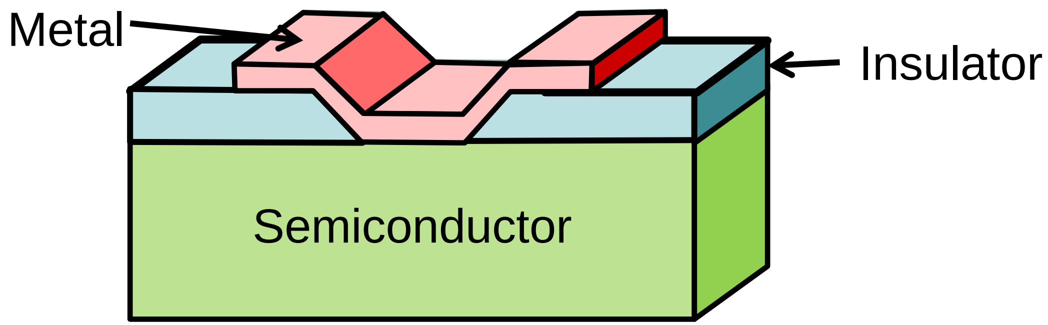
EEE6206 Power Semiconductor Devices:

Section 2b: Metal Semiconductor Contacts

Metal semiconductor contacts

- The metal semiconductor contact
  - Simplest of all structures just consisting of a metal and semiconductor regions

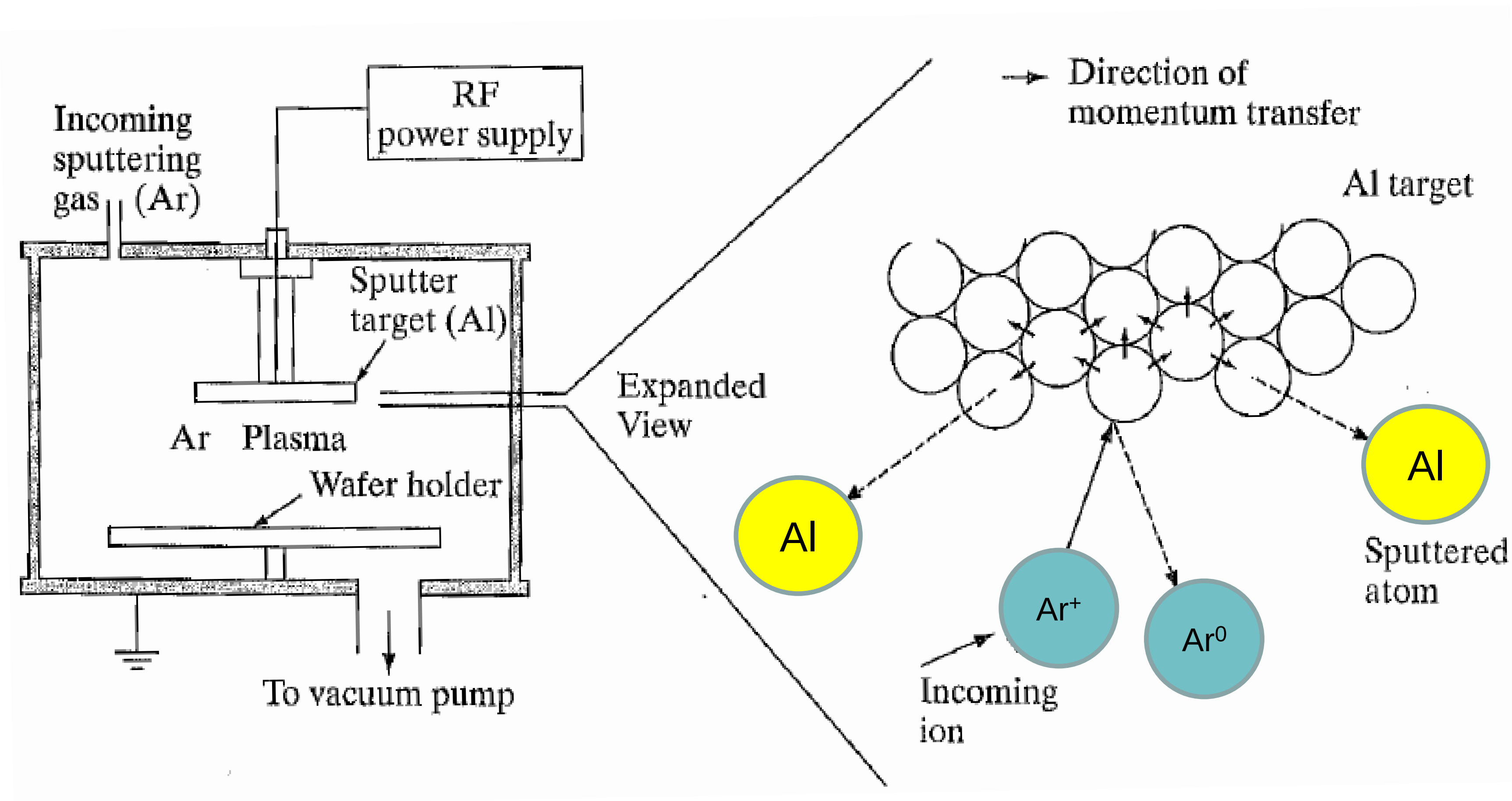


- Control of the semiconductor, doping and metal we can make the contact
- Ohmic
  - linear current-voltage characteristics
  - Used for electrical contacts to cathode/anode and source/drain of the power device
- Schottky contact (rectifying)
  - Electrical characteristics similar to a one sided abrupt p-n diode
  - Unlike p-n junctions, Schottky are operated as a majority carrier device
- Common techniques: Evaporation and Sputtering

Sputtering

- Commonly technique for Aluminium contacts of Silicon
- Sputtered films exhibit excellent uniformity, density, purity and adhesion
- Substrates are placed into the vacuum chamber
- Sputtering starts when a negative charge is applied to the target material (material to be deposited), causing a plasma
- Positive charged gas ions generated in the plasma are attracted to the negative biased target plate at a very high speed
- This collision creates a momentum transfer and ejects atomic size particles from the target. These particles traverse the chamber and are deposited as a thin film onto the surface of the substrates

Aluminium sputtering by Ar^+ Ions



Evaporation

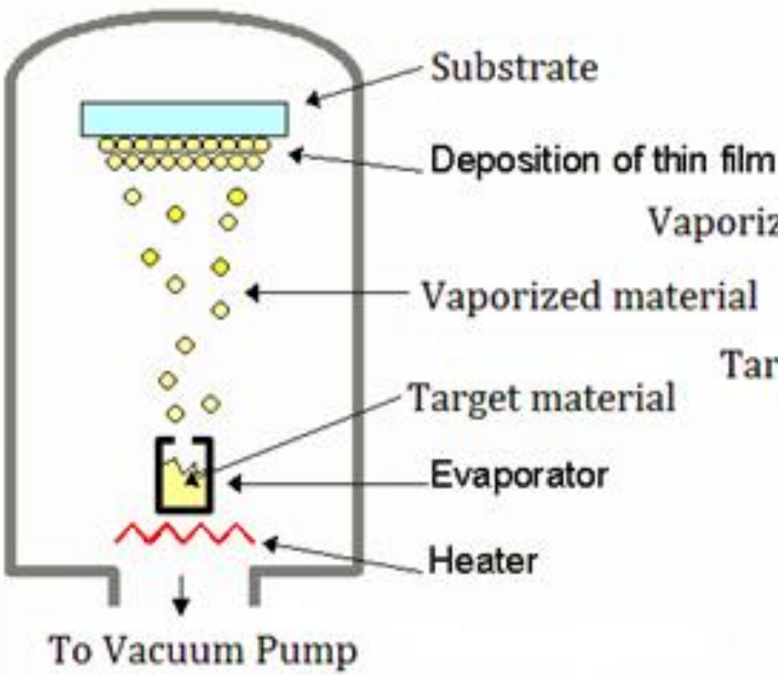
- Evaporation occurs when the material is heated above its melting point in an evacuated chamber
- Evaporated atoms travel at high velocity towards the sample to deposit the metallisation layer
- Different techniques can be used to heat the metal. This could be either resistance heating or bombardment with a high energy electron beam
- Resistive Heating
  - Material is heated until fusion by means of an electrical current passing through a filament or metal plate
  - Evaporated material is then condensed on the substrate
  - The assembly of the technique is simple and results appropriate for depositing metals and compounds with low melting temperature.

Electron beam evaporation technique

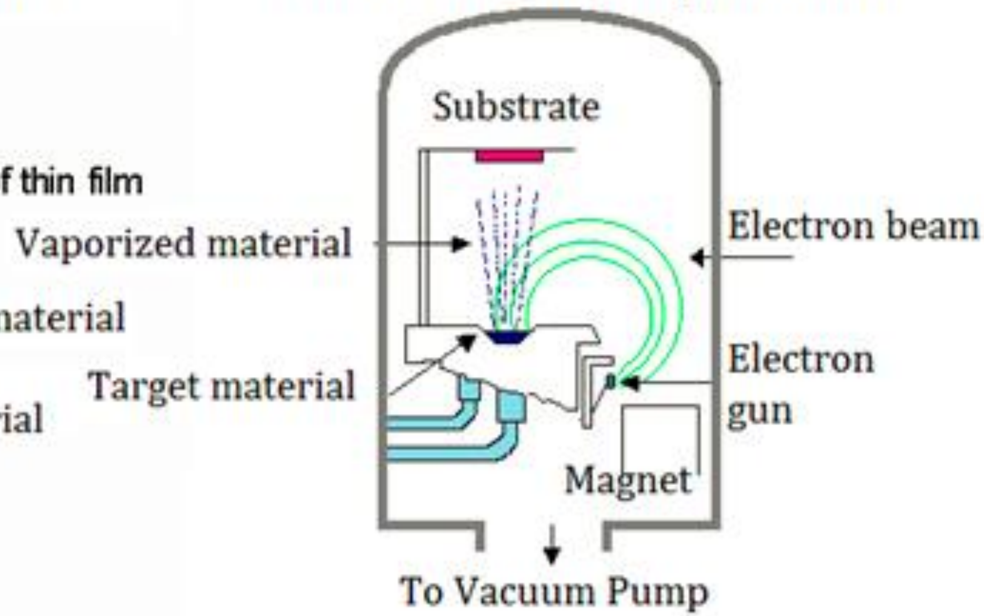
- Heat produced by high energy electron beam bombardment on the material to be deposited
- Electron beam is generated by an electron gun, which uses the thermionic emission of electrons produced by an incandescent filament
- Emitted electrons are accelerated by a high voltage potential (kilovolts)
- A magnetic field is often applied to bend the electron trajectory, allowing the electron gun to be positioned below the evaporation line
- As electrons can be focalized, it is possible to obtain localized heating on the material to evaporate, with a high density of evaporation power.
  - Allows controlling the evaporation rate, from low to very high values, and best of all, the chance of depositing materials with high melting points (eg. Tungsten (W))

