8

Metal semiconductor contacts

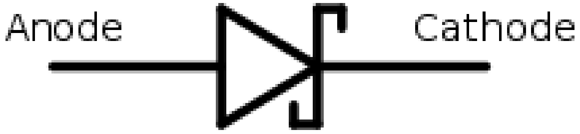
November 2025

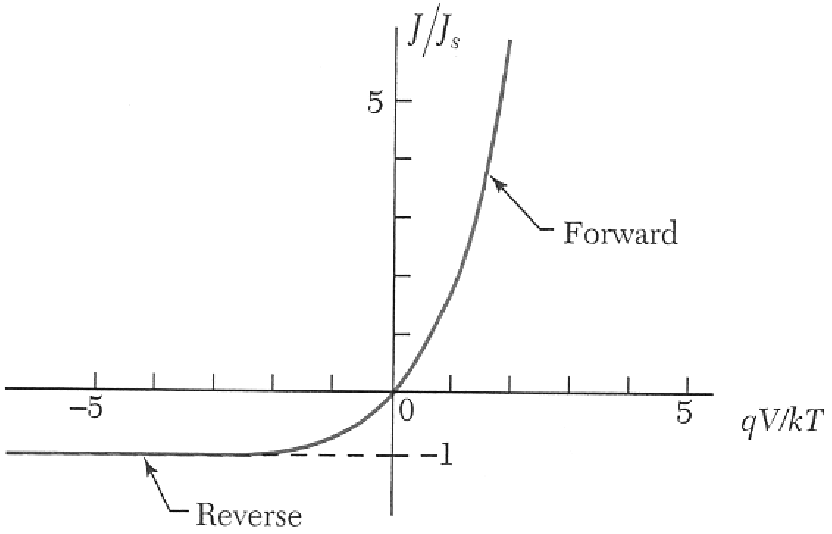
Photoelectric effect
Schottky barriers
Schottky diodes

