ECE606: Solid State Devices
Lecture 17

Schottky Diode

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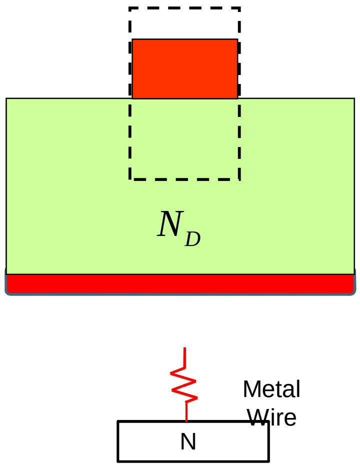
Presentation Outline

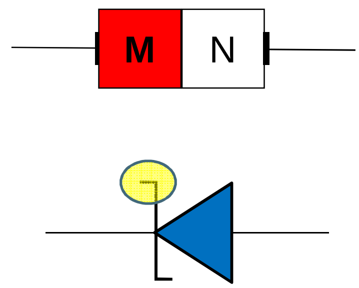
1) Importance of metal-semiconductor junctions
2) Equilibrium band-diagrams
3) DC Thermionic current (simple derivation)
4) Intermediate Summary
5) DC Thermionic current (detailed derivation)
6) AC small signal and large-signal response
7) Additional information
8) Conclusions

Reference: Semiconductor Device Fundamentals, Chapter 14, p. 477

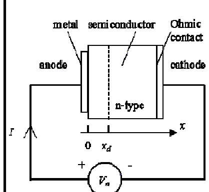
Metal-semiconductor Diode



Symbols

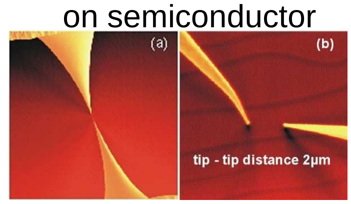


Applications of M-S Diode ....



Detectors

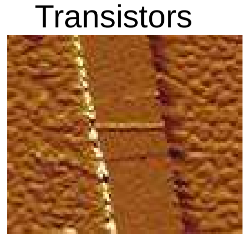
STM(scanning tunneling microscope) on semiconductor

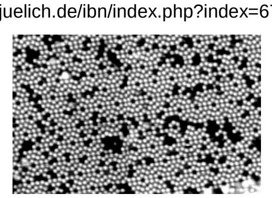


www.fz-juelich.de/ibn/index.php?index=674

Original Bipolar

CNT(carbon nanotube) Transistors





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

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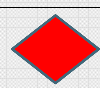
Topic Map

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

Drawing Band Diagram in Equilibrium…

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

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

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

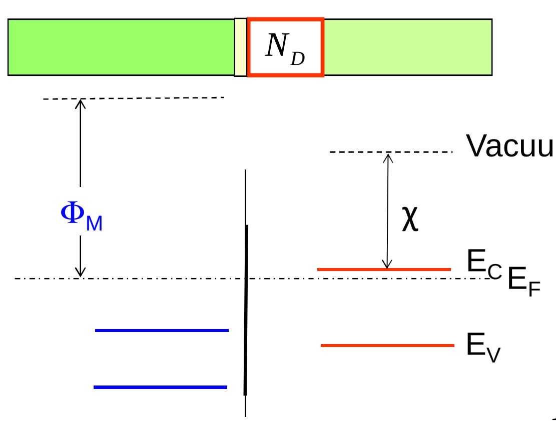
$$\frac{\partial p}{\partial t} = -\frac{1}{q}\nabla \bullet \mathbf{J}_P - r_P + g_P$$

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

DC dn/dt=0
Small signal dn/dt ~ jωtn
Transient --- full sol.