Resistive and electron beam evaporation

Resistance heating evaporation



Electron beam evaporation

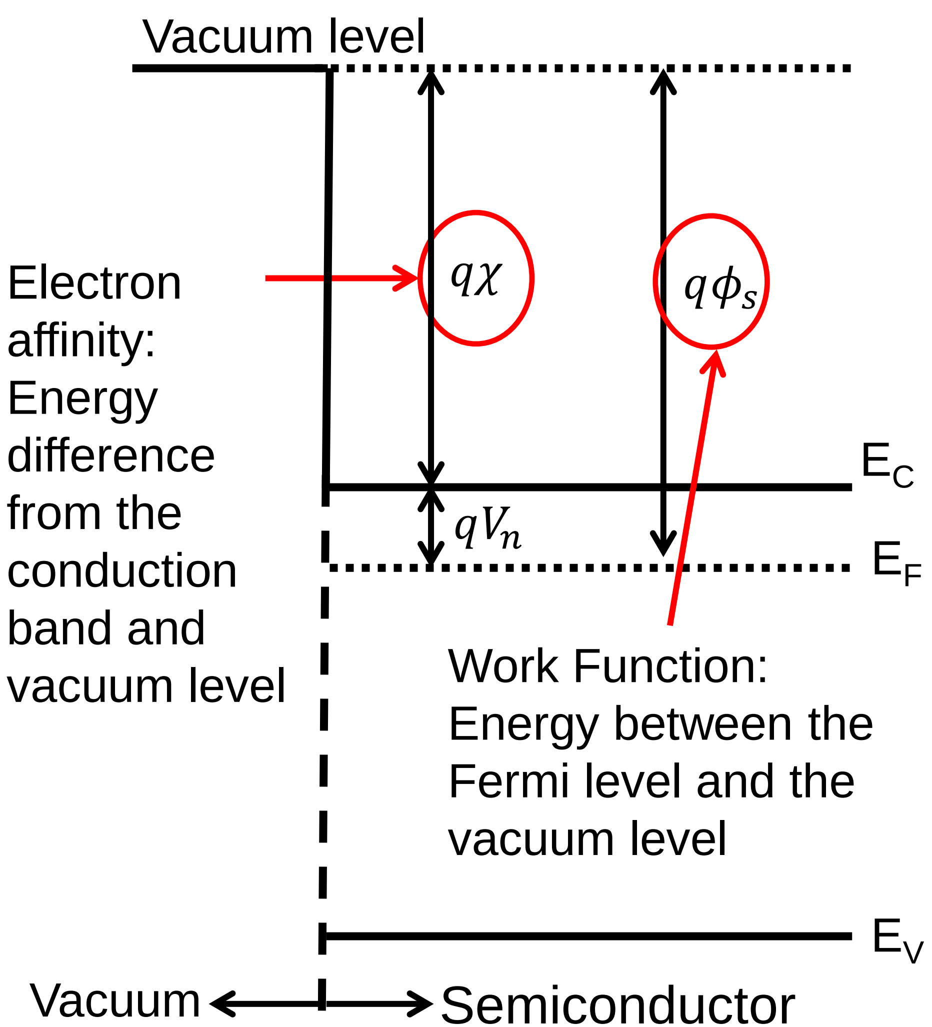


Thermionic emission

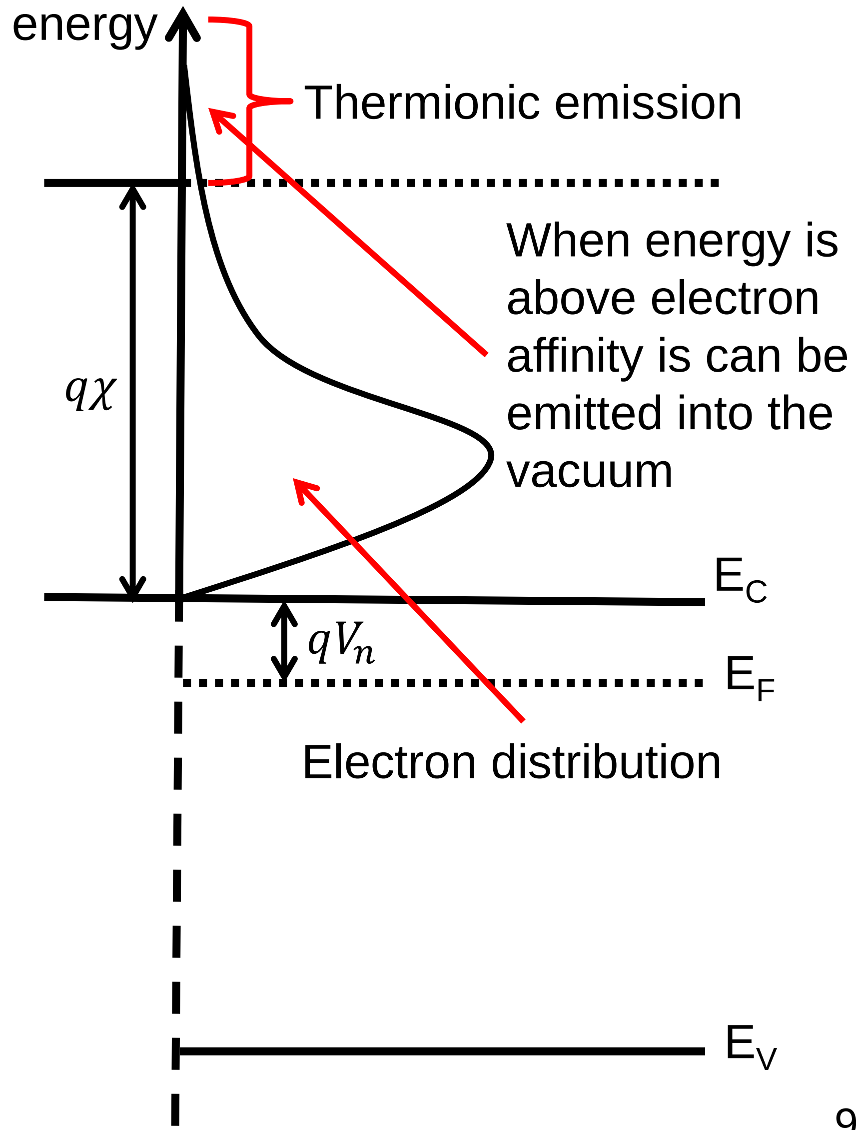
- Considering a P-N Junction, current flows through the junction via a Drift and diffusion process:
  - Carriers are transported through the bulk of the semiconductor (Bulk conduction)
- Current flow through a metal semiconductor contact is via a thermionic emission process
- At the semiconductor surface:
  - Carriers may recombine with the recombination centres due to dangling bonds at the surface region
  - Carriers with sufficient energy could be “thermionically” emitted into the vacuum (Thermionic emission)

Thermionic emission process: n type isolated semiconductor

Band diagram of an isolated n type semiconductor



Thermionic emission process



Thermionic emission electron density

- The electron density with energies above the affinity level $(q\chi)$ can be obtained from an expression to that of electron density in a conduction band

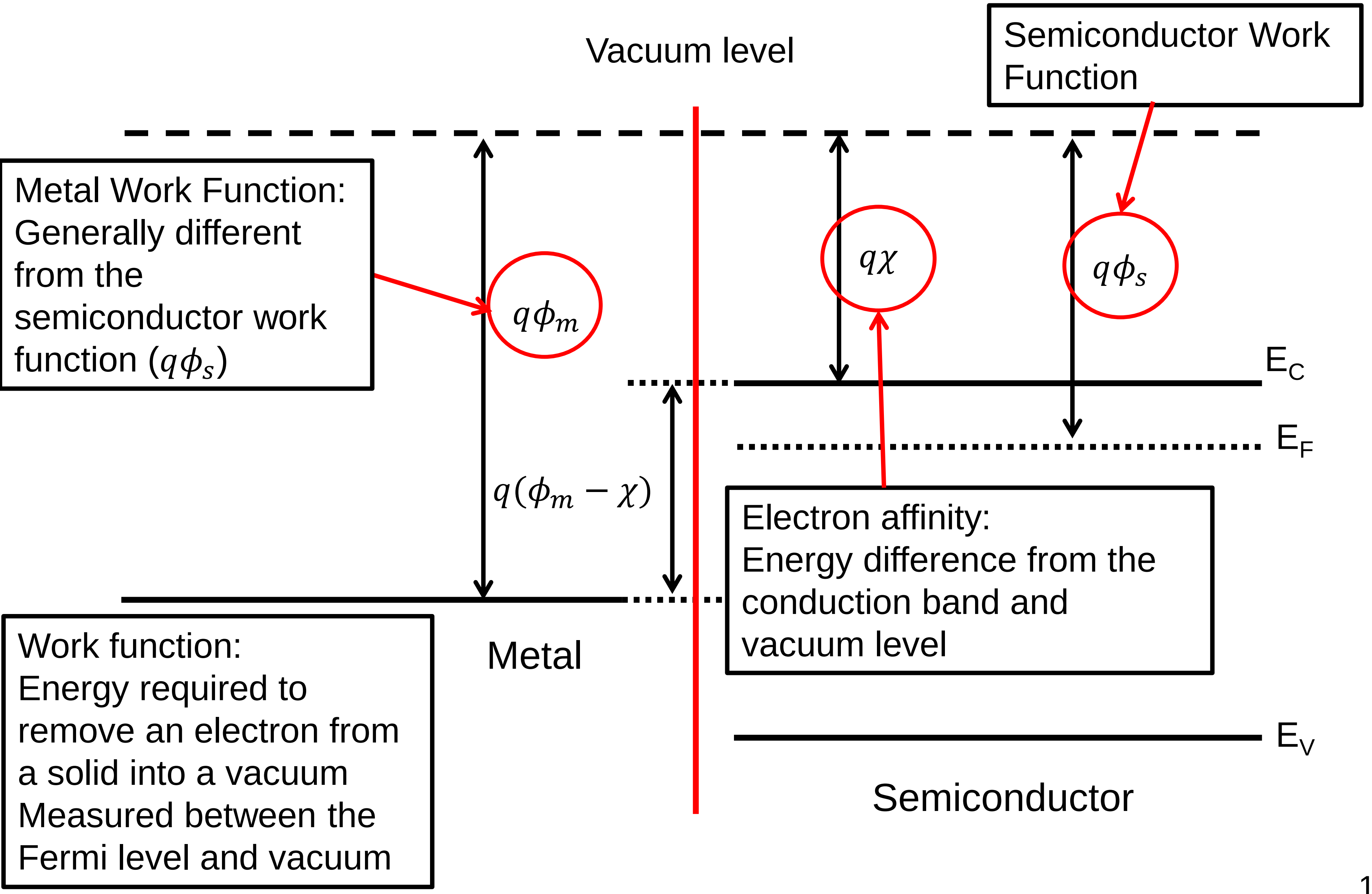
$$n_{th} = \int_{q\chi}^{\infty} n(E)dE = N_C exp^{\left[-\frac{q(\chi+V_n)}{kT}\right]}$$

Electron density through thermionic emission

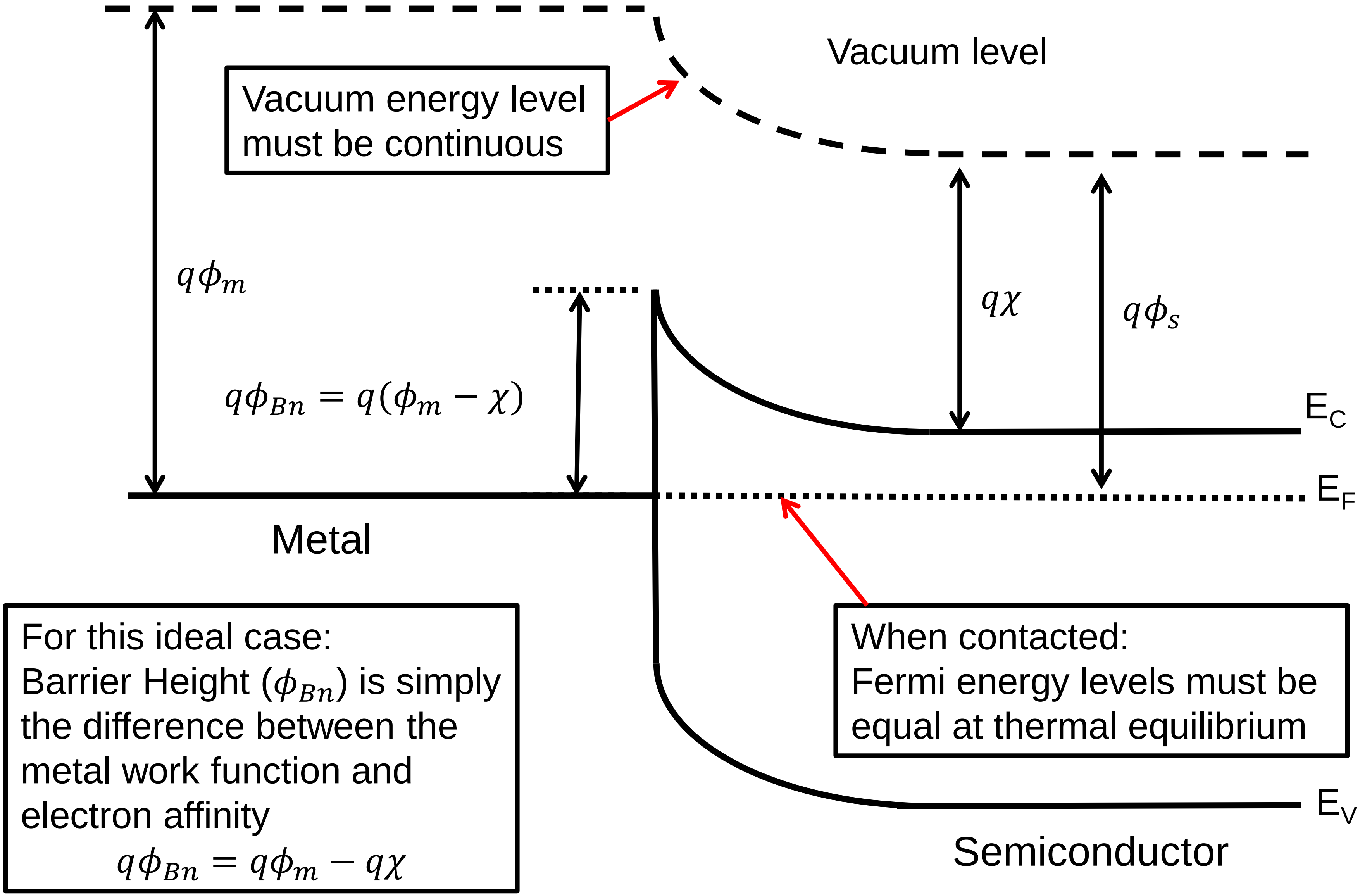
Effective density of states

Difference between bottom of the conduction band and Fermi level

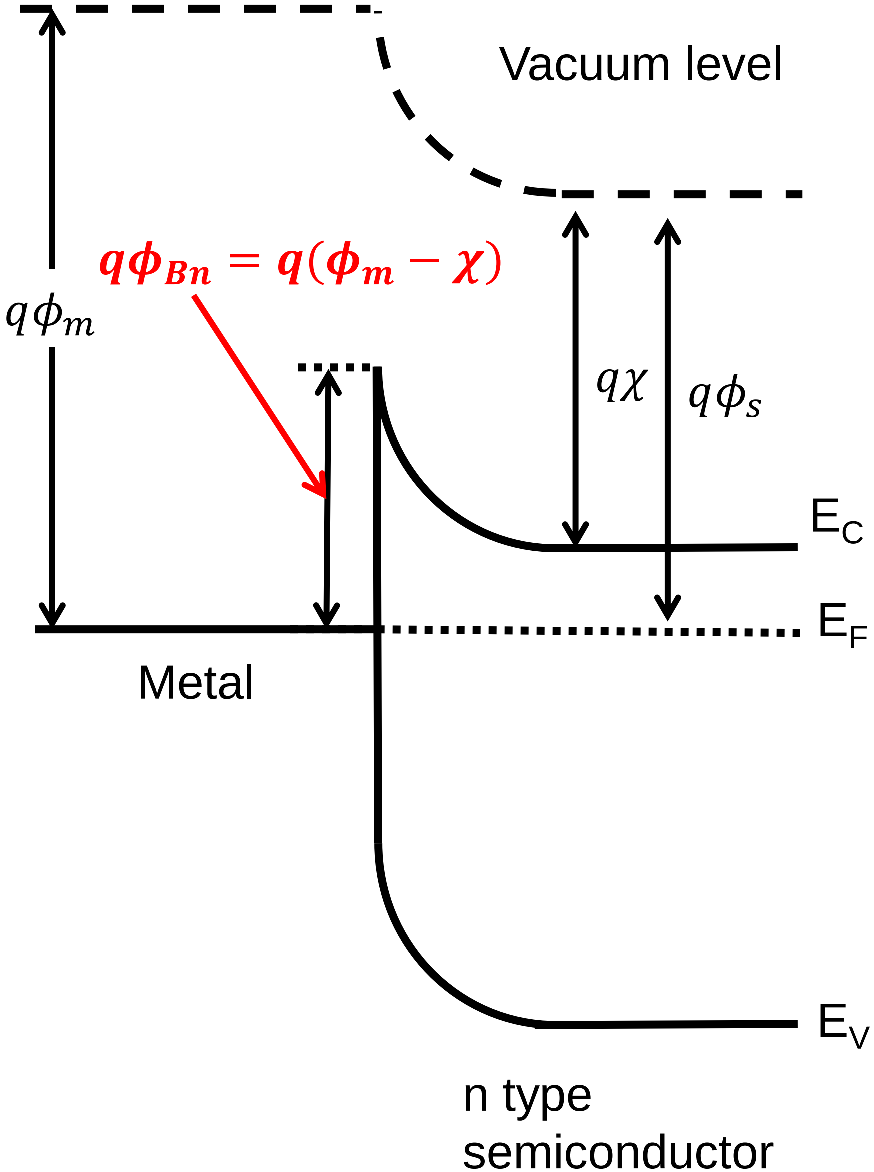
Energy band diagram of an isolated metal and semiconductor

