pn – diodes
Schottky diodes

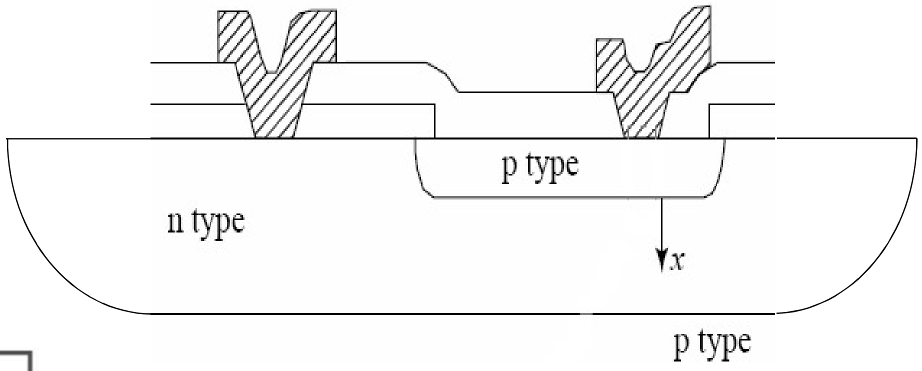
Exam

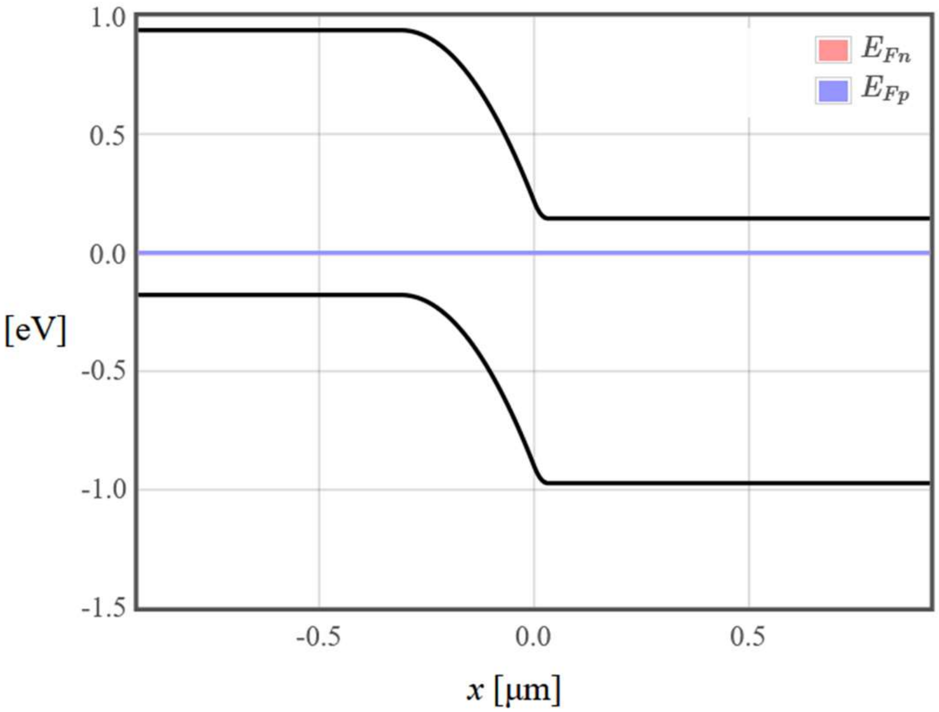
The exam on 22.11.2024 is not for students taking the course this year.

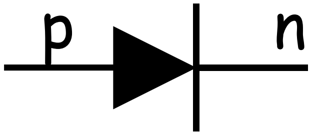
The exam is at the end of the semester

14:00 29.01.2025 P2

pn junctions





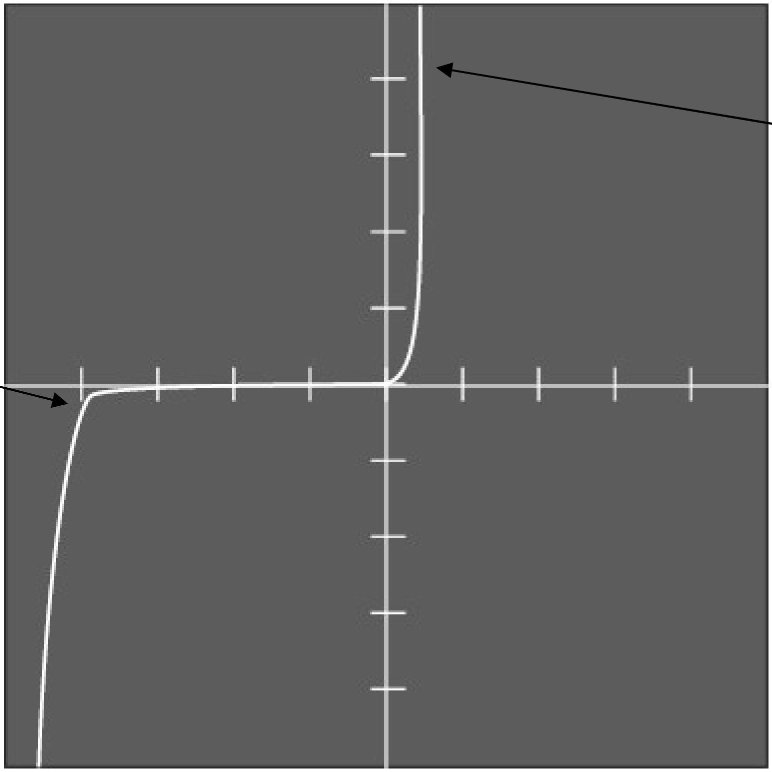


Real diodes

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

n = nonideality factor

$n = 1$ for an ideal diode



series resistance

reverse breakdown voltage

Real diodes

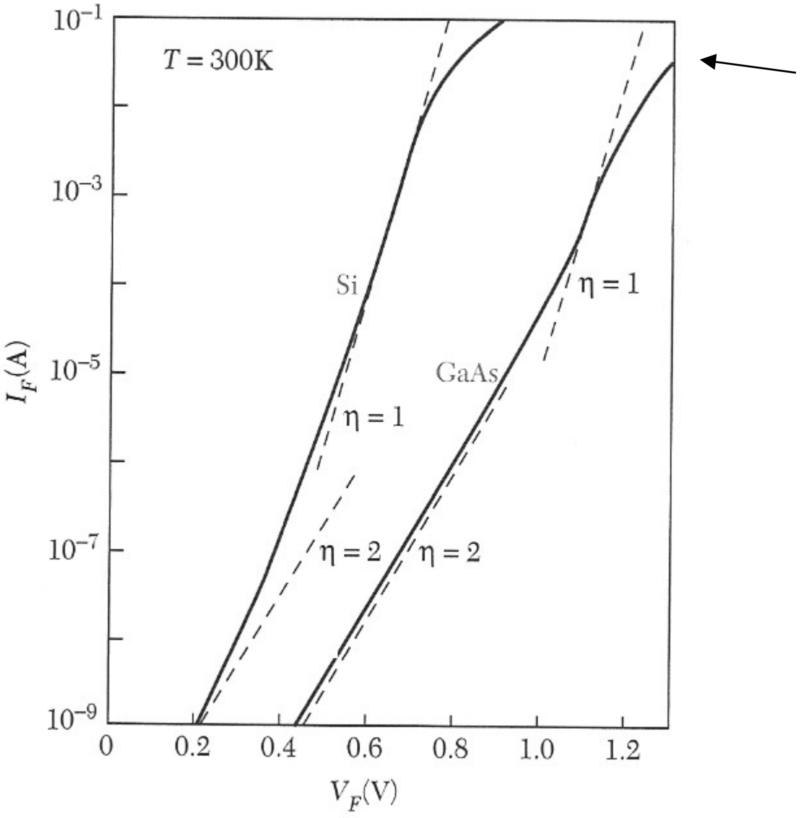
There is constant generation/recombination of electron hole pairs.

In forward bias there is less current due to recombination.

In reverse bias there is an extra current from generation.

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

$$I = I_{s1}\left(\exp\left(\frac{eV}{k_BT}\right) - 1\right) + I_{s2}\left(\exp\left(\frac{eV}{2k_BT}\right) - 1\right)$$

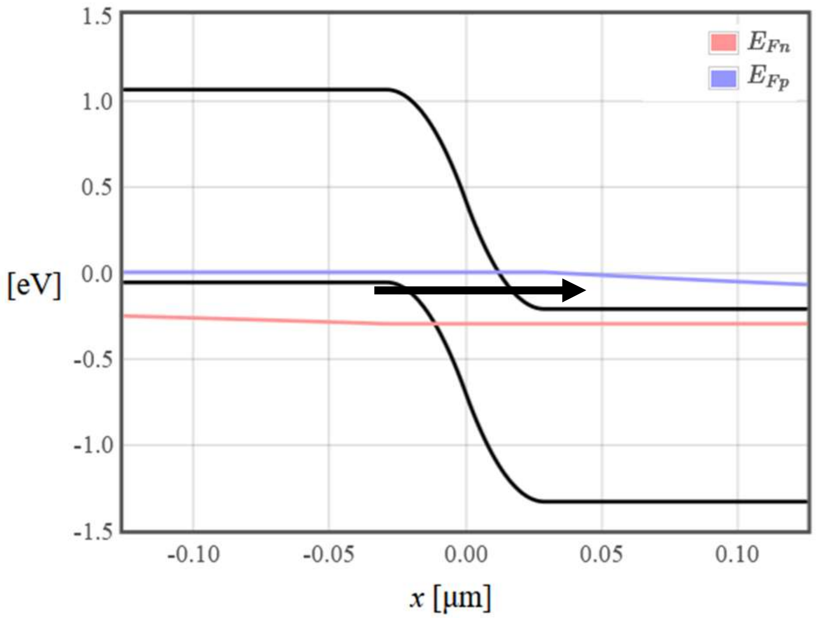


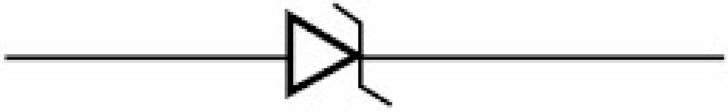
Very high bias: series resistance

High bias: ideal behavior, $n = 1$

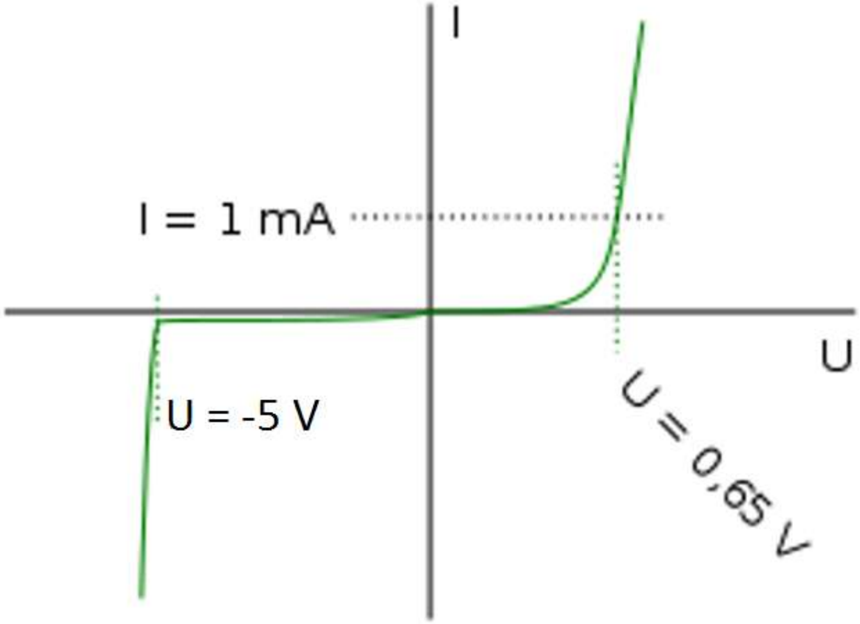
Low bias: recombination dominates, $n = 2$