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

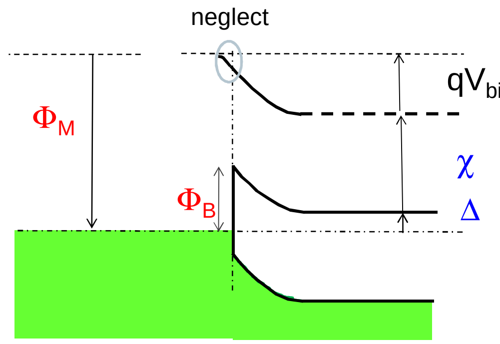


Since N_A is large, x_p is negligible ..

$$N_A x_p = N_D x_n$$

Charge(metal) = charge(semiconductor)

Built-in Potential: bc @Infinity

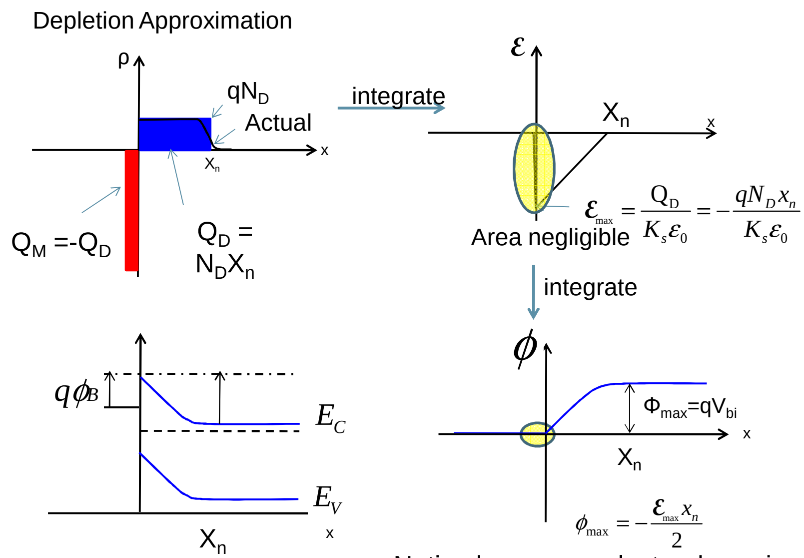


$$\Delta + \chi + qV_{bi} = \Phi_M$$

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

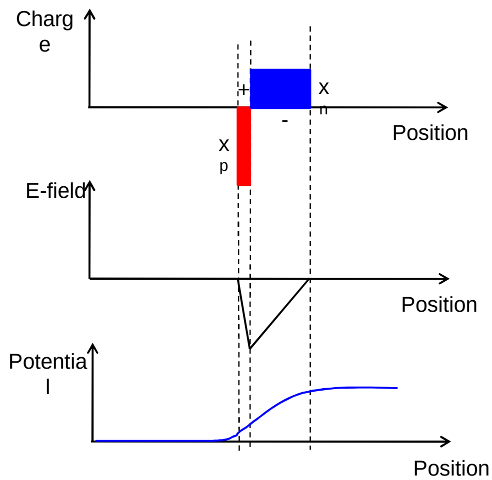
$$= \Phi_B - k_B T \ln \frac{N_D}{N_C}$$ non-degenerate

Analytical Solution (Simple Approach)



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

Complete Analytical Solution



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

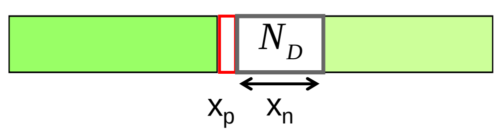
$$\mathcal{E}\left(0^-\right) = \frac{qN_M x_p}{k_s \varepsilon_0} \;?$$

$$\Rightarrow N_D x_n = N_M x_p$$

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

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

Depletion Regions



$$N_D x_n = N_M x_p$$

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

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

$N_M \rightarrow \infty$

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

This is why we can neglect x_p

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Schottky		◆			
BJT/HBT					
MOS					

Band Diagram with Applied Bias…

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

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

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

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

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

Band diagram …

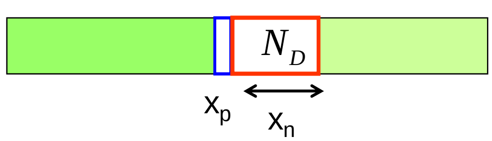
This works for doping-modulated Semiconductors.

