ELEN E3106/4106 Lecture 10

Metal-Semiconductor Junctions and Contacts

Outline

- Rectifying contacts
- Schottky barriers
- Schottky diodes
- Ohmic (non-rectifying) contacts

Assignments:

Reading: Streetman and Banerjee §5.7, C. Hu Ch. 4 Part III

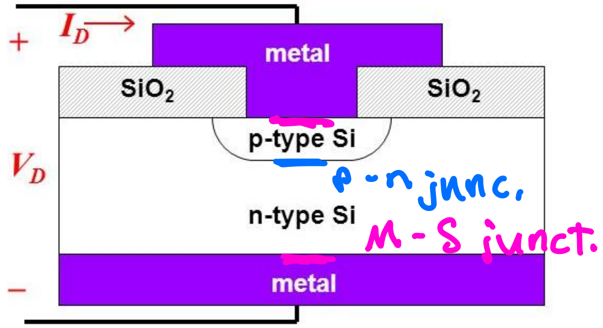
Homework 4 due Fri. Oct. 10th by 5pm

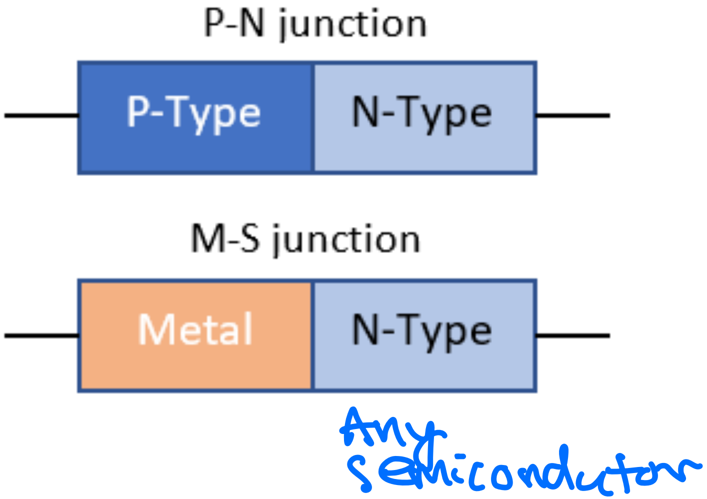
Junction Recap

- Junction = boundary or interface between two types of materials. Examples: p-n, p+-n, n+-p
  n-n, p-p
- Diode = semiconductor device whose principle of operation is based on the junction!
  - The physical structure has other practical components
    - Like contacts!
- Today we will be discussing another type of junction
  - Metal-semiconductor (M-S)

Physical structure:
(an example)

For simplicity, assume that the doping profile changes abruptly at the junction.

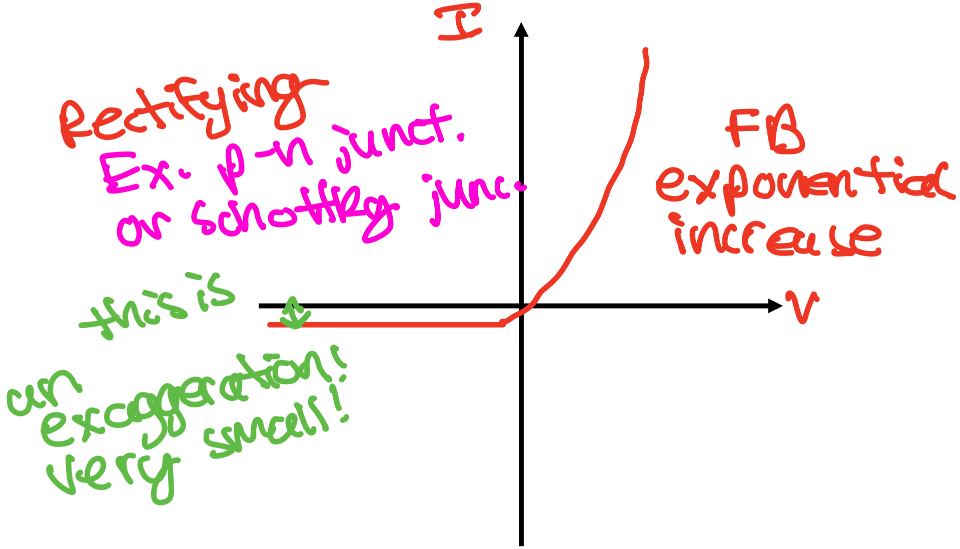




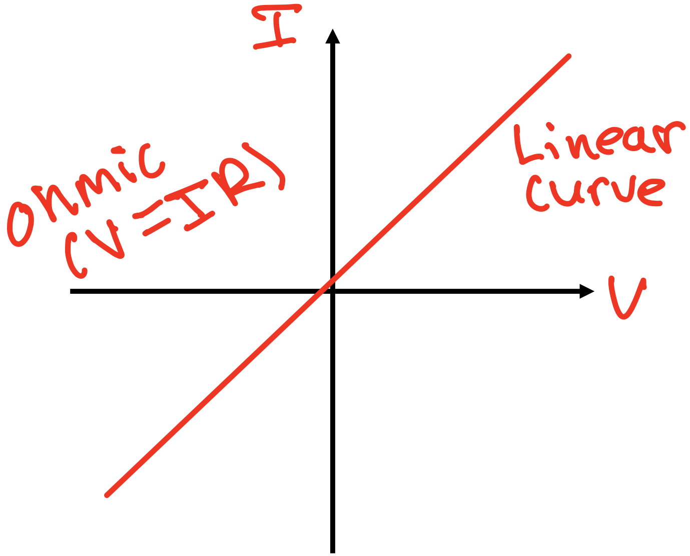
Sources: https://slideplayer.com/slide/6958660/, TechForum | Digi-Key

M-S Junctions

- Crucial to the operation of most semiconductor devices
- When metal and semiconductor are joined, two types of contacts can result:
    1. Rectifying (Schottky)
    2. Non-rectifying (ohmic)