Zener tunneling





(Zener diode)



Electrons tunnel from valence band to conduction band

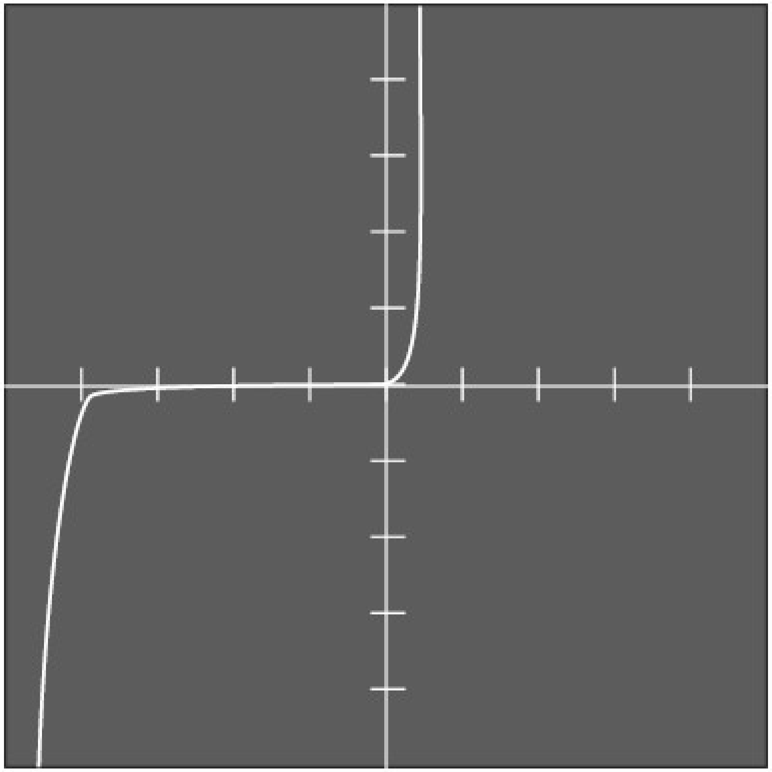
Occurs at high doping

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

Avalanche breakdown

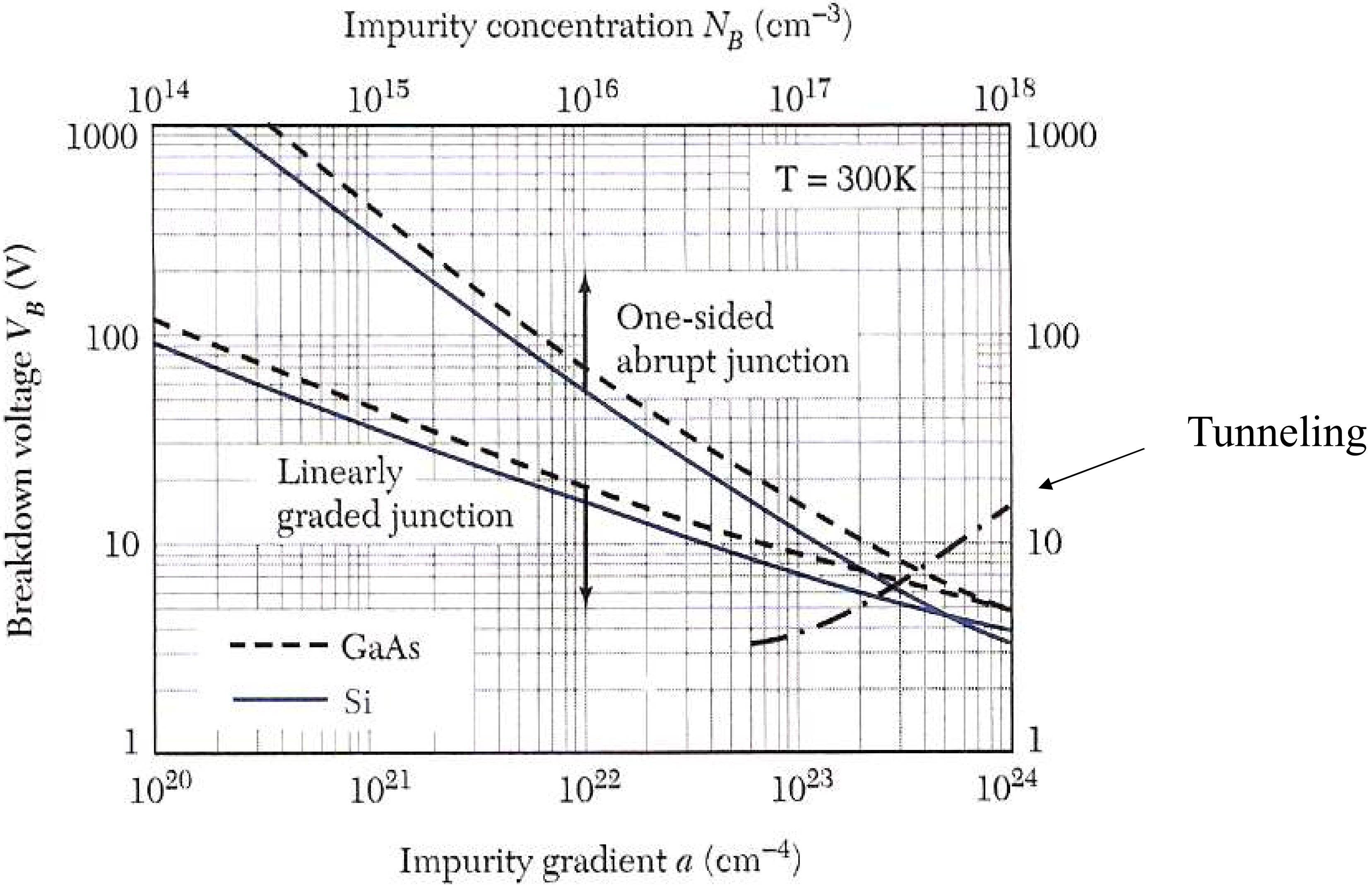
Impact ionization causes an avalanche of current

Occurs at low doping

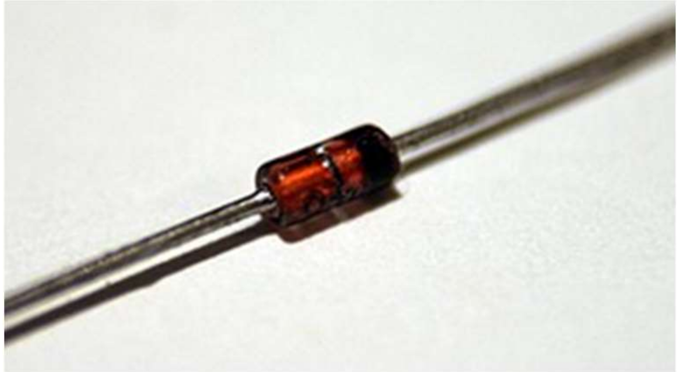


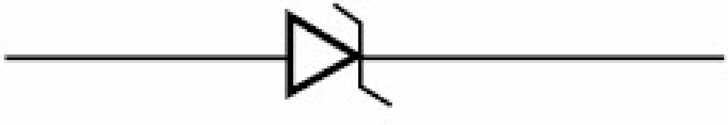
Vertical: 5 mA/div
Horizontal: 5 V/div

Avalanche breakdown



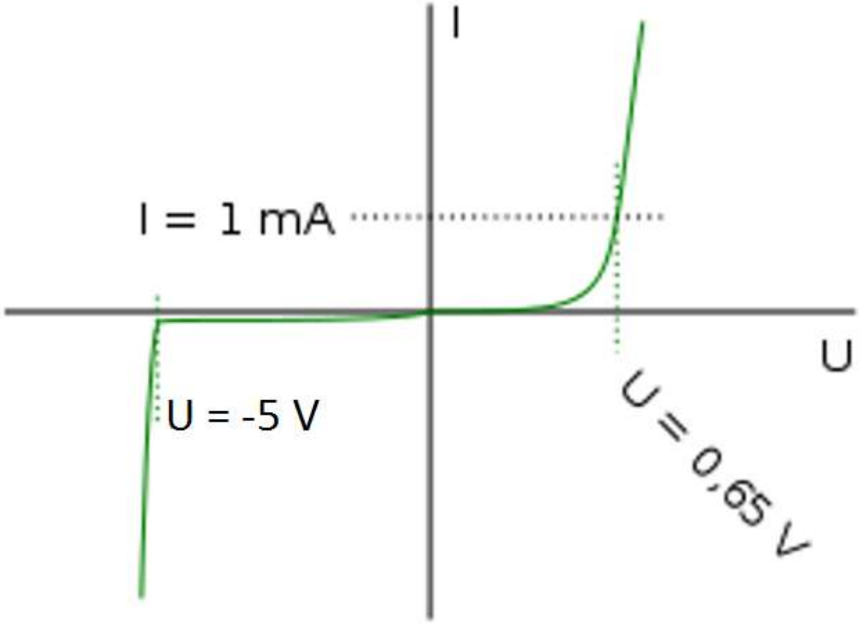
Zener diodes



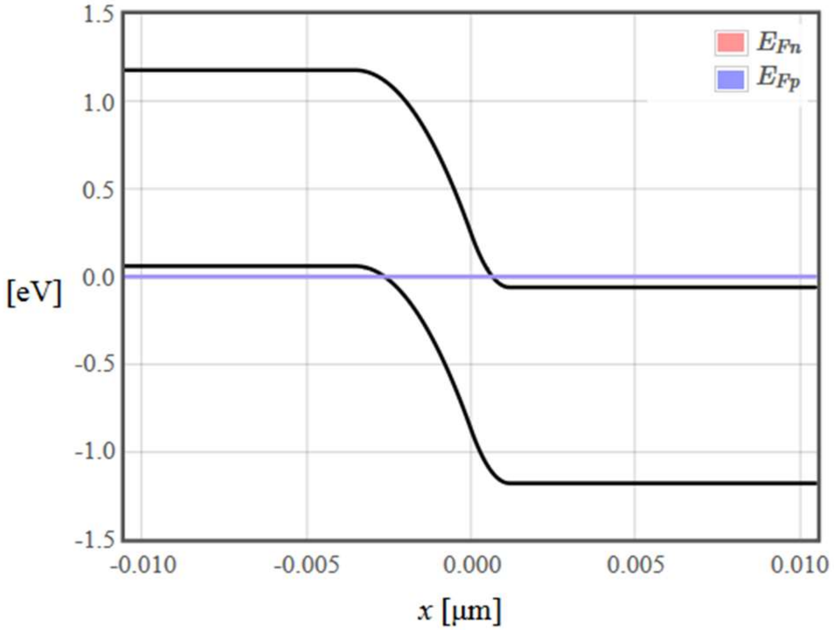


(Zener diode)

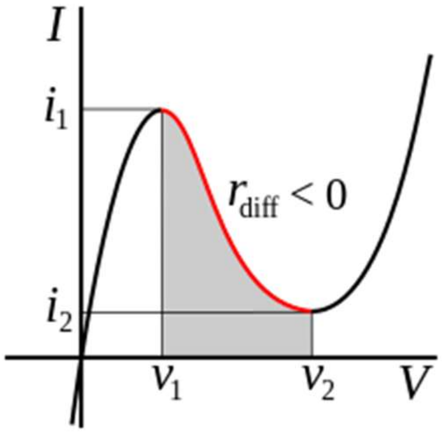
Zener tunneling an avalanche breakdown are present in a Zener diode. The combination is used to make the breakdown voltage temperature independent.