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

Metal-Semiconductor is a HS

Need theory of thermionic emission

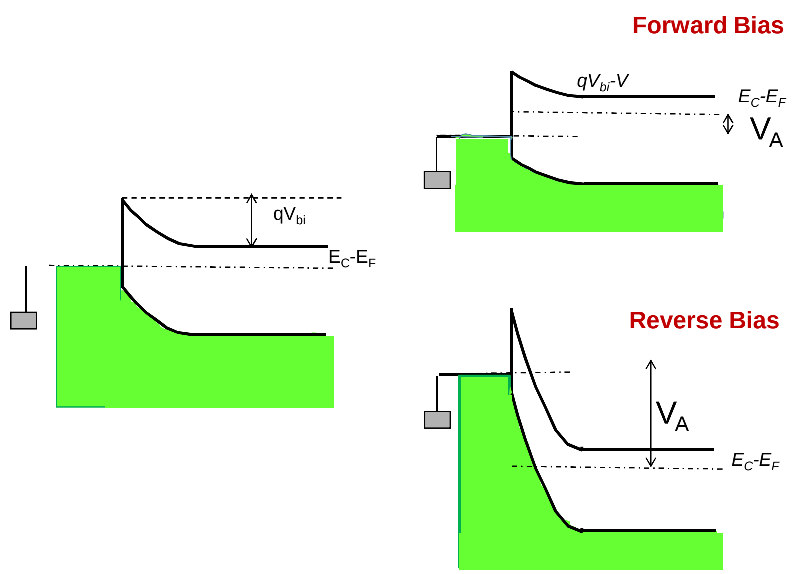
Depletion Regions with Bias

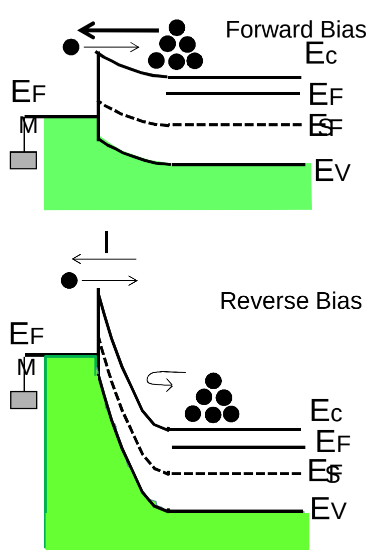


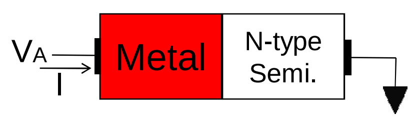
$$x_n = \sqrt{\frac{2k_s\varepsilon_0}{q}\frac{N_M}{N_D\left(N_M+N_D\right)}V_{bi}} \rightarrow \sqrt{\frac{2k_s\varepsilon_0}{q}\frac{1}{N_D}\left(V_{bi}-V_A\right)}$$

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

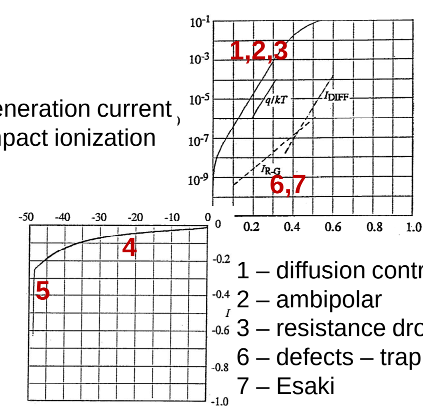
Forward bias: x_n decrease
Reverse bias: x_n increase







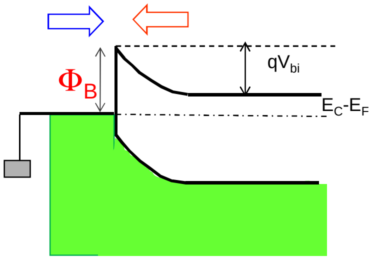
4 – generation current
5 – impact ionization



