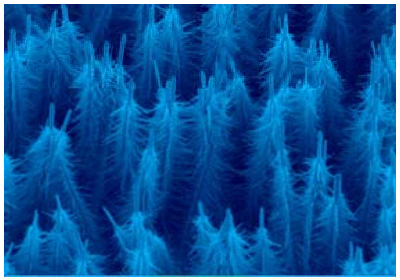
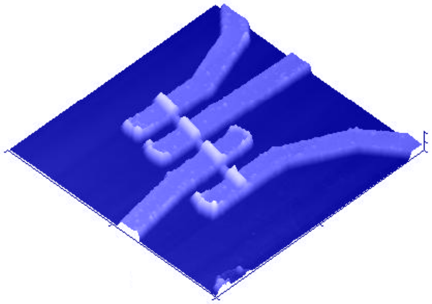
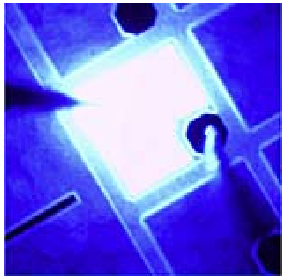
Semiconductor Physics

Devices and applications

János Volk

BME TTK, Nov. 20th, 2018
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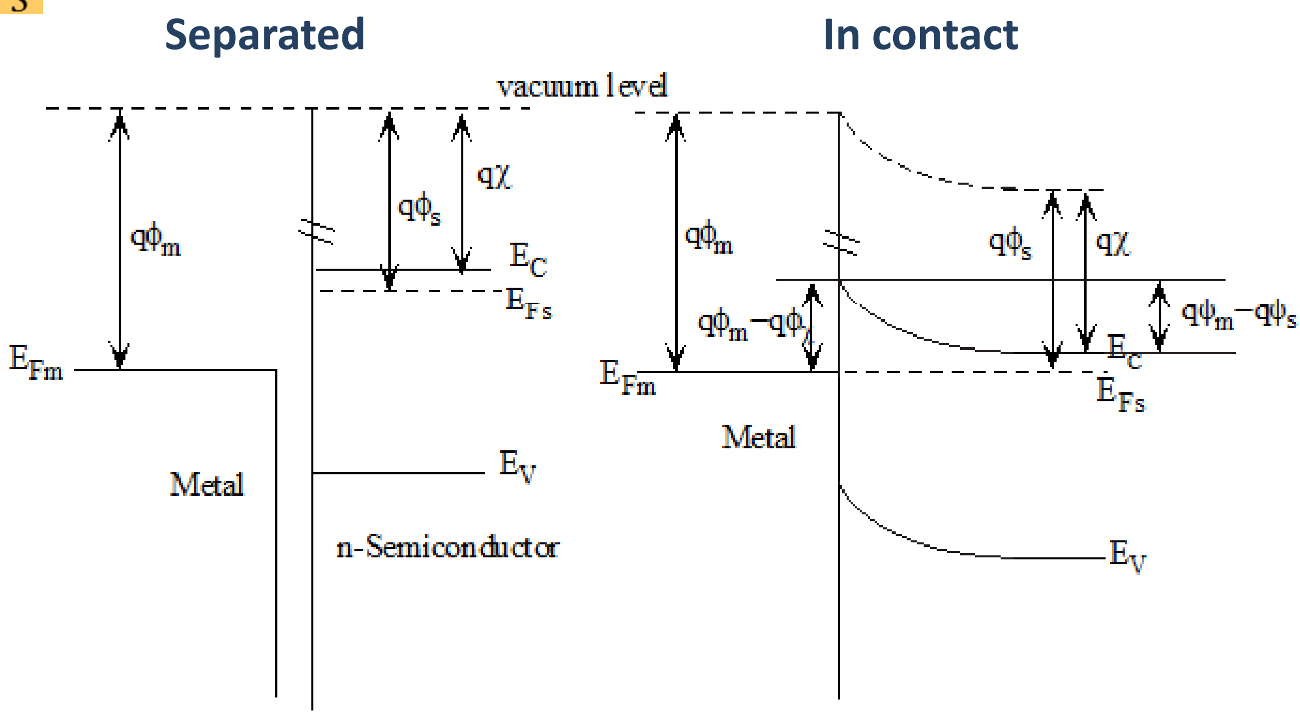
Outlook

- Metal-semiconductor junction
  - Ideal case: Schottky-Mott limit
  - Realistic metal-semiconductor interfaces
  - Current transport
  - Ohmic contact
- Metal-oxide-semiconductor field effect transistor (MOSFET)
  - MOS capacitance
  - MOS transistor
- Heterojunction devices
  - Band-gap engineering,
  - Blue Light Emitting Diode (LED)

Metal – n-type semiconductor contact in ideal case

$\Phi_M > \Phi_S$



Work function of semiconductor: $W = q\Phi_s = q\chi + q\Phi_n$

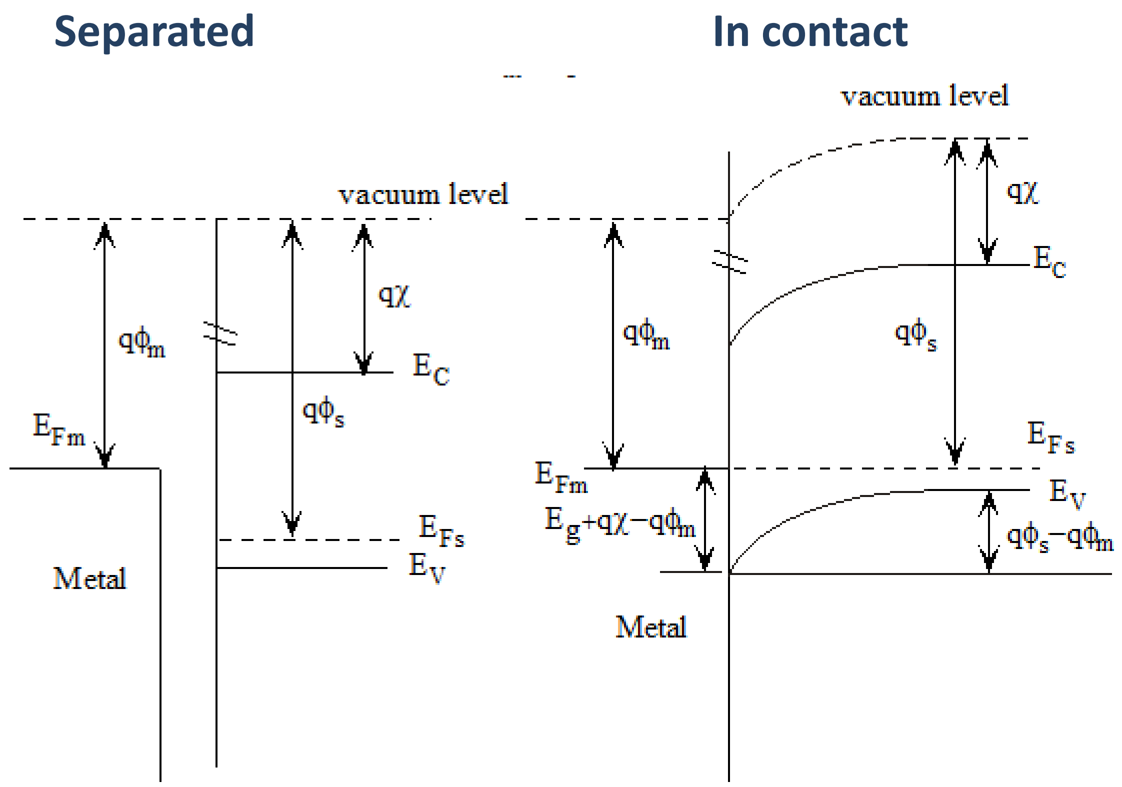
Built-in potential (contact potential): $\Psi_{bi} = \Phi_M - \Phi_s$

Schottky barrier height in Schottky-Mott limit (ideal case): $\Phi_{Bn0} = \Phi_M - \chi$

➡ Φ_{Bn0}, i.e. rectifying properties can be tuned by metal selection (in ideal case)

Metal – p-type semiconductor contact in ideal case

$\Phi_M < \Phi_S$



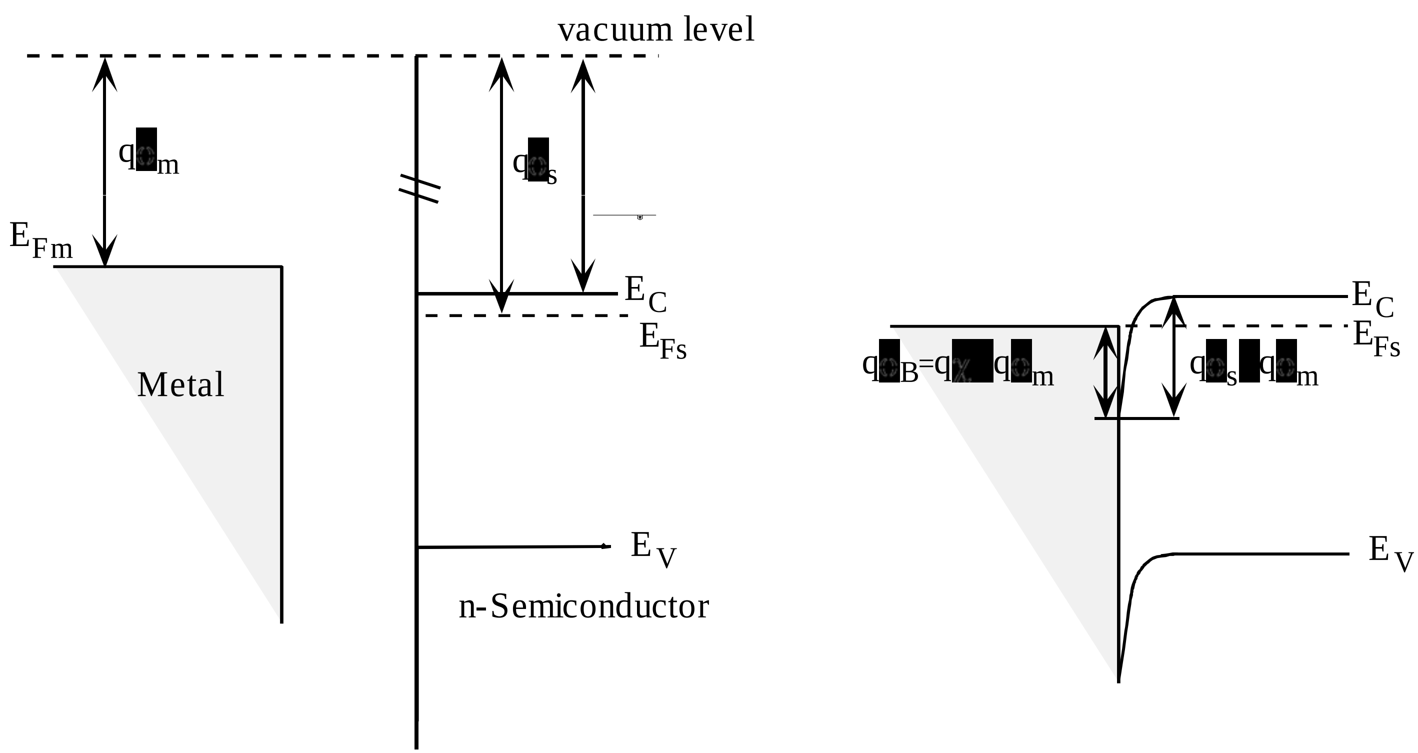
Schottky barrier height: $\Phi_{Bp0} = \varepsilon_G - (\Phi_M - \chi)$

for p- and n-type types of the same semiconductor and metal: $\Phi_{Bp0} + \Phi_{Bn0} = \varepsilon_G$

