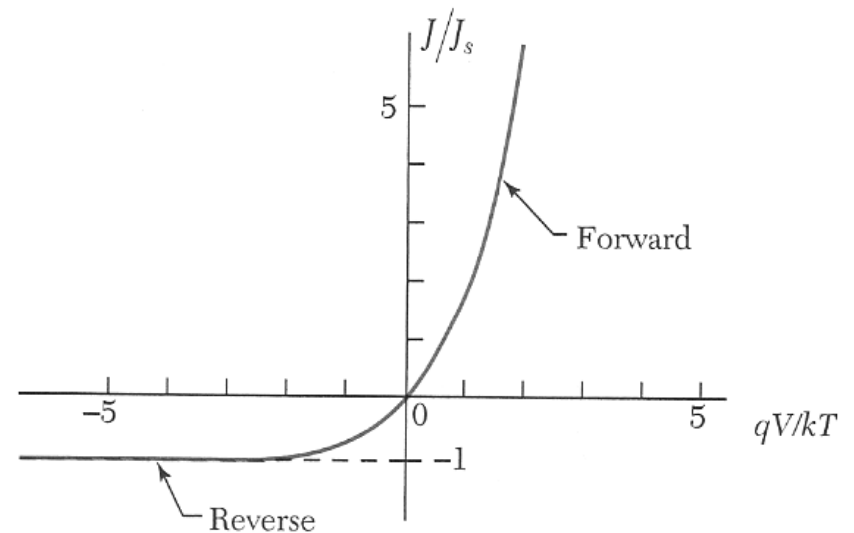


# Metal-Semiconductor Contacts

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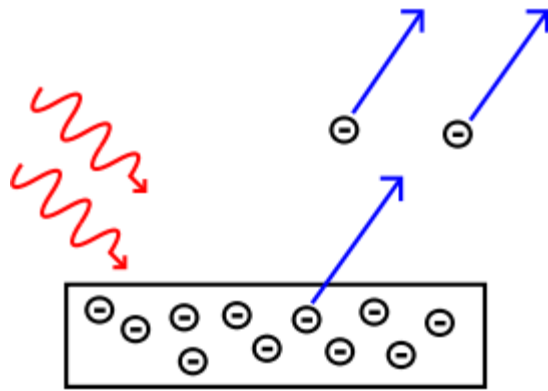
# metal - semiconductor contacts

Photoelectric effect  
 Schottky barriers  
 Schottky diodes  
 Ohmic contacts  
 Thermionic emission  
 Tunnel contacts

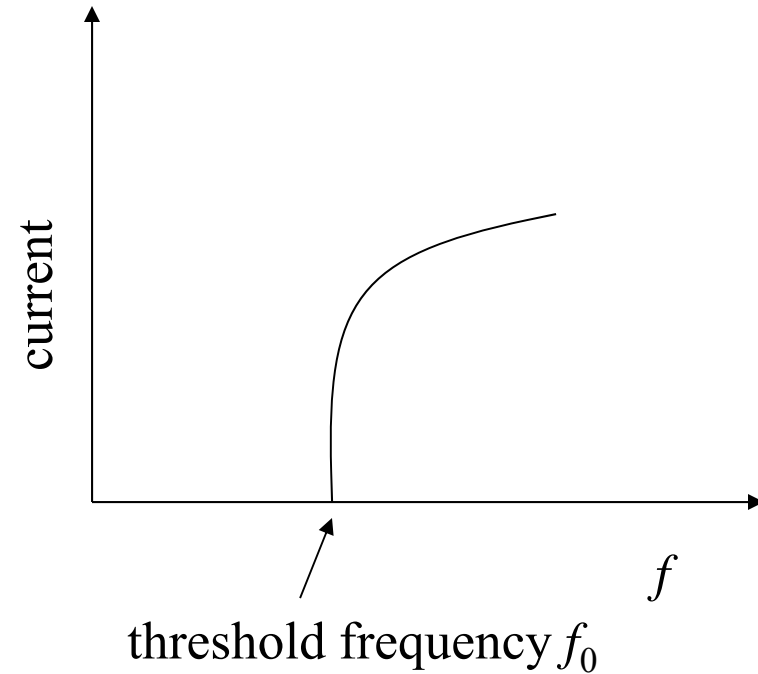


# Photoelectric effect

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$hf_0 = e\phi$  at threshold  
workfunction

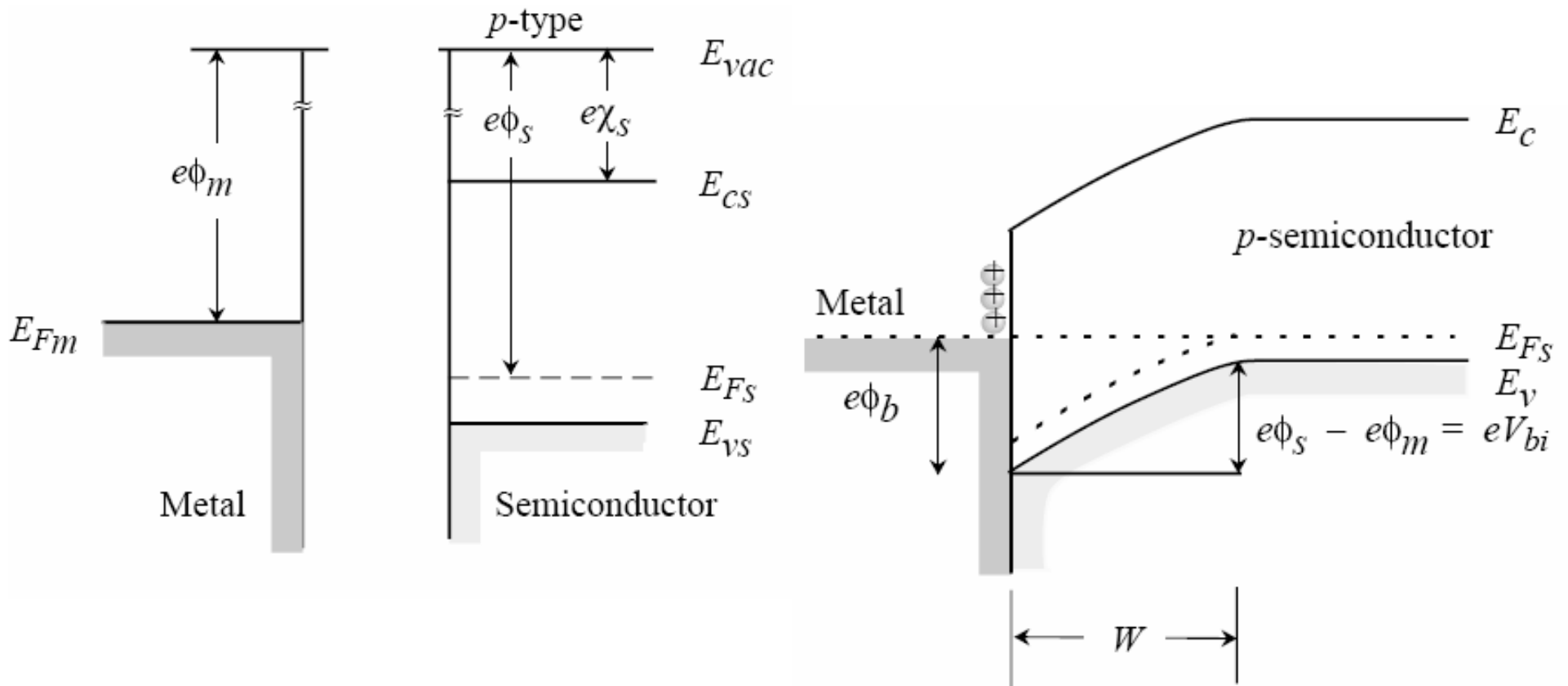


Work functions of some metals	
Element	Work function, $\phi_m$ (volt)
Ag, silver	4.26
Al, aluminum	4.28
Au, gold	5.1
Cr, chromium	4.5
Mo, molybdenum	4.6
Ni, nickel	5.15
Pd, palladium	5.12
Pt, platinum	5.65
Ti, titanium	4.33
W, tungsten	4.55

There is a dipole field at the surface of a metal. This electric field must be overcome for an electron to escape.

