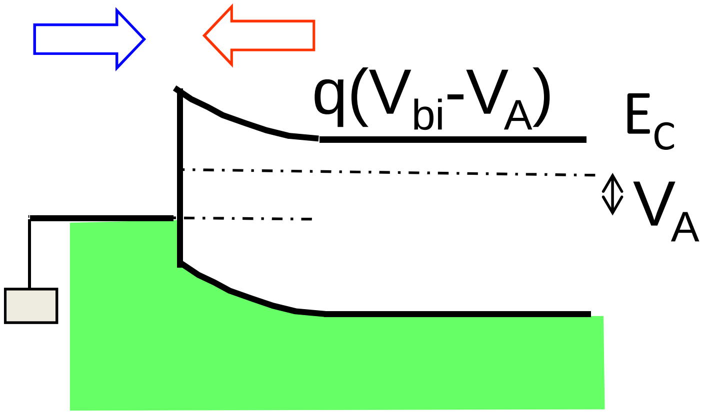








Left Boundary Condition



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

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

$$J_T(V_A = 0) = 0 = J_{m\to s}(0) - J_{s\to m}(0)$$ (detailed balance)

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

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

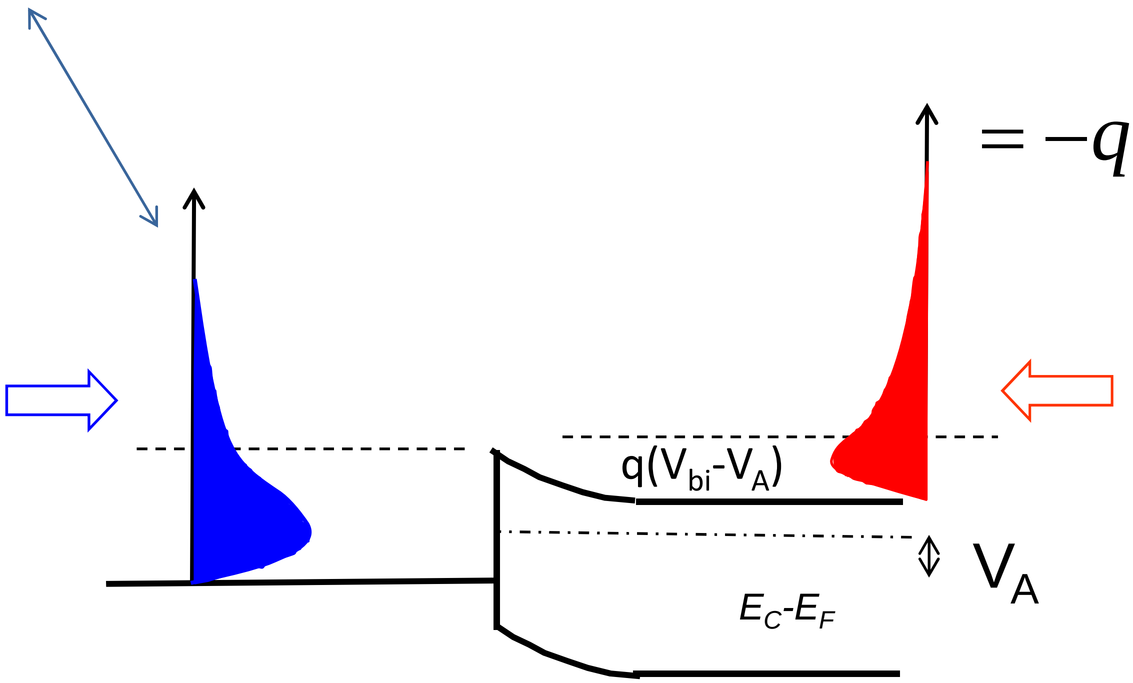
Semiconductor to Metal Flux

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

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

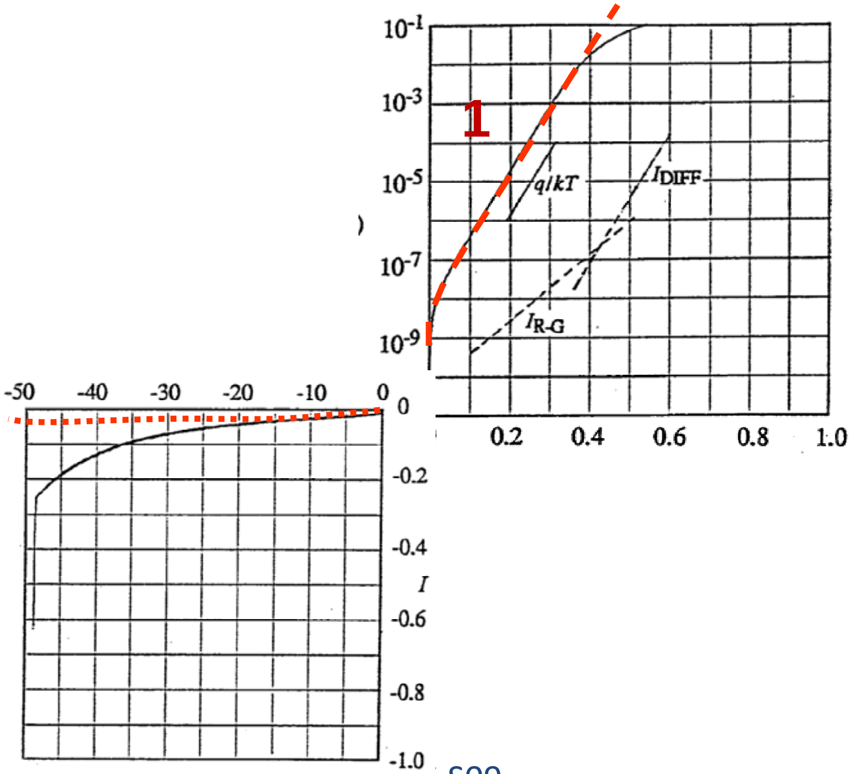
$$= -q\frac{n_s\upsilon_{th}}{2}e^{-\frac{qV_{bi}}{kT}}\times e^{\frac{qV_A}{kT}}$$

