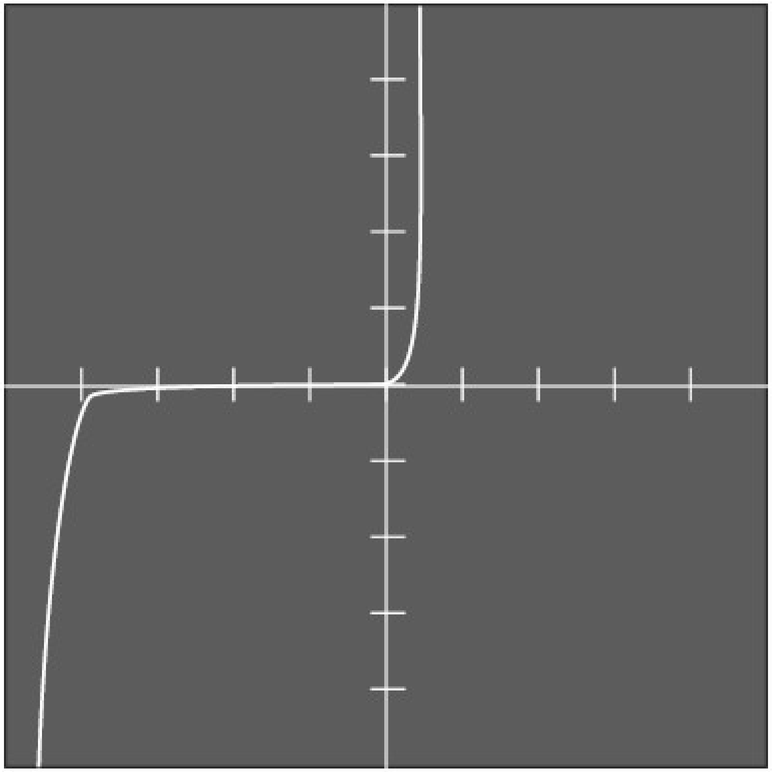
Avalanche breakdown

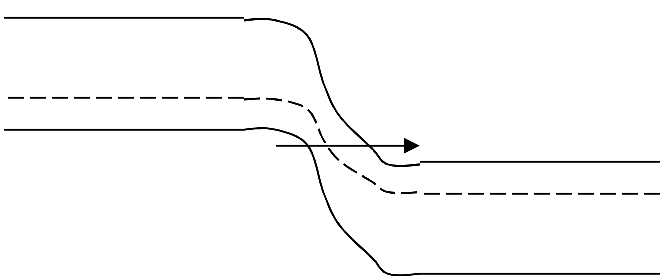
Impact ionization causes an avalanche of current

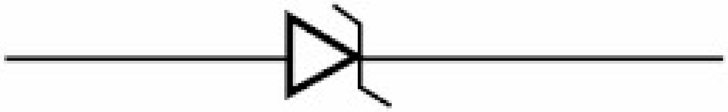
Occurs at low doping



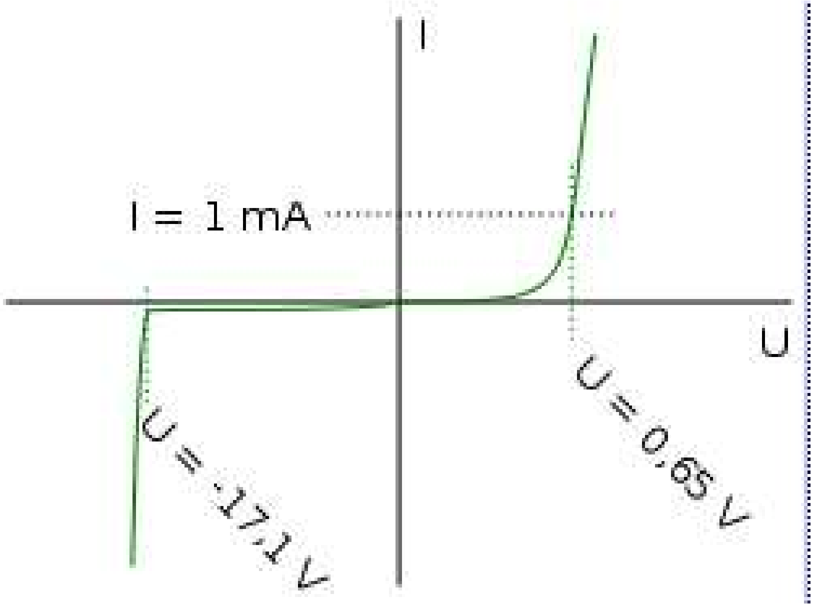
Vertical: 5 mA/div
Horizontal: 5 V/div

Zener tunneling





(Zener diode)

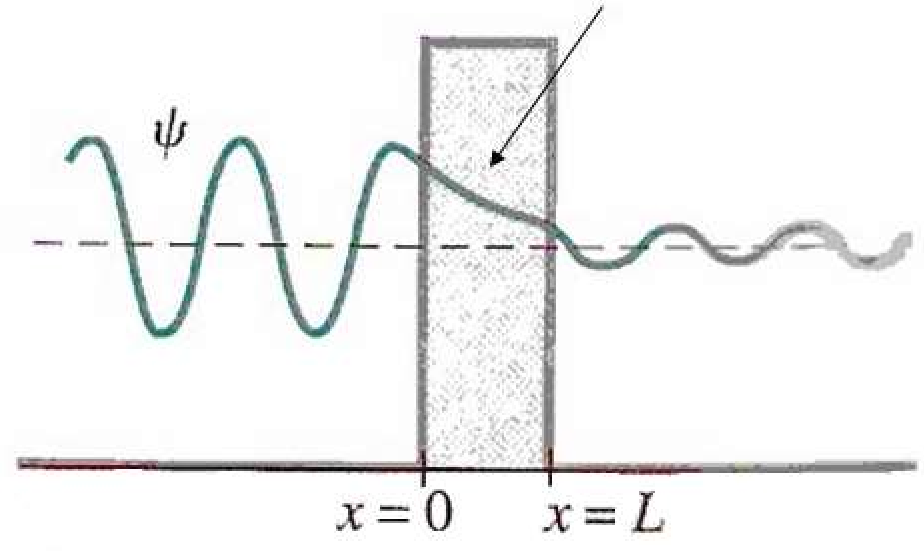


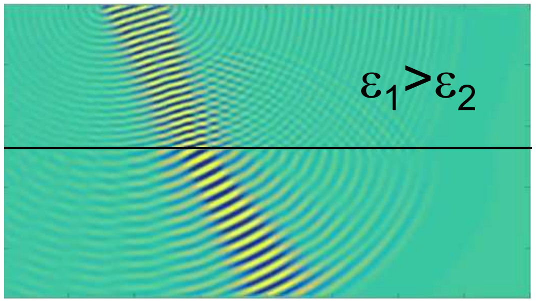
Electrons tunnel from valence band to conduction band

Occurs at high doping

Tunneling

wave decays exponentially in the classically forbidden region





Tunneling is a wave phenomena. Tunneling and total internal reflection are used in a beam splitter.

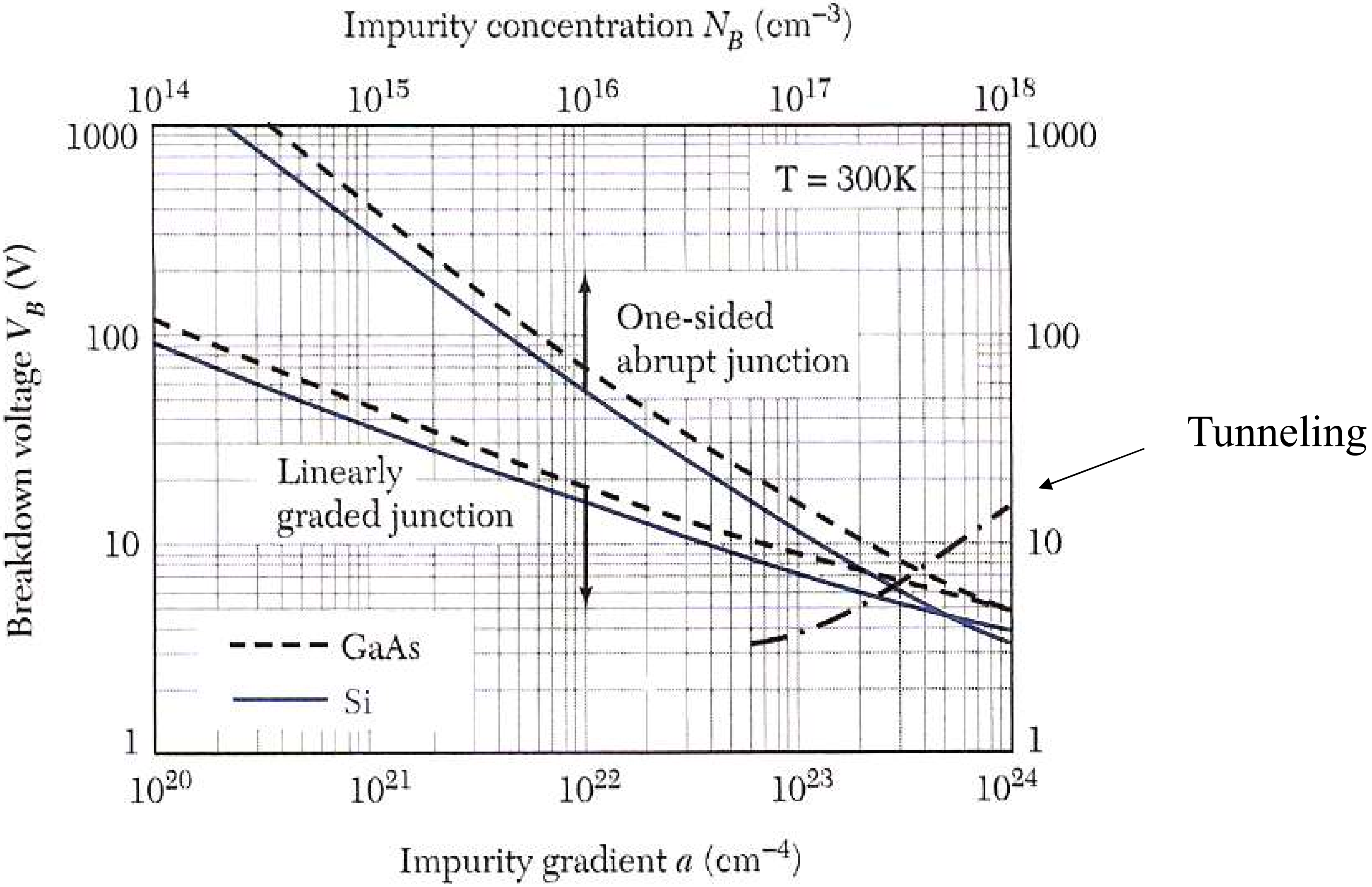
http://lampx.tugraz.at/~hadley/physikm/apps/snell/snell.en.php

Zener tunneling

Breakdown voltage is typically much lower than the breakdown voltage of an avalanche diode and can be tuned by adjusting the width of the depletion layer.

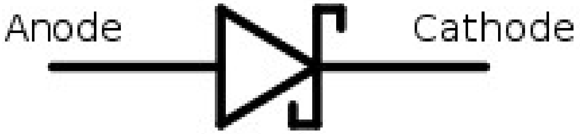
Used to provide a reference voltage.

