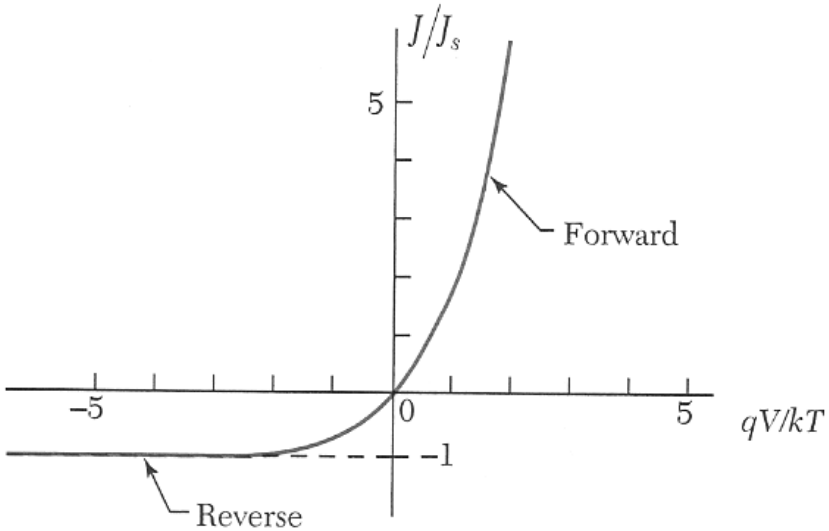
8. Schottky contacts / JFETs

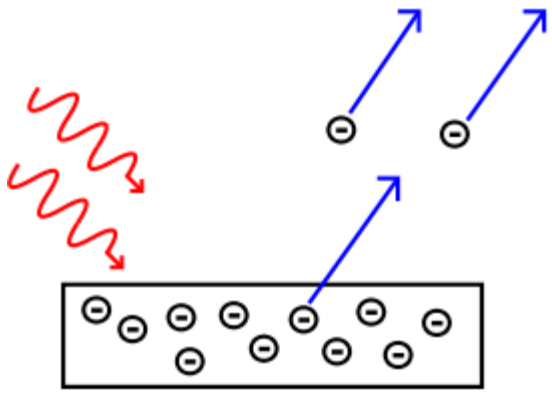
Nov. 21, 2018

metal - semiconductor contacts

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

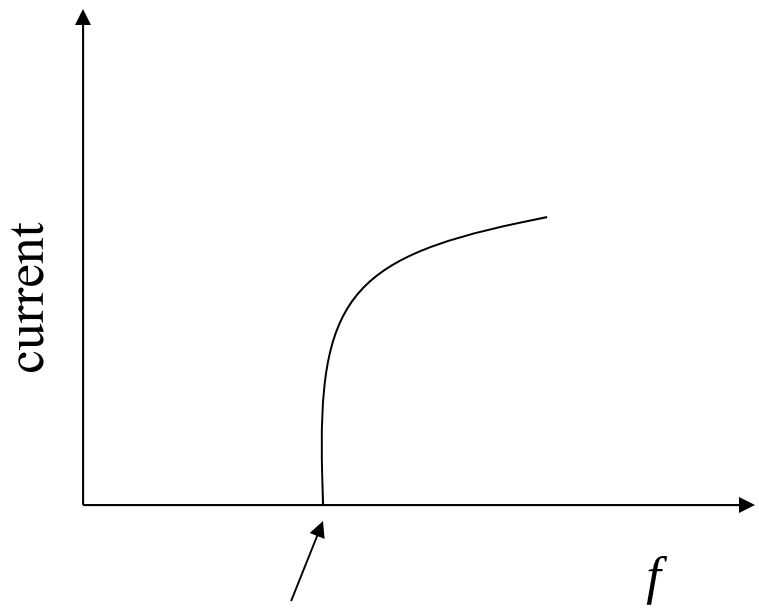


Photoelectric effect



$hf_0 = e\phi$ at threshold

workfunction



threshold frequency f_0

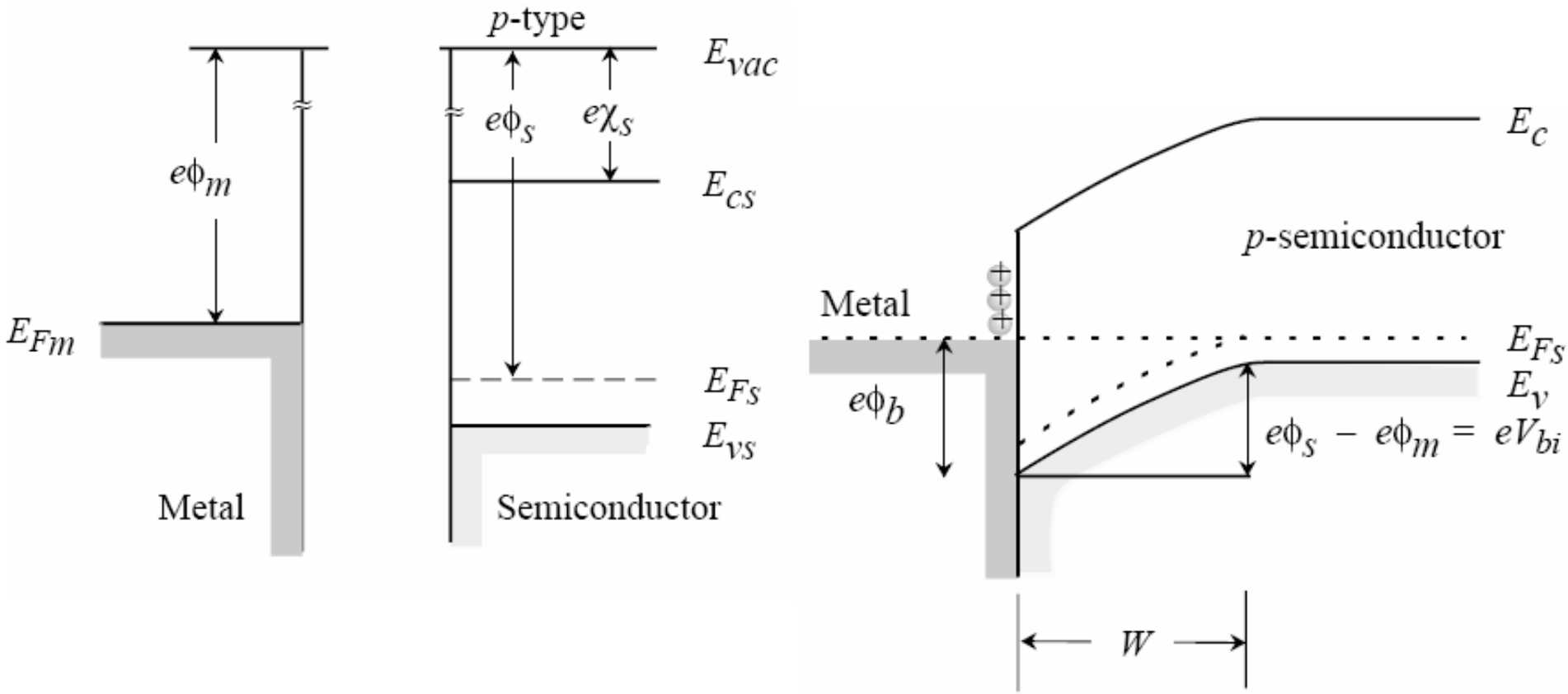
Work functions of some metals

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

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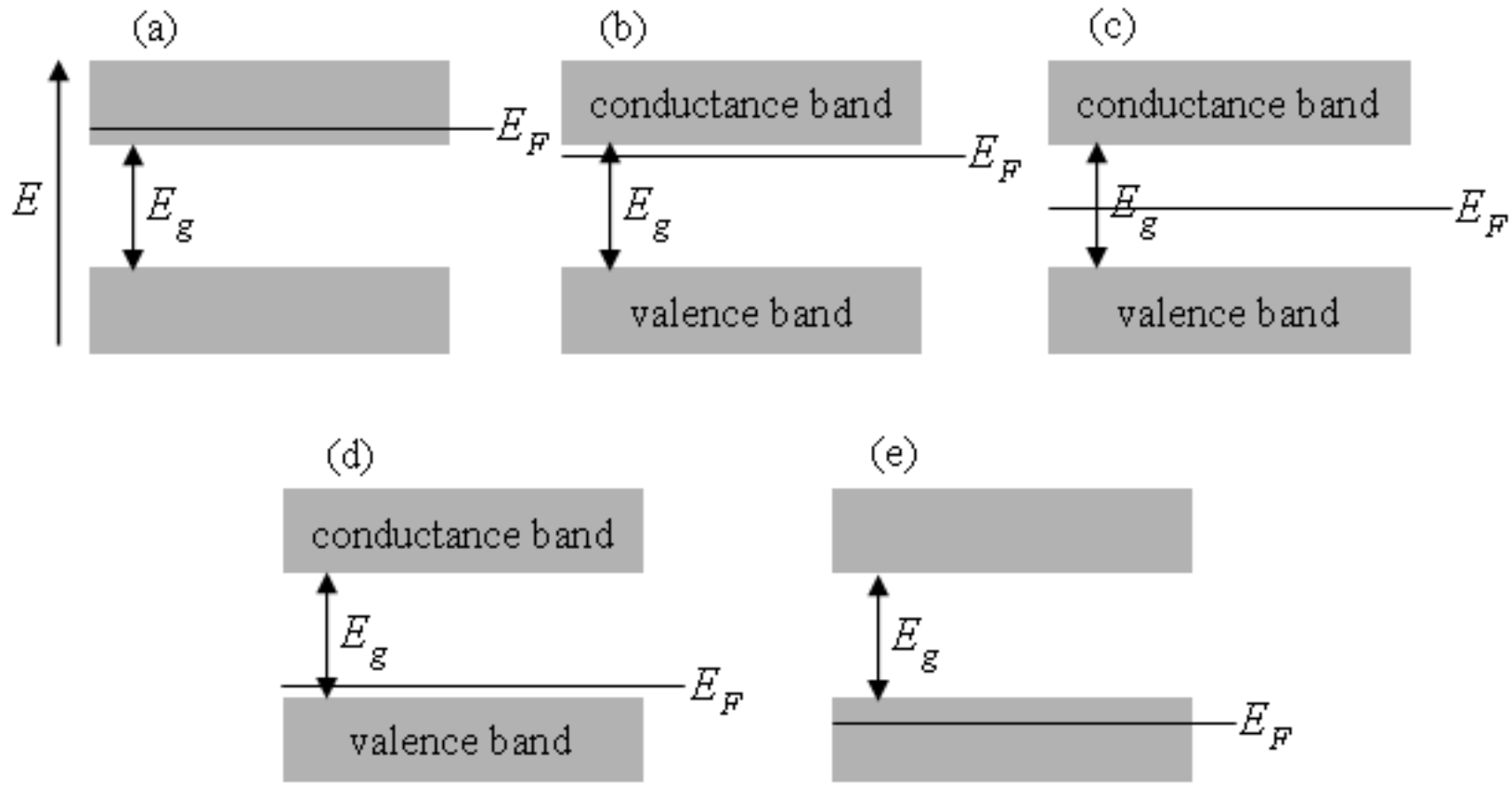
Ti, titanium	4.33
W, tungsten	4.55

