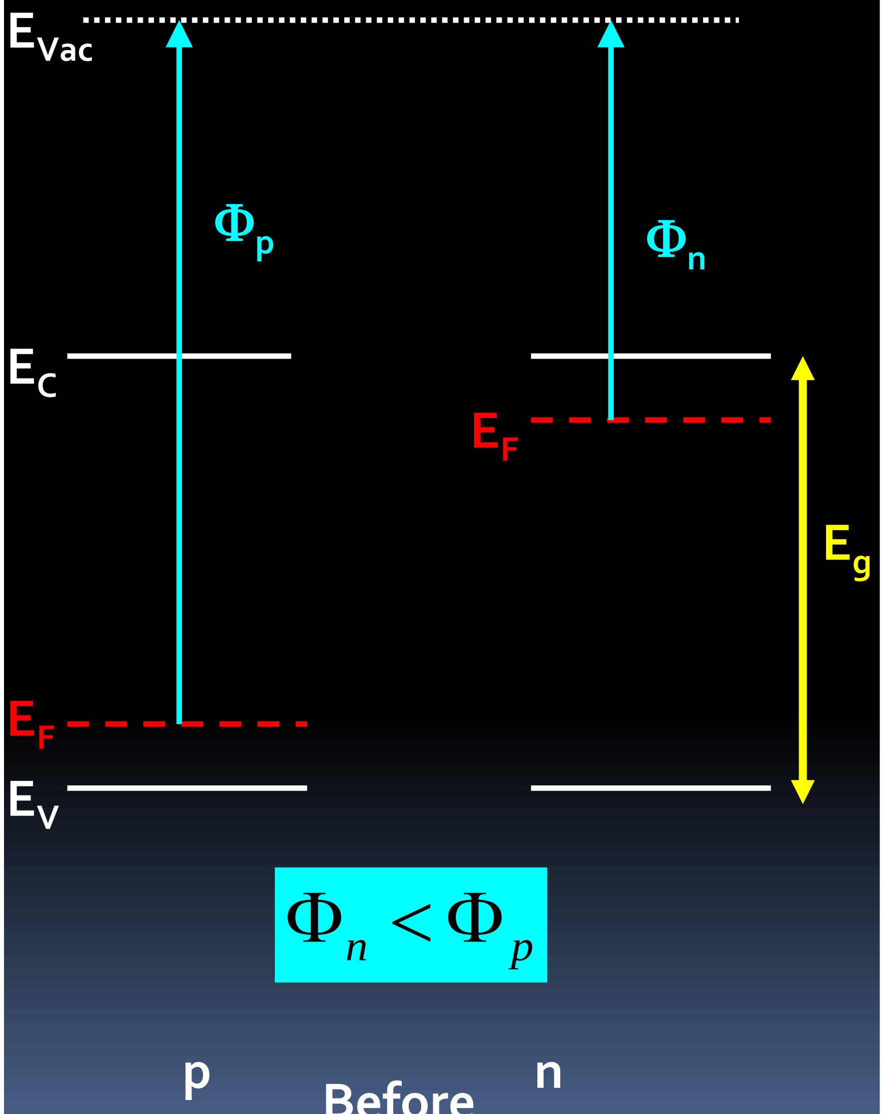
DIODES - 01

Shouvik Datta

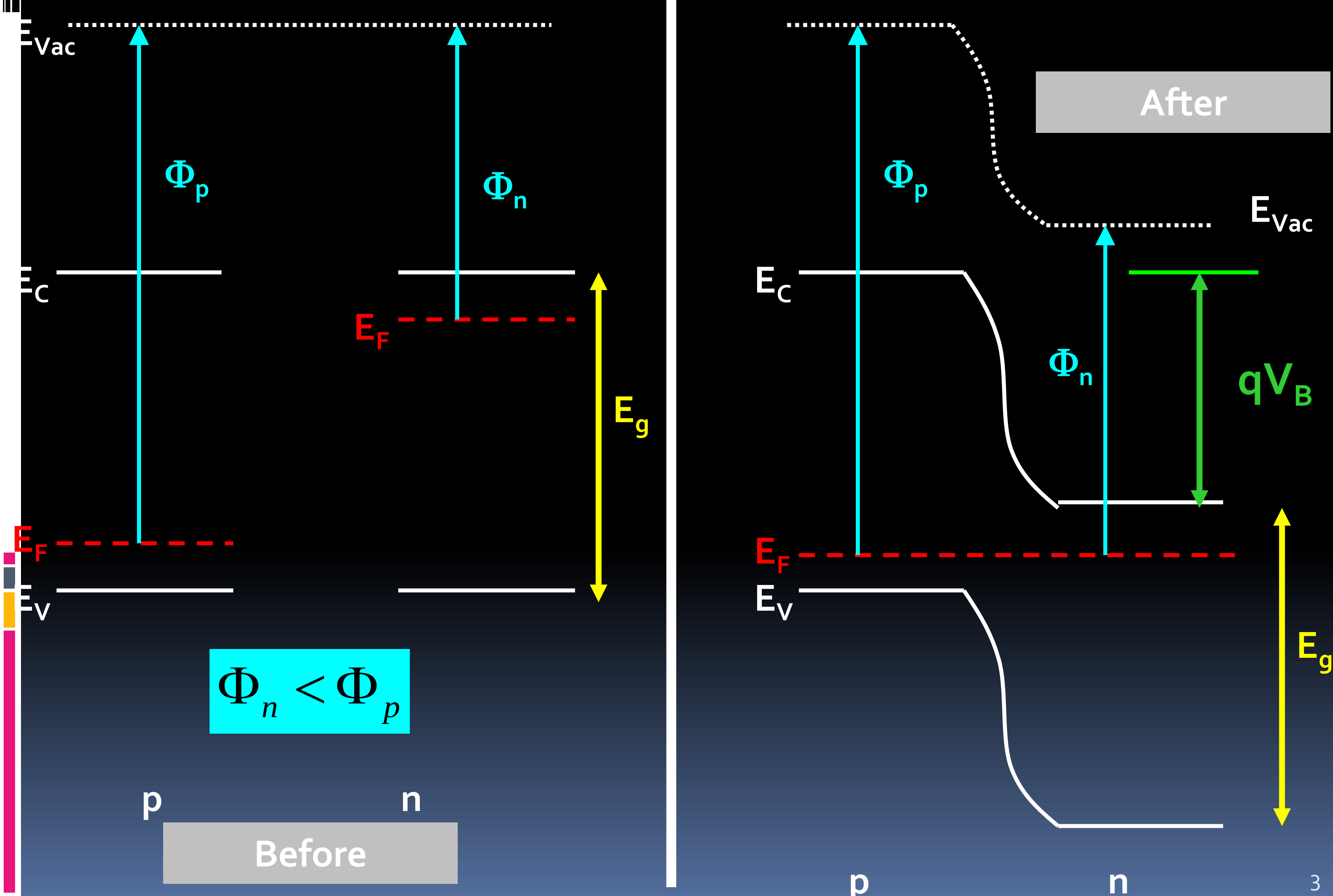
Electronics, PH3144
IISER-Pune

FORMATION OF P-N JUNCTION

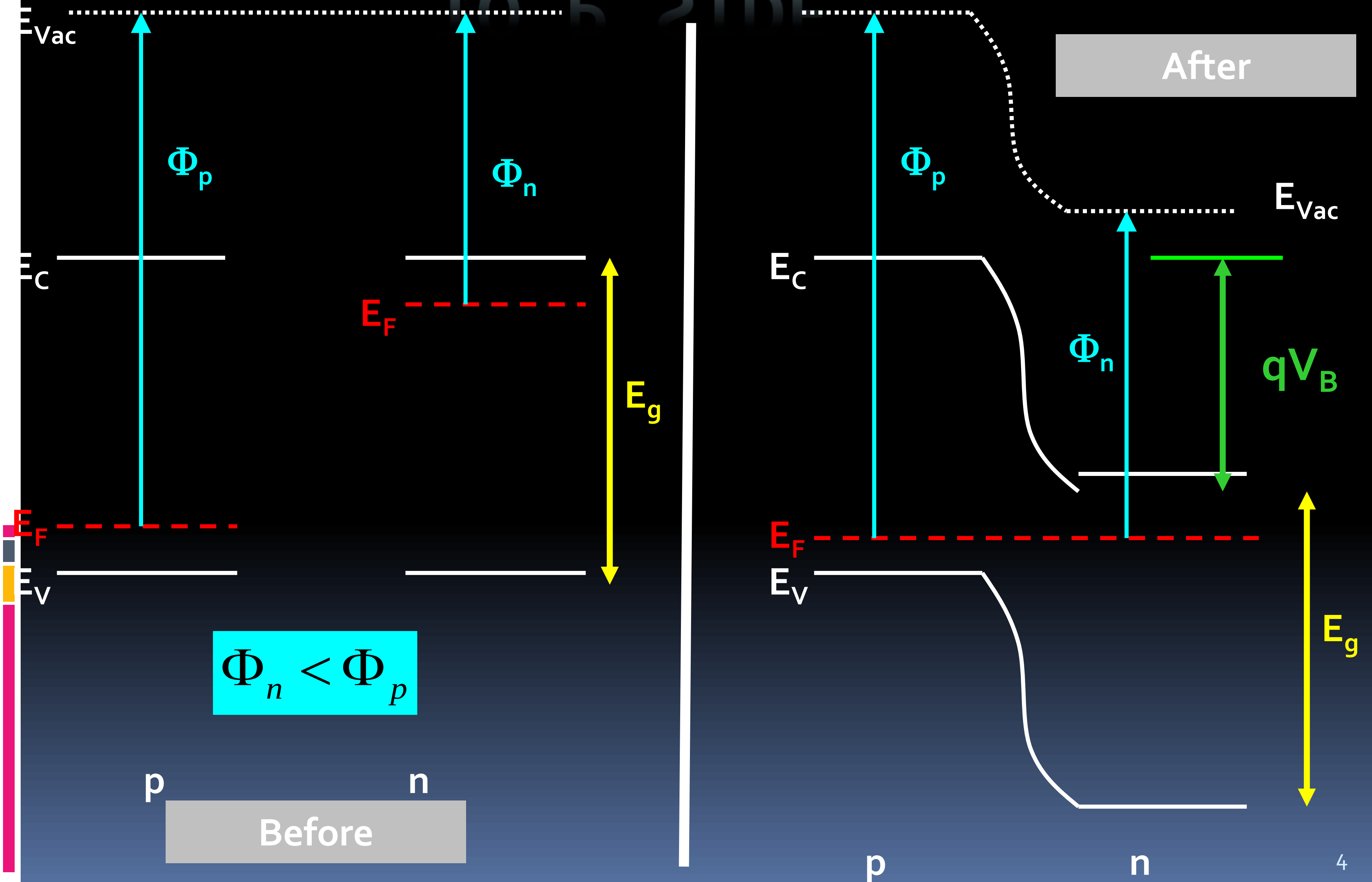


$\Phi \Rightarrow$ Work Function : Energy required for the electron to escape out of the material.