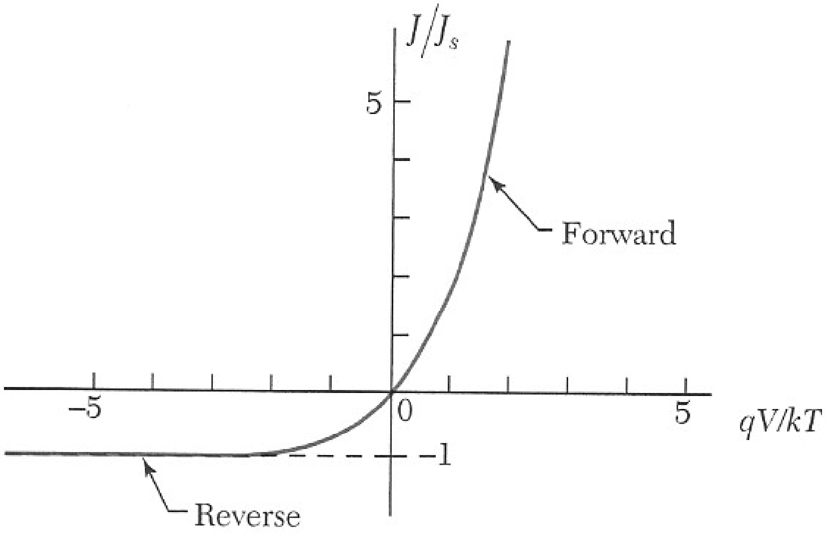
Avalanche breakdown



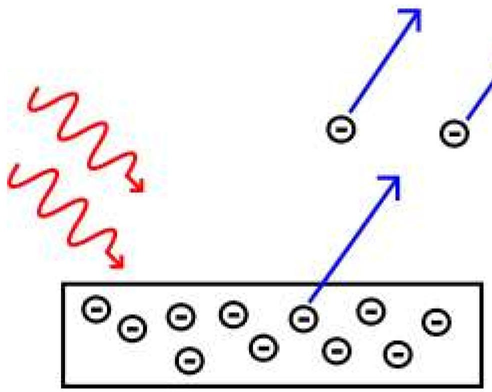
metal - semiconductor contacts

Photoelectric effect
Workfunction
Electron affinity
Interface states
Schottky barriers
Schottky diodes
Ohmic contacts
Thermionic emission
Tunnel contacts



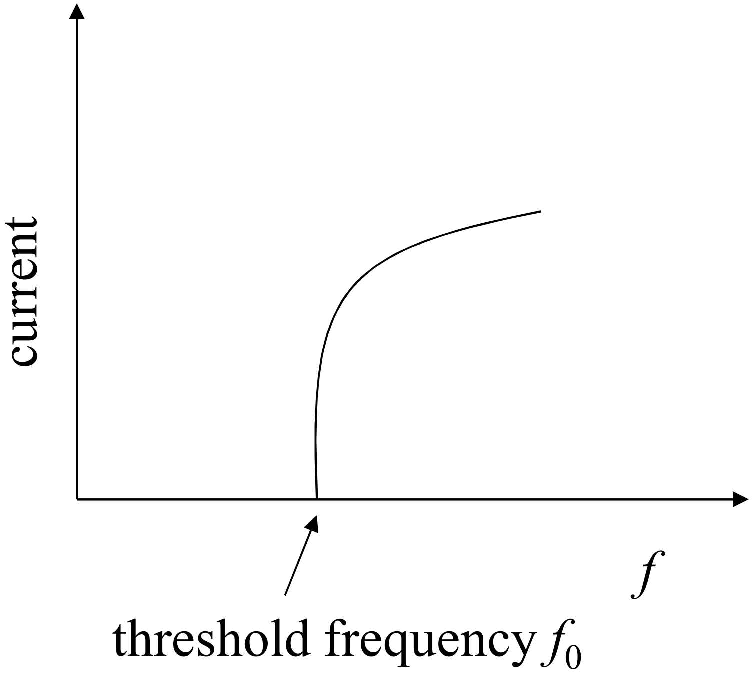


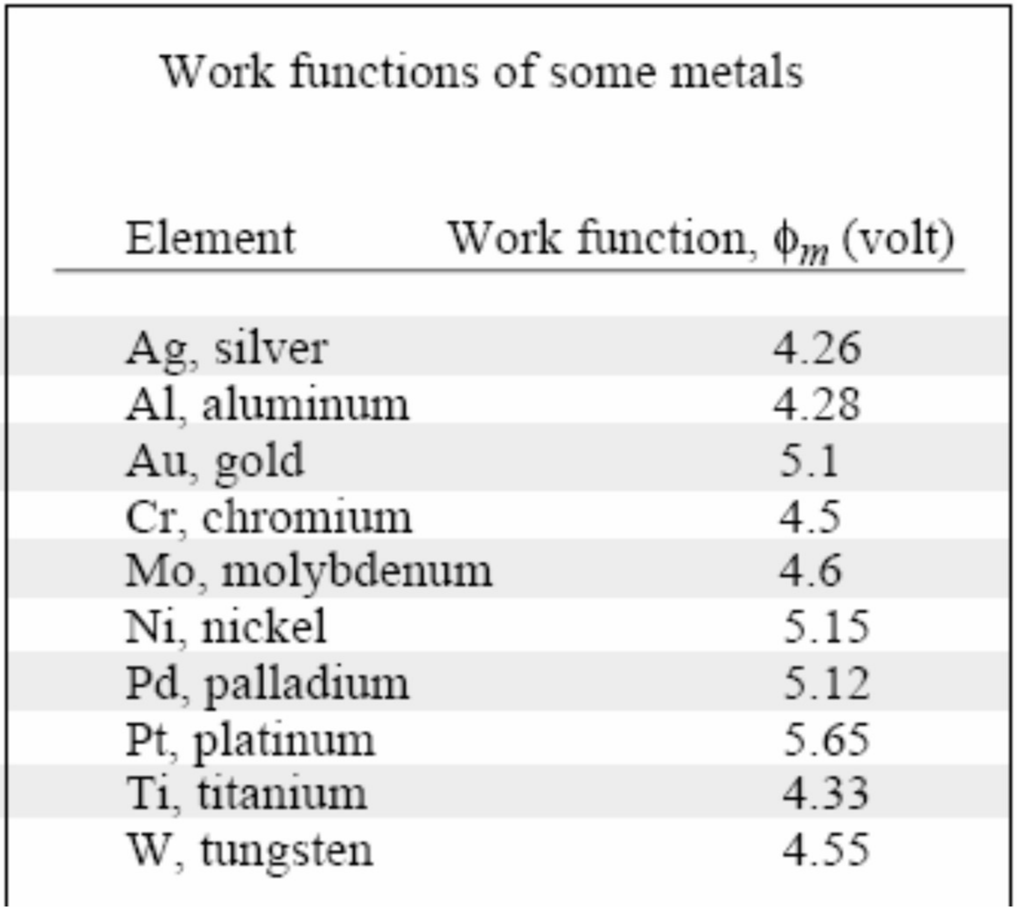
Photoelectric effect



$hf_0 = e\phi$ at threshold

workfunction





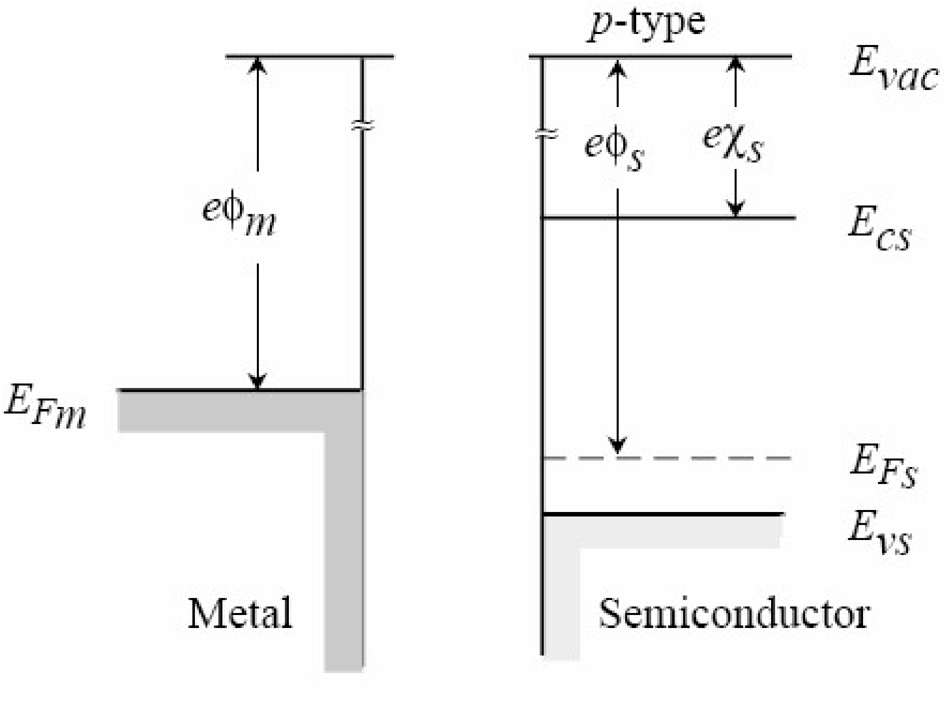
Work functions of some metals

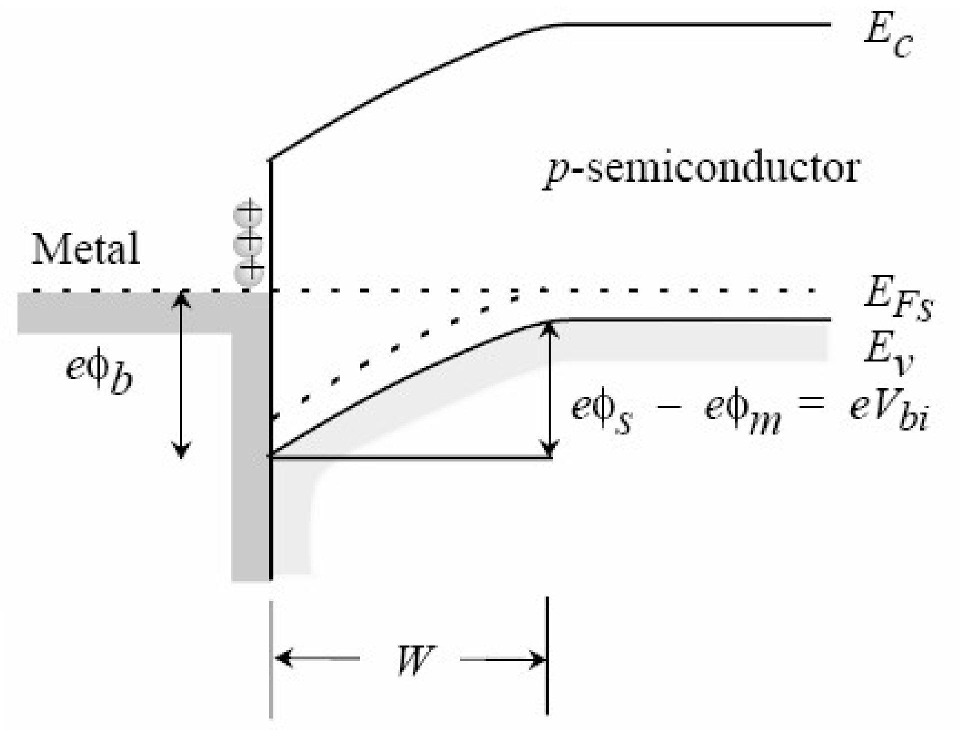
Element	Work function, ϕ_m (volt)
Ag, silver	4.26
Al, aluminum	4.28
Au, gold	5.1
Cr, chromium	4.5
Mo, molybdenum	4.6
Ni, nickel	5.15
Pd, palladium	5.12
Pt, platinum	5.65
Ti, titanium	4.33
W, tungsten	4.55