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

Singh

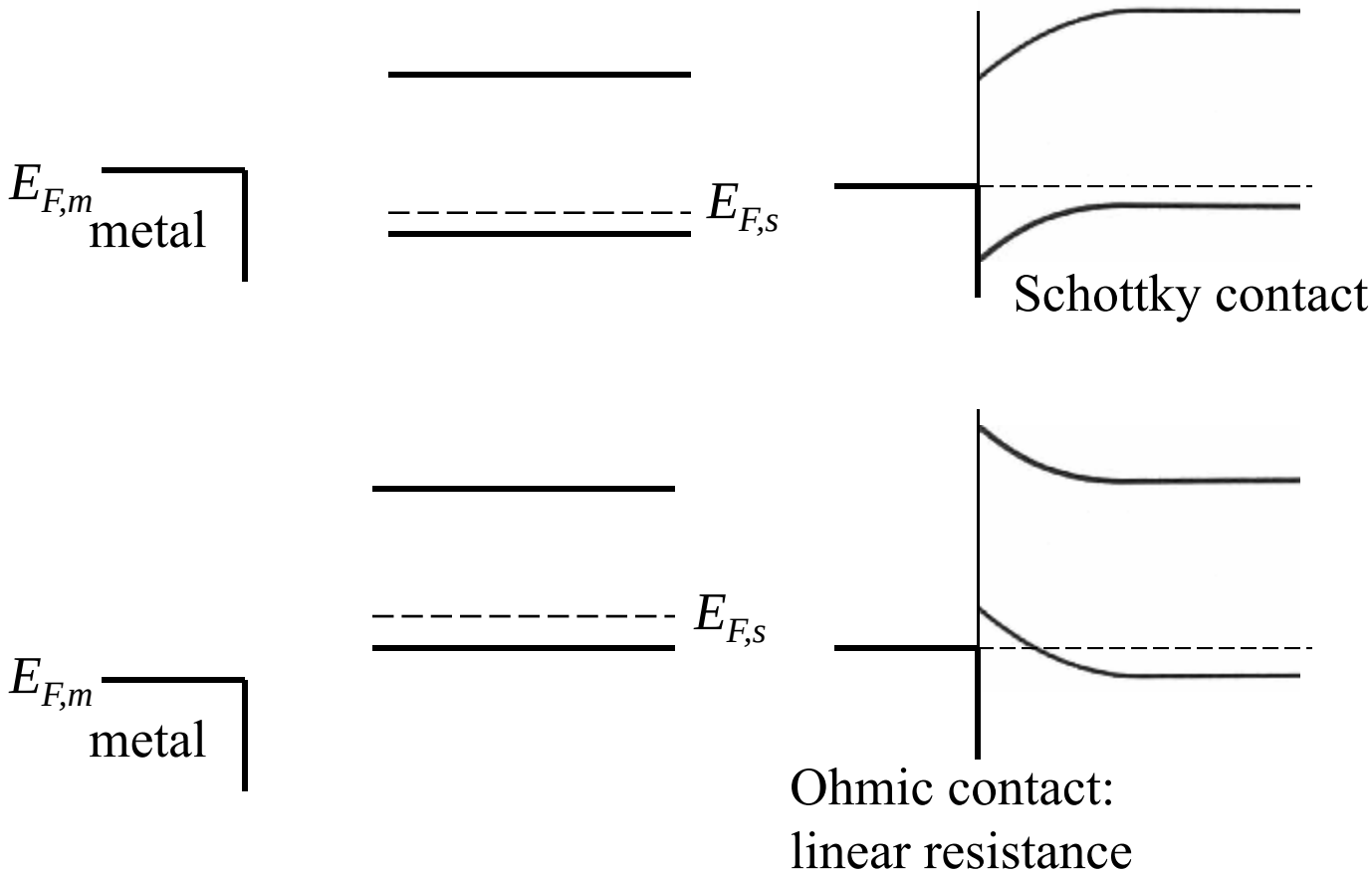


(a) A metal with a small workfunction. (b) An n-type semiconductor. (c) An insulator. (d) A p-type semiconductor. (e) A metal with a large workfunction.