N-type semiconductor with large metal work function

$\Phi_M < \Phi_S$

Separated **In contact**

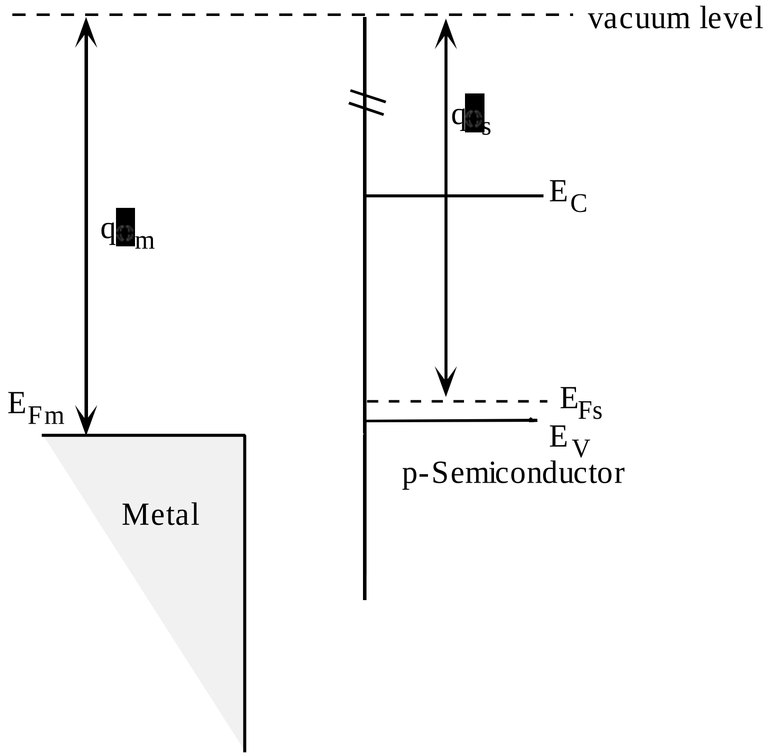


- 2 Dimentional Electron Gas (2DEG) at the interface
- Leads to Ohmic (non-rectifying) behavior automatically
- Requires pair selection of semiconductor and metal which is not practical

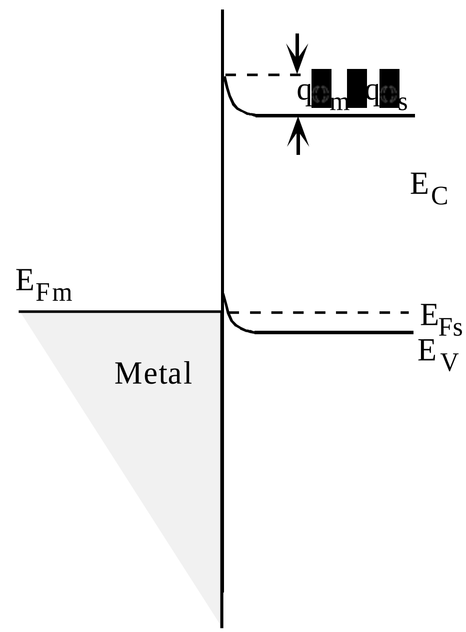
P-type semiconductor contact in ideal case

$\Phi_M > \Phi_S$

Separated



In contact



- 2 Dimentional Hole Gas (2DHG) at the interface
- It would result in an automatic Ohmic contact formation
- But, it’s nearly impossible, especially for wide bandgap semiconductors

Metal-semiconductor contact: ideal case

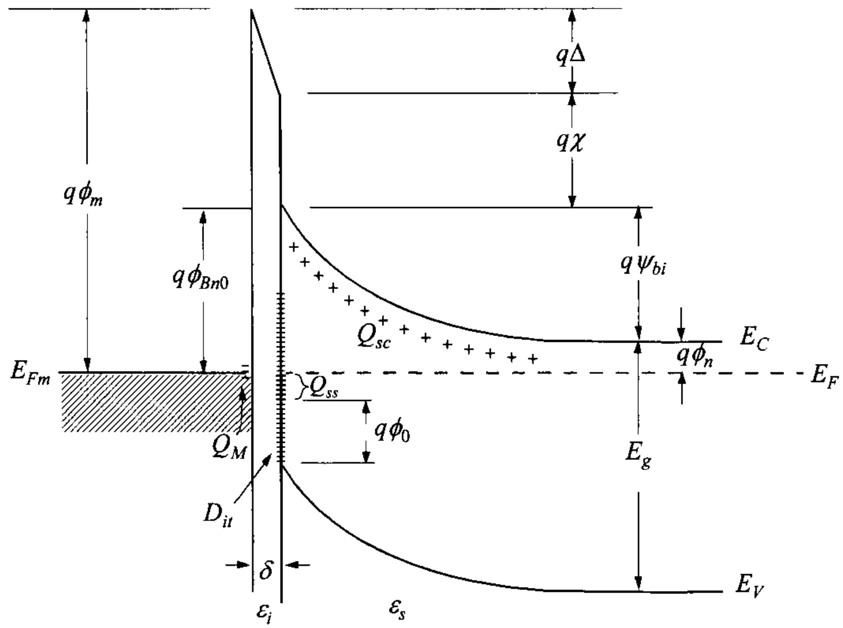
Table 1: Metal Workfunctions

Material	Φ_m (eV)
Mg	3.7
Al	4.3
Ti	4.3
Cr	4.5
W	4.6
Ag	4.64
Au	5.1
Pd	5.1
Ni	5.15
Pt	5.7

Table 2: Electron affinity (χ) of various semiconductors.

Material	Electron affinity χ (eV)
Si	4
Ge	4.03
GaAs	4.07
$In_{0.53}Ga_{0.47}As$	4.5
InAs	4.9
InP	4.38
GaSb	4.06
GaN	4.1

Realistic Schottky contacts



ϕ_m = Work function of metal
ϕ_{Bn0} = Barrier height (without image-force lowering)
ϕ_0 = Neutral level (above E_V) of interface states
Δ = Potential across interfacial layer
χ = Electron affinity of semiconductor
ψ_{bi} = Built-in potential
δ = Thickness of interfacial layer
Q_{sc} = Space-charge density in semiconductor
Q_{ss} = Interface-trap charge
Q_M = Surface-charge density on metal
D_{it} = Interface-trap density
ε_i = Permittivity of interfacial layer (vacuum)
ε_s = Permittivity of semiconductor

If $D_{it}\rightarrow\infty$: Fermi level pinning $\quad \phi_{Bn0} = \varepsilon_G - \Phi_0$

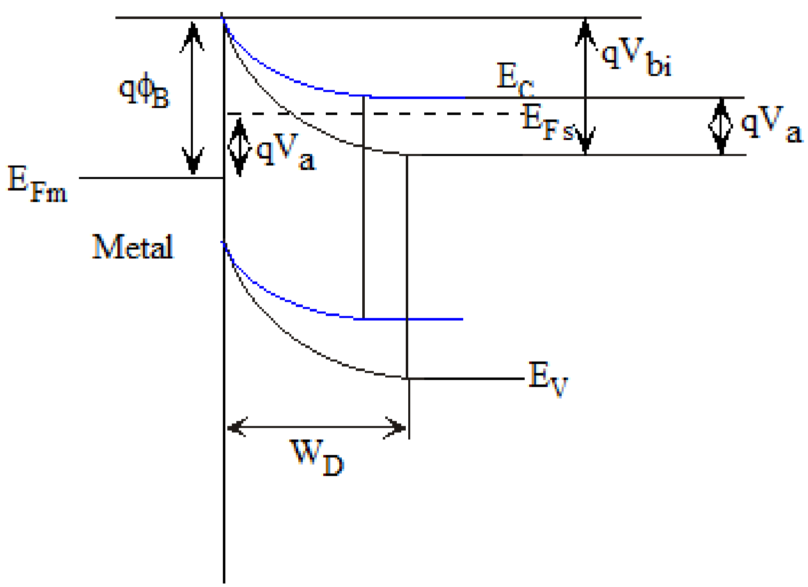
If $D_{it}\rightarrow 0$: Schottky-Mott limit $\quad \phi_{Bn0} = \Phi_M - \chi$

In practice: $\varepsilon_G - \Phi_0 < \phi_{Bn0} < \Phi_M - \chi$

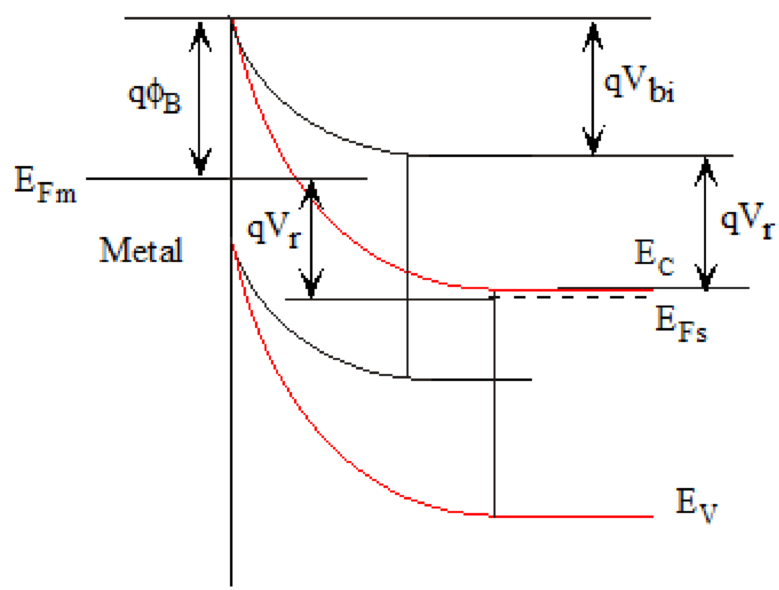
$c = \frac{d\phi_{Bn0}}{d\phi_m}$ depends on the semiconductor family