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



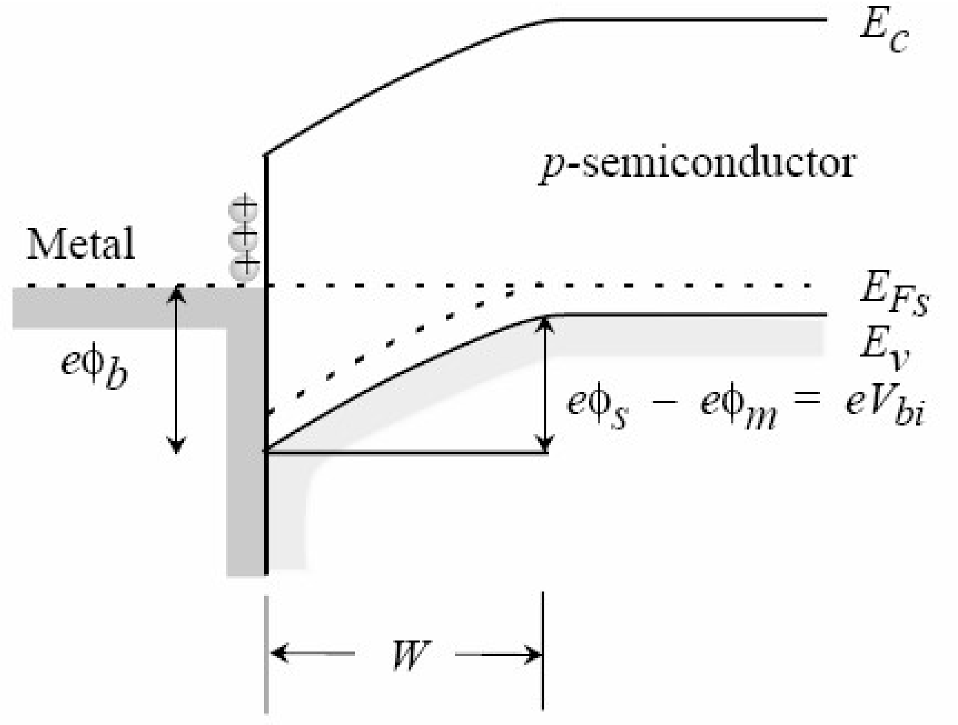


If $\phi_s < \phi_m$, the semiconductor bands bend down.

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

work function - electron affinity

Electrons flow from a low work function material to high work function material. The high work function material becomes negatively charged. You have to push the electrons uphill into the low work function material. This determines the band bending.



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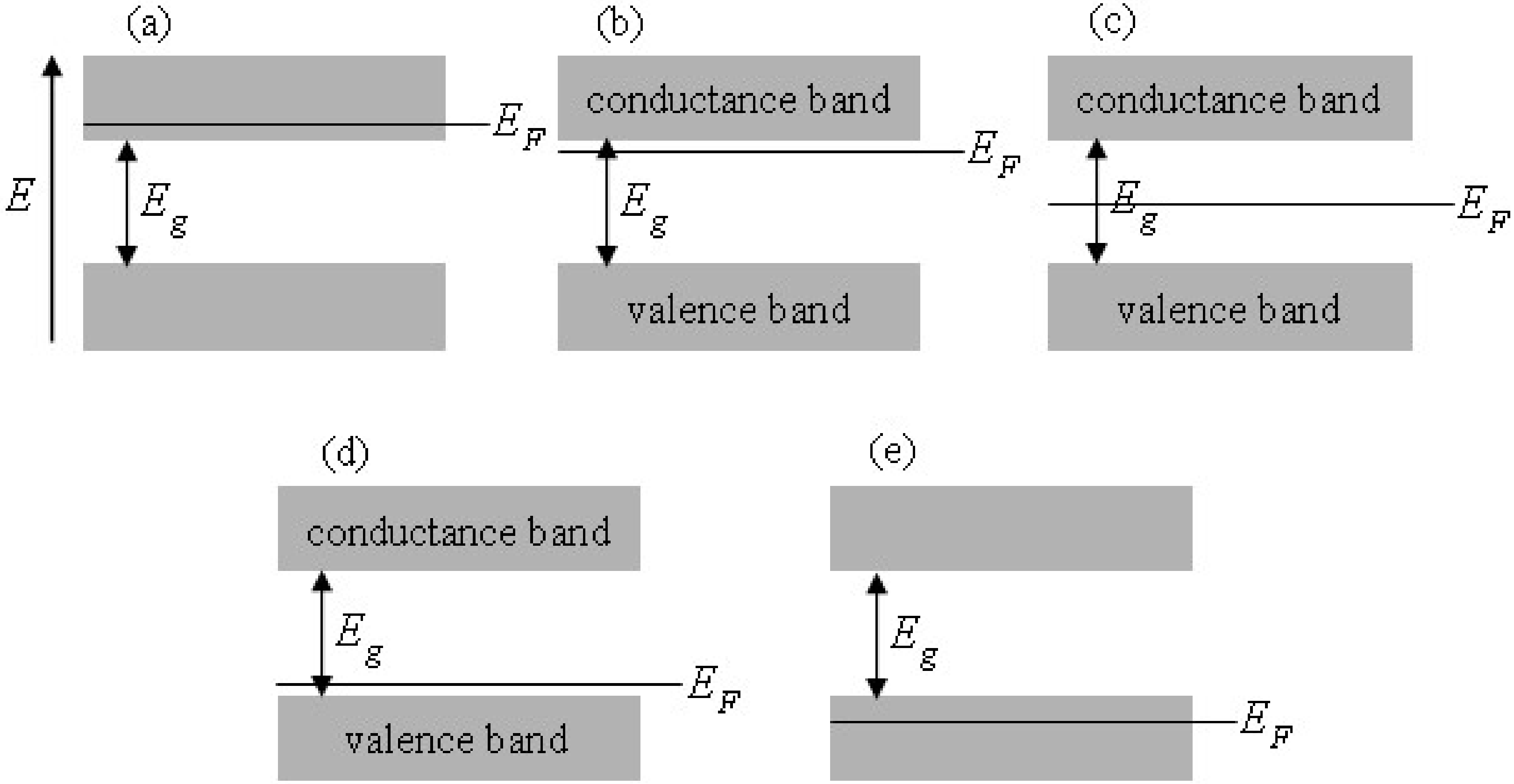
Pt, platinum	5.65
Ti, titanium	4.33
W, tungsten	4.55

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

Singh

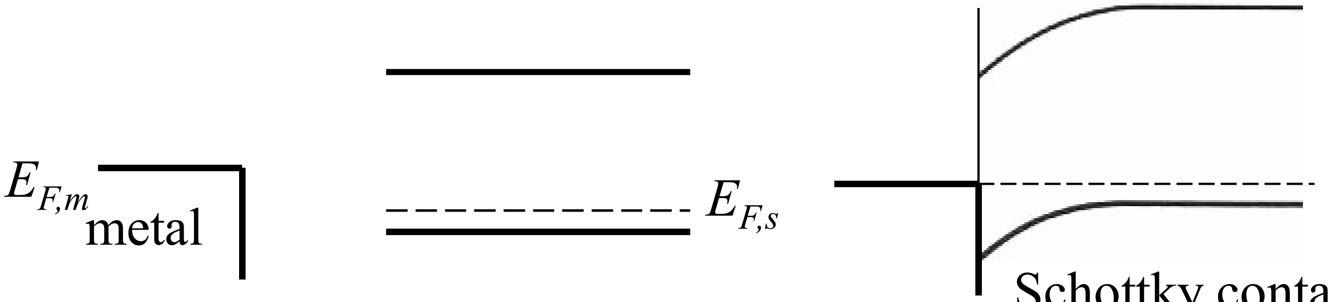


(a) A metal with a small workfunction. (b) An n-type semiconductor. (c) An insulator. (d) A p-type semiconductor. (e) A metal with a large workfunction.

