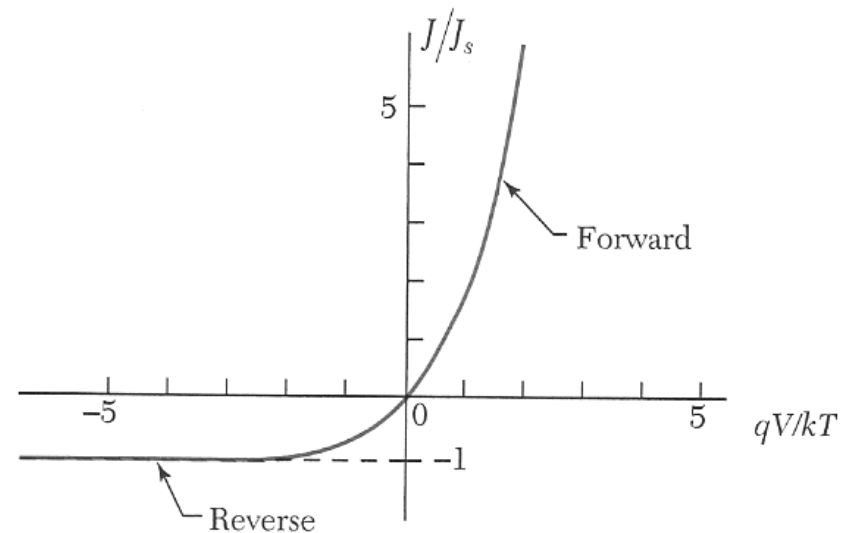


8. Schottky contacts / JFETs

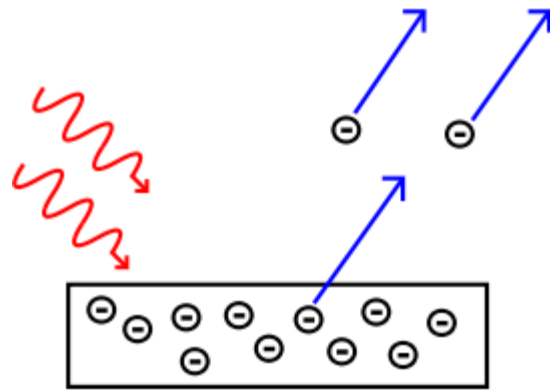
Nov. 20, 2019

metal - semiconductor contacts

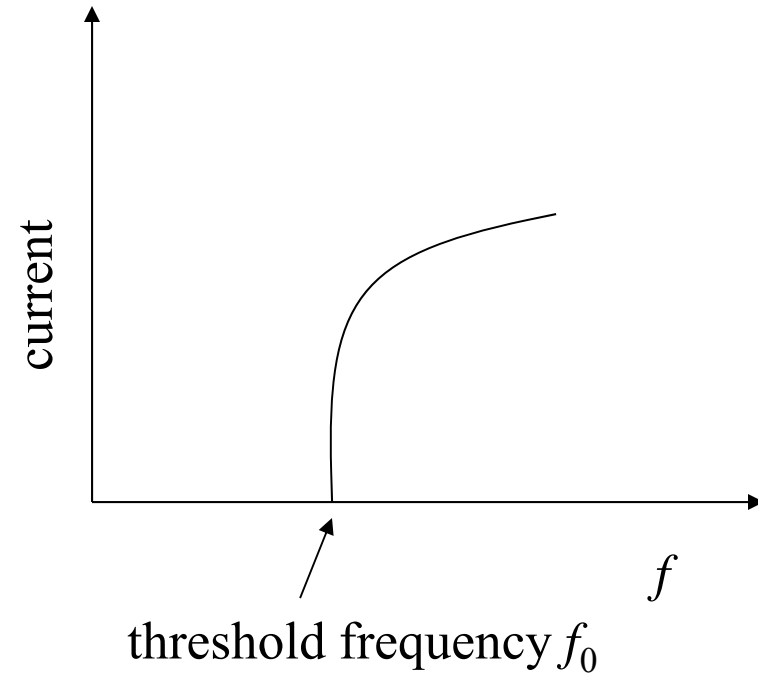
Photoelectric effect
 Schottky barriers
 Schottky diodes
 Ohmic contacts
 Thermionic emission
 Tunnel contacts



Photoelectric effect



$hf_0 = e\phi$ at threshold
workfunction

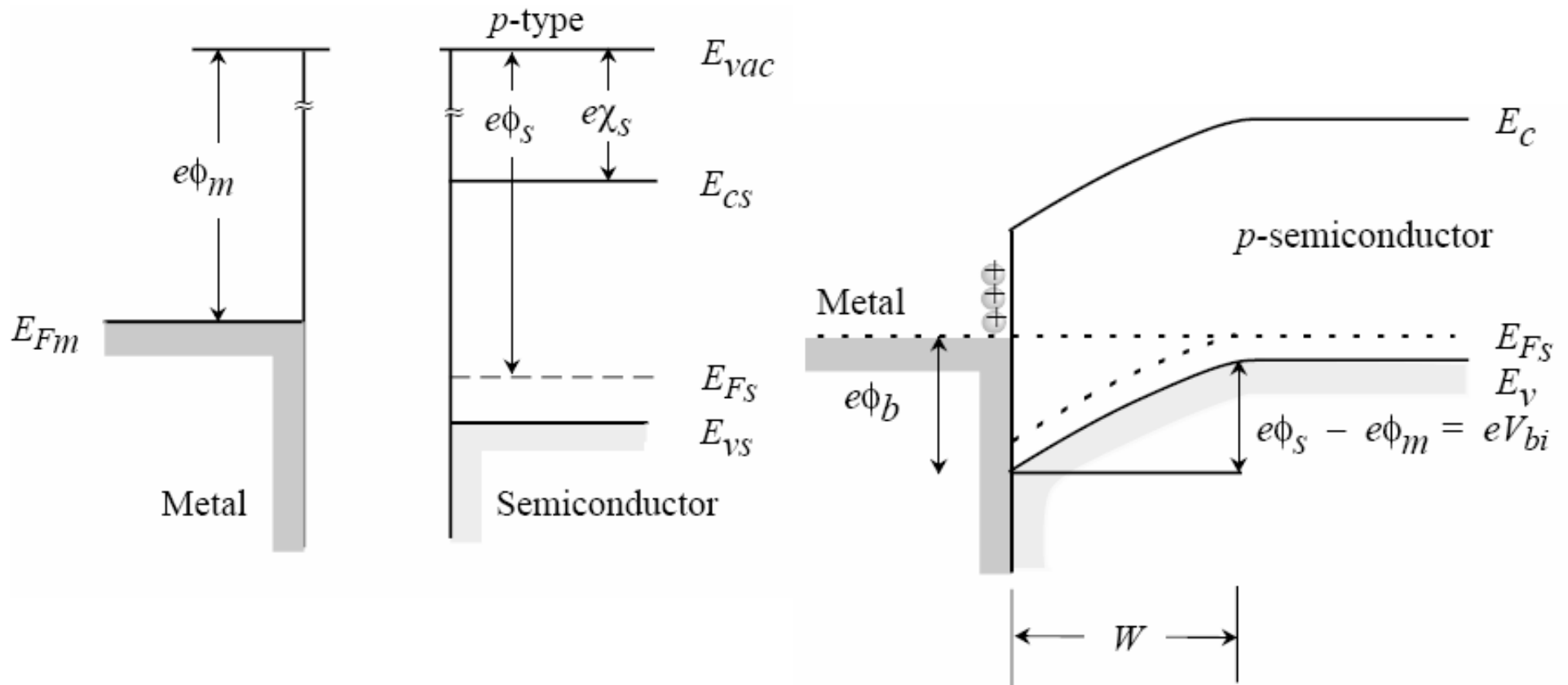


Work functions of some metals	
Element	Work function, ϕ_m (volt)
Ag, silver	4.26
Al, aluminum	4.28
Au, gold	5.1
Cr, chromium	4.5
Mo, molybdenum	4.6
Ni, nickel	5.15
Pd, palladium	5.12
Pt, platinum	5.65
Ti, titanium	4.33
W, tungsten	4.55

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.