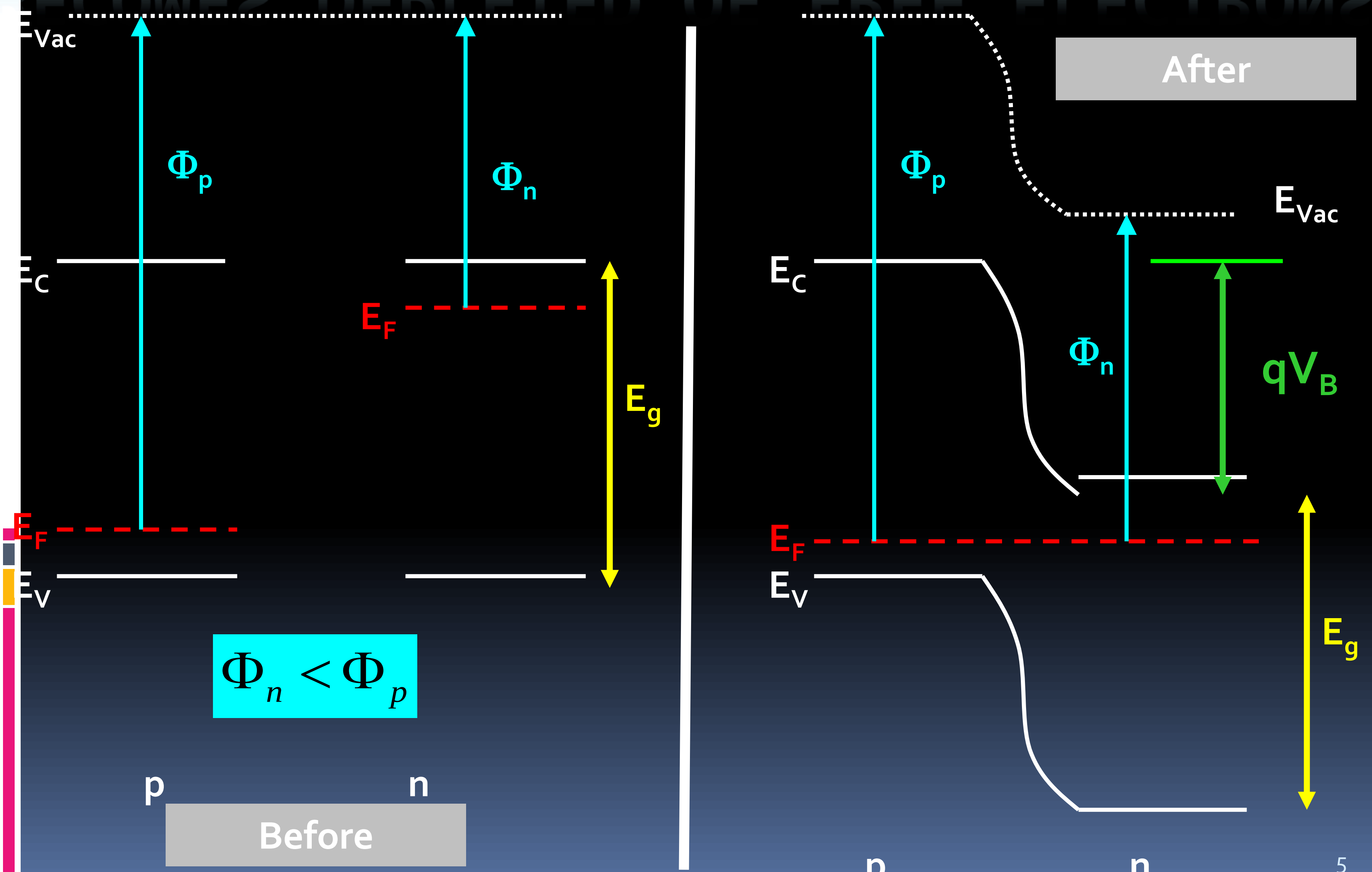
FORMATION OF P-N JUNCTION



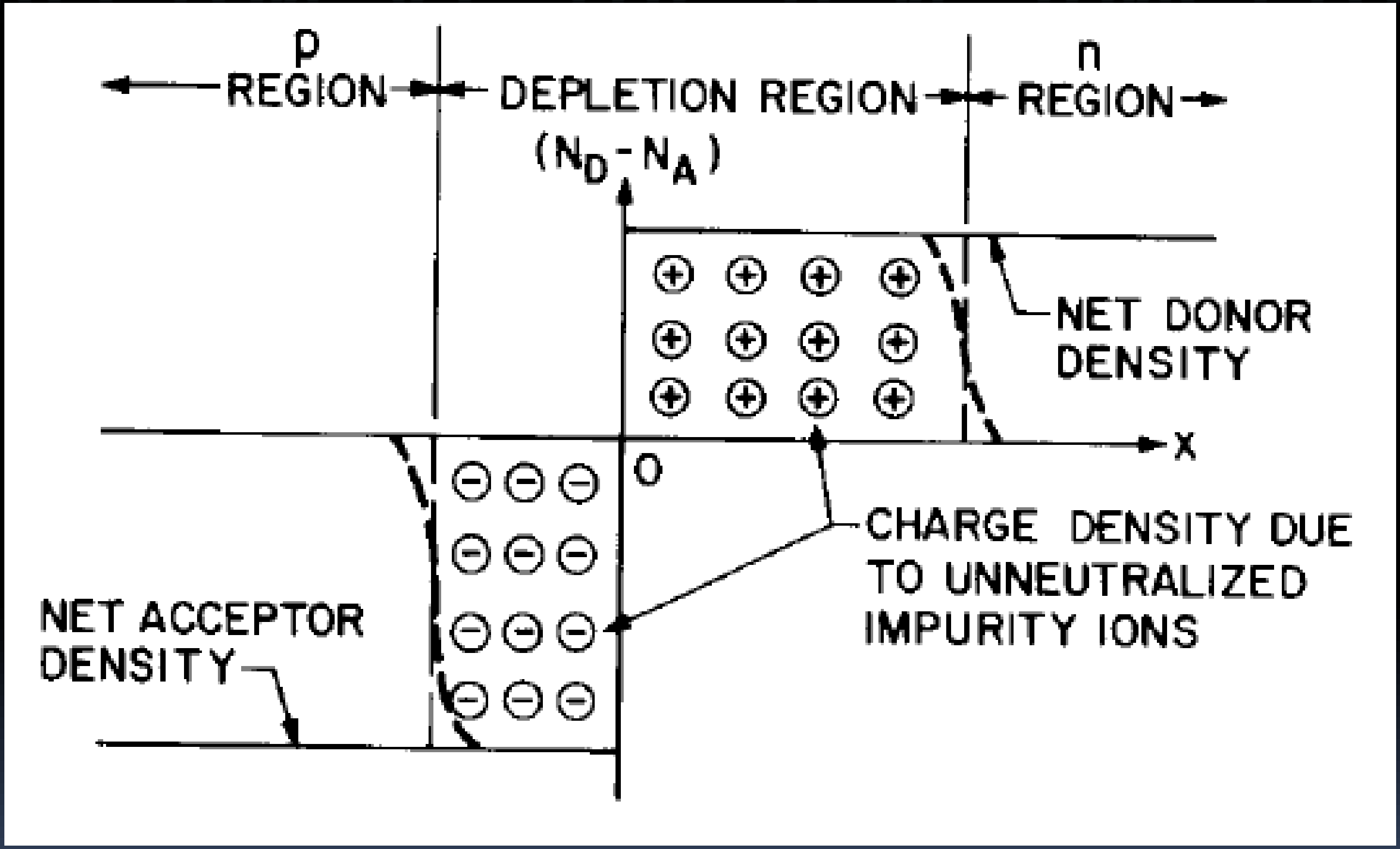
ELECTRON TRANSFER FROM N SIDE TO P SIDE



N TYPE SIDE OF THE JUNCTION BECOMES DEPLETED OF FREE ELECTRONS



FORMATION OF DEPLETION REGION AT THE P-N JUNCTION



Depletion Region : Depleted of Free Charge Carriers (either e or h)

Ch.1 , S. M Sze, Physics of Semiconductor Devices