Singh

# work function - electron affinity



If  $\phi_s < \phi_m$ , the semiconductor bands bend down.

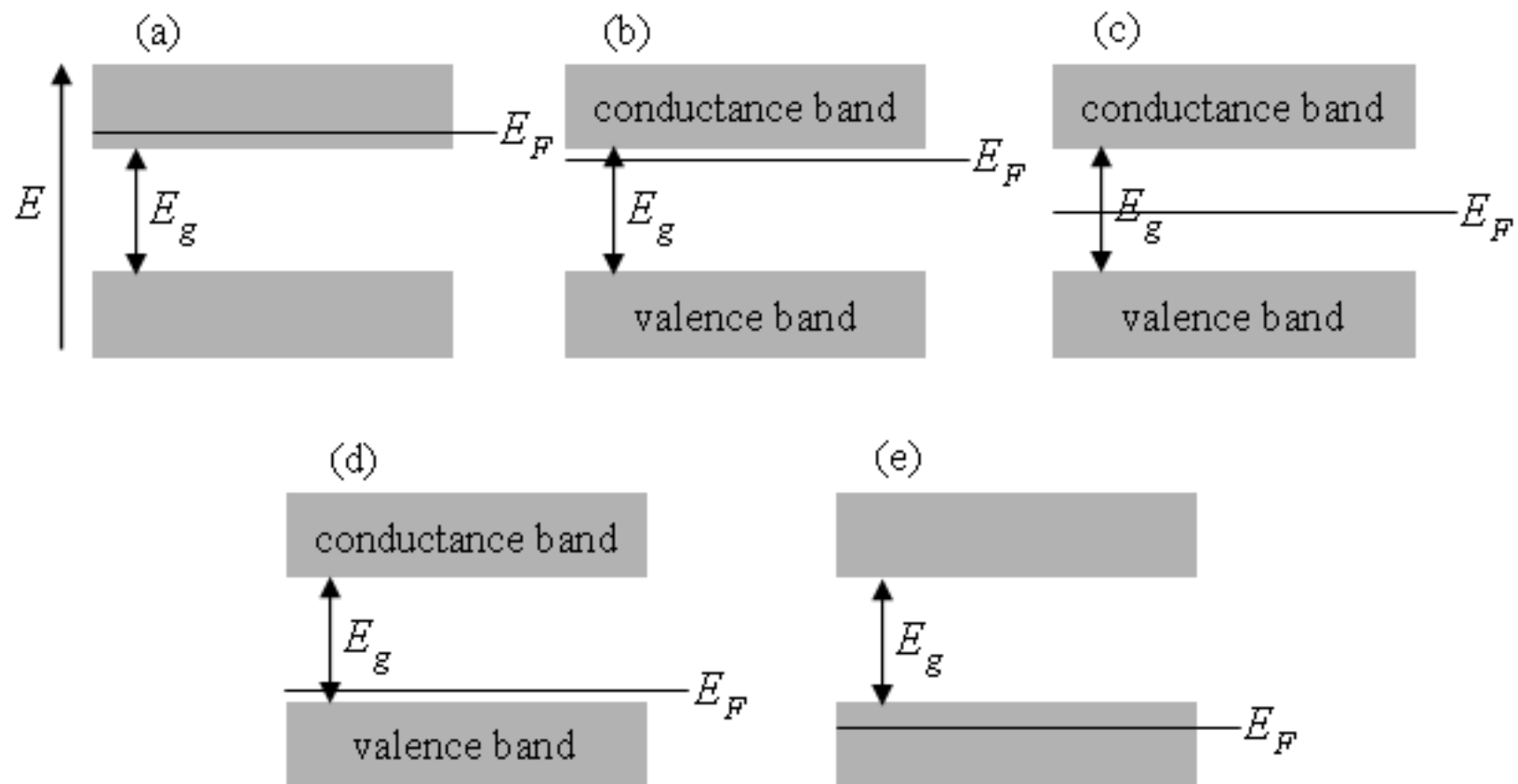
If  $\phi_s > \phi_m$ , the semiconductor bands bend up.

Work functions of some metals

Element	Work function, $\phi_m$ (volt)
Ag, silver	4.26
Al, aluminum	4.28
Au, gold	5.1
Cr, chromium	4.5
Mo, molybdenum	4.6
Ni, nickel	5.15
Pd, palladium	5.12
Pt, platinum	5.65
Ti, titanium	4.33
W, tungsten	4.55

Electron affinity of some semiconductors

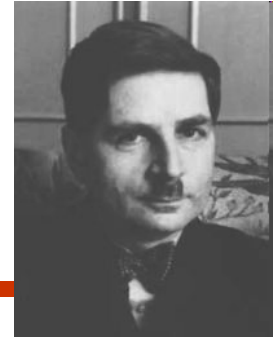
Element	Electron affinity, $\chi$ (volt)
Ge, germanium	4.13
Si, silicon	4.01
GaAs, gallium arsenide	4.07
AlAs, aluminum arsenide	3.5



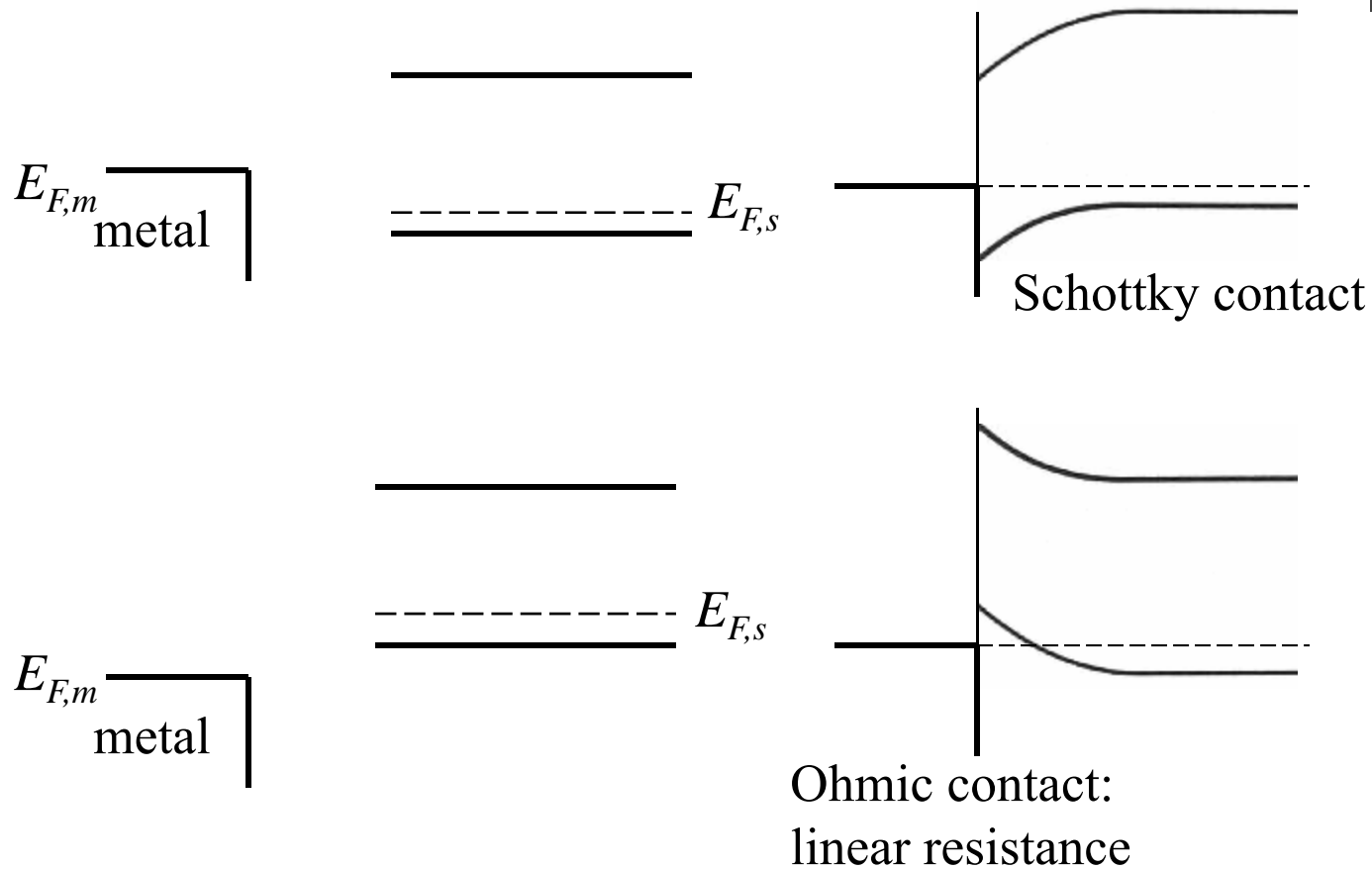
(a) A metal with a small workfunction. (b) An n-type semiconductor. (c) An insulator. (d) A p-type semiconductor. (e) A metal with a large workfunction.