Metal – n-type semiconductor with bias

Forward bias

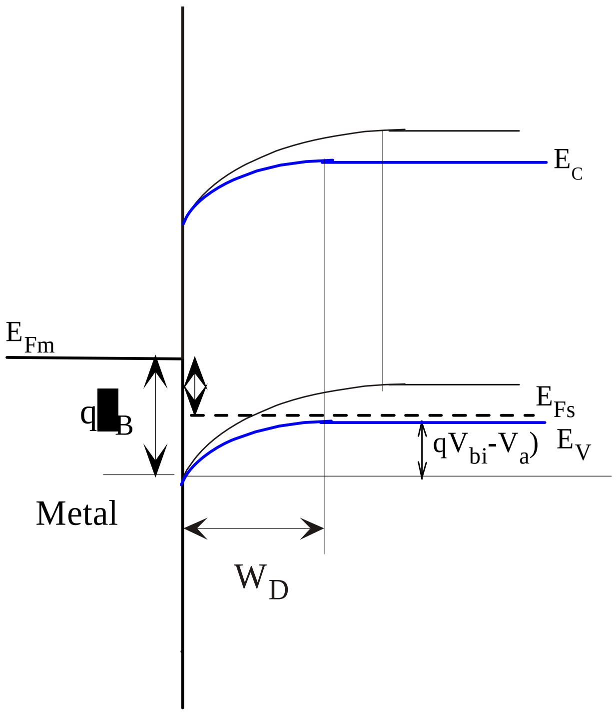


Reverse bias



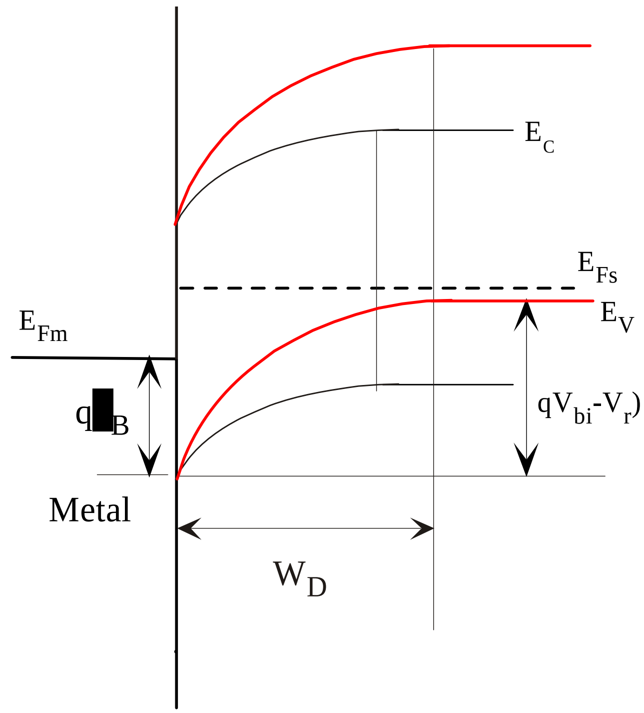
Metal – p-type semiconductor with bias

Forward bias



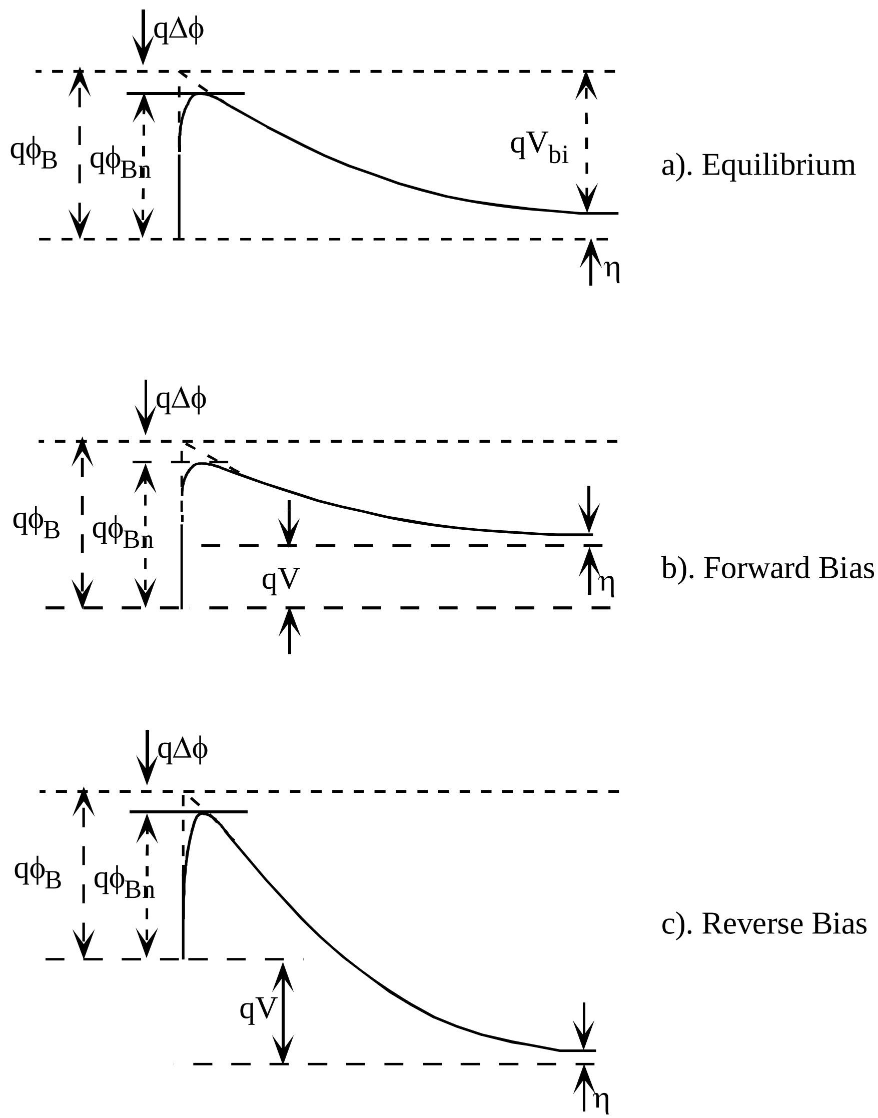
(a)

Reverse bias



(b)

Metal – n-type, conduction band only



- Schottky barrier height is lowered by $q\Delta\Phi$ due to the image charge effect!

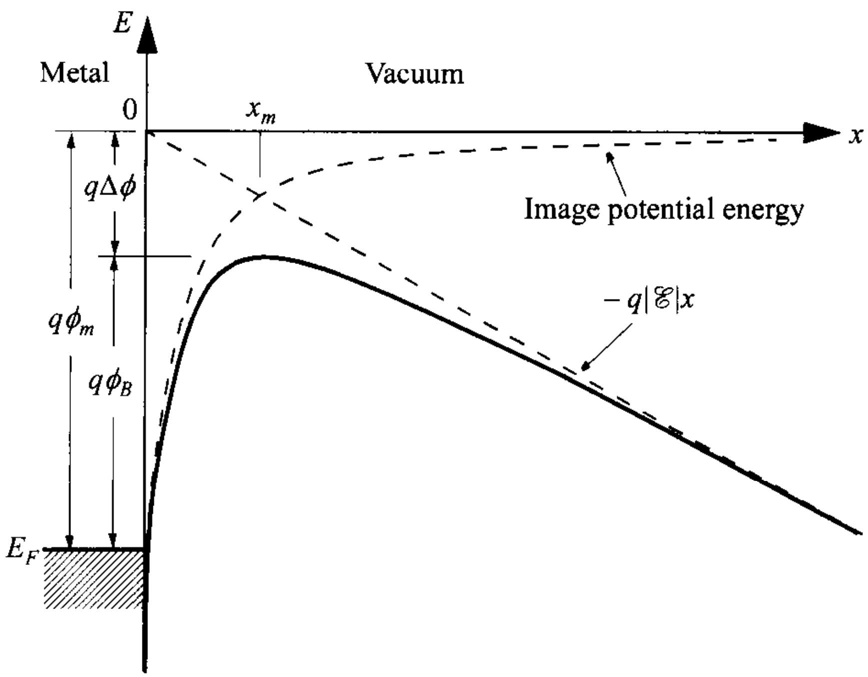
Image-Force Lowering (Schottky-barrier lowering)

Metal-vacuum system

Attractive force toward metal (image force): $F = \frac{-q^2}{4\pi\varepsilon_0(2x)^2}$

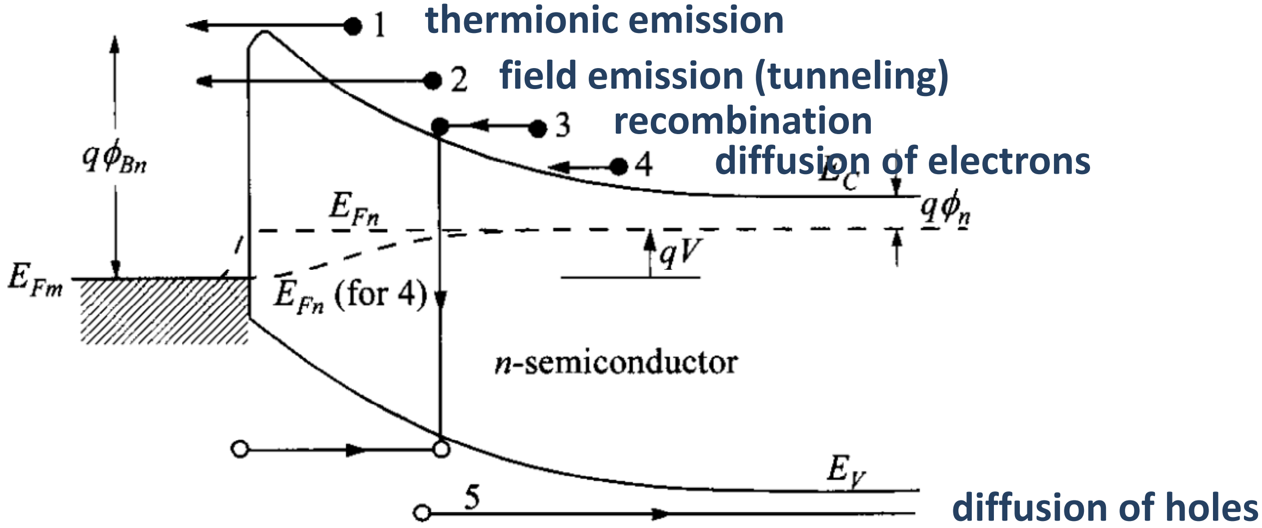
Potential energy: $E = \frac{-q^2}{16\pi\varepsilon_0 x} - q|\varepsilon|x$

Location of the energy maximum (dE/dx=0): $x_m = \sqrt{\frac{q}{16\pi\varepsilon_0|\varepsilon|}}$ $\Delta\Phi = 2|\varepsilon|x_m$



Concept is also valid for metal-semiconductor system.

Current transport on Schottky contact



(1) Thermionic Emission (TE). For lightly or moderately doped semiconductors, $N_d < \approx 10^{17}$ cm^{-3}, the depletion region is relatively wide. It is, therefore, nearly im-possible for electrons to tunnel through the barrier unless aided by defects, which are con-sidered not to exist in this ideal picture.

(2) **Thermionic-Field Emission** (TFE). For intermediately doped semiconductors, $\approx 10^{17} < N_d < \approx 10^{18}$ cm^{-3}, the depletion region is not sufficiently thin to allow direct tunneling of carriers that are more or less in equilibrium. This process requires some energy gain from the bias sufficient to raise the electron energy to a value E_m where the barrier is sufficiently thin for tunneling.