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

Current Flow Concept

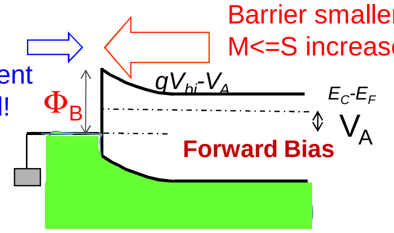
Partition problem in
2 currents
M=>S S<=M



In Equilibrium:
⇨ and ⇦
are equal

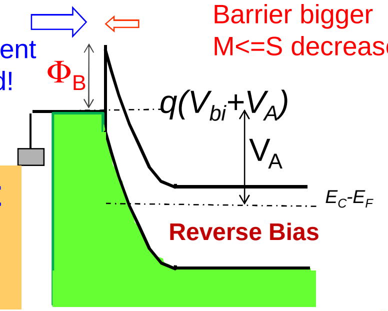
Barrier
The same!
M=>S current
unchanged!

Barrier smaller
M<=S increased



Barrier
The same!
M=>S current
unchanged!

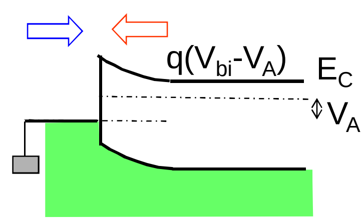
Barrier bigger
M<=S decreased



M=>S current Independent of bias!

Left Boundary Condition

We use thermionic emission because:
1. E_C is not continuous here
2. There's no minority carriers!



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

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

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

M=>S current independent of bias

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

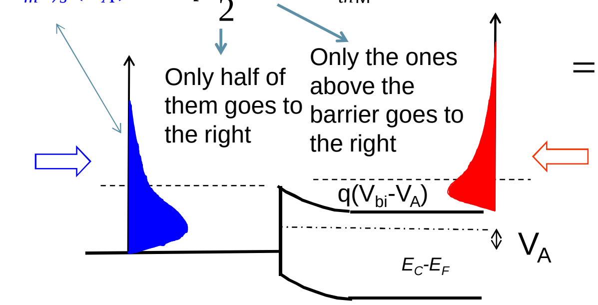
Semiconductor to Metal Flux

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

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

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

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



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

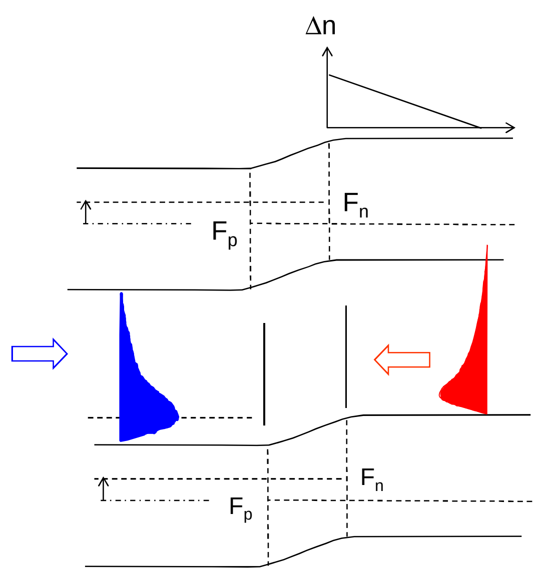
$$= J_{s\to m}(0)\, e^{\frac{qV_A}{kT}}$$

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

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

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

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!).

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.

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Energy Resolved Thermionic Flux

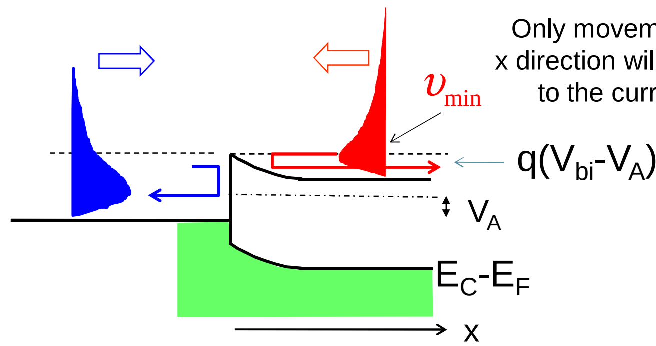
Energy $< \frac{1}{2} m^* \upsilon_{\min}^2$ will be bounced back