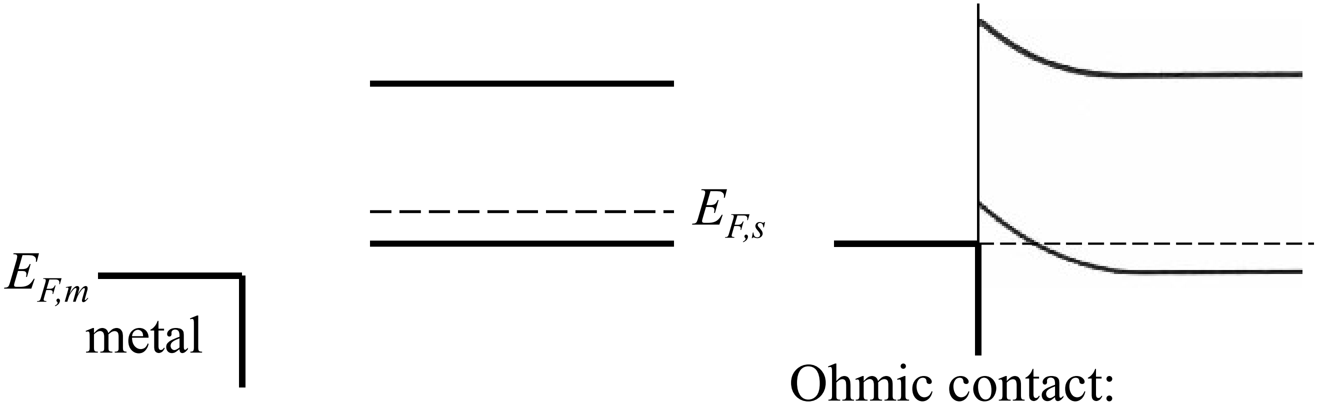
p-type

Walter Schottky

Schottky contact / ohmic contact



Schottky contact



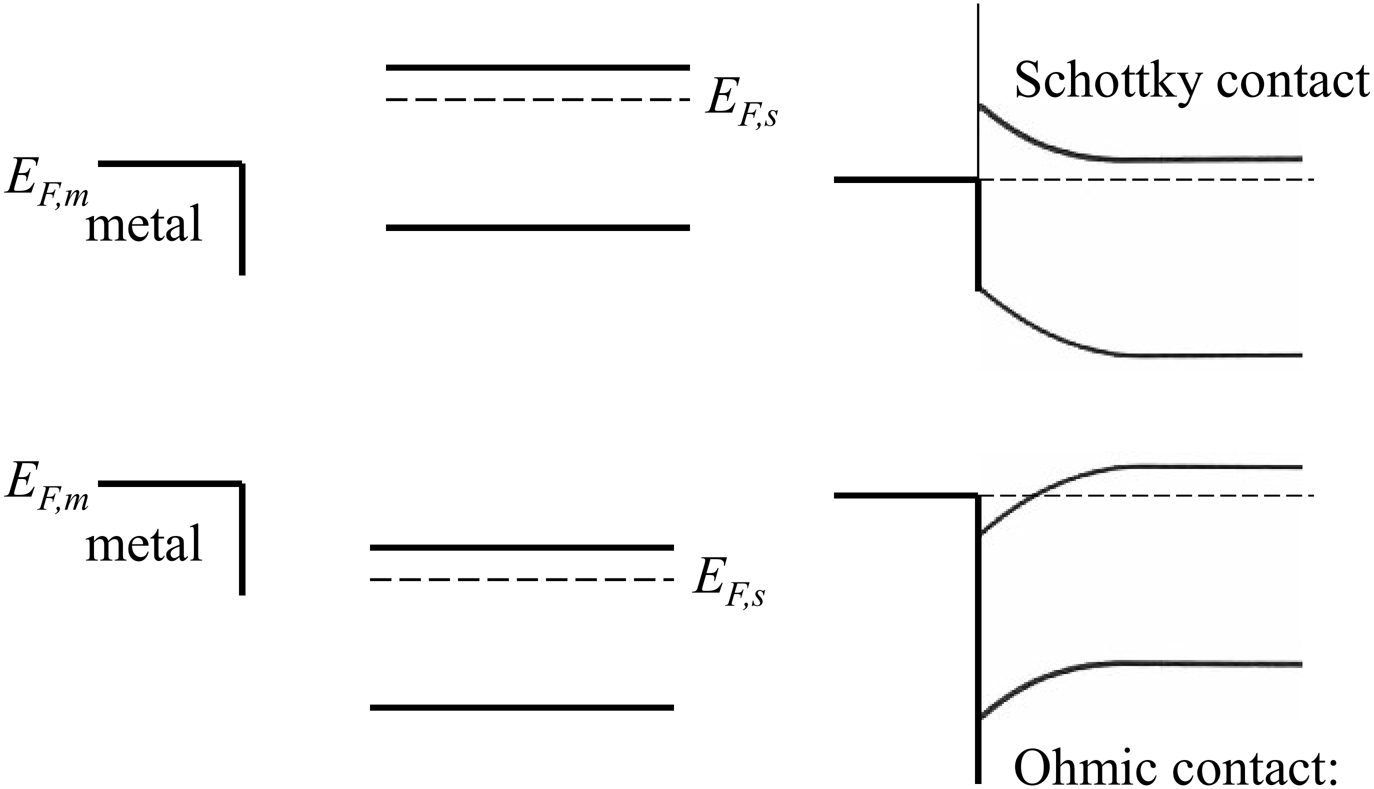
Ohmic contact:
linear resistance

specific contact resistance:

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

n-type

Schottky contact / ohmic contact



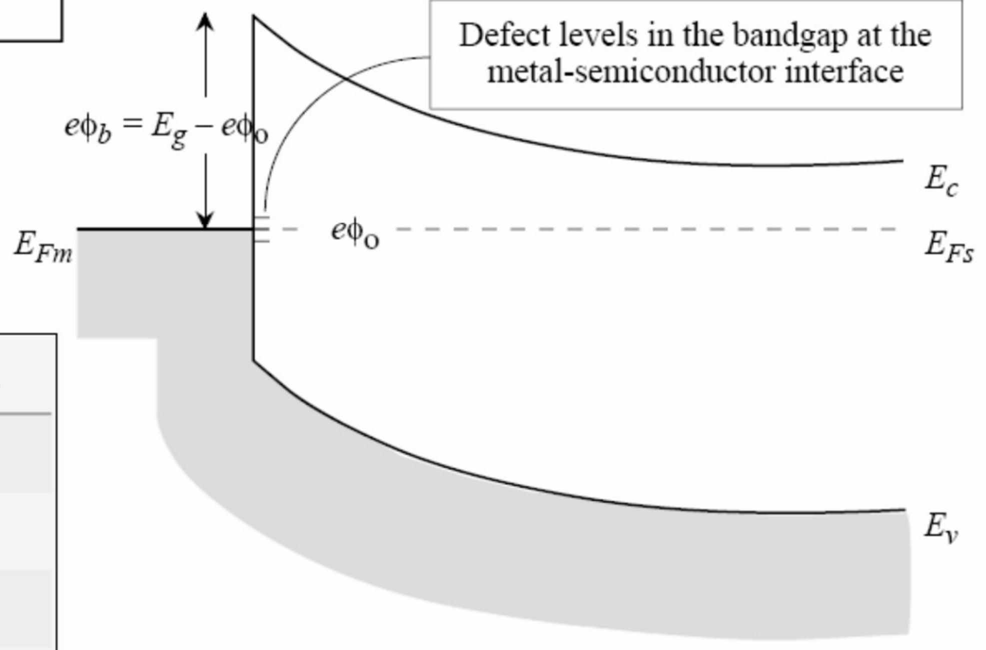
Schottky contact

Ohmic contact:
linear resistance

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

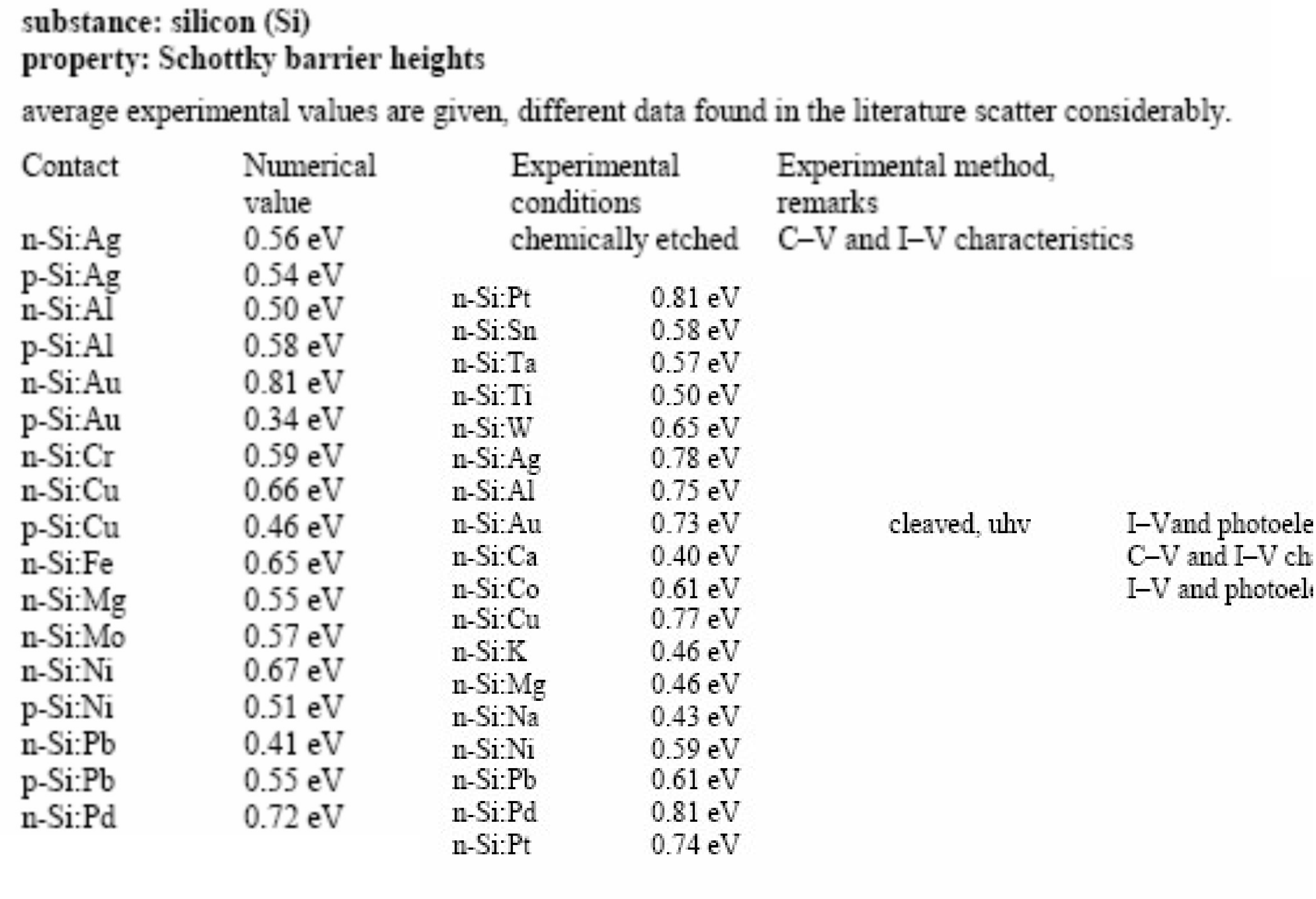
Interface states

Semiconductor surfaces have a large number of defect states (from broken bands, impurities, etc.)



Defect levels in the bandgap at the metal-semiconductor interface

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	



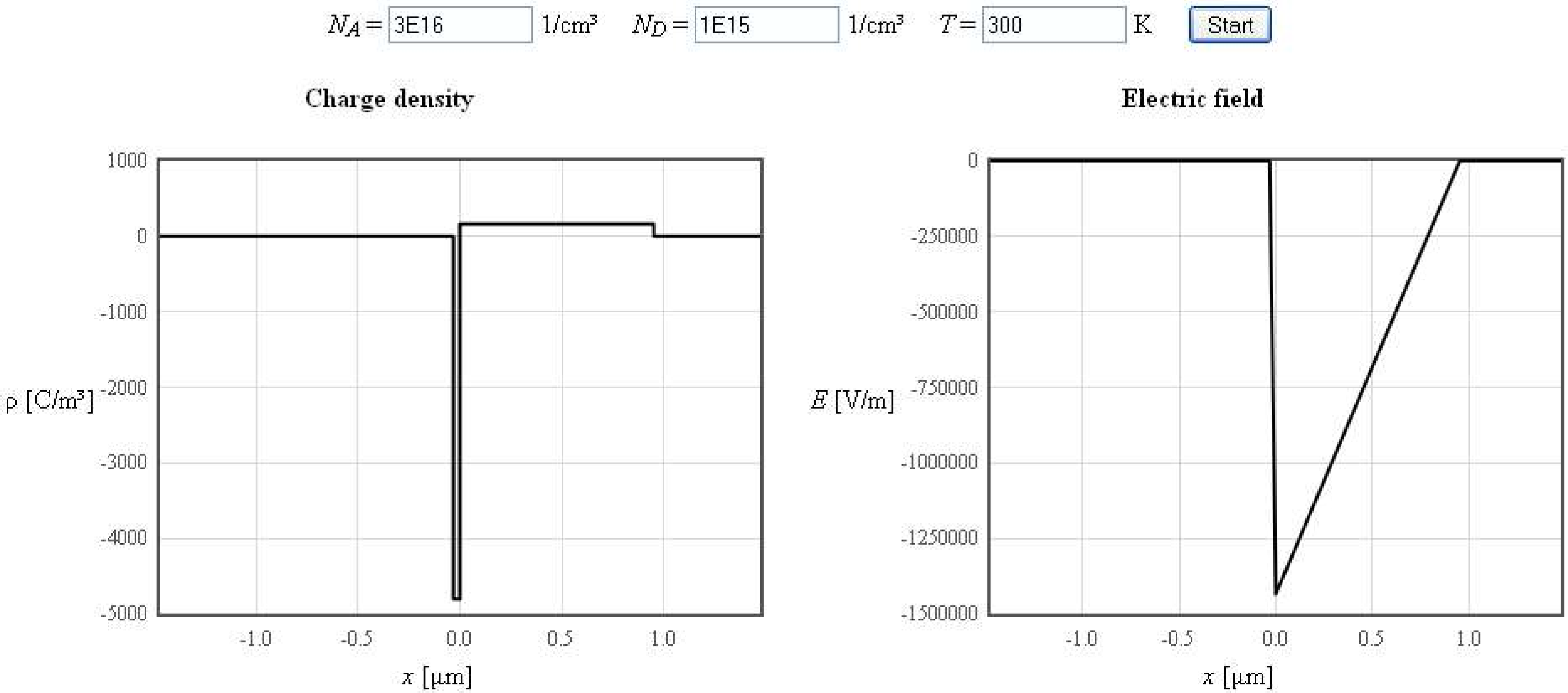
substance: silicon (Si)
property: Schottky barrier heights