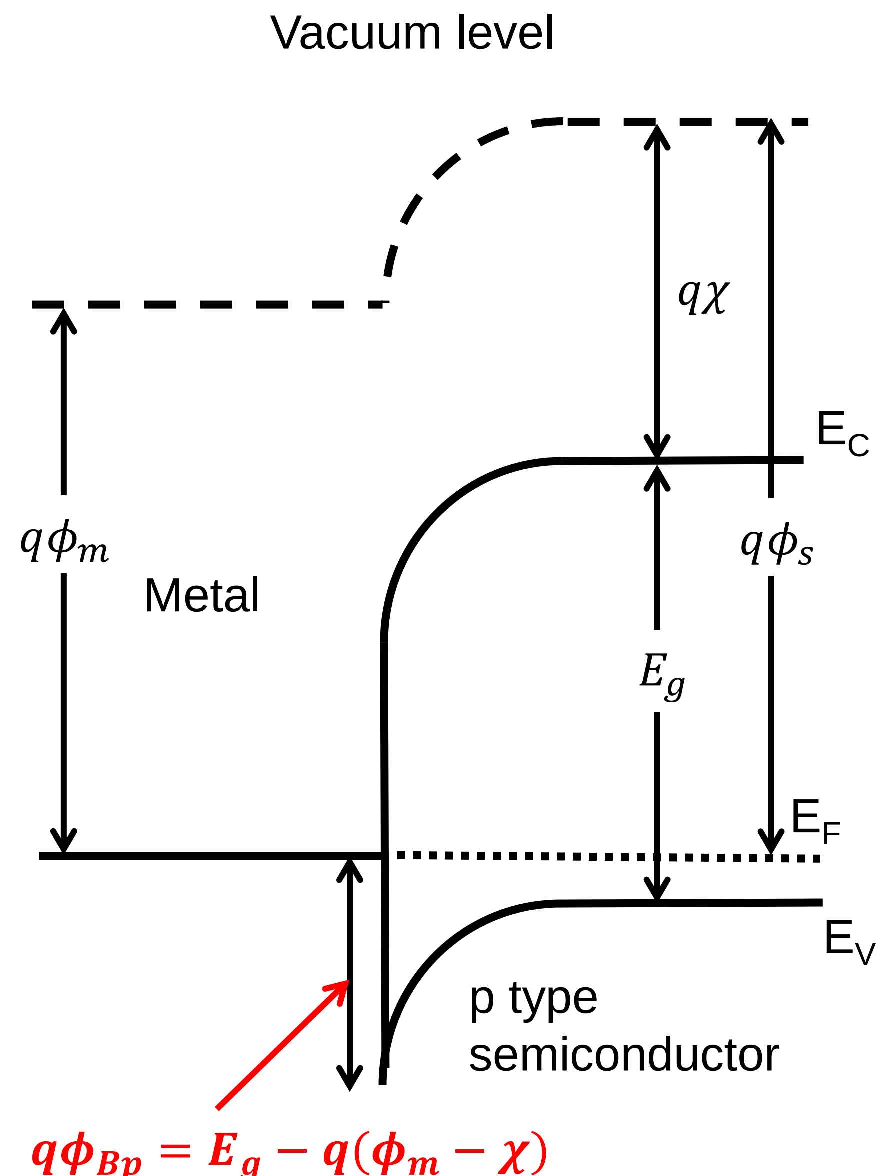


Energy band diagram of an contacted metal and semiconductor

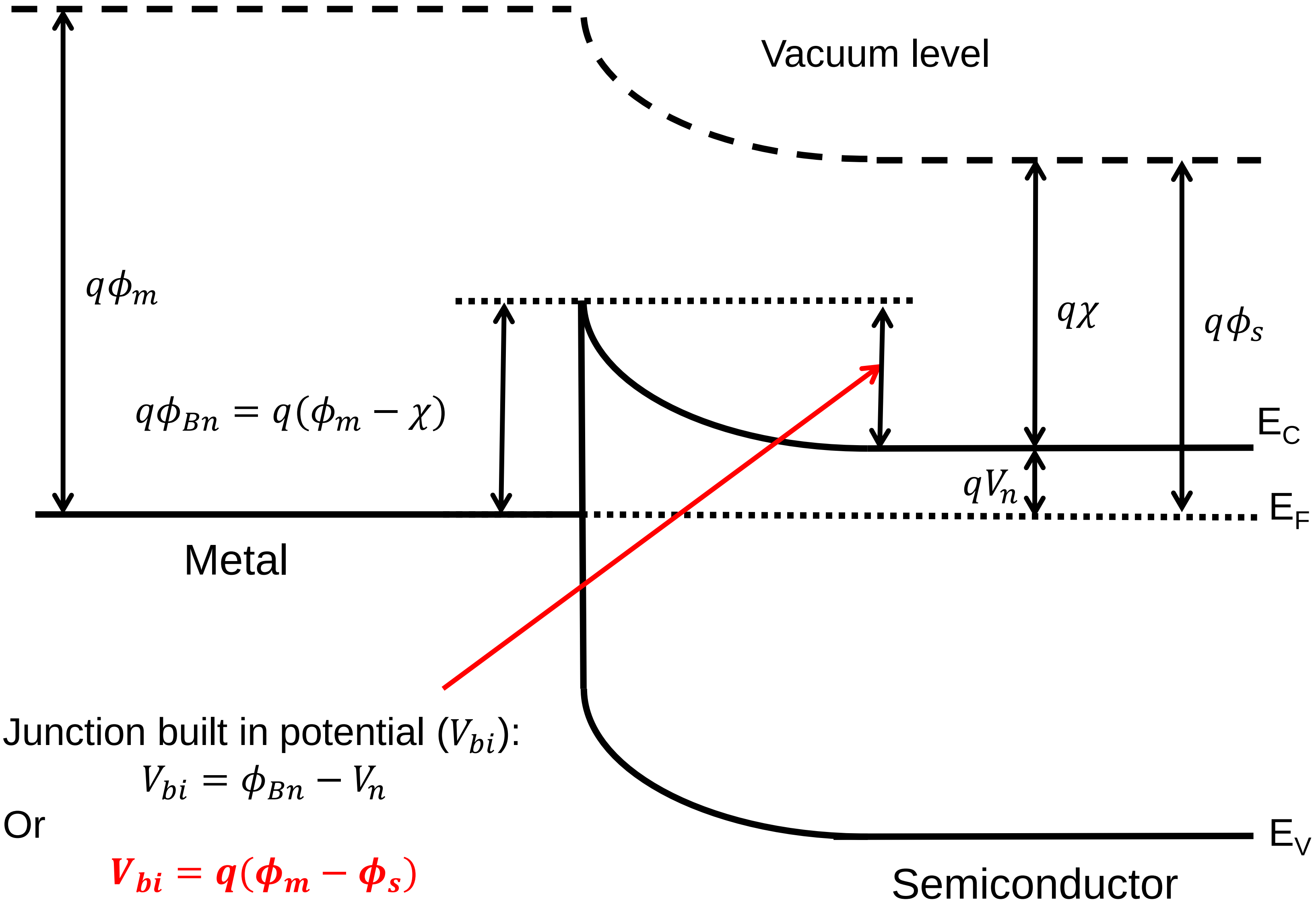


Idealised meatal contacts to p type and n type semiconductors





Energy band diagram of metal /n type semiconductor contact



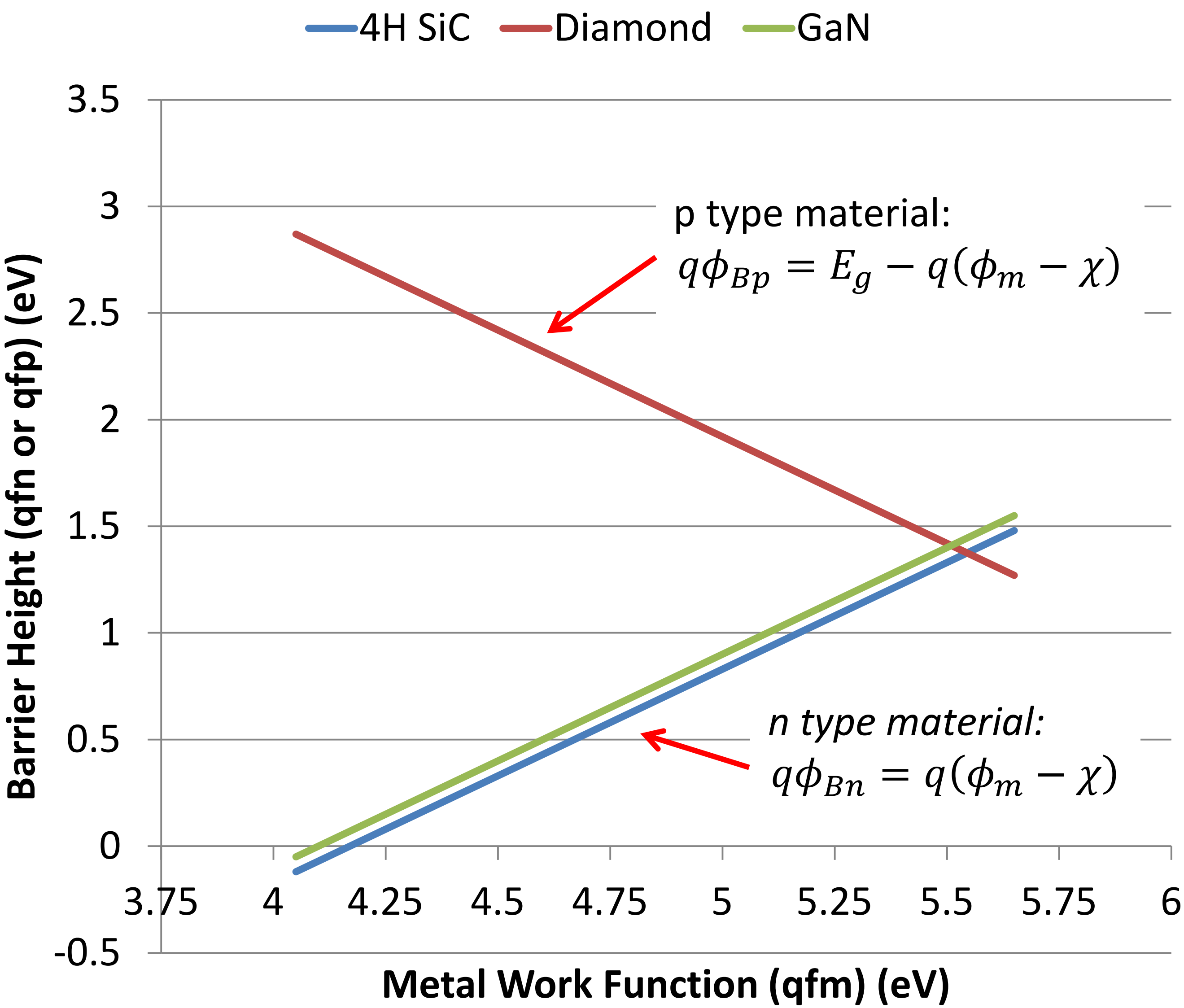
Junction built in potential (V_{bi}):

$$V_{bi} = \phi_{Bn} - V_n$$

Or

$$\boldsymbol{V_{bi} = q(\phi_m - \phi_s)}$$

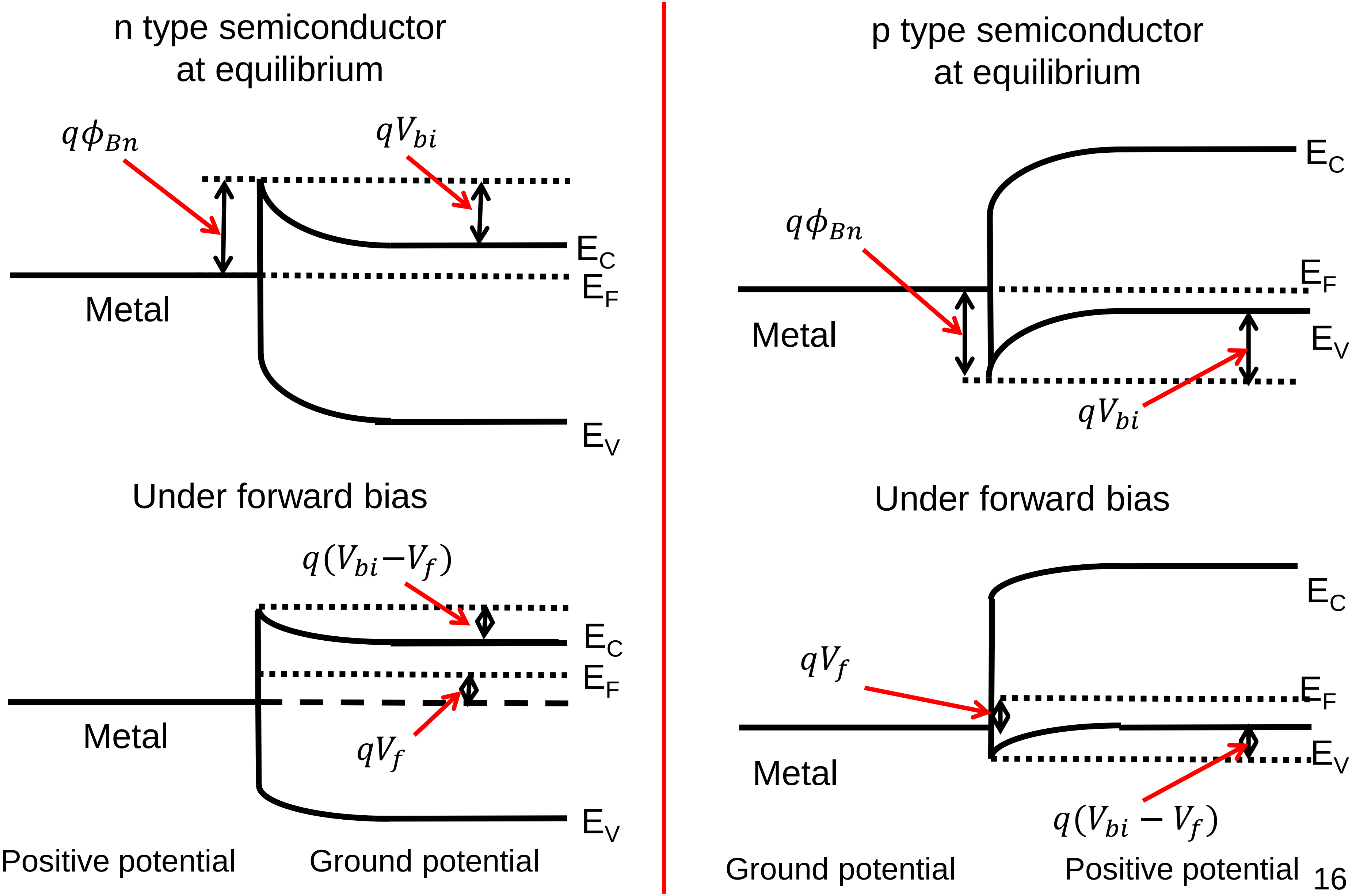
Calculated barrier heights for common metals and WBG materials