~ DOS

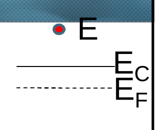
Occupation (non-denegerate)

$$J_{s\to m} = -q \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{-\upsilon_{\min}} \frac{\Omega}{4\pi^3} dk_x dk_y dk_z \, e^{-(E-E_F)\beta} \, \upsilon_x$$

Only movement in the x direction will contribute to the current flux



Thermionic Flux from Semi to Metal ..



$$J_{s\to m} = -q \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{-\upsilon_{\min}} \frac{\Omega}{4\pi^3} dk_x dk_y dk_z \, e^{-(E-E_F)\beta} \, \upsilon_x$$

$$E - E_F = (E - E_C) + (E_C - E_F) = \frac{1}{2} m^* \upsilon_x^2 + \frac{1}{2} m^* \upsilon_y^2 + \frac{1}{2} m^* \upsilon_z^2 + (E_C - E_F)$$

$$= q e^{-(E_c - E_F)\beta} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{-\upsilon_{\min}} \frac{\Omega}{4\pi^3} \frac{d(m^*\upsilon_x)}{\hbar} \frac{d(m^*\upsilon_y)}{\hbar} \frac{d(m^*\upsilon_z)}{\hbar} e^{-\frac{(m\upsilon_x^2 + m\upsilon_y^2 + m\upsilon_z^2)}{2}\beta} \upsilon_x$$

$$J_{s\to m} = \frac{q\Omega (m^*)^3}{4\pi^3 \hbar^3} e^{-(E_c - E_F)\beta} \left[\int_{-\infty}^{\infty} e^{-\left(\frac{m^*\upsilon_y^2}{2}\right)\beta} d\upsilon_y \right] \left[\int_{-\infty}^{\infty} e^{-\left(\frac{m^*\upsilon_z^2}{2}\right)\beta} d\upsilon_z \right] \left[\int_{-\infty}^{-\upsilon_{\min}} d\upsilon_x e^{-\left(\frac{m^*\upsilon_x^2}{2}\right)\beta} \upsilon_x \right]$$

Thermionic Current

$$\upsilon_{\min} = \sqrt{\frac{2q}{m^*}(V_{bi} - V_A)}$$

$$J_{s\to m} = \frac{q\Omega\left(m^*\right)^3}{4\pi^3\hbar^3} e^{-(E_c - E_F)\beta} \left[\int_{-\infty}^{\infty} e^{-\left(\frac{m^*\upsilon_y^2}{2}\right)\beta} d\upsilon_y\right] \left[\int_{-\infty}^{\infty} e^{-\left(\frac{m^*\upsilon_z^2}{2}\right)\beta} d\upsilon_z\right] \left[\int_{-\infty}^{-\upsilon_{\min}} d\upsilon_x e^{-\left(\frac{m^*\upsilon_x^2}{2}\right)\beta} \upsilon_x\right]$$

$$\sqrt{\pi} \qquad \sqrt{\pi} \qquad \frac{1}{2} e^{-q(V_{bi} - V_A)\beta}$$

$$J_{s\to m} = \frac{4\pi q m^* k^2}{h^3} T^2 e^{(E_F - E_C - qV_{bi})\beta} e^{qV_A\beta} = A_0 e^{qV_A\beta}$$

$$J_T = J_{s\to m} - J_{m\to s} = A_0\left(e^{qV_A\beta} - 1\right)$$

Some insight of the Thermionic Current …

Compare to the current of p-n diodes…

$$J_T = J_{s\to m} - J_{m\to s} = A_0\left(e^{qV_A\beta} - 1\right)$$ Schottky diode

$$J_T = -q\left[\frac{D_n}{W_p}\frac{n_i^2}{N_A} + \frac{D_p}{W_n}\frac{n_i^2}{N_D}\right]\left(e^{qV_A\beta} - 1\right)$$ p-n diode

Both of them depends exponentially on V_A, however current of p-n diodes depends more on temperature (since n_i depends strongly on E_g), where the Schottky diode doesn't have that dependence.