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+%2

Schottky barrier



$N_A =$ 3E16 1/cm³ $N_D =$ 1E15 1/cm³ $T =$ 300 K

$$V_{bi} = \phi_s - \phi_m$$

$$E = \frac{eN_D}{\varepsilon_r \varepsilon_0}\left(x - x_n\right) \qquad W \approx x_n = \sqrt{\frac{2\varepsilon\left(V_{bi} - V\right)}{eN_D}} \qquad V = \frac{-eN_D}{\varepsilon}\left(\frac{x^2}{2} - xx_n\right) \qquad 0 > x > x_n$$

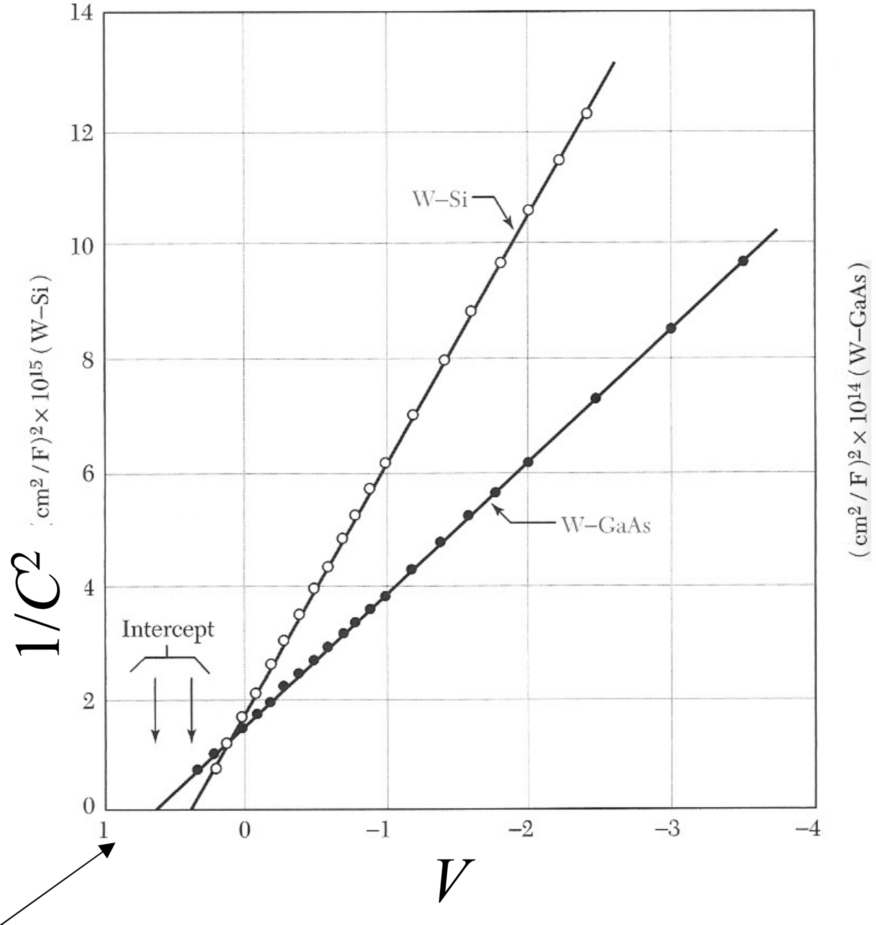
Like a one sided junction, the metal side is heavily doped.

CV measurements

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

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

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



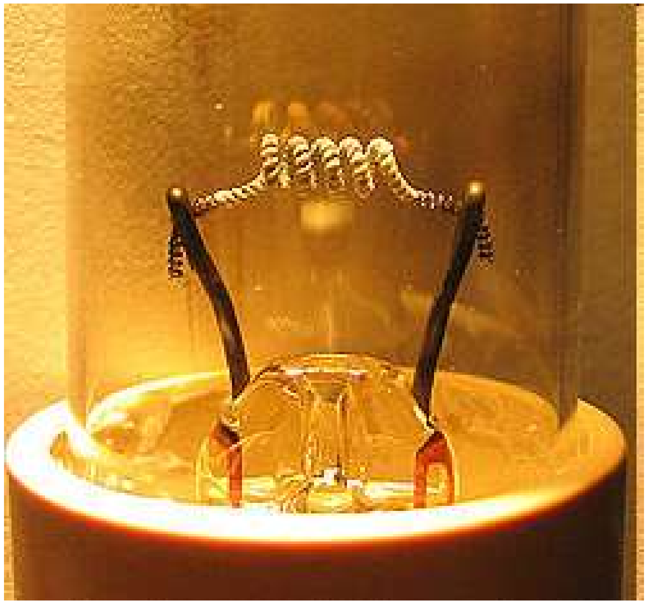
GaAs has larger E_g and V_{bi}

Thermionic emission

1901 Richardson

Owen Willans Richardson

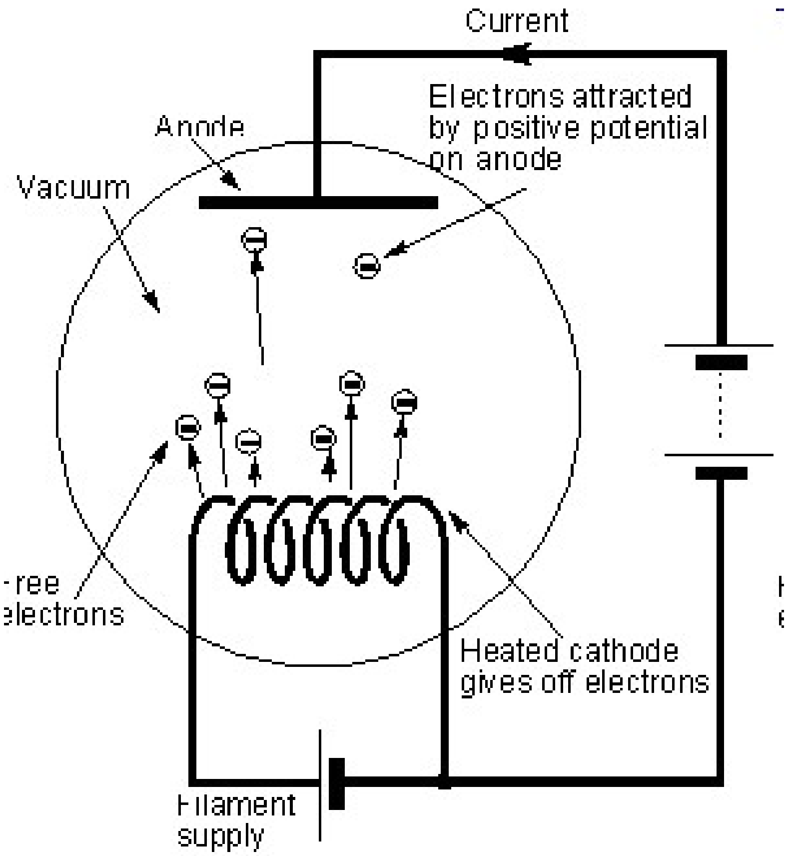
Current from a heated wire is:



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

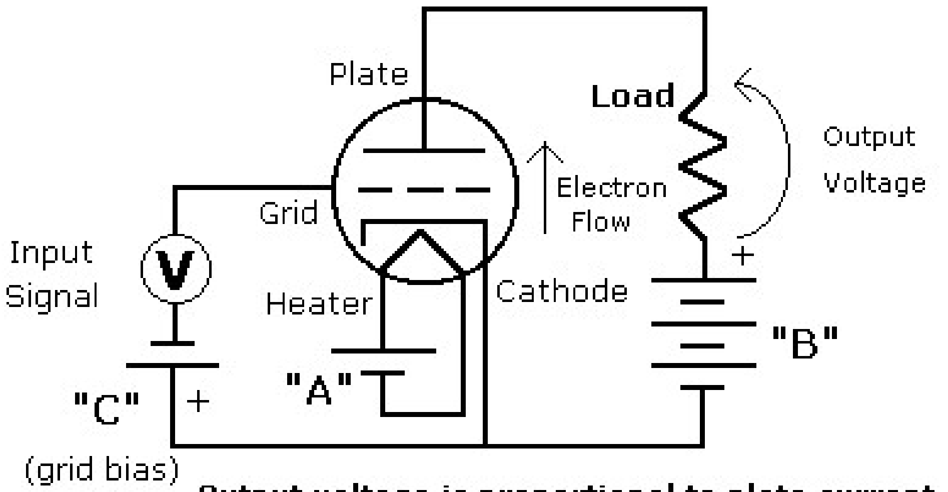
Some electrons have a thermal energy that exceeds the work function and escape from the wire.