Ohmic contacts
Thermionic emission
Tunnel contacts

8

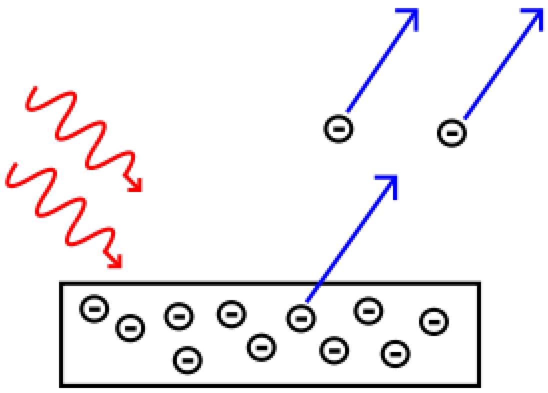
Metal semiconductor contacts





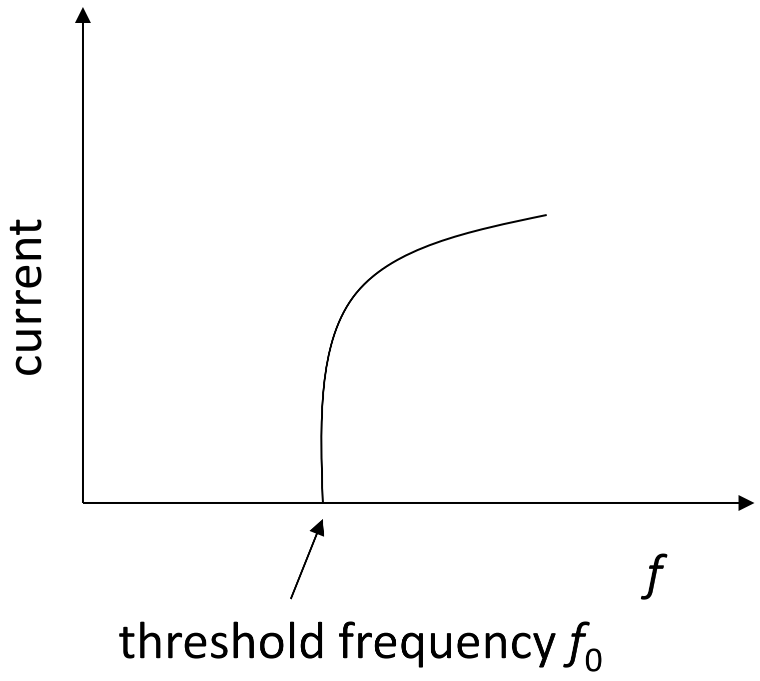
November 13th 2025

photoelectric effect



$hf_0 = e\phi$ at threshold

workfunction



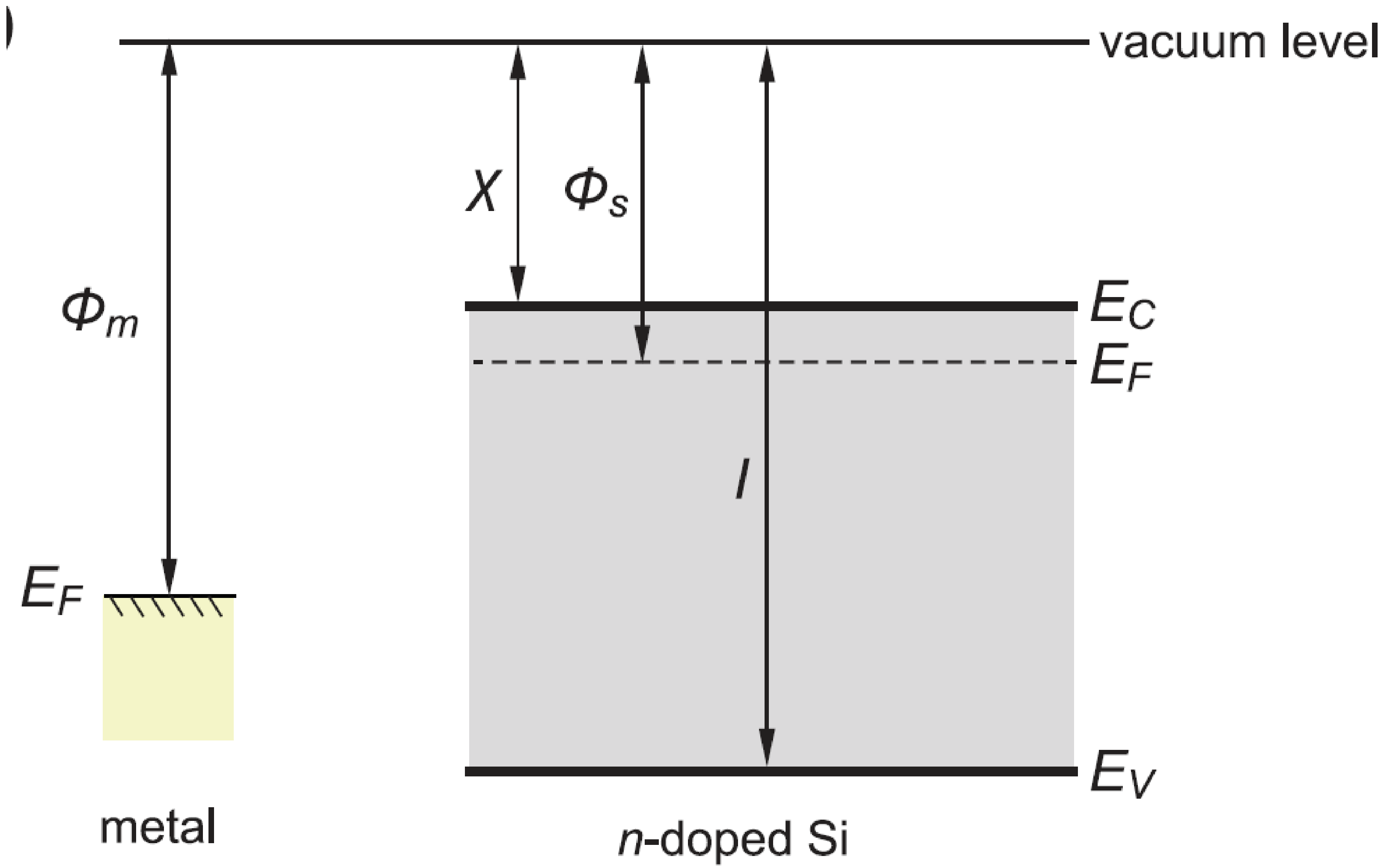
Work functions of some metals

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

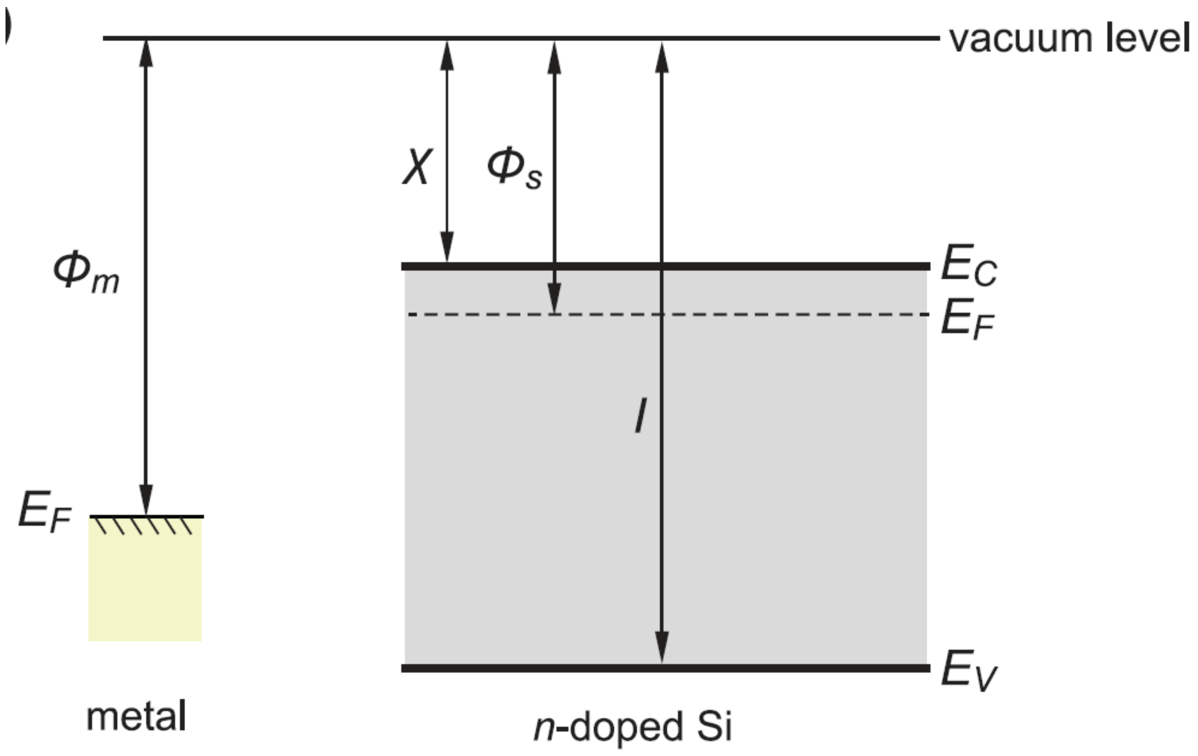
There is a dipole field at the surface of a metal. This electric field must be overcome for an electron to escape.

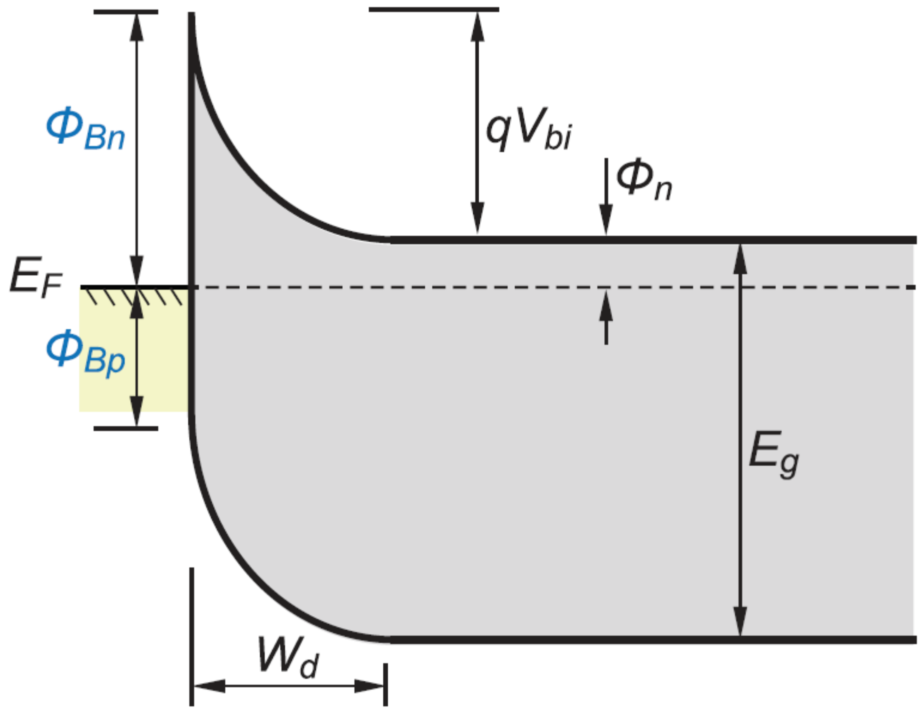
Singh

work function – electron affinity



work function – electron affinity





images: 10.1109/TED.2017.2650216

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
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Au, gold	5.1
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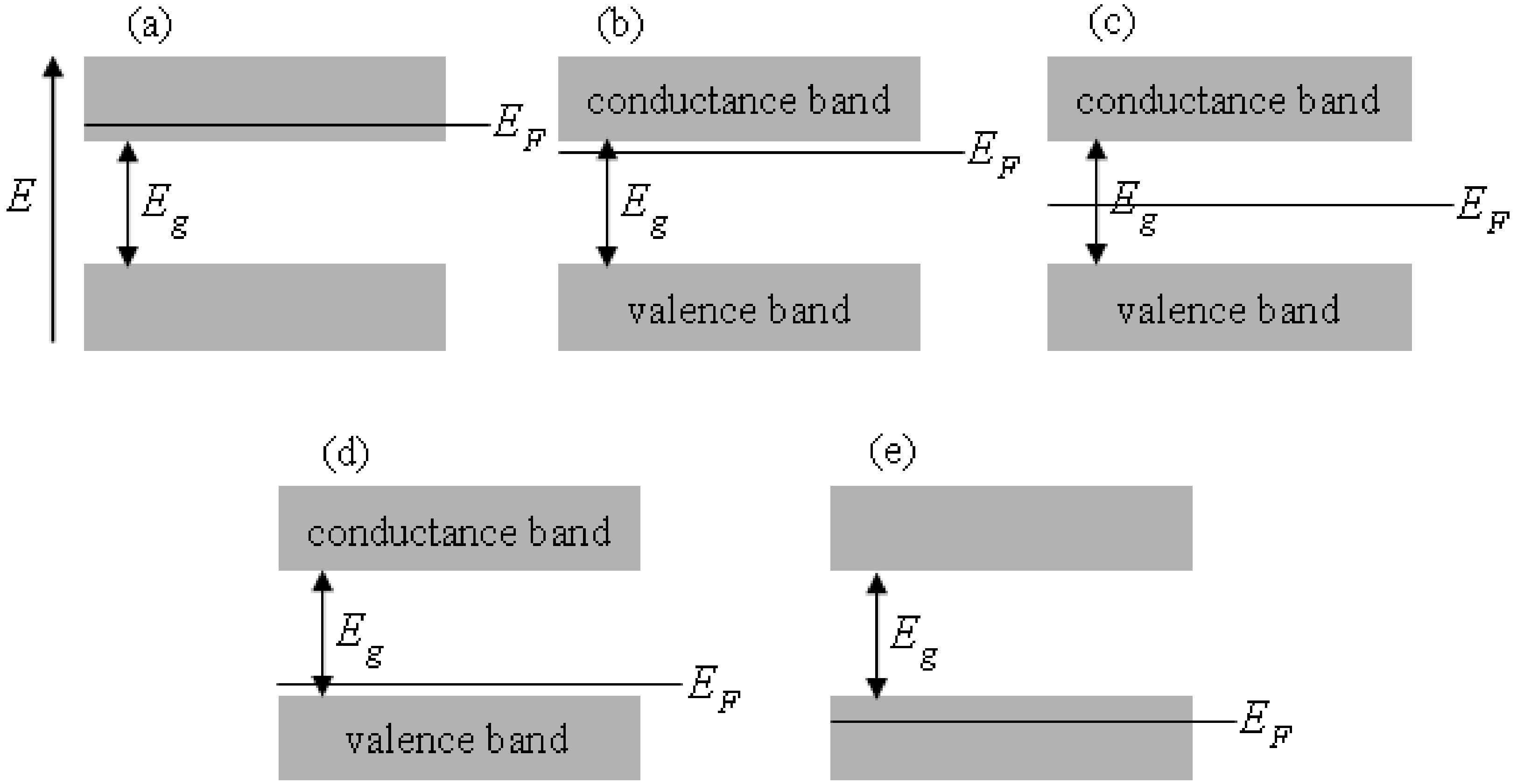
Mo, molybdenum	4.6
Ni, nickel	5.15
Pd, palladium	5.12
Pt, platinum	5.65
Ti, titanium	4.33
W, tungsten	4.55