p-type

Walter Schottky



# Schottky contact / ohmic contact



specific contact resistance:

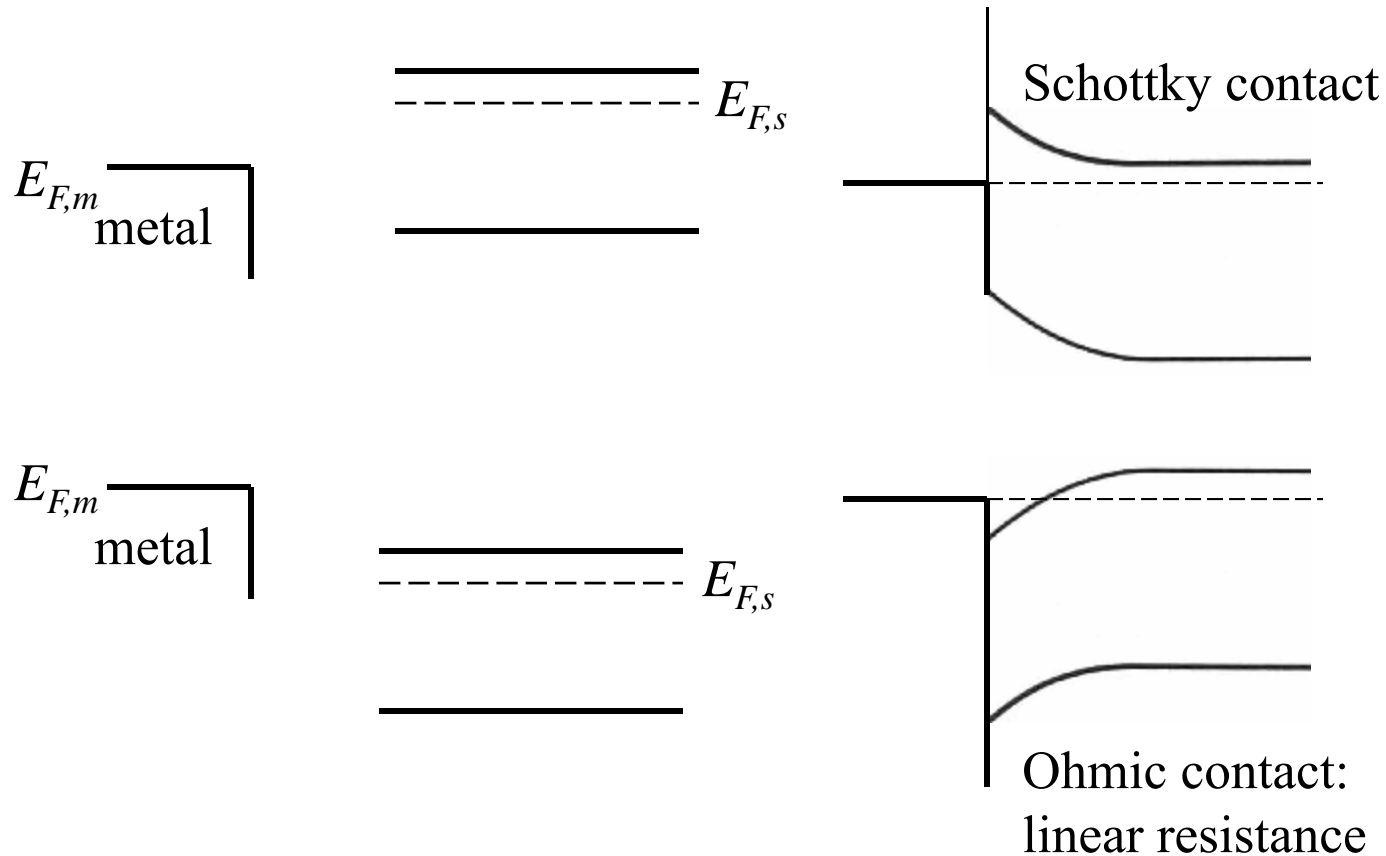
$$R_c = \left( \frac{\partial J}{\partial V} \right)^{-1} \quad \Omega\text{-cm}^2$$



n-type

## Schottky contact / ohmic contact

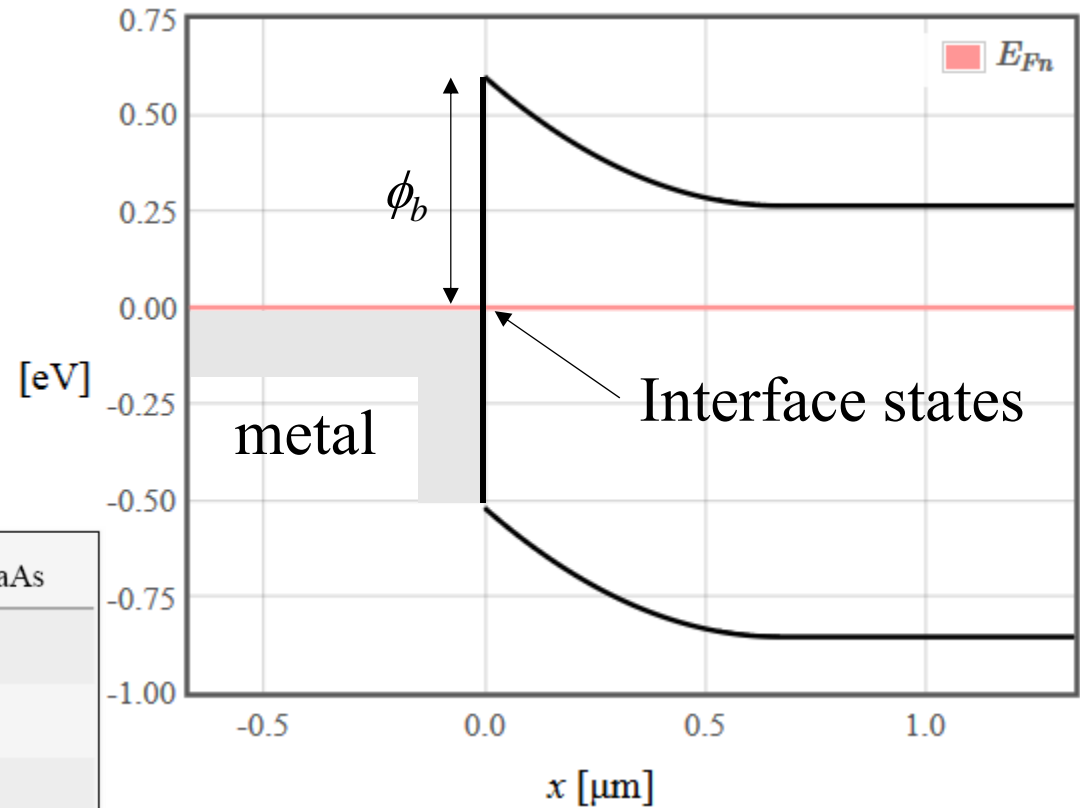
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specific contact resistance:  $R_c = \left( \frac{\partial J}{\partial V} \right)^{-1} \Omega\text{-cm}^2$