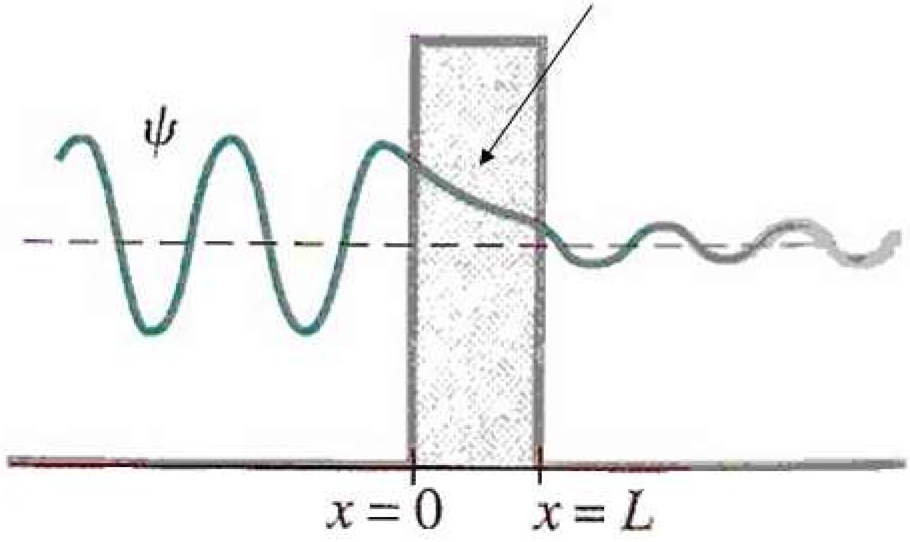
Tunnel diodes / Esaki diodes



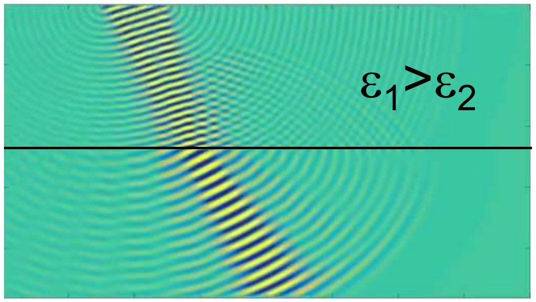
Both sides of the diode are degenerately doped



Tunneling



wave decays exponentially in the classically forbidden region

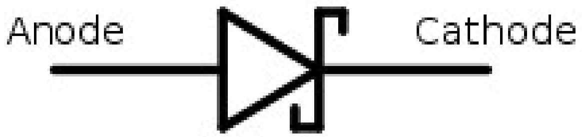


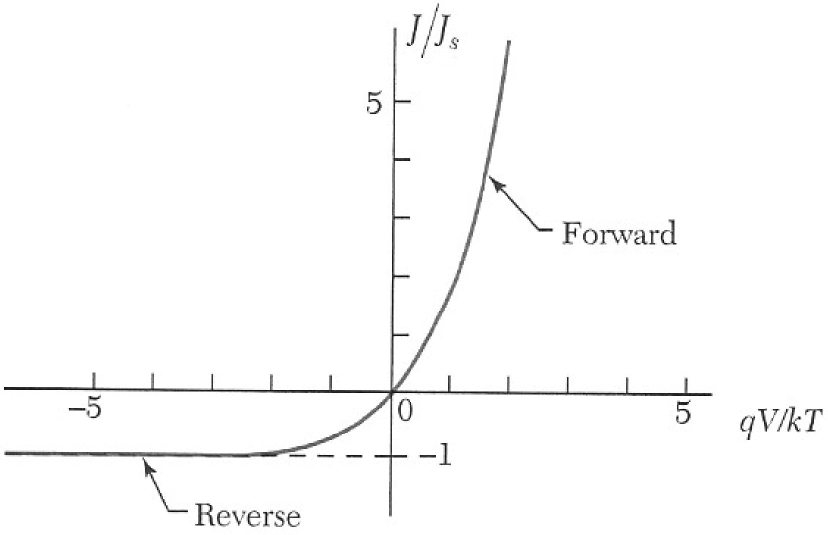
Tunneling is a wave phenomena. Tunneling and total internal reflection are used in a beam splitter.

Metal-Semiconductor Contacts

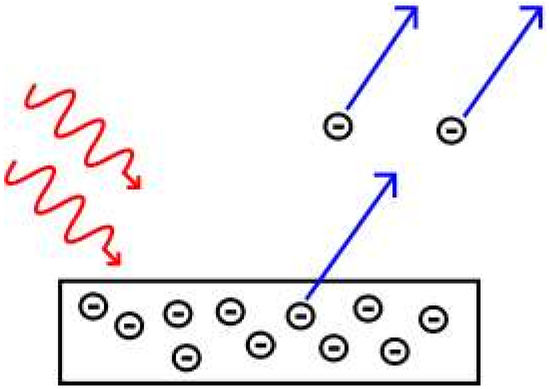
metal - semiconductor contacts

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



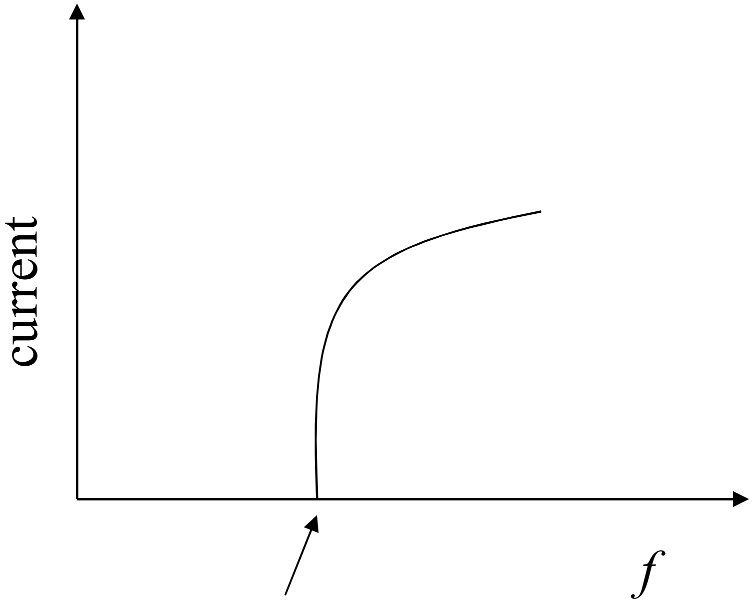


Photoelectric effect

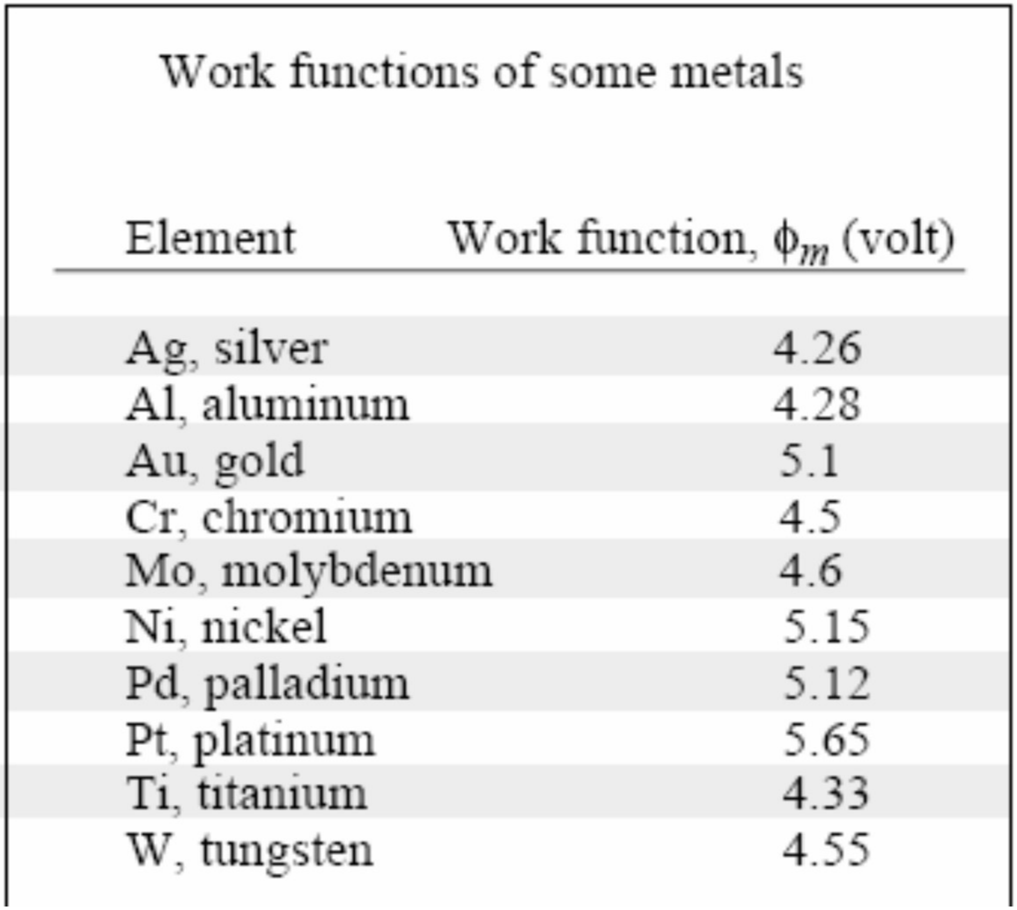


$hf_0 = e\phi$ at threshold

workfunction



threshold frequency f_0



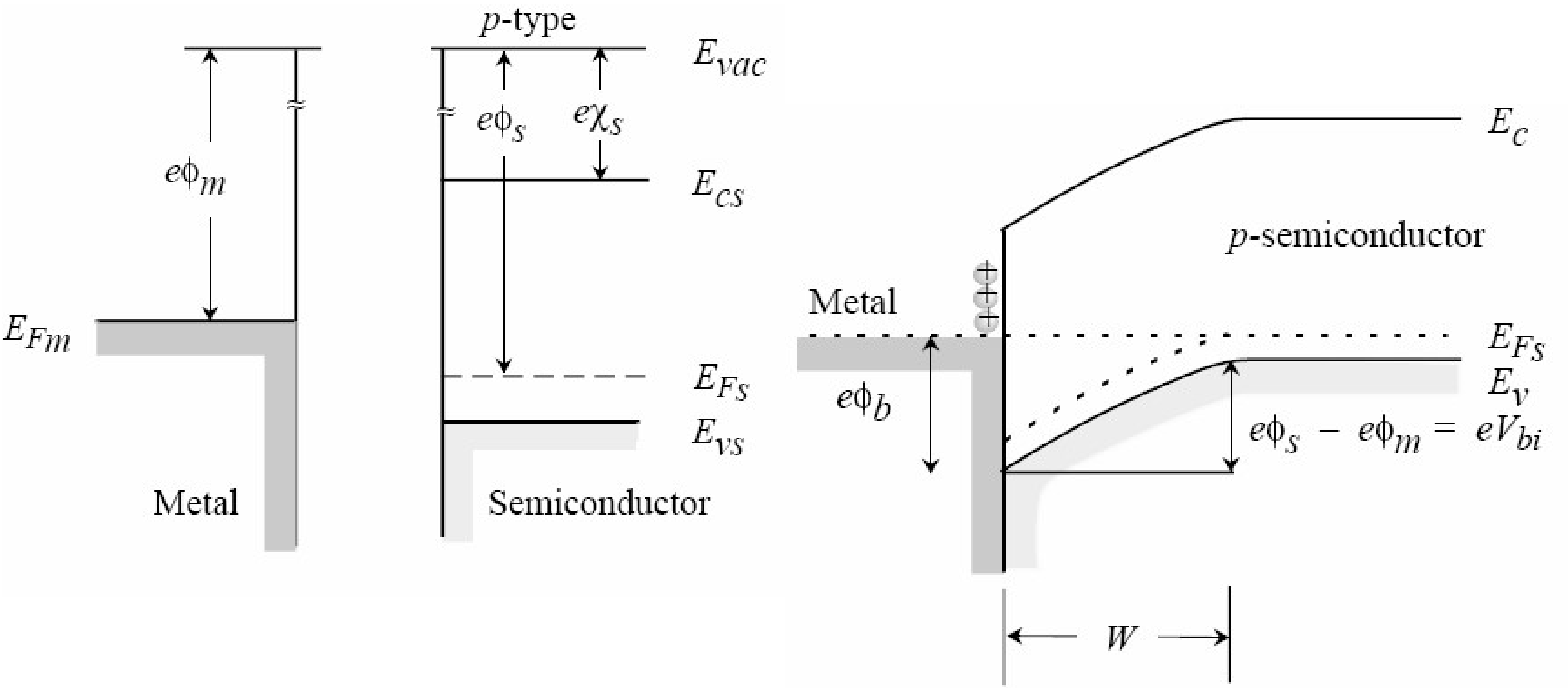
Work functions of some metals

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.