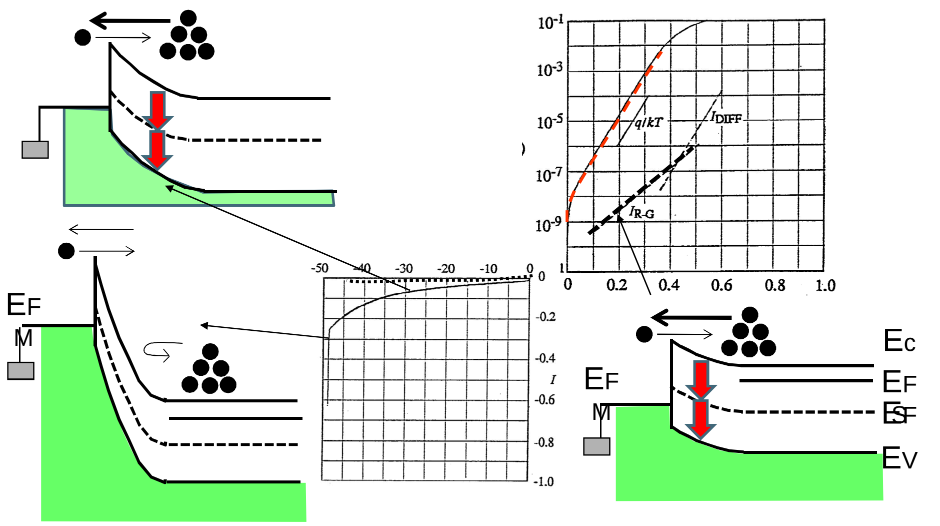
However, E_g hides in…

$$J_{s\to m} = \frac{4\pi q m^* k^2}{h^3} T^2 e^{(E_F - E_C - qV_{bi})\beta} e^{qV_A\beta} = A_0 e^{qV_A\beta}$$

The information of material hides in m*

The information of doping concentration hides in E_F-E_C

Recombination/Generation/Impact-ionization



SAME technique as in p-n junction except integrate to x_p only

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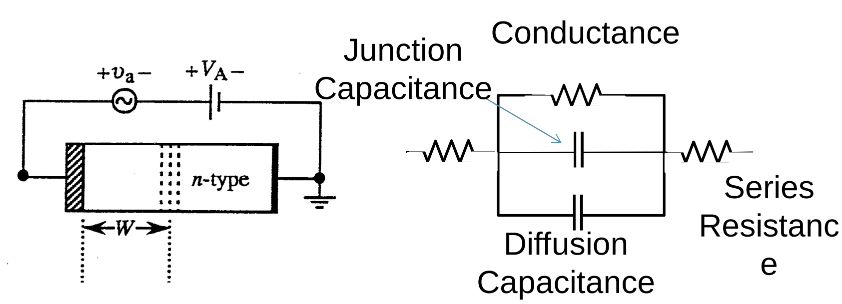
AC response

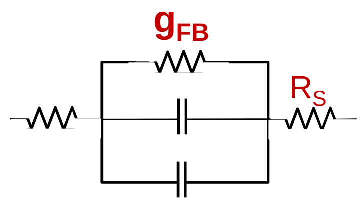


We will not have Diffusion Capacitance here…

Forward Bias Conductance

m depends on which operation regime you are

$$I = I_o\left(e^{q(V_A - R_S I)\beta/m} - 1\right)$$

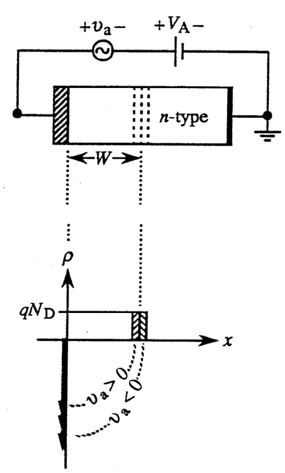


$$\ln\frac{I+I_o}{I_0} = q(V_A - R_S I)\beta/m$$

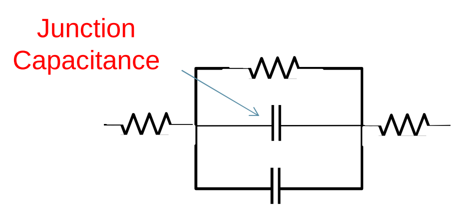
$$\frac{m}{q\beta(I+I_o)} = \frac{dV_A}{dI} - R_S$$