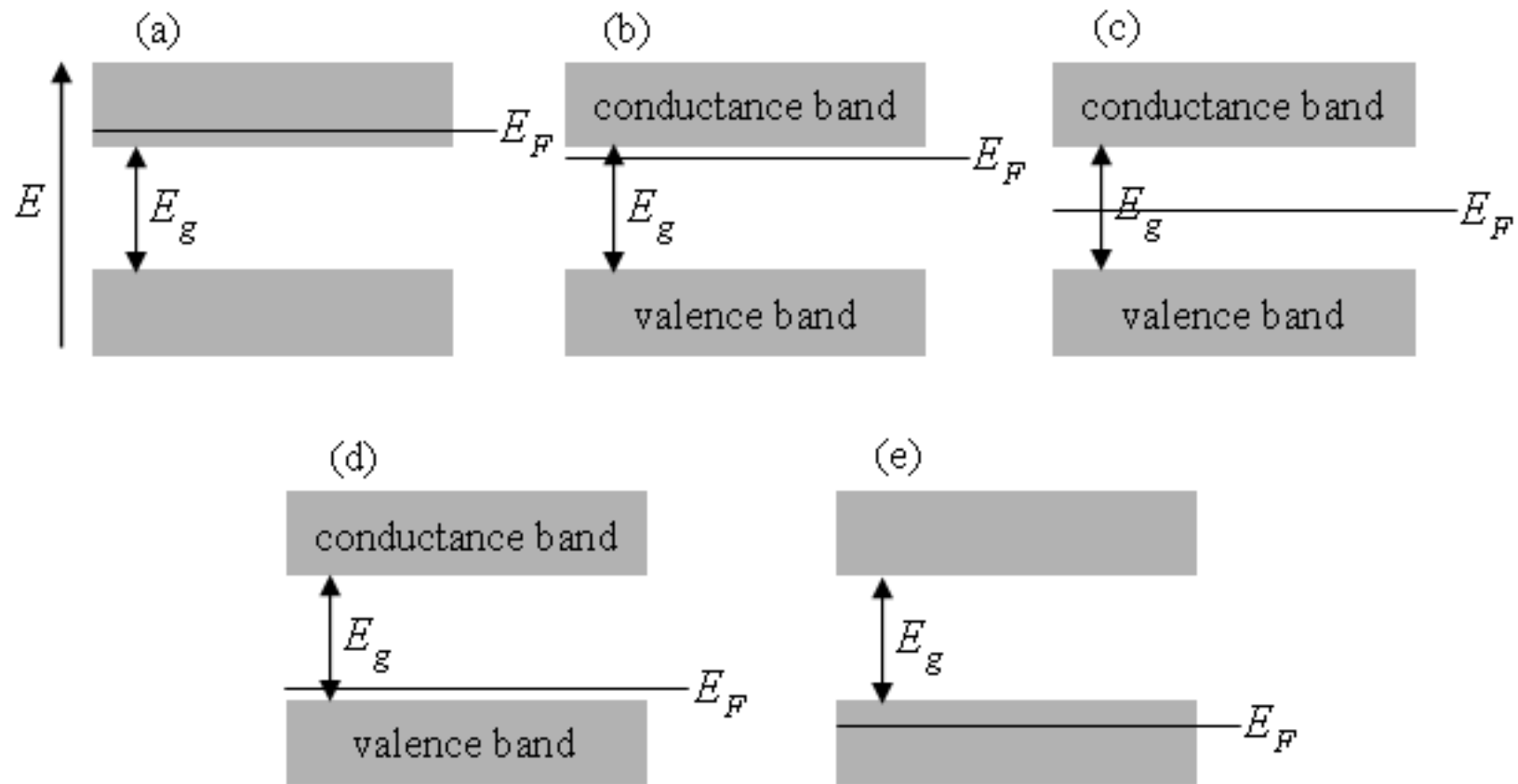
If $\phi_s > \phi_m$, the semiconductor bands bend up.

Work functions of some metals

Element	Work function, ϕ_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

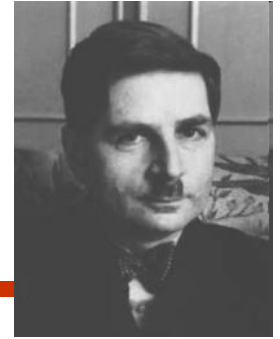
Element	Electron affinity, χ (volt)
Ge, germanium	4.13
Si, silicon	4.01
GaAs, gallium arsenide	4.07
AlAs, aluminum arsenide	3.5



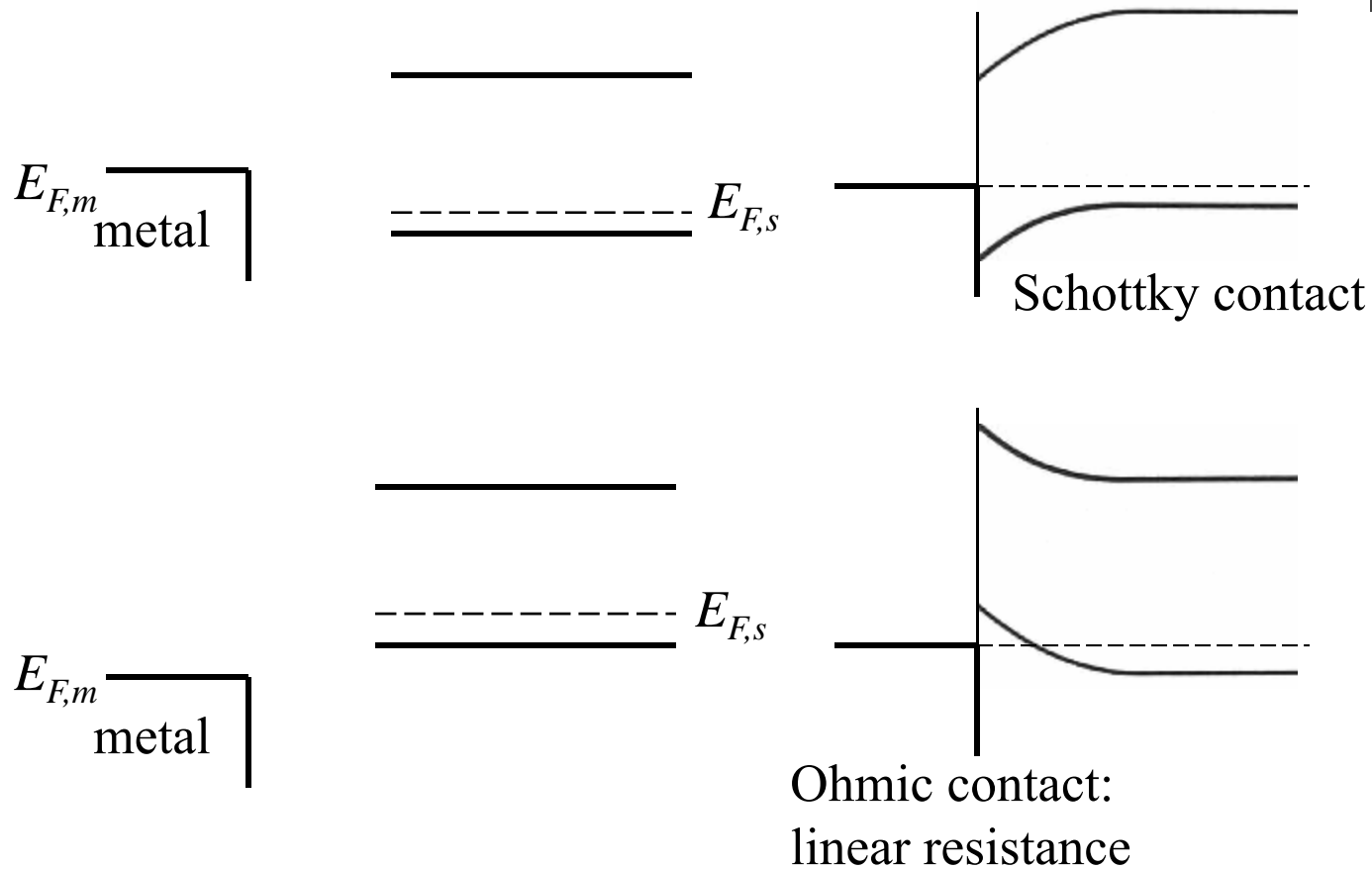
(a) A metal with a small workfunction. (b) An n-type semiconductor. (c) An insulator. (d) A p-type semiconductor. (e) A metal with a large workfunction.

p-type

Walter Schottky



Schottky contact / ohmic contact

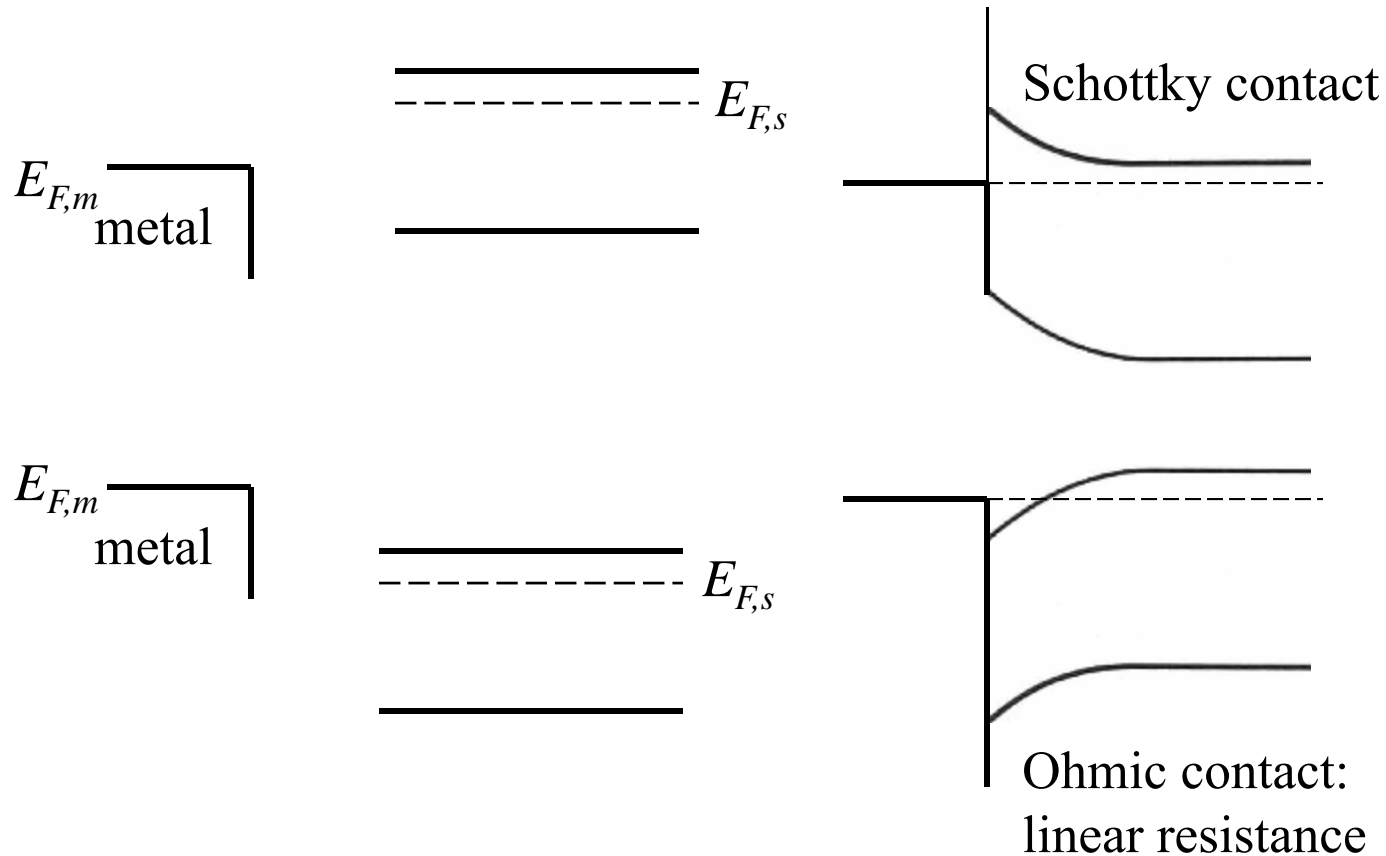


specific contact resistance:

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

n-type

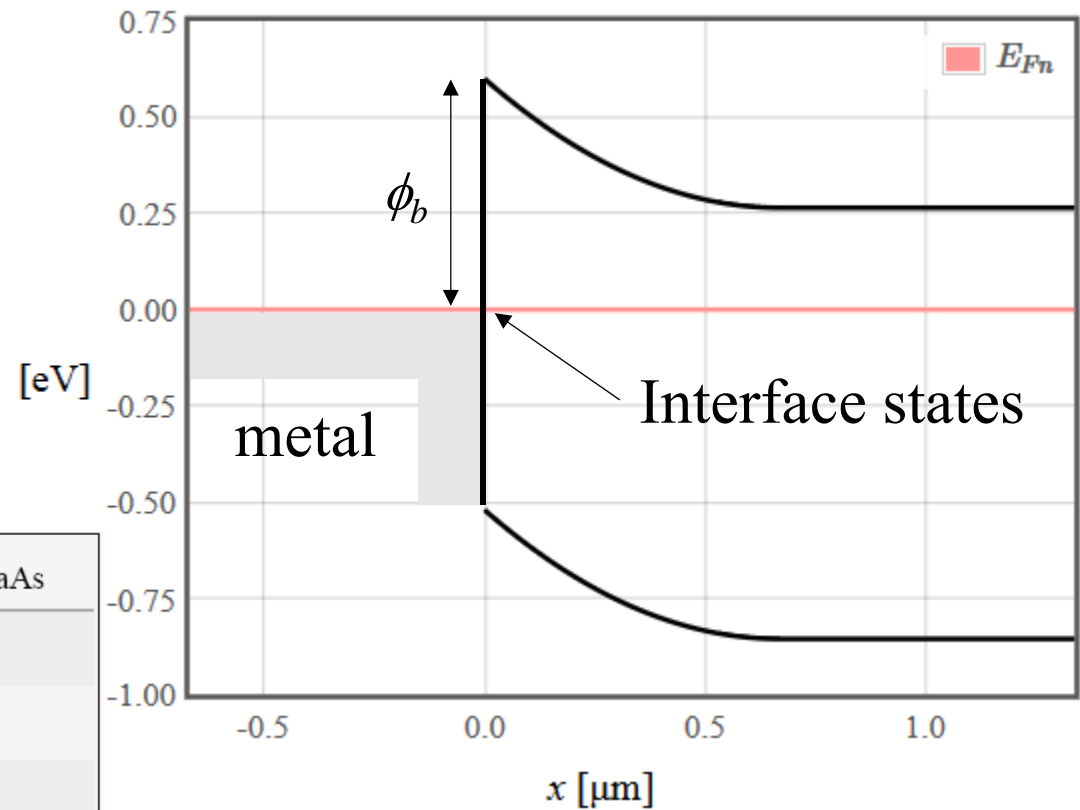
Schottky contact / ohmic contact



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 ₂	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

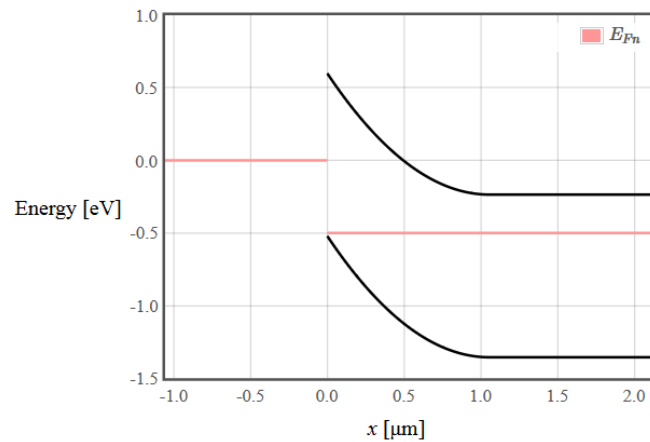
Schottky barrier

$\phi_b = 0.6$ eV
 $E_g = 1.166 - 4.73E-4 * T * T / (T + 636)$ eV
 $N_D = 1E15$ 1/cm³
 $N_c(300) = 2.78E19$ 1/cm³
 $T = 300$ K
 $\epsilon_r = 12$
 $V = -0.5$ V

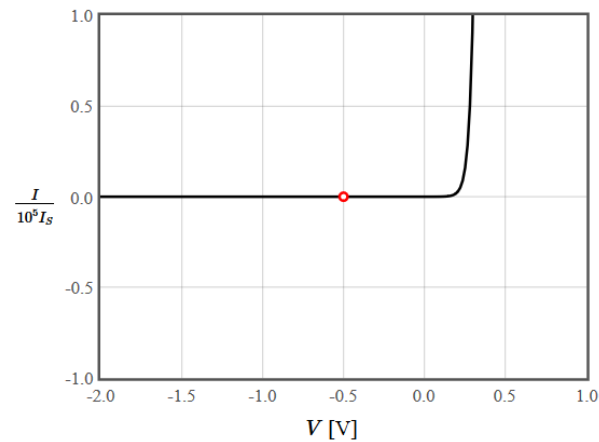
$E_g = 1.12$ eV $W = 1.05$ μ m $V_{bi} = 0.335$ V $C_j = 10.1$ nF/cm²