# Interface states

SCHOTTKY METAL	<i>n</i> Si	<i>p</i> Si	<i>n</i> GaAs
Aluminum, Al	0.7	0.8	
Titanium, Ti	0.5	0.61	
Tungsten, W	0.67		
Gold, Au	0.79	0.25	0.9
Silver, Ag			0.88
Platinum, Pt			0.86
PtSi	0.85	0.2	
NiSi <sub>2</sub>	0.7	0.45	



**substance: silicon (Si)**

**property: Schottky barrier heights**

average experimental values are given, different data found in the literature scatter considerably.

Contact	Numerical value	Experimental conditions	Experimental method, remarks	
n-Si:Ag	0.56 eV	chemically etched	C-V and I-V characteristics	
p-Si:Ag	0.54 eV			
n-Si:Al	0.50 eV	n-Si:Pt	0.81 eV	
p-Si:Al	0.58 eV	n-Si:Sn	0.58 eV	
n-Si:Au	0.81 eV	n-Si:Ta	0.57 eV	
p-Si:Au	0.34 eV	n-Si:Ti	0.50 eV	
n-Si:Cr	0.59 eV	n-Si:W	0.65 eV	
n-Si:Cu	0.66 eV	n-Si:Ag	0.78 eV	
p-Si:Cu	0.46 eV	n-Si:Al	0.75 eV	
n-Si:Fe	0.65 eV	n-Si:Au	0.73 eV	cleaved, uhv
n-Si:Mg	0.55 eV	n-Si:Ca	0.40 eV	I-V and photoele
n-Si:Mo	0.57 eV	n-Si:Co	0.61 eV	C-V and I-V ch
n-Si:Ni	0.67 eV	n-Si:Cu	0.77 eV	I-V and photoel
p-Si:Ni	0.51 eV	n-Si:K	0.46 eV	
n-Si:Pb	0.41 eV	n-Si:Mg	0.46 eV	
p-Si:Pb	0.55 eV	n-Si:Na	0.43 eV	
n-Si:Pd	0.72 eV	n-Si:Ni	0.59 eV	
		n-Si:Pb	0.61 eV	
		n-Si:Pt	0.81 eV	
		n-Si:Pt	0.74 eV	

[http://www.springermaterials.com/navigation/#n\\_240905\\_Silicon+%2528Si%2529](http://www.springermaterials.com/navigation/#n_240905_Silicon+%2528Si%2529)

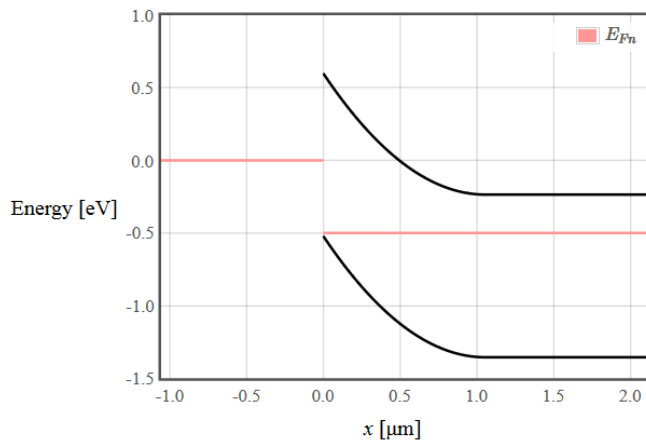
# Schottky barrier

$\phi_b = 0.6$  eV       $N_D = 1E15$  1/cm<sup>3</sup>       $T = 300$  K  
 $E_g = 1.166-4.73E-4*T*(T+636)$  eV       $N_c(300) = 2.78E19$  1/cm<sup>3</sup>       $\epsilon_r = 12$   
 $V = -0.5$  V     

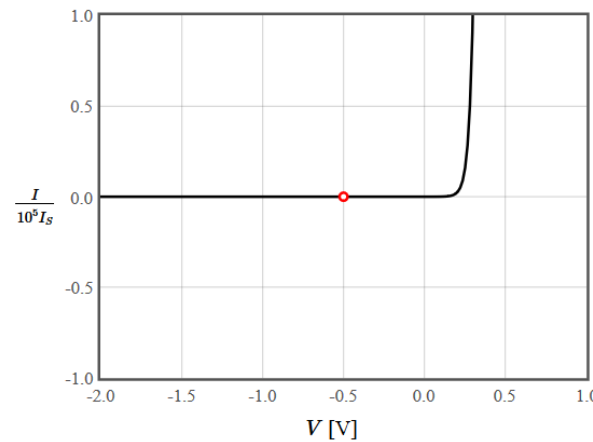
$E_g = 1.12$  eV     $W = 1.05$   $\mu\text{m}$      $V_{bi} = 0.335$  V     $C_j = 10.1$  nF/cm<sup>2</sup>

