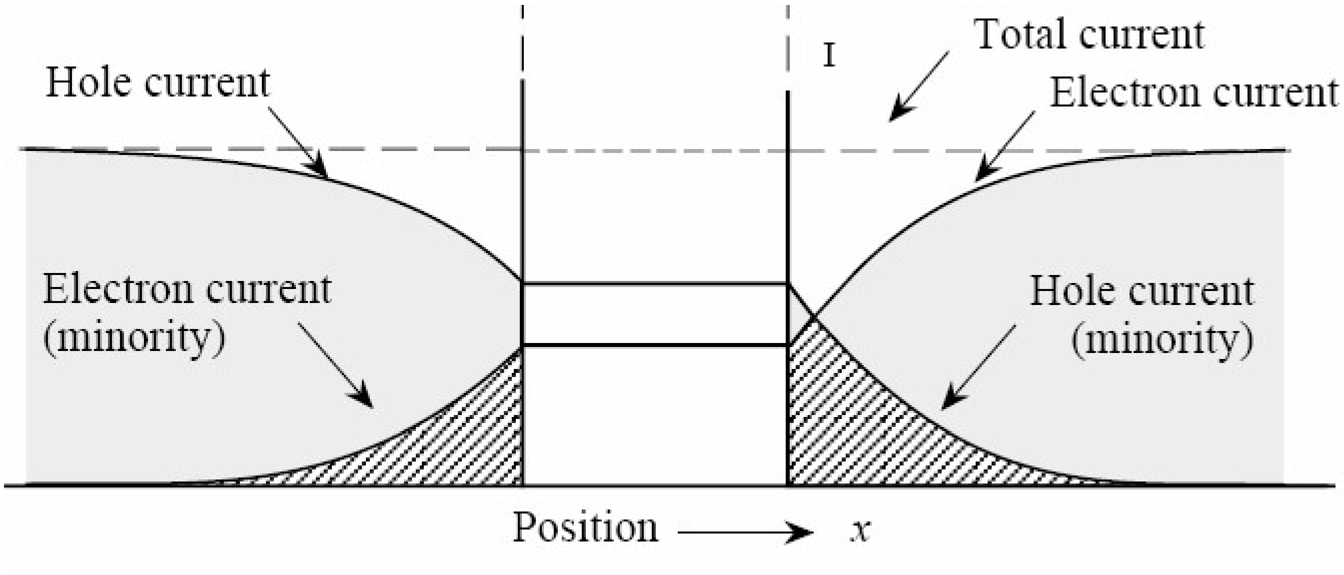
pn - Junctions

Diffusion current

$$J_{diff,p} = \frac{p_{n0} e D_p}{L_p}\left(\exp\left(\frac{eV}{k_B T}\right) - 1\right)$$

$$J_{diff,n} = \frac{n_{p0} e D_n}{L_n}\left(\exp\left(\frac{eV}{k_B T}\right) - 1\right)$$



Long diodes

In a forward biased pn-junction, electrons are injected into the p-side as minority carriers and holes are injected into the n-side as minority carriers. This establishes a concentration gradient of minority electrons on the p-side and a concentration gradient of minority holes on the n-side. A diffusion current flows because of the concentration gradients. As the minority carriers diffuse away from the junction, they recombine with the majority carriers. A diode is called long if all the excess minority carriers recombine before the minority carriers are able to diffuse to a metal contact. In this case the concentration of the minority carriers decays to the equilibrium minority carrier density: $n_{p0} = \frac{n_i^2}{N_a}$ for electrons $p_{n0} = \frac{n_i^2}{N_d}$ for holes. The minority carrier concentrations at the edges of the depletion region are,

$$n_p(x_p) = n_{p_0} \exp\left(\frac{eV}{k_B T}\right)$$

$$p_n(x_n) = p_{n_0} \exp\left(\frac{eV}{k_B T}\right).$$

Here, x_p is the edge of the depletion region on the p-side, x_n is the edge of the depletion region on the n-side, V is the bias voltage, T the absolute temperature, e the elementary charge and k_B is Boltzmann's constant.

For holes and electrons in a semiconductor, the following continuity equations are valid:

$$\frac{\partial p}{\partial t} = -p\mu_p \nabla \cdot \vec{E} - \nabla p \mu_p \vec{E} + D_p \nabla^2 p + G_p - R_p$$

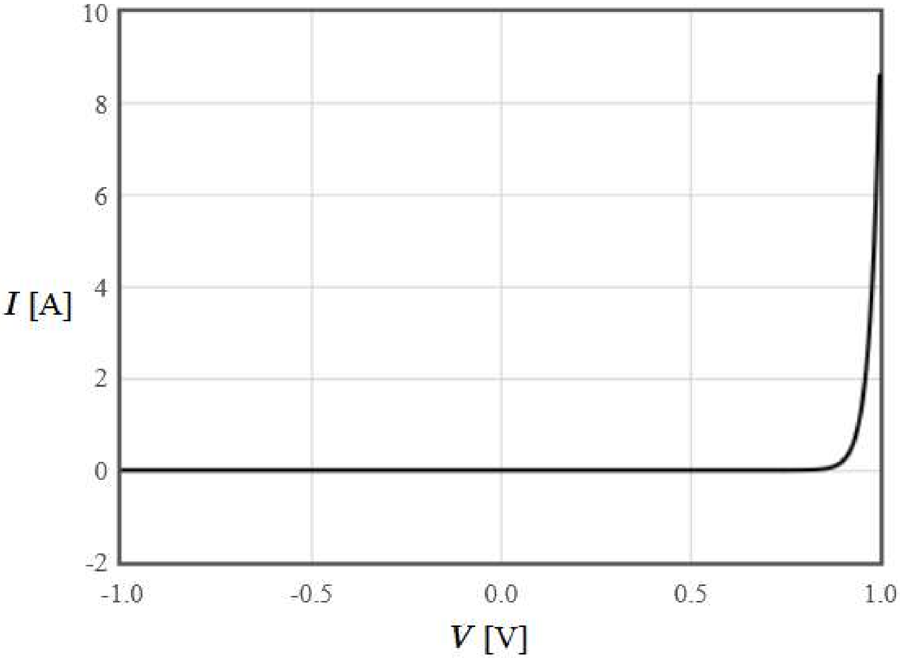
$$\frac{\partial n}{\partial t} = n\mu_n \nabla \cdot \vec{E} + \nabla n \mu_n \vec{E} + D_n \nabla^2 n + G_n - R_n.$$

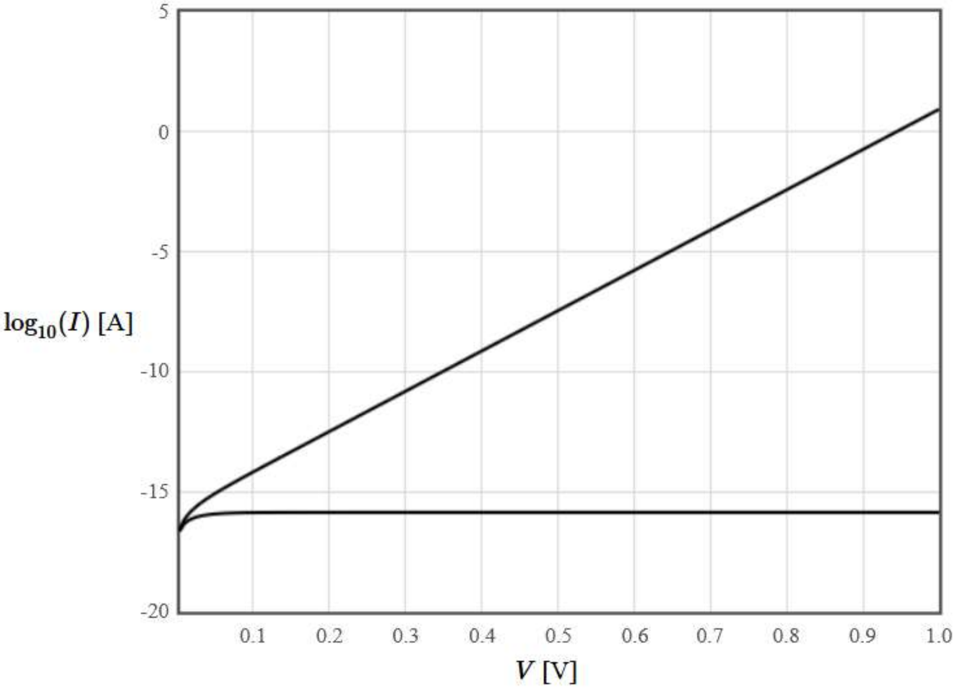
Diode current

$$I = eA\left(\frac{p_{n0}D_p}{L_p}+\frac{n_{p0}D_n}{L_n}\right)\left(\exp\left(\frac{eV}{k_BT}\right)-1\right) = I_s\left(\exp\left(\frac{eV}{k_BT}\right)-1\right)$$

Area

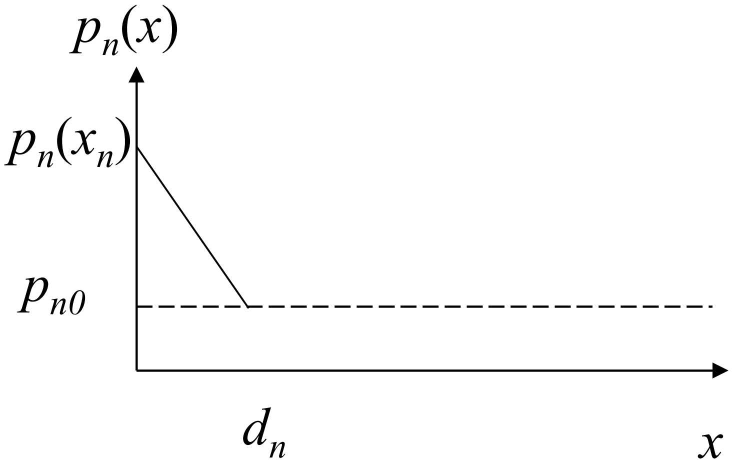
Saturation current





Short diode

n-type



$d_n << L_p$

Metal contact is much closer to the depletion region than the diffusion length

$$J_{diff,p} = -eD_p \frac{dp}{dx}$$

$$J_{diff,p} = -eD_p \frac{dp}{dx} = \frac{eD_p}{d_n}\left(p_n(x_n) - p_{n0}\right)$$

Diffusion current

$$J_{diff,p} = \left(p_n(x_n) - p_{n0}\right)\frac{eD_p}{d_n}$$

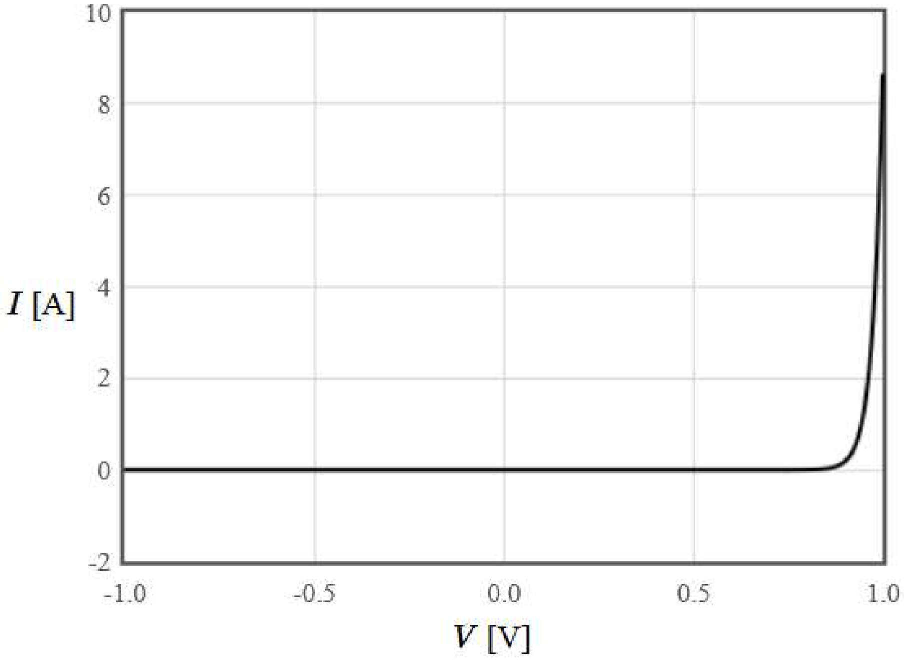
$$J_{diff,p} = \left(p_{n0}\exp\left(\frac{eV}{k_B T}\right) - p_{n0}\right)\frac{eD_p}{d_n}$$