Vacuum diodes



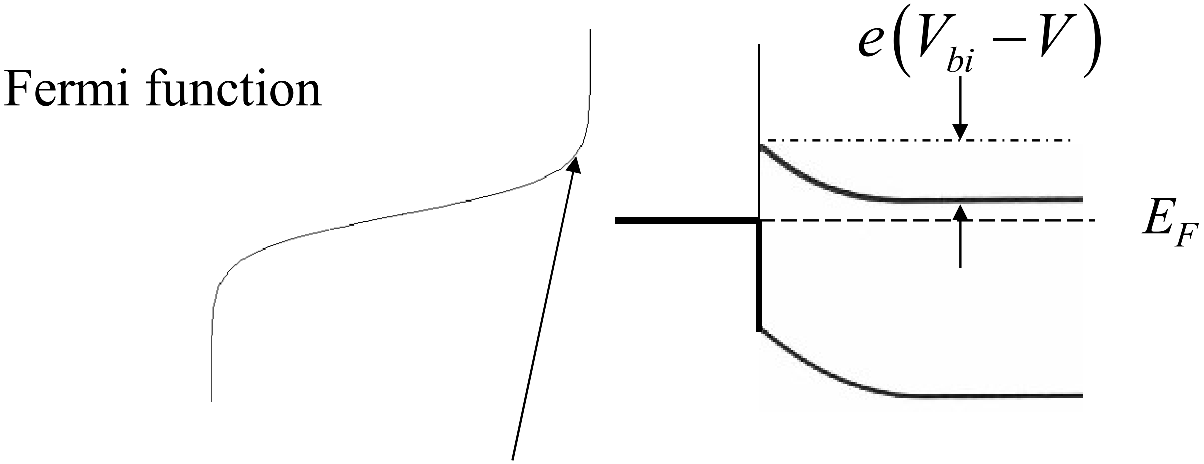
diode

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

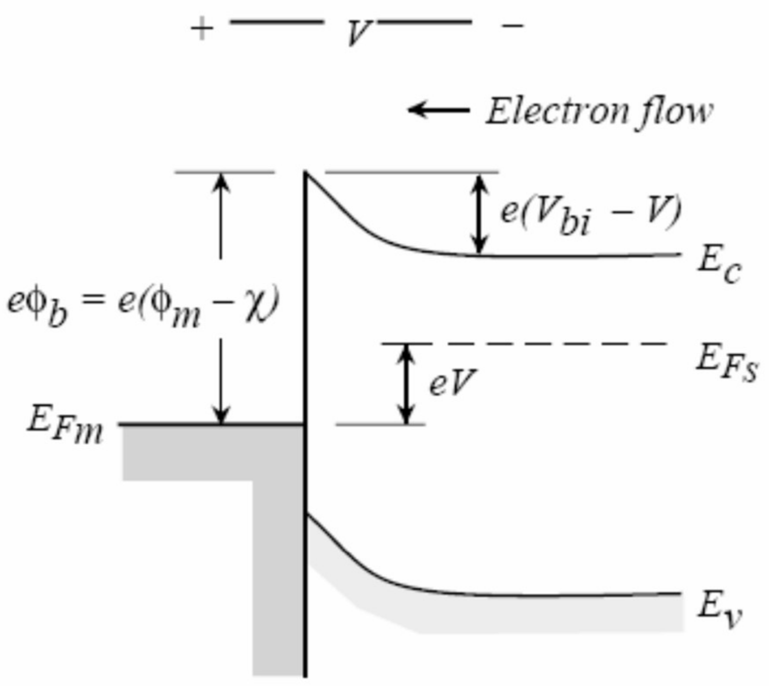
Thermionic emission

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

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

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

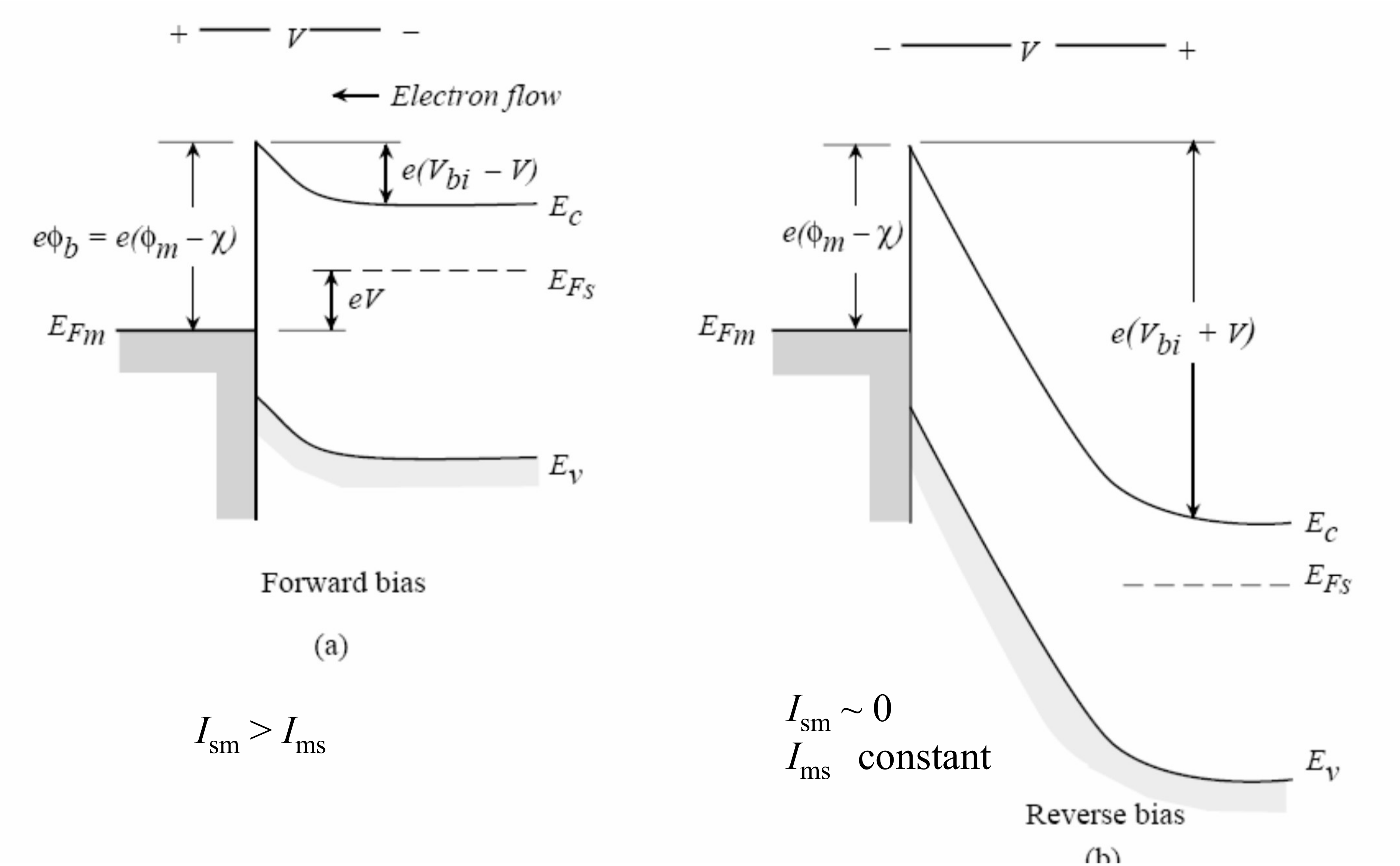
$$I = I_{sm} + I_{ms} = I_s\left(\mathrm{e}^{\frac{eV}{k_B T}} - 1\right)$$



Forward bias

(a)

Schottky barrier



Forward bias

(a)

$I_{sm} > I_{ms}$

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

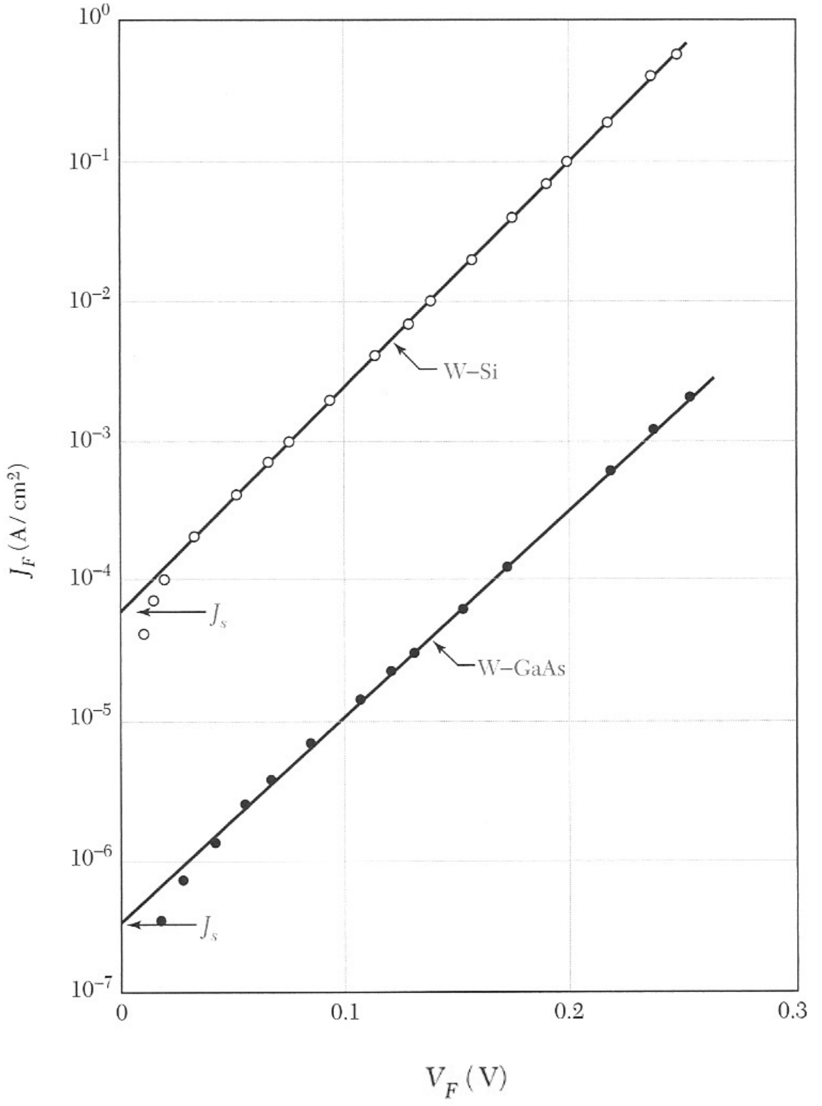
Reverse bias

(b)

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

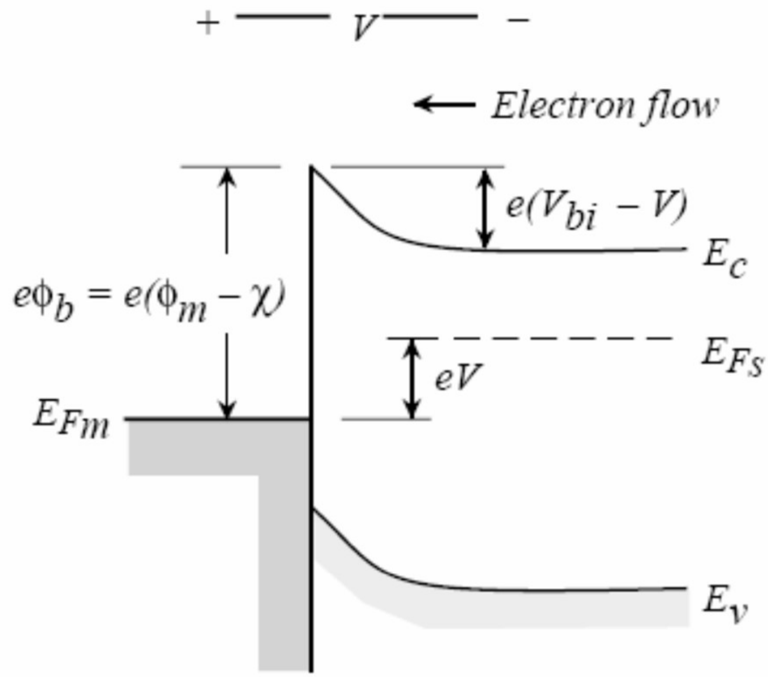
A_R^* = Richardson constant

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.

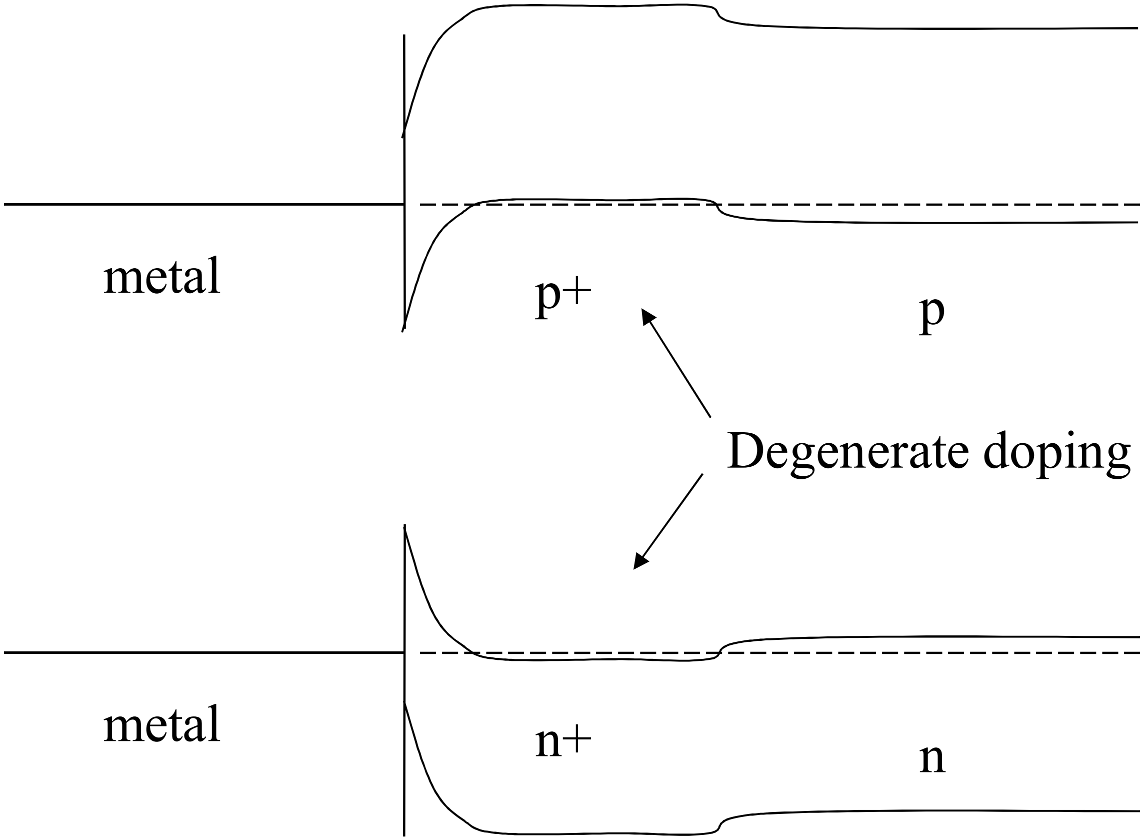
Used as rf mixers.