Electron affinity of some semiconductors

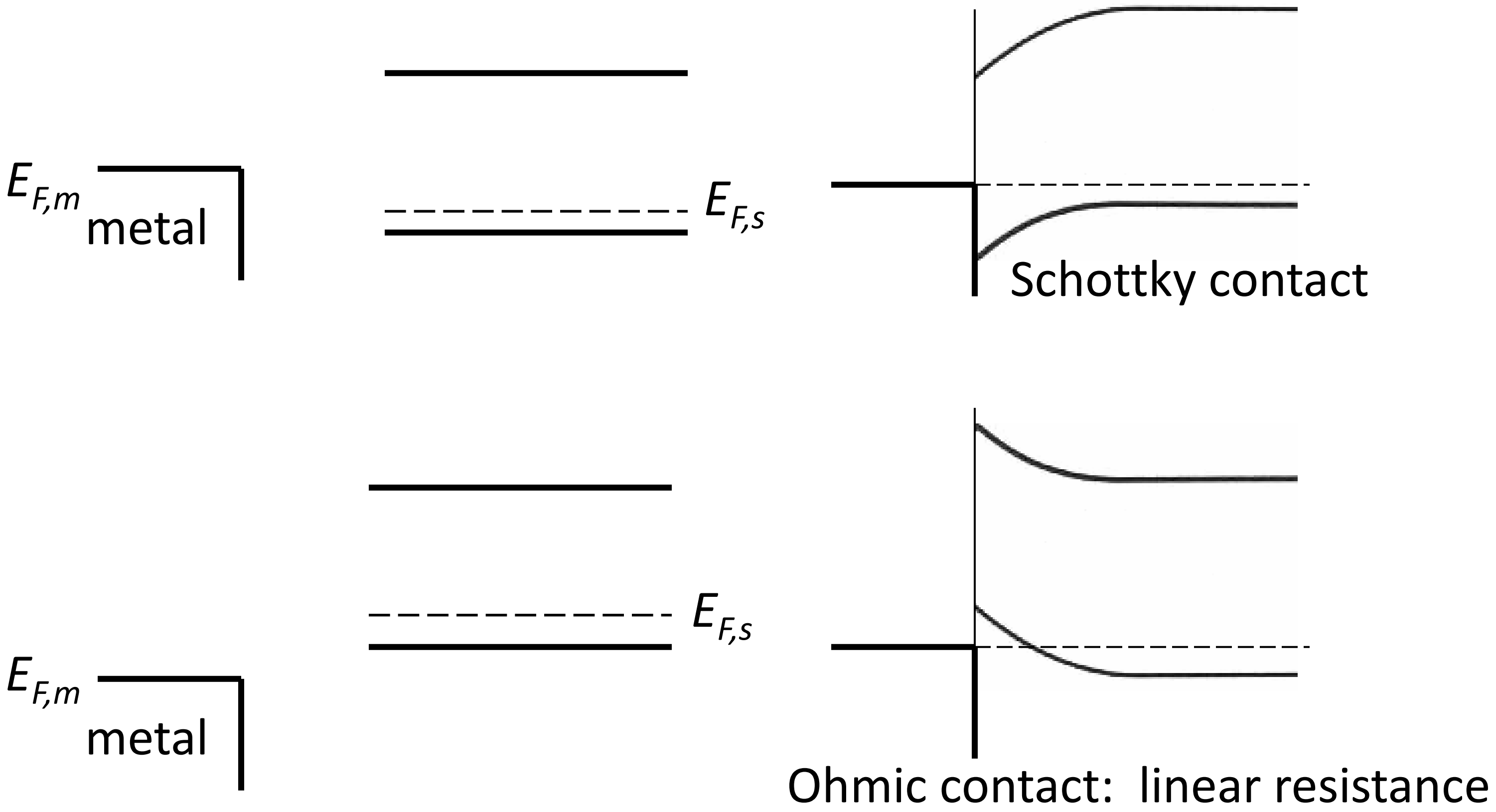
Element	Electron affinity, χ (volt)
Ge, germanium	4.13
Si, silicon	4.01
GaAs, gallium arsenide	4.07
AlAs, aluminum arsenide	3.5

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.

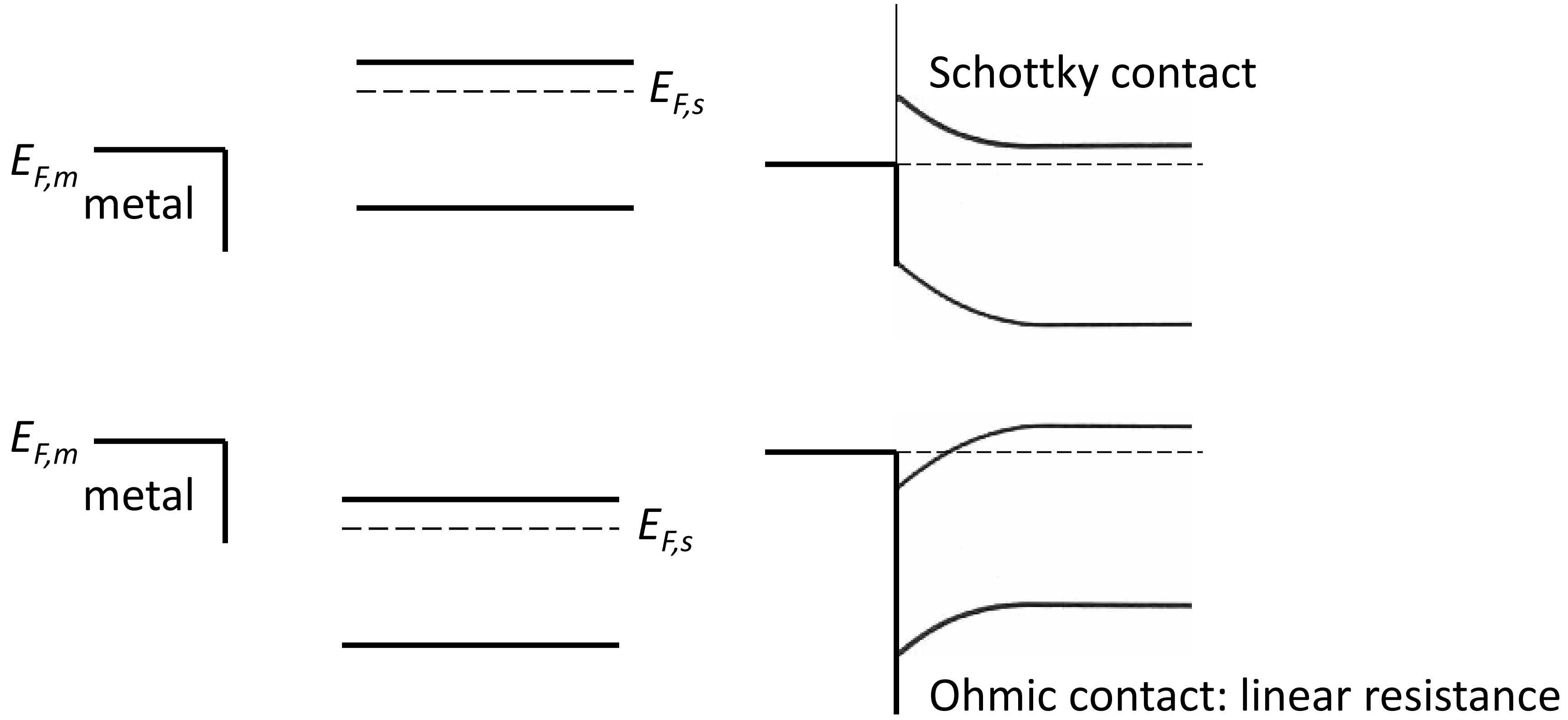
Schottky contact / ohmic contact p-type



Walter Schottky

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

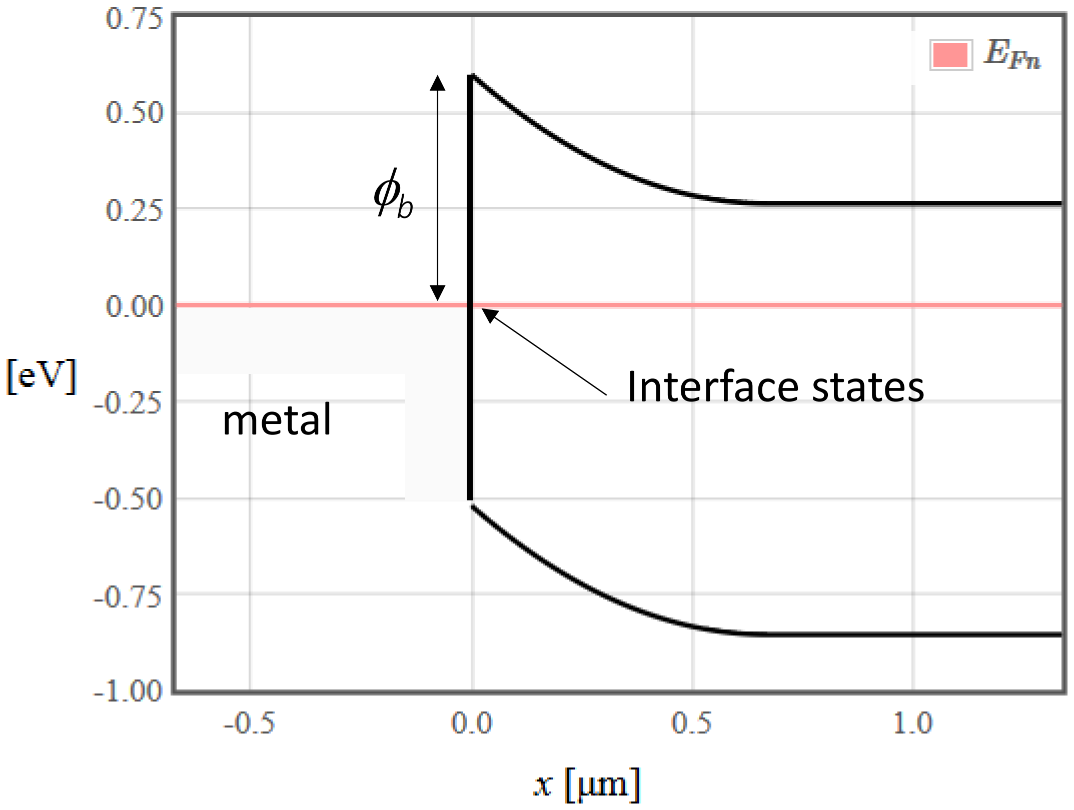
Schottky contact / ohmic contact   n-type