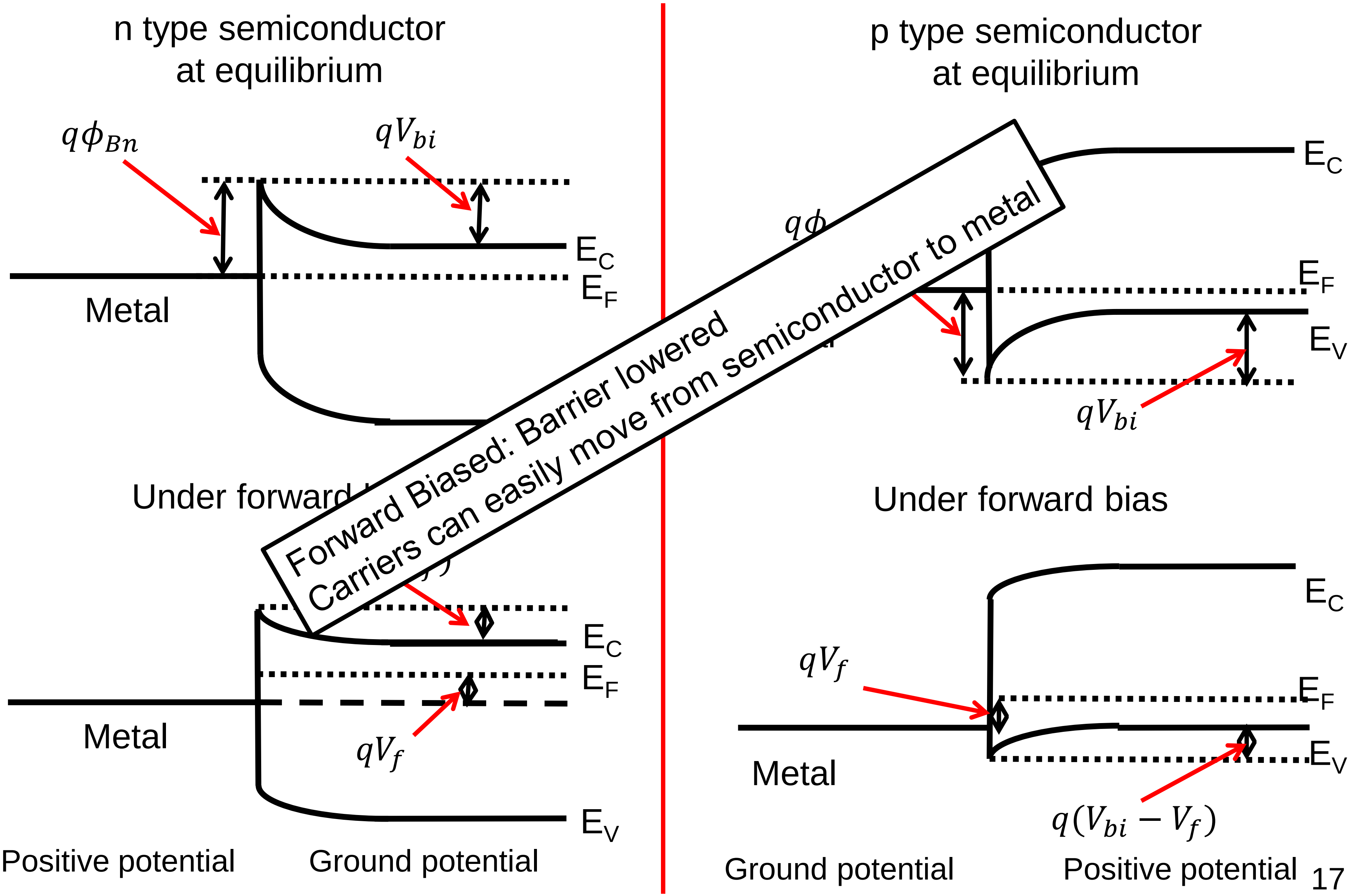
Meta Work function

Metal	Work Function
Zr	4.05 eV
Al	4.28 eV
Ti or Zn	4.33 eV
W	4.55 eV
Mo	4.6 eV
Cu	4.65 eV
Co	5 eV
Ni	5.1 eV
Au	5.15 eV
Pt	5.65 eV

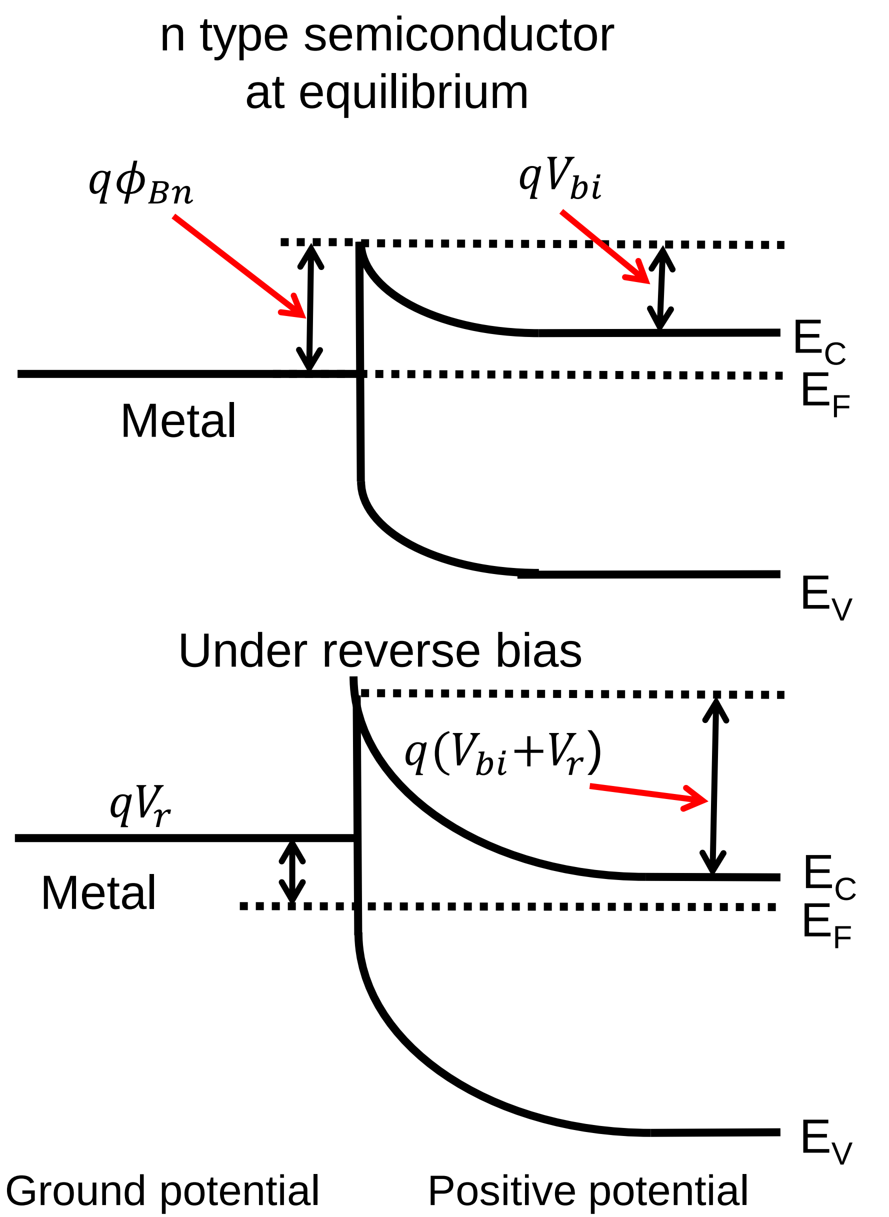
Energy diagram for n and p type semiconductor under applied bias (forward bias)

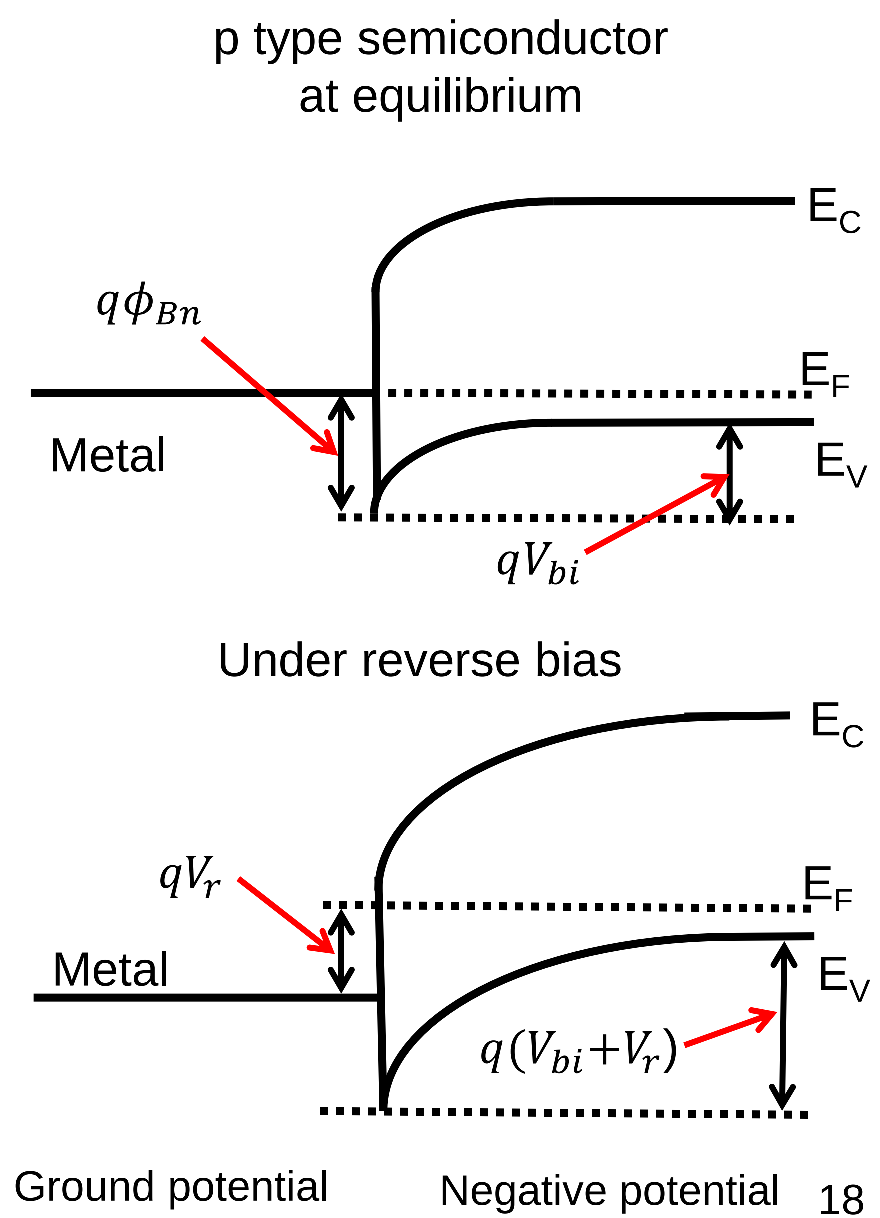


Energy diagram for n and p type semiconductor under applied bias (forward bias)

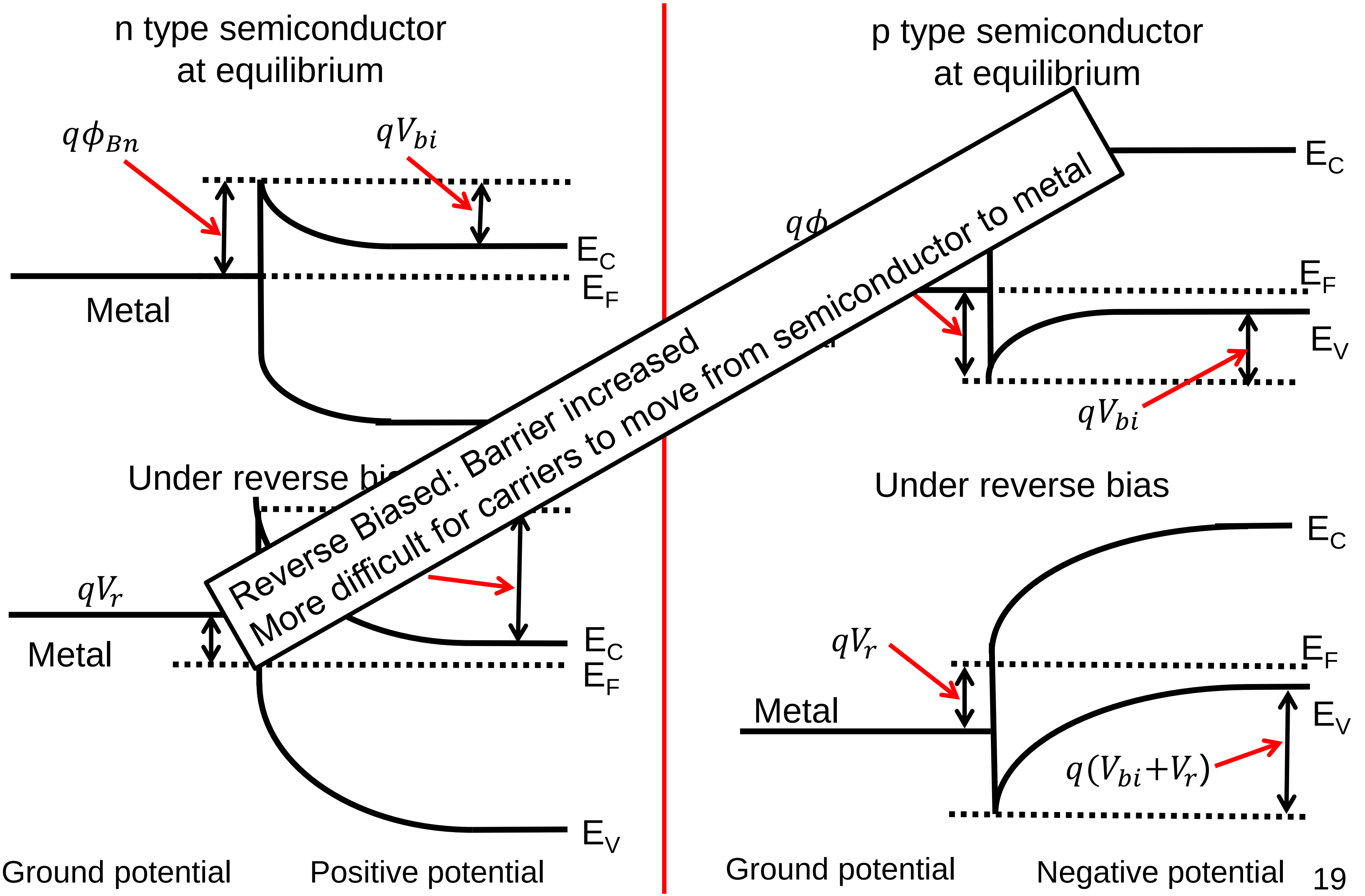


Energy diagram for n and p type semiconductor under applied bias (reverse bias)