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

Band diagram

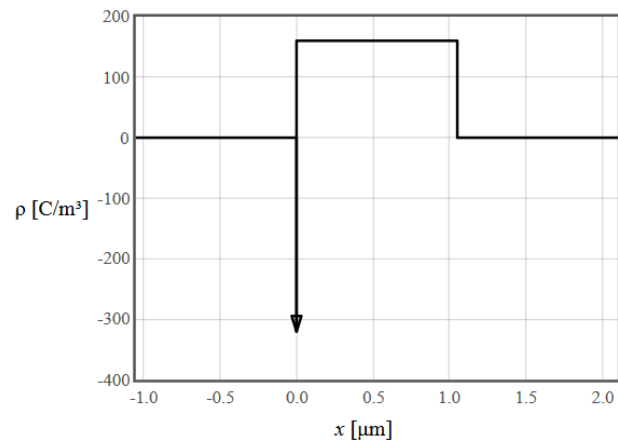


Current-Voltage Characteristics

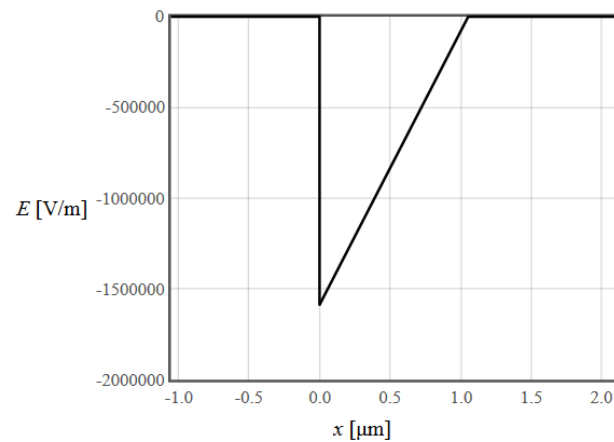


$$W \approx x_n = \sqrt{\frac{2\epsilon(V_{bi} - V)}{eN_D}}$$

Charge density



Electric field



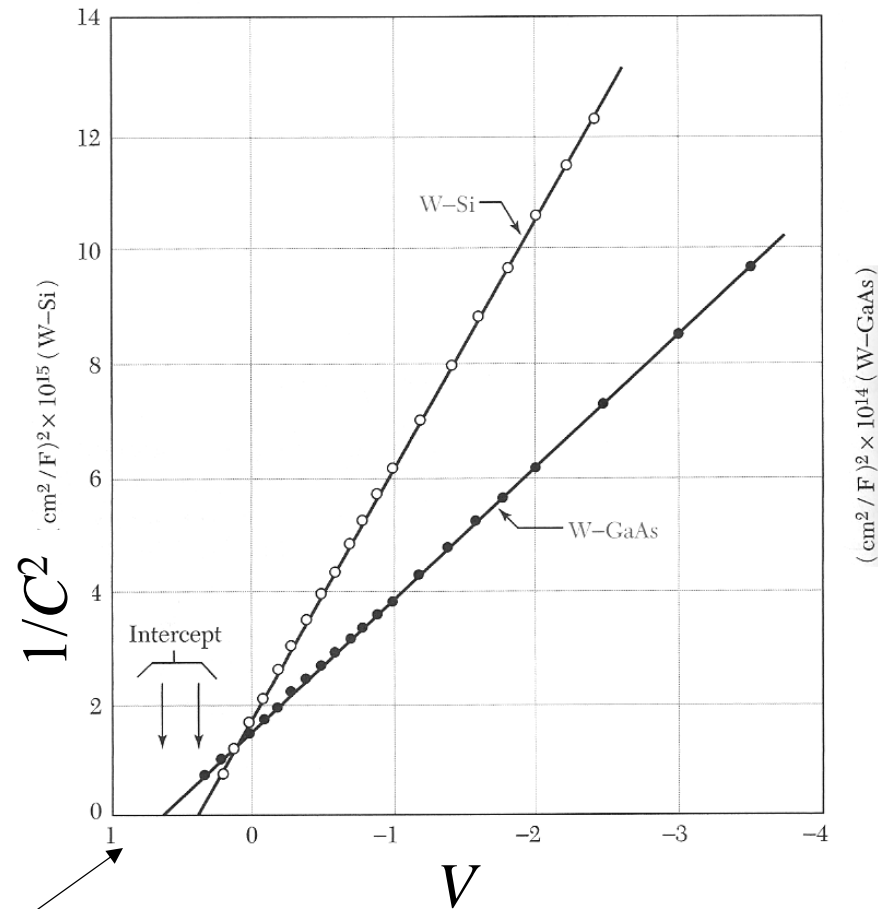
$$V = \frac{-eN_D}{\epsilon} \left(\frac{x^2}{2} - xx_n \right)$$

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}

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

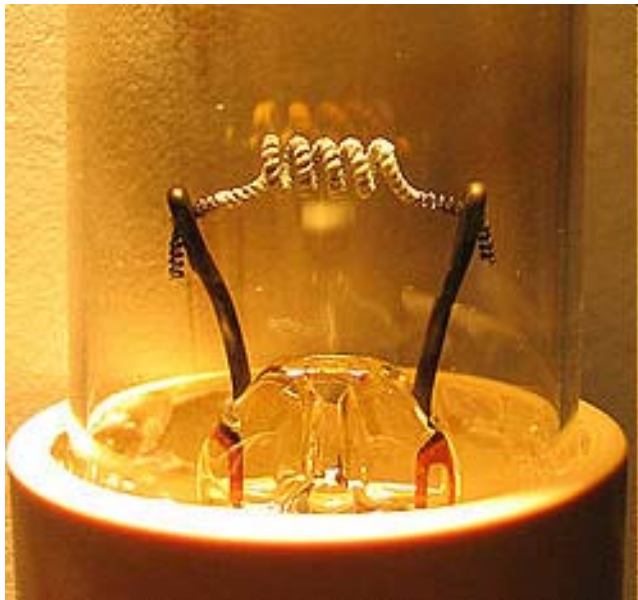
Thermionic emission



1901 Richardson

Owen Willans Richardson

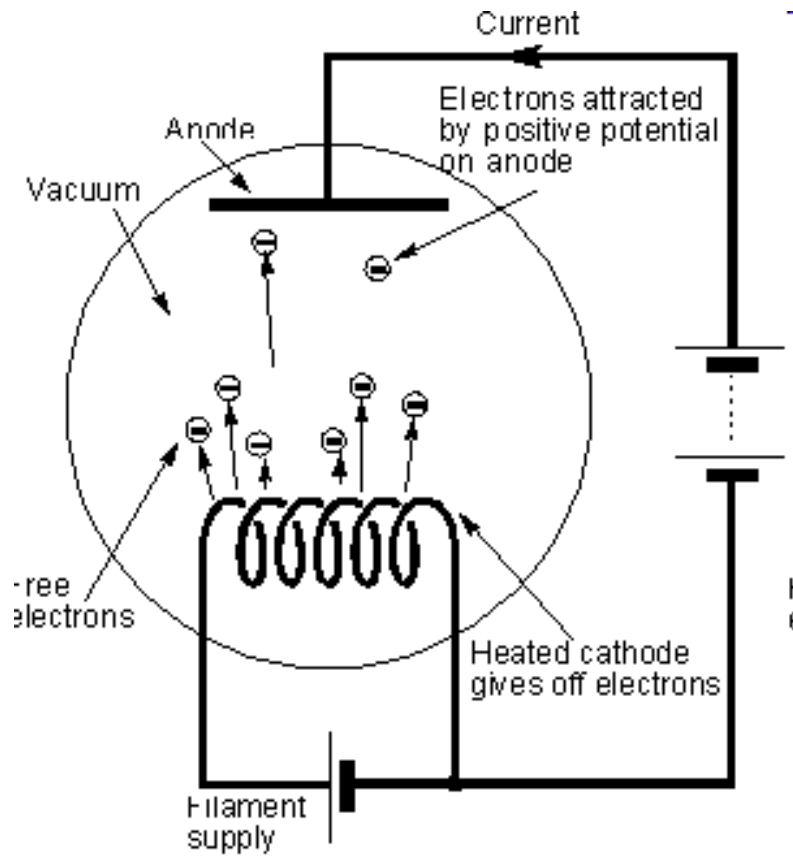
Current from a heated wire is:



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

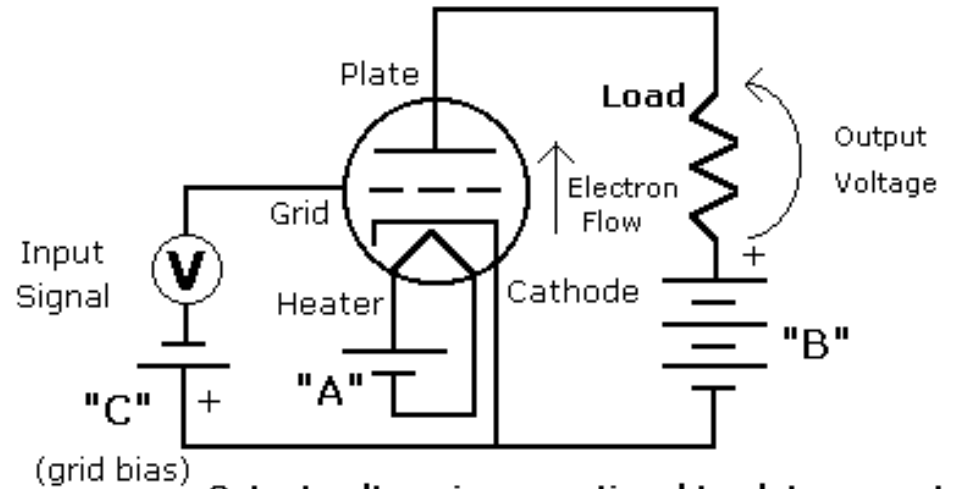
Some electrons have a thermal energy that exceeds the work function and escape from the wire.