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

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	



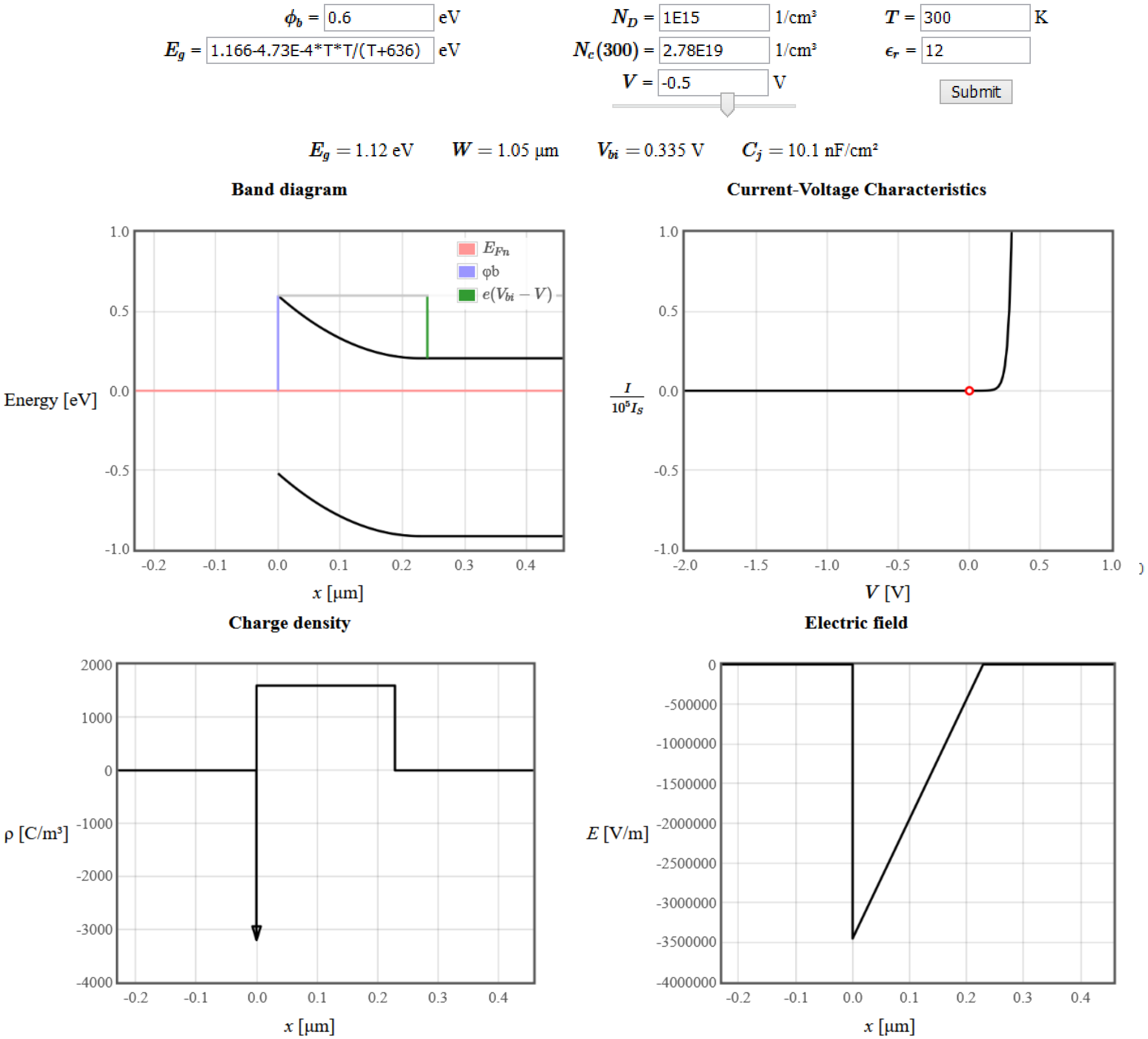
substance: silicon (Si)
property: Schottky barrier heights

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 photoelectric characteristics
n-Si:Ca	0.40 eV		C–V and I–V characteristics
n-Si:Co	0.61 eV		I–V and photoelectric characteristics
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