NO FREE CARRIERS AT THERMAL EQUILIBRIUM

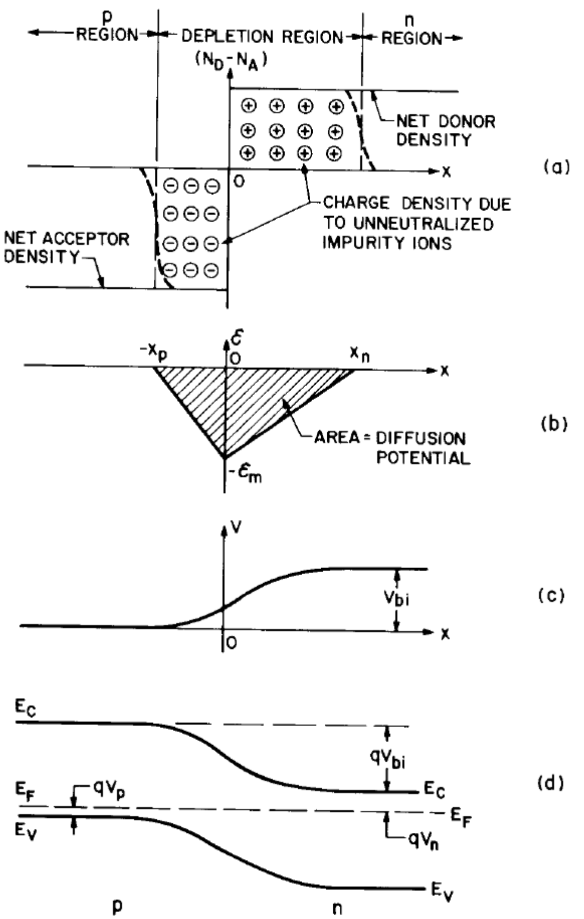


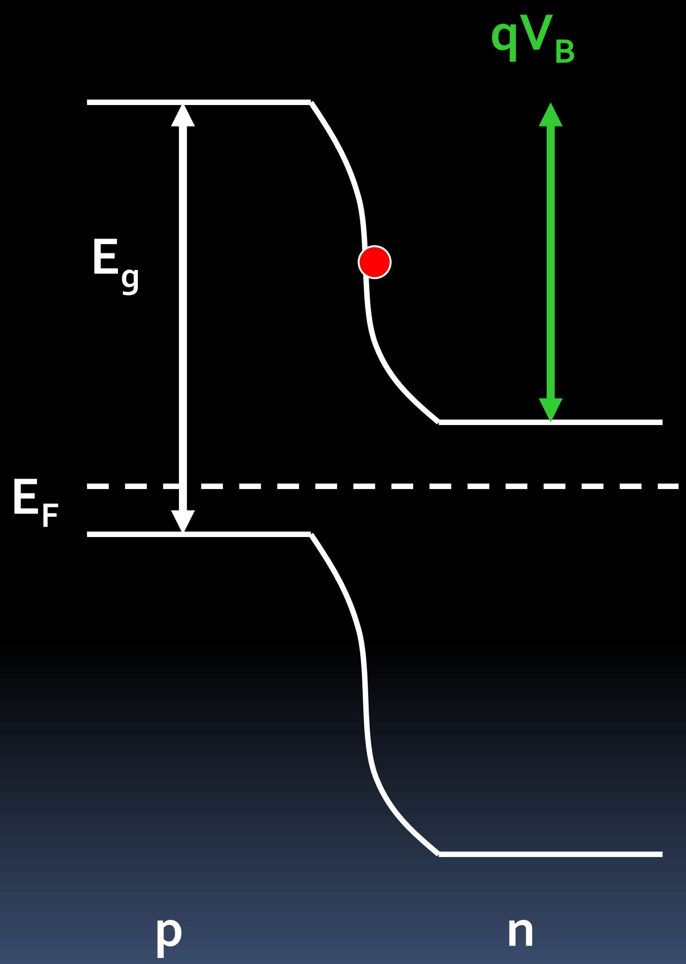
Fig. 10 Abrupt *p-n* junction in thermal equilibrium. (*a*) Space-charge distribution. The dashed lines indicate the majority-carrier distribution tails. (*b*) Electric field distribution. (*c*) Potential variation with distance where V_{bi} is the built-in potential. (*c*) Energy-band diagram.