$$E = \frac{eN_D}{\epsilon_r \epsilon_0} (x - x_n)$$

Band diagram

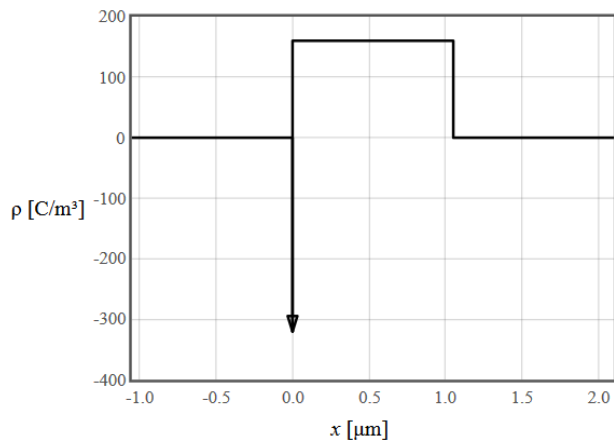


Current-Voltage Characteristics

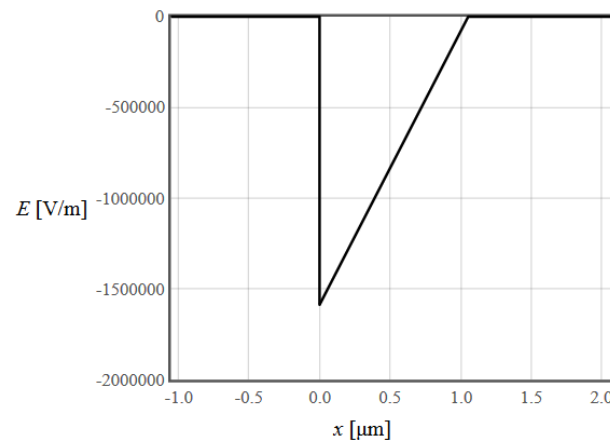


$$W \approx x_n = \sqrt{\frac{2\epsilon(V_{bi} - V)}{eN_D}}$$

Charge density



Electric field



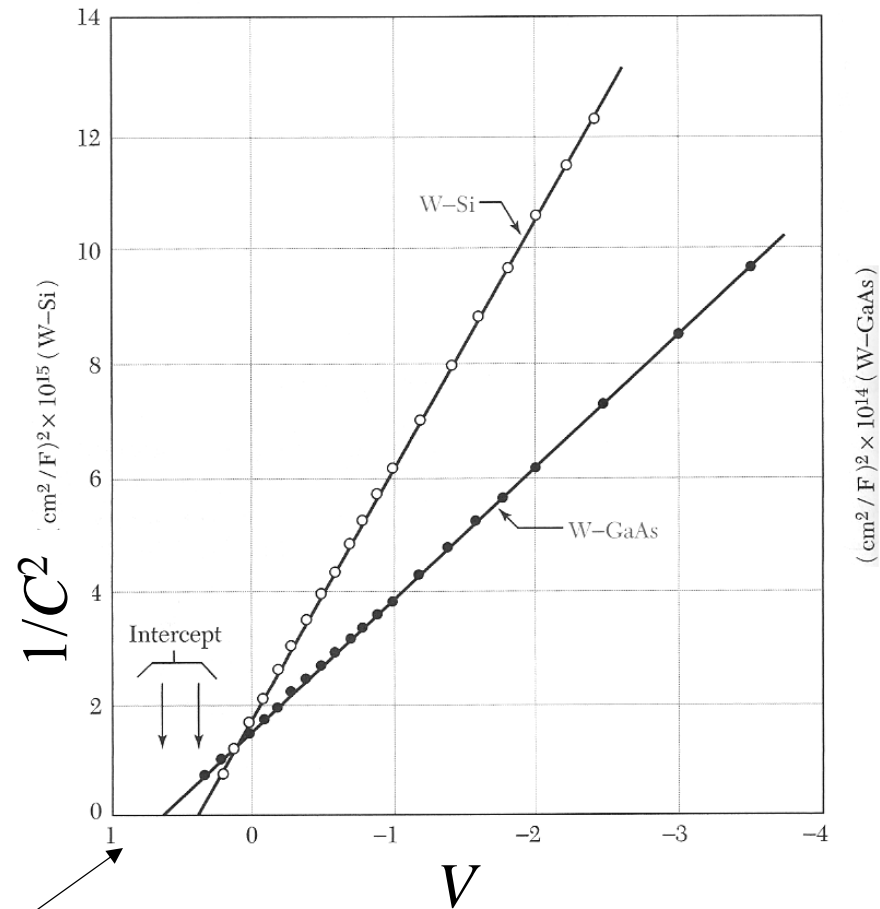
$$V = \frac{-eN_D}{\epsilon} \left( \frac{x^2}{2} - xx_n \right)$$

# CV measurements

$$x_p = \sqrt{\frac{2\epsilon(V_{bi} - V)}{eN_A}}$$

$$C = \frac{\epsilon}{x_p} = \sqrt{\frac{e\epsilon N_A}{2(V_{bi} - V)}} \quad \text{F m}^{-2}$$

$$\frac{1}{C^2} = \frac{2(V_{bi} - V)}{e\epsilon N_A}$$



GaAs has larger  $E_g$  and  $V_{bi}$

$$eV_{bi} = \phi_b - k_B T \ln \left( \frac{N_v(T)}{N_A} \right)$$

# Thermionic emission

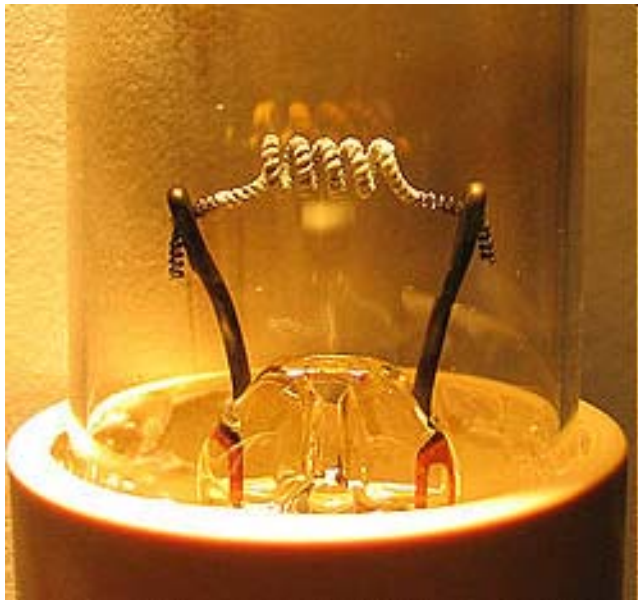
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1901 Richardson

Owen Willans Richardson

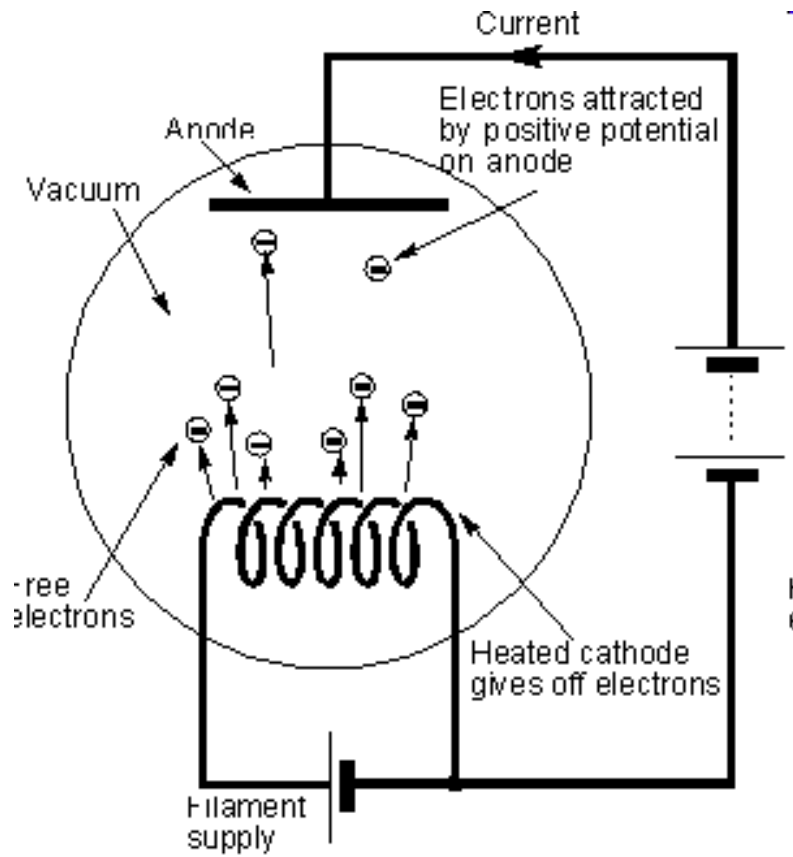
Current from a heated wire is:



$$J = A_R T^2 \exp\left(-\frac{e\phi}{k_B T}\right)$$

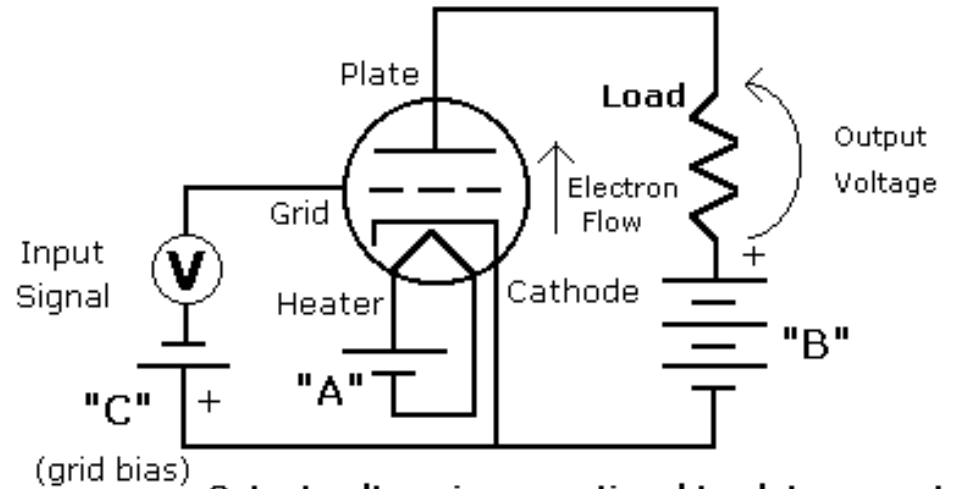
Some electrons have a thermal energy that exceeds the work function and escape from the wire.