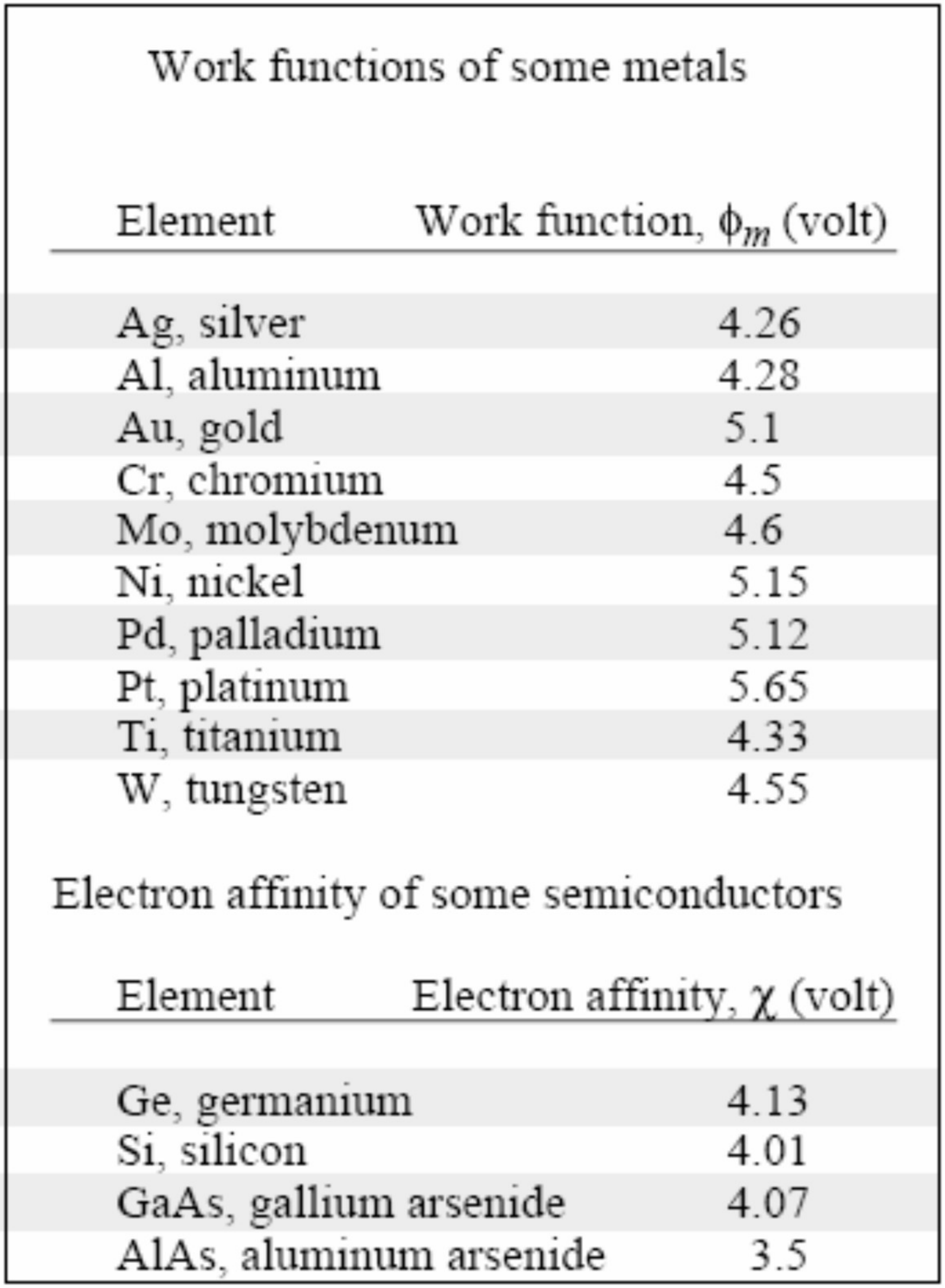
Singh

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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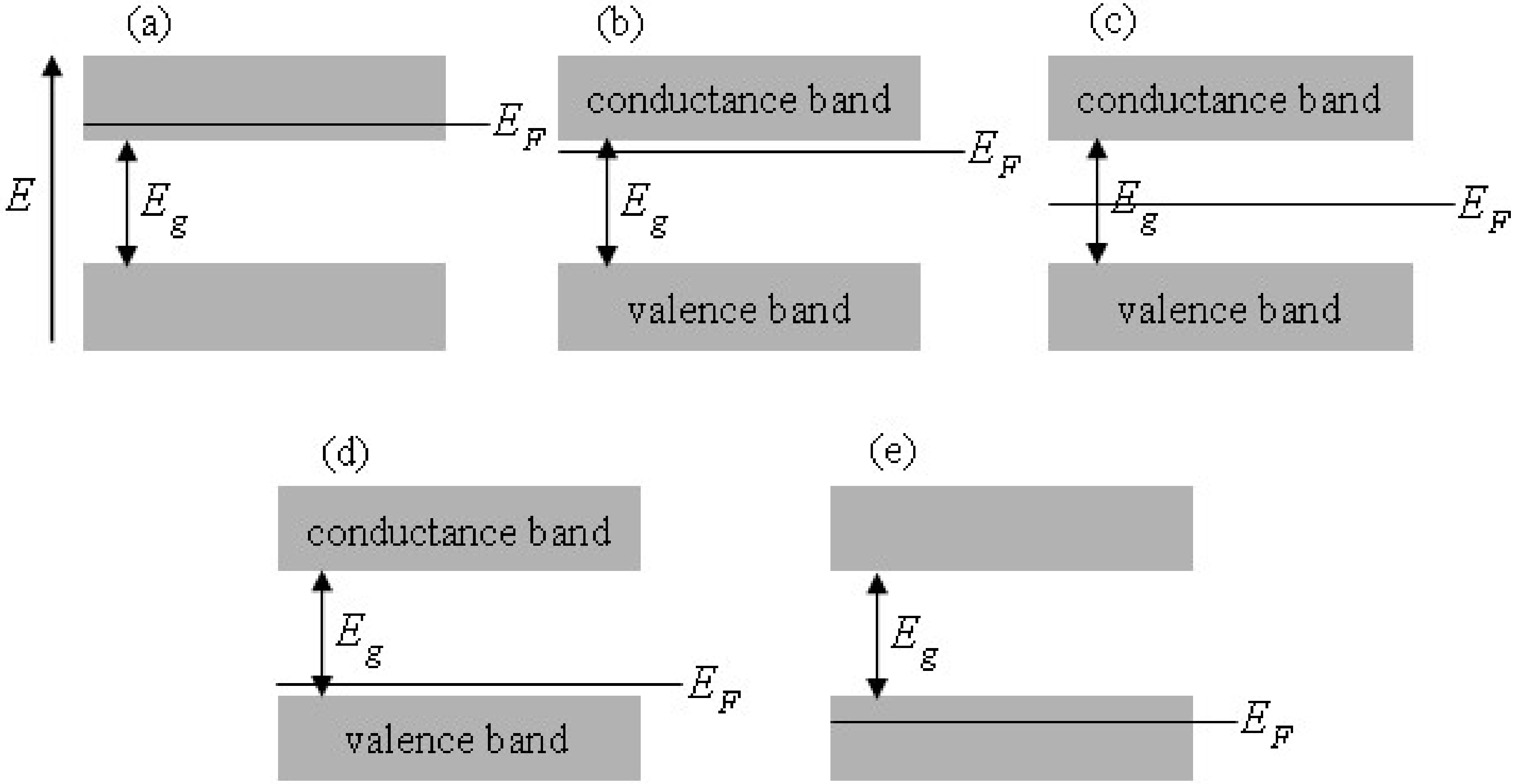
Ti, titanium	4.33
W, tungsten	4.55

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

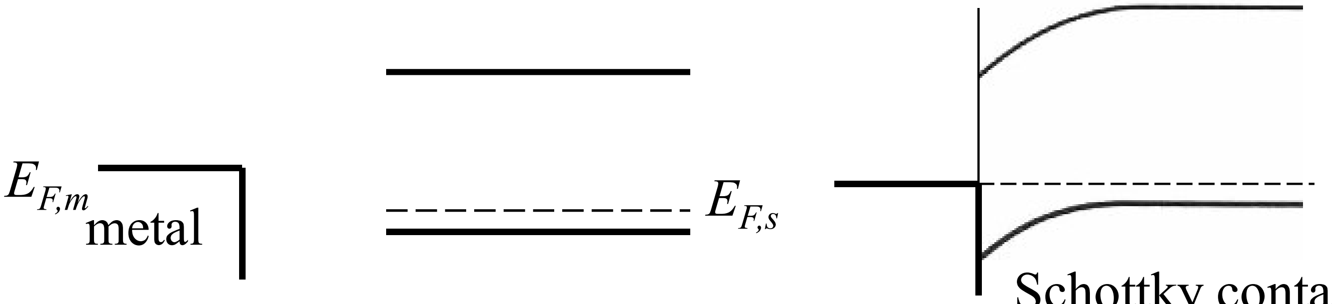


(a) A metal with a small workfunction. (b) An n-type semiconductor. (c) An insulator. (d) A p-type semiconductor. (e) A metal with a large workfunction.