Vacuum diodes

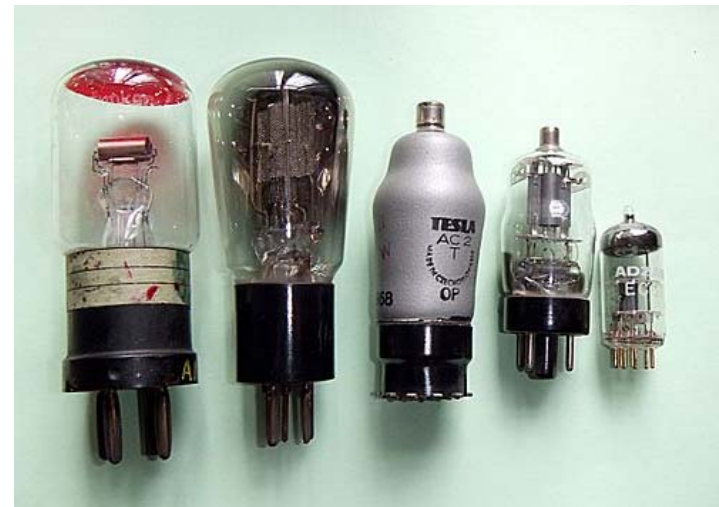


diode

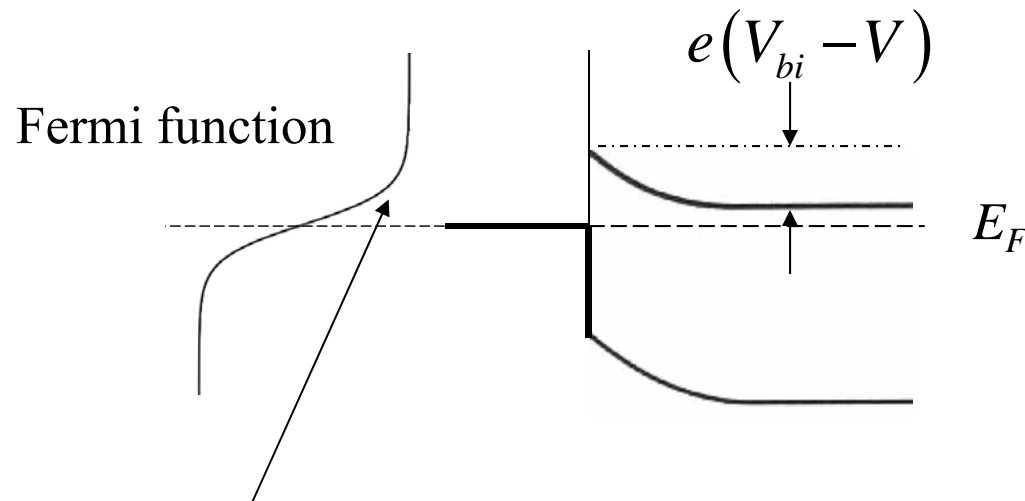
The Common-cathode Triode Amplifier



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



Thermionic emission



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

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

Thermionic emission

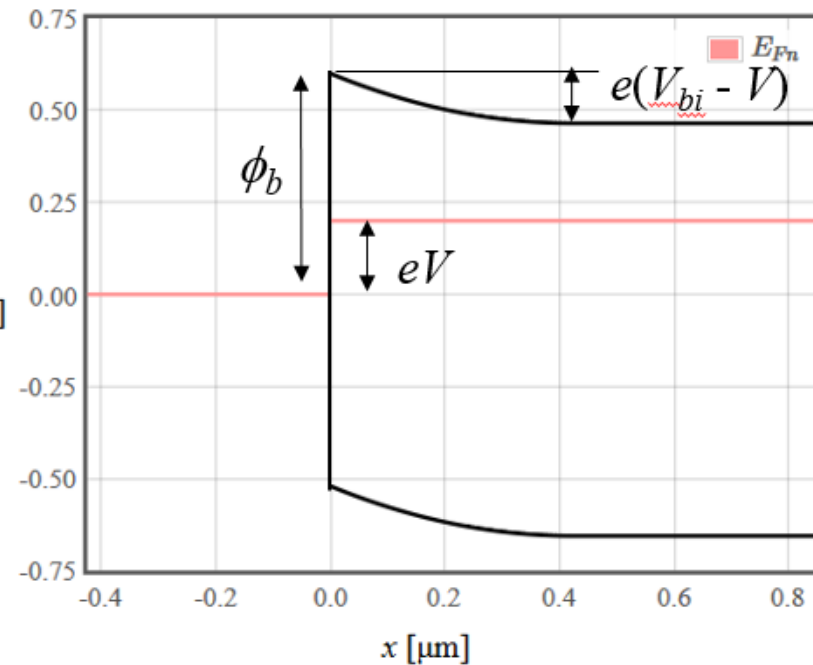
$$n_{th} \propto \exp\left(\frac{-E}{k_B T}\right) = \exp\left(\frac{-e(V_{bi} - V)}{k_B T}\right) = \exp\left(\frac{-eV_{bi}}{k_B T}\right) \exp\left(\frac{eV}{k_B T}\right)$$

Forward bias

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

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

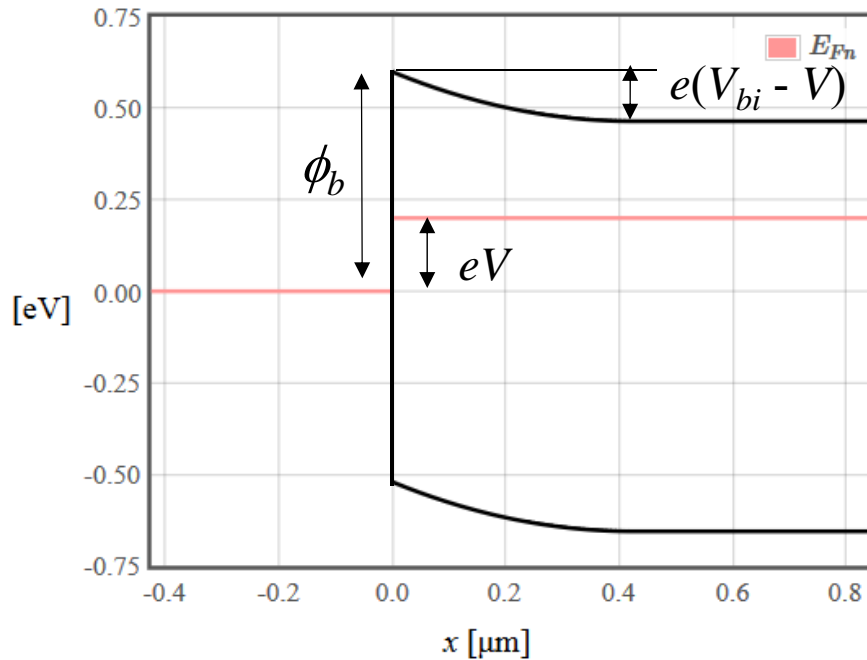
$$I_{ms} = I_{sm} (V = 0)$$



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

Schottky barrier

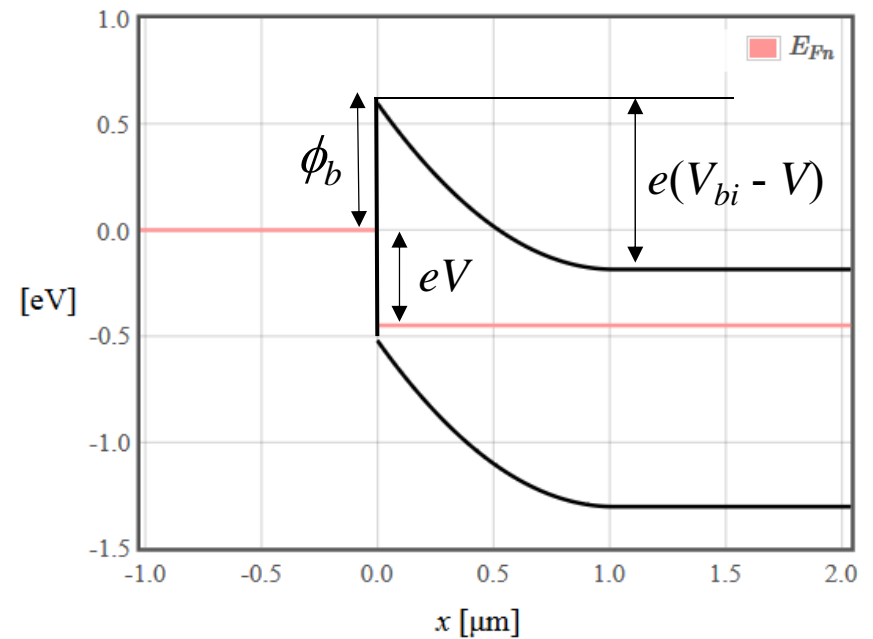
Forward bias



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

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

Reverse bias



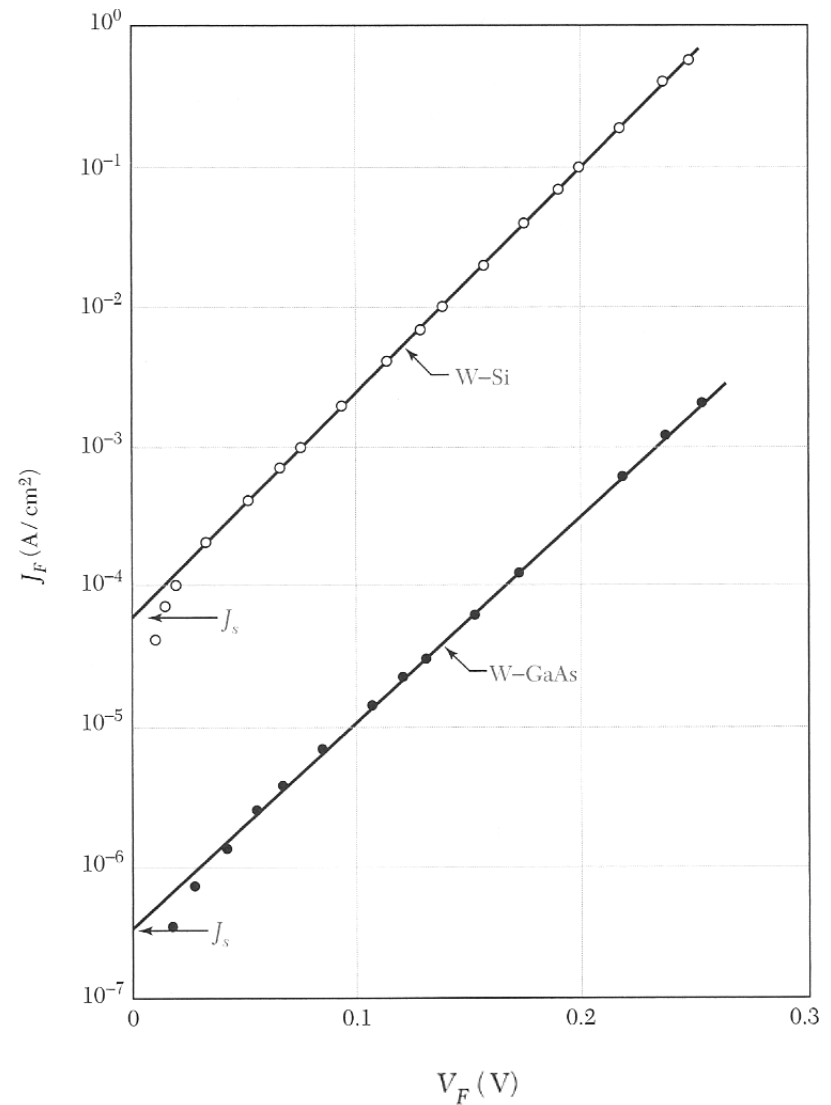
$$I_{sm} \sim 0$$

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

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

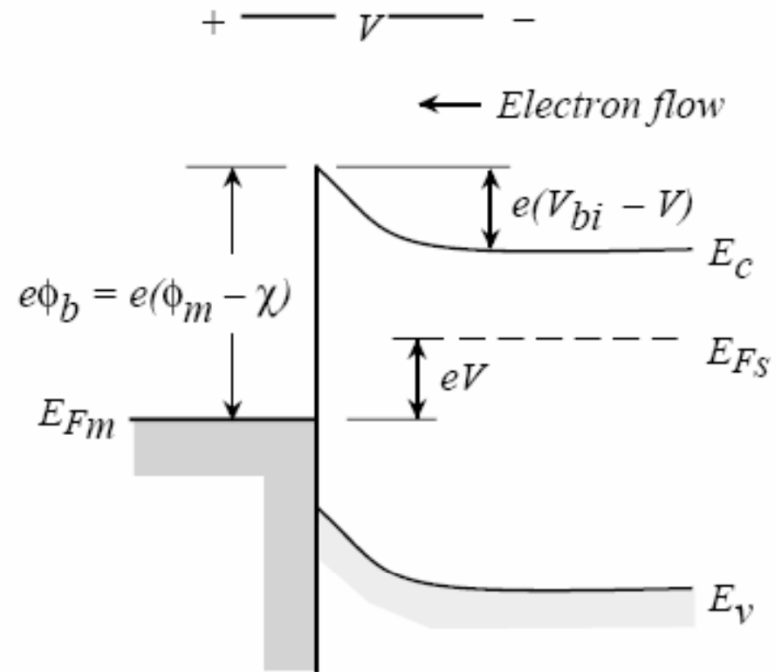
A_R^* = Richardson constant

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



E

(a)

Thermionic emission dominates over diffusion current in a Schottky diode.