$$\frac{1}{g_{FB}} = R_S + \frac{m}{q\beta(I+I_0)}$$

Junction Capacitance (Majority Carriers)



Response time – dielectric
Very fast propagation



$$C_J = \frac{\kappa_s \varepsilon_0 A}{W}$$

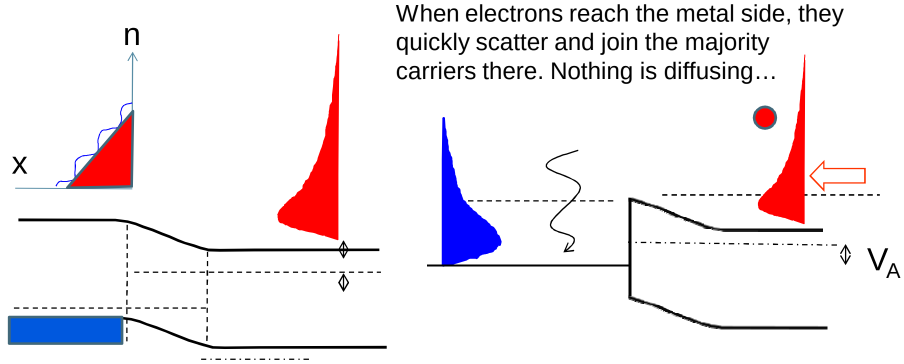
$$C_J = \frac{\kappa_s \varepsilon_0 A}{\sqrt{\frac{2\kappa_s\varepsilon_0}{qN_D}(V_{bi} - V_A)}}$$

No Diffusion Capacitance in Schottky Diode

p-n Diode

Schottky diode

When electrons reach the metal side, they quickly scatter and join the majority carriers there. Nothing is diffusing…

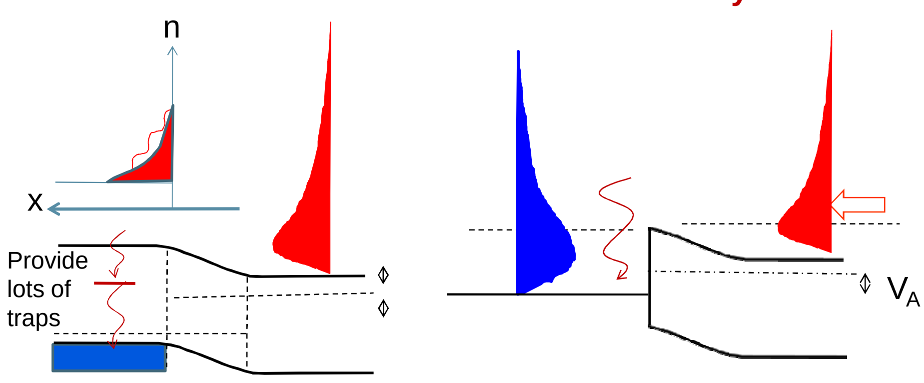


No minority carrier transport and therefore no diffusion capacitance ..

Reducing diffusion capacitance in p-n diode

p-n Diode

Schottky diode



Short minority carrier lifetime in p-n junction diode equivalent to rapid energy relaxation in SB diode.