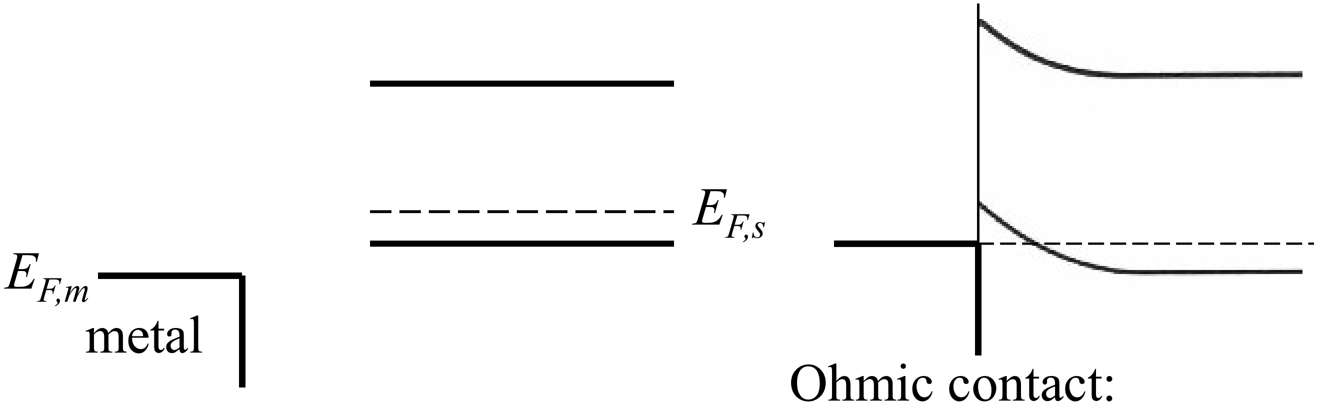
p-type

Walter Schottky

Schottky contact / ohmic contact



Schottky contact

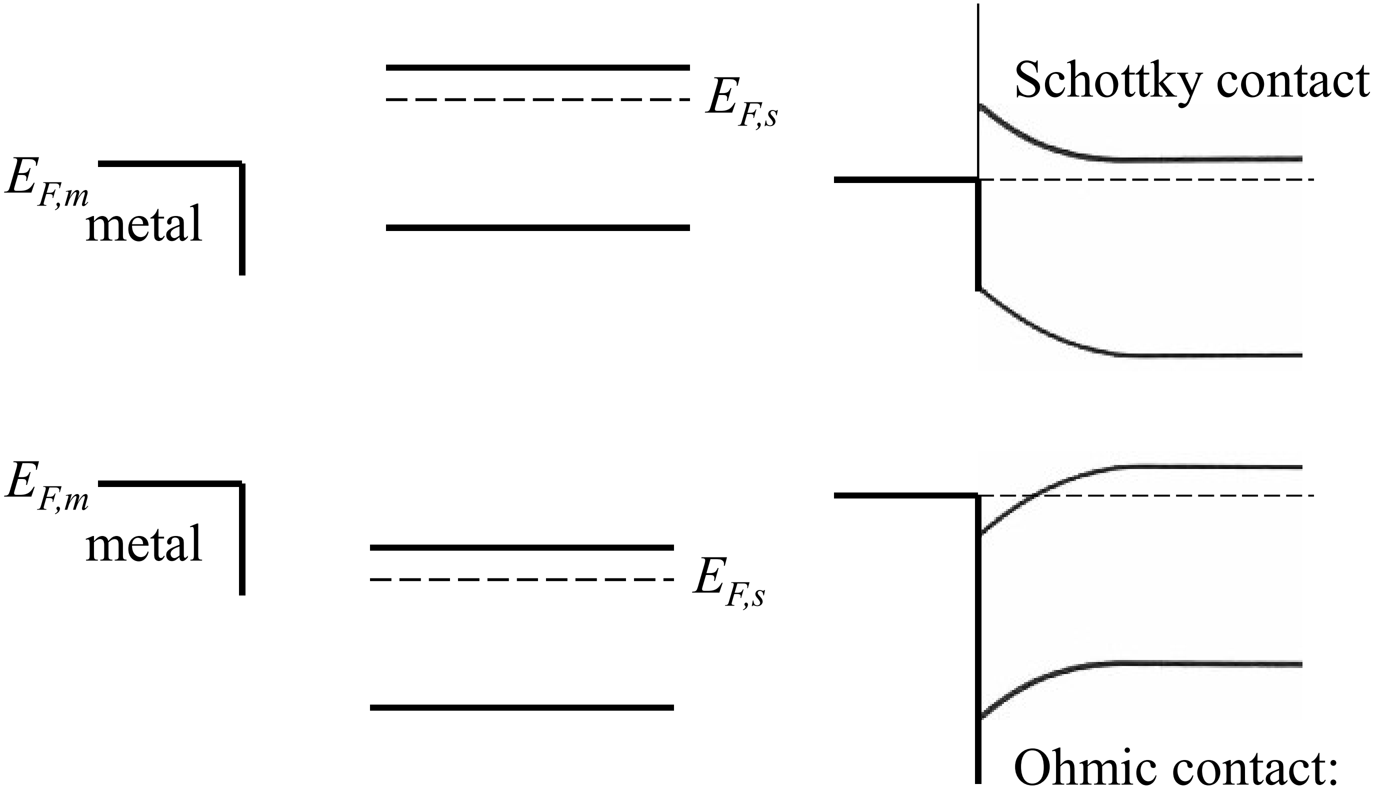


Ohmic contact:
linear resistance

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

n-type

Schottky contact / ohmic contact

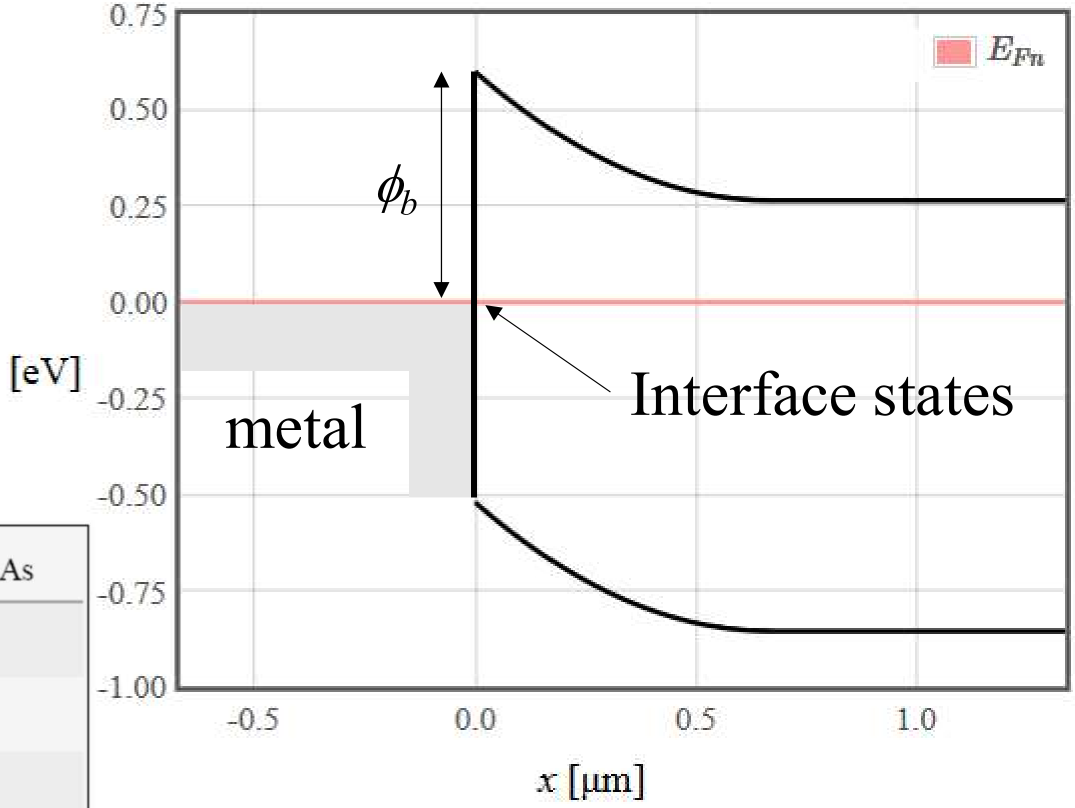


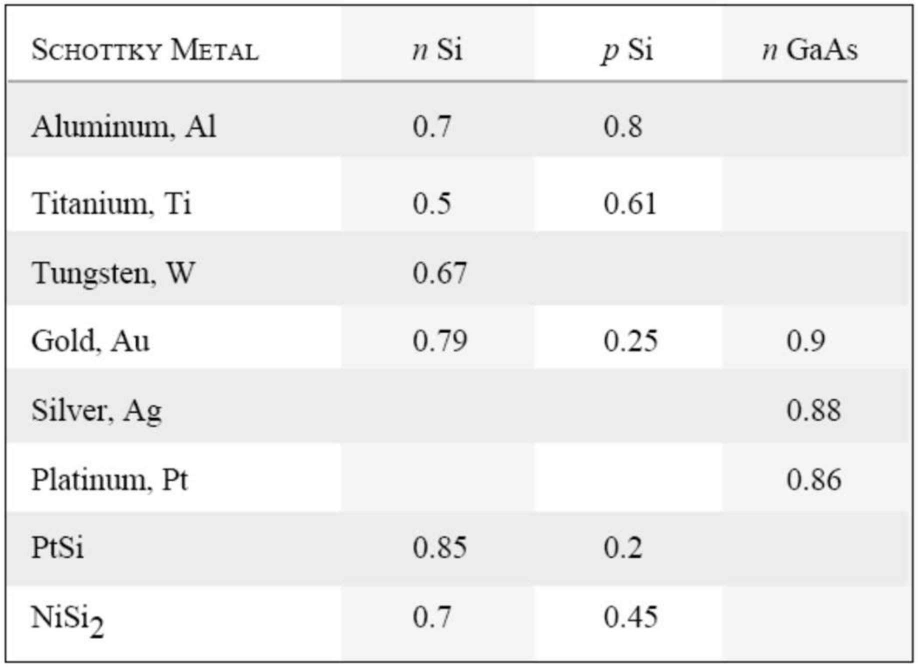
Schottky contact

Ohmic contact:
linear resistance

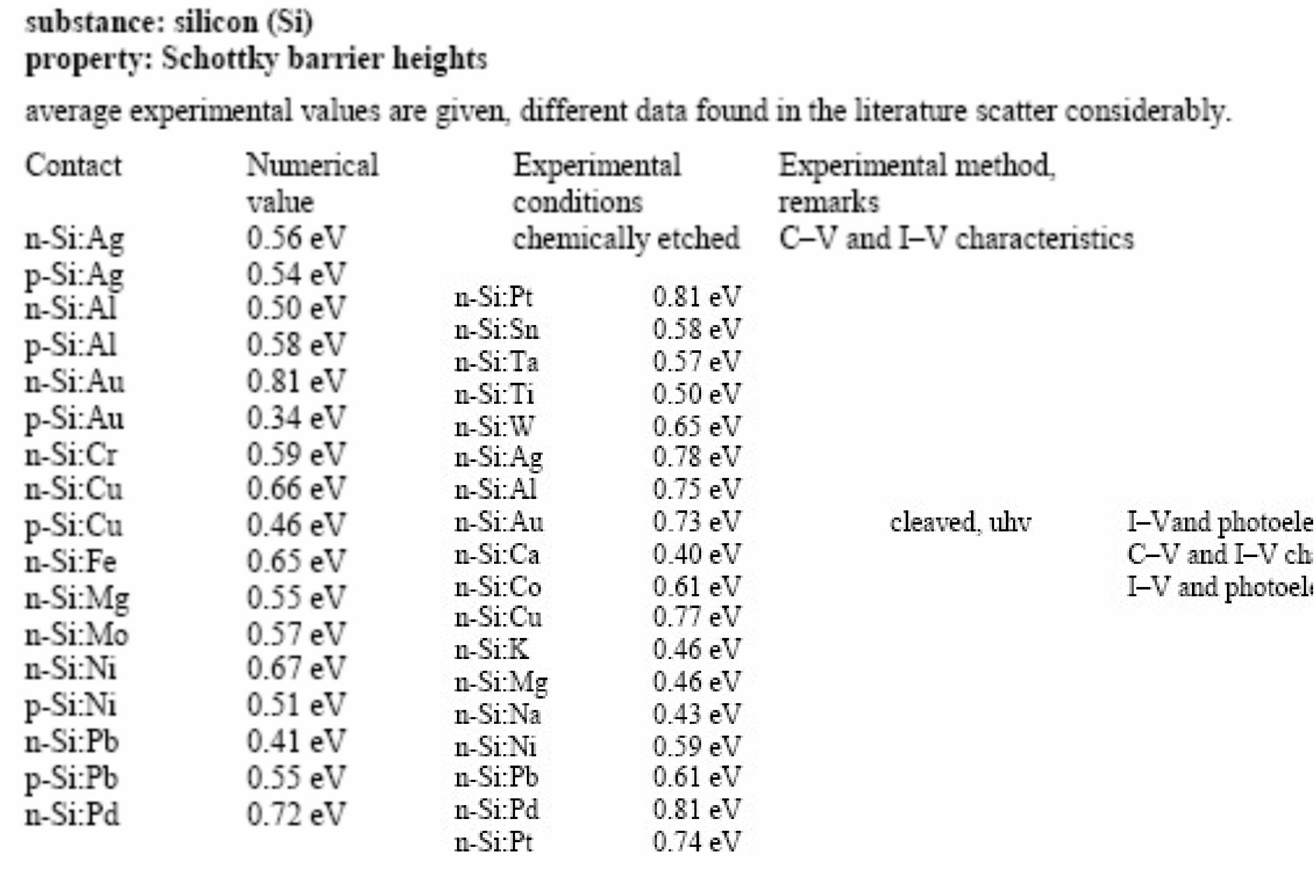
specific contact resistance: $R_c = \left(\frac{\partial J}{\partial V} \right)^{-1}$ Ω-cm^2