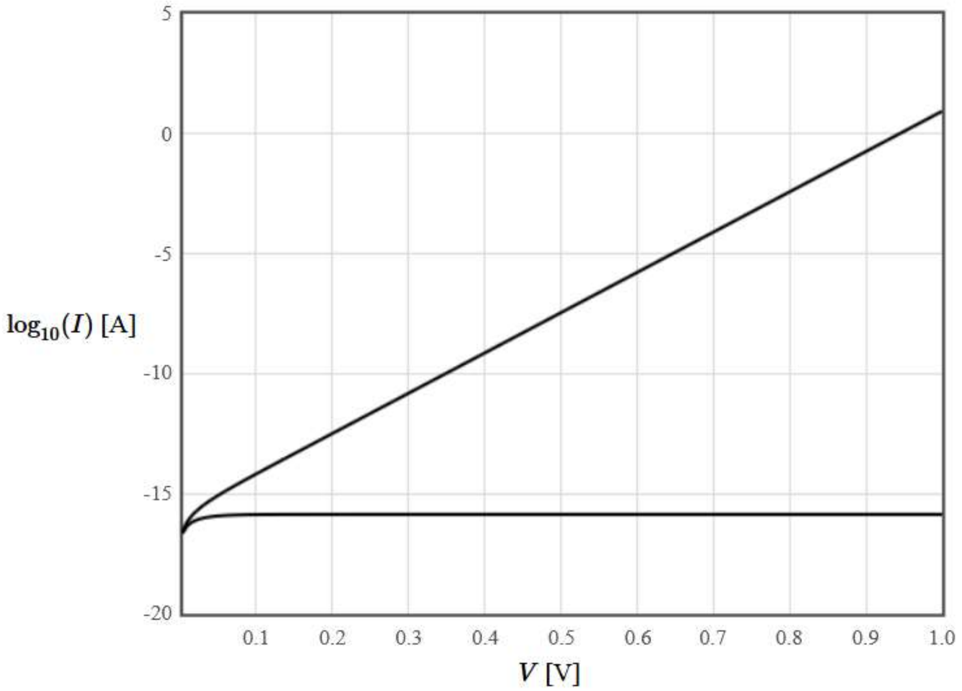
$$J_{diff,p} = \frac{p_{n0}eD_p}{d_n}\left(\exp\left(\frac{eV}{k_B T}\right) - 1\right)$$

Short diode current

$$I = eA\left(\frac{p_{n0}D_p}{d_n}+\frac{n_{p0}D_n}{d_p}\right)\left(\exp\left(\frac{eV}{k_BT}\right)-1\right)=I_s\left(\exp\left(\frac{eV}{k_BT}\right)-1\right)$$

Area

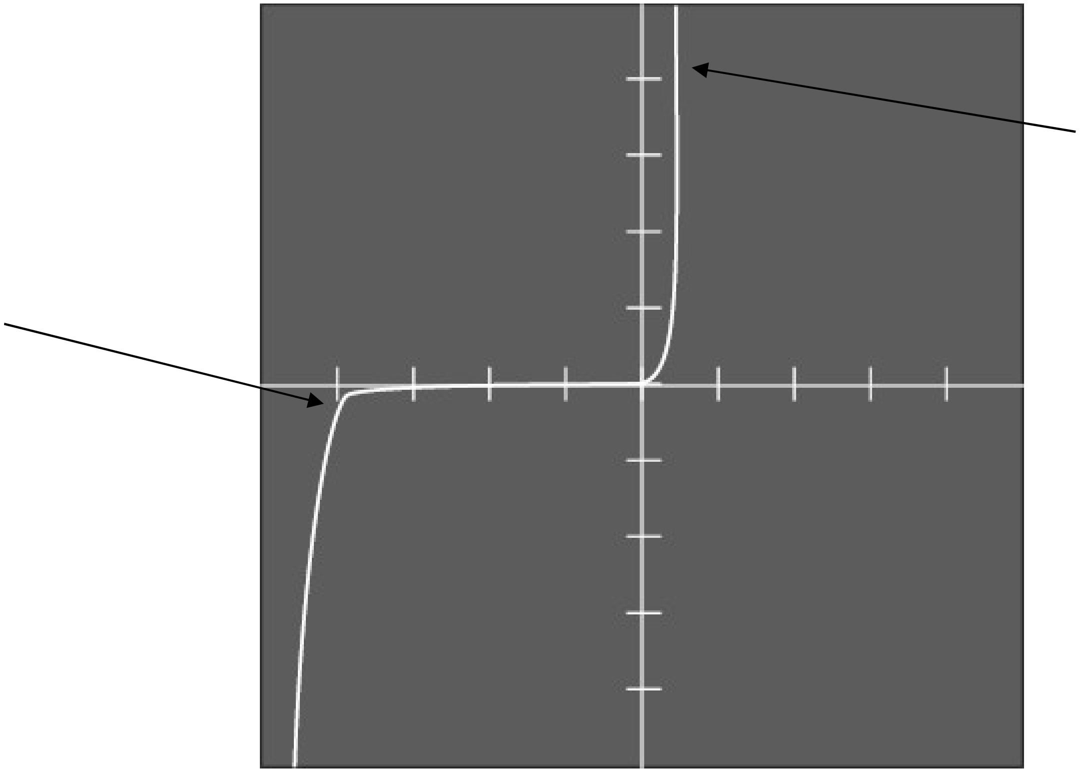




Real diodes

$$I = I_s\left(\exp\left(\frac{eV}{nk_BT}\right) - 1\right)$$

n = nonideality factor
$n = 1$ for an ideal diode



series resistance

reverse
breakdown
voltage

Real diodes

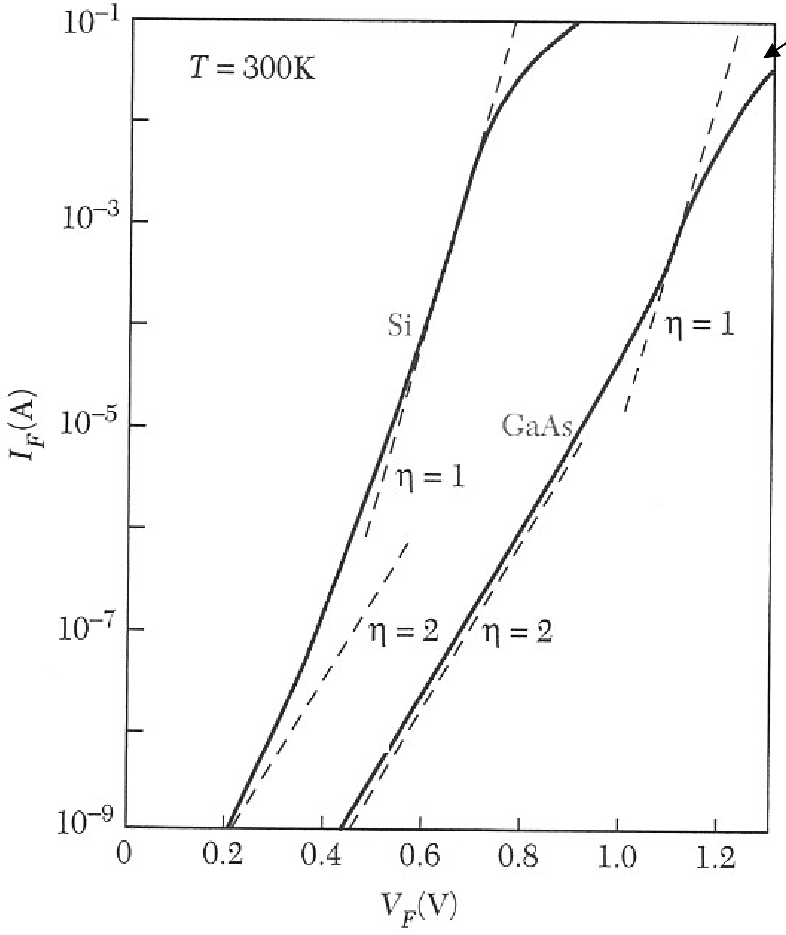
There is constant generation/recombination of electron hole pairs.

In forward bias there is an extra current from recombination.

In reverse bias there is an extra current from generation.

Low bias: recombination dominates, $n = 2$

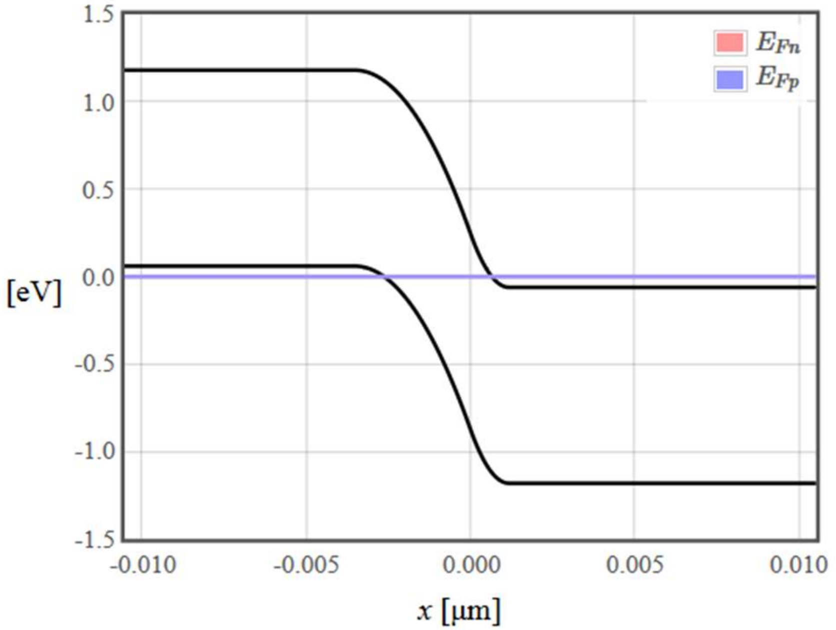
$$I = I_s\left(\exp\left(\frac{eV}{nk_BT}\right) - 1\right)$$