p-type

Walter Schottky

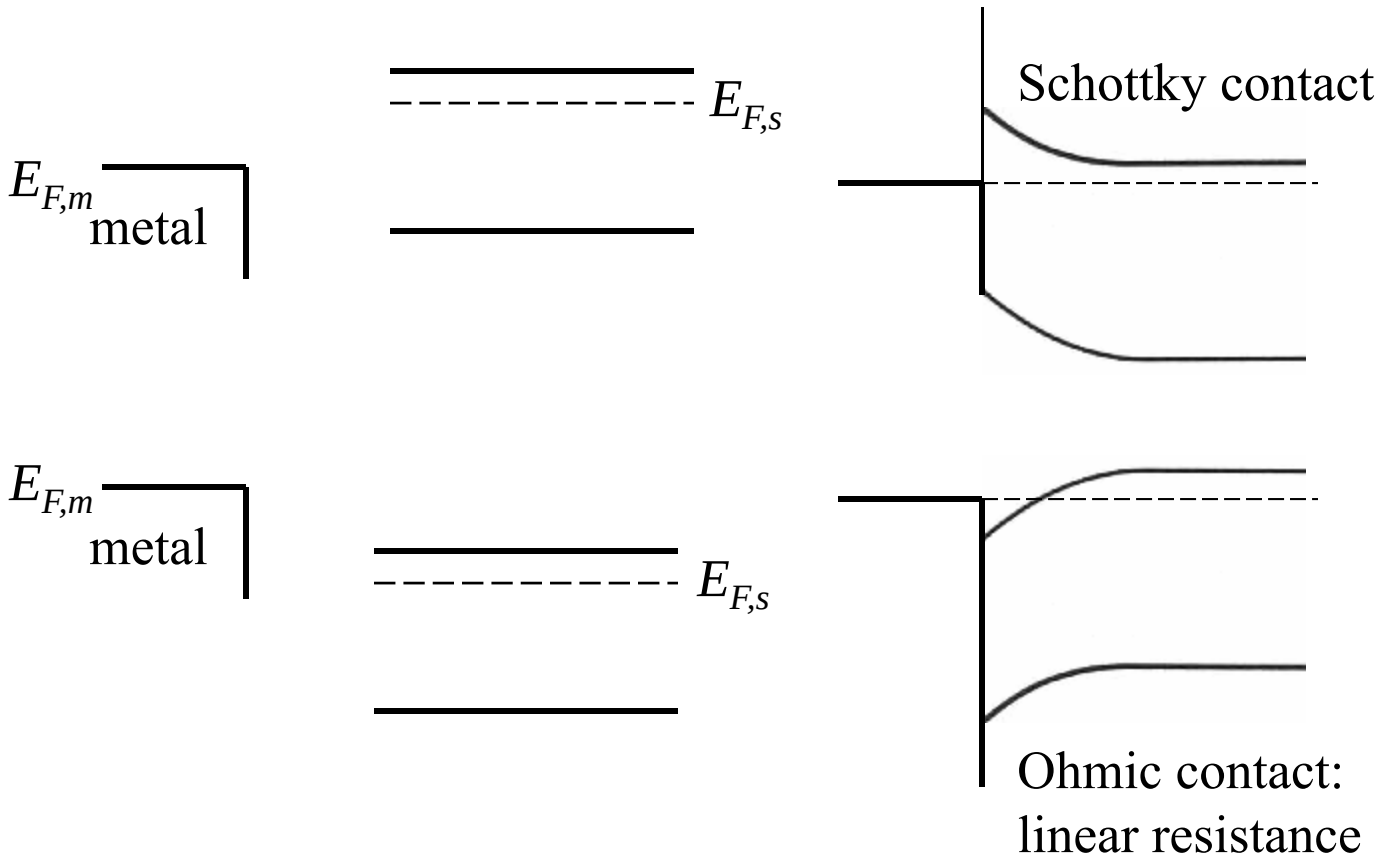
Schottky contact / ohmic contact



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

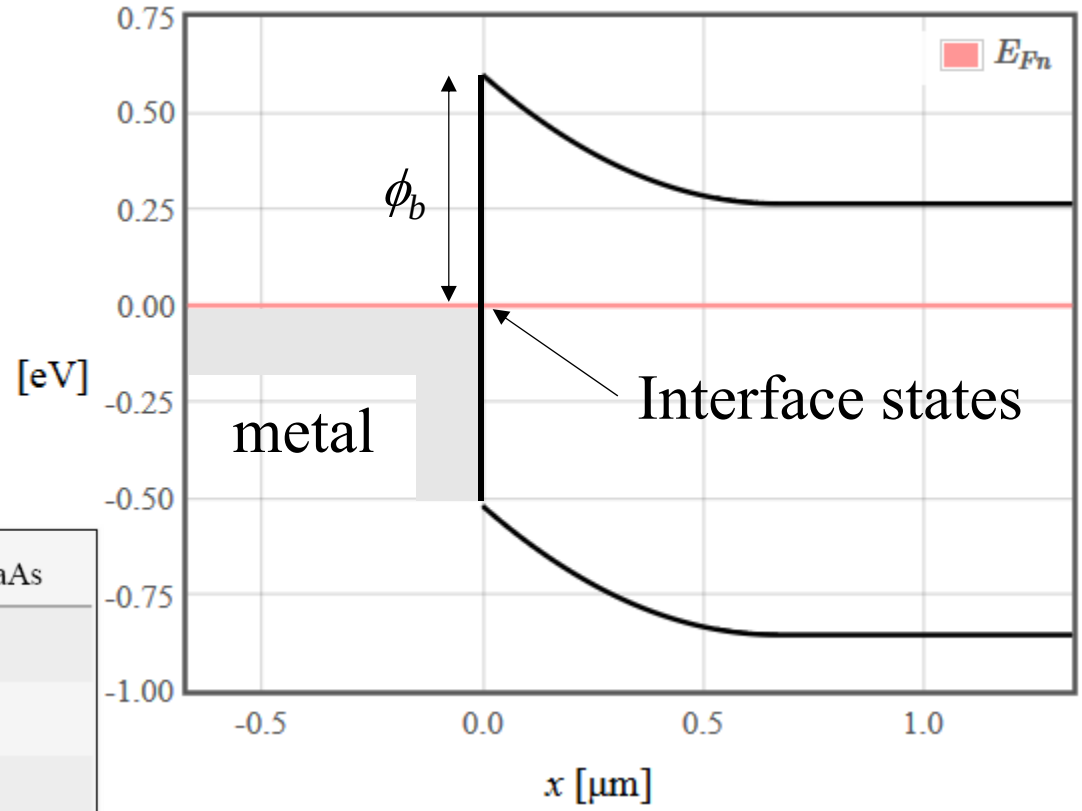
n-type

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	*n* Si	*p* Si	*n* 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	

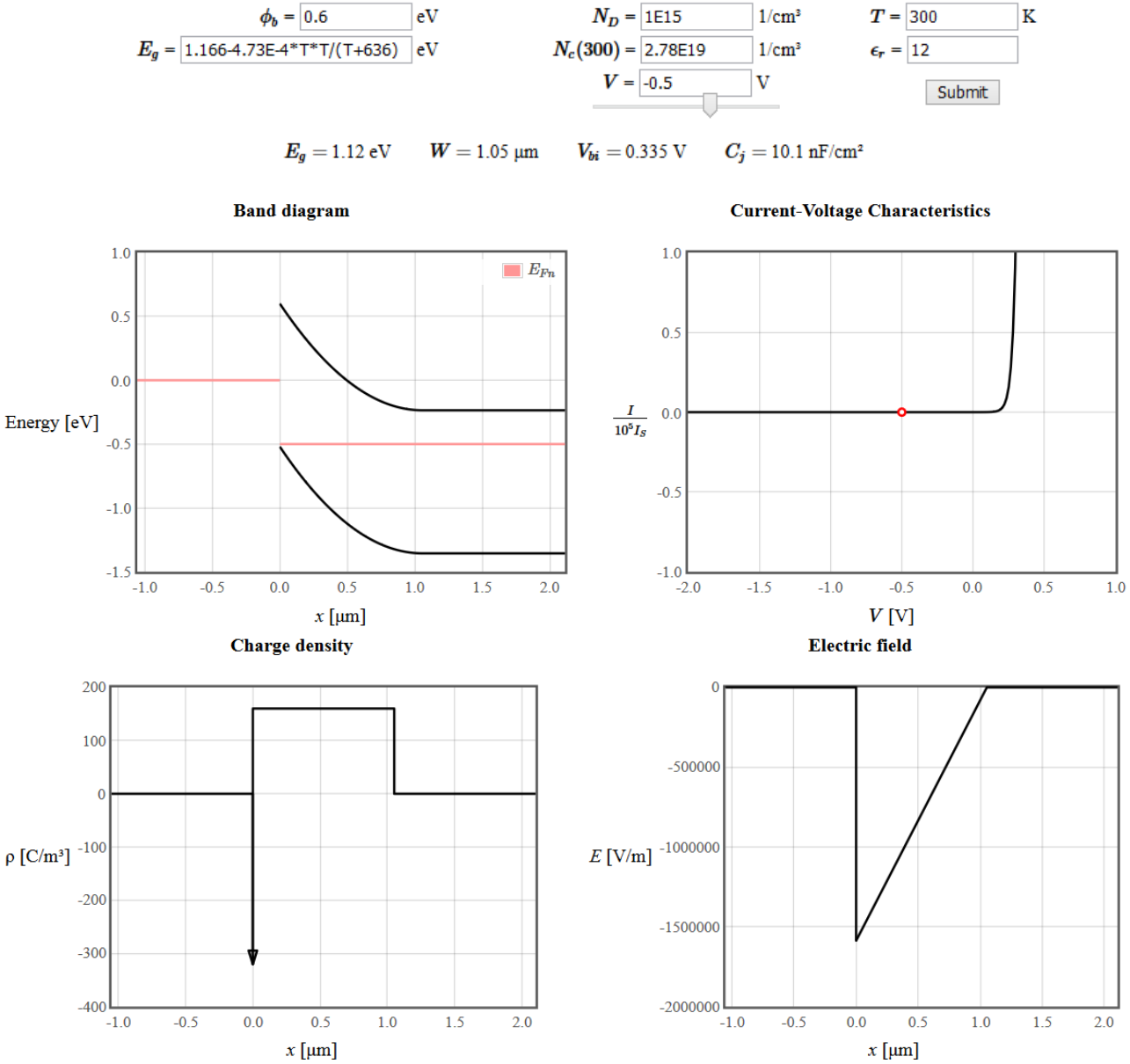
substance: silicon (Si)
property: Schottky barrier heights

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

http://www.springermaterials.com/navigation/#n_240905_Silicon+%2528Si%2529

Schottky barrier



$$E = \frac{eN_D}{\varepsilon_r \varepsilon_0}\left(x - x_n\right)$$

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

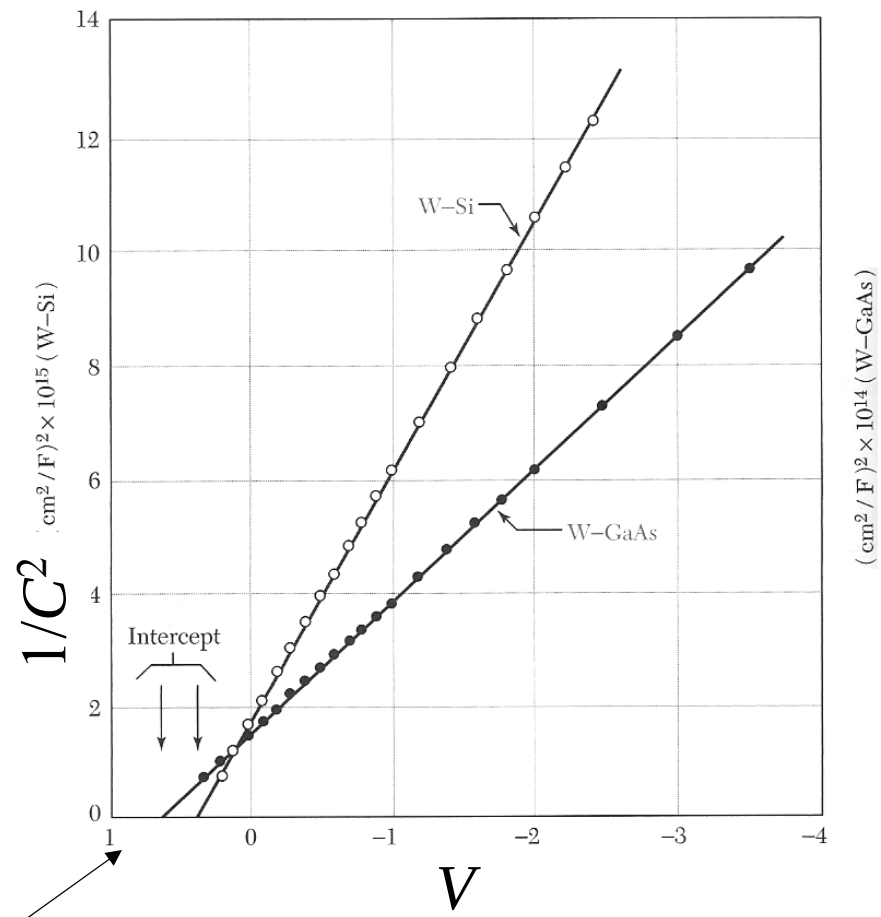
$$V = \frac{-eN_D}{\varepsilon}\left(\frac{x^2}{2} - xx_n\right)$$