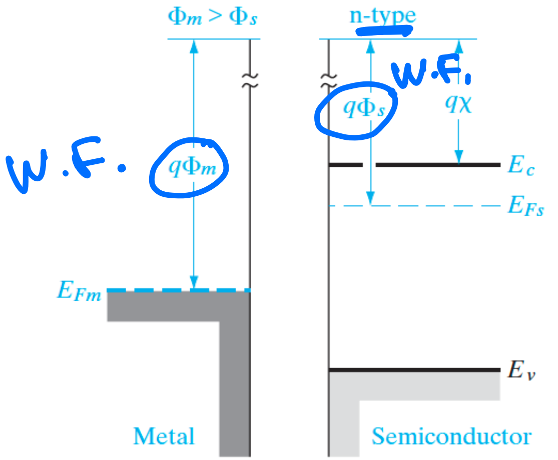
- Rectifying means that current can only pass in one direction
- Non-rectifying means current can pass in both directions

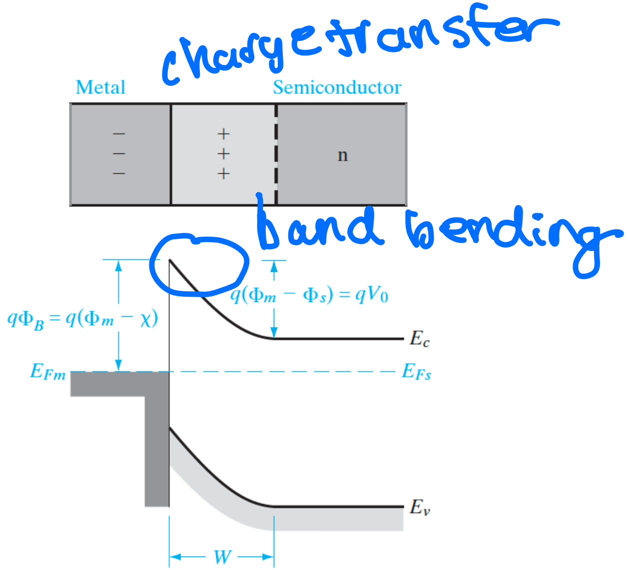


- Question: Is a p-n diode rectifying?
  Yes!

Schottky Barrier Formation

- Recall: We discussed the metal work function $q\Phi_m$ (eV)
  - Energy needed to eject an e^- from E_F to vacuum outside the metal
- The semiconductor also has a work function $q\Phi_s = q\Phi_{vac} - E_F$
- Metal and semi brought in contact--> charge transfer occurs
- Because we are in equilibrium, E_F must align
- Let's consider when $\Phi_m > \Phi_s$ (n-type)
- Electrostatic potential of semiconductor must be raised (bands bend downward)





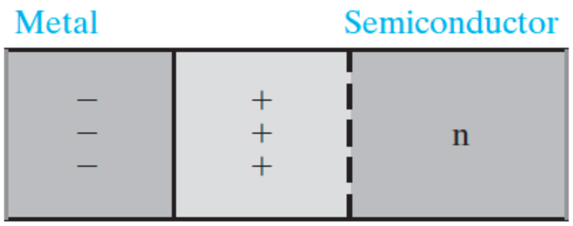
Sources: Textbook

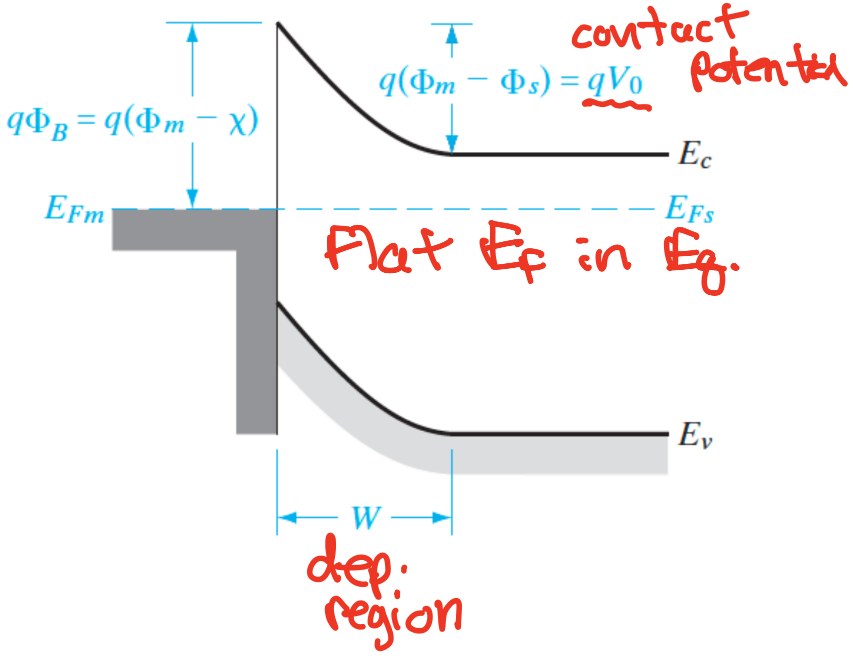
Schottky Barrier Depletion Region

- Depletion region __W__ will form
  - __(+)__ charge from uncompensated donors (n-type) __N_d^+__ in semiconductor
  - __(−)__ charge is on the metal
- Built-in contact potential __V_0__ $= \Phi_m - \Phi_s$
- The case is similar to p$^+$-n approximation
  - (-) charge on metal is a very thin sheet to the left of junction

$$C_j \quad \boxed{= \left[\frac{2\epsilon V_0}{q}\left(\cancelto{0}{\frac{1}{N_a}} + \frac{1}{N_d}\right)\right]^{1/2}}$$