(3) **Field Emission** (FE). In heavily doped semiconductors, $N_d > \approx 10^{18}$ cm^{-3}, the depletion region is narrow even for cold and cool electrons at the bottom of the conduction band or at the Fermi level, the latter is for degenerate semiconductors, and direct electron tunneling from the semiconductor to the metal is allowed

Thermionic emission regime

$$J_{te} = J_{te0}\left(e^{-\frac{qV}{kT}} - 1\right) \qquad \text{with} \qquad J_{te0} = A^{*}T^{2}e^{-\frac{q(\phi_{B} - \Delta\phi)}{kT}}$$

- J_{te0} : saturation current
- A*: effective Richardson constant

Richardson constant for free space: $$A^{*}_{free} = \frac{4\pi q k^{2} m_{0}}{h^{3}}$$

which equals to 120 ($Acm^{-2}K^{-2}$)

Richardson for n-type constant is: $$A^{*} = A^{*}_{free}\left(\frac{m_{e}^{*}}{m_{0}}\right)$$

Richardson for p-type constant is: $$A^{*} = A^{*}_{free}\left(\frac{m_{hh}^{*}}{m_{0}}\right)$$

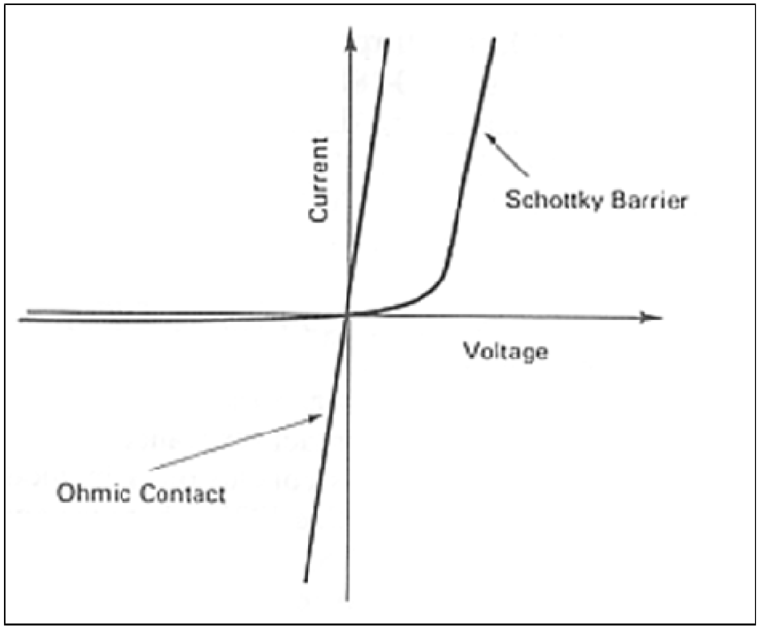
Experimental expression: $$J = J_{0}\left[\exp\left(\frac{qV}{\eta kT}\right) - 1\right]$$

Where η is the ideality factor: 1 for purely thermionic, >1 for thermionic field (TFE) emission

Ohmic contact

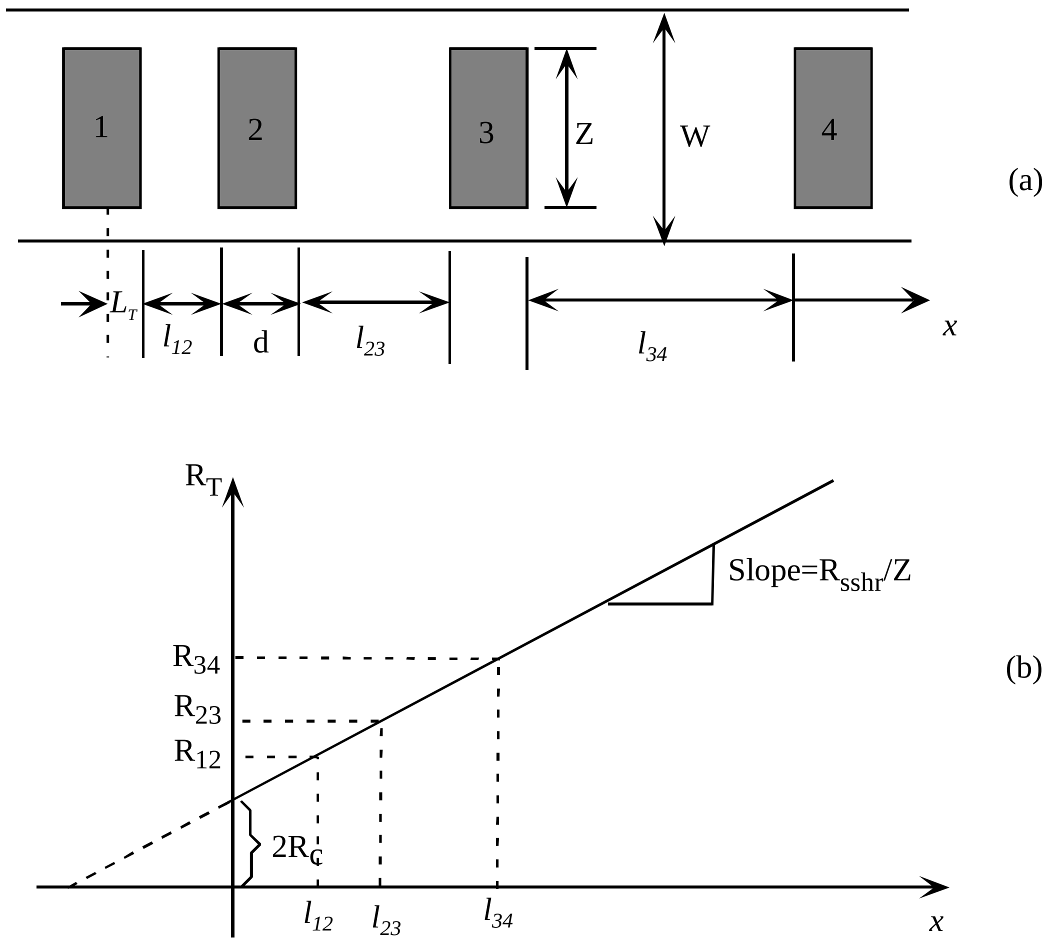
- Metal-semiconductor contact with negligible junction resistance
- Low resistance contact is a must for all of the semiconductor devices
- By minimizing the Schottky barrier height or/and applying a highly doped intermediate layer

$$Rc = \left(\frac{\partial V}{\partial j}\right)_{V=0}$$



Transmission Line Method (TLM)

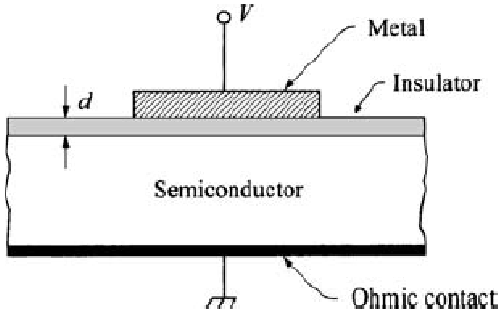
- To determine contact resistivity (Ωcm²) and sheet resistance (Ω/□)



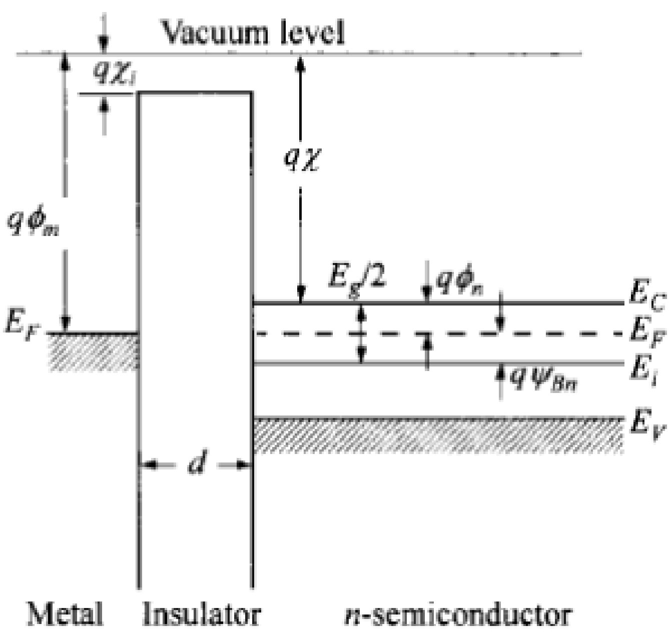
Metal-Insulator-Semiconductor (MIS) capacitor

Idealization:

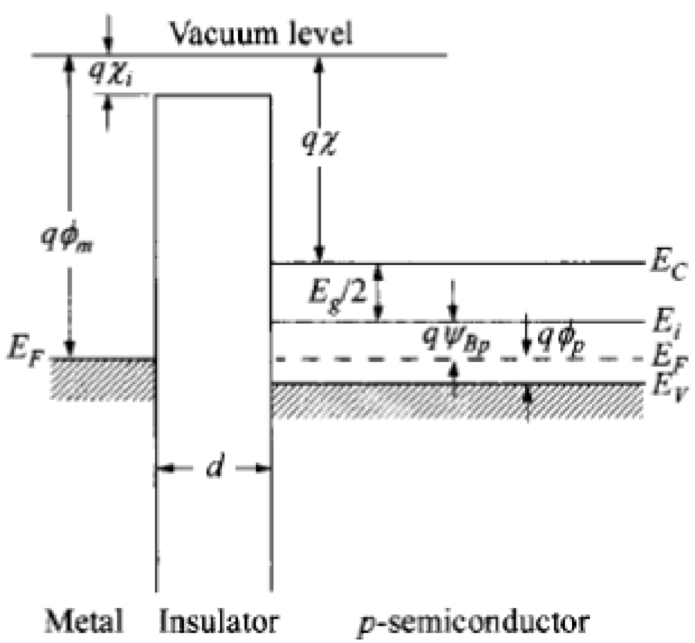
- Charges from the semiconductor and metal with equal but opposite sign; no interface trap, oxide charge etc.
- No current transport through the insulator
- For the sake of simplicity: ϕ_{MS}=0 (flat band)