Schottky diodes

Majority carrier current dominates.

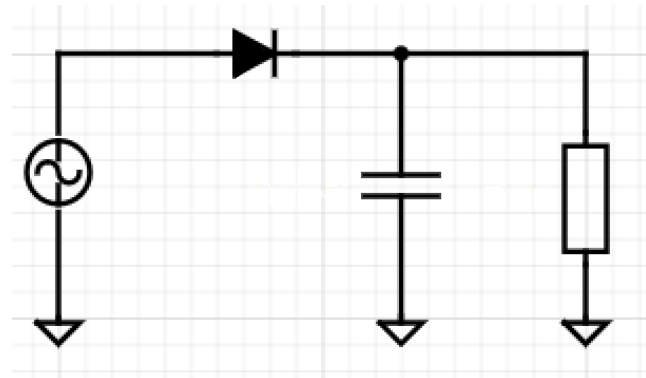
nonideality factor = 1.

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

Used as rf mixers.

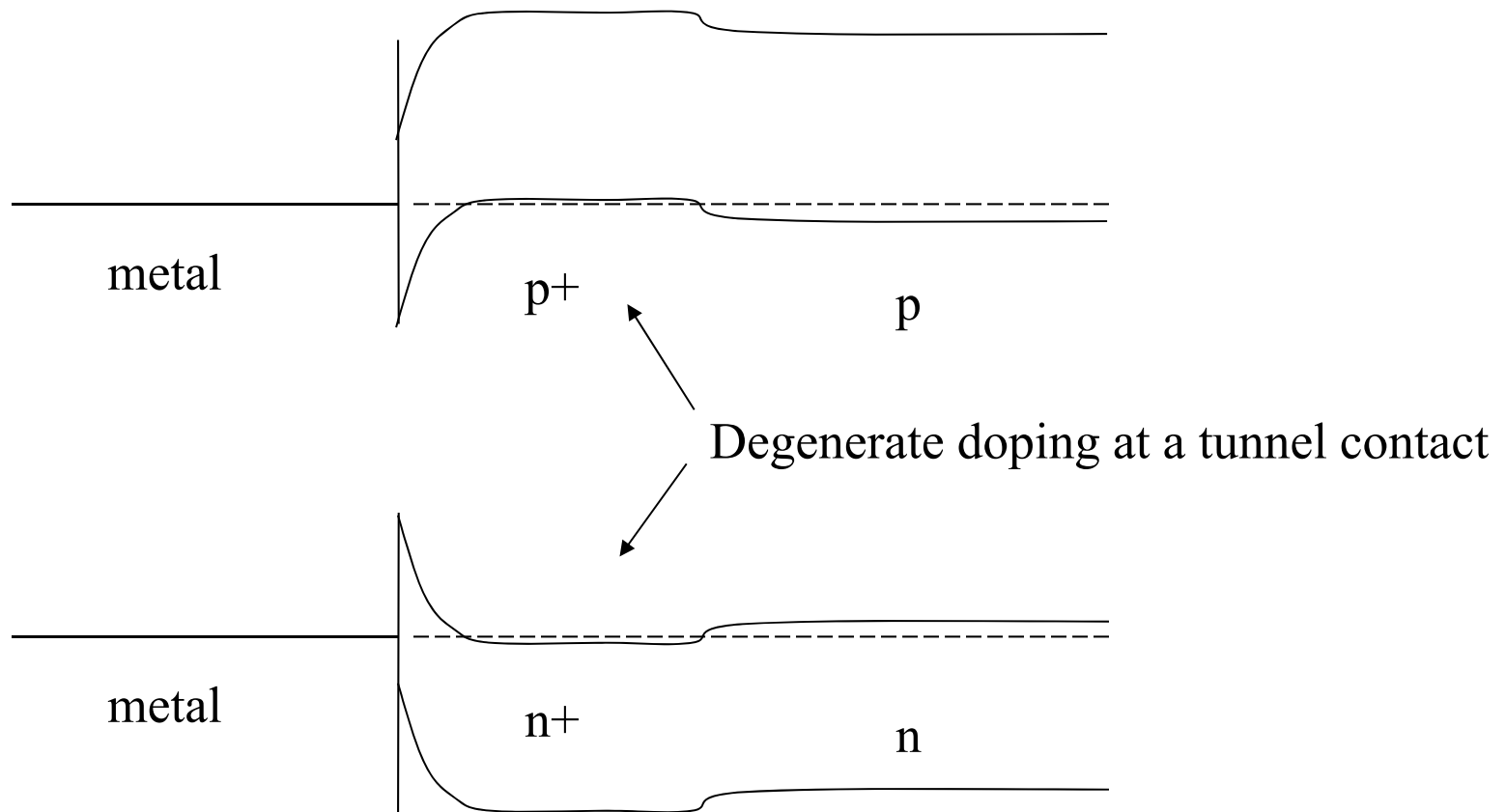
Low turn on voltage - high reverse bias current

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



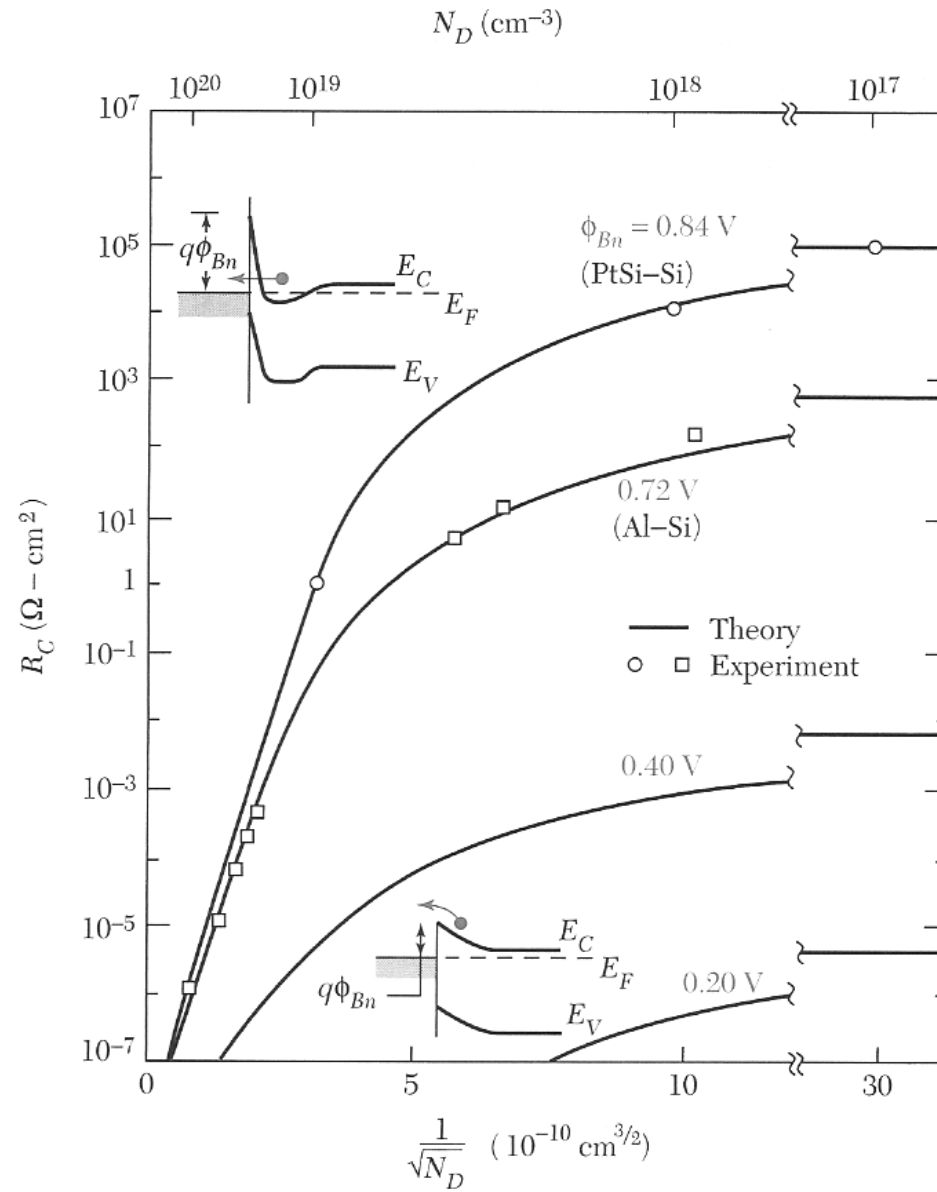
Tunnel contacts

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



Tunnel contacts have a linear resistance.