$$C = A\frac{\varepsilon_s}{W_{\text{dep}}}$$

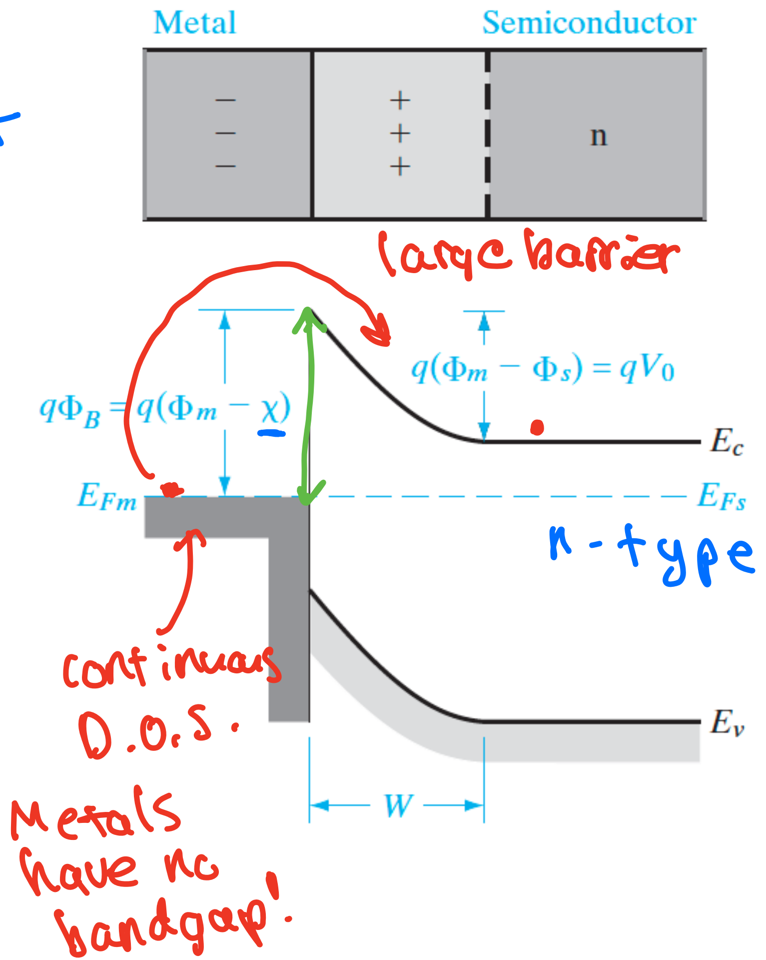




Sources: Textbook

Schottky Barrier Height

- An energy barrier exists at the metal-semiconductor interface barrier to current flow!
- Schottky barrier height is denoted
  $q\Phi_B$ (eV)
- Φ_B depends on: (V)
  - Metal
  - Semiconductor
- The electron affinity, χ, is measured from the vacuum level to the semiconductor band edge $\chi = E_{vac} - E_c$
- $\Phi_B = \Phi_m - \chi$



Sources: Textbook

Schottky Barrier on p-type semiconductor

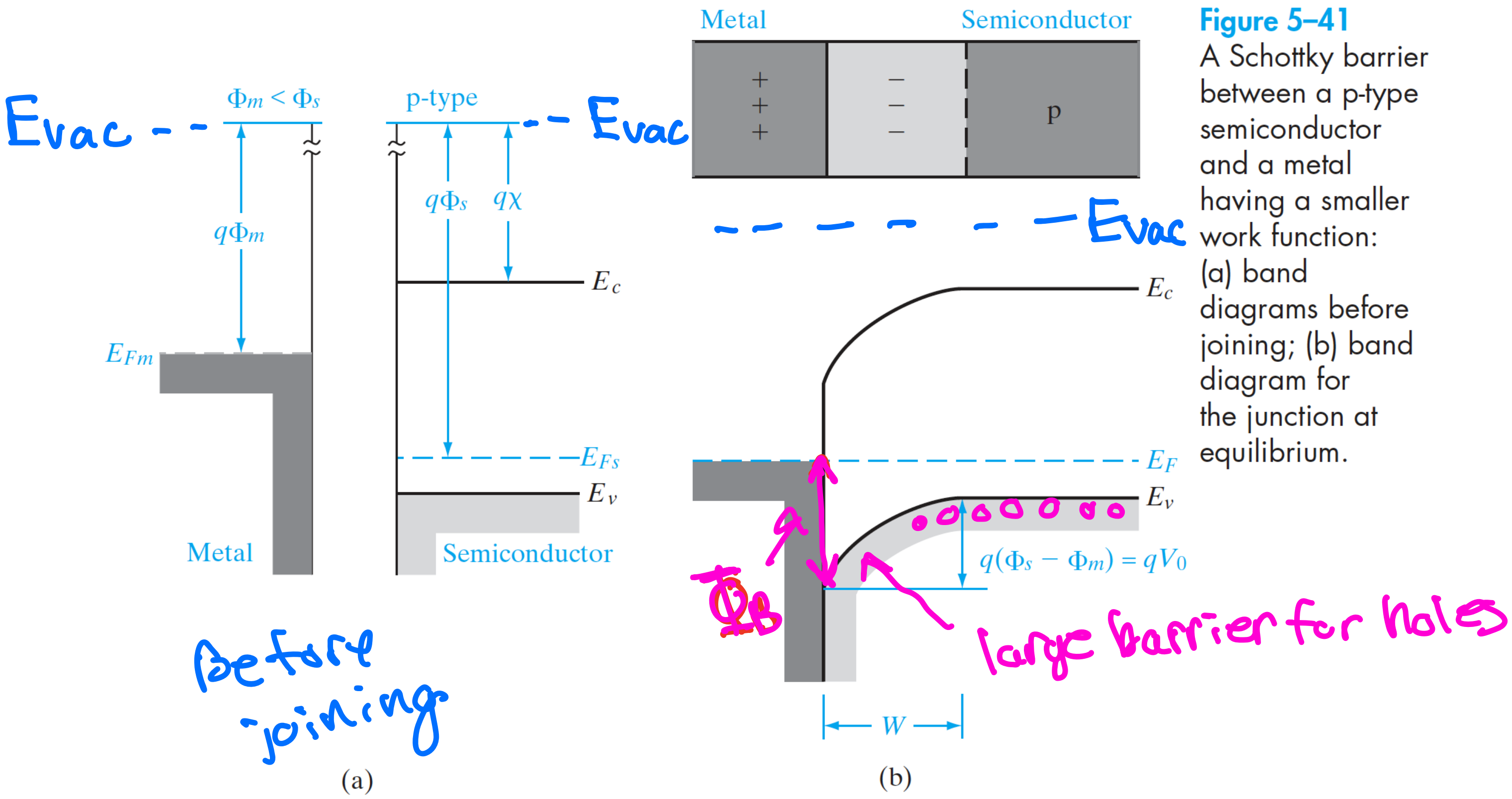


Figure 5–41
A Schottky barrier between a p-type semiconductor and a metal having a smaller work function: (a) band diagrams before joining; (b) band diagram for the junction at equilibrium.