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

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

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

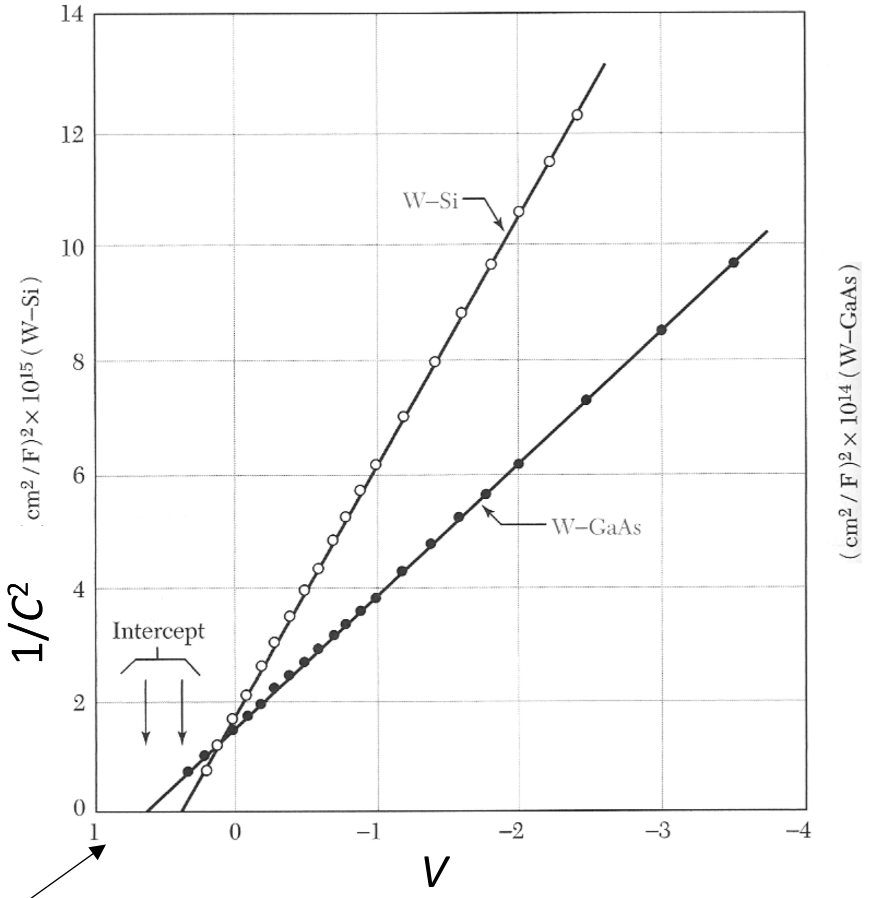
$$0 > x > x_n$$

CV measurements

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

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

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

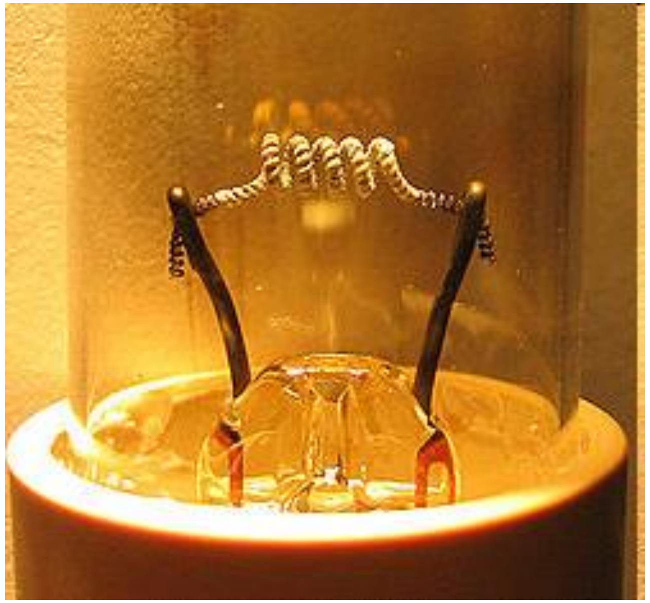


GaAs has larger E_g and V_{bi}

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

thermionic emission

1901 Richardson



Owen Willans Richardson

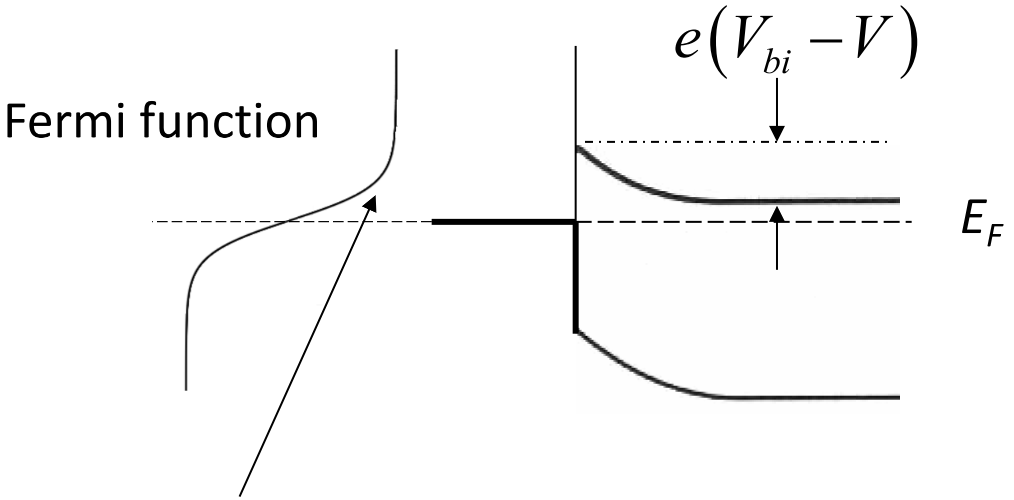
Current from a heated wire is:

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

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

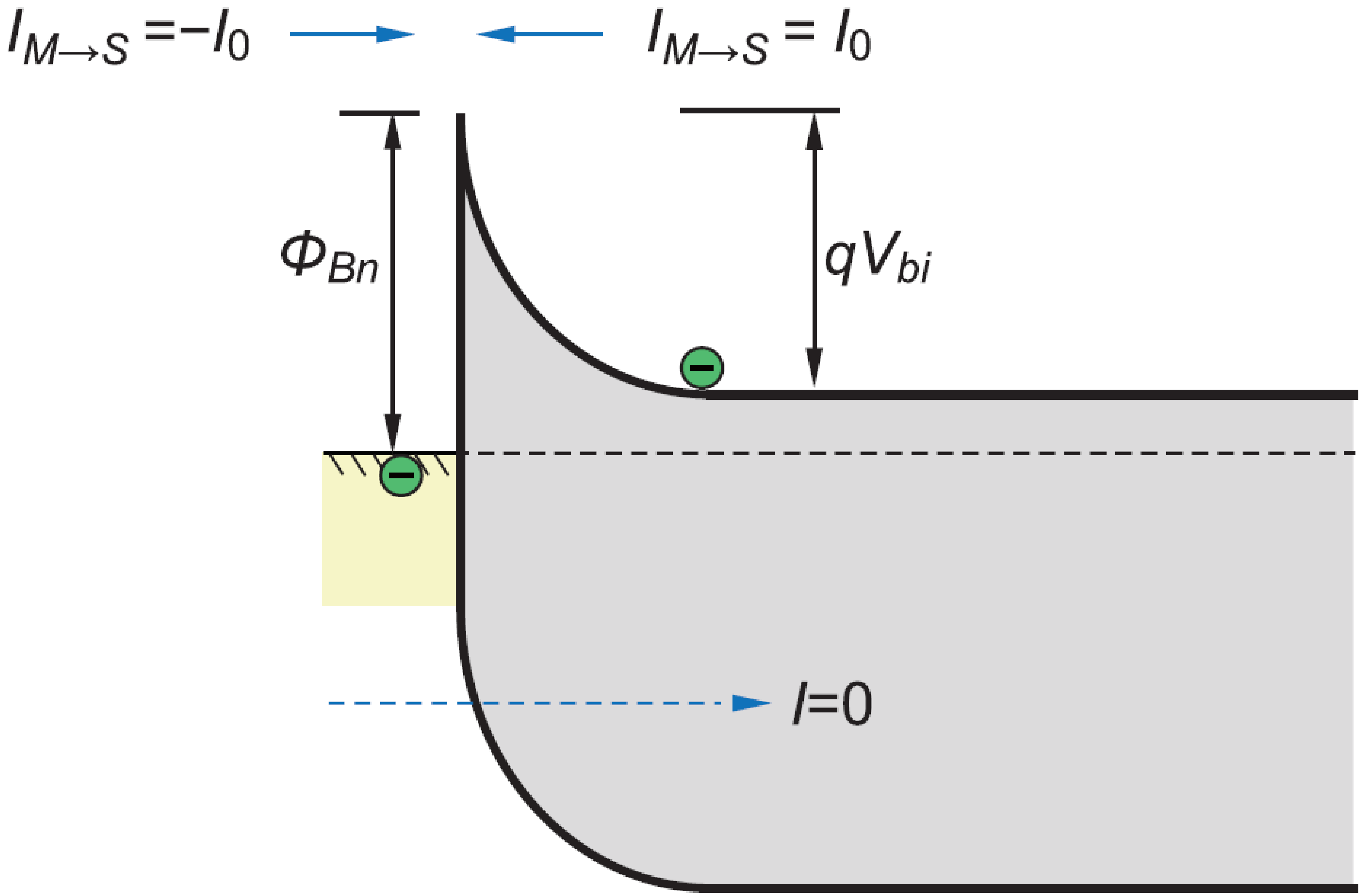
thermionic emission

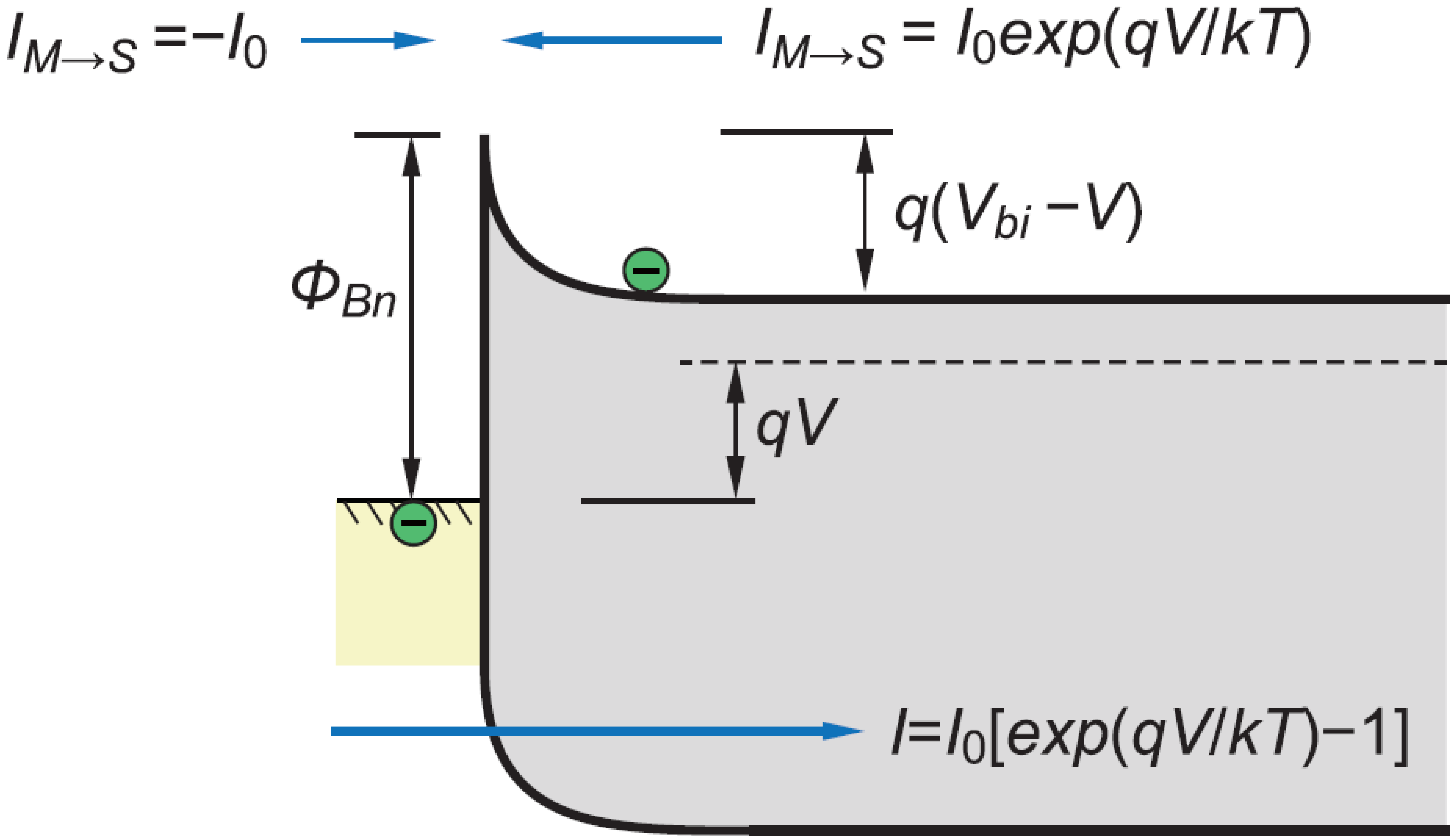


$$f(E) \approx \exp\left(\frac{E_F - E}{k_B T}\right) = \exp\left(\frac{E_F}{k_B T}\right)\exp\left(\frac{-E}{k_B T}\right) \propto \exp\left(\frac{-E}{k_B T}\right)$$