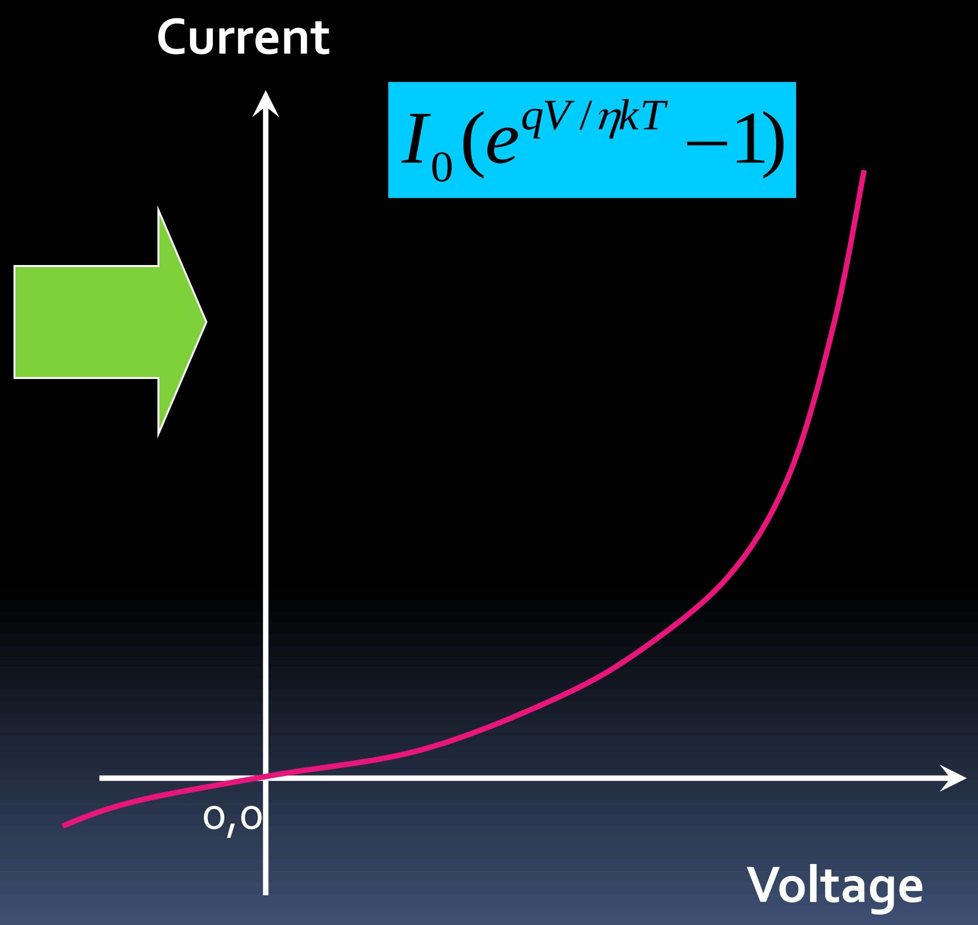
$$(E_C - E_F) >> k_B T$$
$$(E_F - E_V) >> k_B T$$

You can apply electrostatics $\Rightarrow$

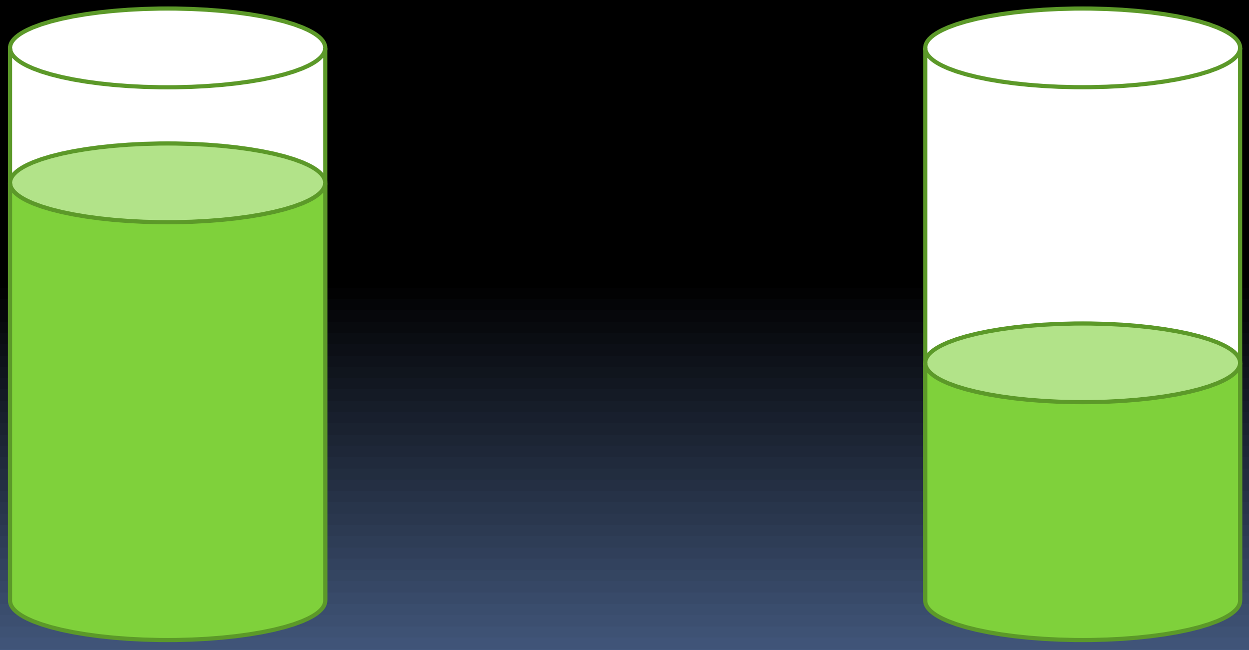
Solve Poissons equation in the depletion region