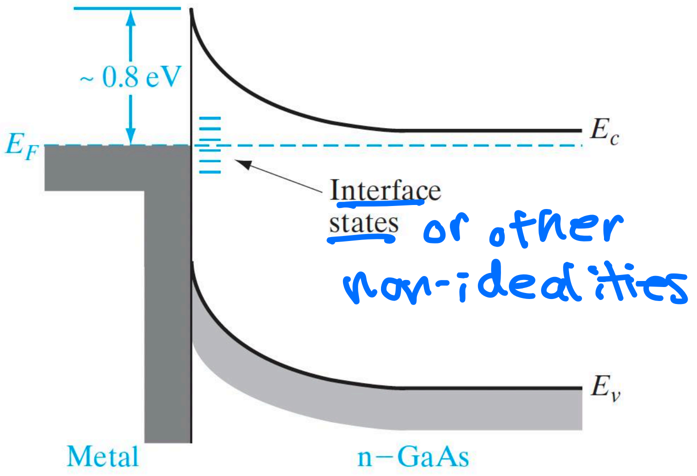
Sources: Textbook

Fermi Level Pinning

- Why does Φ_B vary with the choice of the metal?
  metal
  $\Phi_B = \Phi_M - \chi$ ← semiconductor
- Clear trend that Φ_B increases with increasing metal work function (n-type)
- We would expect 1 eV change in Φ_m to result in 1eV change in Φ_B
  - Quantitatively not true!
- So far our discussion has looked at *ideal* Schottky barrier behavior
- In reality, the M-S junction is not ideal
  - Surface states due to incomplete covalent bonds
  - Interface roughness (measure w/ AFM)
  - Thin interfacial layers
- These can pin the Fermi level at a certain position regardless of metal work function

TABLE 4–4 Measured Schottky barrier heights for electrons on N-type silicon (ϕ_{Bp}) and for holes on P-type silicon (ϕ_{Bp}). (From [7].)

Metal	Mg	Ti	Cr	W	Mo	Pd	Au	Pt
ϕ_{Bn} (V) n-type	0.4	0.5	0.61	0.67	0.68	0.77	0.8	0.9
ϕ_{Bp} (V) p-type		0.61	0.50		0.42		0.3	
Work Function ψ_M (V)	3.7	4.3	4.5	4.6	4.6	5.1	5.1	5.7



Sources: C. Hu, *Modern Semiconductor Devices for Integrated Circuits*, Textbook

Using *C-V* Data to Determine Schottky Barrier Height

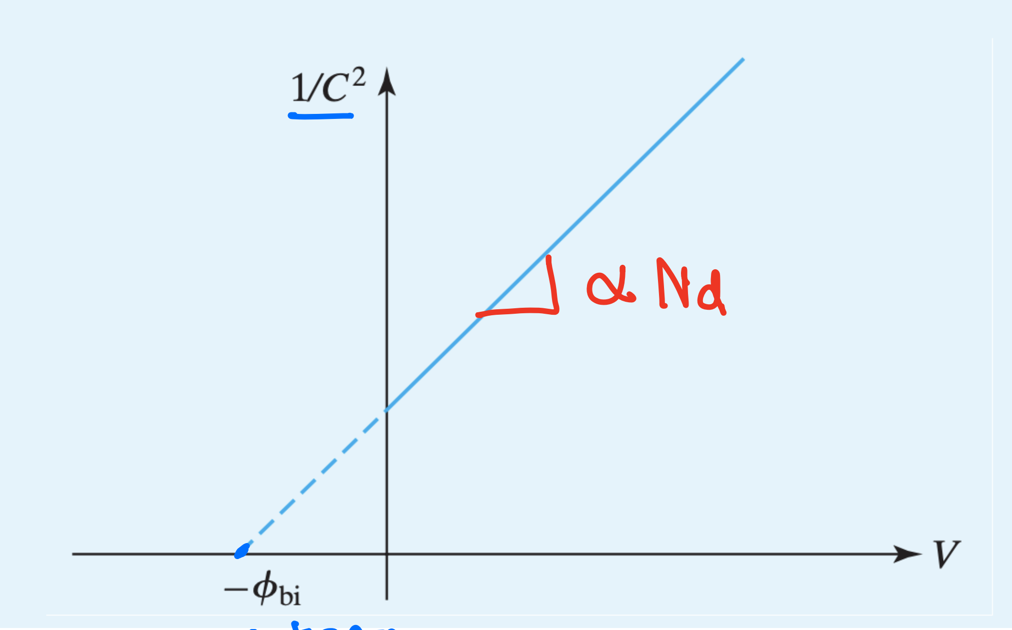
$$C = A\frac{\varepsilon_s}{W_{dep}}$$

$\Phi_{bi} = V_0$

$$\frac{1}{C^2} = \frac{2(\phi_{bi}+V)}{qN_d\varepsilon_s A^2}$$

← n-semi

$$W_{dep} = \sqrt{\frac{2\varepsilon_s(\phi_{bi}+V)}{qN_d}}$$



x-intercept

Similar to
p⁺-n junction

$$q\phi_{bi} = q\phi_{Bn} - (E_c - E_F) = q\phi_{Bn} - kT\ln\frac{N_c}{N_d}$$

← DOS

Sources: C. Hu, *Modern Semiconductor Devices for Integrated Circuits*

Explanation of Rectifying *I-V* Characteristics

- Rectifying, with easy current flow in the forward direction and little current in the reverse direction