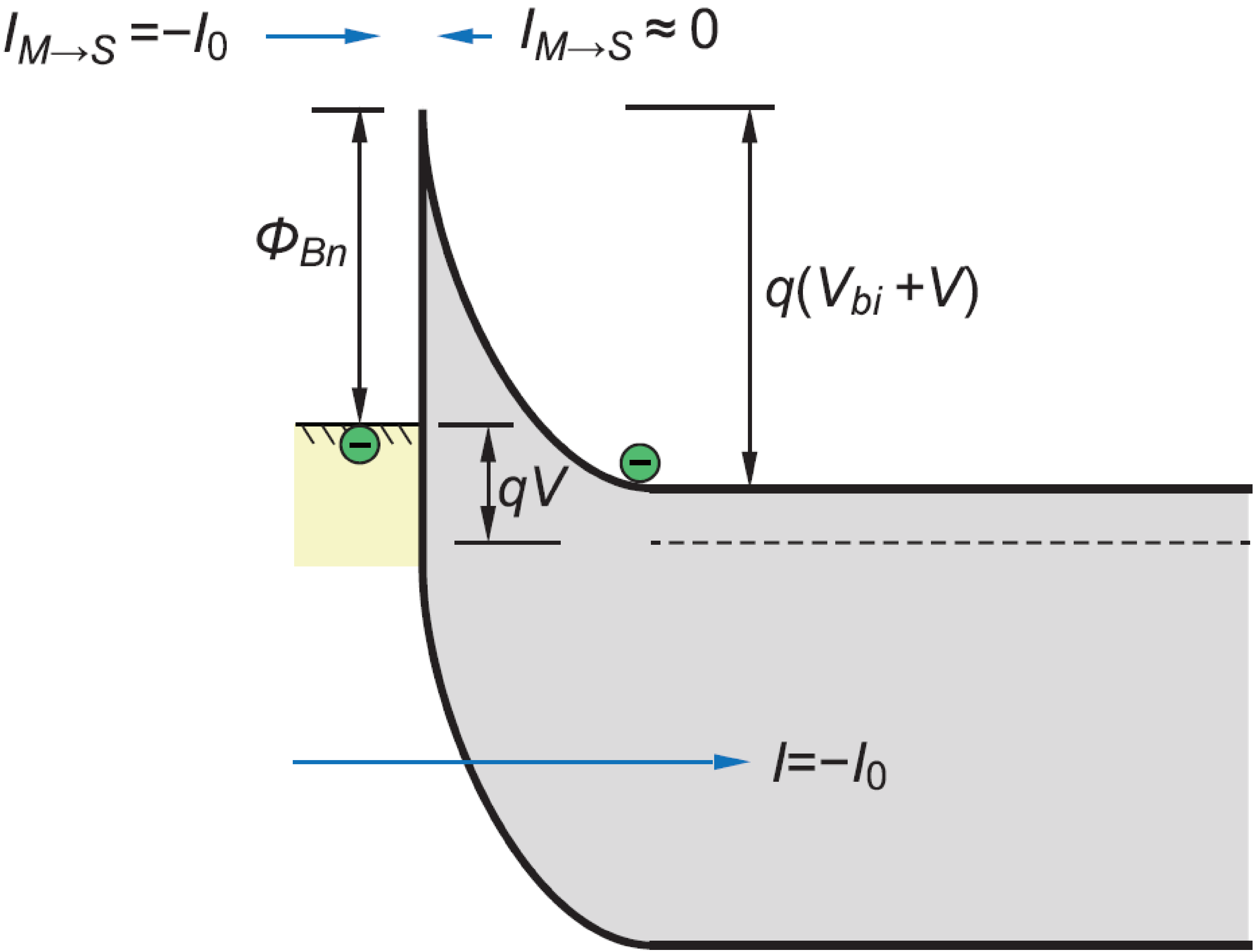
density of electrons with enough energy to go over the barriers $\propto \exp\left(\frac{-E}{k_B T}\right)$

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


$I_{M\rightarrow S} = -I_0$
$I_{M\rightarrow S} = I_0$
Φ_{Bn}
qV_{bi}
$I=0$

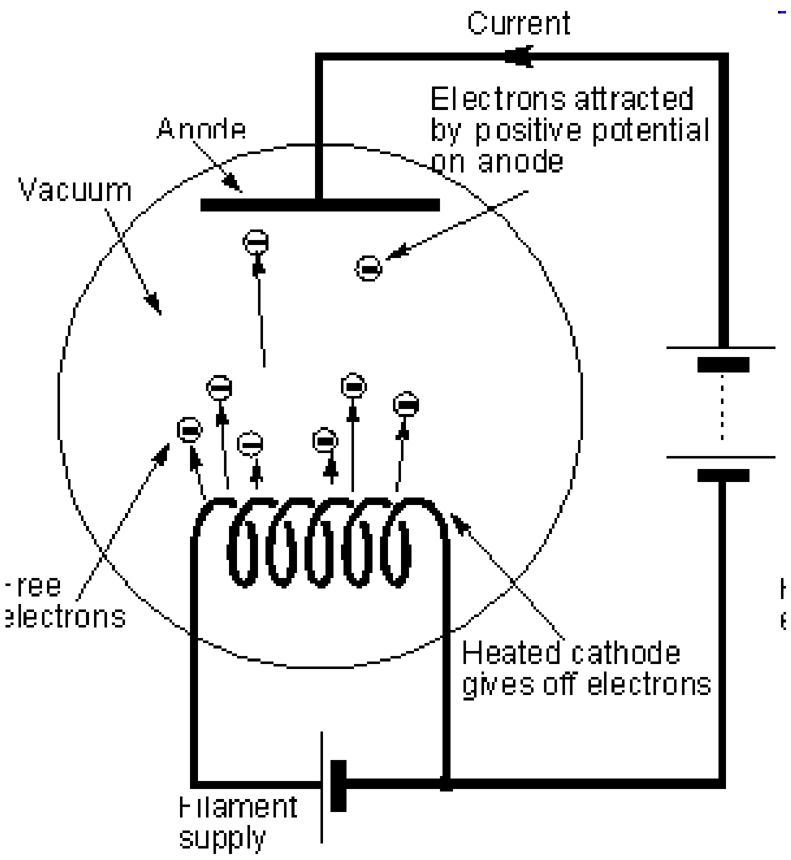


$I_{M\rightarrow S} = -I_0$
$I_{M\rightarrow S} = I_0 exp(qV/kT)$
Φ_{Bn}
$q(V_{bi} - V)$
qV
$I = I_0[exp(qV/kT) - 1]$



$I_{M\to S} = -I_0$
$I_{M\to S} \approx 0$
Φ_{Bn}
$q(V_{bi} + V)$
qV
$I = -I_0$

vacuum diodes



diode

thermionic emission

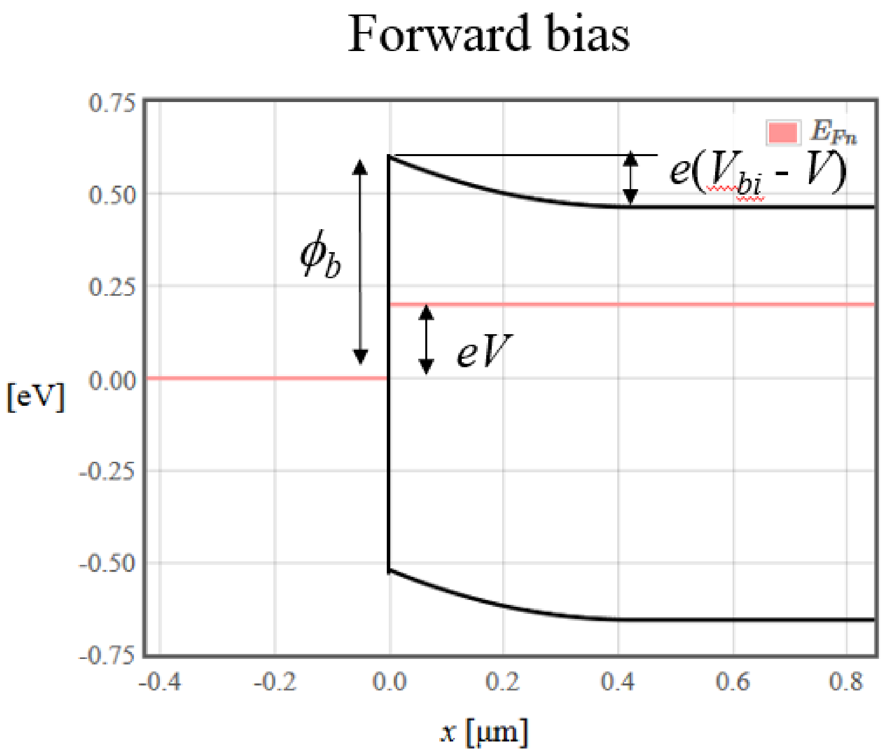
$$n_{th} \propto \exp\left(\frac{eV}{k_B T}\right)$$