CV measurements

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

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

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



GaAs has larger E_g and V_{bi}

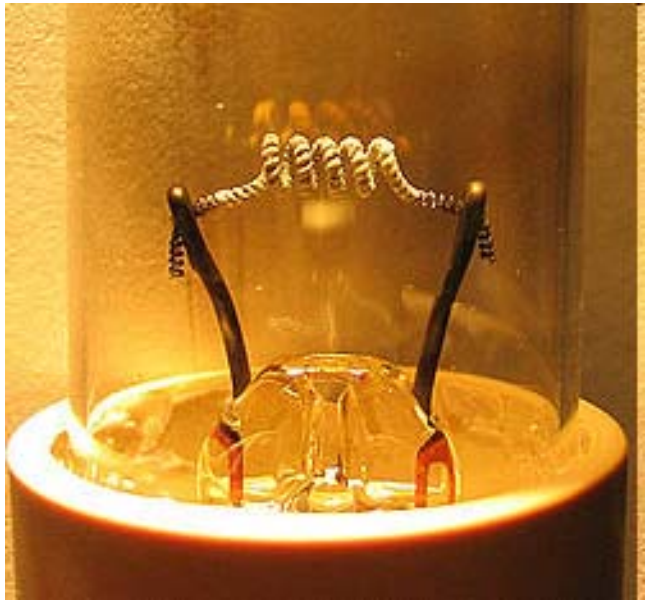
$$eV_{bi} = \phi_b - k_B T \ln\left(\frac{N_v(T)}{N_A}\right)$$

Thermionic emission

1901 Richardson

Owen Willans Richardson

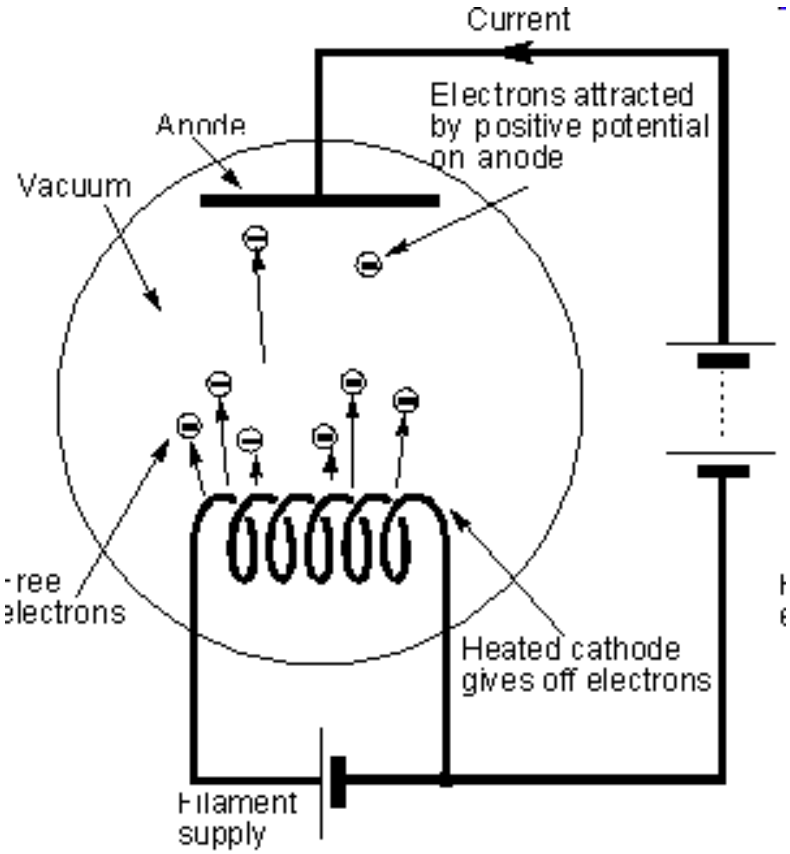
Current from a heated wire is:



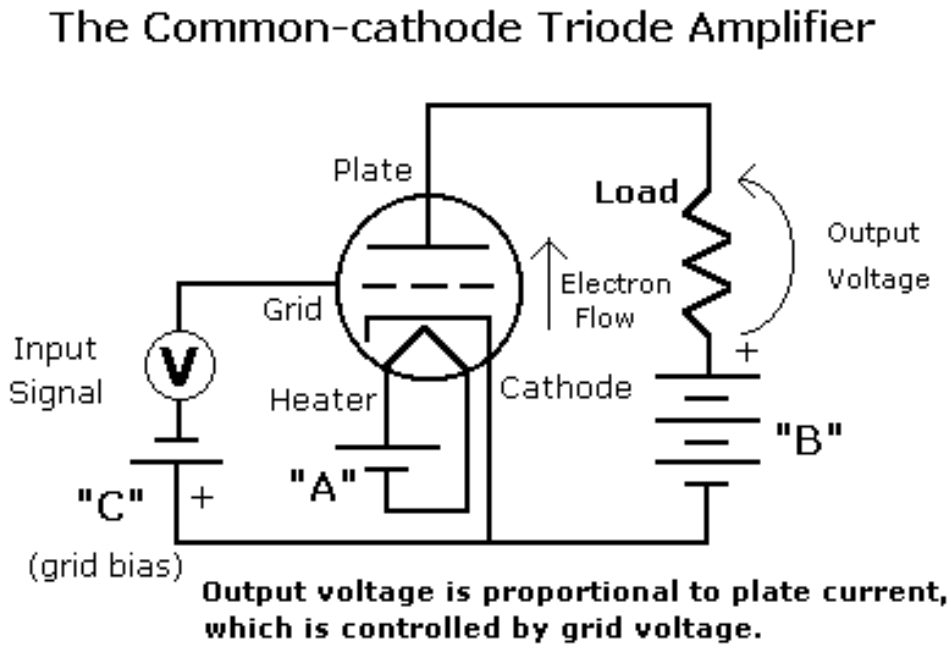
$$J = A_R T^2 \exp\left(-\frac{e\phi}{k_B T}\right)$$

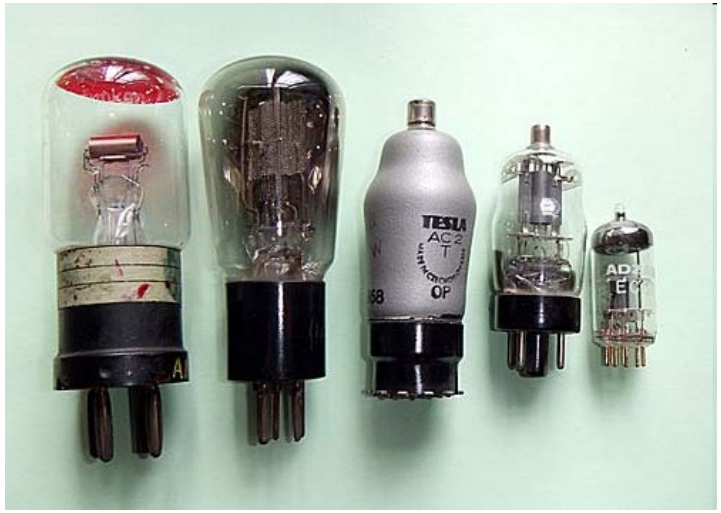
Some electrons have a thermal energy that exceeds the work function and escape from the wire.

Vacuum diodes

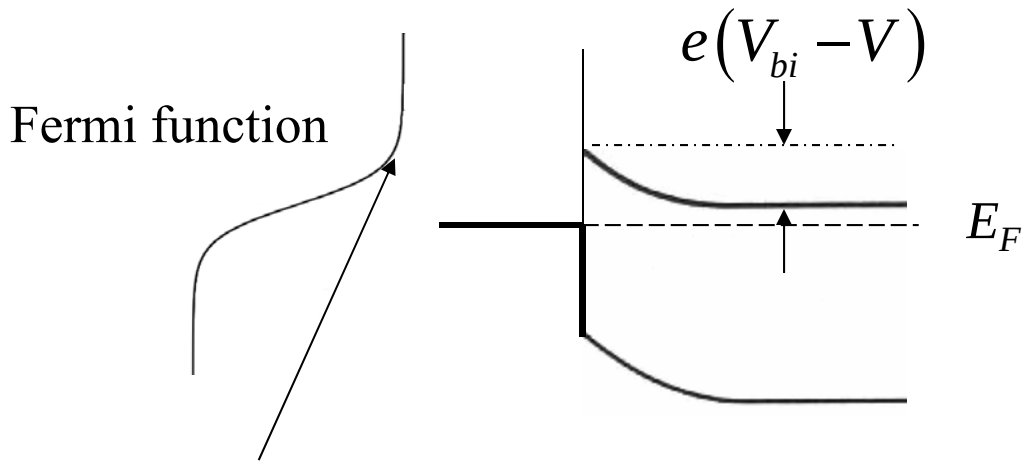


diode





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 $\propto \exp\left(\frac{-E}{k_B T}\right)$