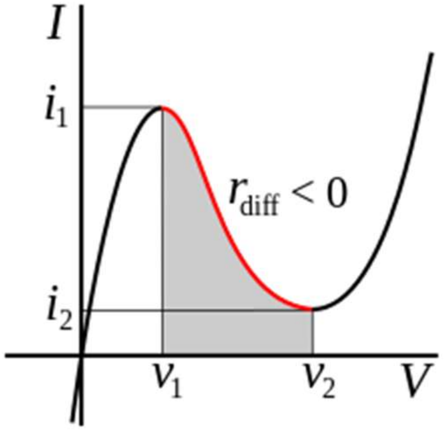


Very high bias: series resistance

High bias: ideal behavior, $n = 1$

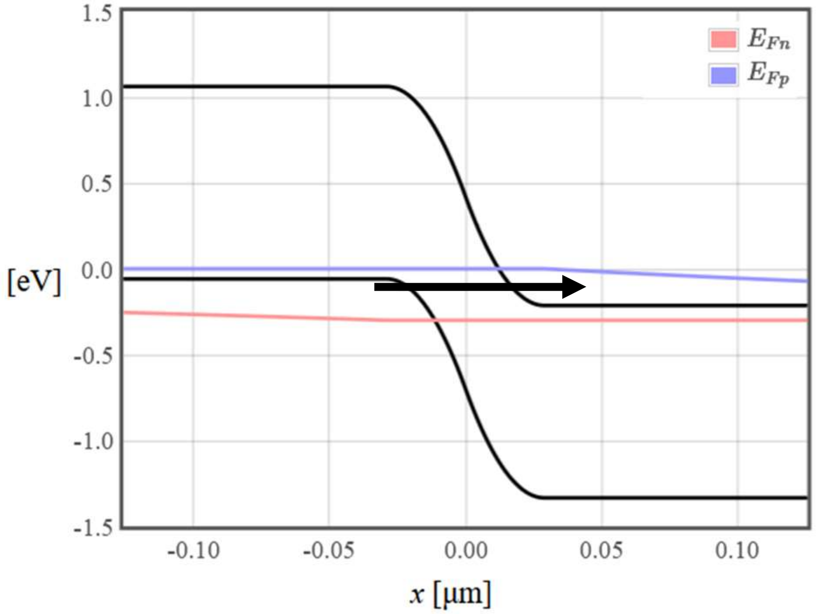
Tunnel diodes / Esaki diodes

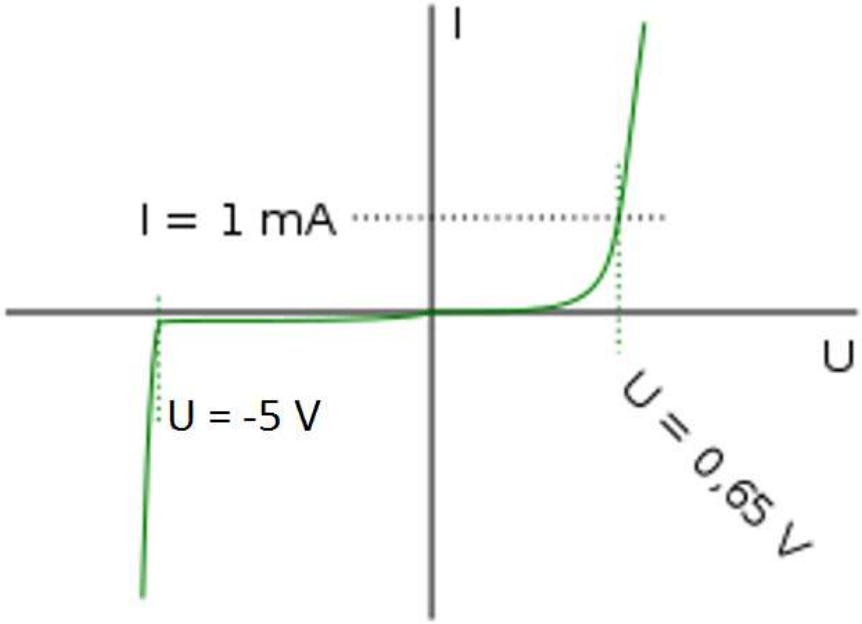




Both sides of the diode are degenerately doped

Zener tunneling





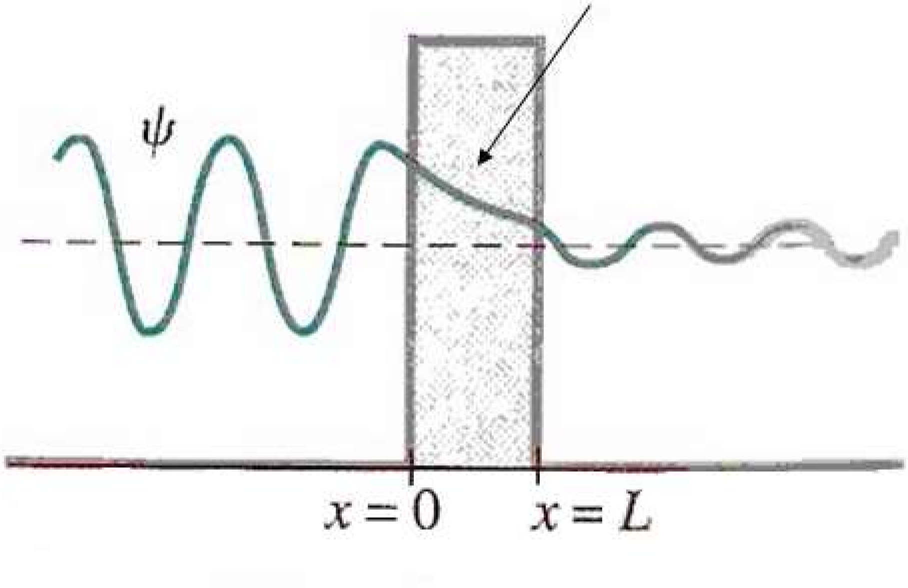
Electrons tunnel from valence band to conduction band

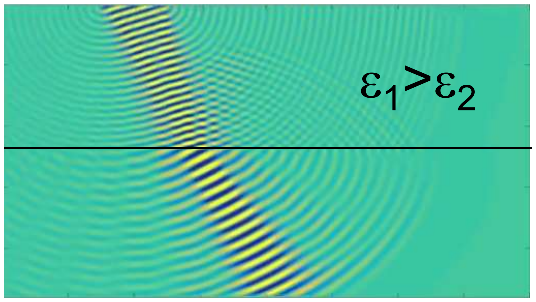
Occurs at high doping

$|V_{\text{zener}}| < 5.6\text{ V}$

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.

Zener tunneling

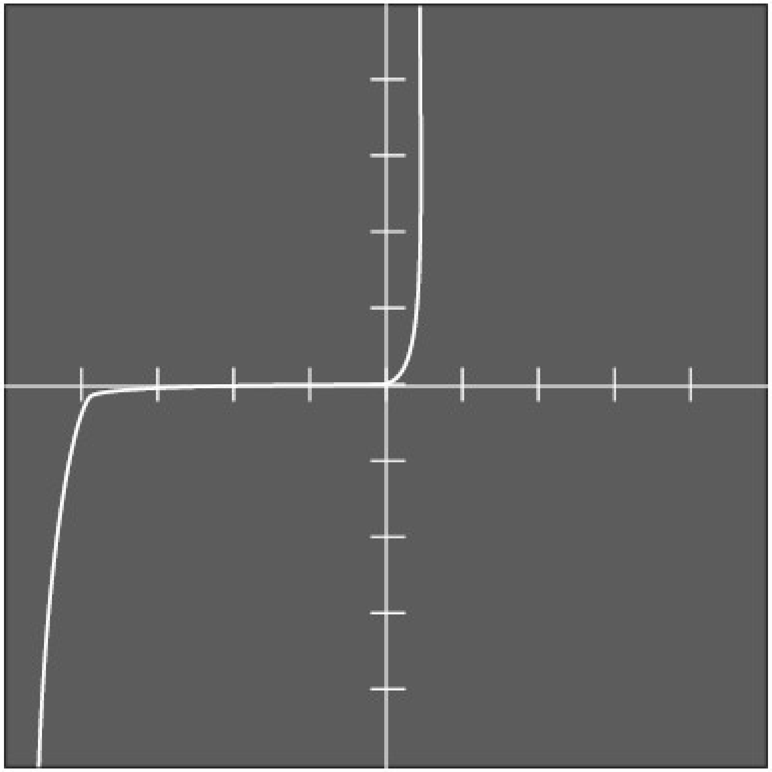
Breakdown voltage is typically much lower than the breakdown voltage of an avalanche diode and can be tuned by adjusting the width of the depletion layer.

Used to provide a reference voltage.

Avalanche breakdown

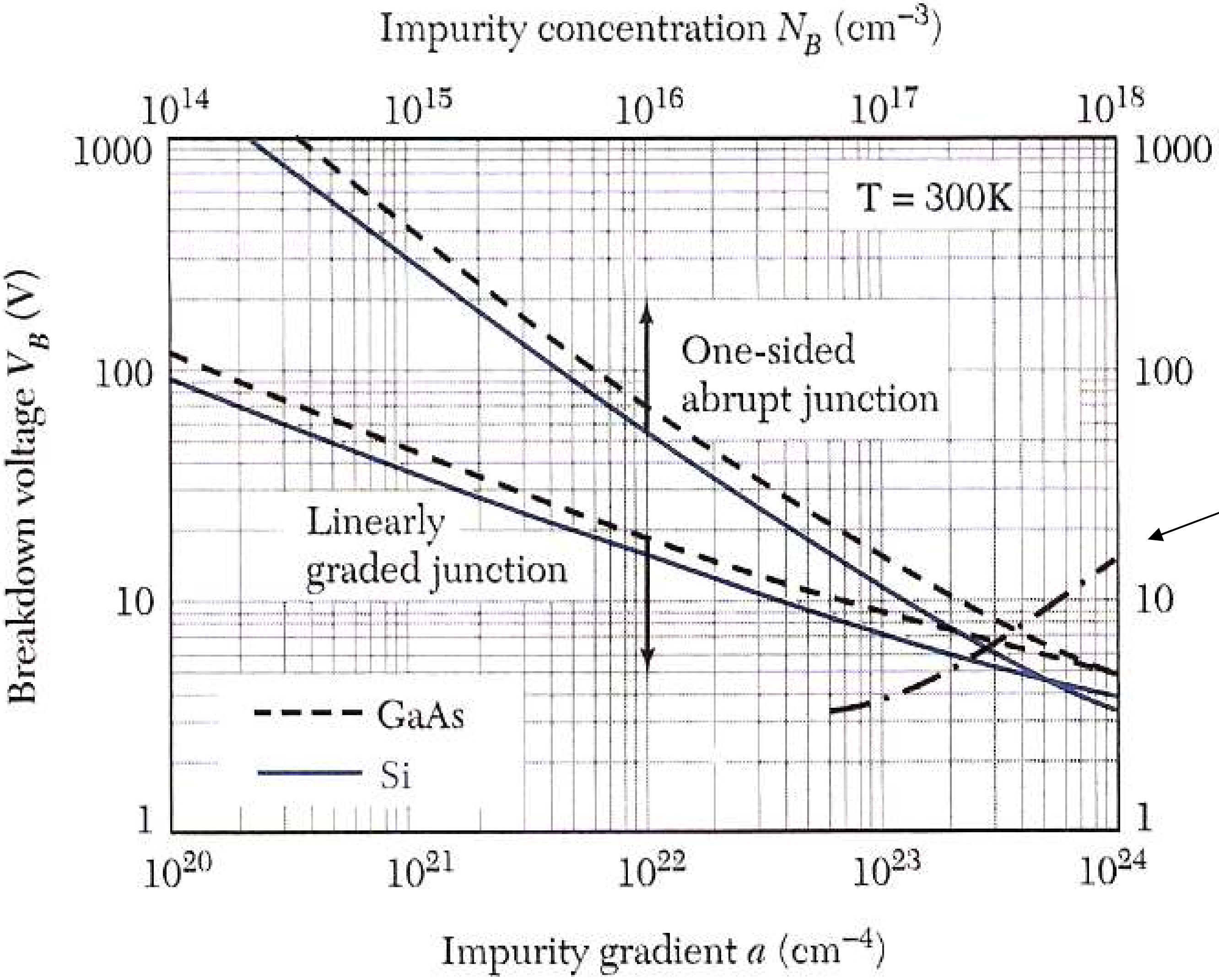
Impact ionization causes an avalanche of current