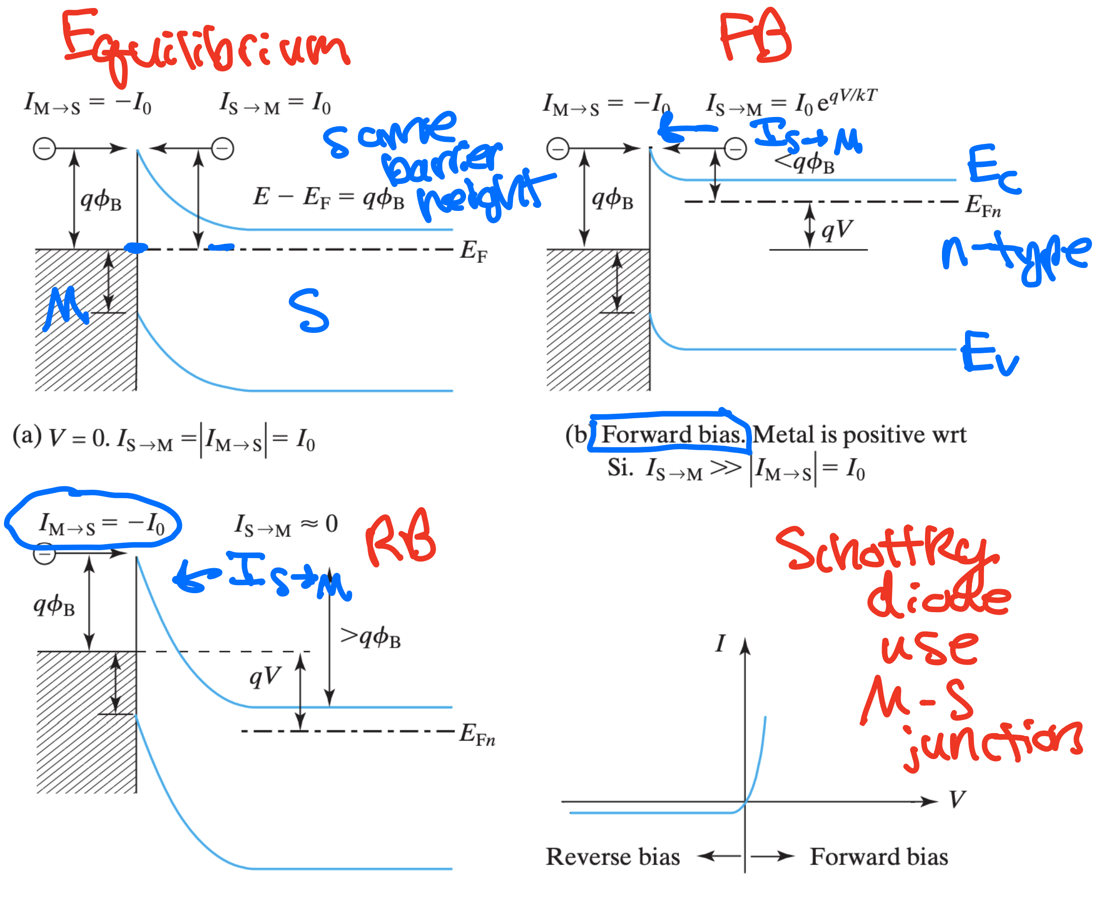
$$I = I_0(e^{qV/kT} - 1)$$

- Forward current due to injection of majority carriers

- Left-traveling e⁻ have a thermal velocity
  - Thermionic emission theory

v_{th} (thermal velocity)

$-x$-dir.



(a) $V = 0$. $I_{S\to M} = |I_{M\to S}| = I_0$

(b) Forward bias. Metal is positive wrt Si. $I_{S\to M} >> |I_{M\to S}| = I_0$

(c) Reverse bias. Metal is negative wrt Si. $I_{S\to M} << |I_{M\to S}| = I_0$

(d) Schottky diode *IV*.

Sources: C. Hu, *Modern Semiconductor Devices for Integrated Circuits*

Reverse Saturation Current

- Reverse saturation current is I_0
- Not as simply derived as in p-n diode, but what does it depend on?

Unaffected by bias (voltages)

Depends on Φ_B

- Is it affected by the bias voltage?

$$I_0 \propto e^{-q\Phi_B/kT}$$

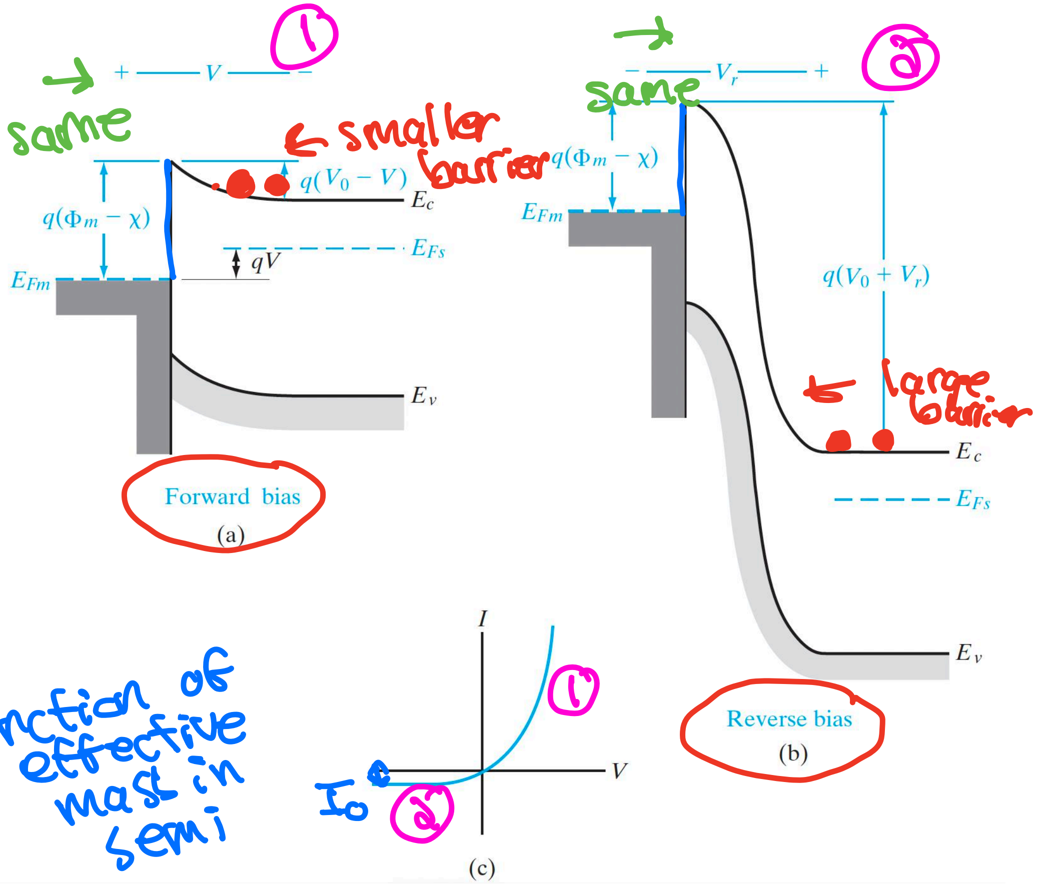
A is area

$$I_0 = AKT^2 e^{-q\phi_B/kT}$$

function of effective mass in semi

- Richardson constant: $K = \dfrac{4\pi q m_n k^2}{h^3}$
  - Units: $A/(cm^2K^2)$