# Vacuum diodes



diode

## The Common-cathode Triode Amplifier

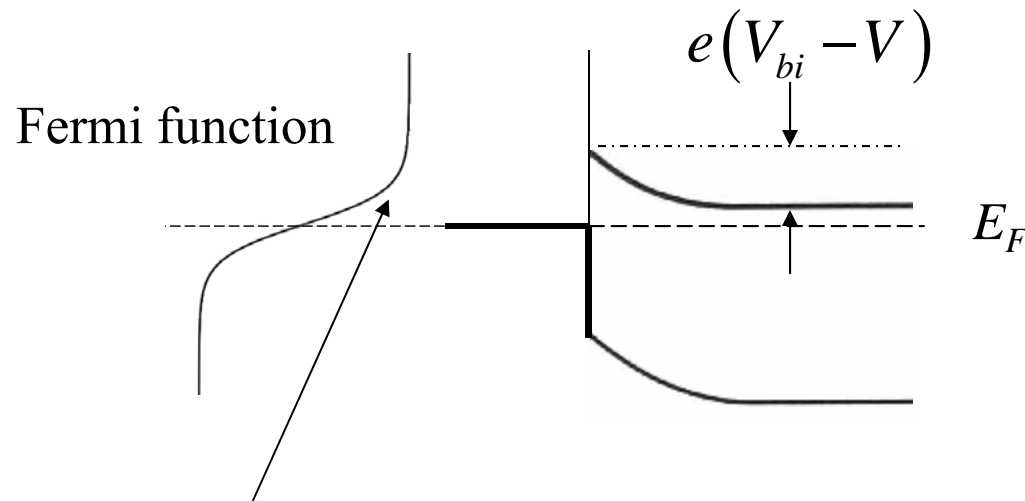


**Output voltage is proportional to plate current, which is controlled by grid voltage.**



# Thermionic emission

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$$f(E) \approx \exp\left(\frac{E_F - E}{k_B T}\right) = \exp\left(\frac{E_F}{k_B T}\right) \exp\left(\frac{-E}{k_B T}\right) \propto \exp\left(\frac{-E}{k_B T}\right)$$

The density of electrons with enough energy to go over the barriers  $\propto \exp\left(\frac{-E}{k_B T}\right)$



# Thermionic emission

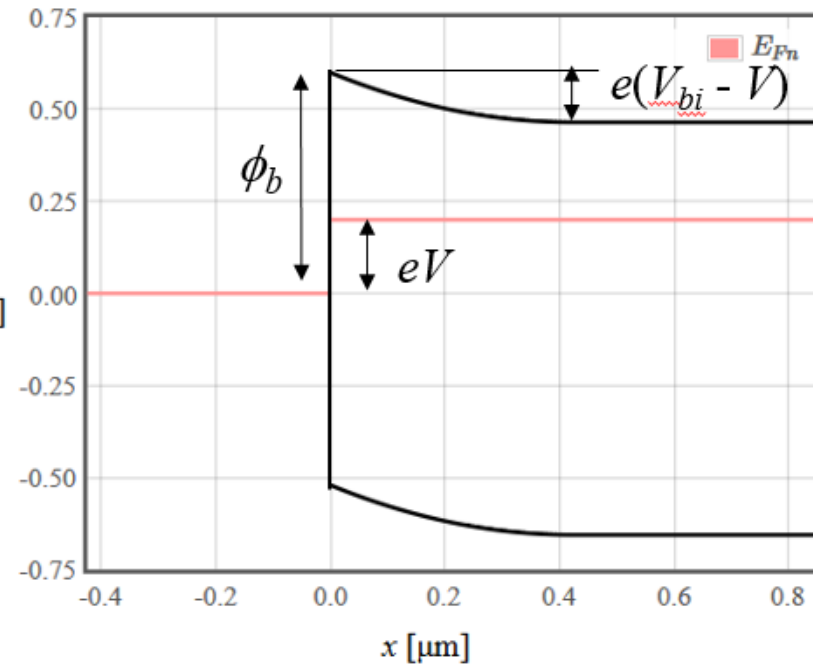
$$n_{th} \propto \exp\left(\frac{-E}{k_B T}\right) = \exp\left(\frac{-e(V_{bi} - V)}{k_B T}\right) = \exp\left(\frac{-eV_{bi}}{k_B T}\right) \exp\left(\frac{eV}{k_B T}\right)$$