CURRENT VOLTAGE CHARACTERISTICS OF P-N JUNCTION

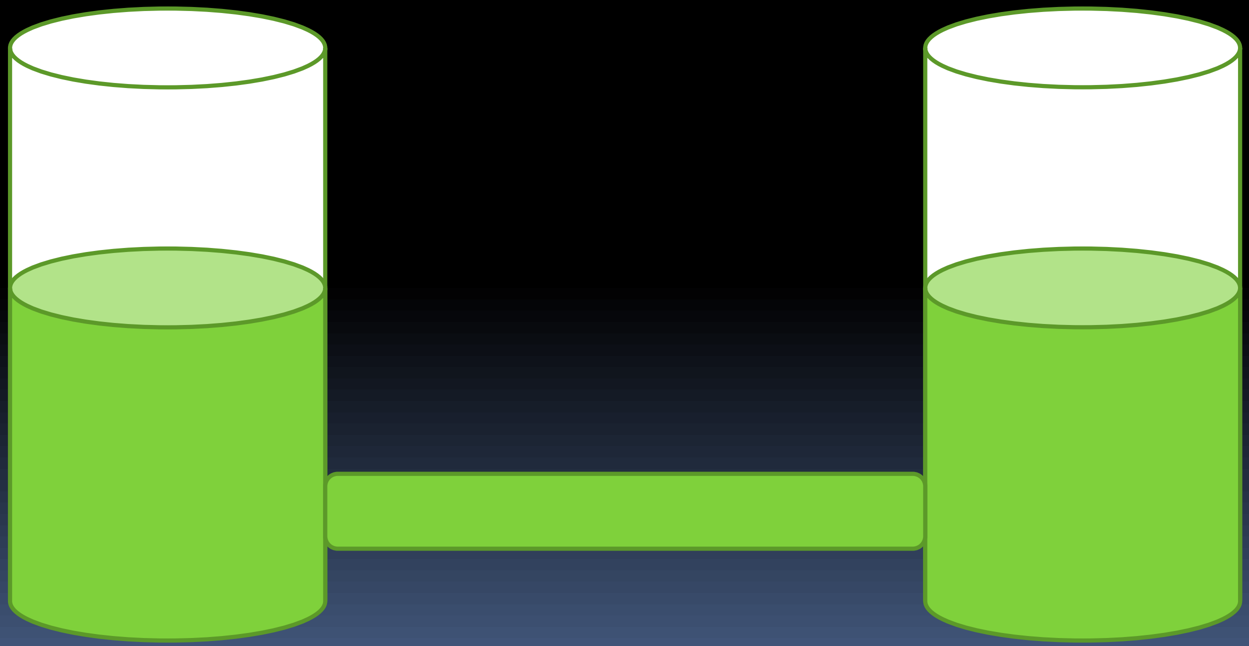




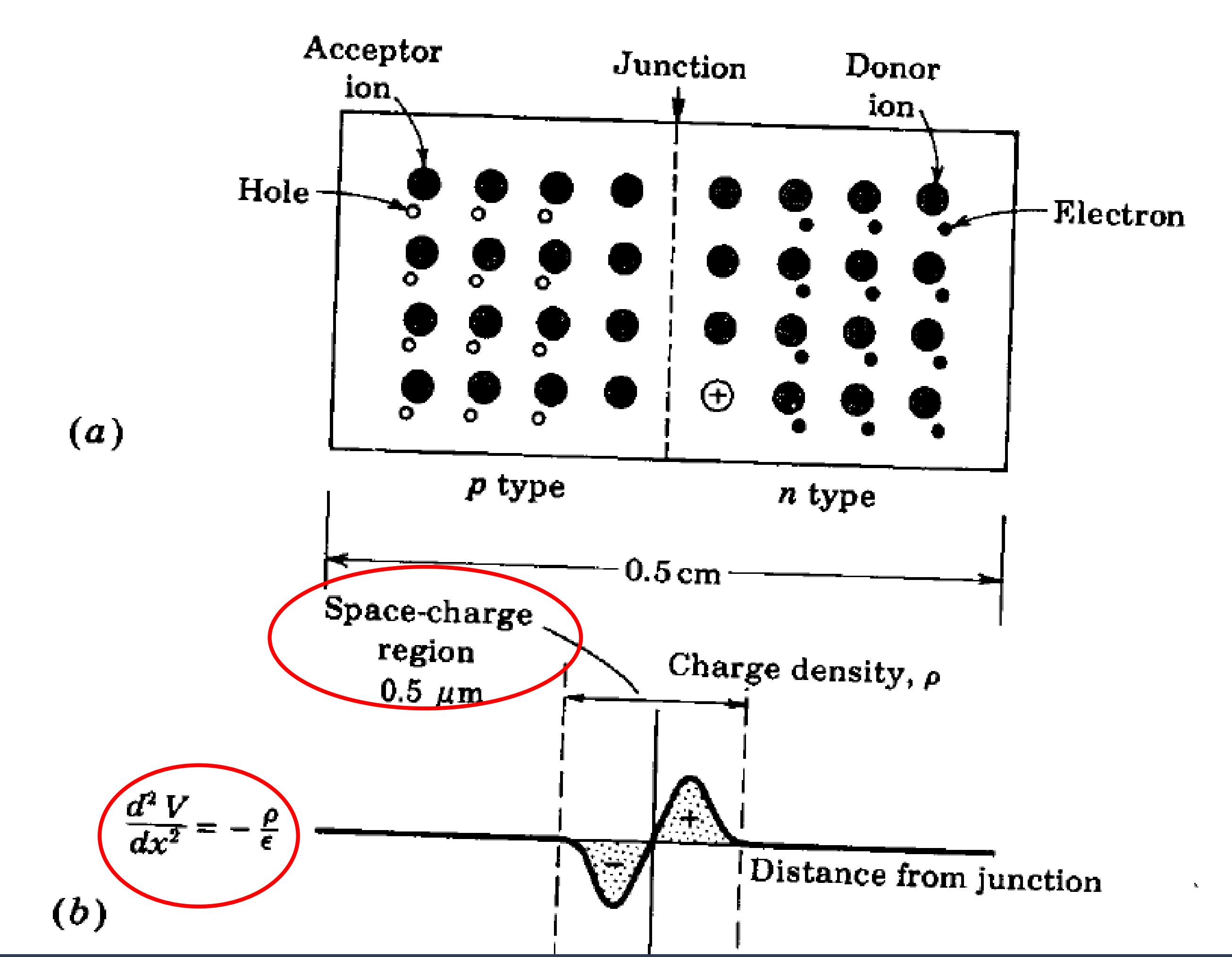
REMEMBER
- THE ANALOGY OF WATER LEVELS IN TWO BEAKERS



REMEMBER
- THE ANALOGY OF WATER LEVELS IN TWO BEAKERS AT EQUILIBRIUM AFTER THEY ARE JOINED TOGETHER.