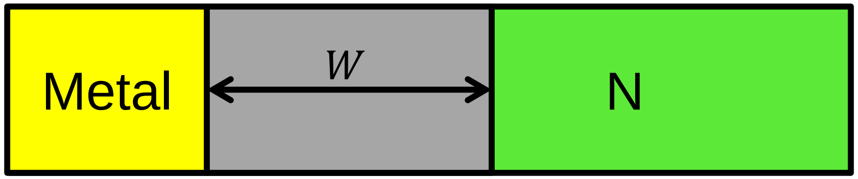


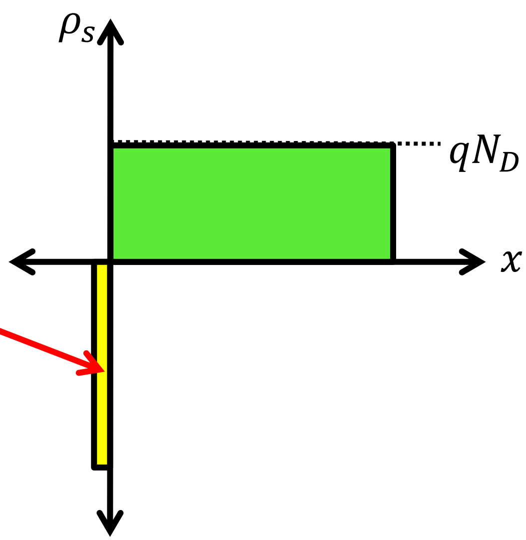


Energy diagram for n and p type semiconductor under applied bias (reverse bias)

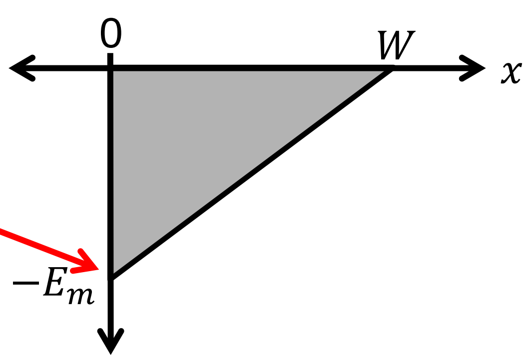


Charge and field distribution for a metal semiconductor contact





Compensation charge exists in a very narrow region and is therefore equivalent to an abrupt junction



Maximum field located at the interface

$$E_{(x)} = \frac{qN_D}{\varepsilon_s}(W - x) = E_m - \frac{qN_D}{\varepsilon_s}x$$

$$E_m = \frac{qN_D W}{\varepsilon_s}$$

- Voltage across the space charge region
  - Area under the electric field curve

$$V_{bi} - V = \frac{E_m W}{2} = \frac{qN_D W^2}{2\varepsilon_s}$$

  - Depletion width (W)

$$W = \sqrt{\frac{2\varepsilon_s (V_{bi} - V)}{qN_D}}$$

  - Space charge density in the semiconductor:

$$Q_{sc} = qN_D W = \sqrt{2\varepsilon_s qN_D (V_{bi} - V)}$$

Example: Depletion layer width

- Find the deletion layer width for a Schottky diode with a n-drift region doping density of 1e14 and an applied bias of 300V. Assume the built in potential of the junction to be 0.5V

Example: Depletion layer width

- Find the deletion layer width for a Silicon Schottky diode with a n-drift region doping density of 1e14 and an applied bias of -300V. Assume the built in potential of the metal semiconductor interface (V_{bi}) to be 0.5V

$$W = \sqrt{\frac{2 \times \varepsilon_s (V_{bi} - V)}{q N_D}} = \sqrt{\frac{2 \times 11.7 \times 8.85 \times 10^{-14} (0.5 + 300)}{1.6 \times 10^{-19} \times 1 \times 10^{14}}}$$

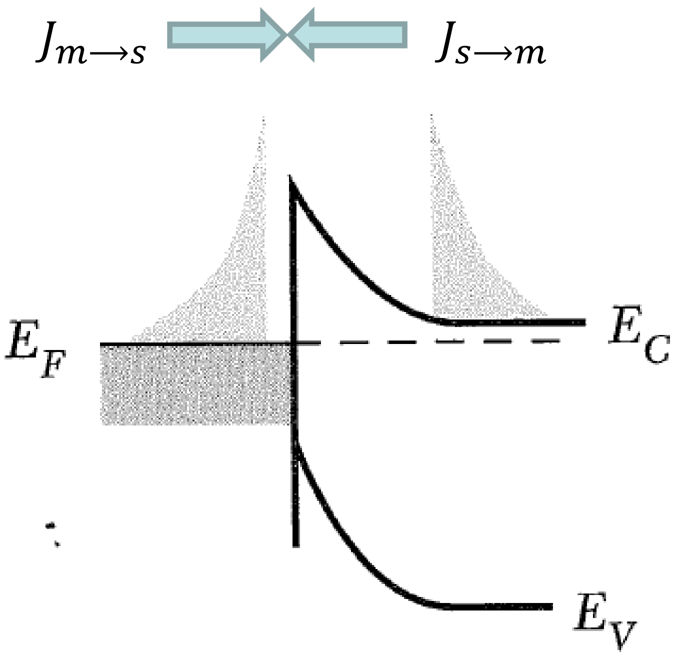
$$W = 0.00624 \text{ cm}$$

$$W = 62.4 \mu m$$

Schottky barrier

- Refers to a metal semiconductor contact having a large barrier height and a doping concentration lower than the density of states in the valence or conduction band
  - i.e. ϕ_{Bn} or $\phi_{Bp} \gg kT$ (25.9meV)
  - $N_A$or $N_D \ll n_i$
- Current transport in a Schottky barrier is due mainly to majority carrier: i.e. electrons in n type material and holes in p type material
  - Contrast to PN junctions where carrier transport is due to minority carriers: i.e. holes carriers in n type material and electron carriers in p
- For Schottky diodes operated at moderate temperatures (~300K)
  - Dominant transport mechanism is thermionic emission of majority carriers from the semiconductor over the potential barrier into the metal

Metal semiconductor contact: Equilibrium conditions



- If an electron energy level is above the barrier height can be emitted from the semiconductor into the vacuum
  - Previously the emitted electrons from a surface

$$n_{th} = N_C\ exp^{\left[-\frac{q(\chi+V_n)}{kT}\right]} \quad n_{th} = N_C\ exp^{\left[-\frac{q(\phi_{Bn})}{kT}\right]}$$

- At thermal equilibrium:

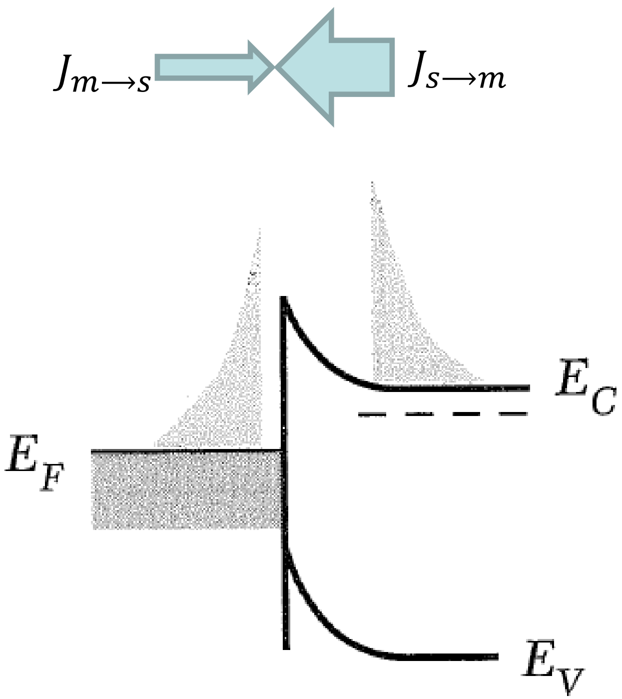
$$|J_{m\rightarrow s}| = |J_{s\rightarrow m}| \leq \propto n_{th}$$

- Or:

$$|J_{m\rightarrow s}| = |J_{s\rightarrow m}| = C_1 N_c exp^{\left[-\frac{q(\phi_{Bn})}{kT}\right]}$$

Probability constant

Metal semiconductor contact: Forward bias



- When a forward bias is applied the number of emitted electrons change to:

$$n_{th} = N_C\ exp^{\left[-\frac{q(\phi_{Bn}-V_f)}{kT}\right]}$$

- $J_{s\to m}$ results in the current out of the semiconductor into the metal and is therefore altered by the same value
- Electron flux from the metal to the semiconductor is the same as thermal equilibrium: the barrier (ϕ_{Bn}) remains the same
- The net current under forward bias is:

$$J = J_{s\to m} - J_{m\to s}$$

$$= C_1 N_c exp^{\left[-\frac{q(\phi_{Bn}-V_f)}{kT}\right]} - C_1 N_c exp^{\left[-\frac{q\phi_{Bn}}{kT}\right]}$$

$$\boldsymbol{J = C_1 N_c exp^{\left[-\frac{q\phi_{Bn}}{kT}\right]}\left(exp^{\left[\frac{qV_f}{kT}\right]} - 1\right)}$$

Metal semiconductor contact: Reverse bias

- Using the same arguments as for forward bias the net current is identical except that V_f is replaced by $-V_r$

$$\boldsymbol{J = C_1 N_c exp^{\left[-\frac{q\phi_{Bn}}{kT}\right]}\left(exp^{\left[\frac{-qV_r}{kT}\right]} - 1\right)}$$

- Coefficients $C_1 N_c$ has been found to be equal to $A^* T^2$
  - Where A^* is called the effective Richardson constant ($^{A}/_{K^2} - cm^2$)

Material	Richardson constant (A/K² – cm²)
Silicon	n type: 110 p type: 32
4H SiC	n type: 138
GaN	n type: 22.4
Diamond	n type: 120.2

Current voltage characteristic

- From:

$$J = C_1 N_c exp^{\left[-\frac{q\phi_{Bn}}{kT}\right]}\left(exp^{\left[\frac{-qV_r}{kT}\right]} - 1\right)$$

- The current voltage characteristic of a metal semiconductor contact under thermionic emission conditions is given by:

Junction bias

$$\boldsymbol{J = J_s\left(exp^{\left[\frac{qV}{kT}\right]} - 1\right)}$$

$$\boldsymbol{J_s = A^* T^2 exp^{\left[-\frac{q\phi_{Bn}}{kT}\right]}}$$

Saturation current density

Barrier height example

- Calculate the room temperature knee voltage for a 4H SiC/Nickle metal semiconductor contact. Consider the semiconductor is n type with a doping of 1e15 #cm^3, room temperature intrinsic carrier concentration (ni)=4.35e-10#cm^3, Bandgap=3.23eV, Richardson constant of 138A/K^2, metal work function of 5.1eV and an electron affinity of 4.17eV

Barrier height example

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- #1: Calculate the positon of the Fermi level:

$$E_F - E_i = \frac{kT}{q}\ln\left(\frac{N_D}{n_i}\right) = 0.0259\ln\left(\frac{10^{15}}{4.35\times10^{-10}}\right) = 1.45\text{eV}$$

- #2: Calculate the semiconductor work function:

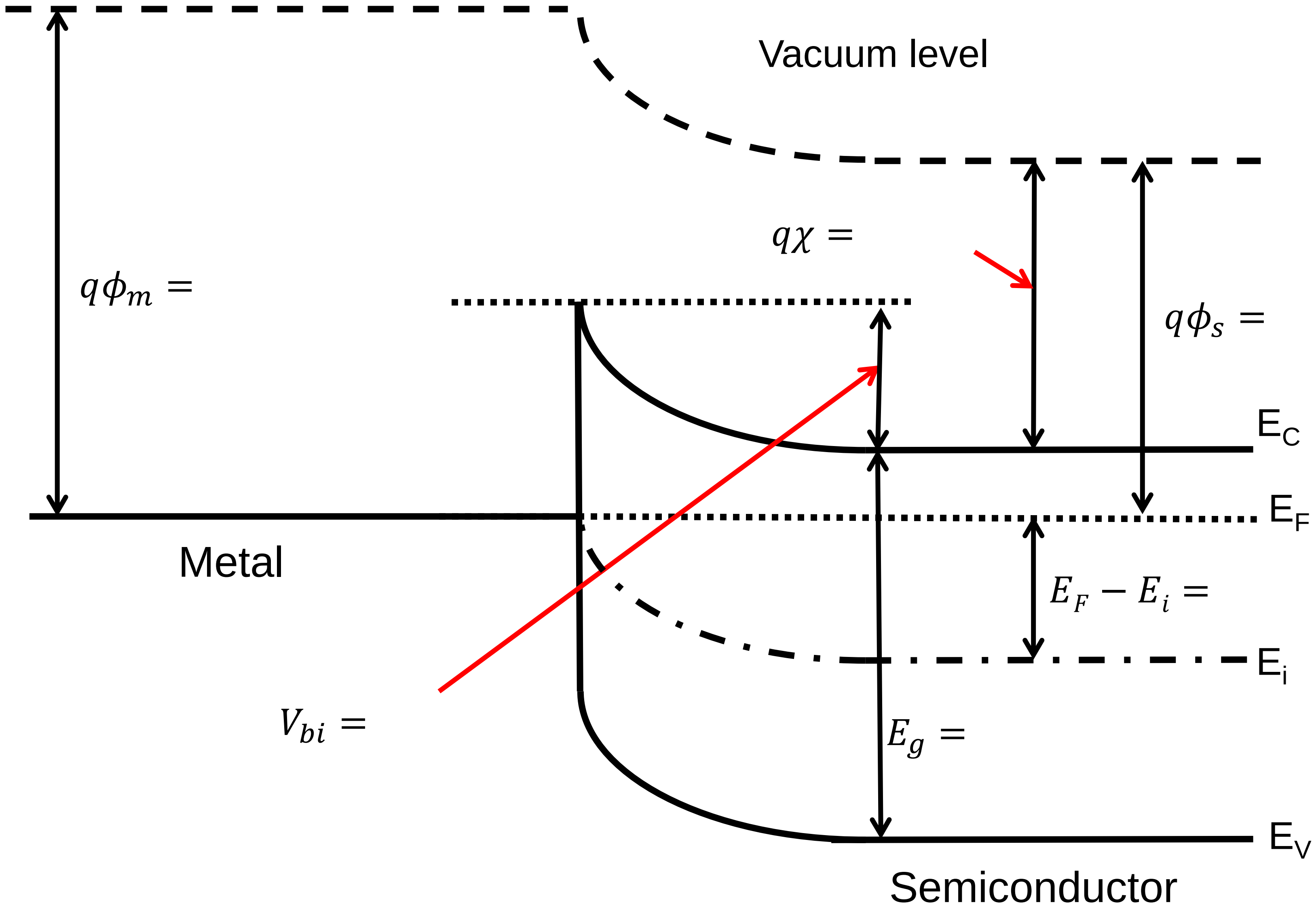
$$q\phi_s = \frac{E_g}{2} - (E_i - E_F) + \chi$$

$$q\phi_s = \frac{3.23}{2} - 1.45 + 4.17 = 4.33eV$$

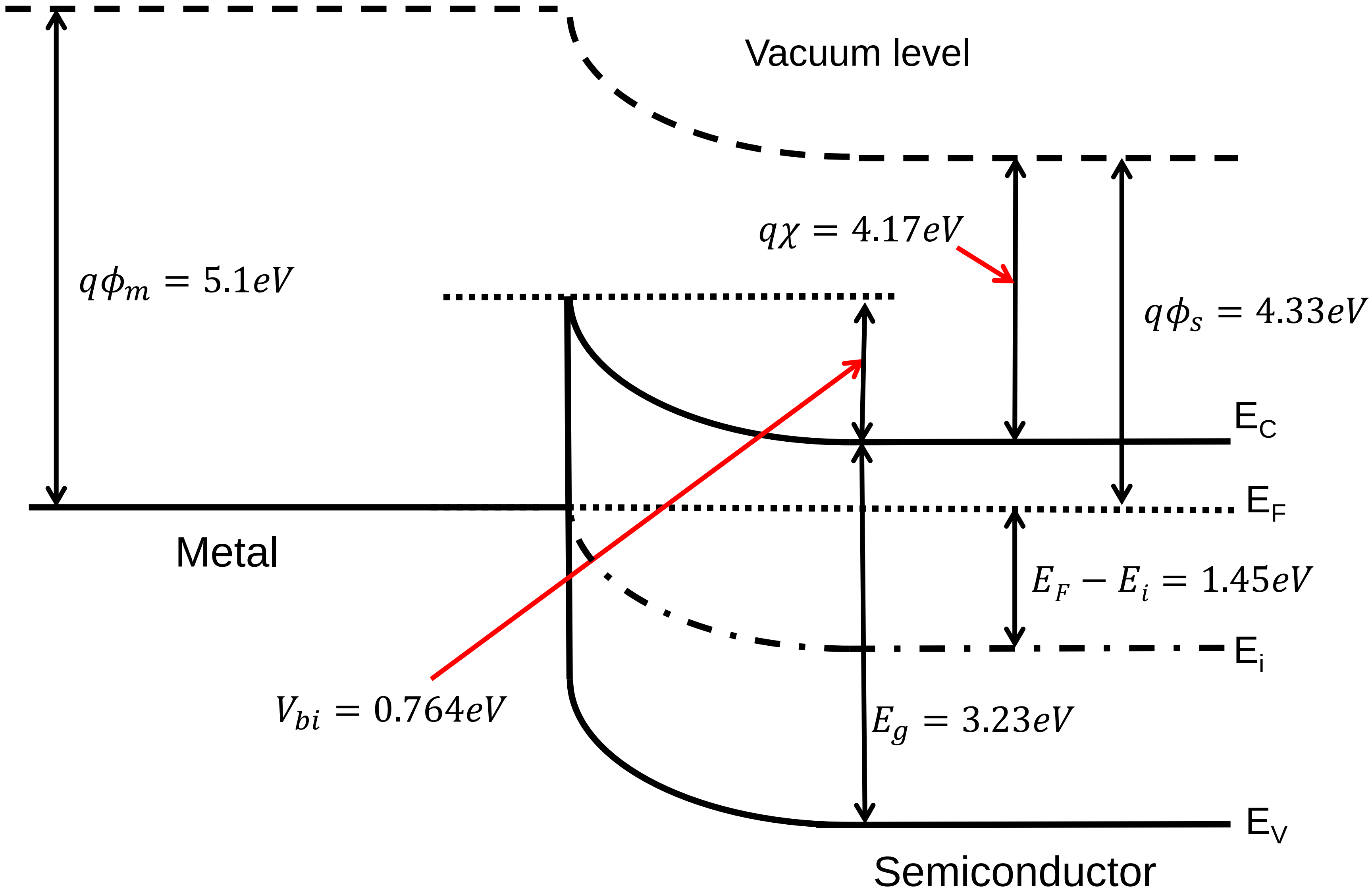
- #3: Calculate the knee voltage:

$$qV_{bi} = q(\phi_m - \phi_s) = 5.1 - 4.33 = 0.77eV$$

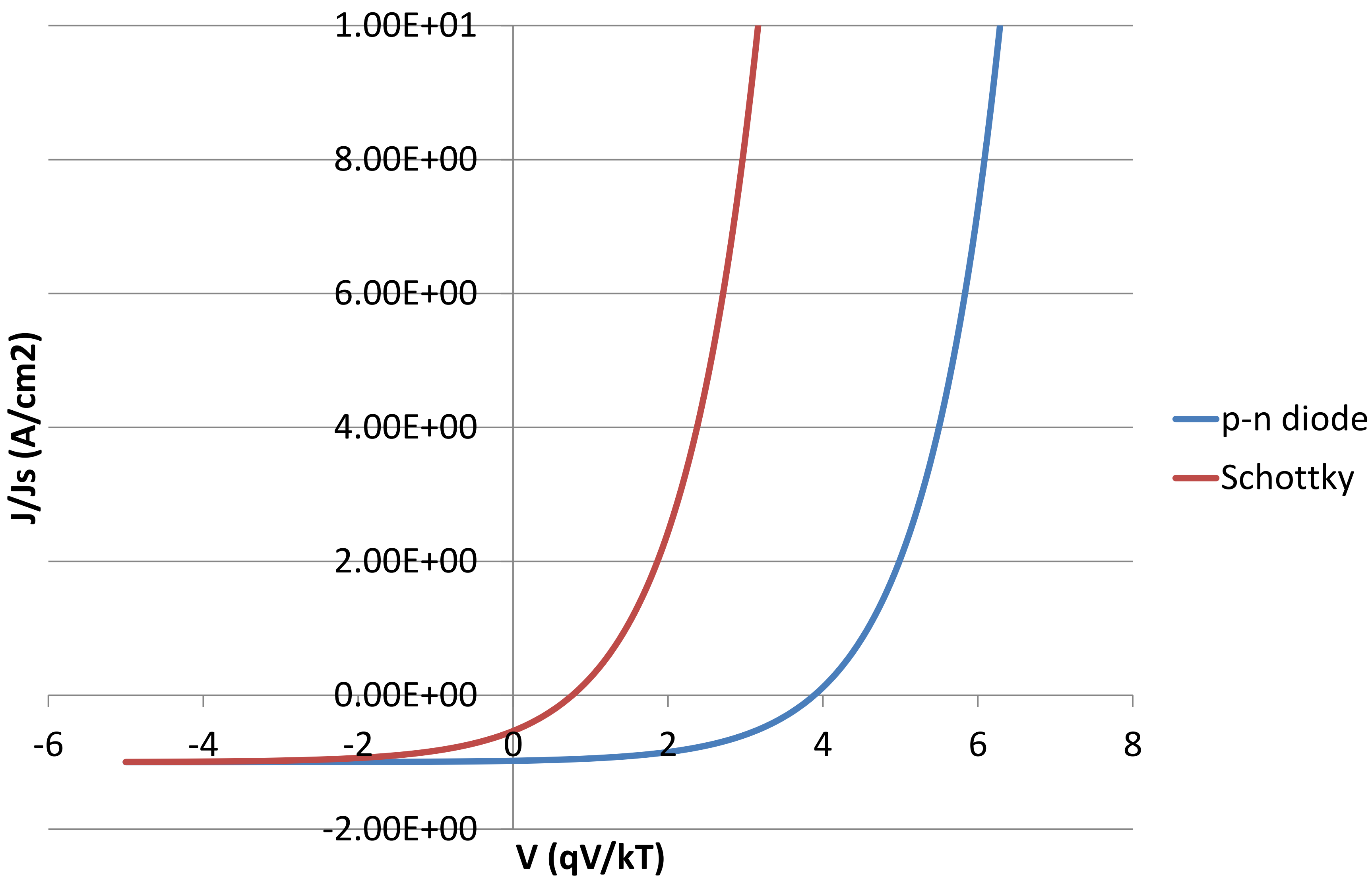
4H SIC / Nickle Schottky diode band diagram



4H SIC / Nickle Schottky diode band diagram



Comparison of a 4H SIC Schottky diode to a P-N Junction



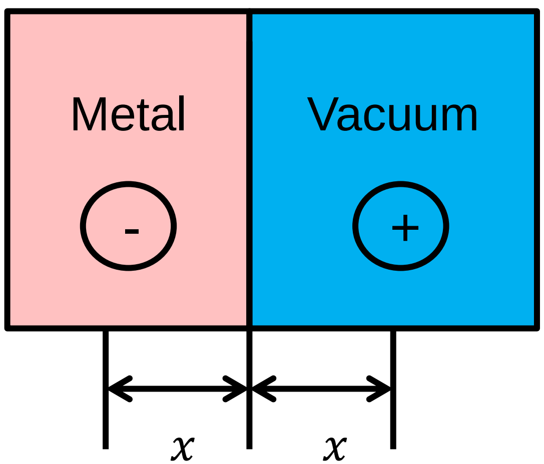
Barrier height lowering

- Image charges build on the metal electrode as carriers approaches the metal-semiconductor interface
- The potential associated with these charges reduces the effective barrier height
- This reduction tends to be small compared to the barrier height itself
  - This effect is of interest since it has a dependency on the applied voltage and leads to a voltage dependence of the reverse bias current

Image force

- When an electron is at a distance x from the metal a positive charge will be induced on the metal surface

Image force



- Electrostatic force between the positive and negative particles which are both at a distance x away from the interface. At $x = 0$ this is given by:

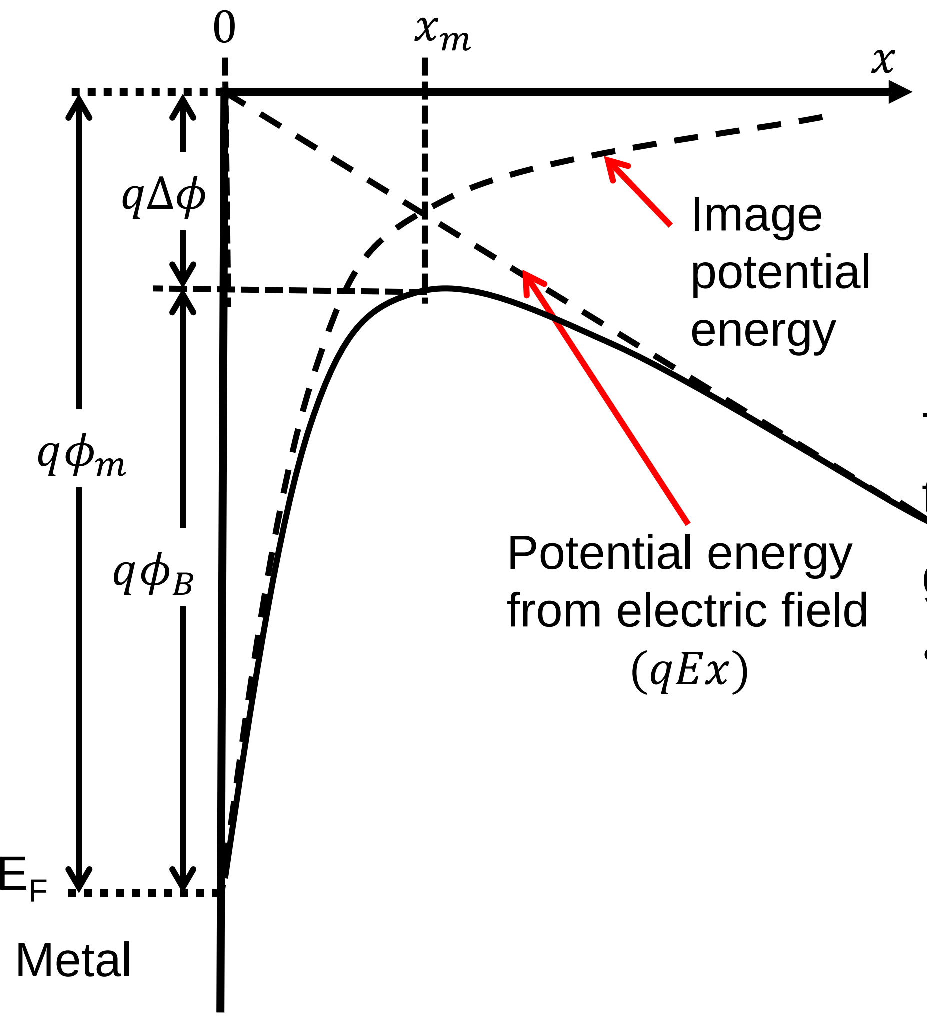
$$F(x) = qE(x) = \frac{-q^2}{4\pi\varepsilon_s(2x)^2}$$