Contacts



Transport mechanisms

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.

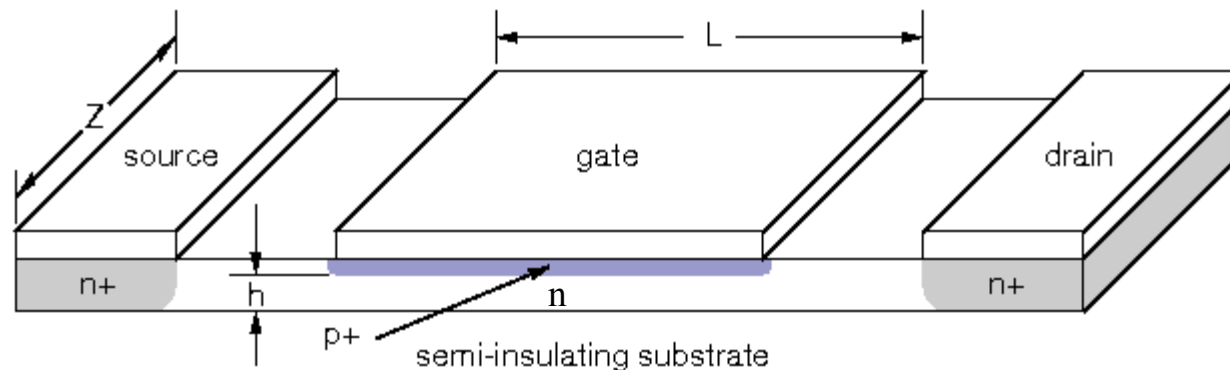
In a Schottky diode, thermionic emission dominates.

JFETs - MESFETs - MODFETs

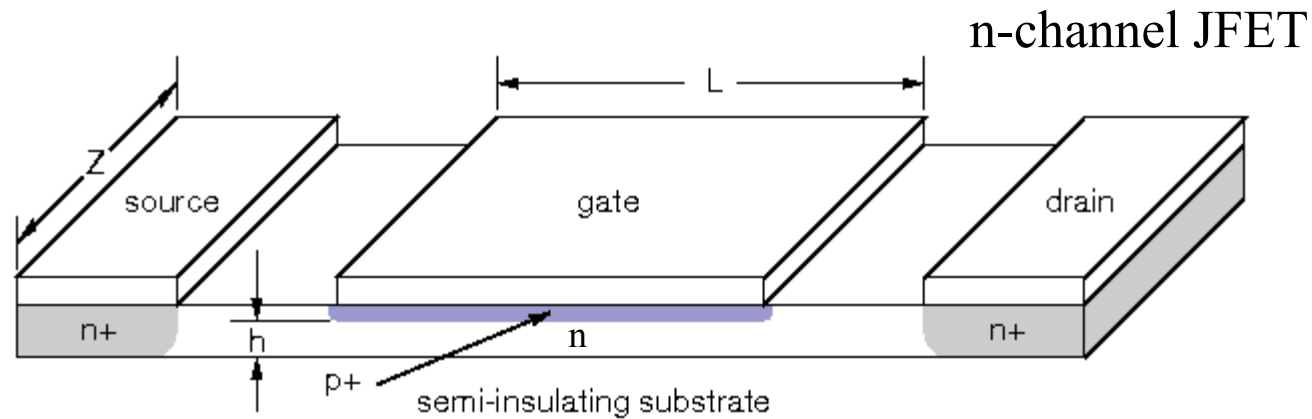
Junction Field Effect Transistors (JFET)

Metal-Semiconductor Field Effect Transistors (MESFET)

Modulation Doped Field Effect Transistors (MODFET)



JFET



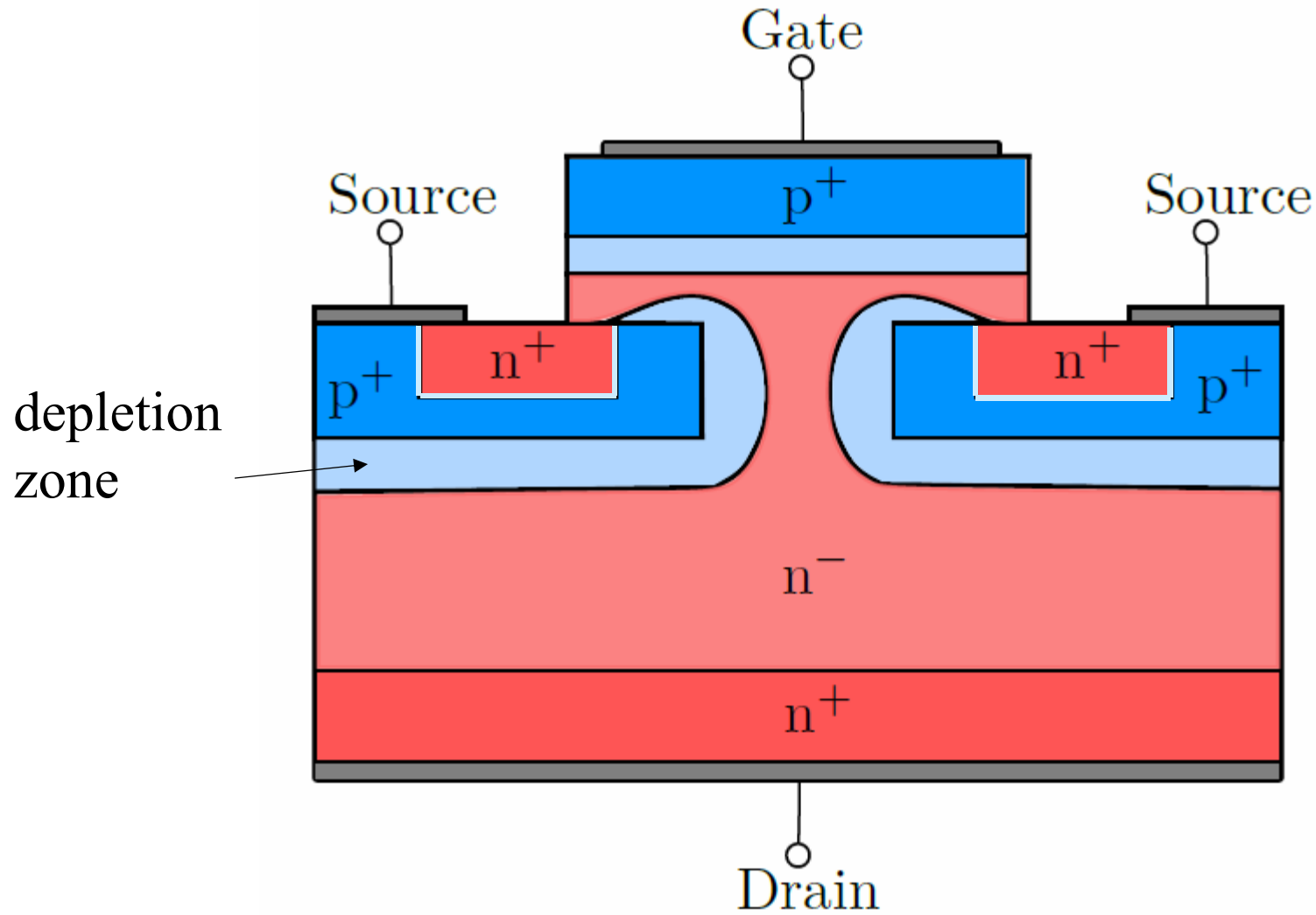
For $N_A \gg N_D$

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

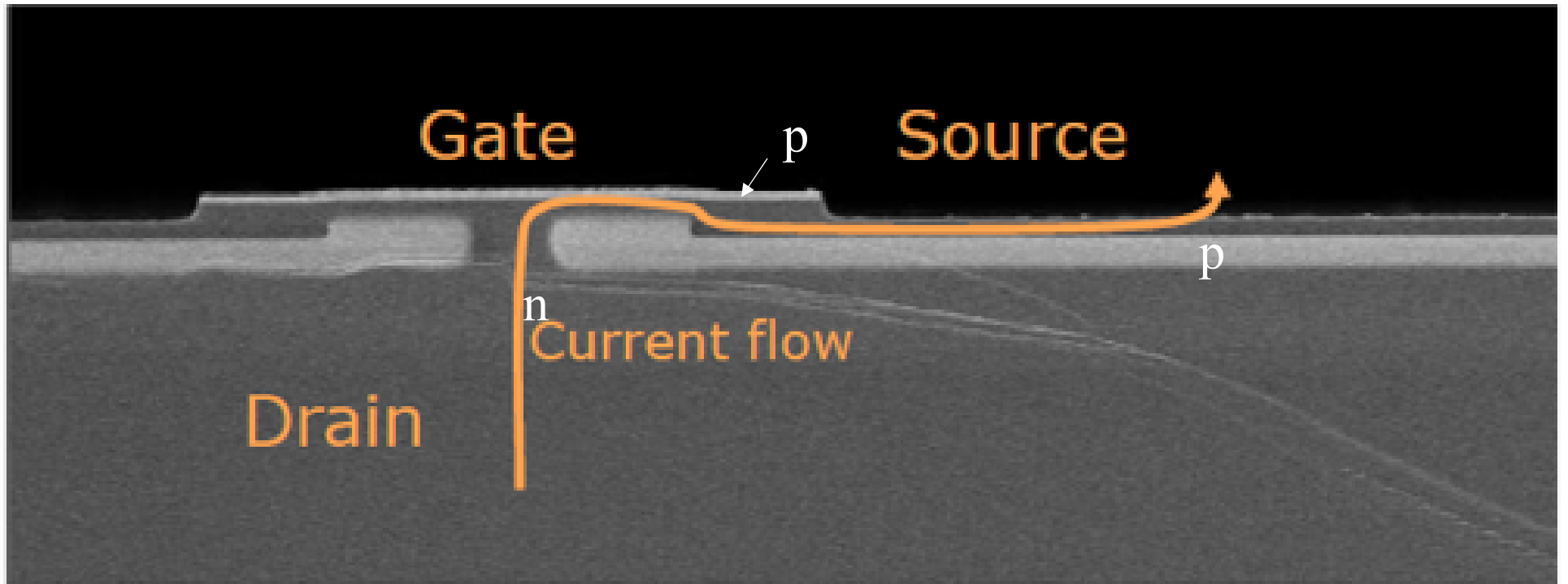
Depletion mode $h > x_n = \sqrt{\frac{2\epsilon V_{bi}}{eN_D}}$ conducting at $V_g = 0$