Low turn on voltage - high reverse bias current

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

Tunnel contacts

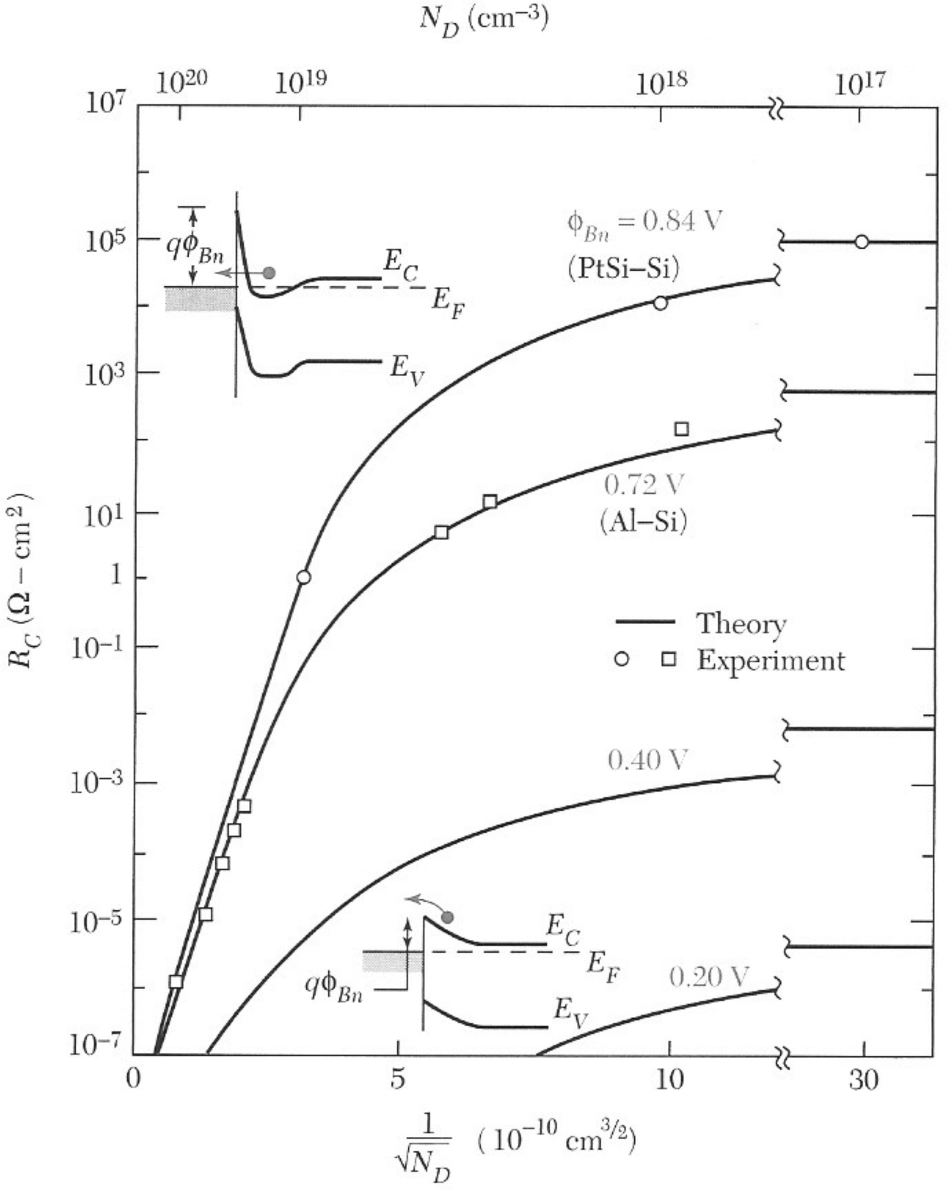
For high doping, the Schottky barrier is so thin that electrons can tunnel through it.



Degenerate doping at a tunnel contact

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 ($\Omega - $cm^2)
$q\phi_{Bn}$
E_C
E_F
E_V
$\phi_{Bn} = 0.84$ 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.

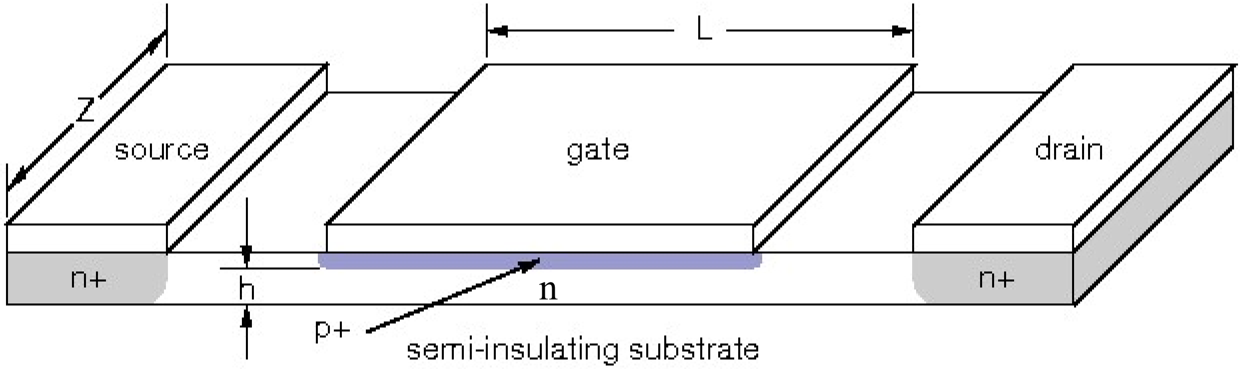
In a forward biased pn-junction, diffusion dominates.

In a tunnel contact, tunneling dominates.

In a Schottky diode, thermionic emission dominates.