Forward bias

$$n_{th} \propto \exp\left(\frac{eV}{k_B T}\right)$$

$$I_{sm} \propto n_{th} \propto \exp\left(\frac{eV}{k_B T}\right)$$

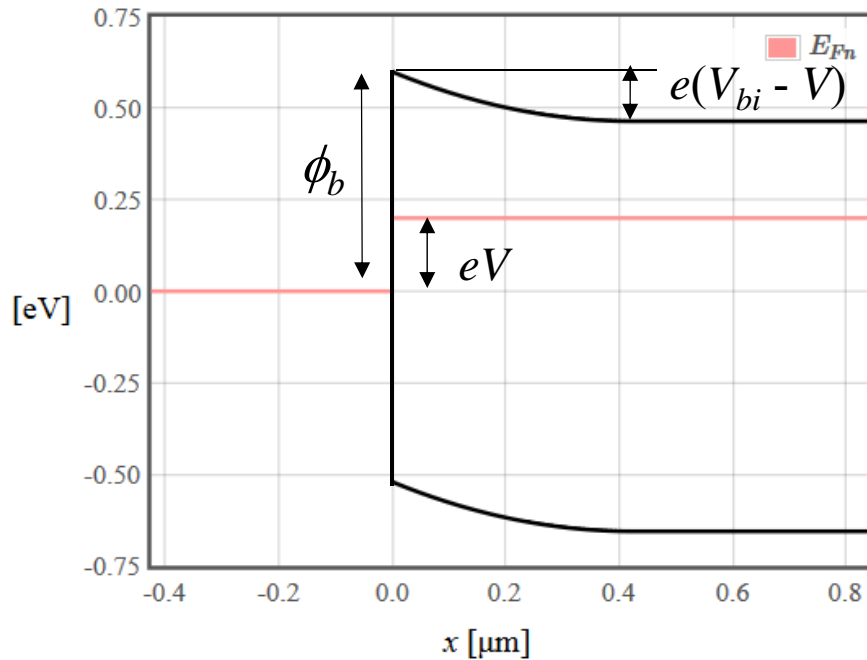
$$I_{ms} = I_{sm} (V = 0)$$



$$I = I_{sm} + I_{ms} = I_{ms} \left( e^{\frac{eV}{k_B T}} - 1 \right)$$

# Schottky barrier

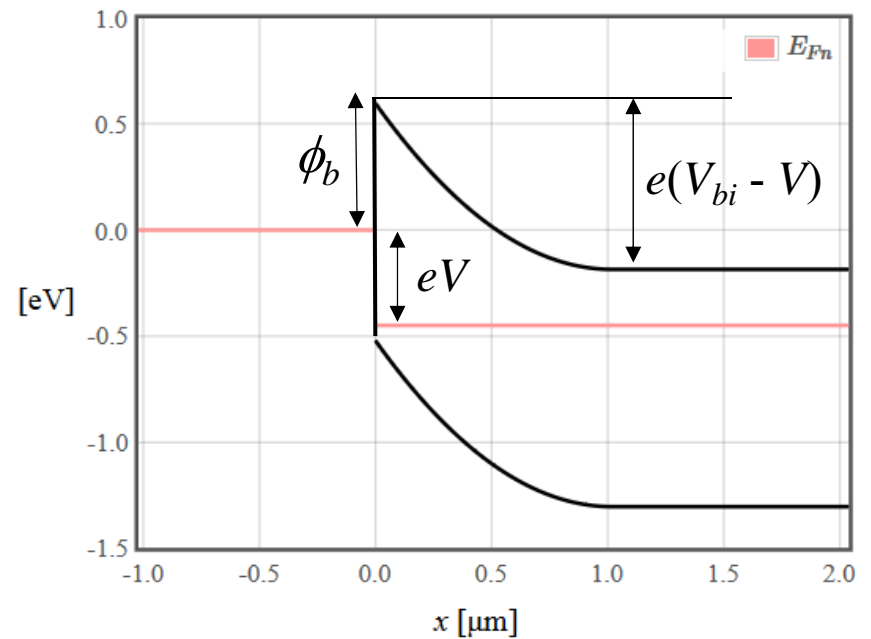
Forward bias



$$I_{sm} \sim \exp(eV/k_B T)$$

$$I_{ms} \text{ constant}$$

Reverse bias



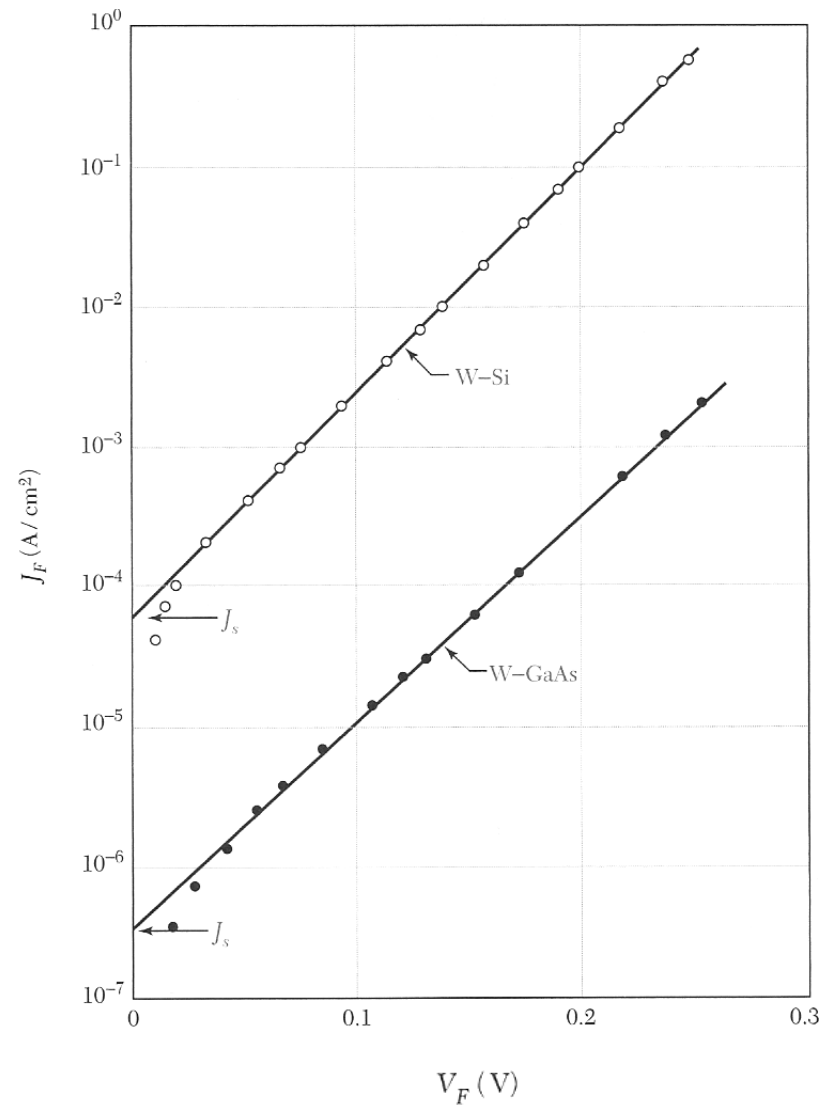
$$I_{sm} \sim 0$$

$$I_{ms} \text{ constant}$$

# Thermionic emission

$$I = I_{sm} + I_{ms} = I_s \left( e^{\frac{eV}{k_B T}} - 1 \right)$$

Nonideality factor = 1



# Thermionic emission

$$I_s = AA_R^* T^2 \exp\left(\frac{-e\phi_b}{k_B T}\right)$$

$A$  = Area

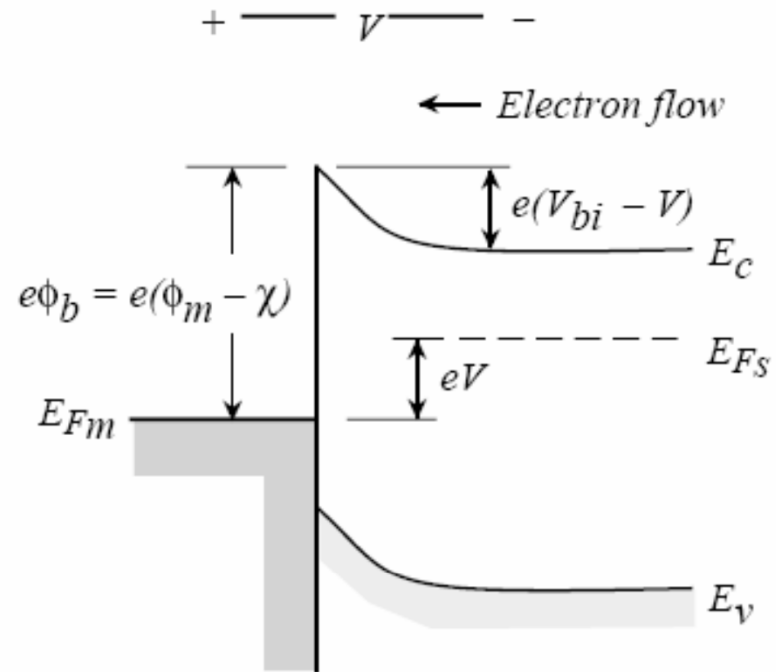
$A_R^*$  = Richardson constant

n-Si  $A_R^* = 110 \text{ A K}^{-2}\text{cm}^{-2}$

p-Si  $A_R^* = 32 \text{ A K}^{-2}\text{cm}^{-2}$

n-GaAs  $A_R^* = 8 \text{ A K}^{-2}\text{cm}^{-2}$

p-GaAs  $A_R^* = 74 \text{ A K}^{-2}\text{cm}^{-2}$



Forward bias

(a)

Thermionic emission dominates over diffusion current in a Schottky diode.

# Schottky diodes

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Majority carrier current dominates.

nonideality factor = 1.

Fast response, no recombination of electron-hole pairs required.

Used as rf mixers.