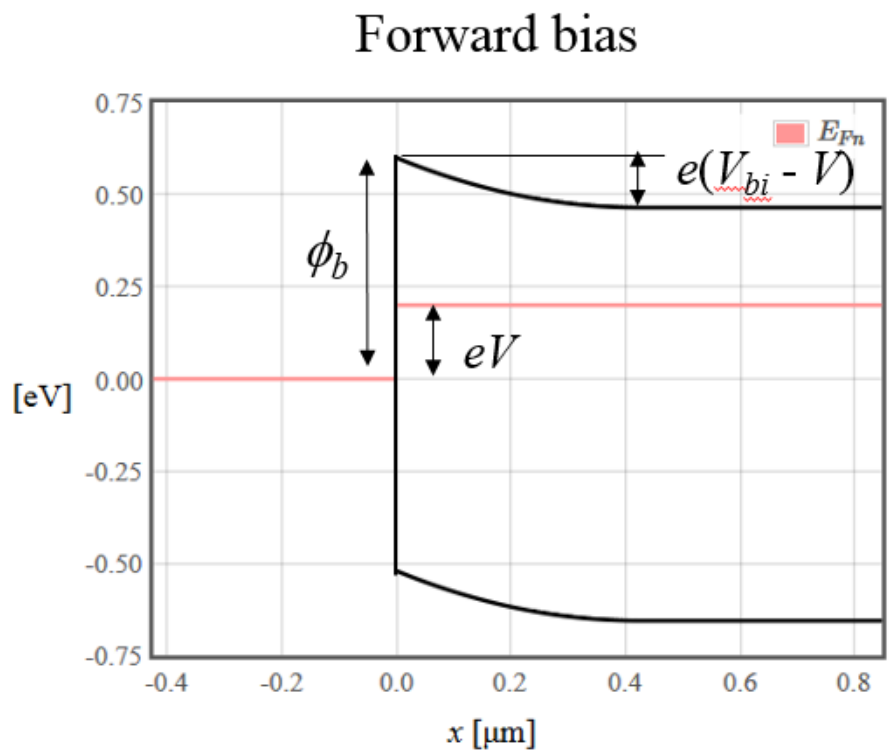
Thermionic emission

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

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

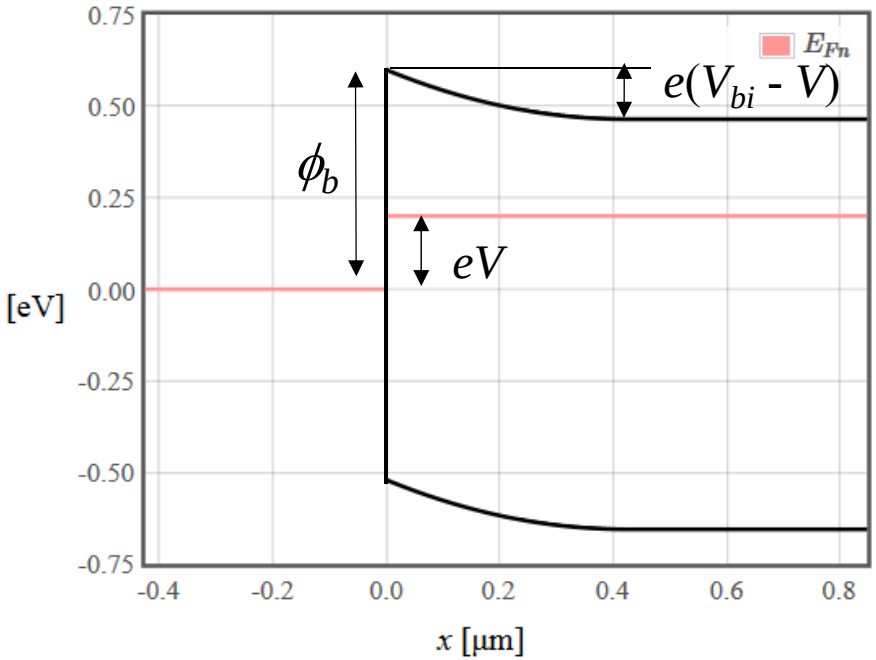
$$I_{ms} = I_{sm}(V = 0)$$

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



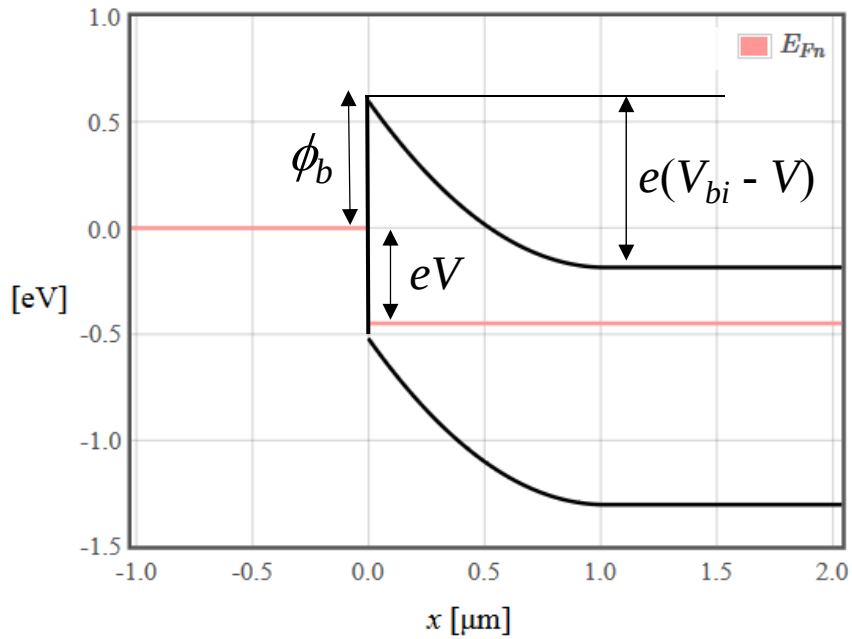
Schottky barrier

Forward bias



$I_{sm} \sim \exp(eV/k_BT)$
I_{ms} constant

Reverse bias

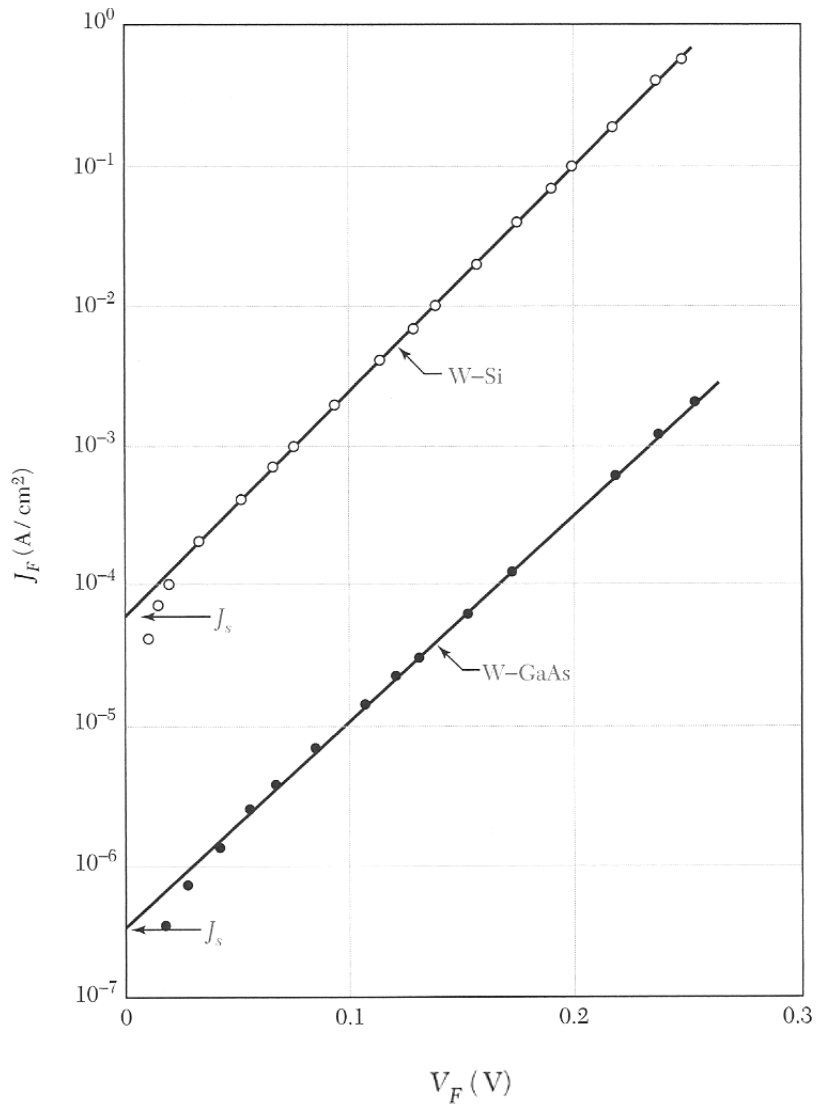


$I_{sm} \sim 0$
I_{ms} constant

Thermionic emission

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

Nonideality factor = 1

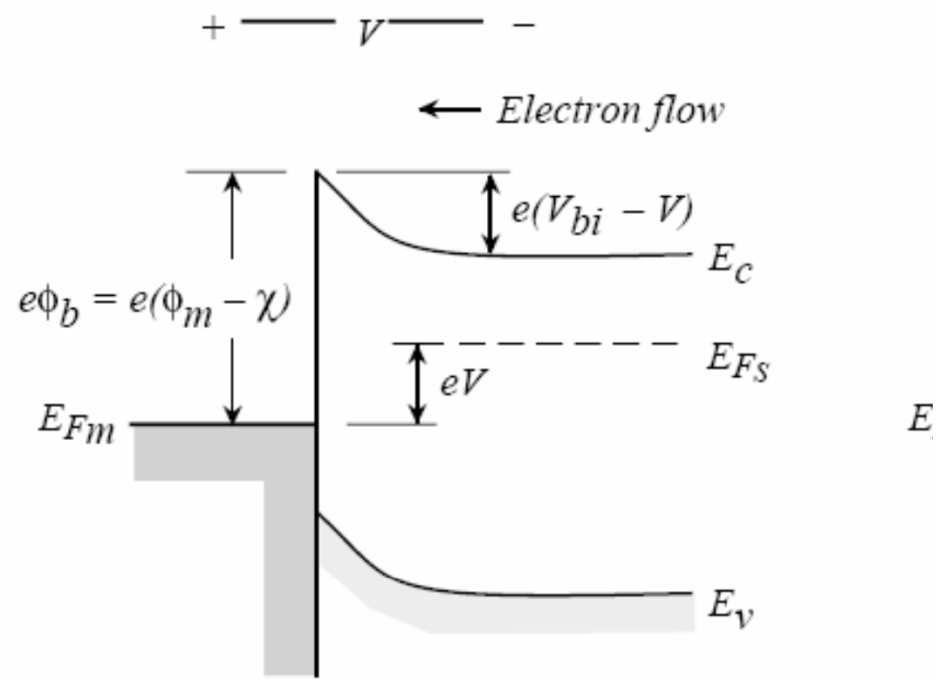