Occurs at low doping



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

Avalanche breakdown

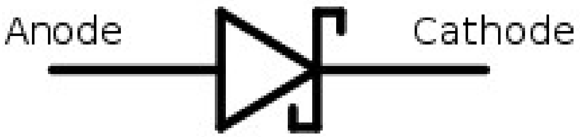


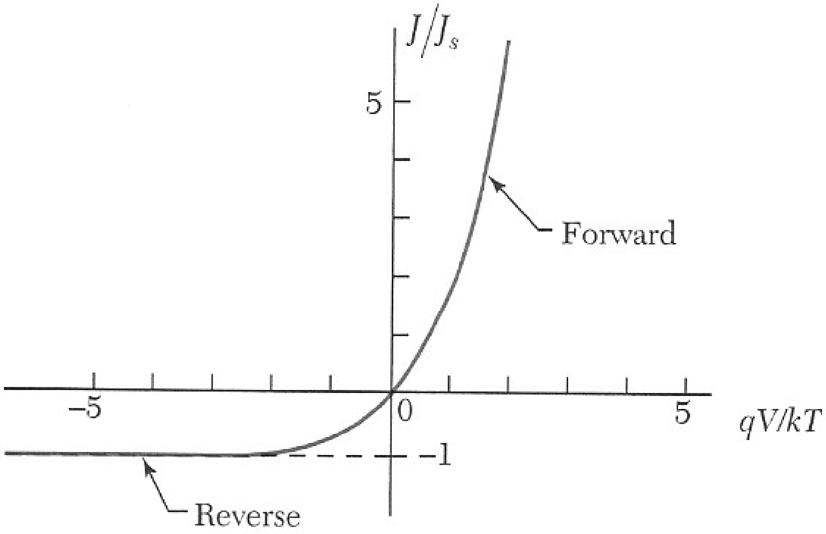
Tunneling

Metal-Semiconductor Contacts

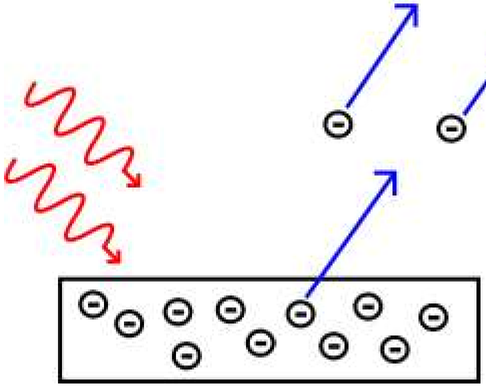
metal - semiconductor contacts

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



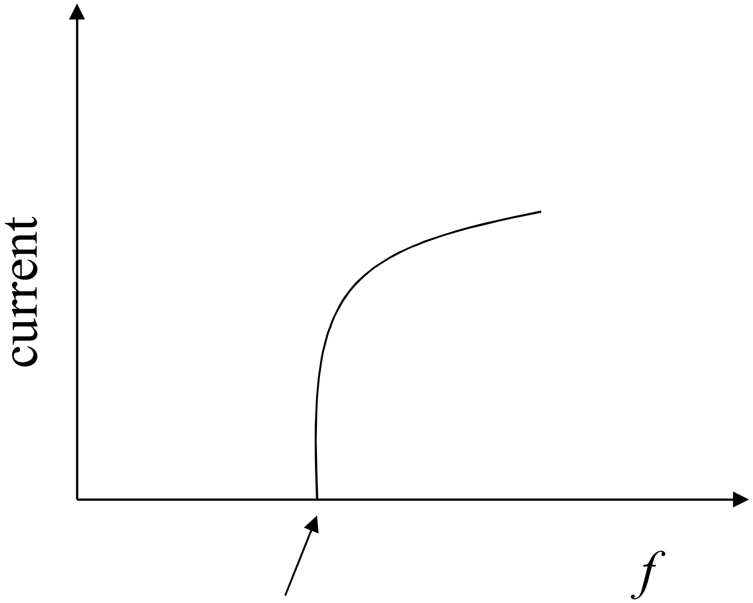


Photoelectric effect

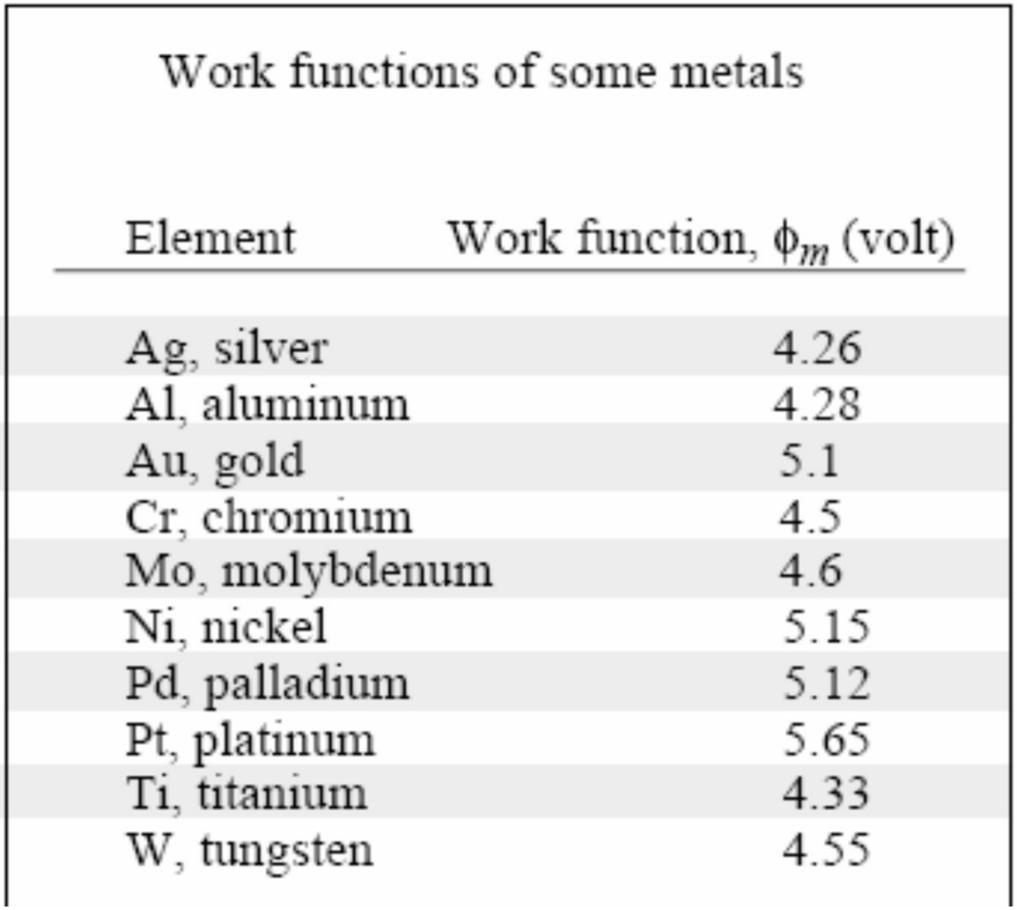


$hf_0 = e\phi$ at threshold

workfunction



threshold frequency f_0



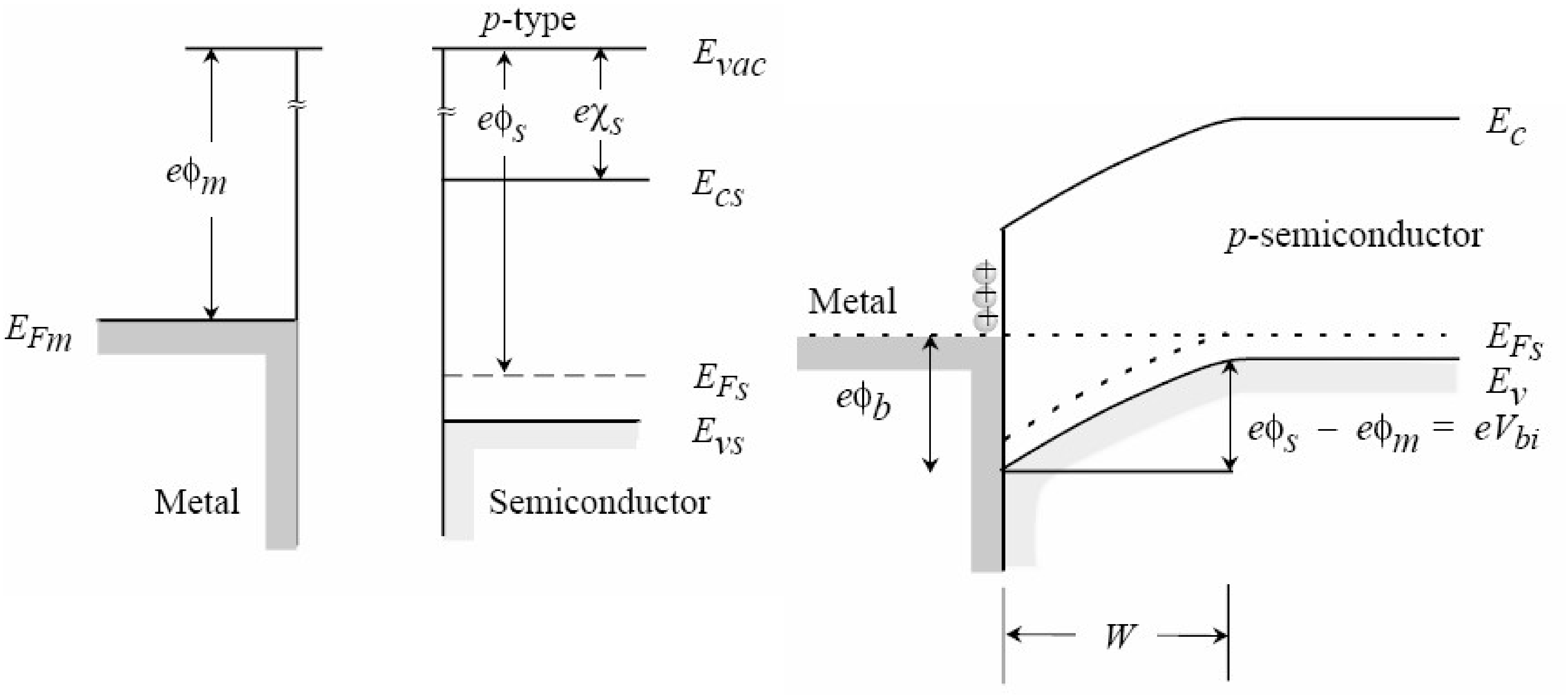
Work functions of some metals

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.