n-type



p-type

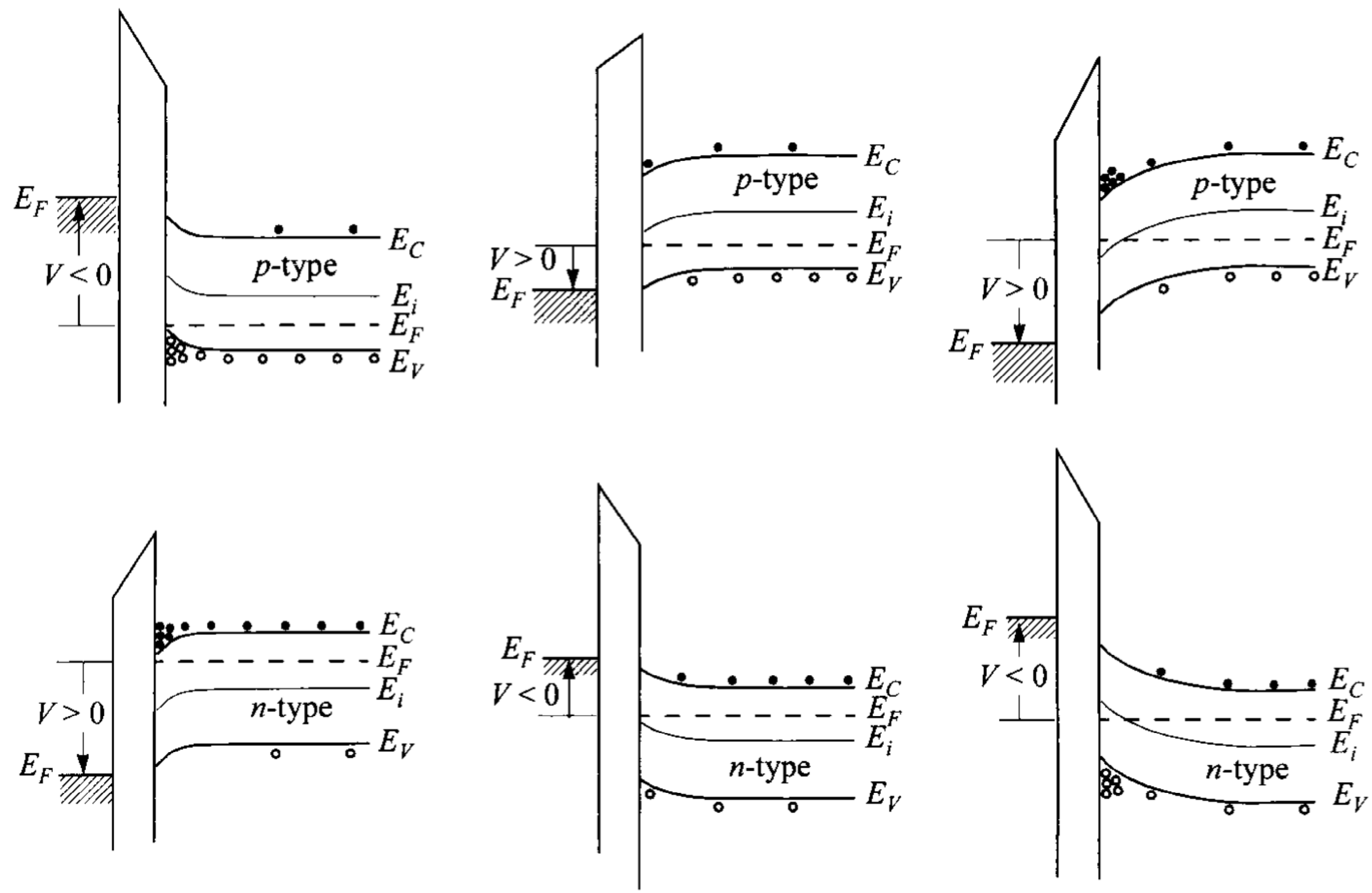


Metal-Insulator-Semiconductor capacitor

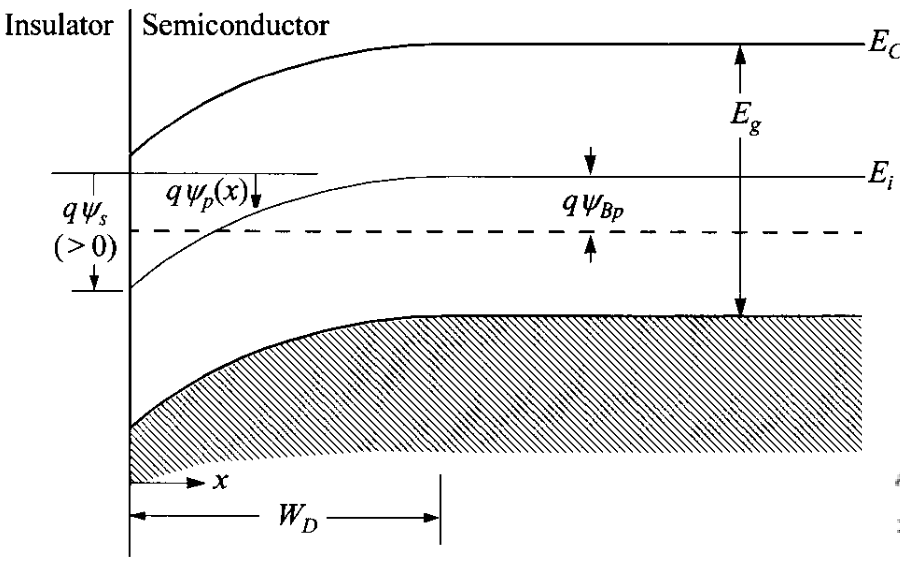
Accumulation | **Depletion** | **Inversion**

p-type

n-type



Metal-Insulator-Semiconductor capacitor

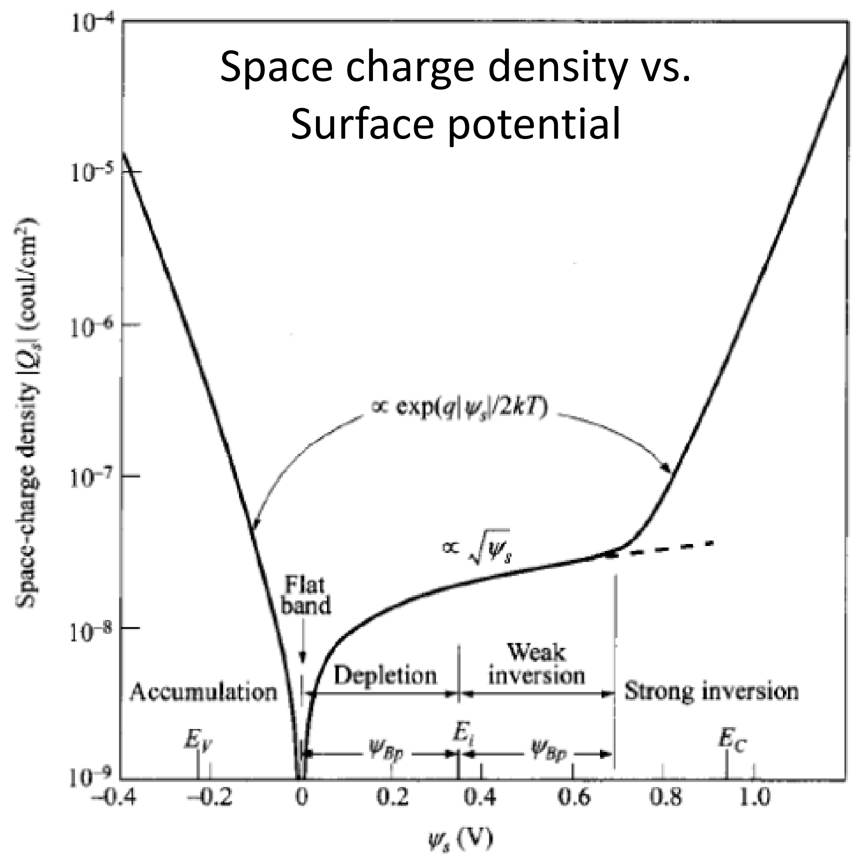


$$\psi_p(x) \equiv -\frac{[E_i(x) - E_i(\infty)]}{q}.$$

By solving the Poisson equation

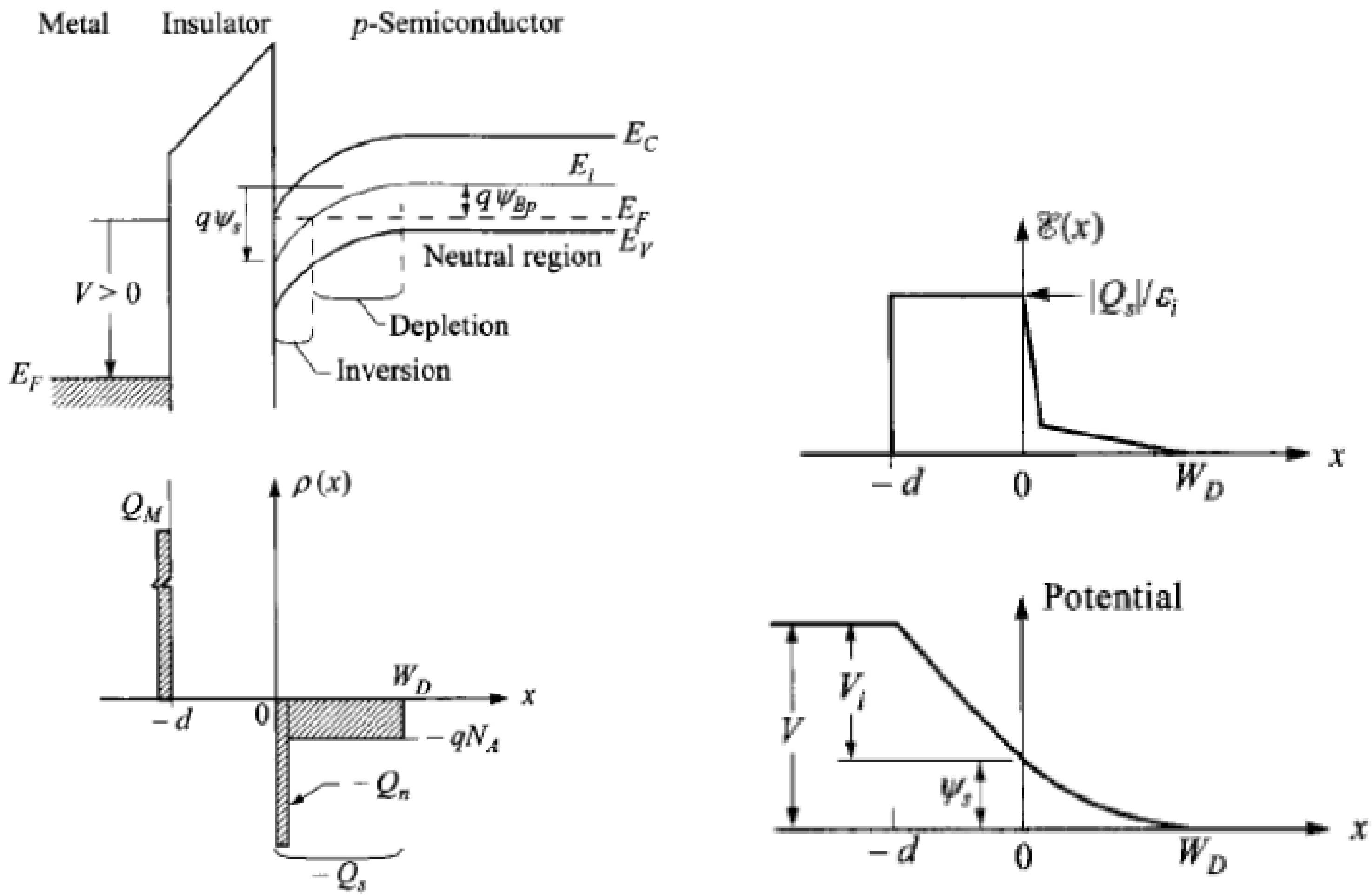
$$\frac{d^2\psi_p}{dx^2} = -\frac{\rho(x)}{\varepsilon_s},$$