Thermionic emission

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

A = Area
A_R^* = Richardson constant

n-Si $A_R^* = 110$ A K^{-2}cm^{-2}
p-Si $A_R^* = 32$ A K^{-2}cm^{-2}
n-GaAs $A_R^* = 8$ A K^{-2}cm^{-2}
p-GaAs $A_R^* = 74$ A K^{-2}cm^{-2}



Forward bias

(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.

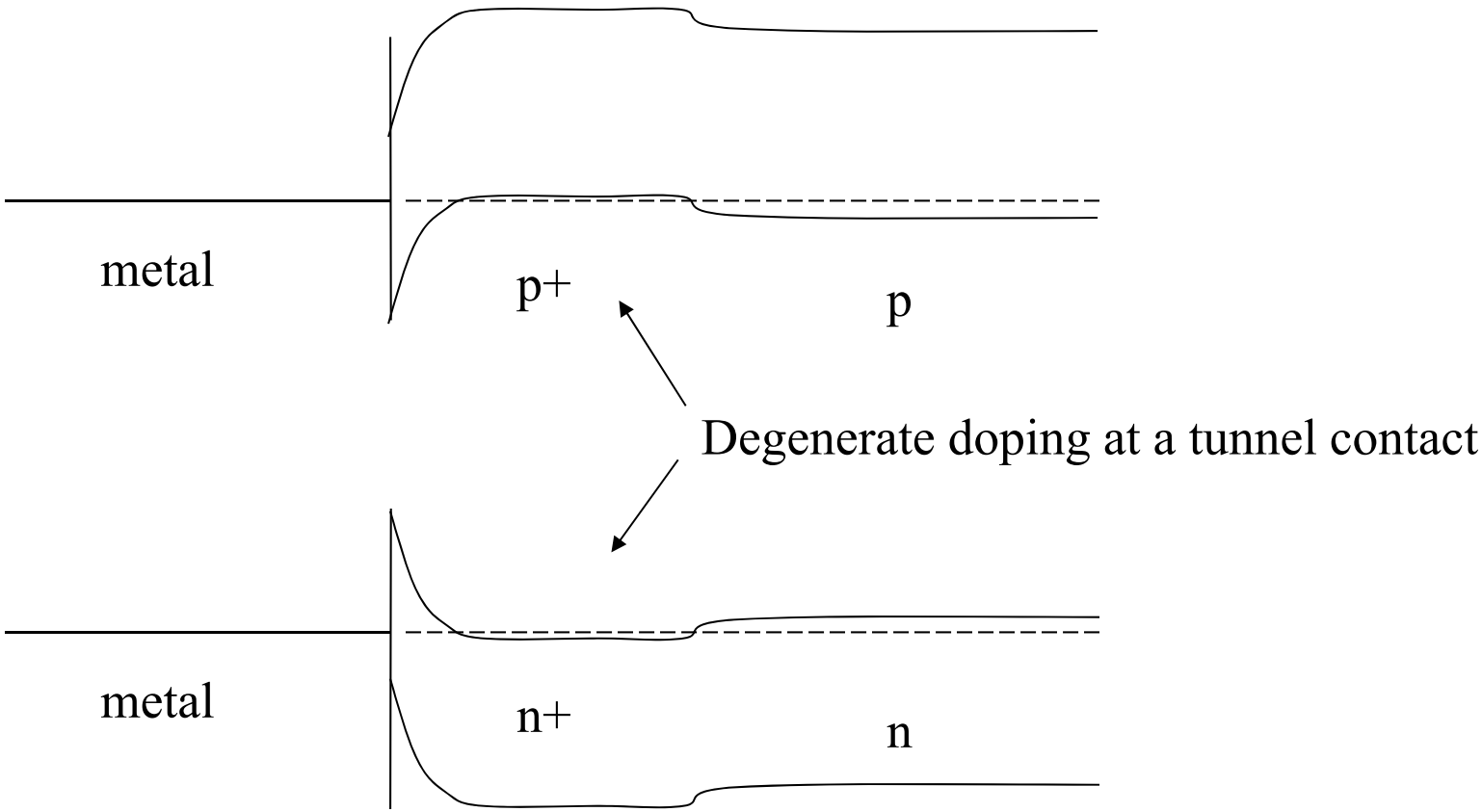
Used as rf mixers.

Low turn on voltage - high reverse bias current

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

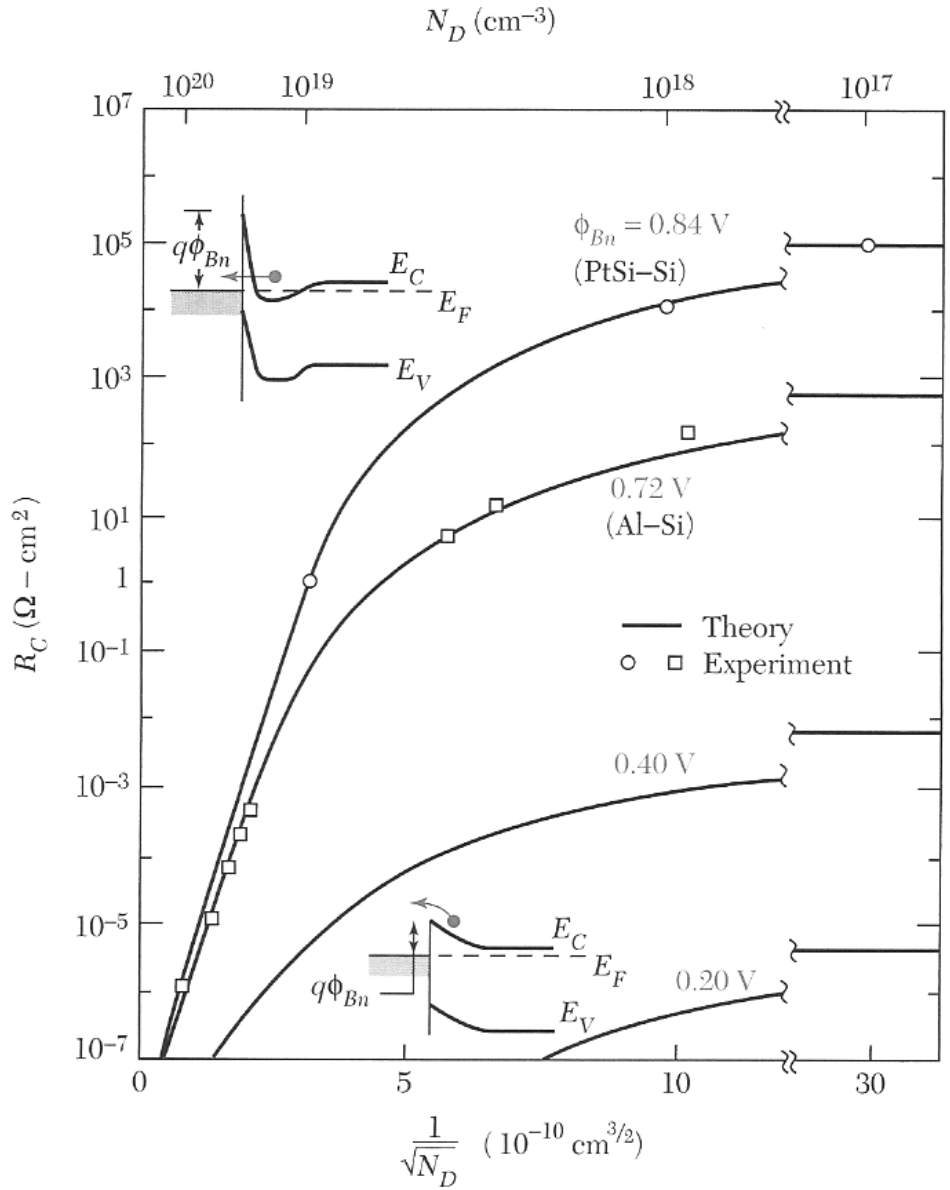
Tunnel contacts

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



Tunnel contacts have a linear resistance.