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

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

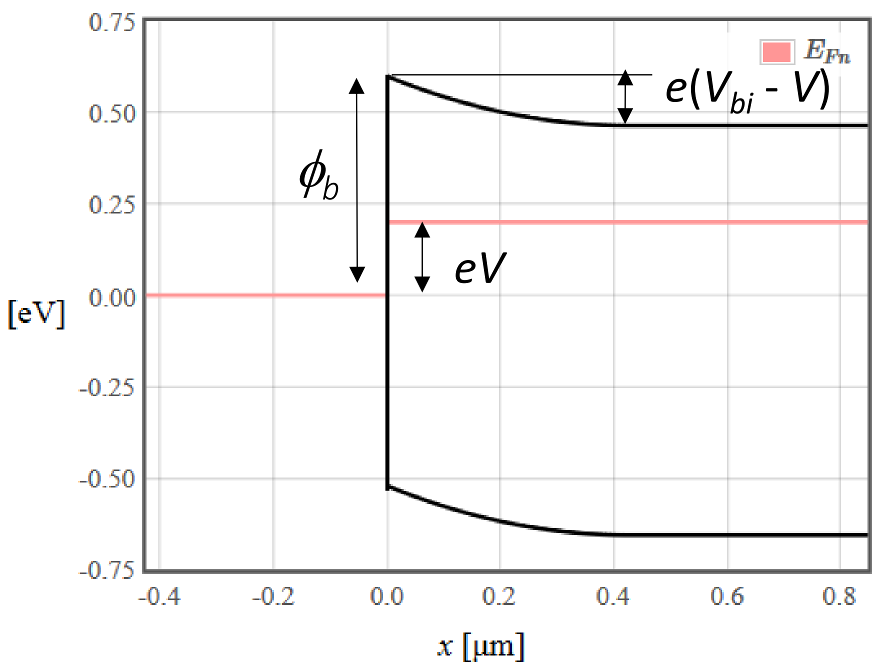
$$I = I_{sm} + I_{ms} = I_{ms}(T)\left(\exp\left(\frac{eV}{k_B T}\right) - 1\right)$$