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



Total Flux…

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



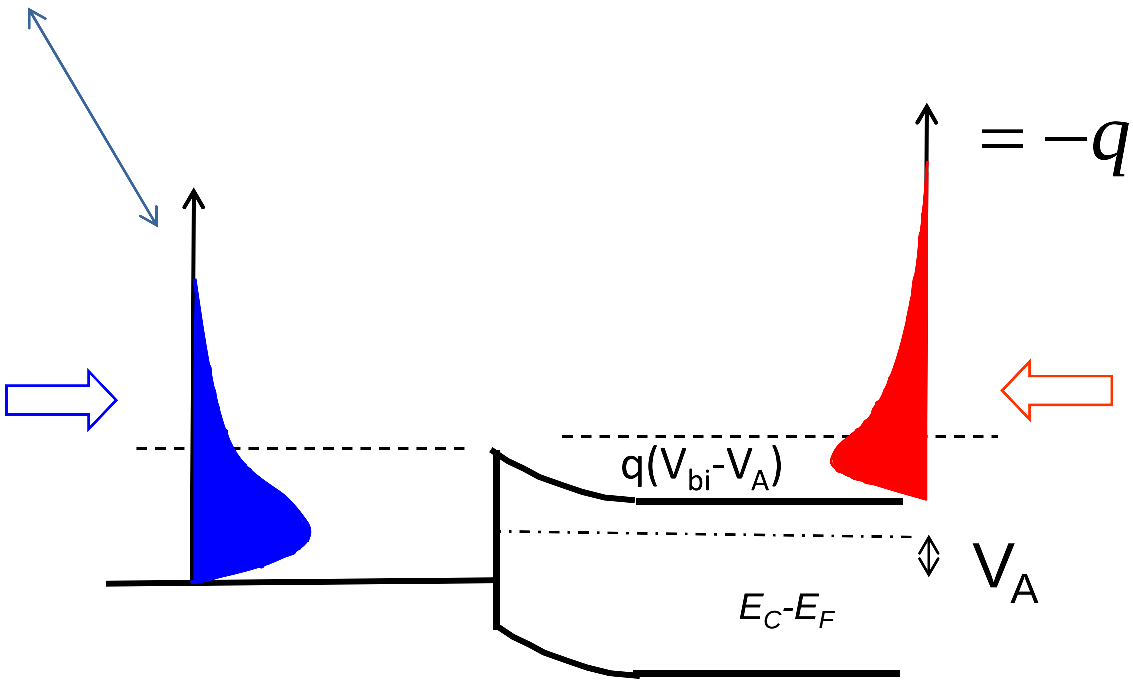
Semiconductor to Metal Flux

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

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

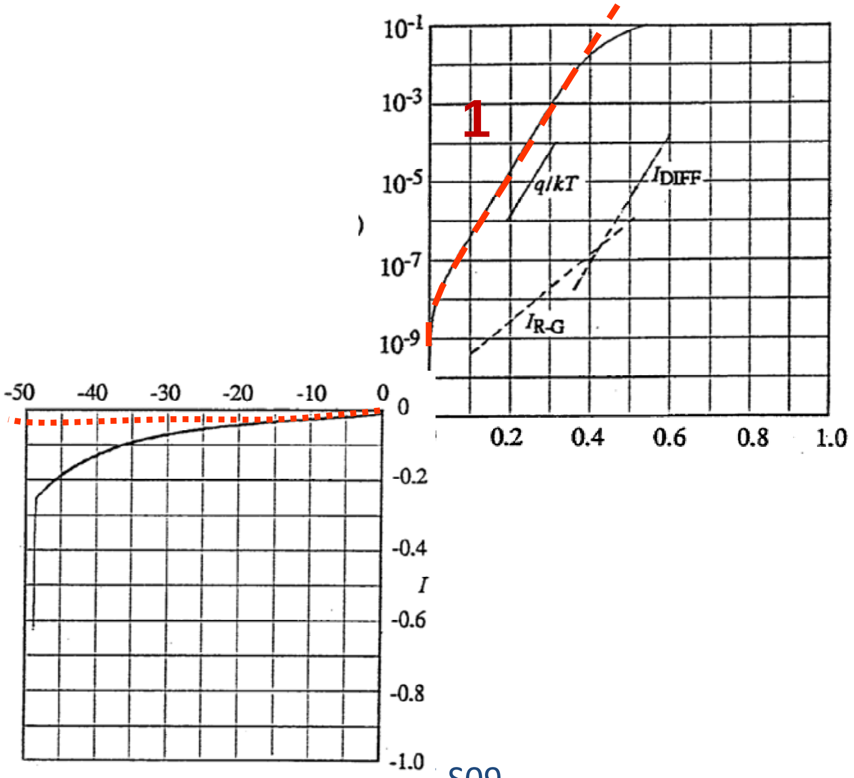
$$= -q\frac{n_s\upsilon_{th}}{2}e^{-\frac{qV_{bi}}{kT}}\times e^{\frac{qV_A}{kT}}$$