$$\rho(x) = q(N_D^+ - N_A^- + p_p - n_p),$$

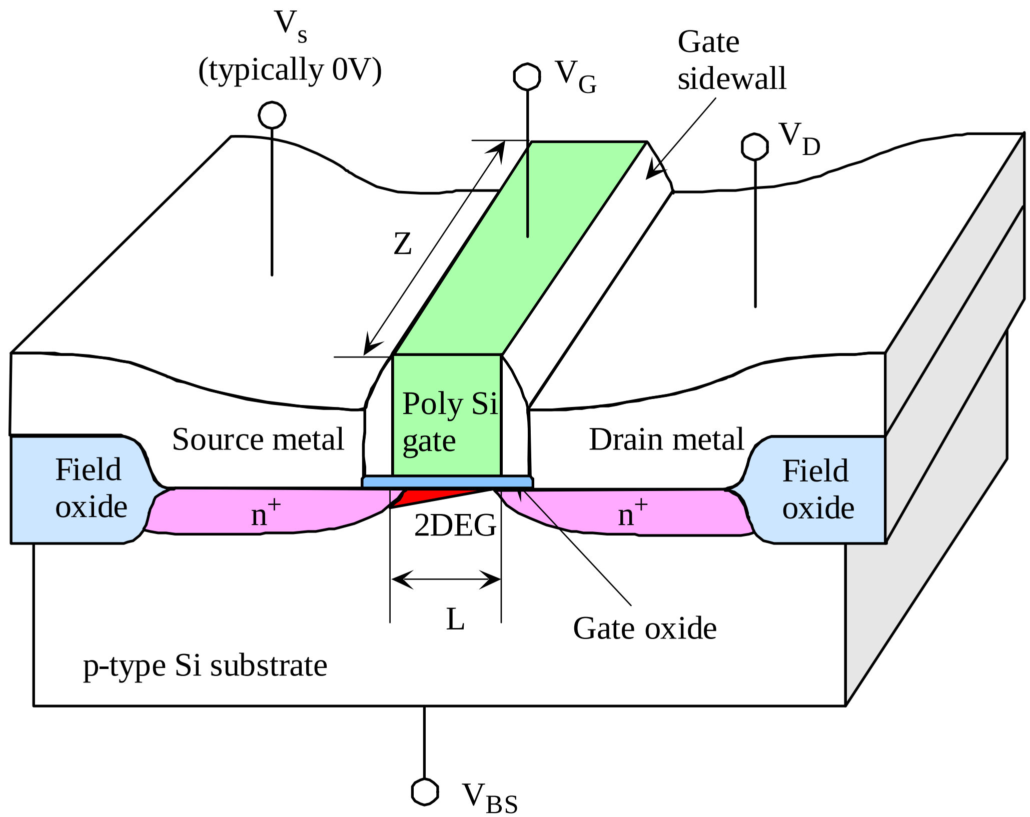


Metal-Insulator-Semiconductor capacitor

P-type case in strong inversion

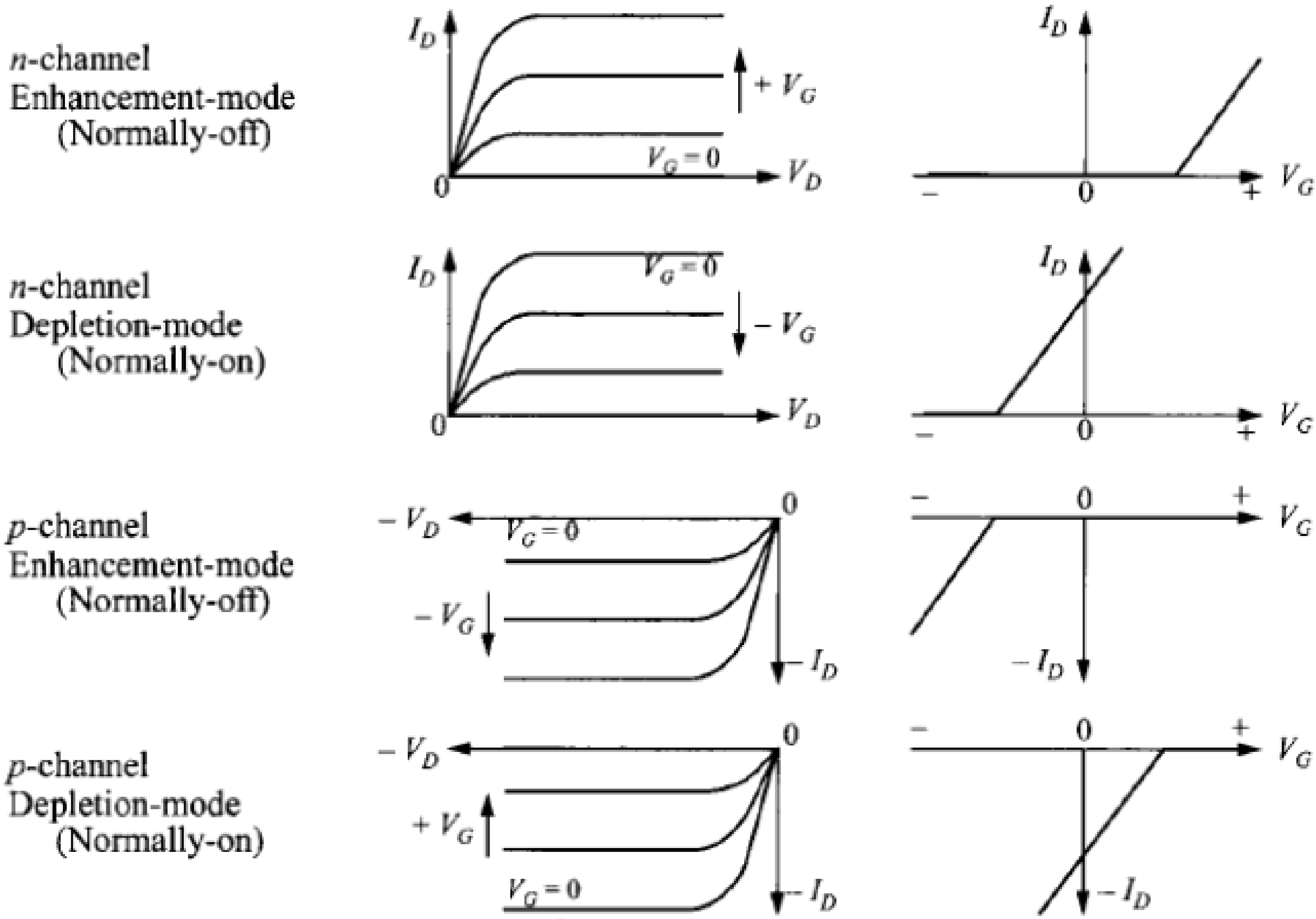


Metal-Oxide-Semiconductor field-effect transistor (MOSFET)

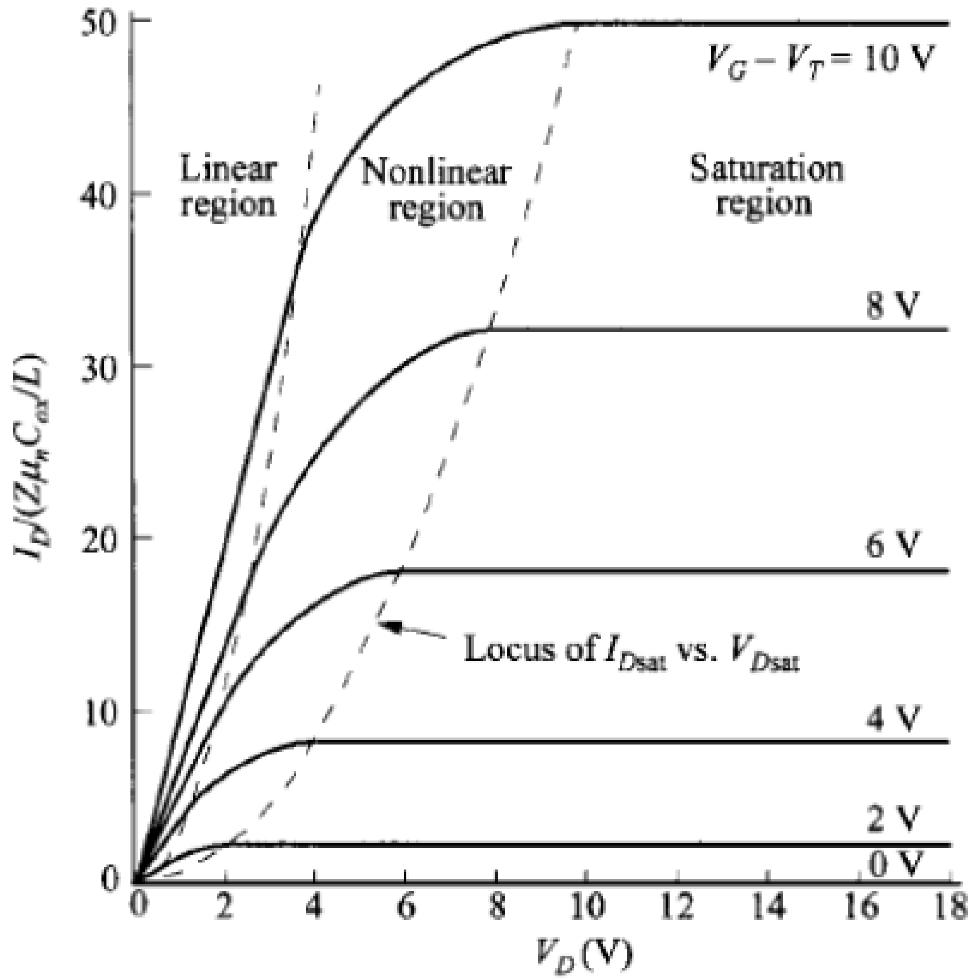


- **Source** terminal supplies charge carriers
- **Drain** terminal sinks charge carriers
- **Gate** terminal controls the conduction between source and drain
- **Bulk** terminal on the substrate

Versions of MOSFET

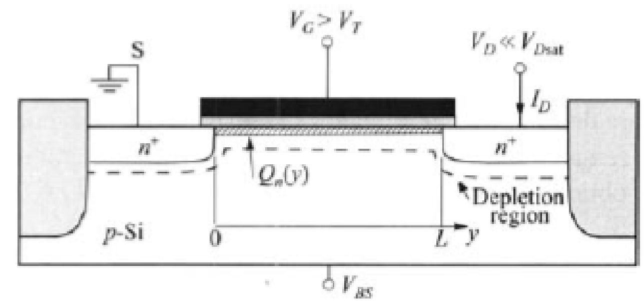


Idealized drain current characteristics for n-channel, enhancement type transistor