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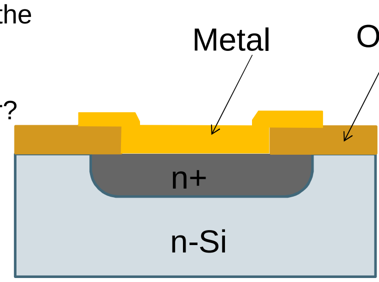
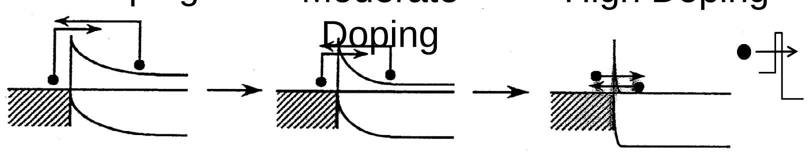
Ohmic Contact vs. Schottky contacts ..

What if we just want the p-n junction? How to reduce the barrier of Metal-Semiconductor?

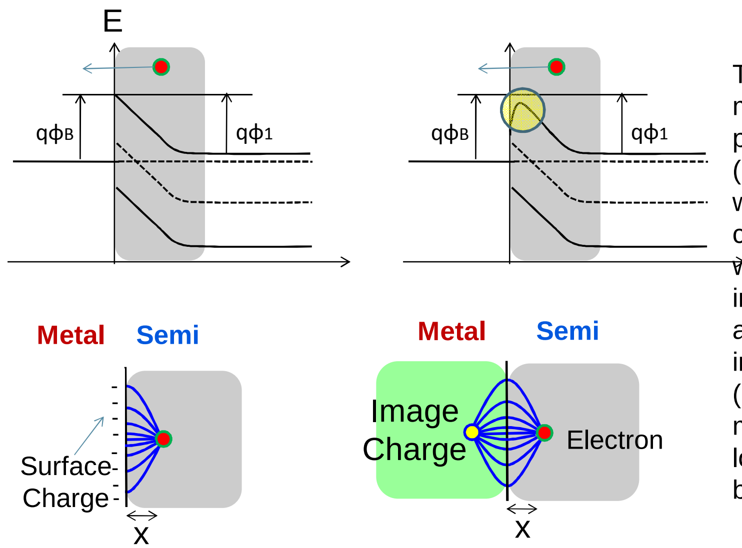


For majority carriers: there's not barrier
For minority carriers: high doping allows them to tunnel through
→Metal will just act like Ohmic Contact

Low Doping | Moderate Doping | High Doping



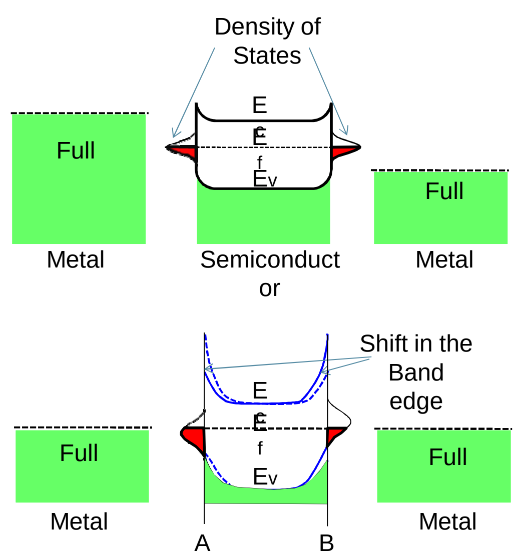
Lowering of Schottky Barrier



The fields on the metal must be perpendicular (otherwise there will be tangential current flow which is impossible) as if there's an image charge (positive) in the metal, results in lowering the barrier height

Ref. Sze/Ng., p. 143

Fermi-level Pinning



Why sometimes we don't get conductance at all?

surface states bends E_C/E_V so that the Fermi level is at the center of the bandgap, they exchange carriers with metals, blocking the bulk semiconductor inside→ no modulation in potential barrier even you connected to different metals.

Regardless the workfunction, no modulation in potential.
(e.g. Modern high-k dielectrics)

Conclusion

1) Schottky diodes have wide range of applications in practical devices.
2) The key distinguishing feature of Schottky diode is that it is a majority carrier device.
3) We use a different technique to calculate the current in a majority carrier device.
   => thermionic emission.
4) Elimination of diffusion capacitance make the response of the diodes very fast.