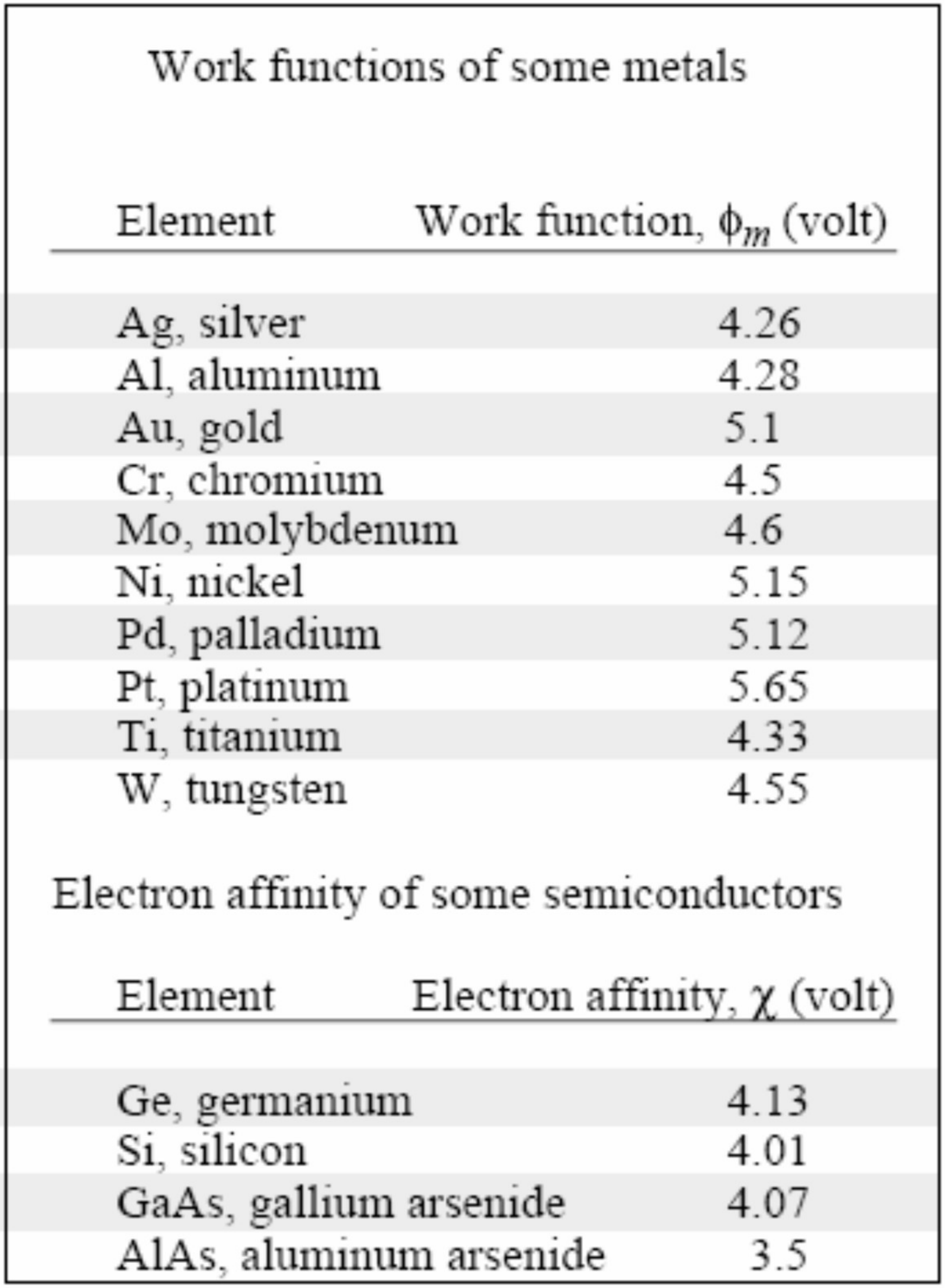
Singh

work function - electron affinity



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

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



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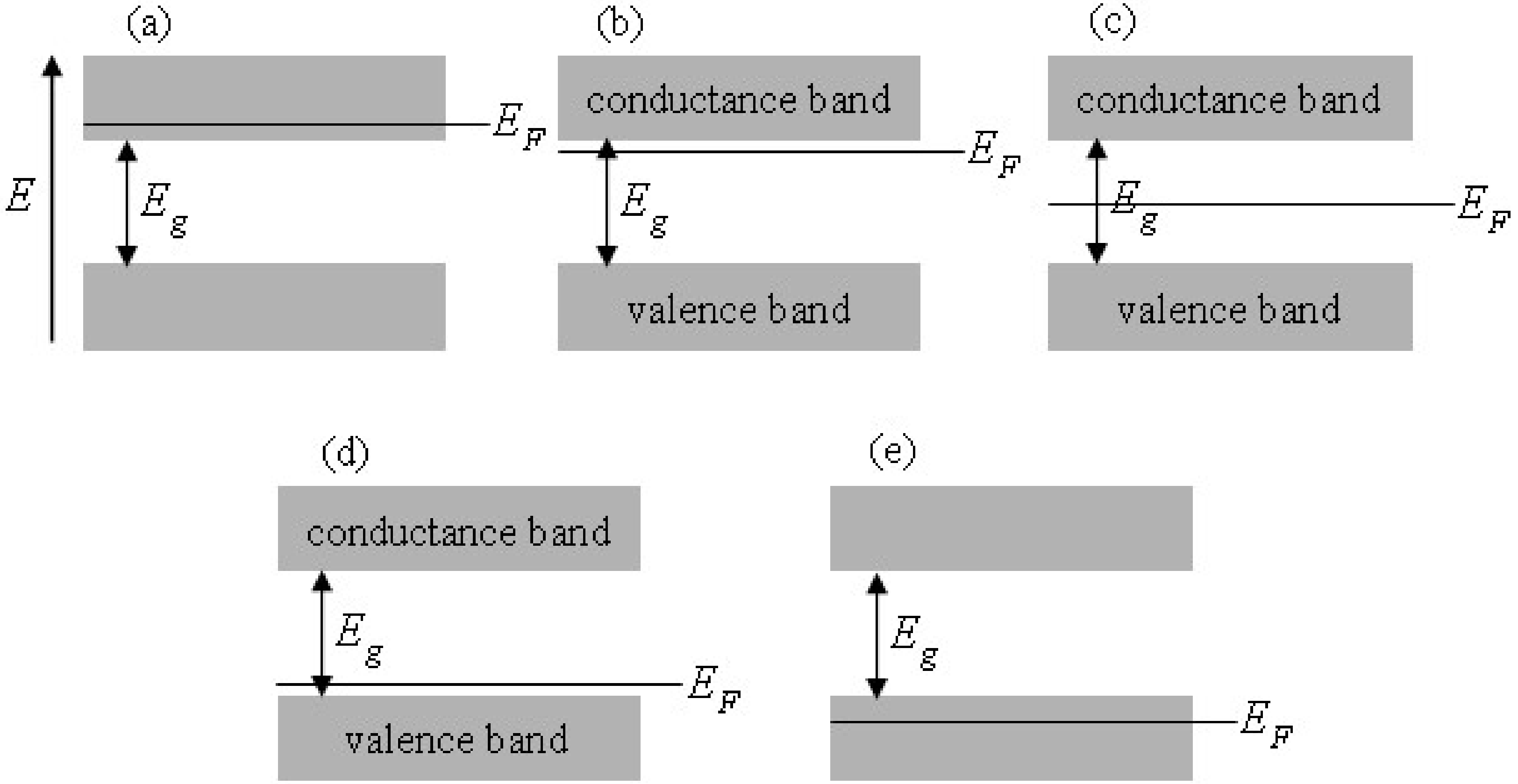
Pd, palladium	5.12
Pt, platinum	5.65
Ti, titanium	4.33
W, tungsten	4.55

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

Singh

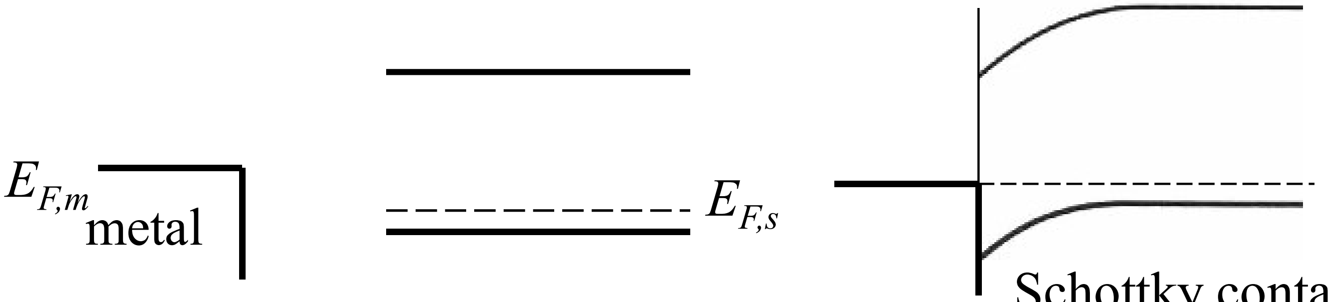


(a) A metal with a small workfunction. (b) An n-type semiconductor. (c) An insulator. (d) A p-type semiconductor. (e) A metal with a large workfunction.

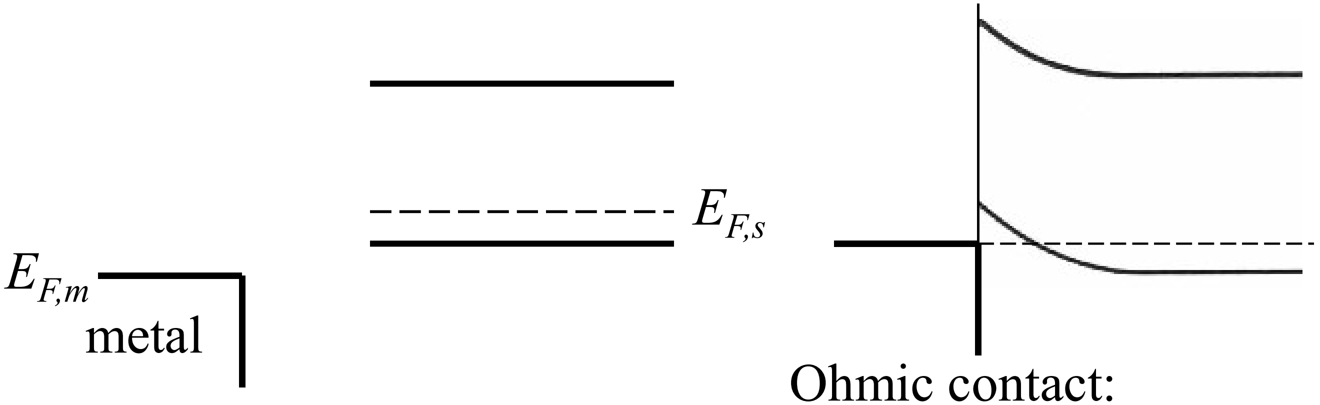
p-type

Schottky contact / ohmic contact

Walter Schottky



Schottky contact



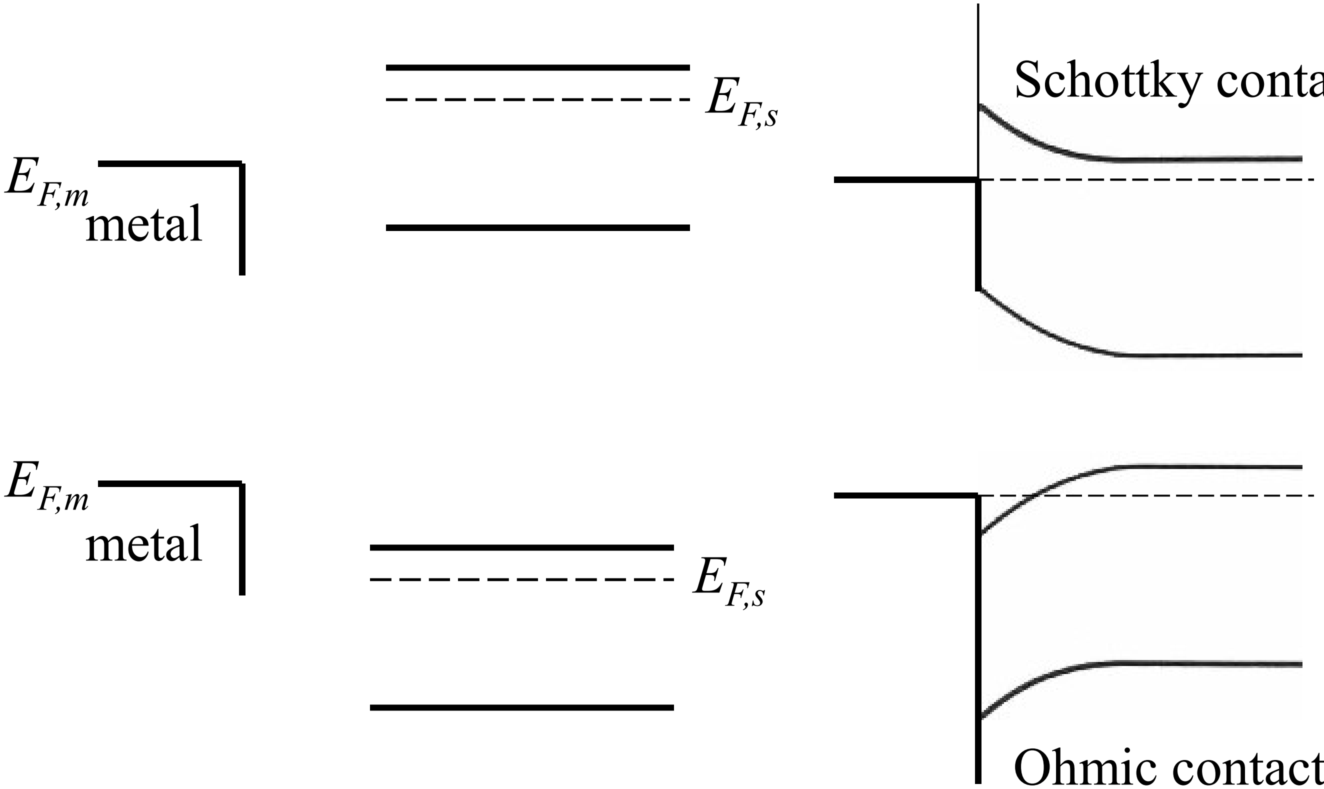
Ohmic contact:
linear resistance

specific contact resistance:

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

n-type

Schottky contact / ohmic contact

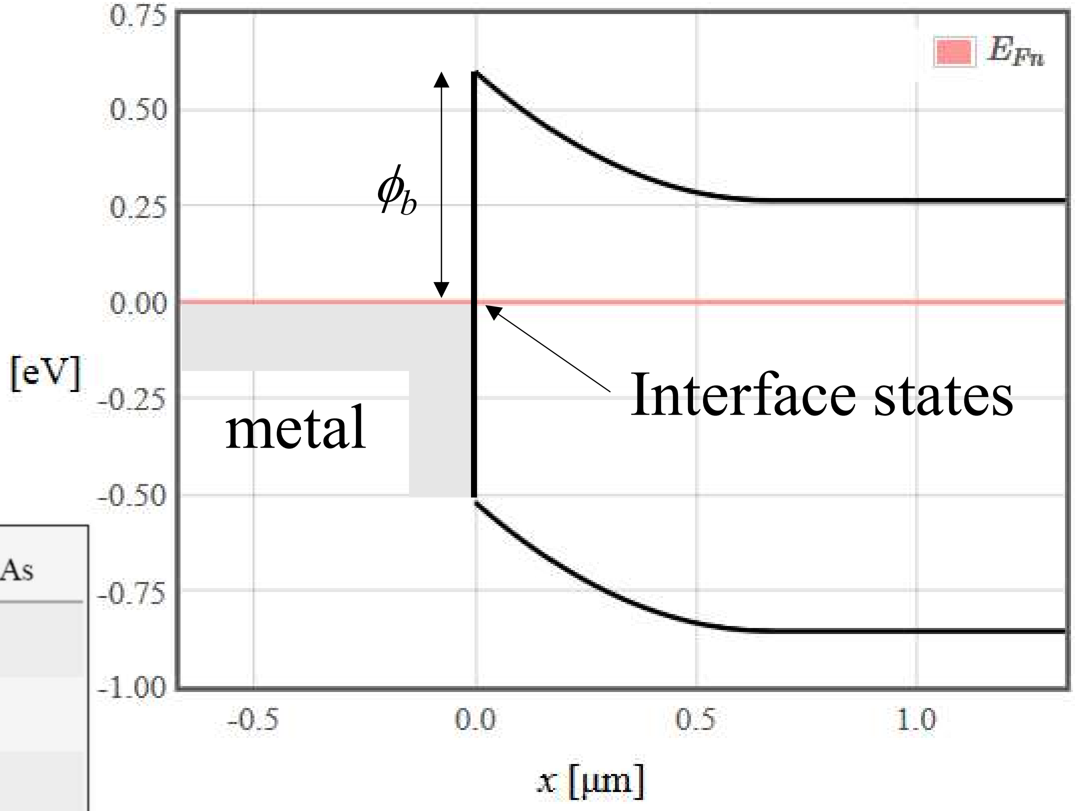


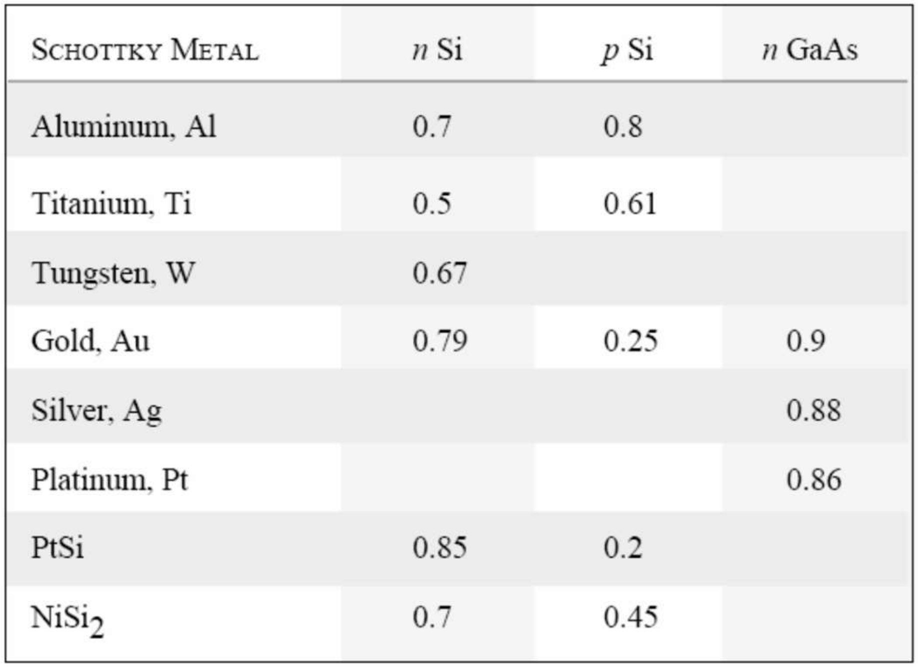
Schottky contact

Ohmic contact:
linear resistance

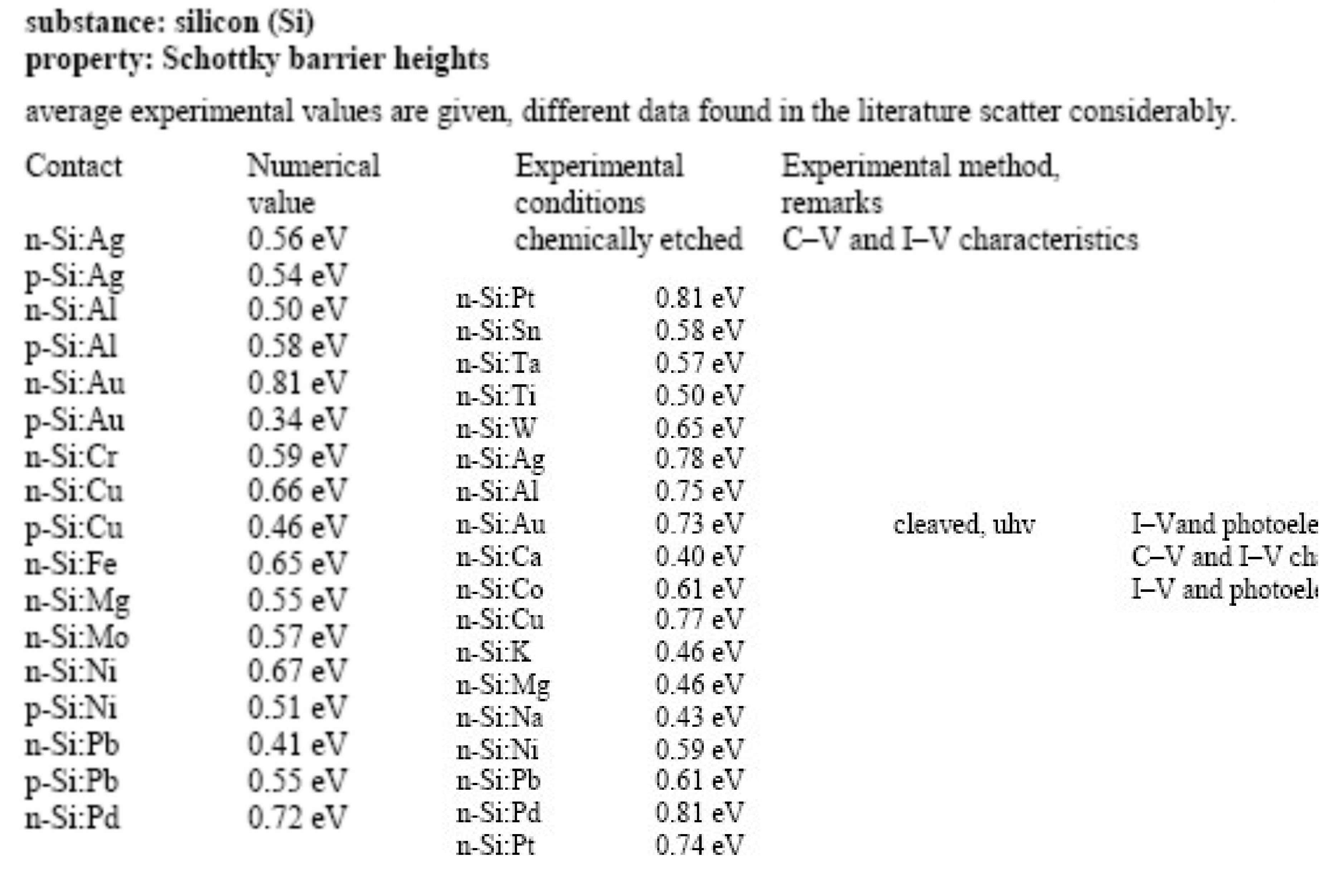
specific contact resistance: $$R_c = \left(\frac{\partial J}{\partial V}\right)^{-1}$$ Ω-cm^2

Interface states





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

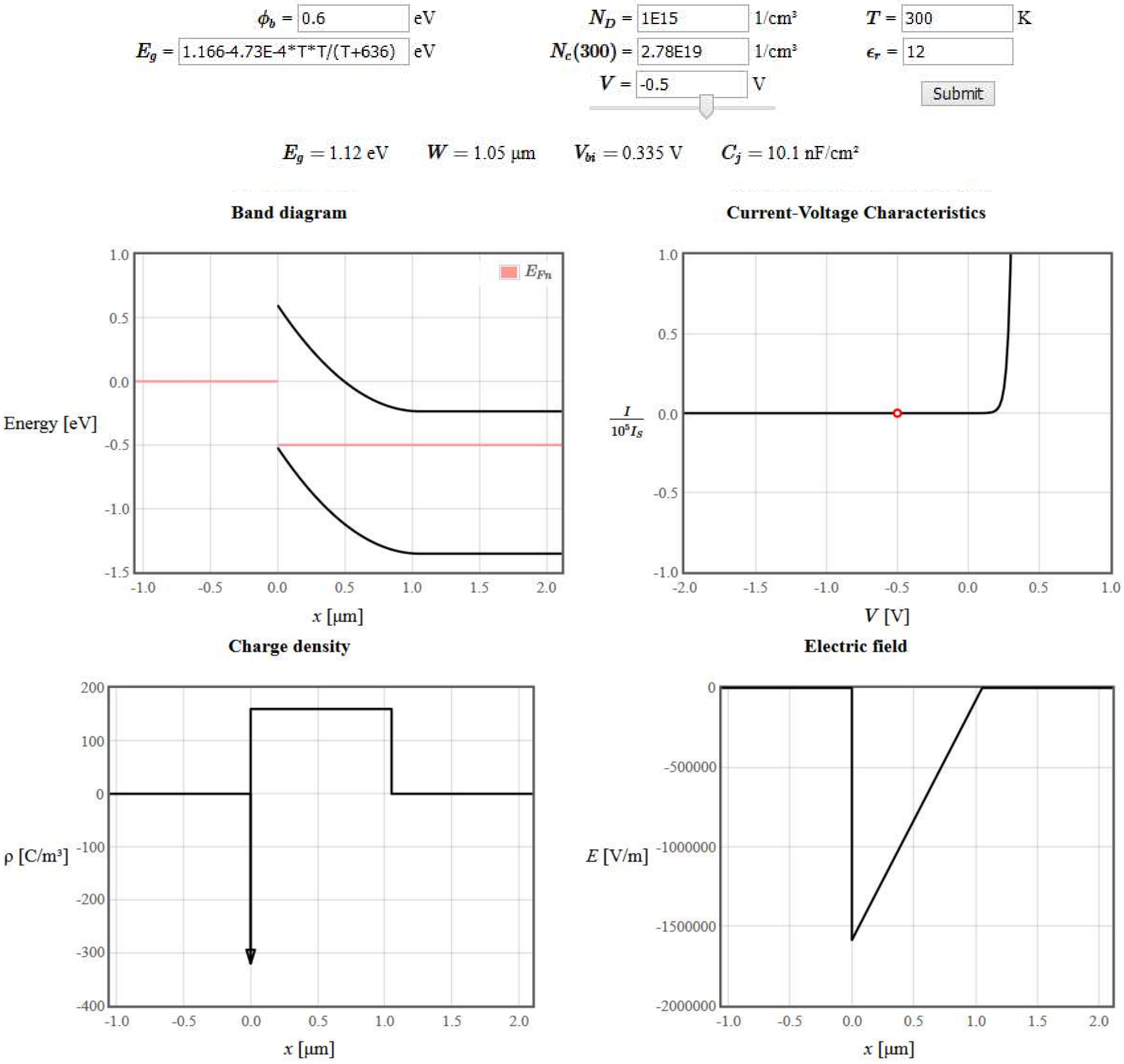
average experimental values are given, different data found in the literature scatter considerably.

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



ϕ_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

V = -0.5 V

T = 300 K

ϵ_r = 12

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

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

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

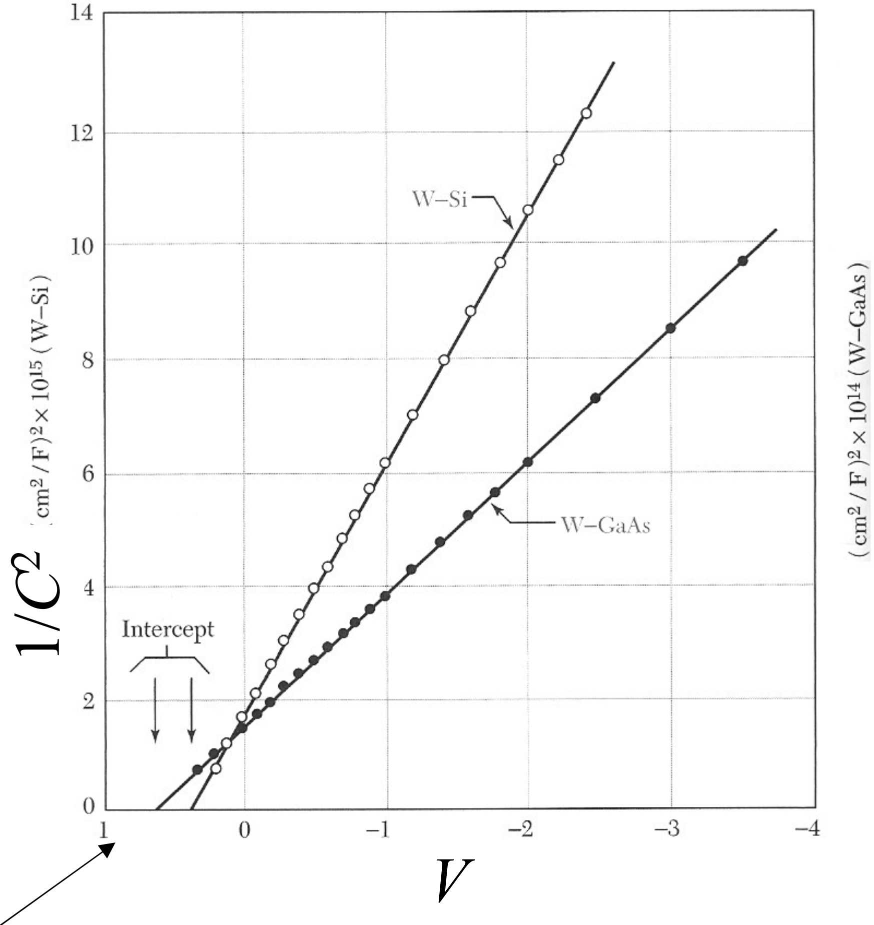
$$V = \frac{-eN_D}{\varepsilon}\left(\frac{x^2}{2} - x x_n\right)$$

CV measurements

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

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

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



GaAs has larger E_g and V_{bi}

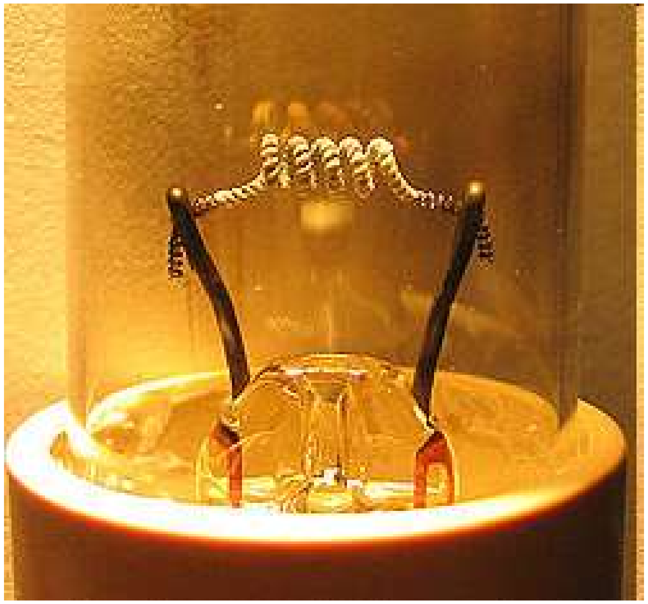
$$eV_{bi} = \phi_b - k_B T \ln\left(\frac{N_v(T)}{N_A}\right)$$