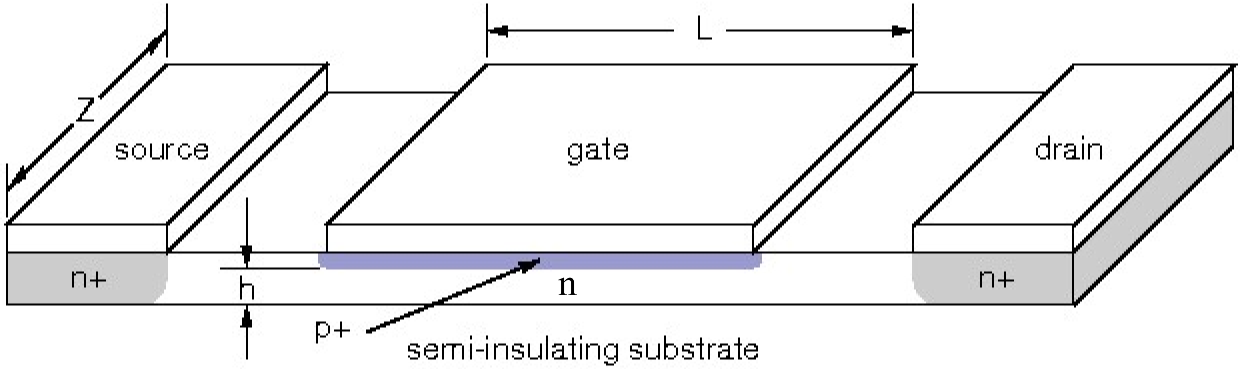
JFETs - MESFETs - MODFETs

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



JFET

n-channel JFET



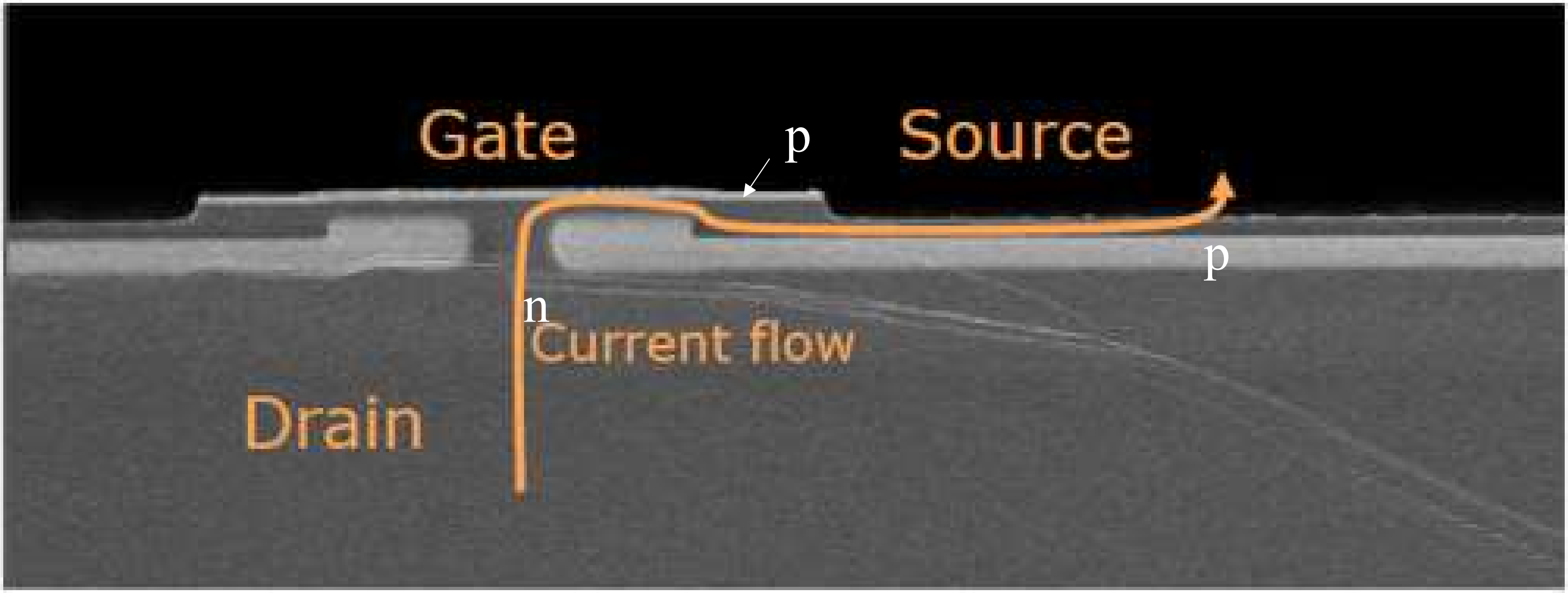
For $N_A >> N_D$

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

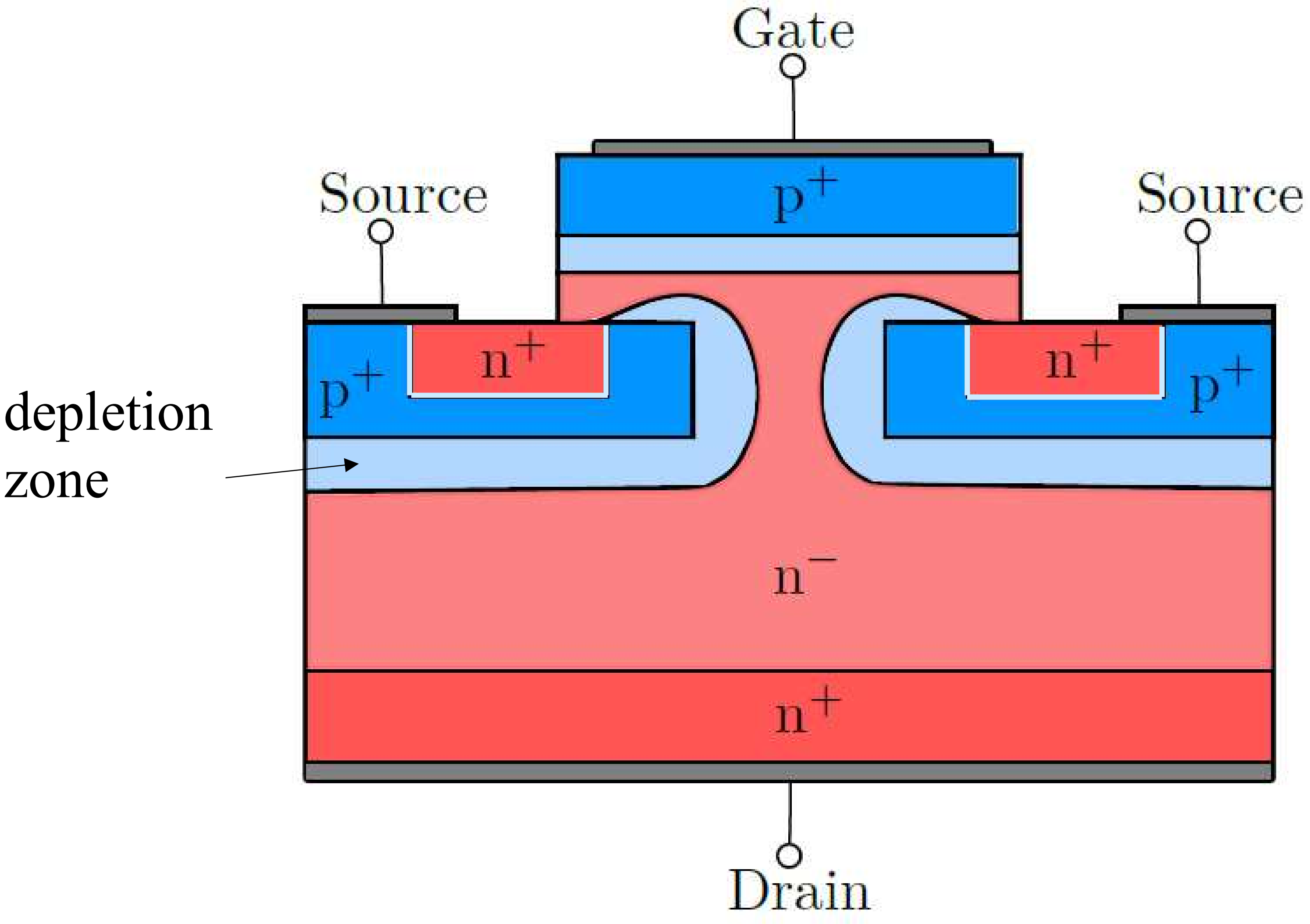
Depletion mode $h > x_n = \sqrt{\frac{2\varepsilon V_{bi}}{eN_D}}$ conducting at $V_g = 0$

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

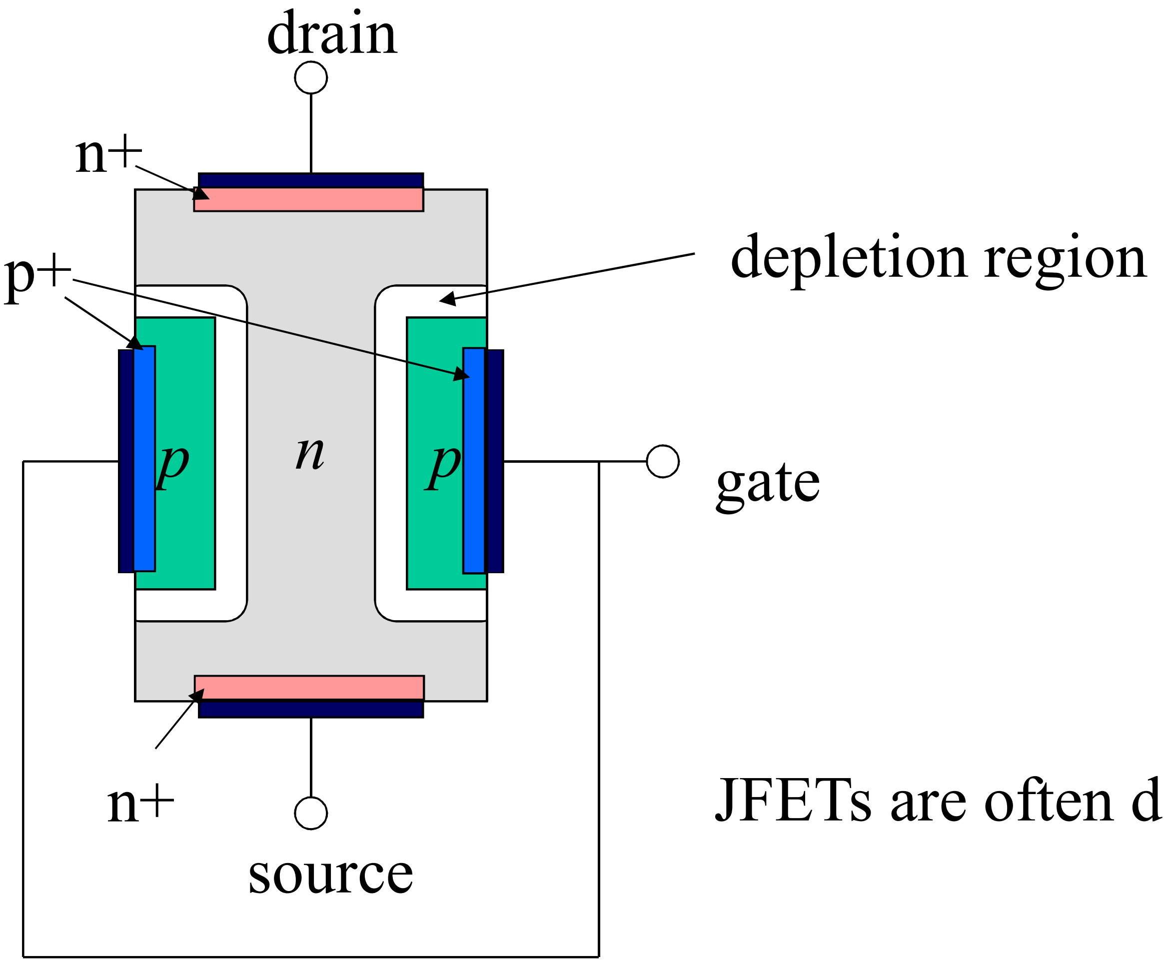
Power SiC JFET



n-channel (power) JFET



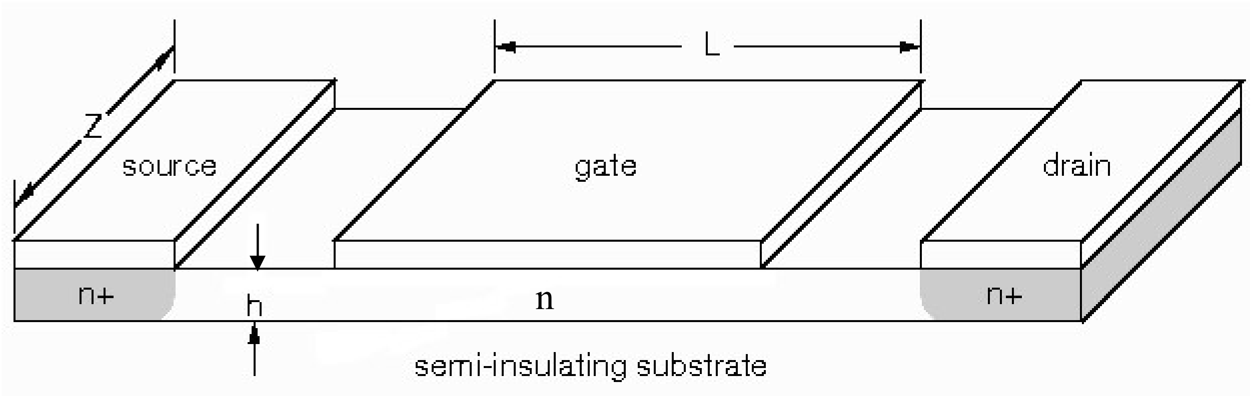
n-channel JFET



JFETs are often discrete devices

MESFET

Metal-Semiconductor Field Effect Transistors

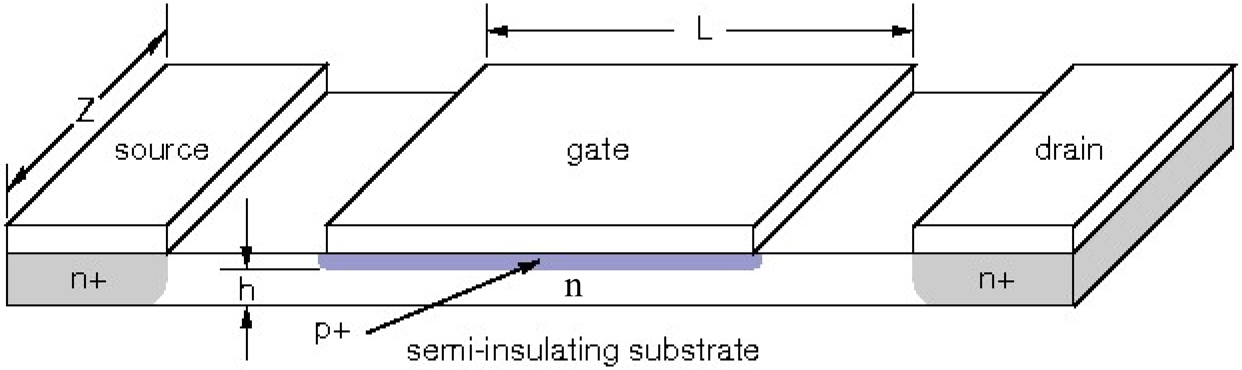


Depletion layer created by Schottky barrier

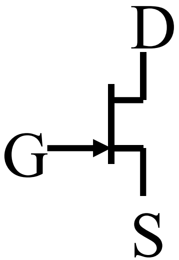
$$x_n = \sqrt{\frac{2\varepsilon(V_{bi} - V)}{eN_D}}$$

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

JFET

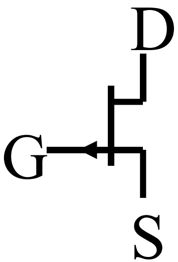


n-channel JFET



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, $V_p = V_{bi} - V$.

JFET

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