Enhancement mode $h < x_n = \sqrt{\frac{2\epsilon V_{bi}}{eN_D}}$ nonconducting at $V_g = 0$

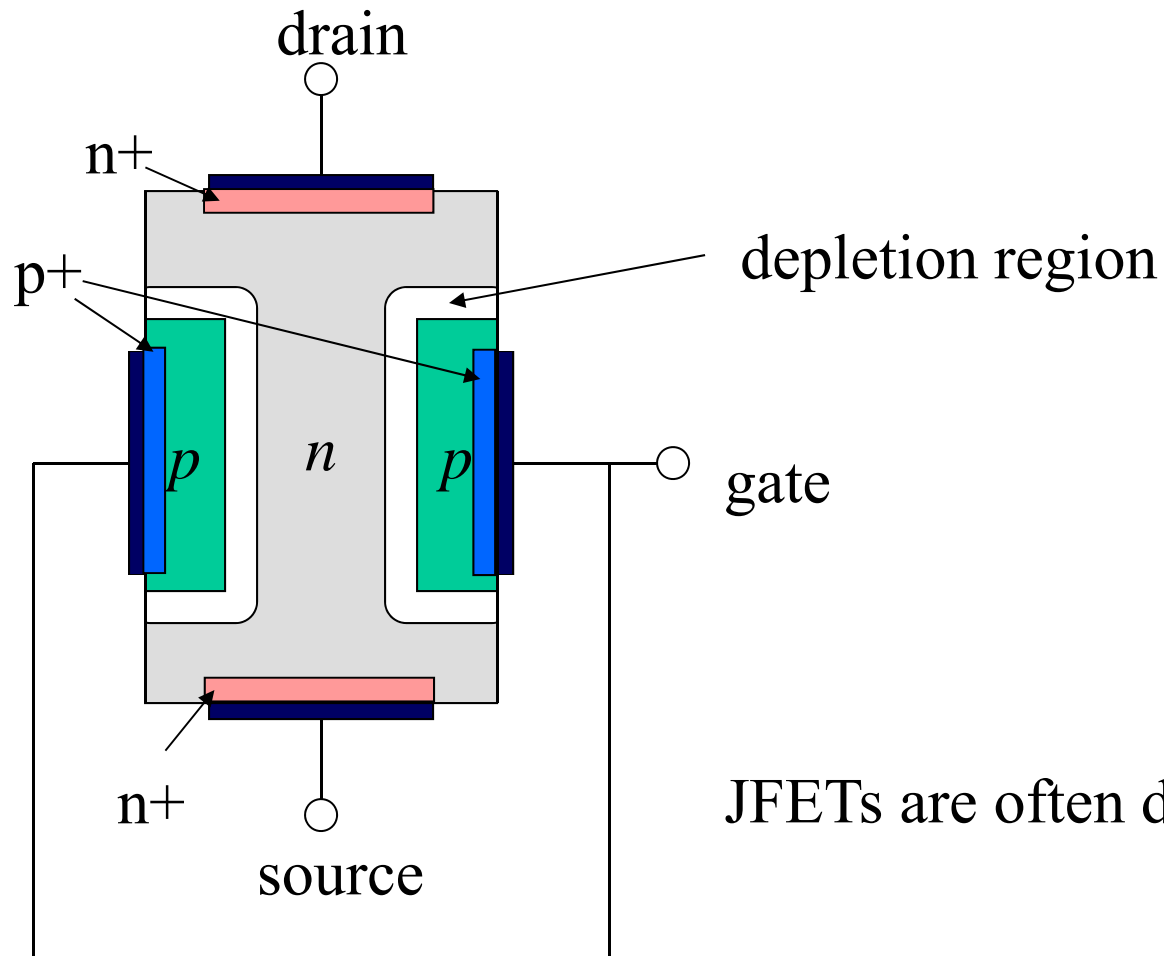
n-channel (power) JFET



Power SiC JFET



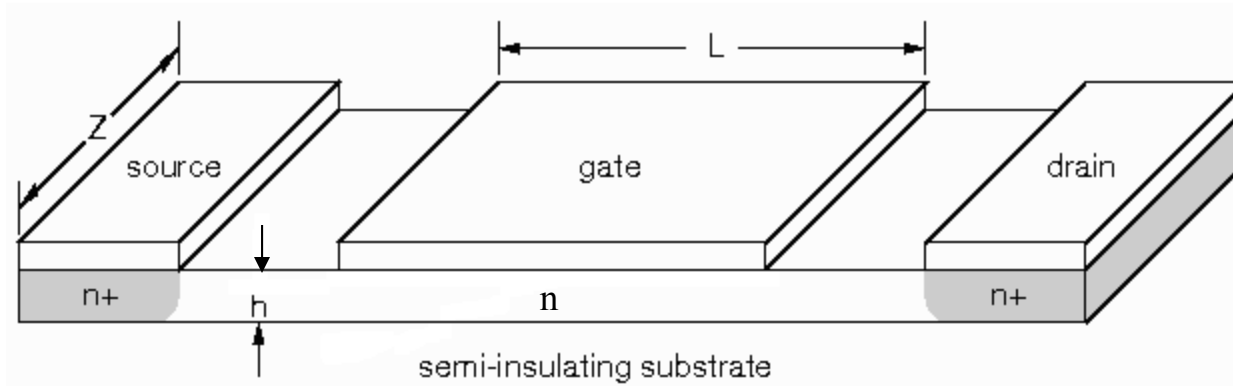
n-channel JFET



JFETs are often discrete devices

MESFET

Metal-Semiconductor Field Effect Transistors

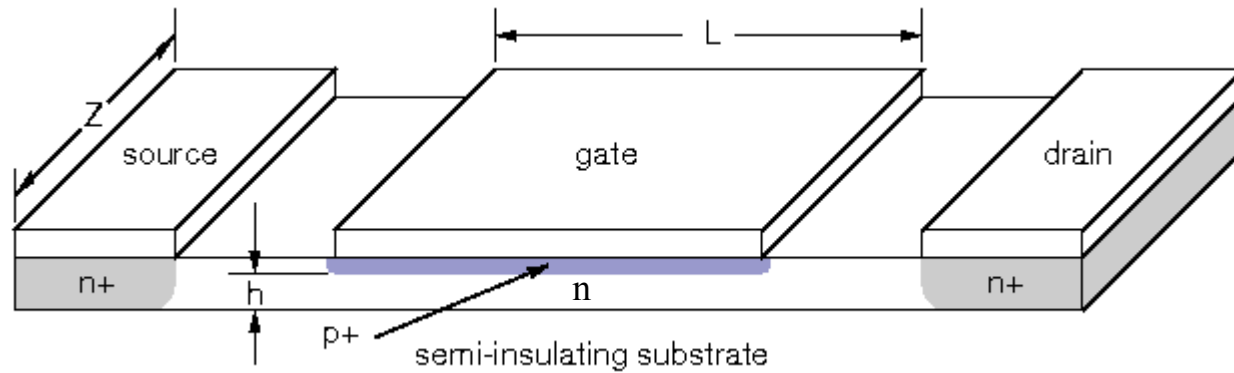


Depletion layer created by Schottky barrier

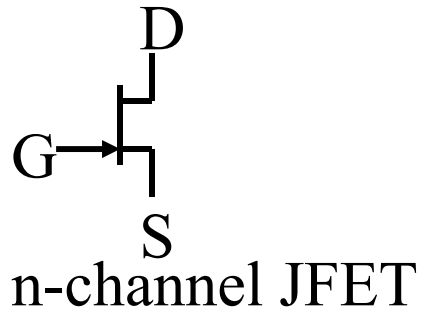
$$x_n = \sqrt{\frac{2\epsilon(V_{bi} - V)}{eN_D}}$$

Fast transistors can be realized in n-channel GaAs, however GaAs has a low hole mobility making p-channel devices slower.

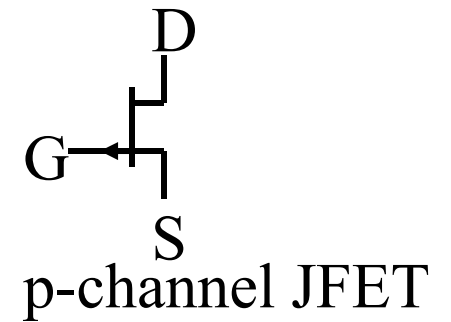
JFET



n-channel JFET



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



Pinch-off at $h = x_n$

At Pinch-off,
$$V = V_{bi} - \frac{eN_D h^2}{2\epsilon}$$

JFET

The drain is the side of the transistor that gets pinched off.