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



Schottky barrier

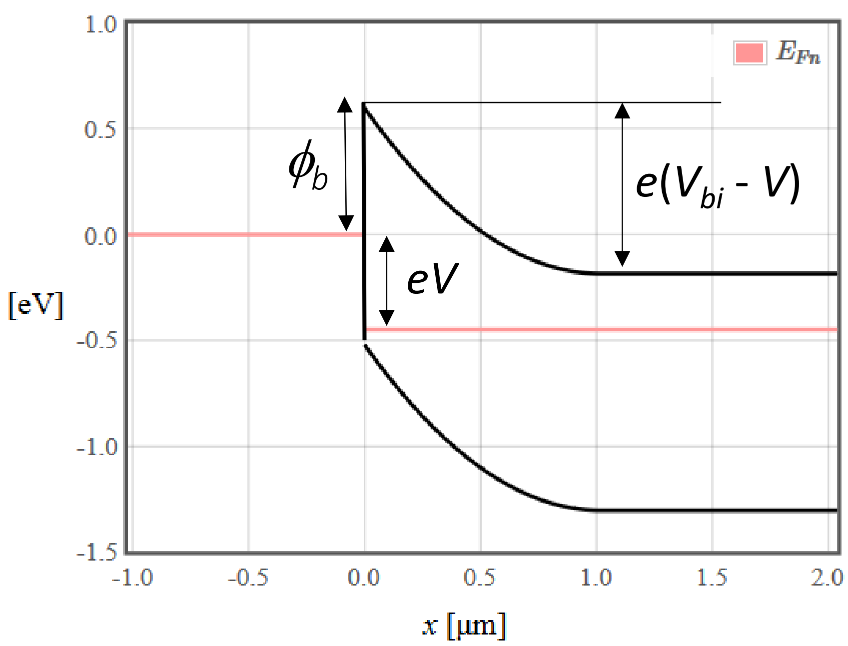
Forward bias



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

I_{ms} constant

Reverse bias



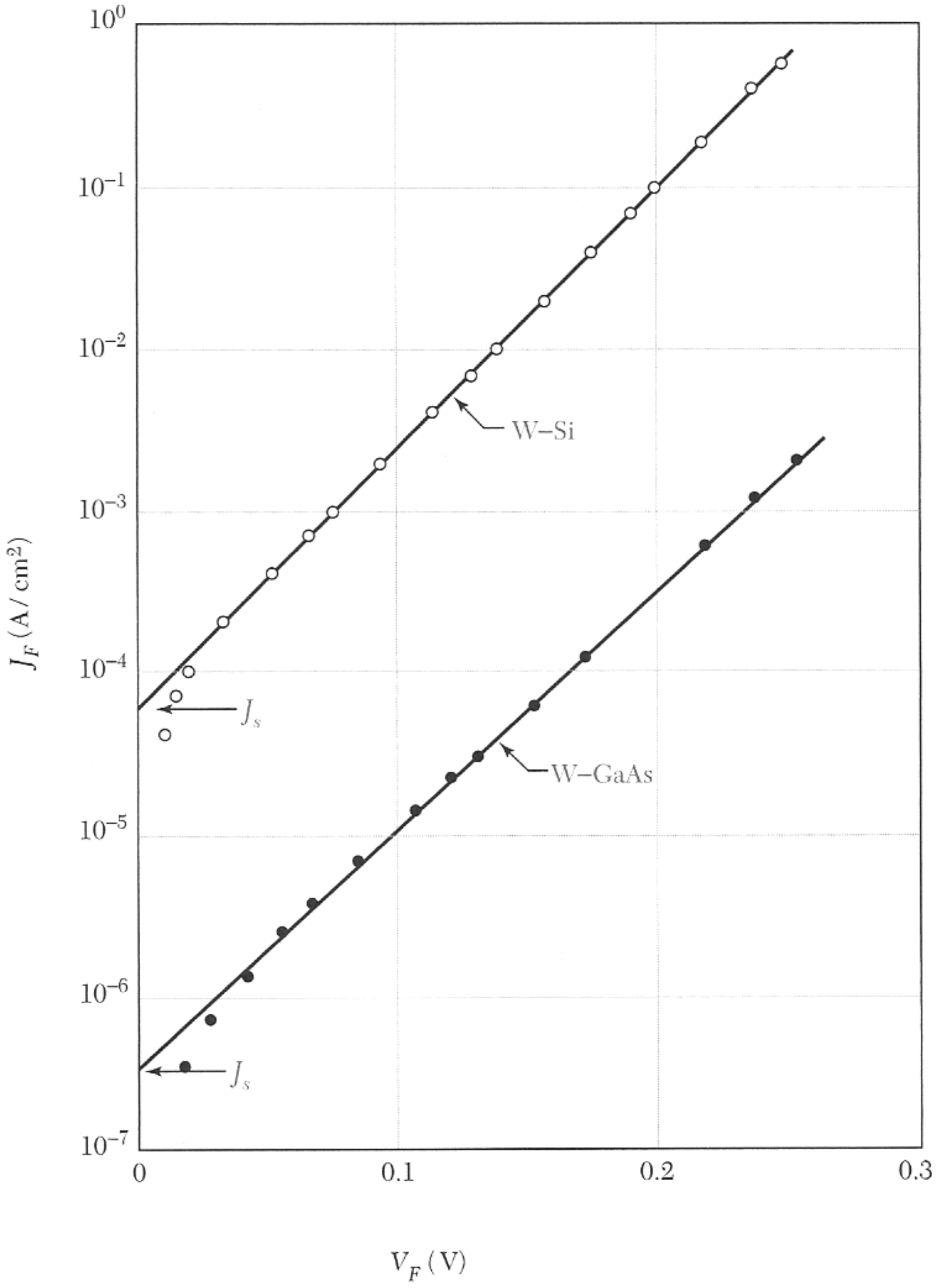
I_{sm} ~ 0

I_{ms} constant

thermionic emission

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

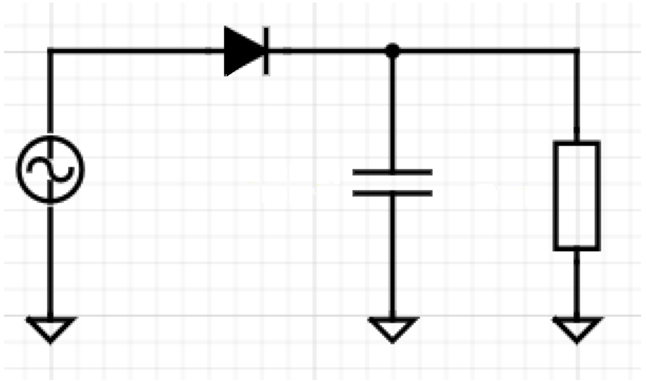
Nonideality factor = 1



Schottky diodes

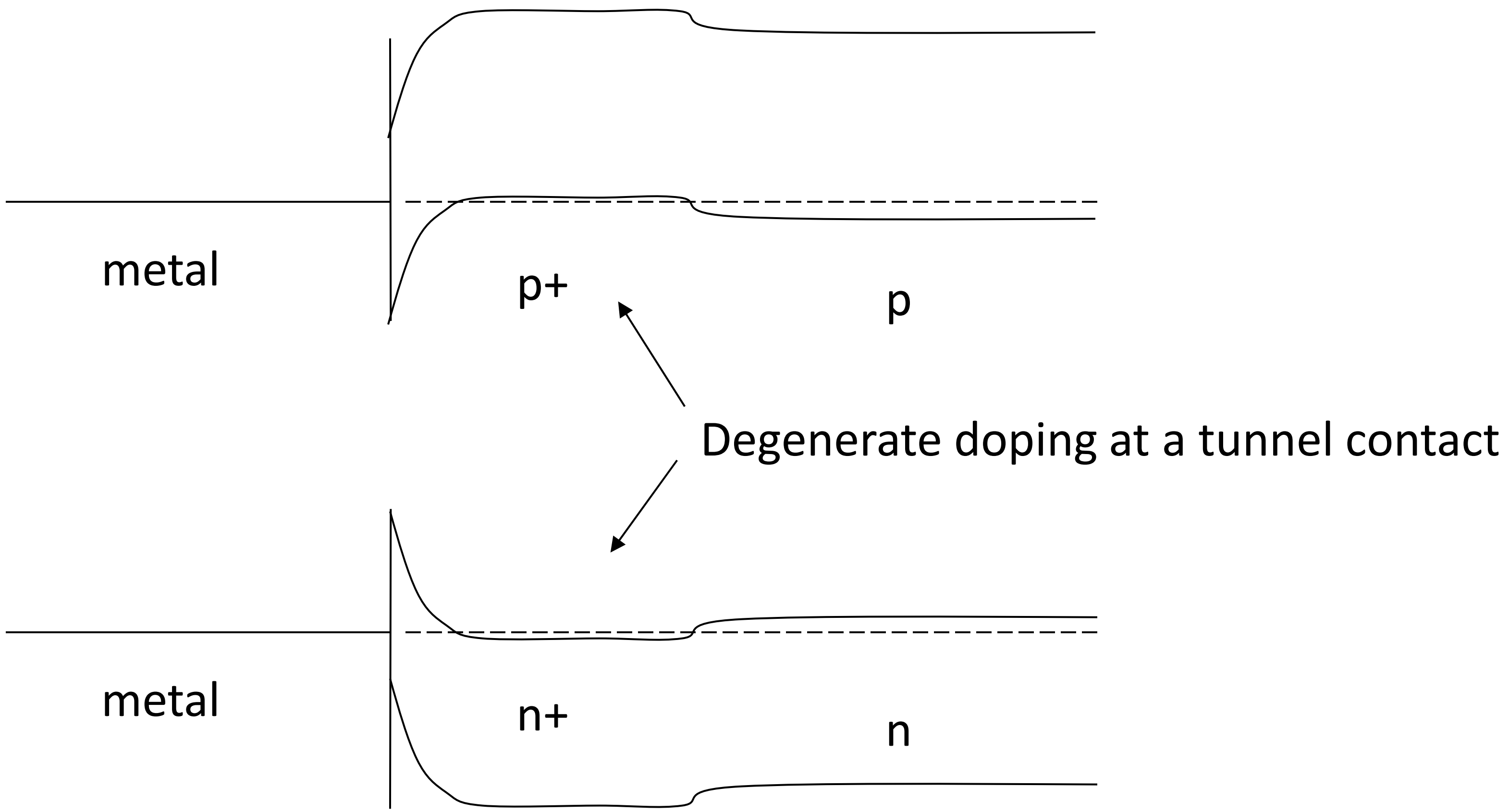
- Majority carrier current dominates.
- nonideality factor ~ 1.
- Fast response, no recombination of electron-hole pairs required.
- Used as rf mixers.
- Low **turn on voltage** - high **reverse bias current**

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



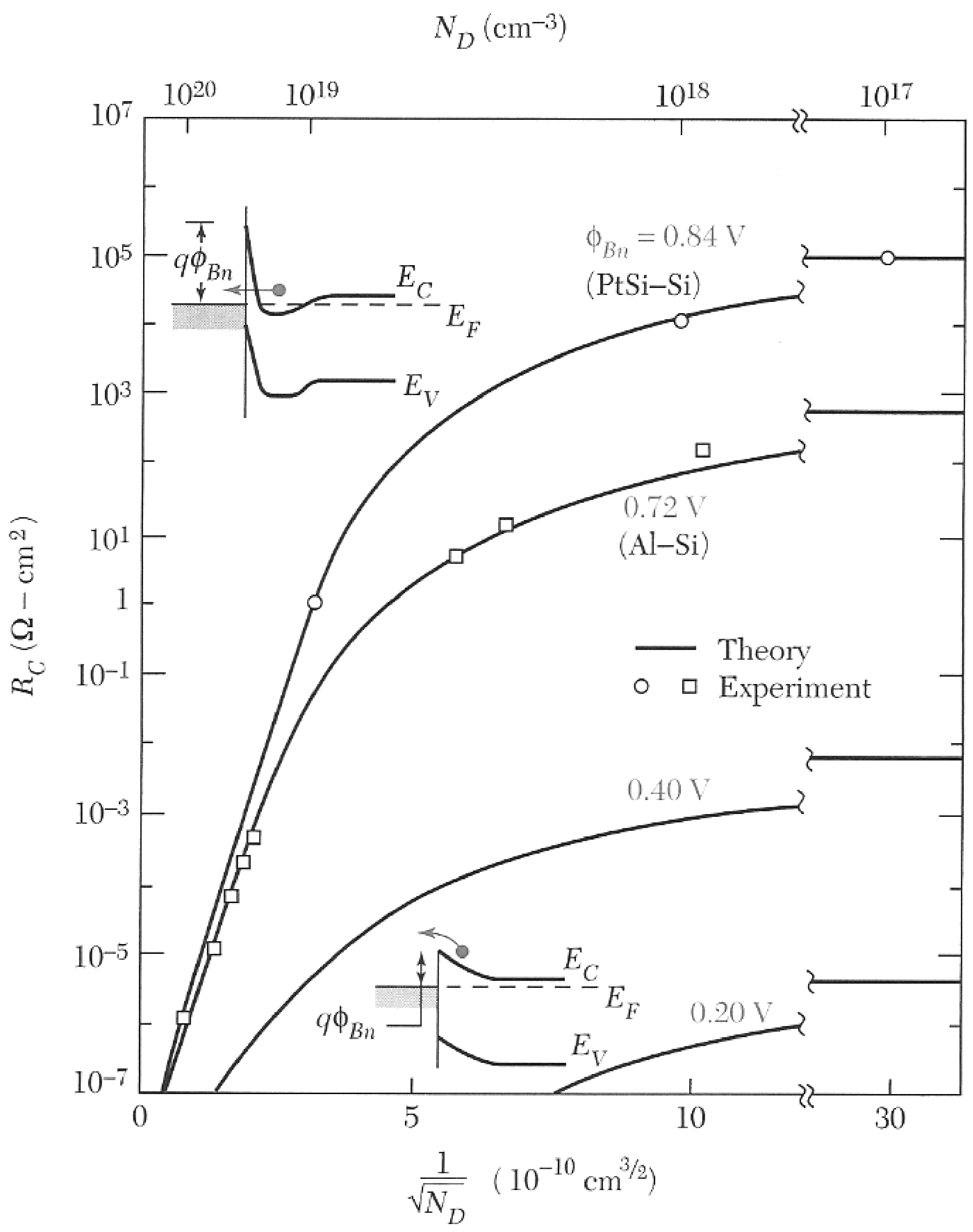
tunnel contact

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}
R_C (Ω – cm^2)
10^7 10^5 10^3 10^1 1 10^{-1} 10^{-3} 10^{-5} 10^{-7}
$q\phi_{Bn}$
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.