Fundamental parameter for thermionic emission



Sources: Textbook

Schottky Diode Equations

- Desired: Φ barrier height, low I_0 (leakage current)

  is high

- Ideal diode equation:

$$I = \underline{I_0}(e^{qV/kT} - 1)$$

- Taking into account non-idealities, forward current is:

ideality complex

$$I = \underset{\text{Area}}{A}\overset{K}{\cancel{A^*}}T^2 e^{-q\Phi_B/kT} e^{qV/\mathbf{n}kT}$$

- Ideality factor n varies from 1-2 like p-n junction, but arises for different reasons

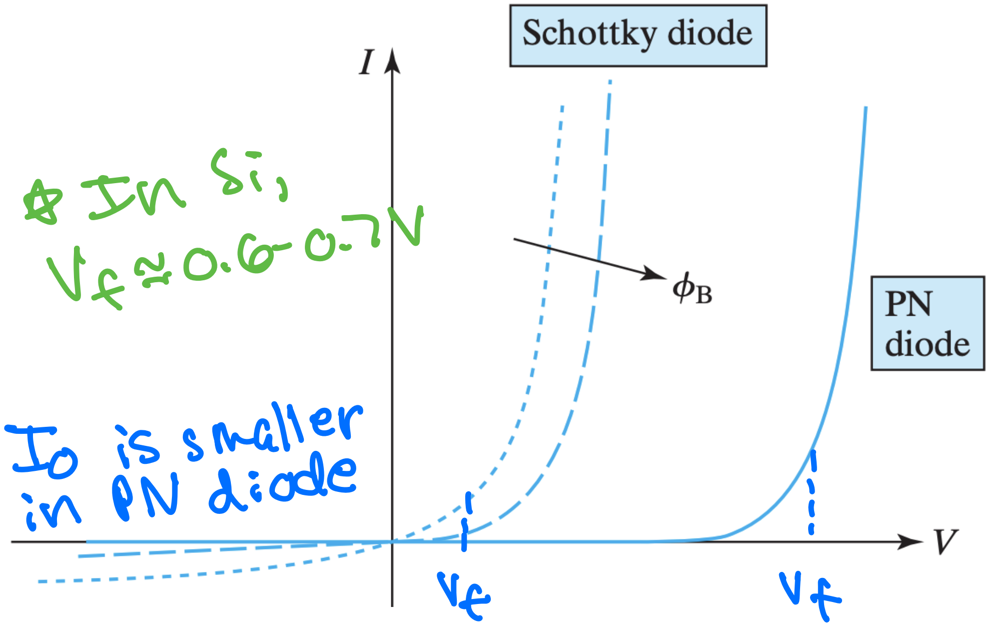
Sources: Textbook

Schottky Diode Applications

- Advantages over p-n diode:
  - High-frequency properties and switching speed are generally better
  - Simpler fabrication process ✓
  - I_0 of a Schottky diode can be 10^3–10^8 times larger
    - Preferred in low-voltage and high-current applications
- Are there downsides to larger I_0? Yes, larger power consumption in RB ($P=IV$)

Share ideal diode eq.

$$I = I_0(e^{qV/kT} - 1)$$



* In Si, $V_f \approx 0.6$–0.7V

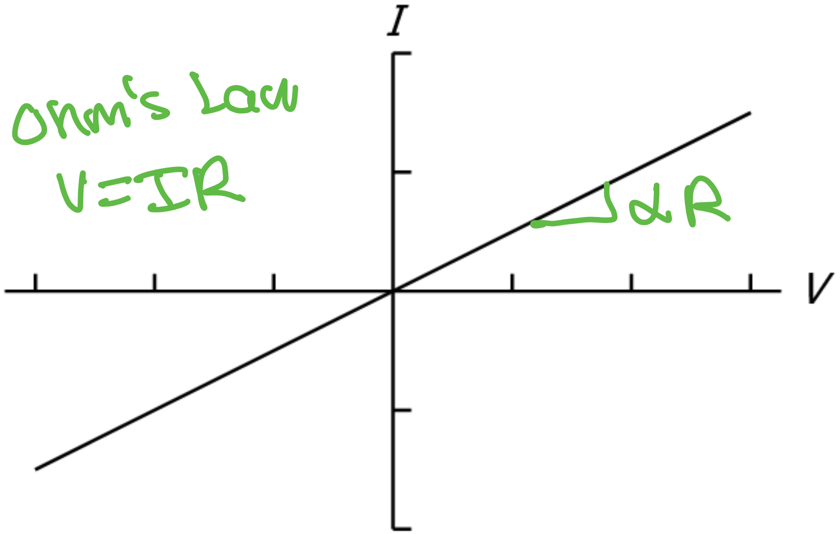
I_0 is smaller in PN diode

V_f: point where you start to see exponential increase in I

Sources: C. Hu, *Modern Semiconductor Devices for Integrated Circuits*, Textbook

Non-Rectifying (Ohmic) Contacts

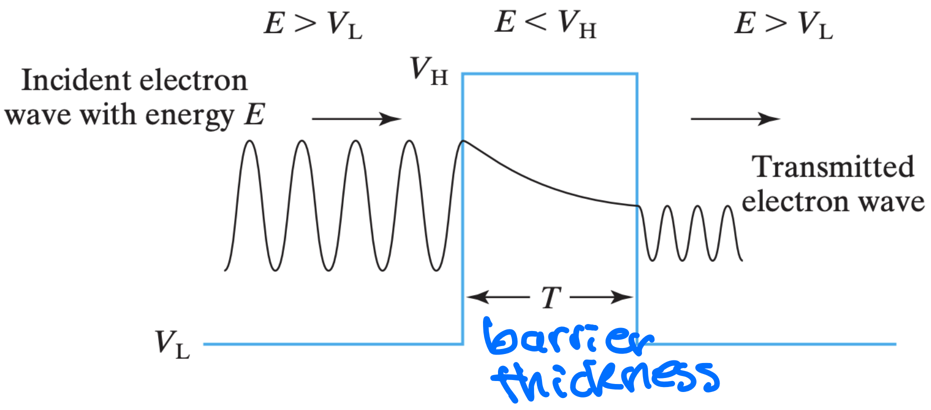
- M-S contacts are ohmic when we have linear I–V characteristic in both biasing directions
- What are the applications?
  - Contacting and interconnecting different regions of devices
- Desired properties of ohmic contacts:
  - Low resistance
  - No tendancy to rectify
- 2 methods to formation:
- 1) Low barrier height
- 2) Heavily dope the semiconductor!
  - More practical!