NO FREE CARRIERS AT THE JUNCTION



You may apply electrostatics

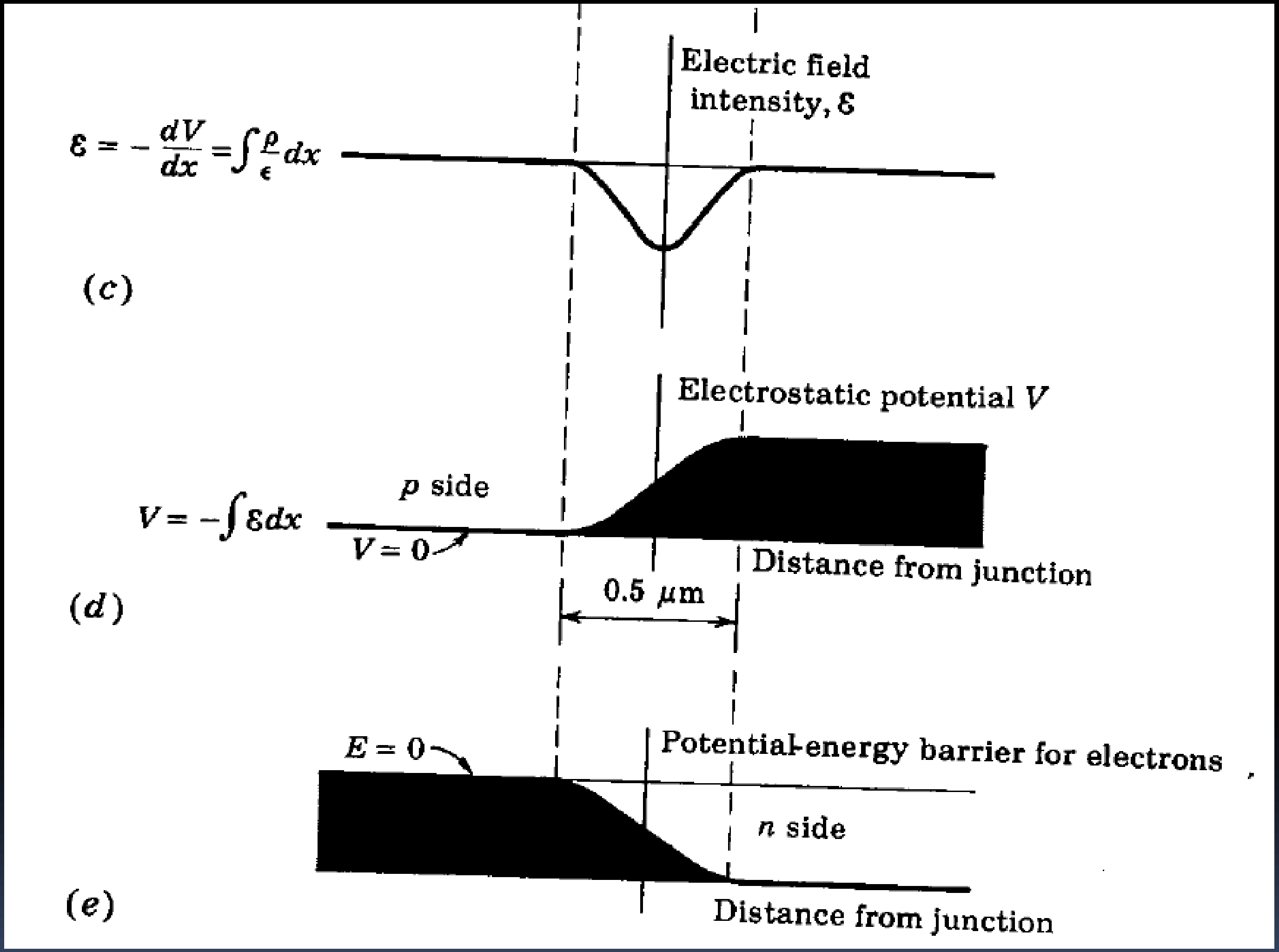
$\Rightarrow$

Solve Poissons equation in the depletion region

Schematic Diagram of p-n junction and charge density

Fig 3.1, Milman & Halkias, Integrated Electronics

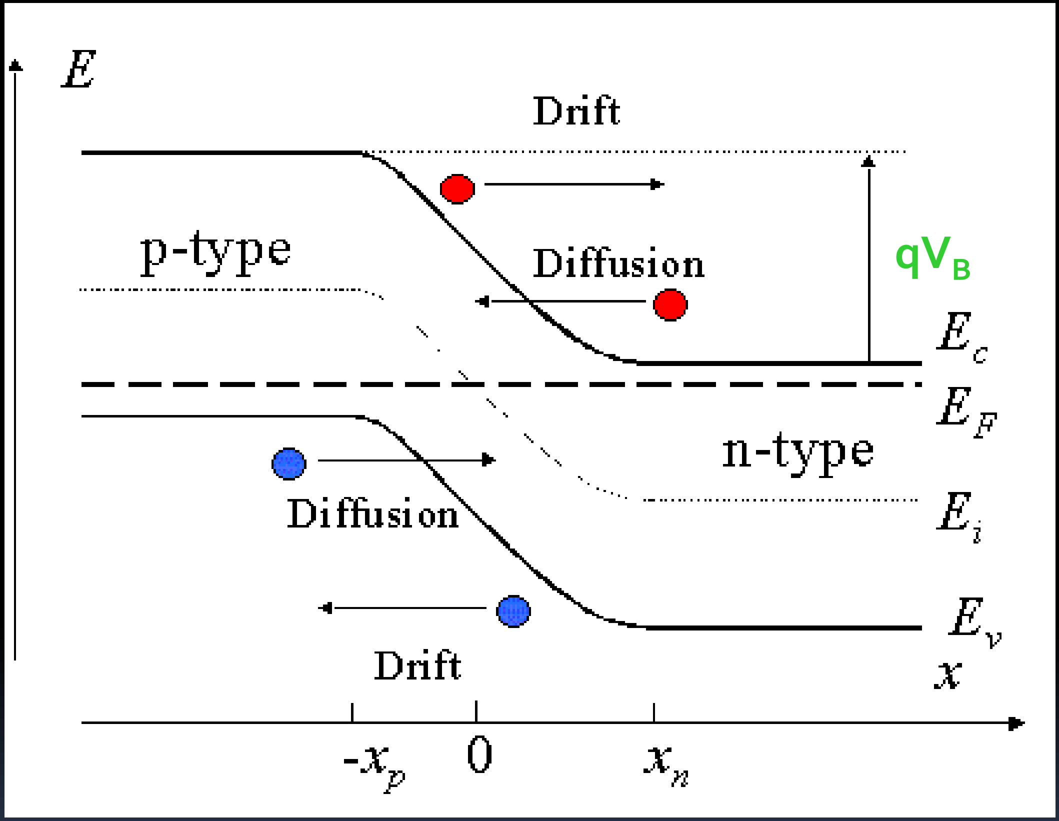
BUILT-IN-POTENTIAL (V_B)



Schematic Diagram of electric field and potential energy across a p-n junction

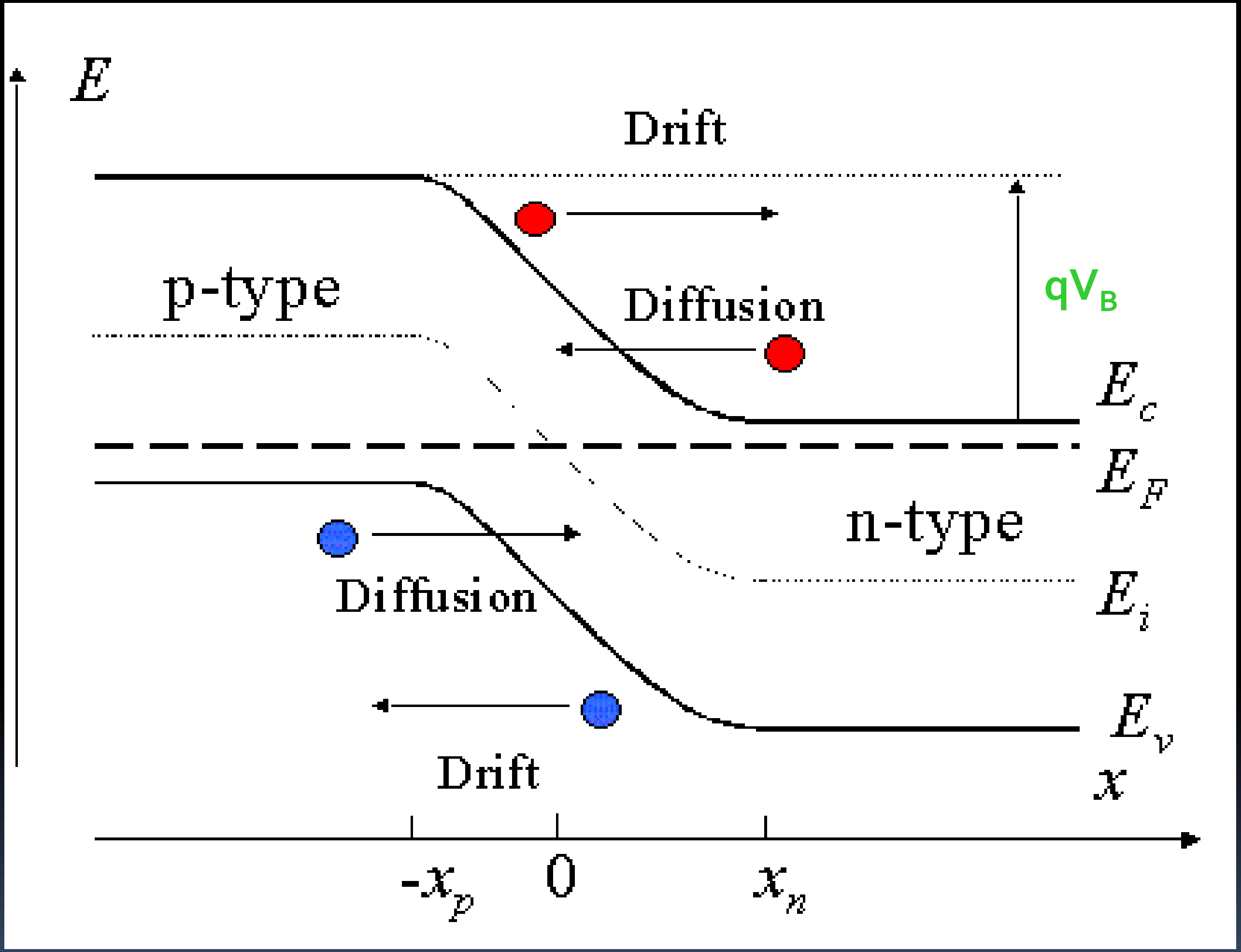
Fig 3.1, Milman & Halkias, Integrated Electronics