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	



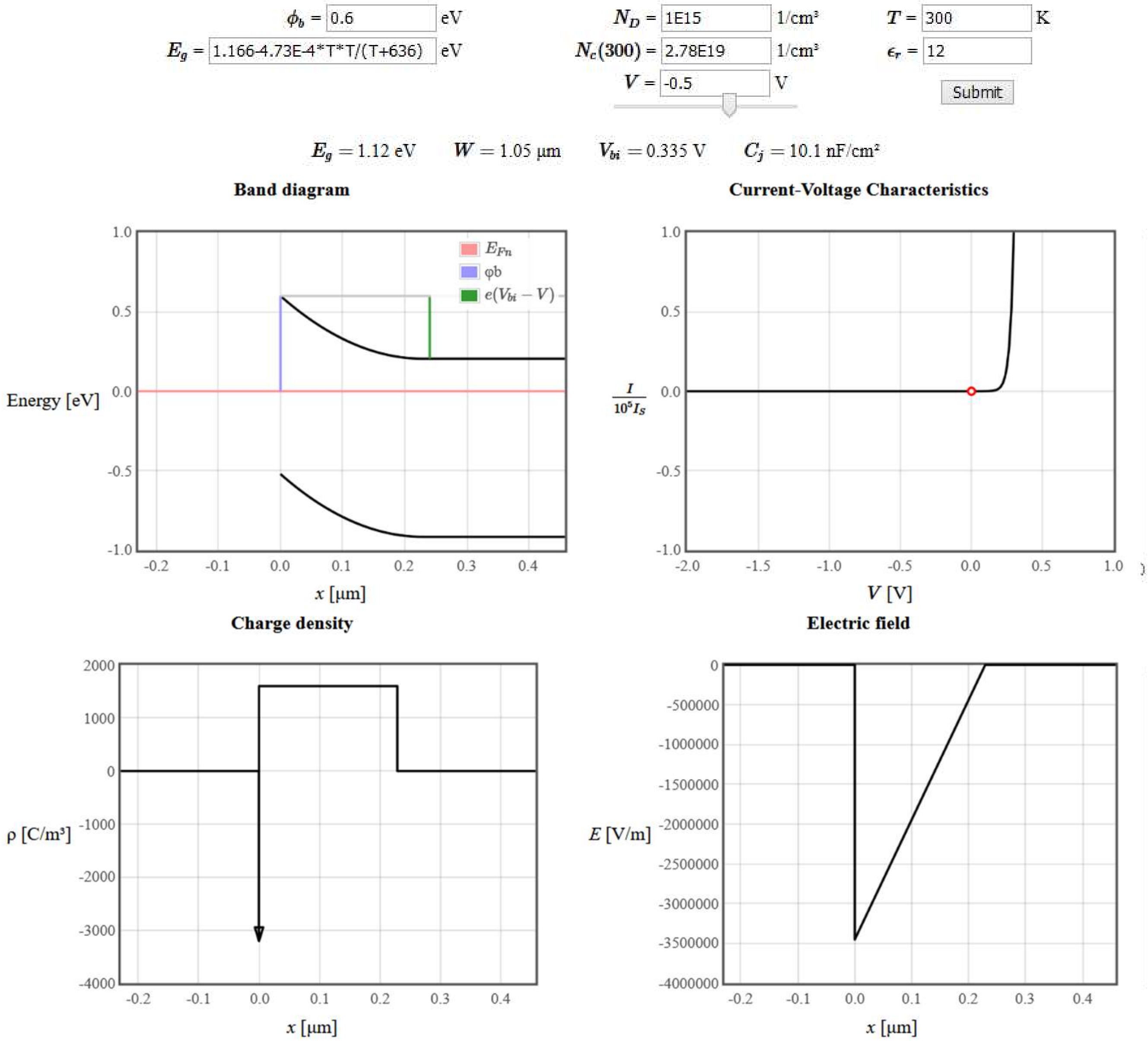
substance: silicon (Si)
property: Schottky barrier heights

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

Band diagram

Current-Voltage Characteristics

Charge density

Electric field

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

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

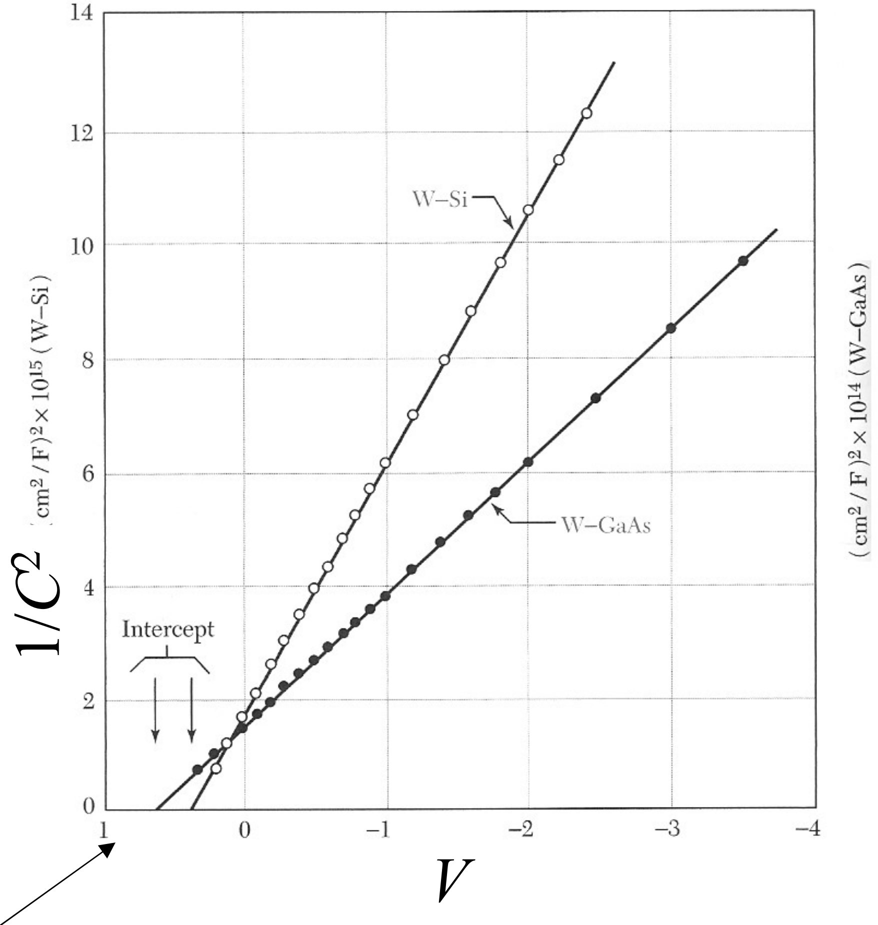
$$V = \frac{-eN_D}{\varepsilon}\left(\frac{x^2}{2} - x x_n\right)$$

CV measurements

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

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

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



GaAs has larger E_g and V_{bi}

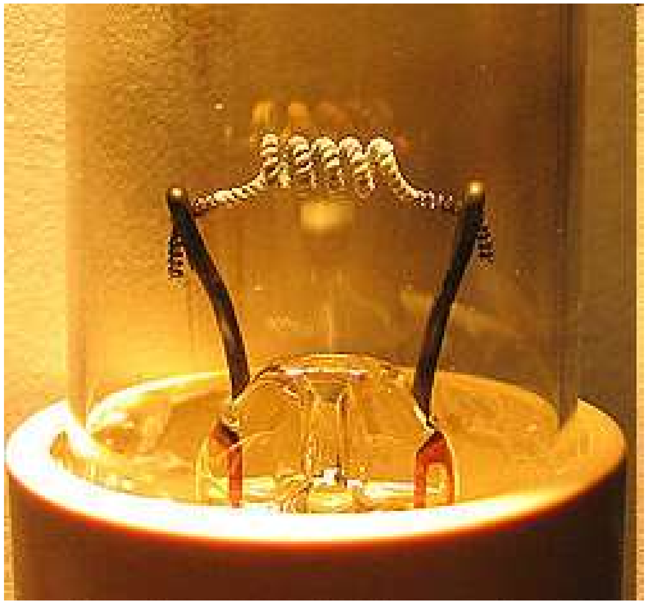
$$eV_{bi} = \phi_b - k_B T \ln\left(\frac{N_v(T)}{N_A}\right)$$

Thermionic emission

1901 Richardson

Owen Willans Richardson

Current from a heated wire is:

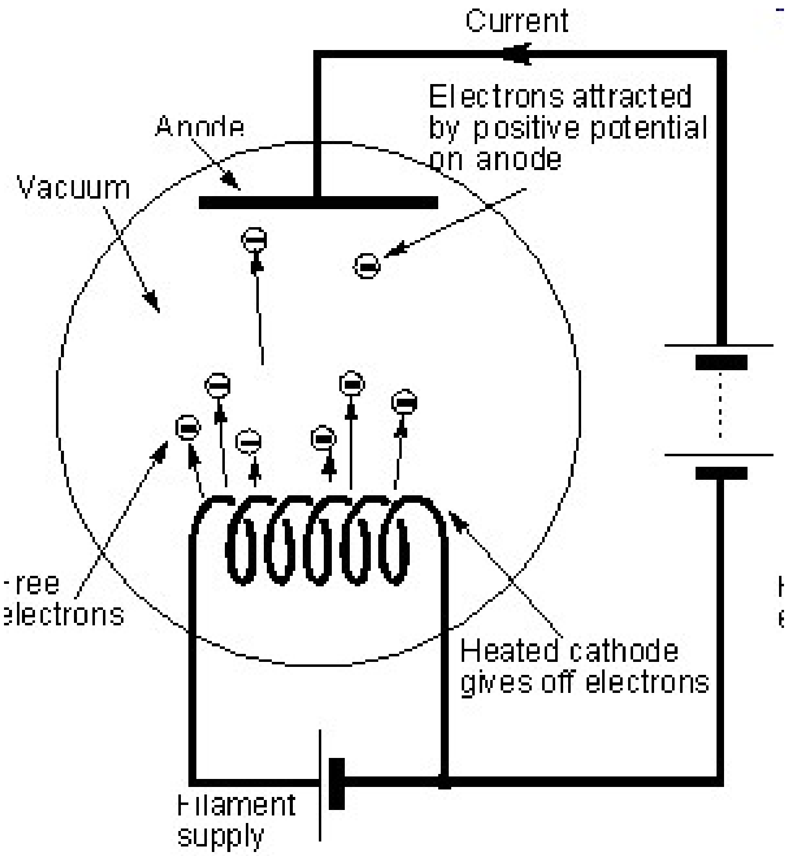


$$I = \frac{Aem^* k_B^2}{2\pi^2\hbar^3} T^2 \exp\left(-\frac{\phi_b}{k_B T}\right)\left(\exp\left(\frac{eV}{k_B T}\right) - 1\right)$$