- The corresponding potential equals

$$\phi(x) = \int_x^\infty E(x) = \frac{q^2}{16\pi\varepsilon_o x}$$

- This corresponds to the potential energy of an electron at a point x from the metal surface

Barrier Lowering



- When an external electric field (E) is applied to the contact, the total potential energy (PE) as a function of distance is the sum of the force associated with the electric field and the image force

$$PE(x) = \frac{q^2}{16\pi\varepsilon_o x} + qE(x)$$

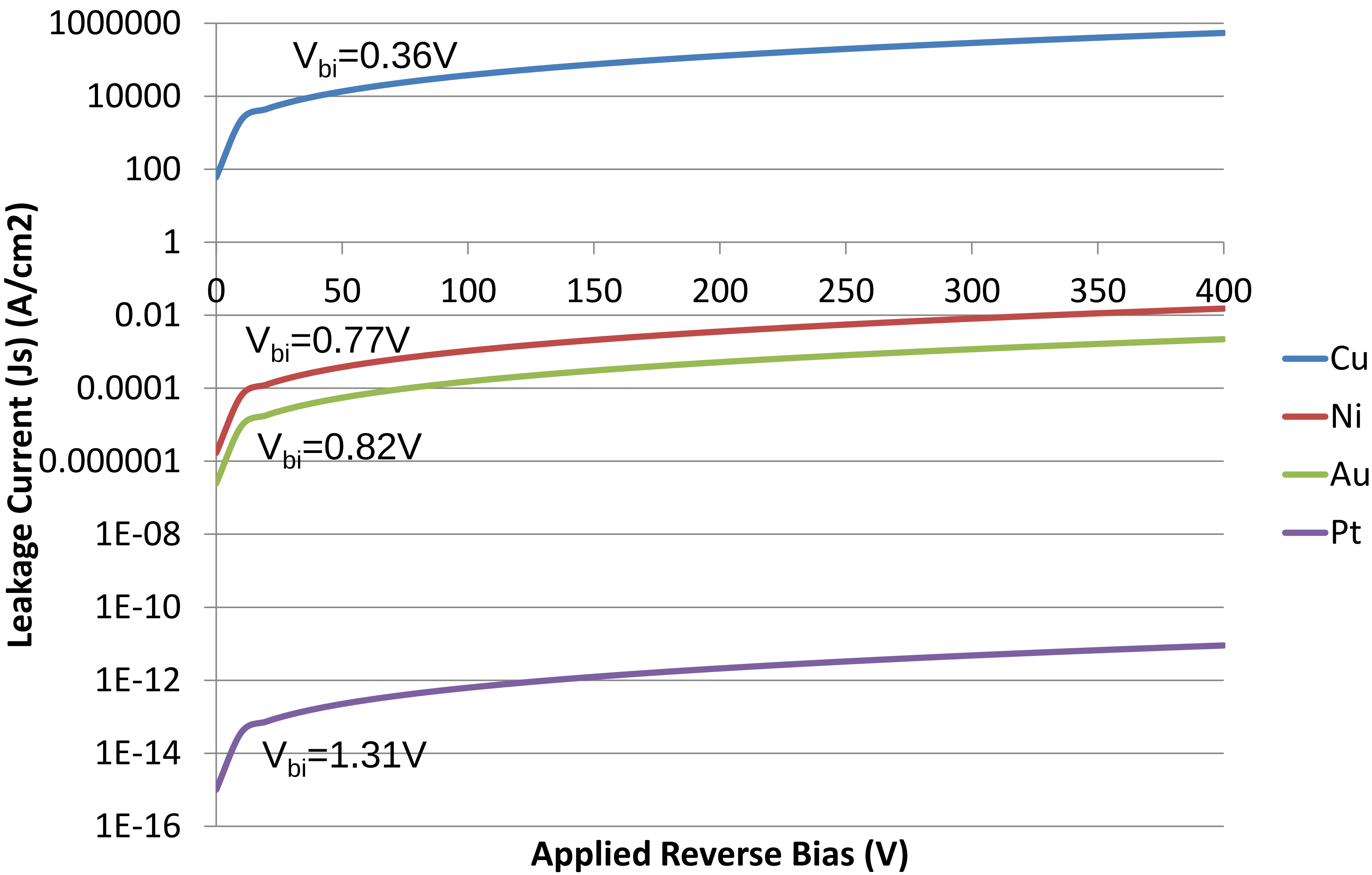
The Schottky barrier lowering ($\Delta\phi$) and the location of the lowering (x_m) are given by the position $\frac{d(PE(x))}{dx} = 0$

- Or…

$$x_m = \sqrt{\frac{q}{16\pi\varepsilon_o E}} \ cm$$

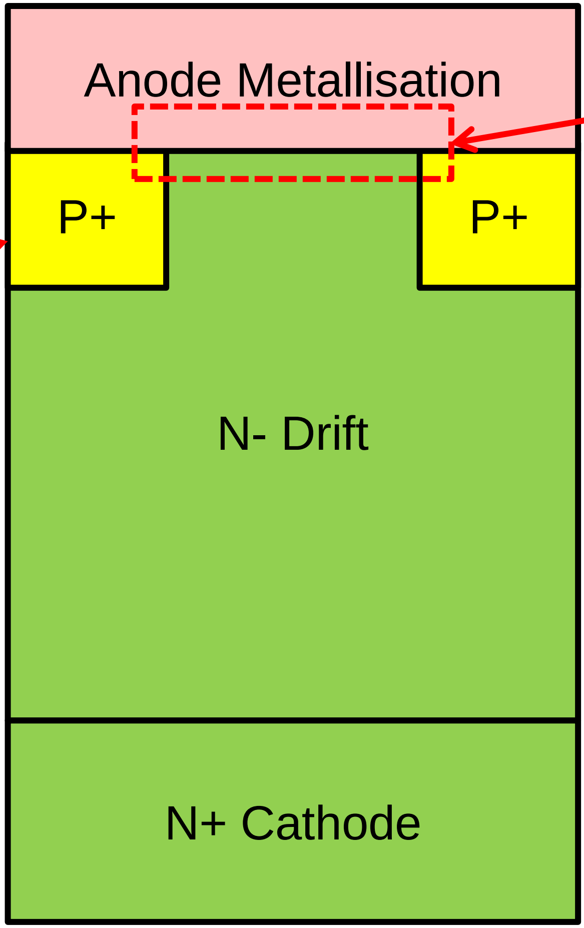
$$\Delta\phi = \sqrt{\frac{qE}{4\pi\varepsilon_o}} \ V$$

Influence of barrier lowering upon off state leakage current



- Trade off exists between off state leakage and diode turn on knee voltage
  - Lower the V_{bi} results in lower turn on knee voltage and high junction leakage
- Solution:
  - To merge the Schottky diode with a PiN junction
    - P-N junction’s do not suffer from barrier lowering effects

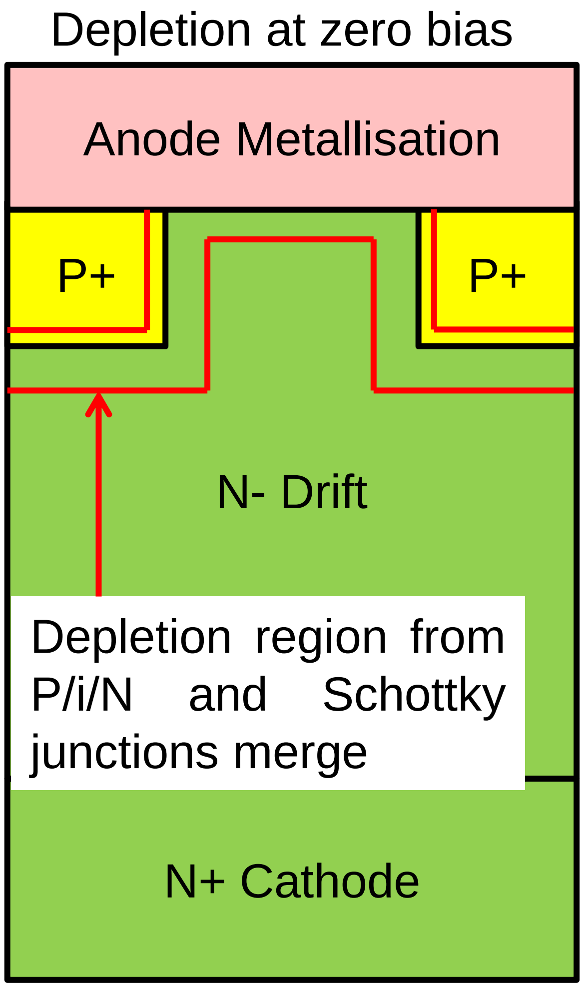
Merged Schottky PiN diode (MPS)

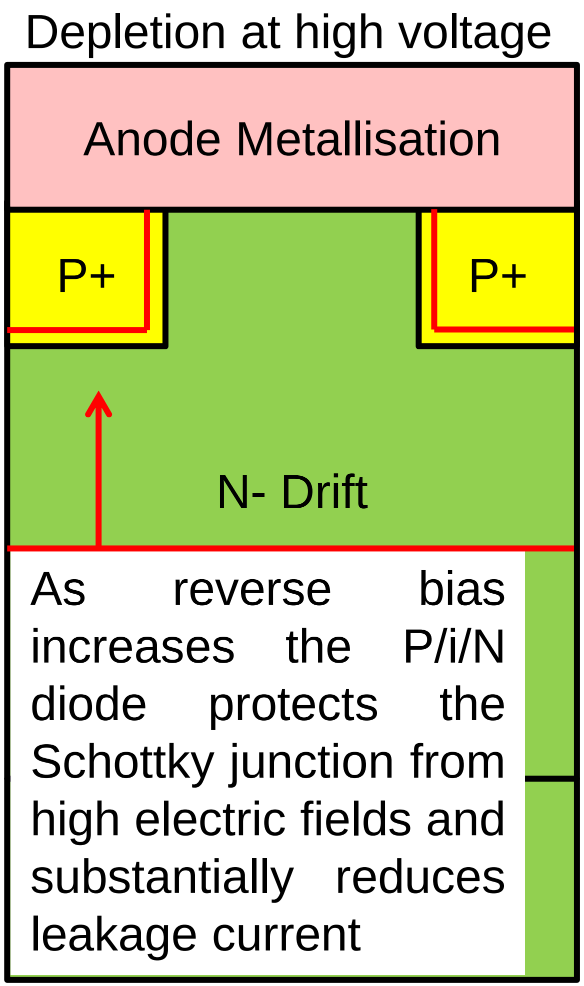


Schottky Junction:
Used to reduce Vbi below the knee voltage of a wide bandgap semiconductor

PN Junction:
Depletion from p+n- junction used to protect the metal semiconductor junction from barrier lowering

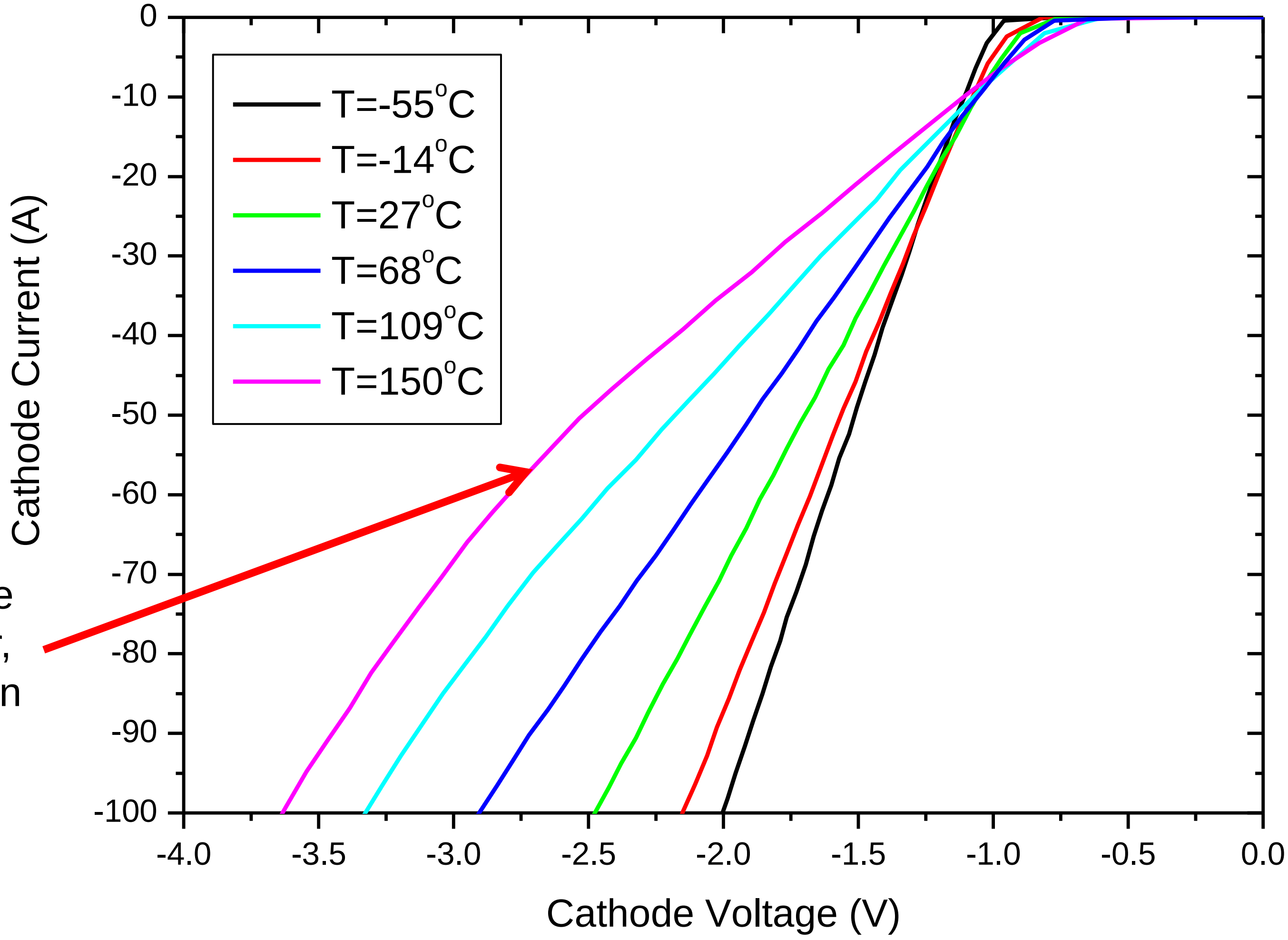
Merged Schottky PiN diode (MPS): During the reverse blocking