DIFFUSION OF MAJORITY CARRIERS :ELECTRON AND HOLES



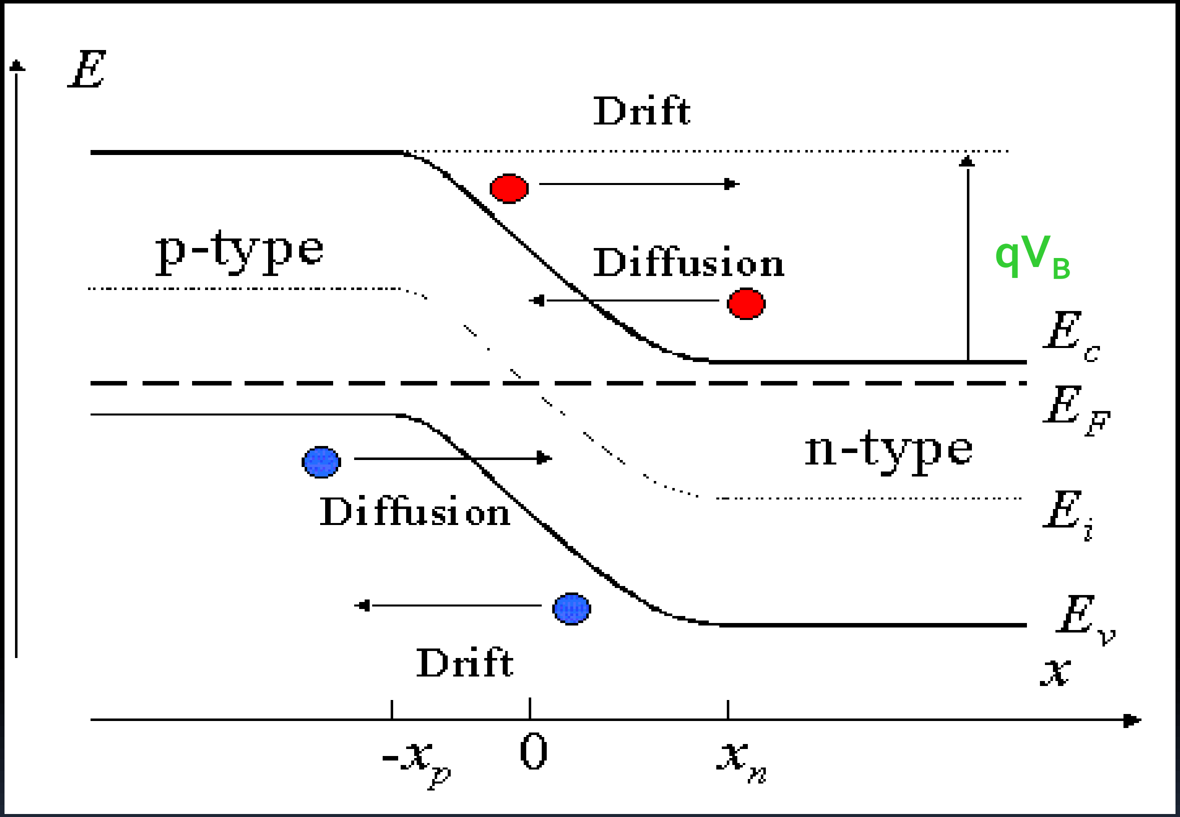
Since the concentration of electrons in the n type side of the junction is much more than that of in the p side. A large number of electrons tend to diffuse from n type side to the p type side. The opposite is true for hole diffusing from p type side to the n type side.

DRIFT OF MINORITY CARRIERS



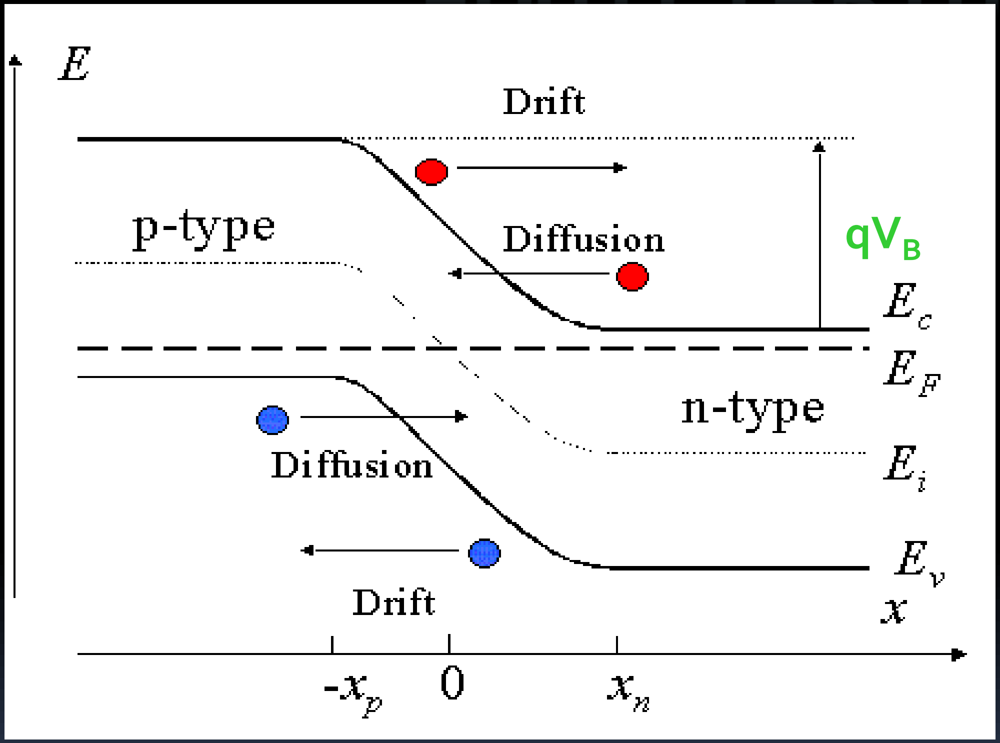
Drift of minority carriers from the opposite sides of the p-n junction and diffusion of majority carriers towards the junction.

DYNAMIC THERMAL EQUILIBRIUM



The dynamic equilibrium is established when the electric field of the space charge region is strong enough to null the current across the junction