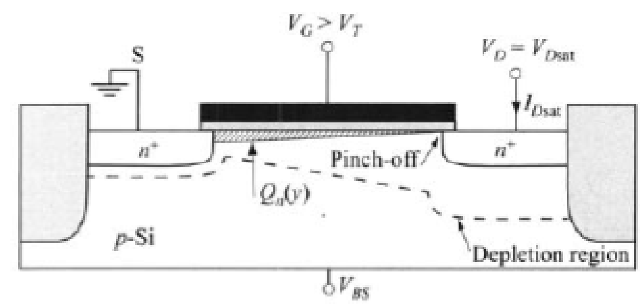


Idealized drain current characteristics for n-channel, enhancement type transistor

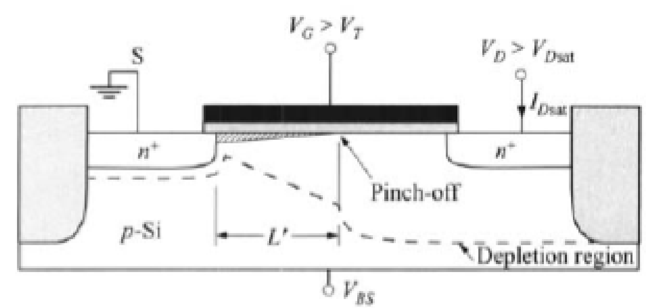
linear region for $V_G > V_T$
and $V_D < (V_G - V_T)$;



onset of saturation at pinch-off,
$V_G > V_T$ and $V_D = (V_G - V_T)$;



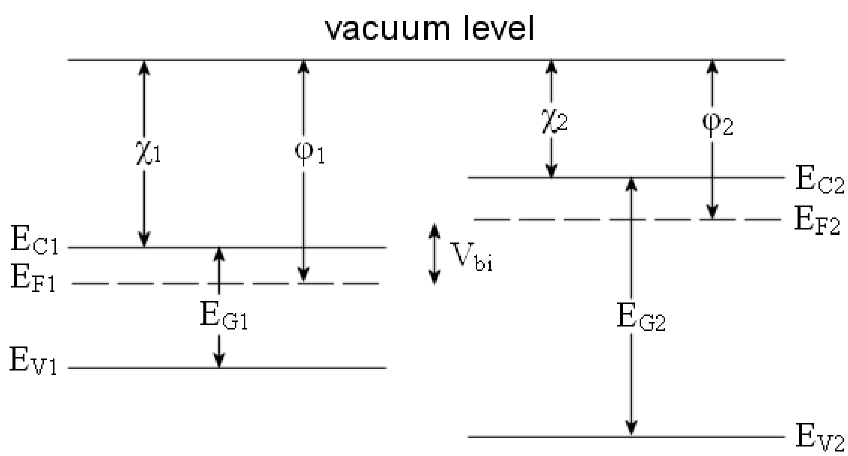
strong saturation, $V_G > V_T$
and $V_D > (V_G - V_T)$.



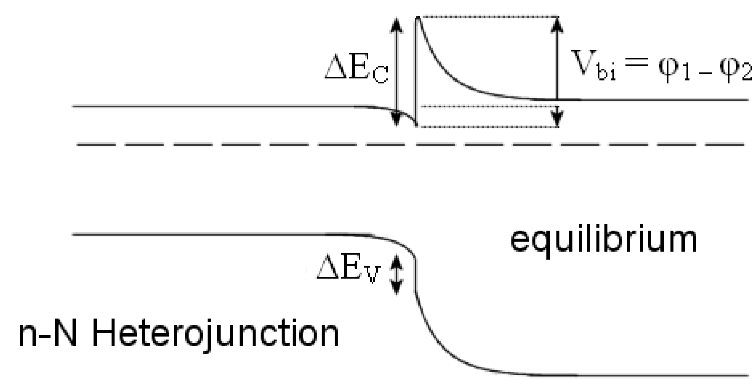
V1

Semiconductor heterojunctions

Separated



In contact



Band offsets calculated by Anderson's rule:

$$\Delta\varepsilon_c = (\chi_2 - \chi_1) \qquad \Delta\varepsilon_v = (\chi_1 + \varepsilon_{G1}) - (\chi_2 + \varepsilon_{G2})$$

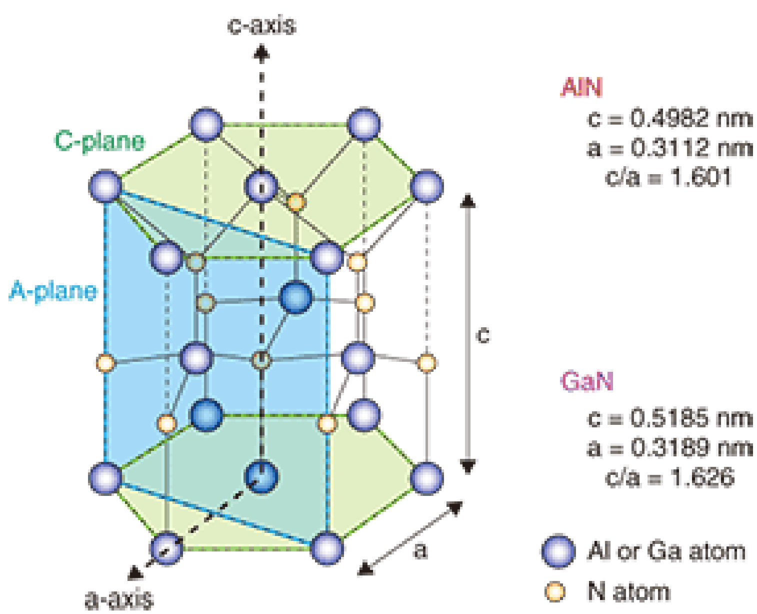
One example on heterojunction and band engineering: multi-quantum well LED

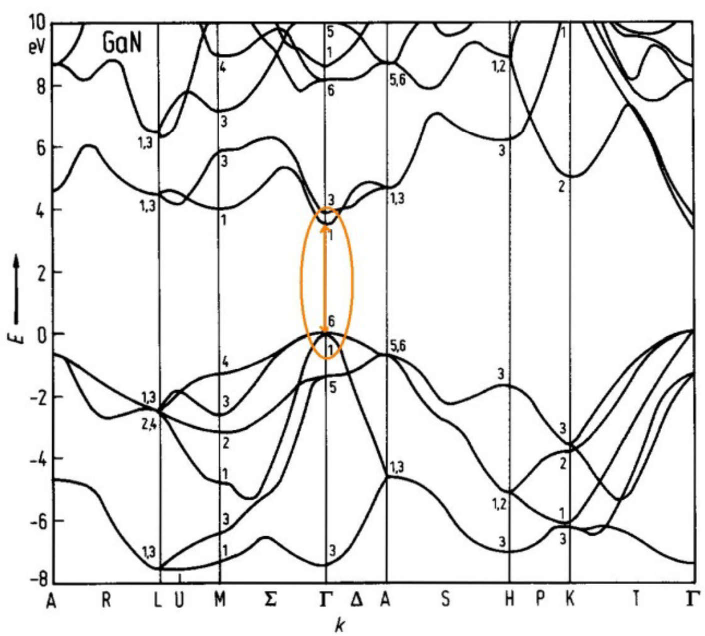
Slide 25

V1 Volk78; 2018.11.19.

GaN, as LED and LD material

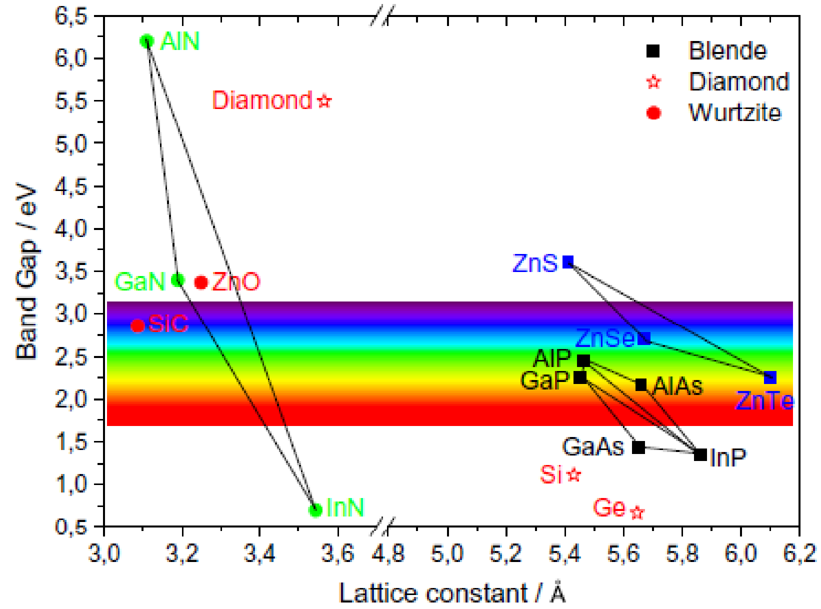
- Stabile crystal structure: hexagonal wutzite (C_{6v}^{4}-$P6_3mc$, hcp)
- Wide direct bandgap (3,4 eV; 365 nm; 300 K-n)
- Stabile n- and p-type doping are established (with Si and Mg)

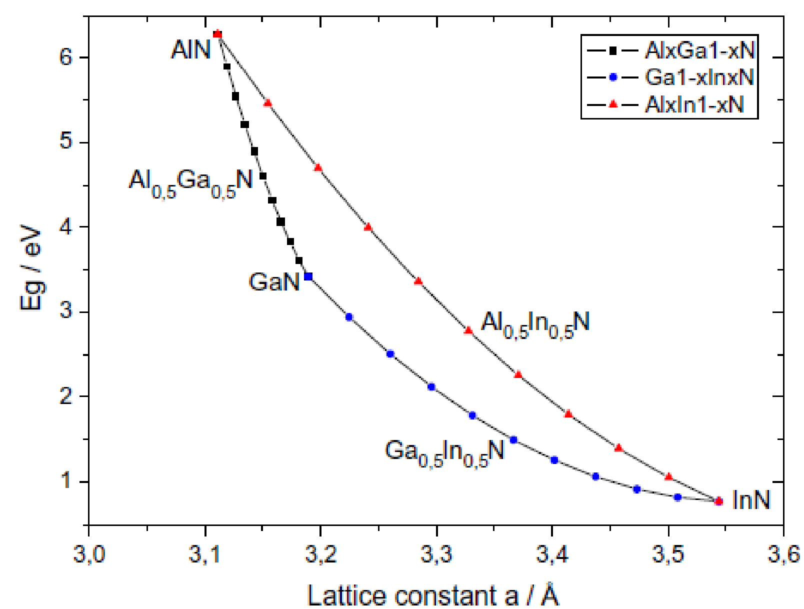




GaN

- Epitaxial layer on sapphire, SiC, GaN or even Si substrate up to 8”
- contains high density of threading dislocation
- Bandgap engineering: AlGaN, InGaN