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

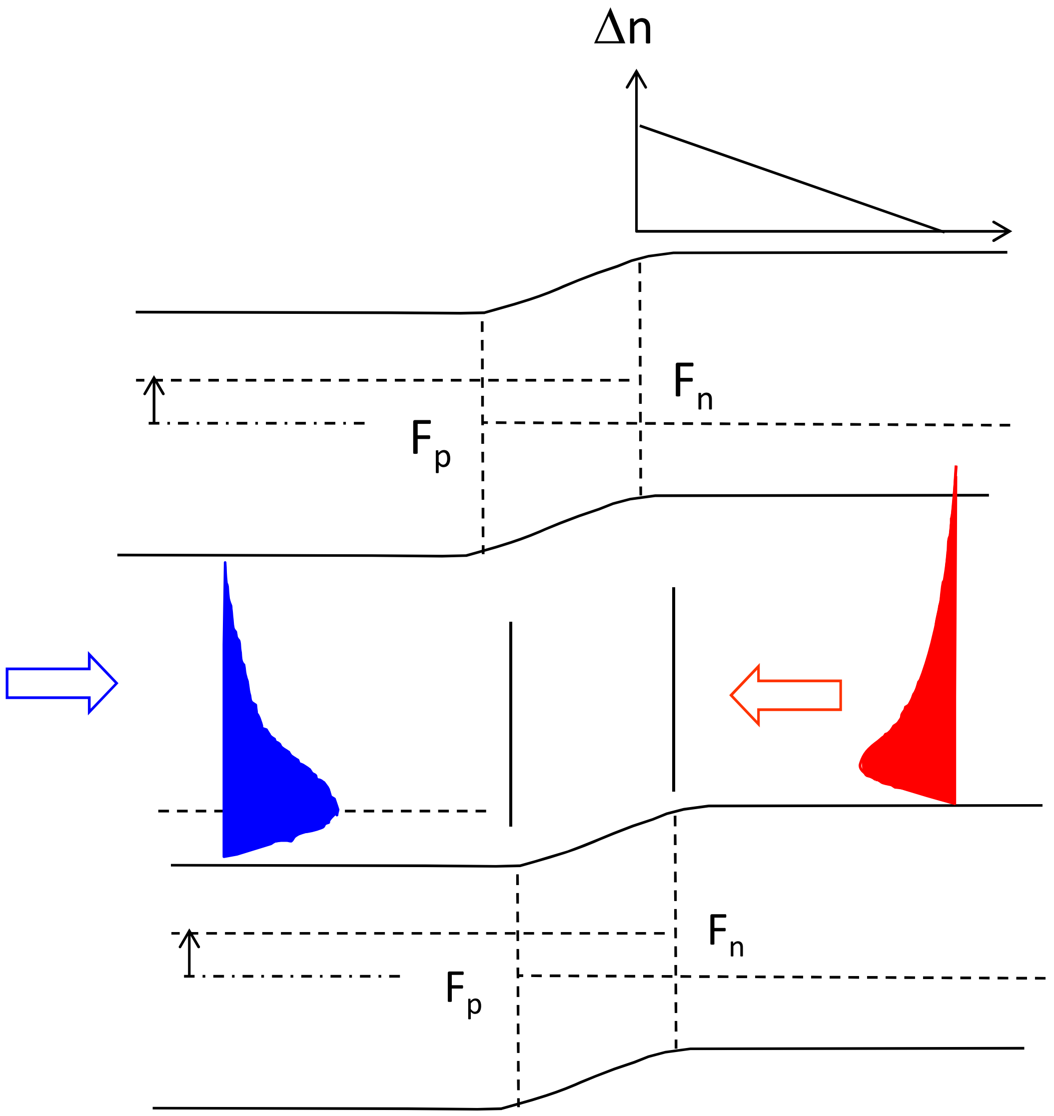


Total Flux…

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



Diffusion vs. Thermionic Emission



Check that both gives the same result for a diode…

Conclusion

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.