•Sources: DOI: 10.13140/RG.2.2.14746.75200

Quantum Mechanical Tunneling

- *There is a finite probability for e⁻ to tunnel through a potential barrier!*
- Even if e- doesn't have enough energy
- e- with energy *E* arriving at barrier with high V_H
- Traveling wave decays
- Emerges from barrier with reduced amplitude
- Tunneling probability increases exponentially with decreasing barrier thickness



$$P \approx \exp\left(-2T\sqrt{\frac{8\pi^2 m}{h^2}(V_H - E)}\right)$$

probability

Sources: C. Hu, *Modern Semiconductor Devices for Integrated Circuits*

Heavily Doped Ohmic Contacts

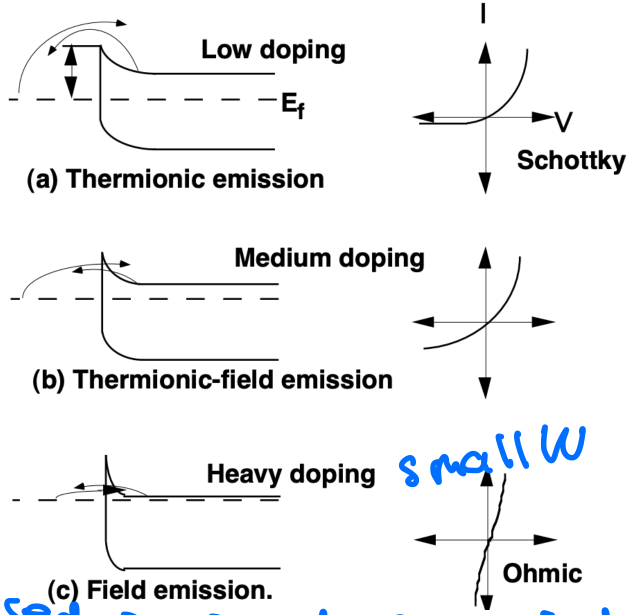
- With high dopant concentrations, barrier becomes thin

$$T \approx W_{dep}/2 = \sqrt{\varepsilon_s \phi_{Bn}/(2qN_d)}$$

- High probability e- can pass through the barrier by tunneling
- Typical depletion layer width _W__ of heavily doped Si?

Tens of angstroms

- Tunneling probability largely independent applied bias
  - Constant resistance (ohmic) contact



small W

used instead of metal

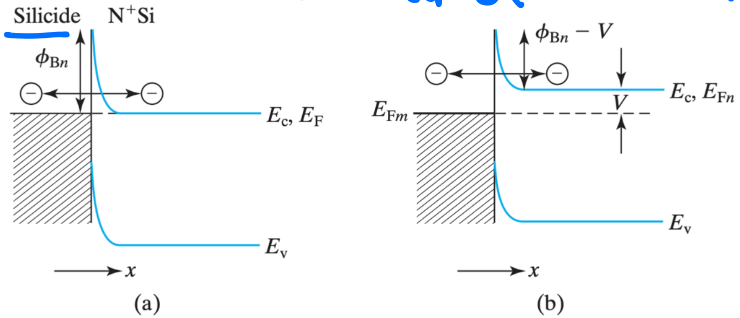
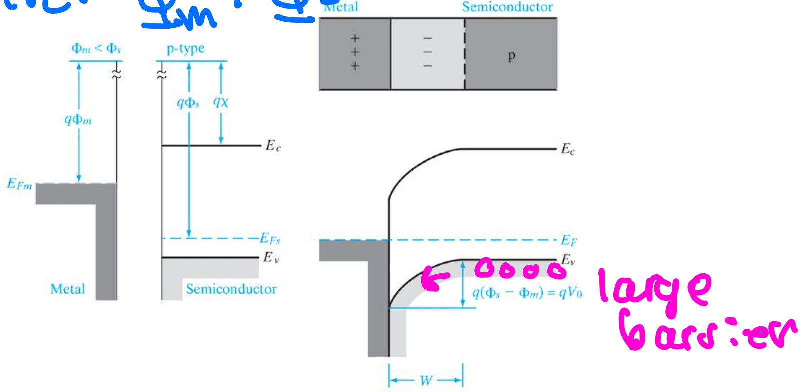


FIGURE 4–44 (a) Energy band diagram of metal–N^+ Si contact with no voltage applied and (b) the same contact with a voltage, V, applied to the contact.

Sources: https://web.stanford.edu/class/ee311/NOTES/Ohmic_Contacts.pdf, C. Hu, *Modern Semiconductor Devices for Integrated Circuits*

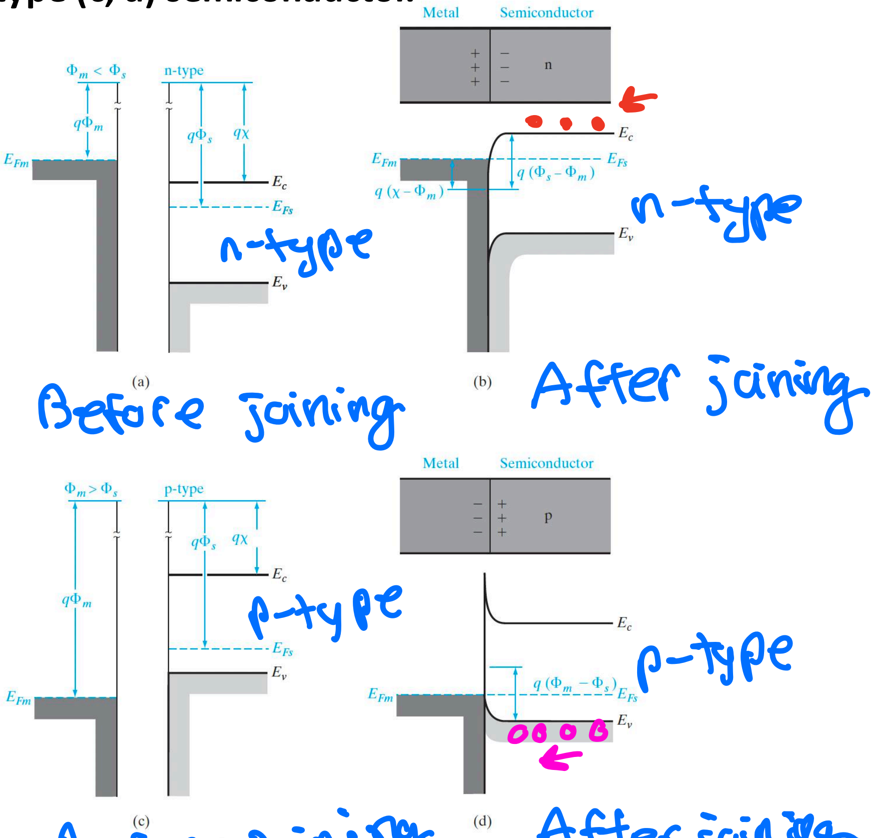
Summary of Schottky and ohmic contacts (low barrier height, method of formation #1):