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

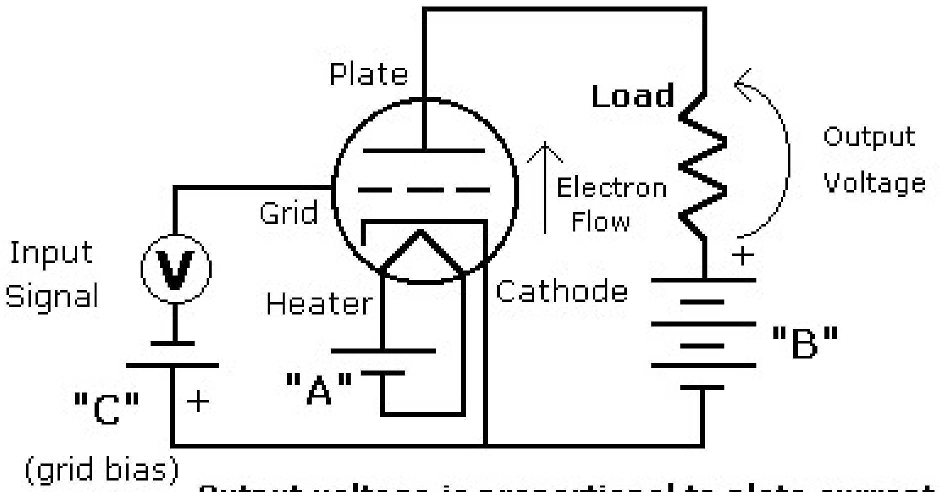
http://lampz.tugraz.at/~hadley/psd/L6/richardson.html

Vacuum diodes



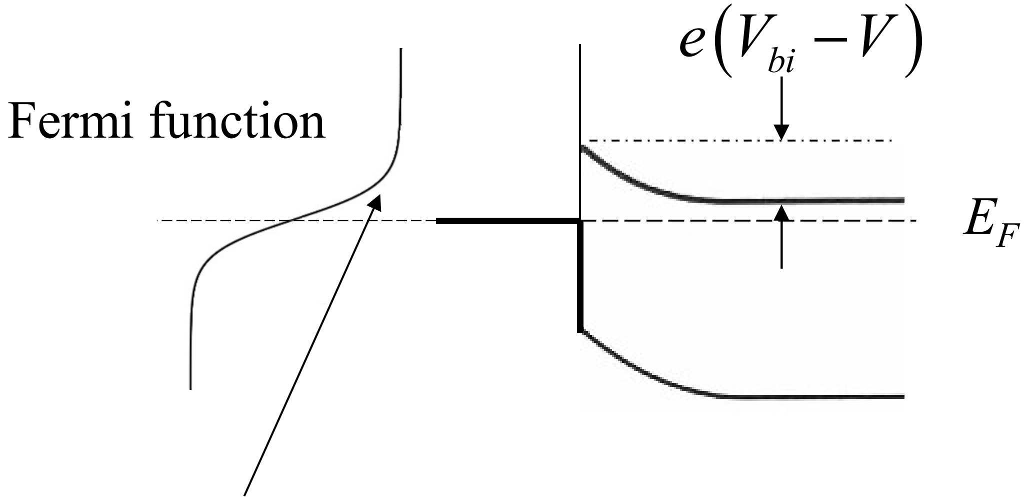
diode

The Common-cathode Triode Amplifier



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

Thermionic emission



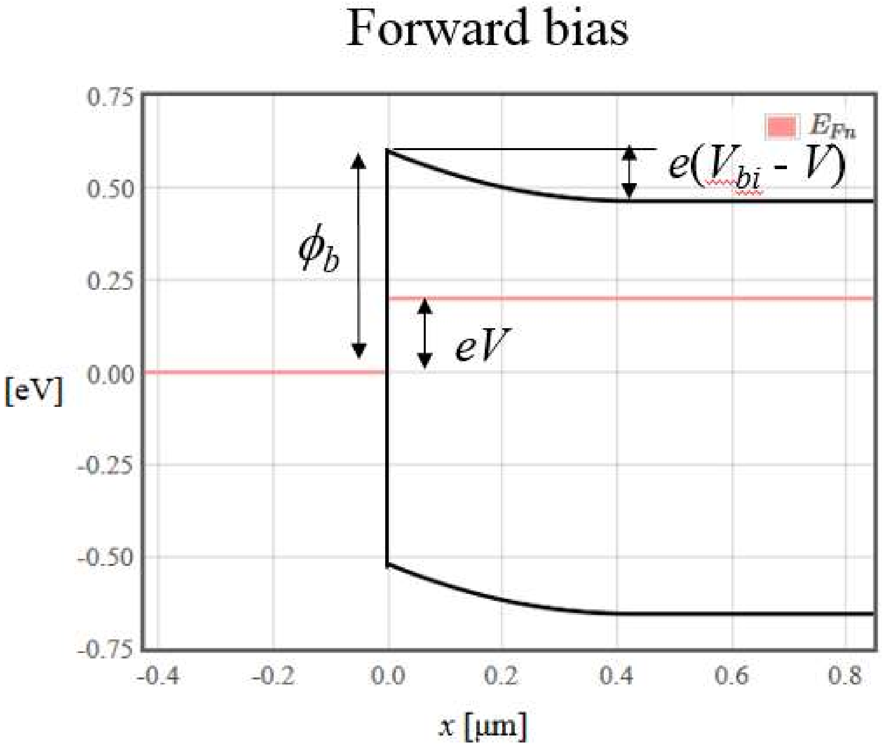
$$f(E) \approx \exp\left(\frac{E_F - E}{k_B T}\right) = \exp\left(\frac{E_F}{k_B T}\right)\exp\left(\frac{-E}{k_B T}\right) \propto \exp\left(\frac{-E}{k_B T}\right)$$

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

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

Thermionic emission

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


Forward bias

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

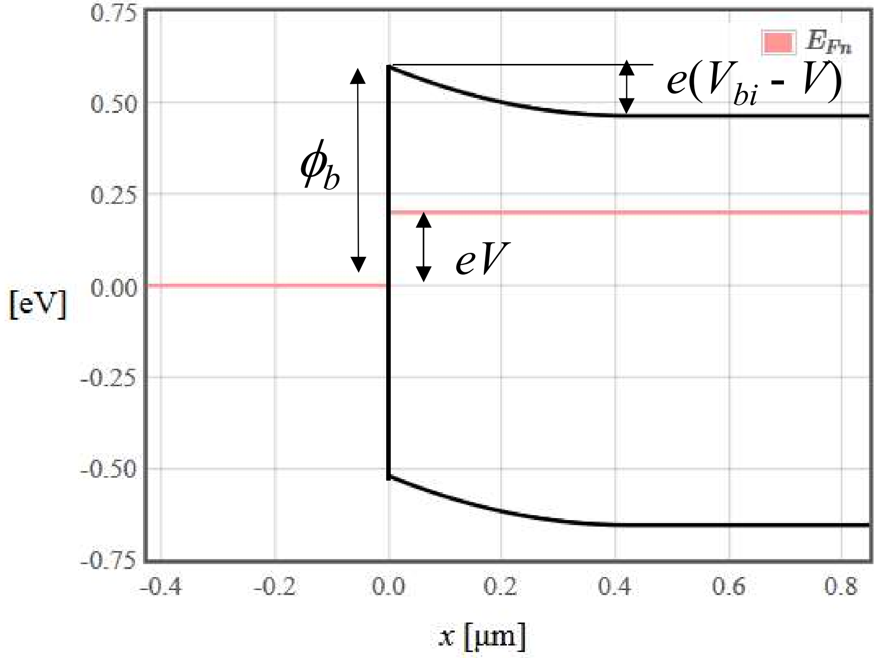
$$I_{ms} = I_{sm}(V = 0)$$

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

$$I = \frac{Aem^* k_B^2}{2\pi^2 \hbar^3} T^2 \exp\left(-\frac{\phi_b}{k_B T}\right)\left(\exp\left(\frac{eV}{k_B T}\right) - 1\right)$$

Schottky barrier

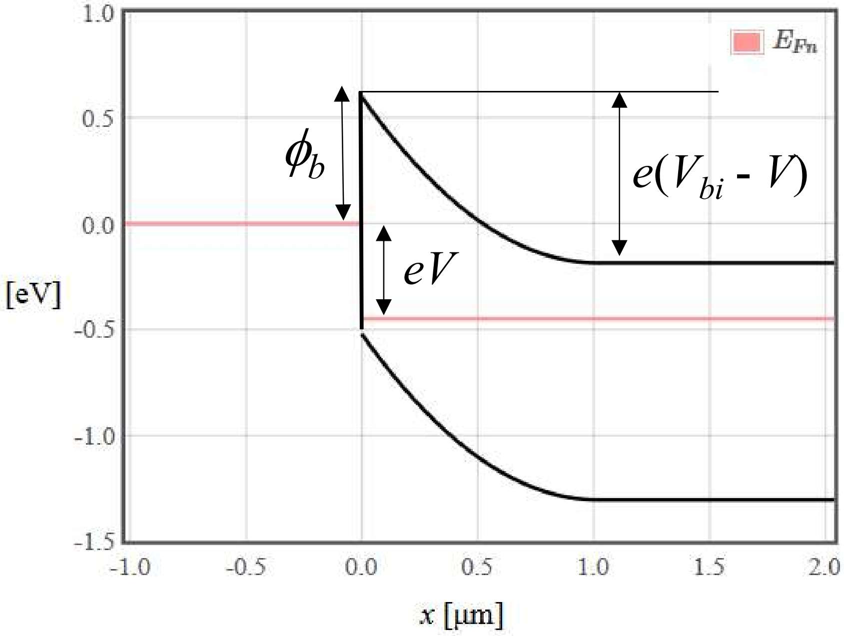
Forward bias



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

I_{ms} constant

Reverse bias



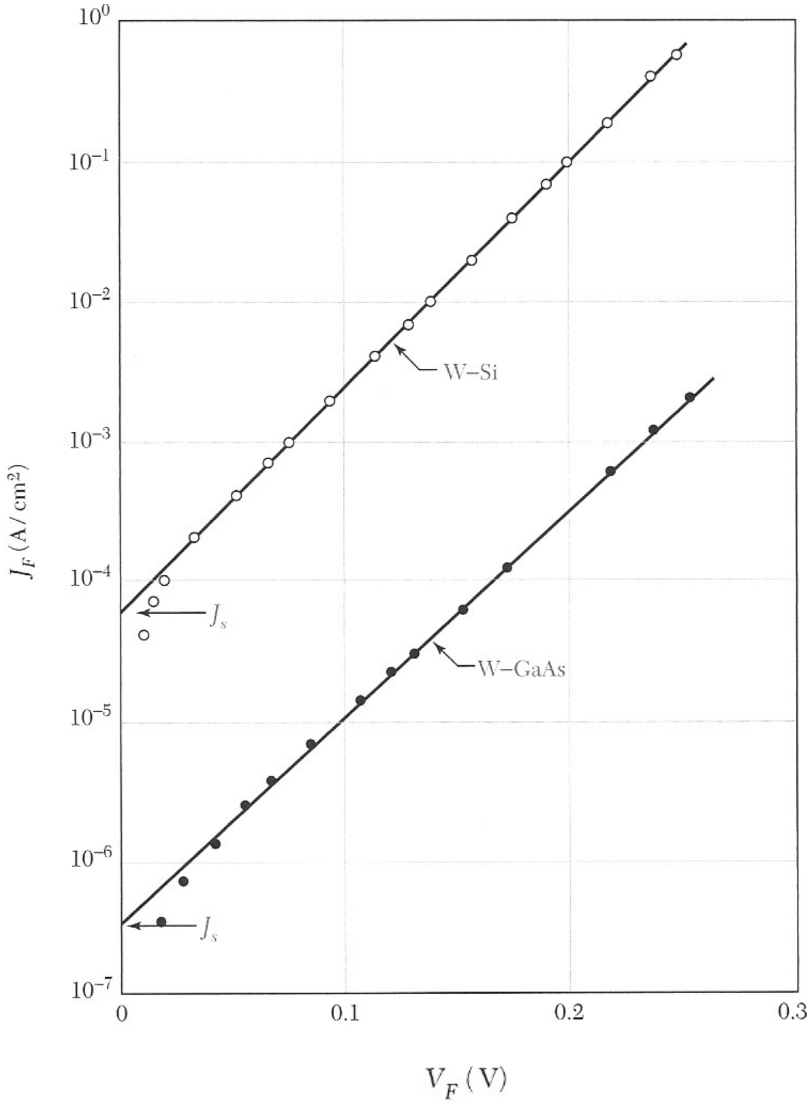
$I_{sm} \sim 0$

I_{ms} constant

Thermionic emission

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

Nonideality factor = 1



Schottky diodes

Majority carrier current dominates.