Contacts


N_D (cm^{-3})
10^{20}
10^{19}
10^{18}
10^{17}
10^7
10^5
10^3
10^1
1
10^{-1}
10^{-3}
10^{-5}
10^{-7}
R_C (Ω – cm^2)
$q\phi_{Bn}$
E_C
E_F
E_V
ϕ_{Bn} = 0.84 V
(PtSi–Si)
0.72 V
(Al–Si)
Theory
Experiment
0.40 V
0.20 V
0
5
10
30
$\frac{1}{\sqrt{N_D}}$ (10^{-10} cm$^{3/2}$)

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.

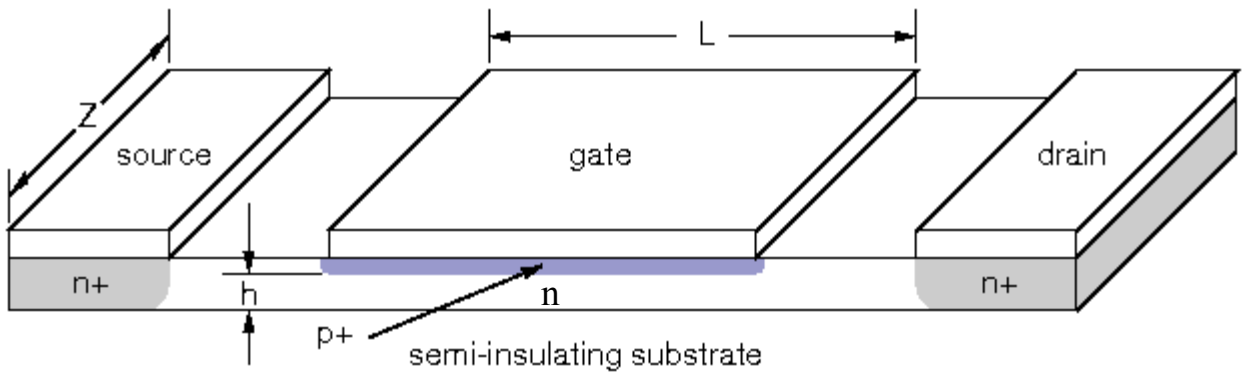
In a forward biased pn-junction, diffusion dominates.

In a tunnel contact, tunneling dominates.

In a Schottky diode, thermionic emission dominates.

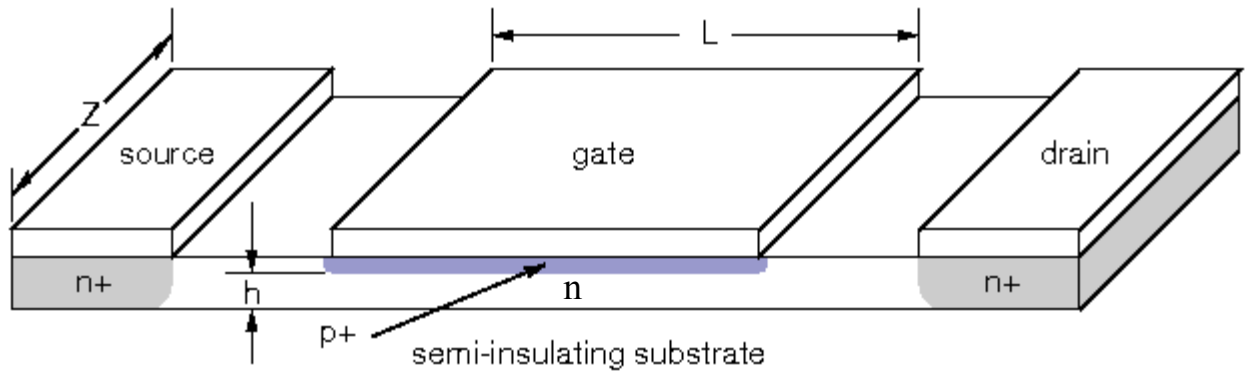
JFETs - MESFETs - MODFETs

Junction Field Effect Transistors (JFET)
Metal-Semiconductor Field Effect Transistors (MESFET)
Modulation Doped Field Effect Transistors (MODFET)