- Metal/n-type semiconductor:
  - Schottky: $\Phi_s < \Phi_M$
  - Ohmic: $\Phi_M < \Phi_s$
- Metal/p-type semiconductor:
  - Schottky: $\Phi_s > \Phi_M$
  - Ohmic: $\Phi_m > \Phi_s$



Schottky barrier on p–type semiconductor and a metal with a smaller work function.

Ohmic contacts on n-type (a, b) and p-type (c, d) semiconductor.

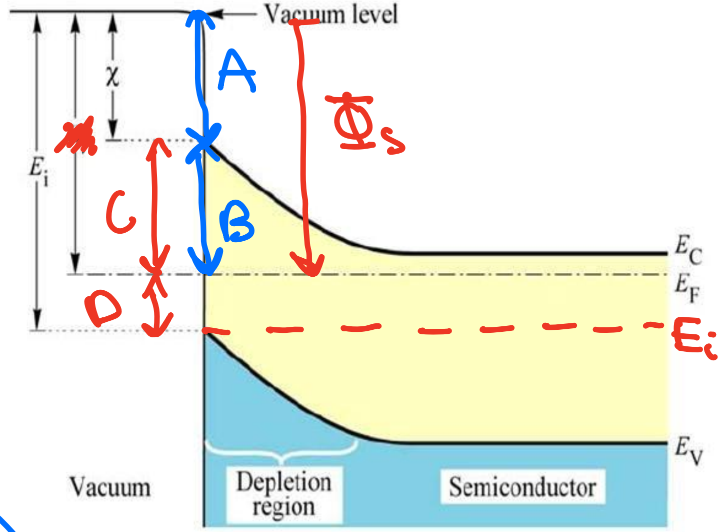


Sources: Textbook

How do we find semiconductor work function?

- Φ_s : Work function of the semiconductor = $E_{vac} - E_F$
- χ: Electron affinity of the semiconductor = $E_{vac} - E_C$

- Looking at a band diagram, this means we can find Φ_s if we are given χ and the doping



- n-type semiconductor example:
- $\Phi_s = \underbrace{(E_{vac} - E_C)}_{A = \chi} + \underbrace{(E_C - E_F)}_{B}$
- $\Phi_s = (E_{vac} - E_C) + \underbrace{(E_C - E_i)}_{C} - \underbrace{(E_F - E_i)}_{D}$
- $\Phi_s = \chi + \frac{E_g}{2} - (E_F - E_i)$

- Recall: Equilibrium carrier concentrations (cm^{-3}):
- $n_0 = n_i e^{(E_F - E_i)/kT}, p_0 = n_i e^{(E_i - E_F)/kT}$

Rearrange

$$\Phi_s = \chi + \frac{E_g}{2} - kTln\left(\frac{n_0}{n_i}\right)$$

(n-type)

•Sources:DOI: 10.13140/RG.2.1.3560.5927

Contact Resistance

* H is not dimensionless but treated as material-dependent constant

- Desired: low contact resistance
- An important property of contacts is the specific contact resistance, R_c R (Ω)
  - Units: Ω·mm
- A measure of how easily current flows through a contact
- For an n-type semiconductor:

$$R_c \equiv \frac{V}{J} = \frac{2 \cdot e^{H\phi_{Bn}/\sqrt{N_d}}}{q v_{thx} H \sqrt{N_d}}$$

A/mm

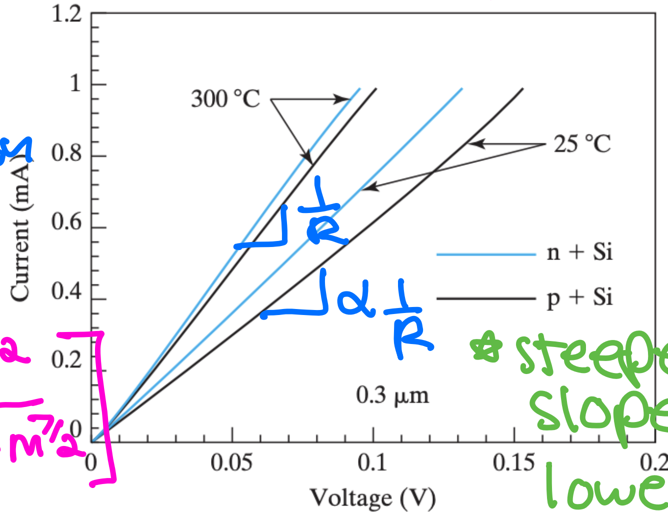
$$\propto e^{H\phi_{Bn}/\sqrt{N_d}}$$

in x-direction

$$v_{thx} = -\sqrt{2kT/\pi m_n}$$

$$H \equiv \frac{4\pi}{h}\sqrt{(\varepsilon_s m_n)/q} \quad \left[\frac{C^{1/2}}{kg \cdot m^{7/2}}\right]$$

H is the tunneling factor, acts as proportionality term connecting barrier height and doping concentration



* steeper slope = lower resistance

I-V **characteristics of a 0.3 micron diameter TiS_2 contact on n+ and p+ Si.**

- Recall, v_{th} is the thermal velocity
- Same thing true for p-type, but we replace N_d, Φ_{Bn}, m_n by N_a, Φ_{Bp}, m_p

Sources: C. Hu, *Modern Semiconductor Devices for Integrated Circuits,* Textbook