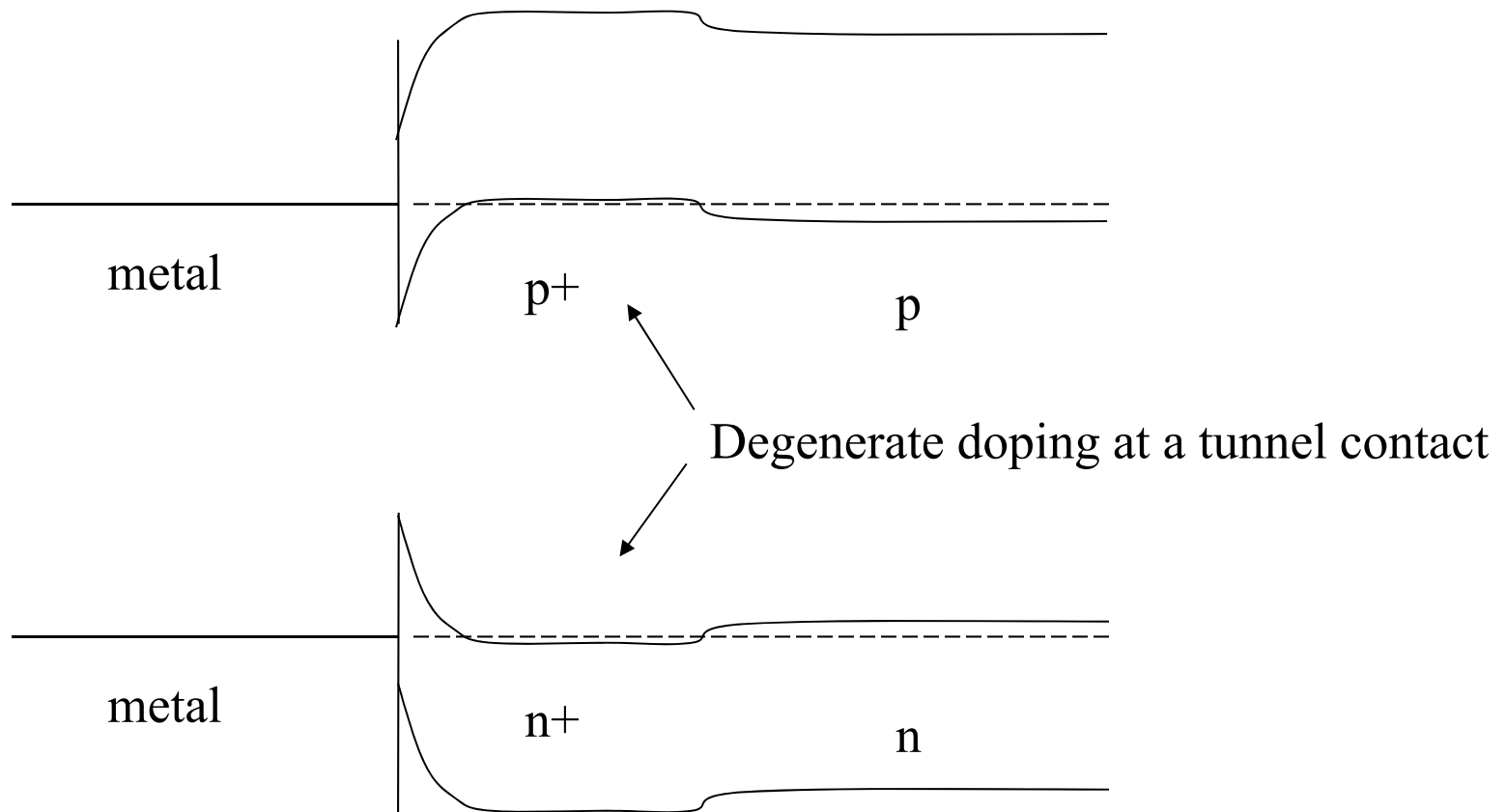
Low turn on voltage - high reverse bias current

$$I = I_s \left( e^{\frac{eV}{k_B T}} - 1 \right)$$

# Tunnel contacts

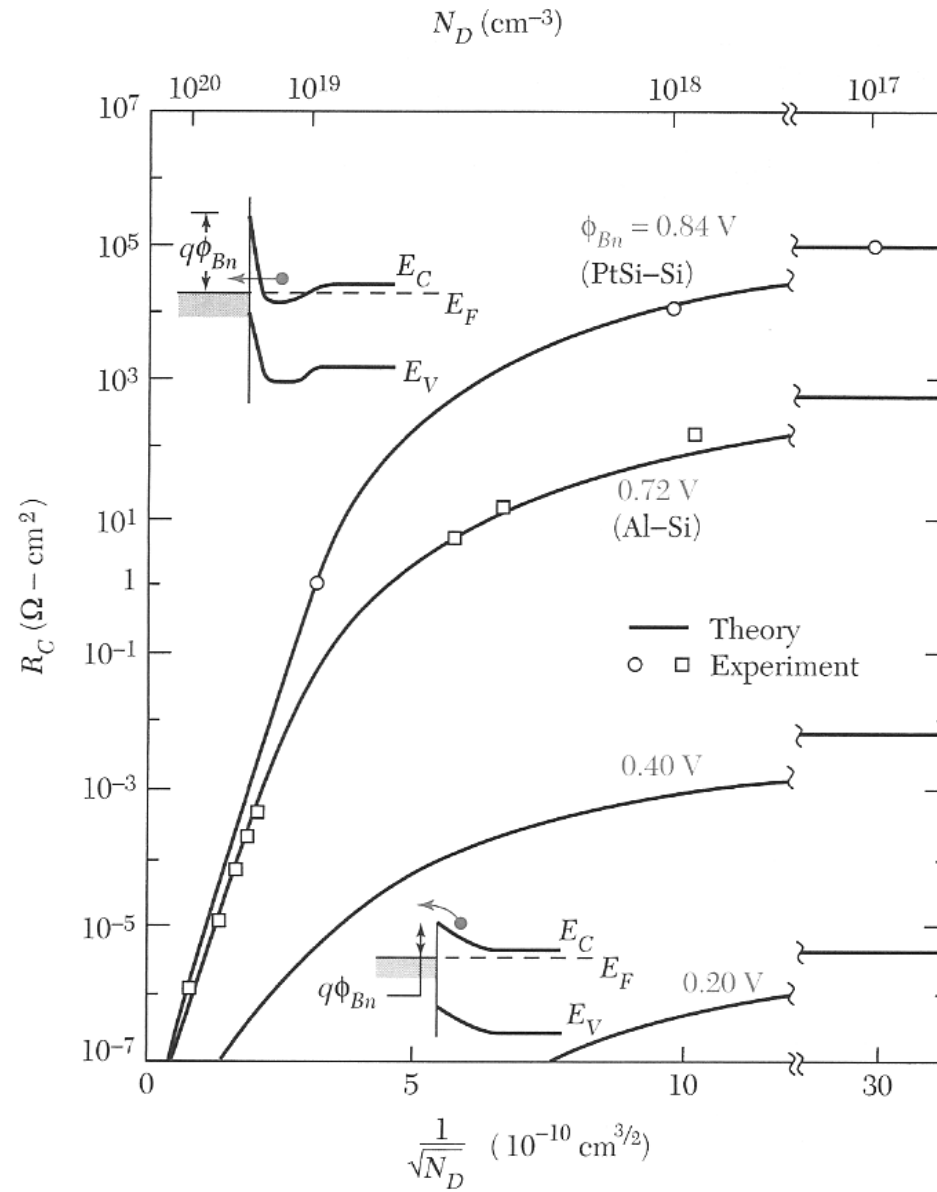
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For high doping, the Schottky barrier is so thin that electrons can tunnel through it.



Tunnel contacts have a linear resistance.

# Contacts



# Transport mechanisms

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Drift

Diffusion

Thermionic emission

Tunneling

All mechanisms are always present.

One or two transport mechanisms can dominate depending on the device and the bias conditions.

In a forward biased pn-junction, diffusion dominates.

In a tunnel contact, tunneling dominates.

In a Schottky diode, thermionic emission dominates.