Thermionic emission

1901 Richardson

Owen Willans Richardson

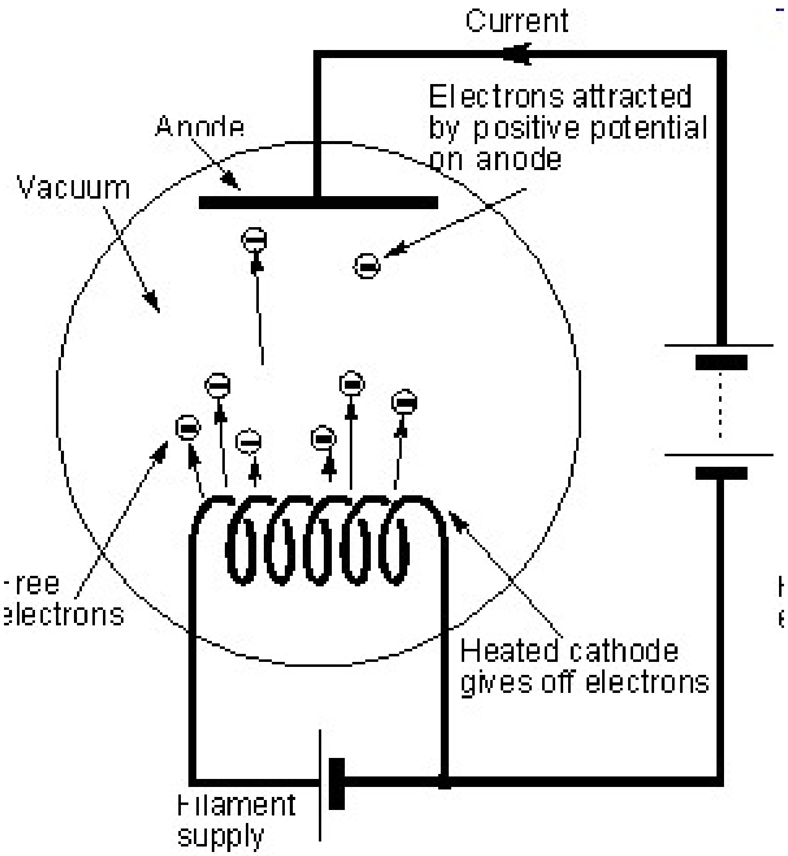
Current from a heated wire is:



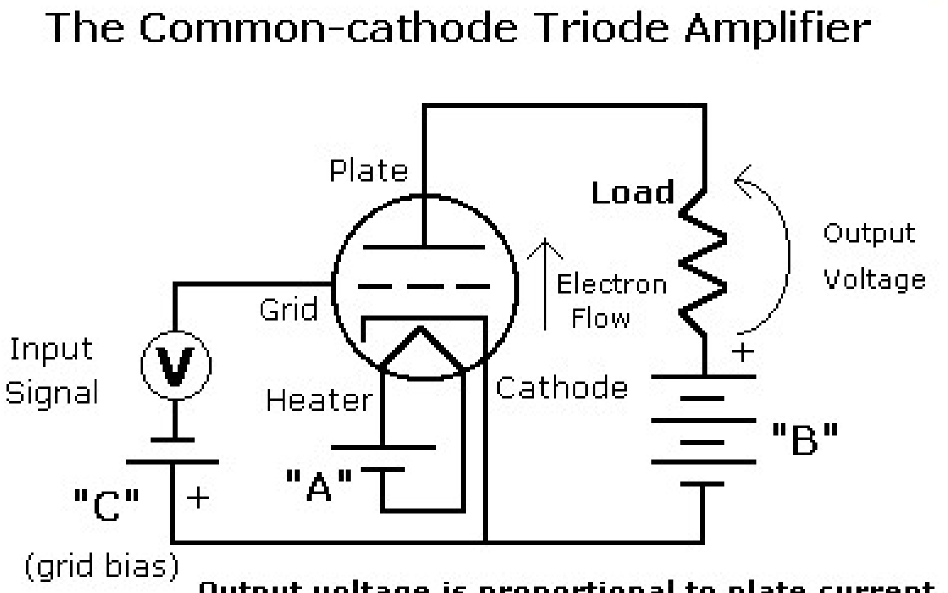
$$J = A_R T^2 \exp\left(-\frac{e\phi}{k_B T}\right)$$

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

Vacuum diodes

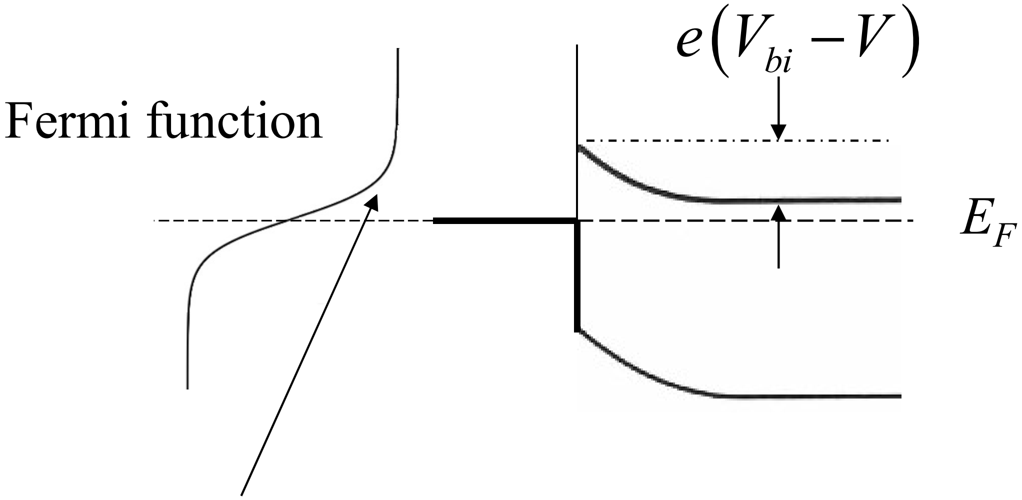


diode



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

Thermionic emission



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

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

Thermionic emission

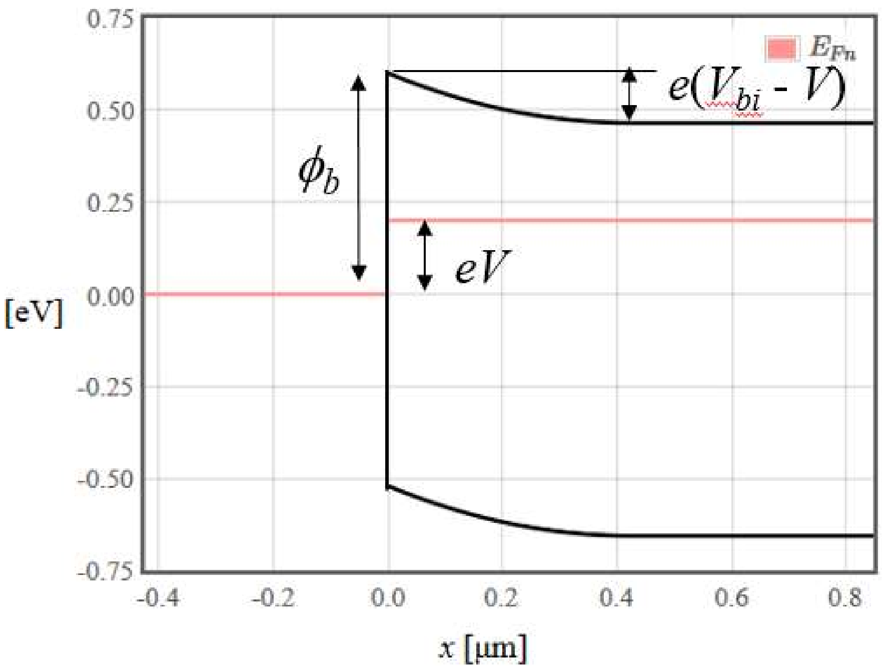
$$n_{th} \propto \exp\left(\frac{-E}{k_B T}\right) = \exp\left(\frac{-e\left(V_{bi} - V\right)}{k_B T}\right) = \exp\left(\frac{-eV_{bi}}{k_B T}\right)\exp\left(\frac{eV}{k_B T}\right)$$

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

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

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

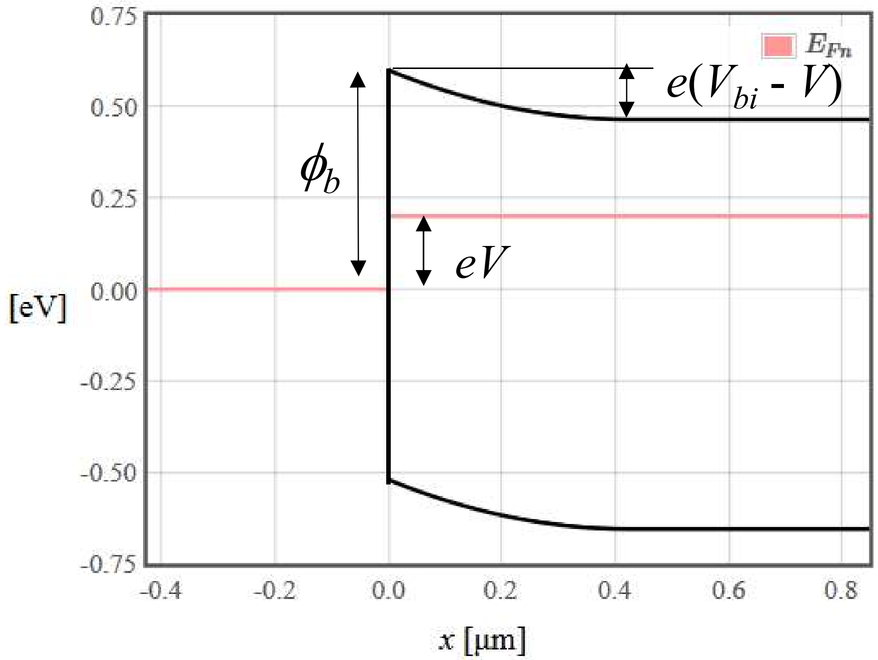
Forward bias



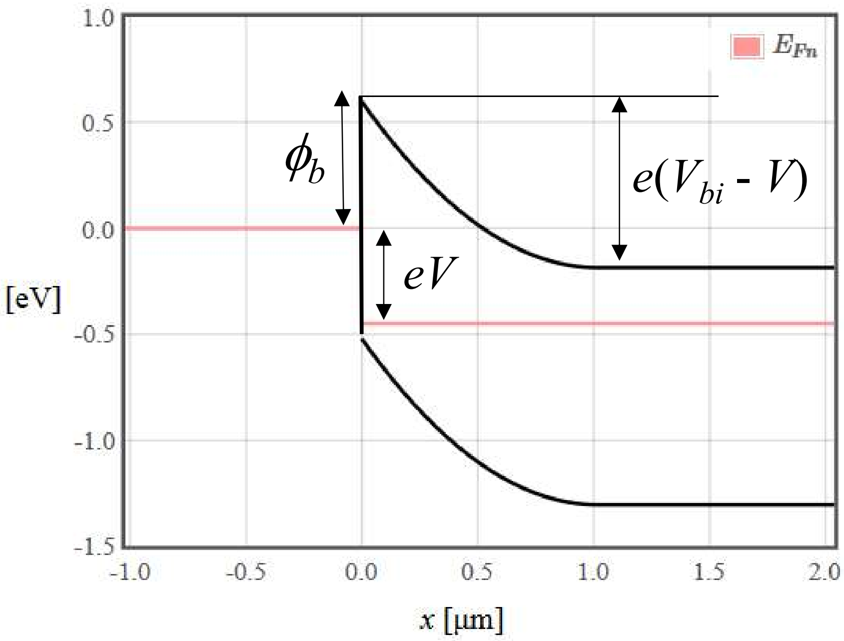
$$I = I_{sm} + I_{ms} = I_{ms}\left(\mathrm{e}^{\frac{eV}{k_B T}} - 1\right)$$