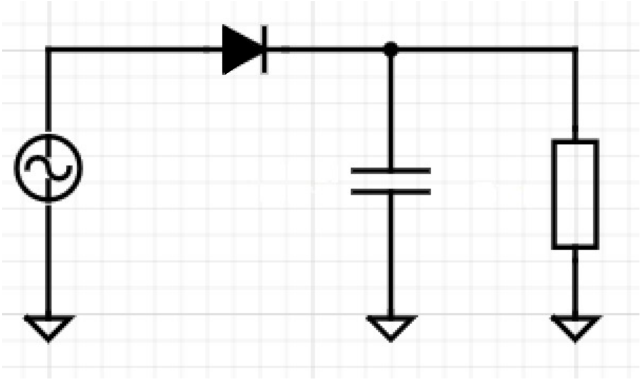
nonideality factor ~ 1.

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

Used as rf mixers.

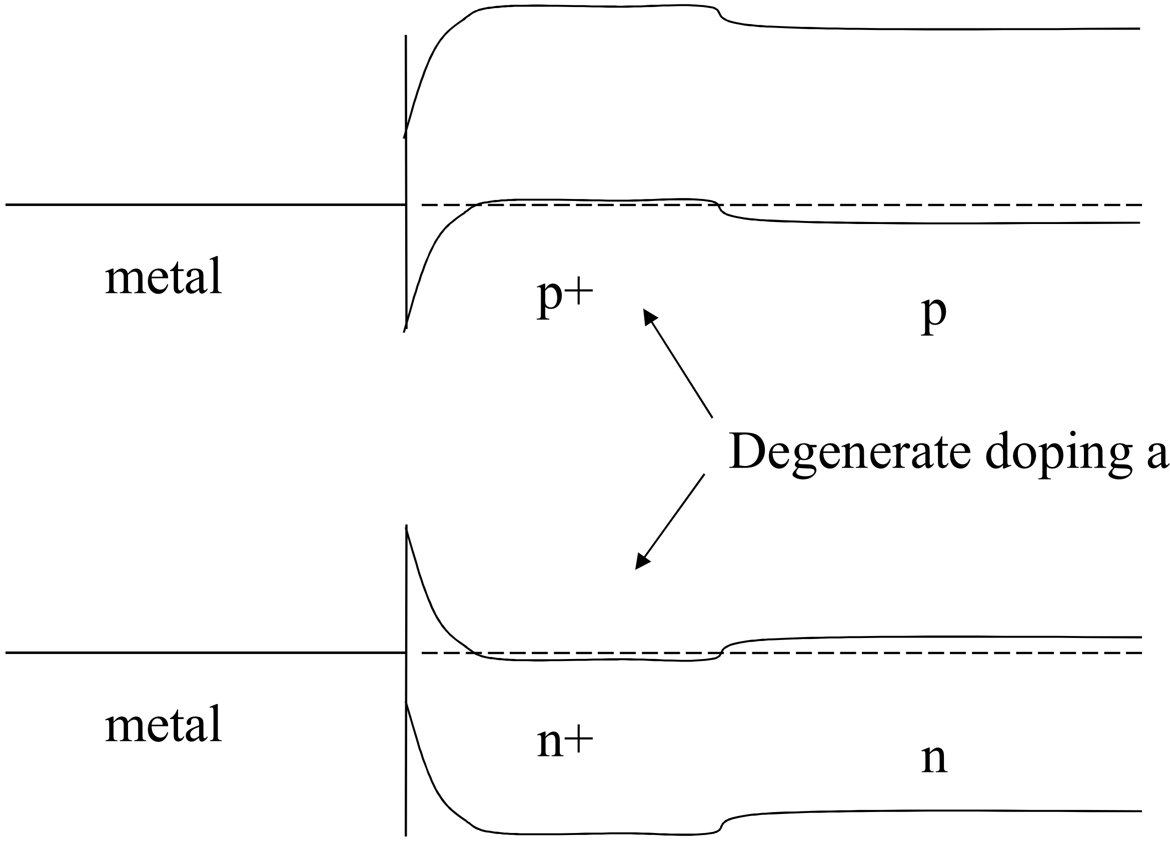
Low turn on voltage - high saturation current

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



Tunnel contacts

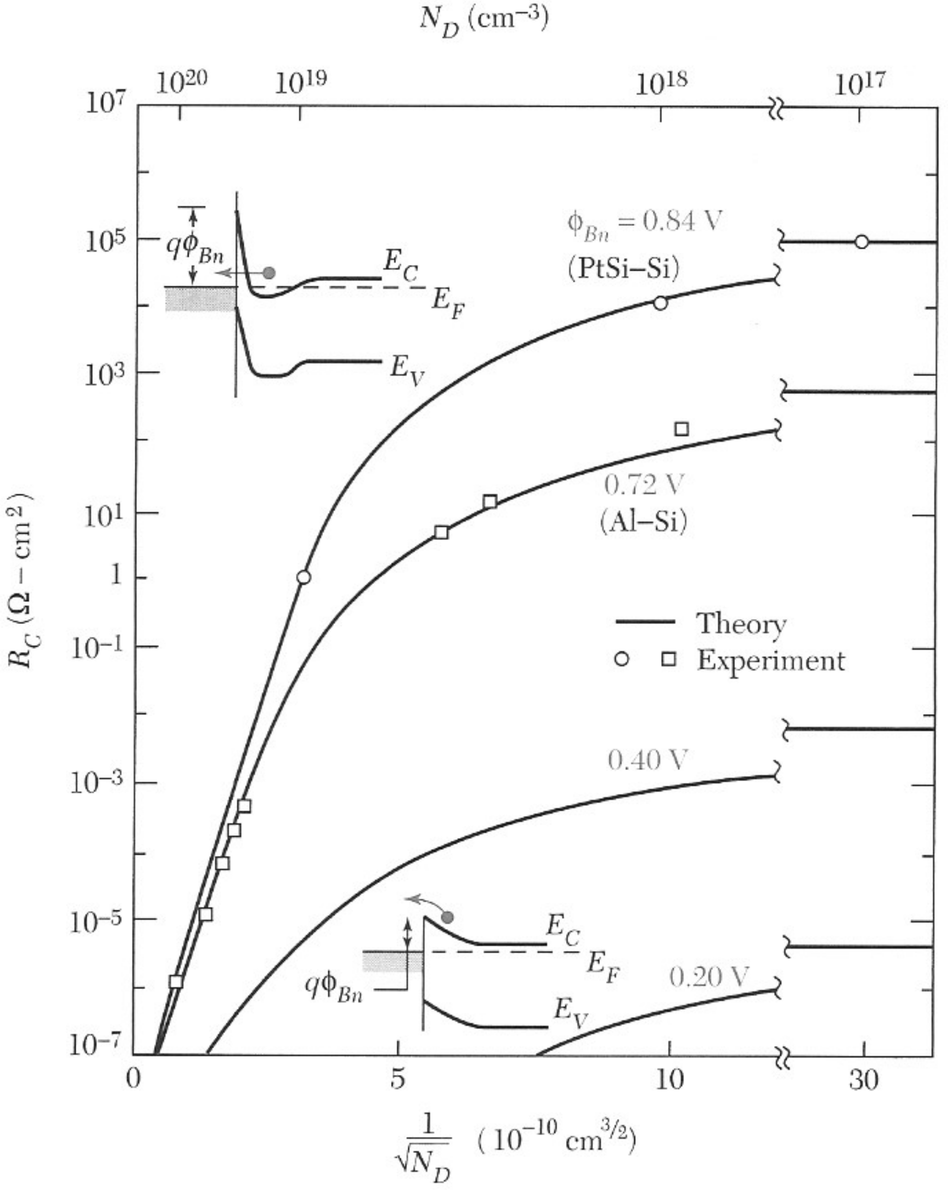
For high doping, the Schottky barrier is so thin that electrons can tunnel through it.



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.

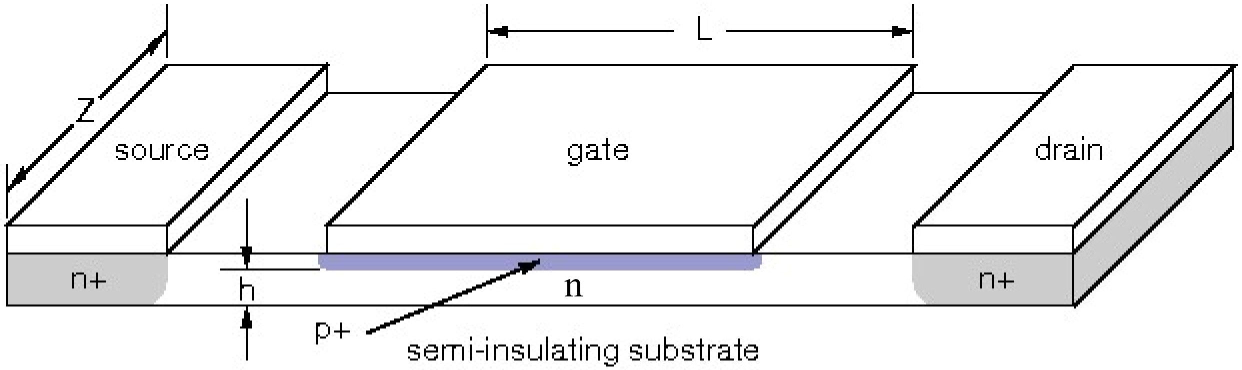
In a forward biased pn-junction, diffusion dominates.

In a tunnel contact, tunneling dominates.

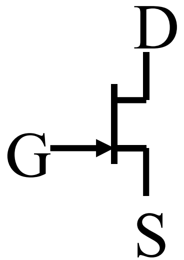
In a Schottky diode, thermionic emission dominates.

Junction Field Effect Transistors (JFETs)

JFET

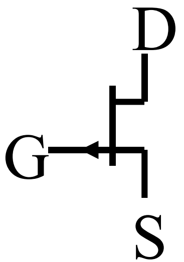


n-channel JFET



n-channel JFET

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



p-channel JFET

Pinch-off at $h = x_n$

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

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