JFET

n-channel JFET



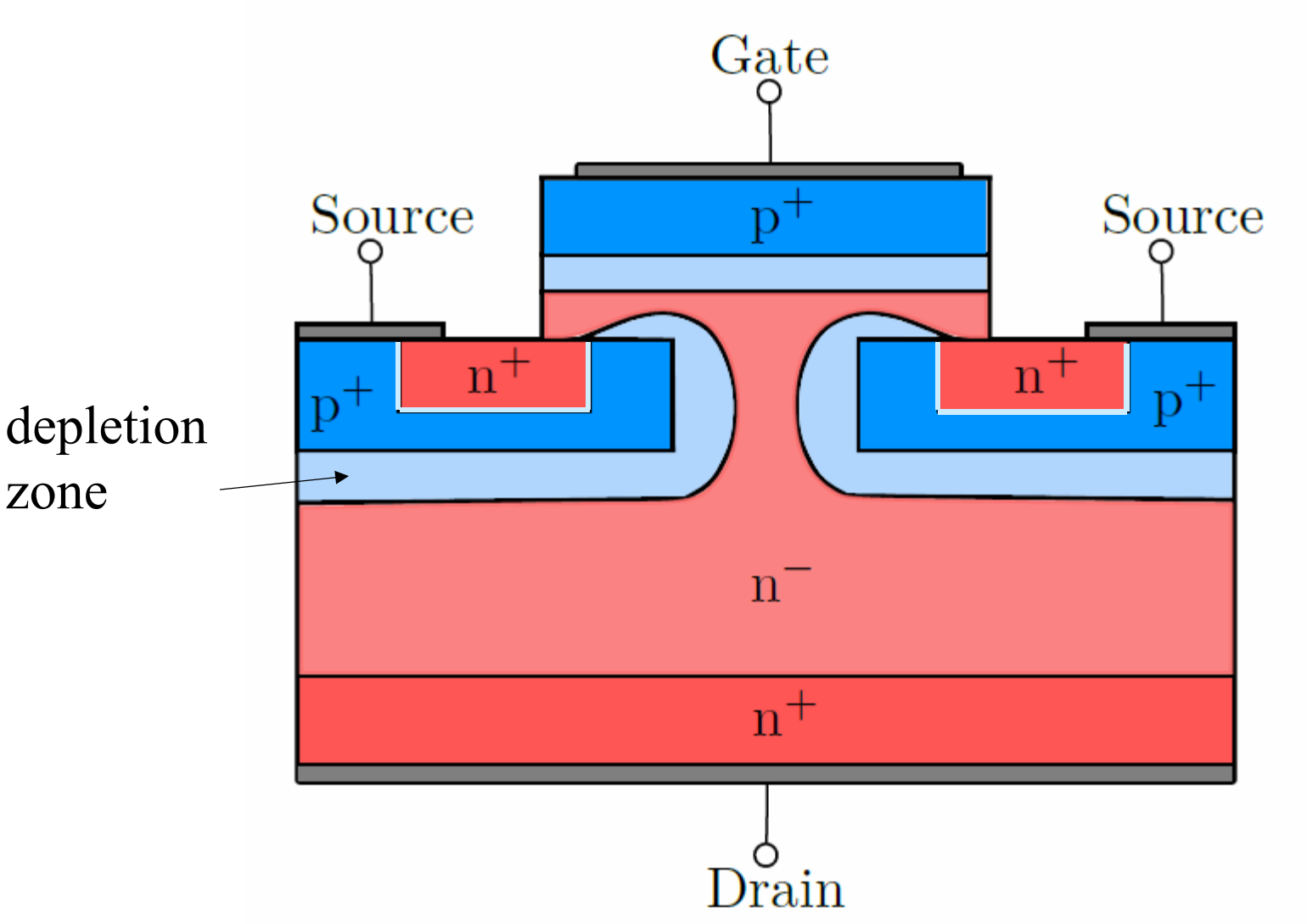
For $N_A >> N_D$

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

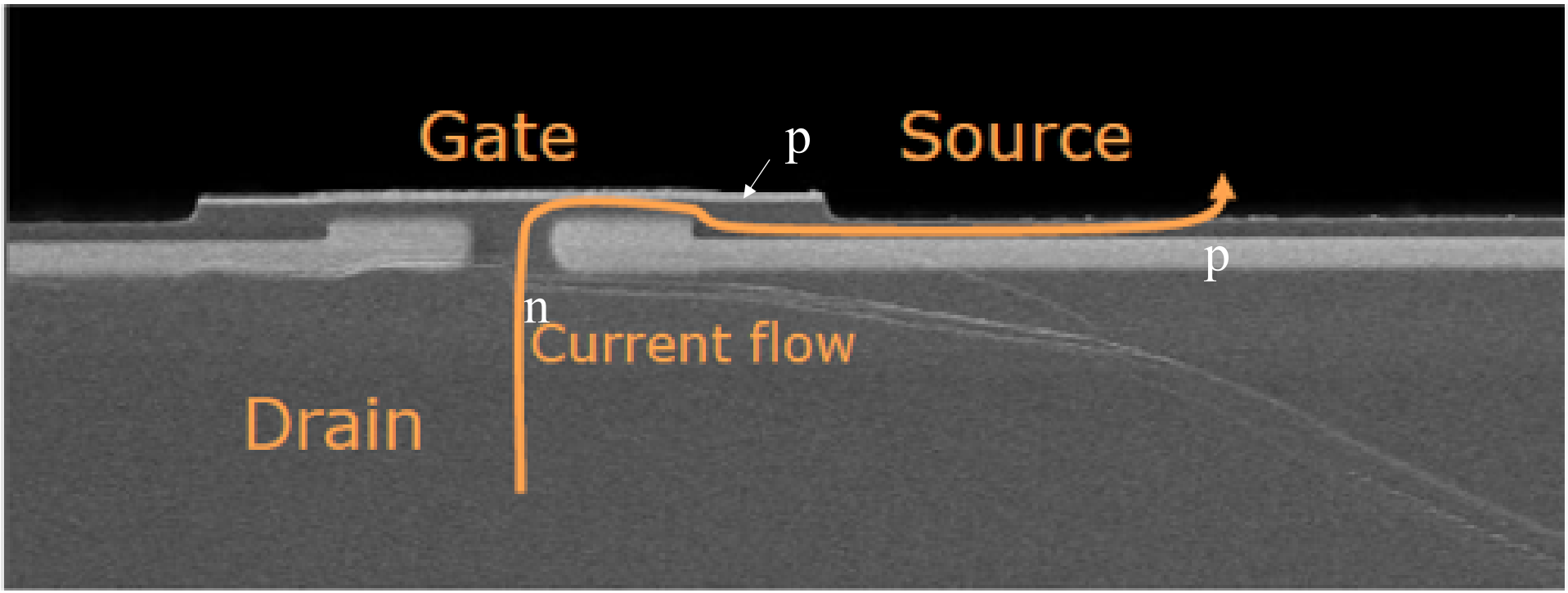
Depletion mode $\quad h > x_n = \sqrt{\frac{2\varepsilon V_{bi}}{eN_D}}$ $\quad$ conducting at $V_g = 0$

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

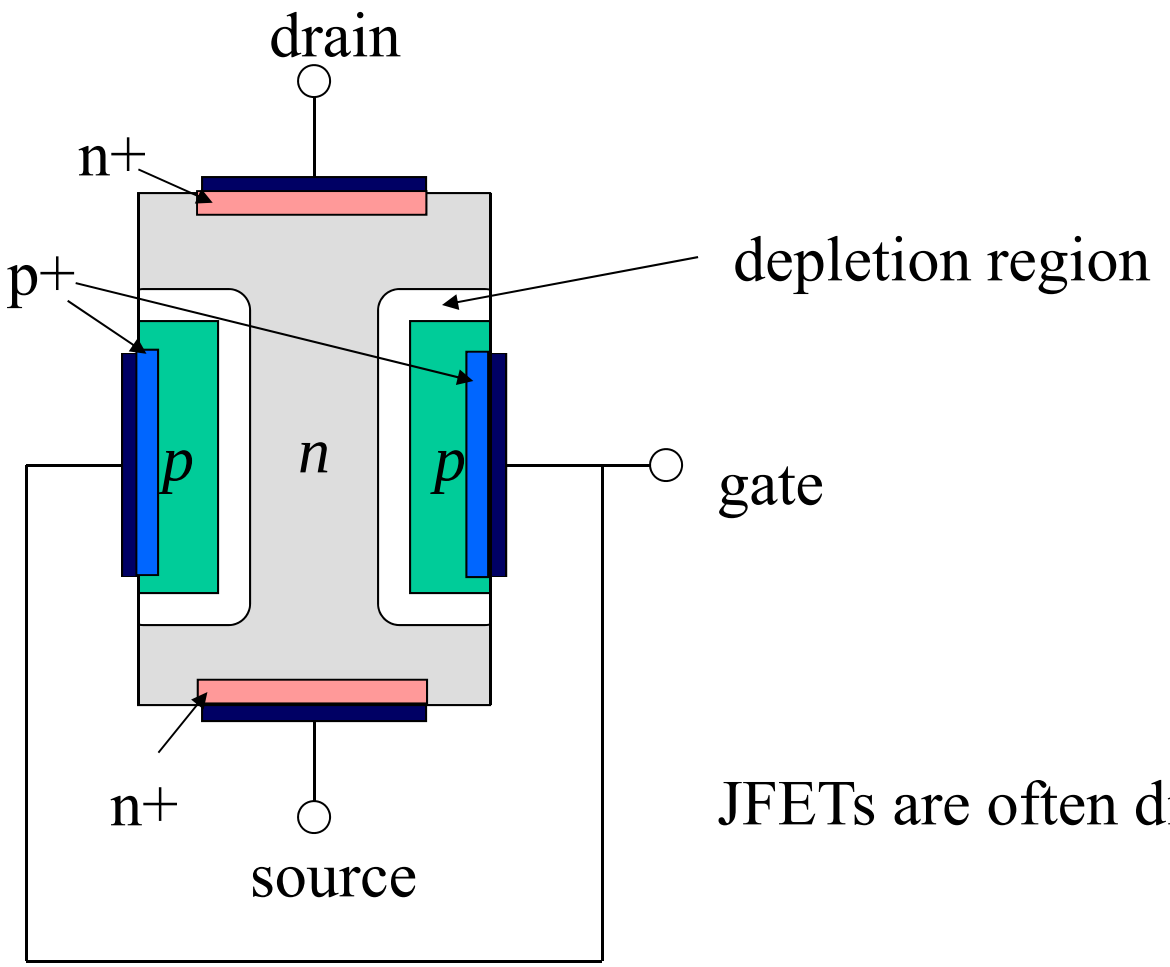
n-channel (power) JFET



Power SiC JFET



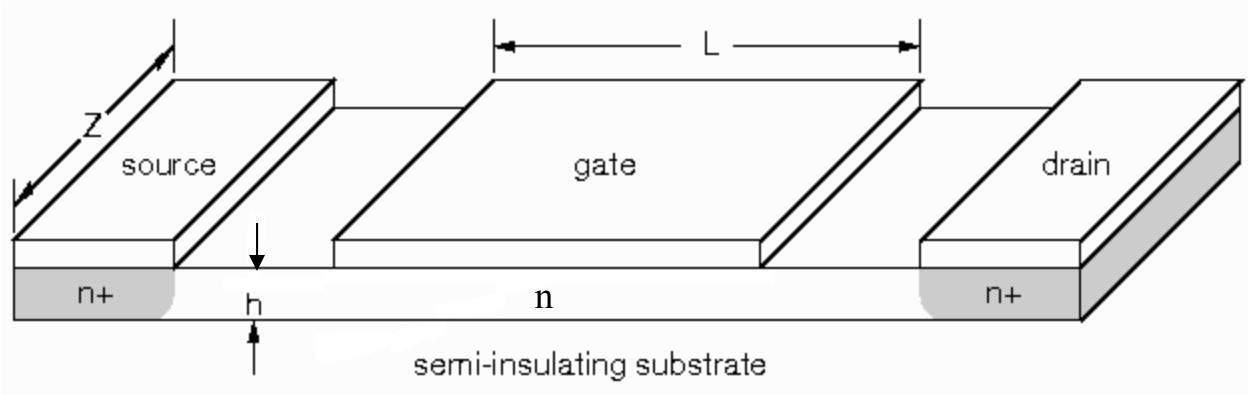
n-channel JFET



JFETs are often discrete devices

MESFET

Metal-Semiconductor Field Effect Transistors

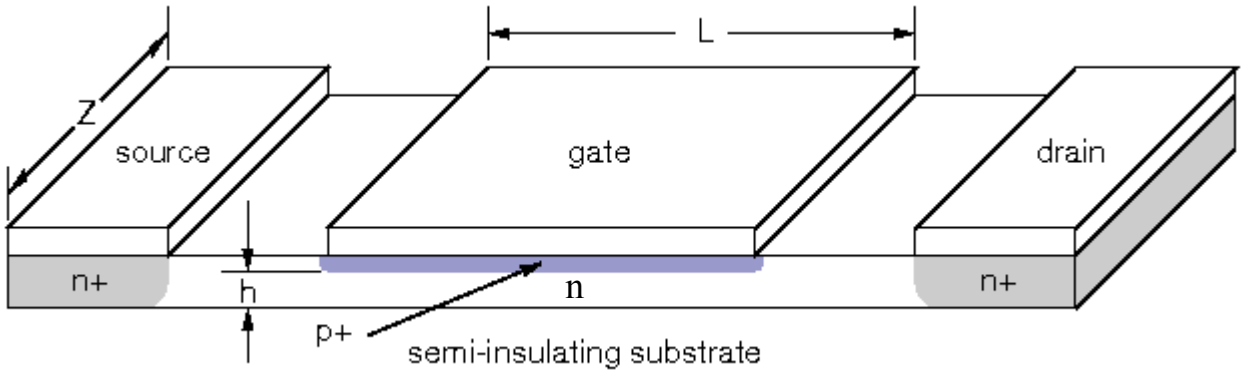


Depletion layer created by Schottky barrier

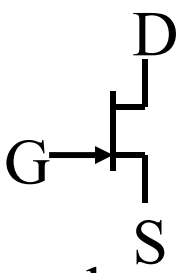
$$x_n = \sqrt{\frac{2\varepsilon(V_{bi} - V)}{eN_D}}$$

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

JFET

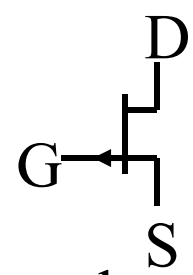


n-channel JFET



n-channel JFET

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



p-channel JFET

Pinch-off at $h = x_n$

$$V_p = \frac{eN_D h^2}{2\varepsilon}$$

V_p = pinch-off voltage

At Pinch-off, $V = V_{bi} - V_p$.