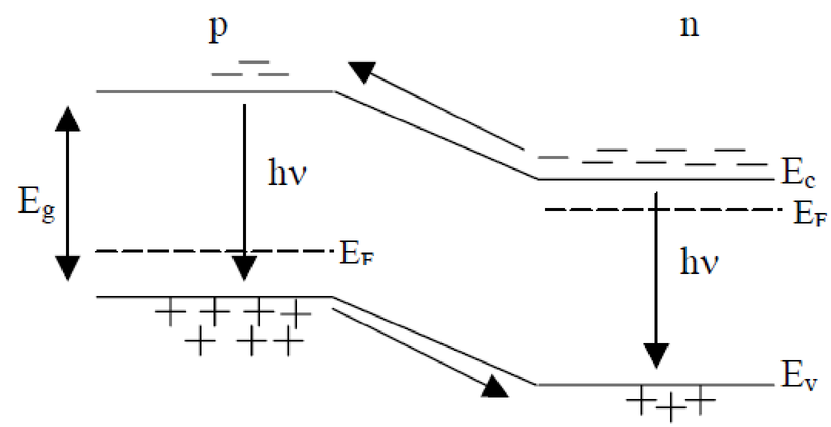




Light Emitting Diode

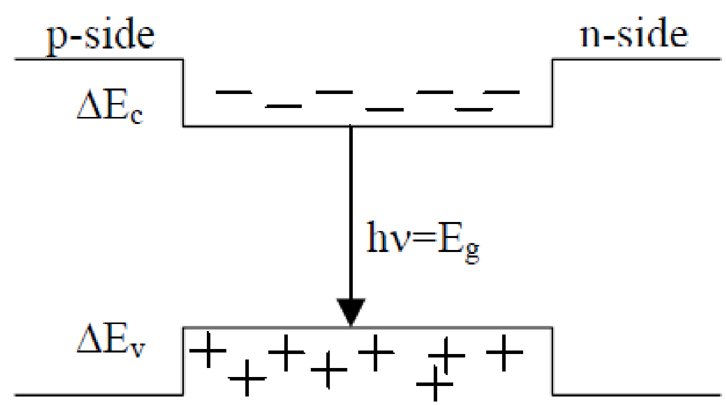
Simple LED: p-n homojunction

- low degree of spontanous radiating recombination

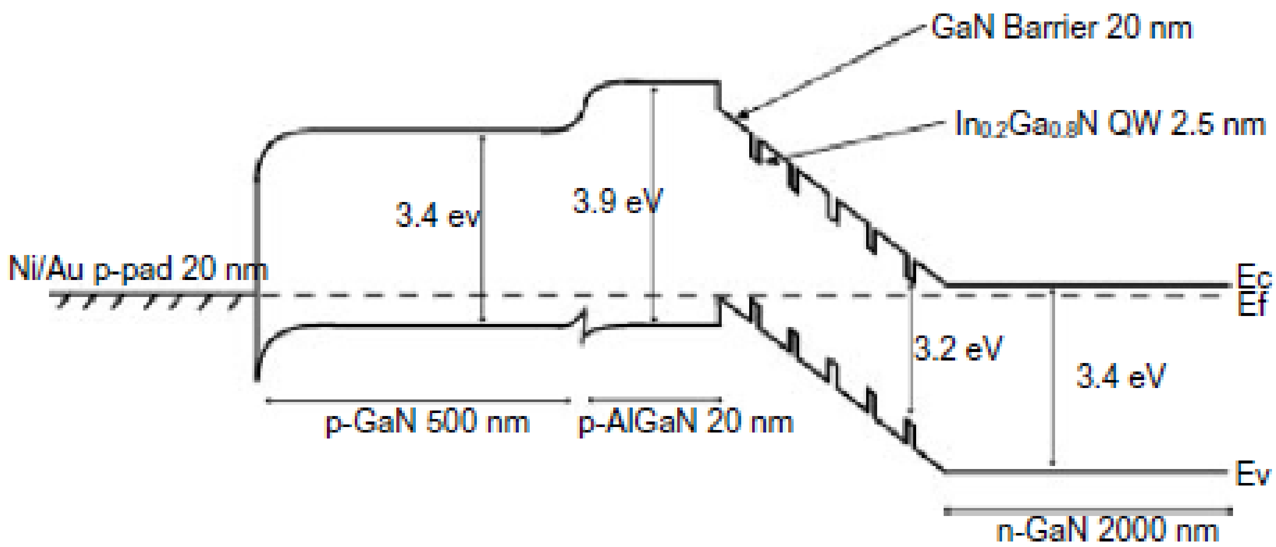


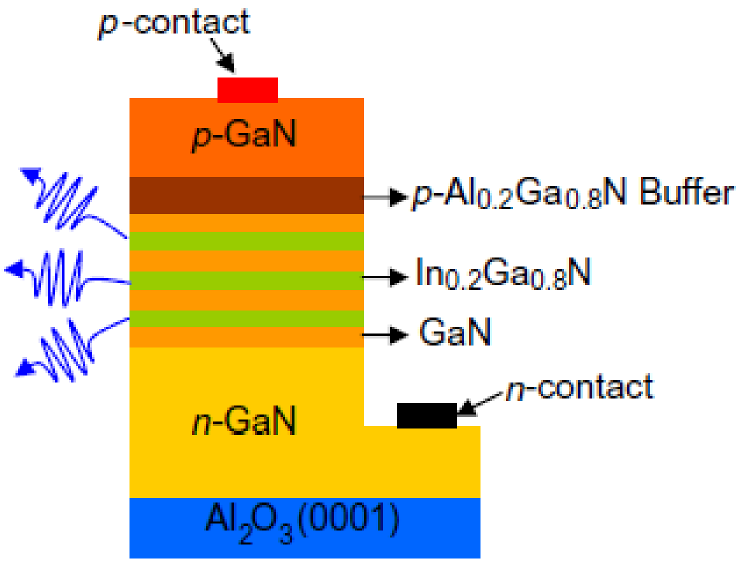
Quantum well by heterojuntions

- High radiating recombination rate: $R = B \cdot n \cdot p$

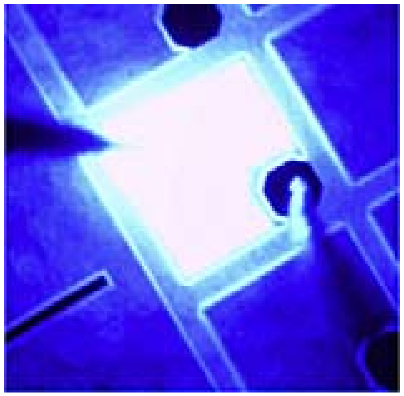


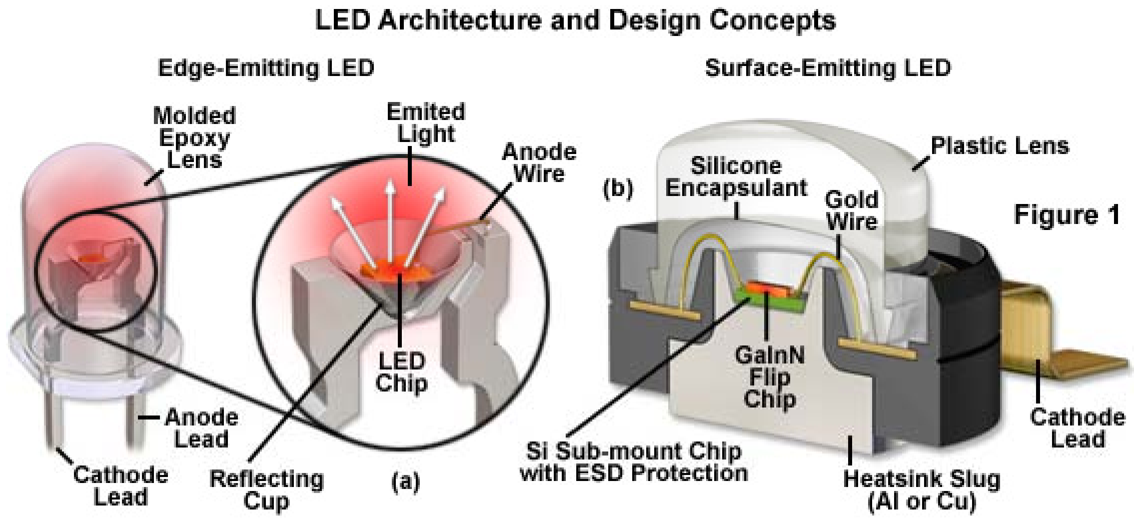
III-N „multiquantumwell” LED structure

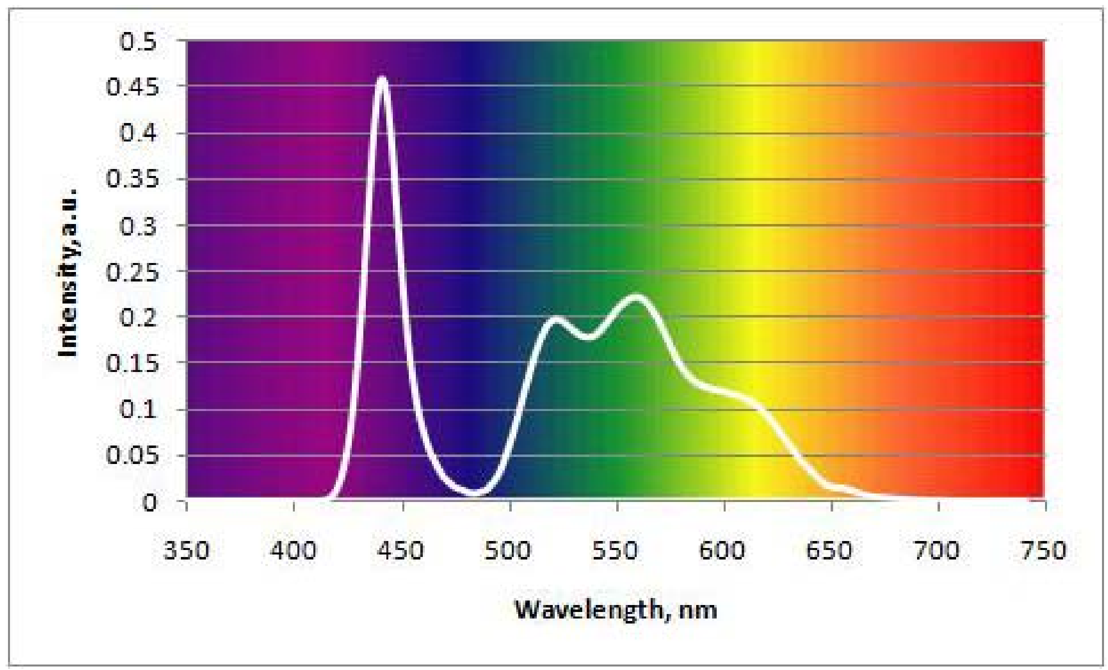




III-N LEDs




LED Architecture and Design Concepts
Edge-Emitting LED
Surface-Emitting LED
Molded Epoxy Lens
Emited Light
Anode Wire
LED Chip
Anode Lead
Cathode Lead
Reflecting Cup
(a)
(b)
Silicone Encapsulant
Gold Wire
Plastic Lens
Figure 1
GaInN Flip Chip
Si Sub-mount Chip with ESD Protection
Heatsink Slug (Al or Cu)
Cathode Lead


Intensity,a.u.
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
350
400
450
500
550
600
650
700
750
Wavelength, nm