Schottky barrier

Forward bias



Reverse bias



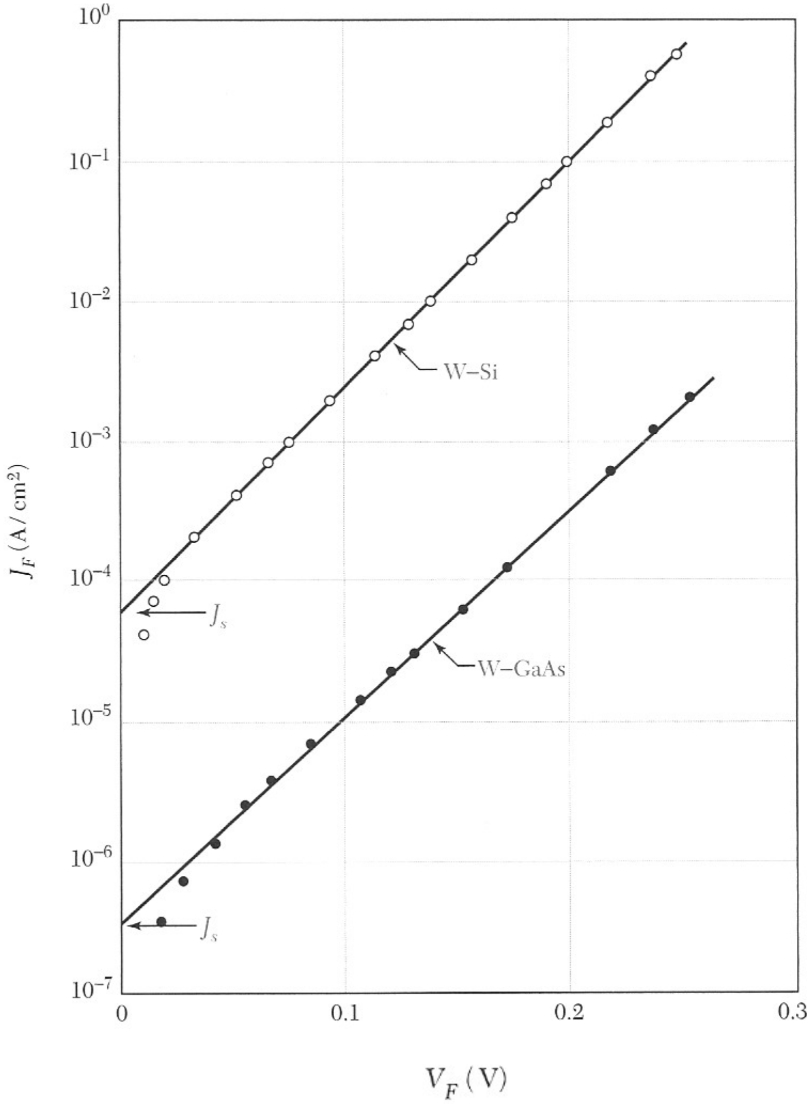
$I_{\mathrm{sm}} \sim \exp(eV/k_BT)$
I_{ms} constant

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

Thermionic emission

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

Nonideality factor = 1

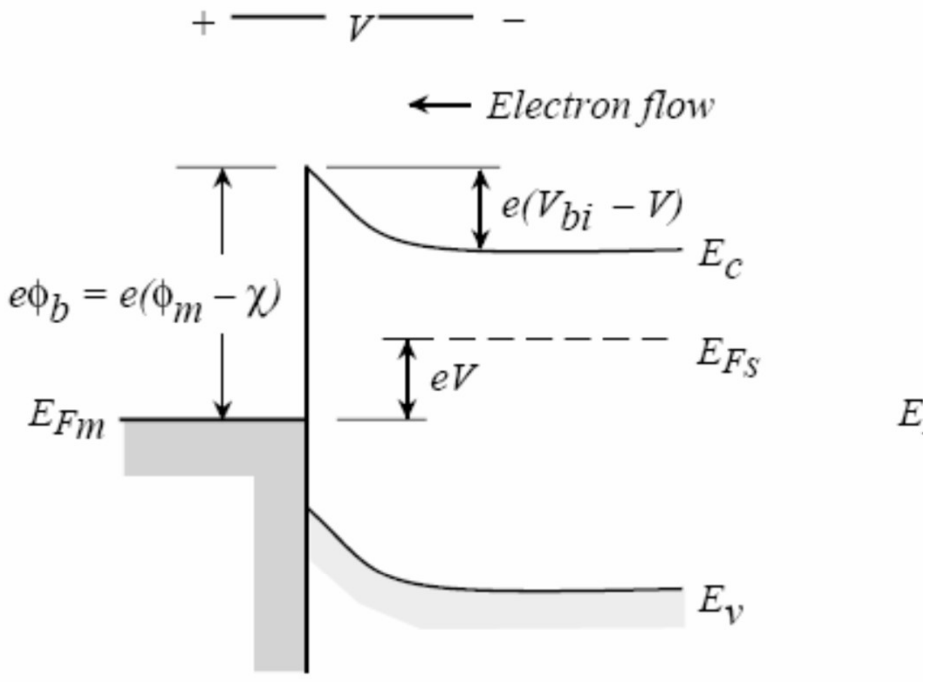


Thermionic emission

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

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.

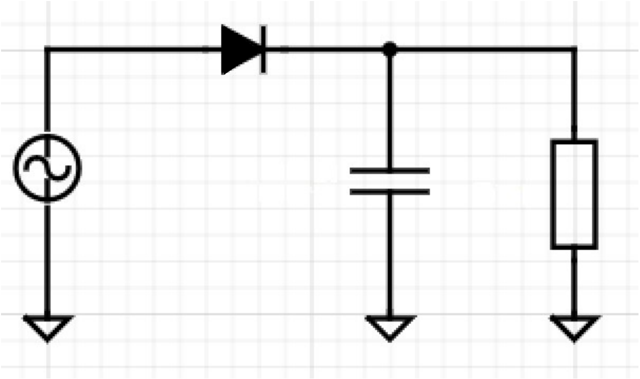
nonideality factor = 1.

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

Used as rf mixers.

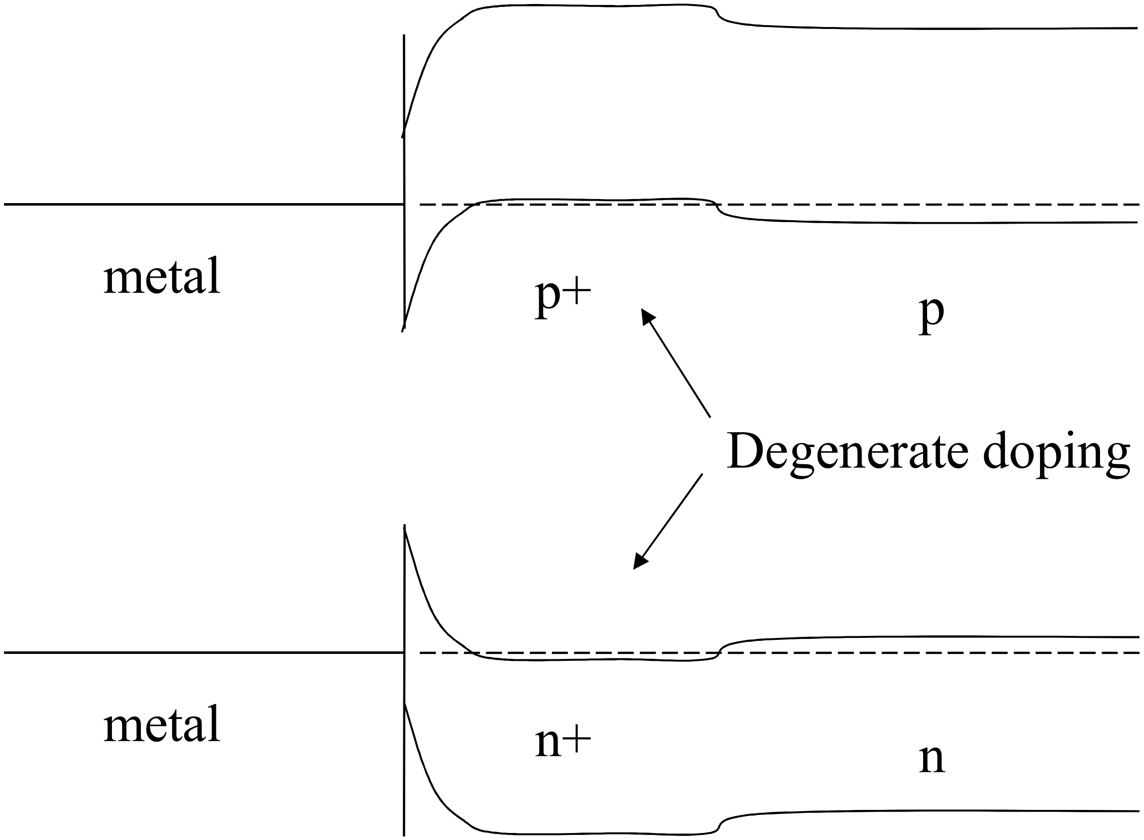
Low turn on voltage - high reverse bias current

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



Tunnel contacts

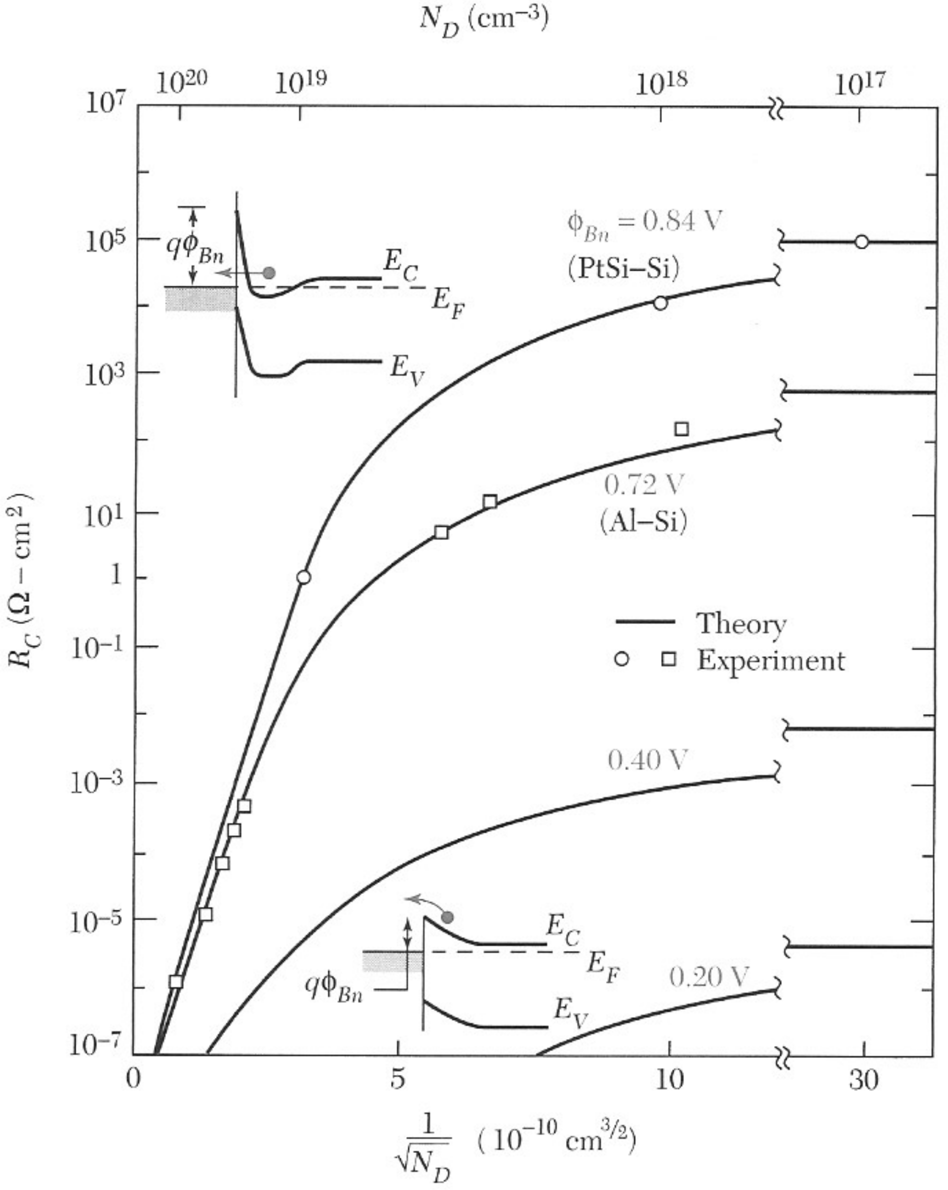
For high doping, the Schottky barrier is so thin that electrons can tunnel through it.



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 (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.