- The majority of WBG high voltage Schottky diodes are MPS structures. This has enabled the reduction on turn on knee voltage and leakage currents

IV characteristic of a 1200V SiC Schottky diode: Forward bias



Divergence from linear, P-N junction becoming active

Ohmic contact

- An ohmic contact is a metal semiconductor contact hat has a negligible contact resistance relative to the bulk or series resistance of the semiconductor
- A satisfactory ohmic contact should not significantly degrade device performance and can pass the required current with a voltage drop that is small compared with the drop across the active region of the device
- A figure of merit for ohmic contacts is the specific contact resistance R_c, defined as:

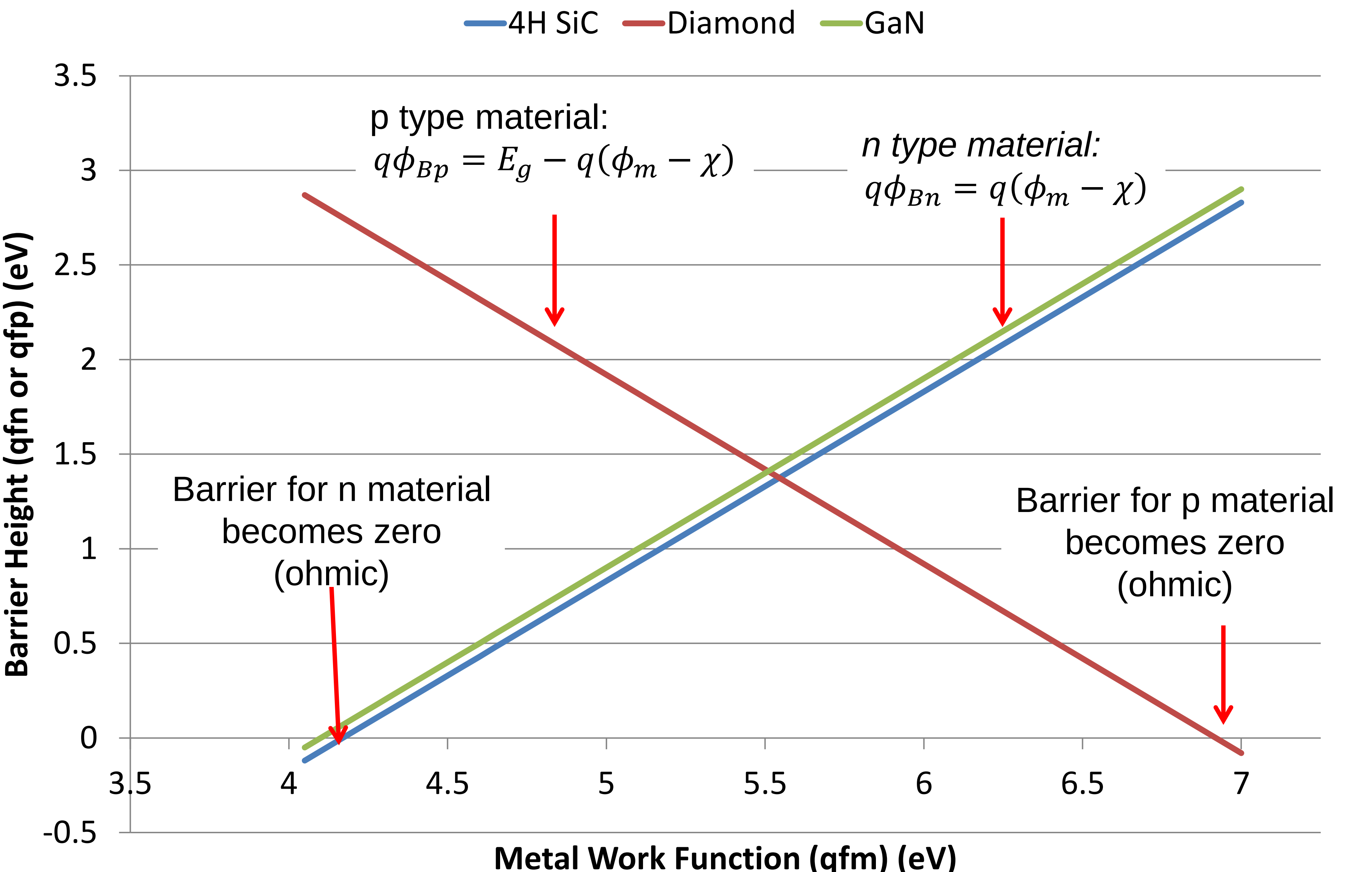
$$R_c \equiv \left(\frac{dJ}{dV}\right)^{-1}_{V=0} \; \Omega - cm^2$$

- For a metal-semiconductor contact with low doping concentrations, the thermionic emission current dominates current transport, therefore:

$$R_c = \frac{k}{qA^*T} exp\left(\frac{q\phi_{Bn}}{kT}\right)$$

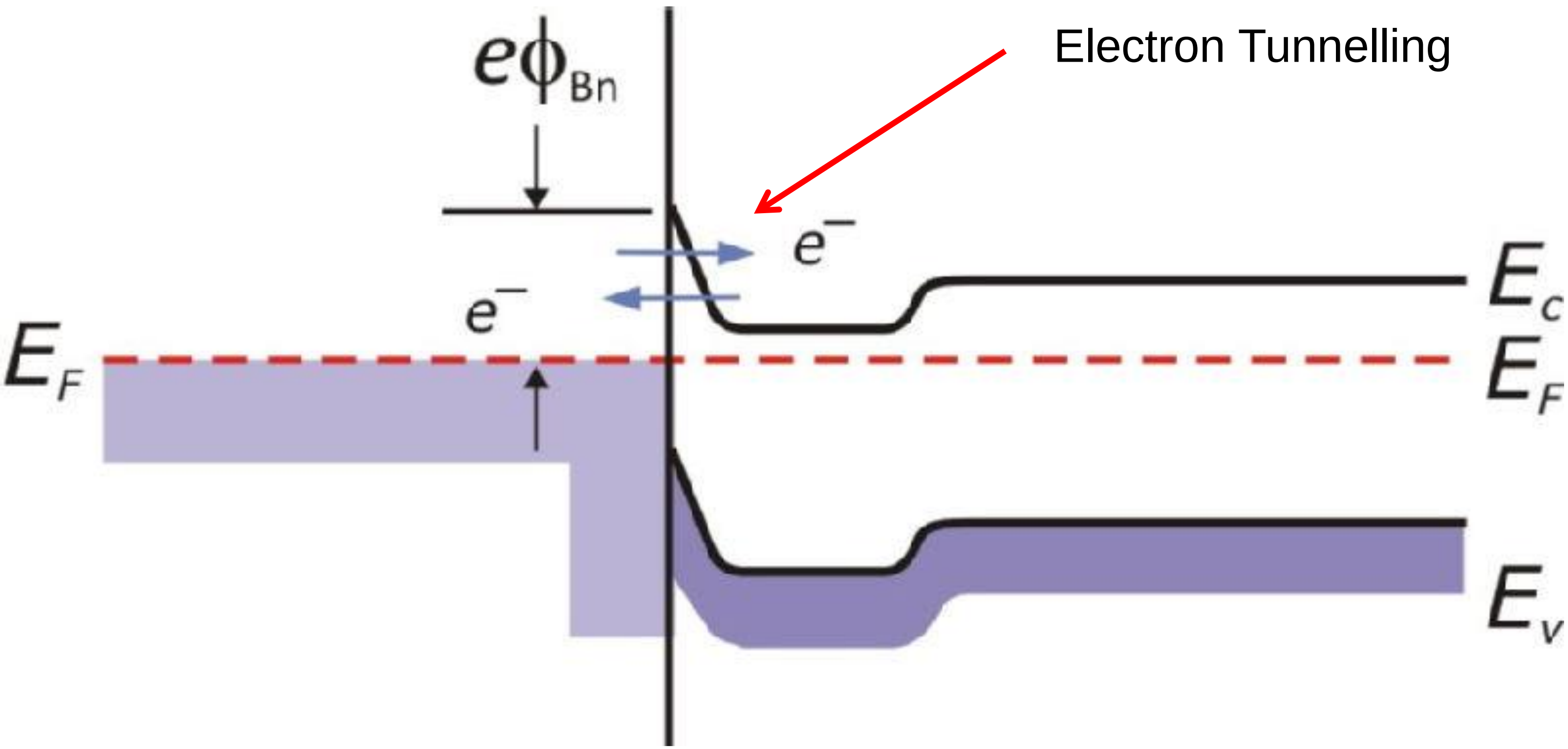
- Which shows that a metal-semiconductor contact with a low barrier height should be used to obtain a small R_c
- i.e: For n type contact: $\boldsymbol{\phi_{ms} < \phi_s}$ For p type contact: $\boldsymbol{\phi_{ms} > \phi_s}$

Calculated barrier heights for common metals and WBG materials



Ohmic contacts: Tunnelling

- For contacts with high doping concentrations, the barrier width becomes very narrow and tunnelling current becomes dominate:



Electrical contact to high doped semiconductors

- The tunnelling current is proportional to the tunnelling probability

$$I \sim exp\left[2W\sqrt{2m_n(q\phi_B - qV)/\hbar^2}\right]$$

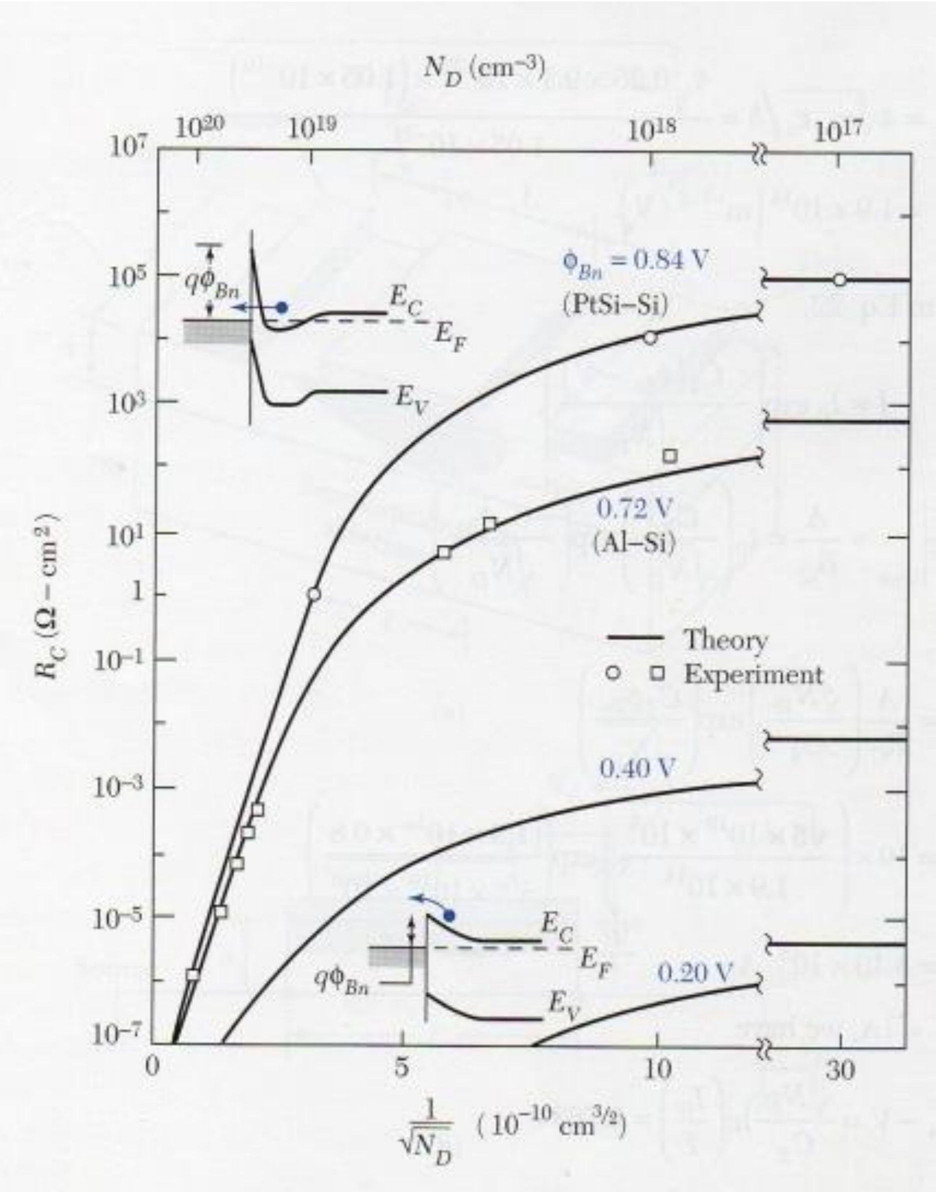
- Substituting $\sqrt{\left(\frac{2\varepsilon_s}{qN_D}\right)(\phi_{Bn} - V)}$ for W obtains:

$$I \sim exp\left[-\frac{C_2(\phi_{Bn} - V)}{\sqrt{N_D}}\right]$$

- Where C_2 is equal to $C_2 = 4\sqrt{\frac{m_n\varepsilon_s}{\hbar}}$
- The specific contact resistance for high doping is thus:

$$R_c \sim exp\left(\frac{C_2\phi_{Bn}}{\sqrt{N_D}}\right) = exp\left(\frac{4\sqrt{m_n\varepsilon_s\phi_{Bn}}}{\sqrt{N_D}\hbar}\right)$$

Calculated and measured values of specific contact resistance



- For doping concentrations greater than 1e19#/cm^3
  - Contact resistance dominated by tunnelling process and decreases rapidly with concentration
- For doping concentrations ~ 1e17#/cm^3 current flow is dominated by thermionic emissions
  - independent of doping
- A high doping concentration and low barrier heights must be used to obtain low contact resistance
  - These two approaches are used to make practical ohmic contacts for power device technologies