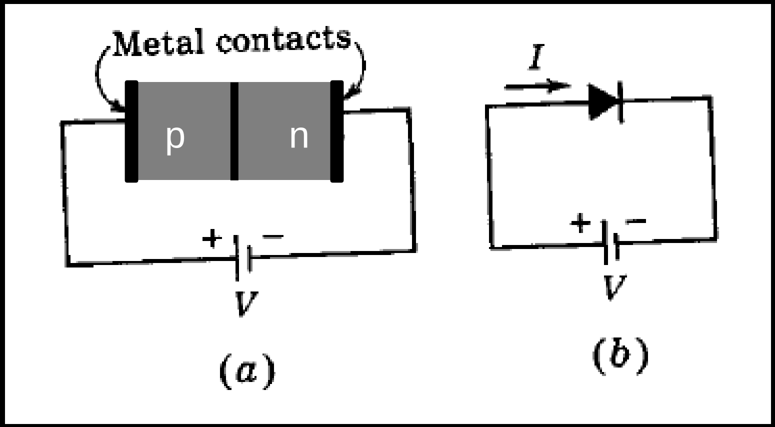
ZERO NET CURRENT ACROSS THE P-N JUNCTION UNDER DYNAMIC THERMAL EQUILIBRIUM



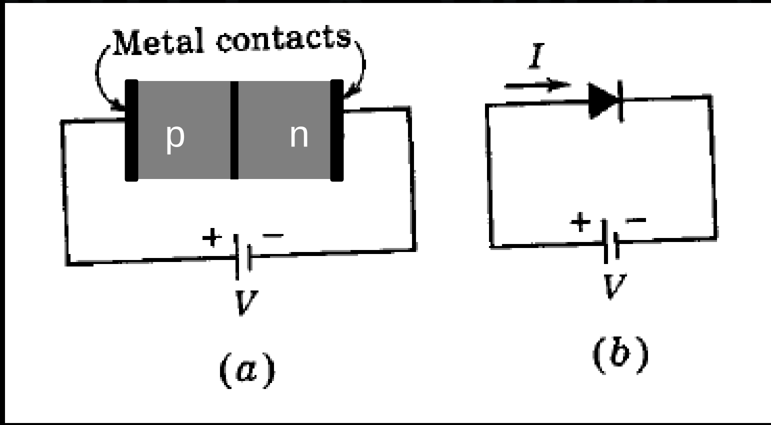
$$I_0^{\,L} - I_0^{\,R} = 0$$

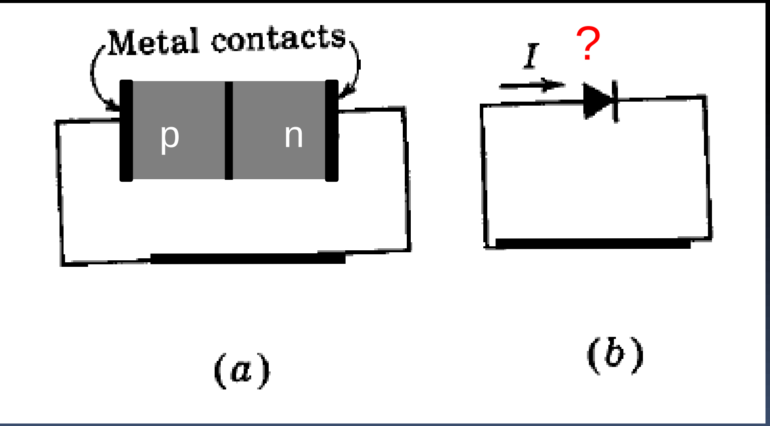
Under Equilibrium, the drift of electron (hole) current must be equal and opposite to the diffusion of electron (hole) so that the net electron (hole) is reduced to zero.

BIASED P-N JUNCTION

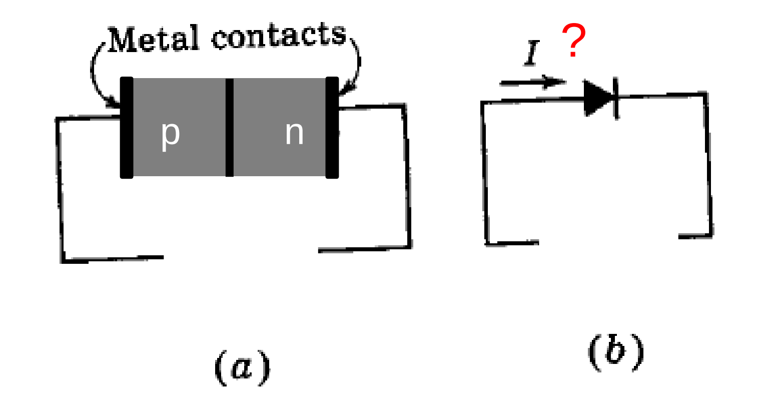


IS THERE ANY DIFFERENCE BETWEEN SHORT CIRCUIT & OPEN CIRCUIT ?





Short Circuit



Open Circuit

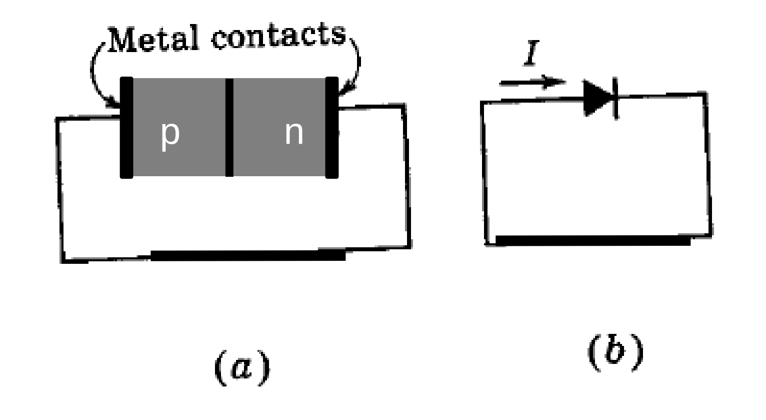
IT IS NOT POSSIBLE TO MEASURE THE BUILT IN POTENTIAL OF A P-N JUNCTION WITH A VOLTMETER.

$$I = I_0^{\,L} - I_0^{\,R} = 0$$

Built-in-potential do not drive
any current across the external circuit !

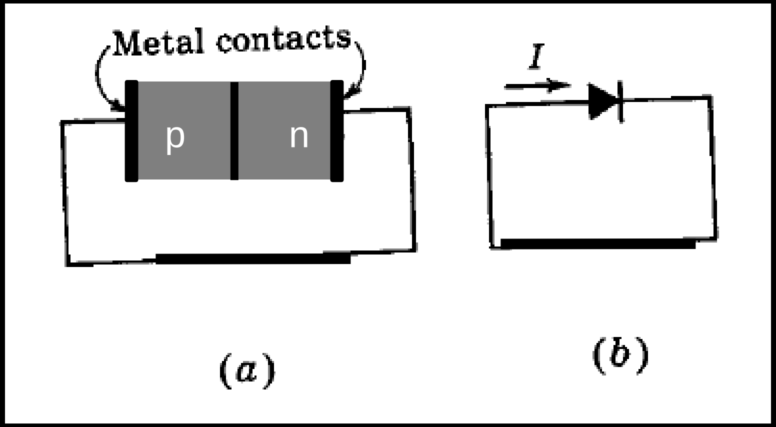
Built-in-potential $\neq$ Electro Motive Force (emf)

WHAT HAPPENS TO KIRCHOFF’S VOLTAGE LAW IN THE SHORT CIRCUIT CONDITION ?



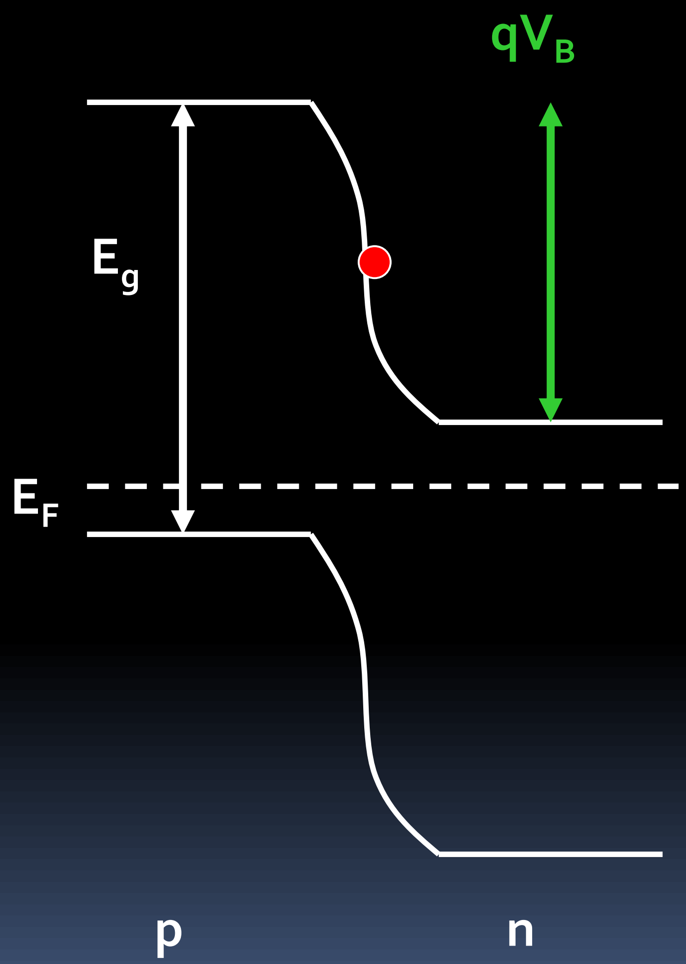
Milman & Halkias, Integrated Electronics

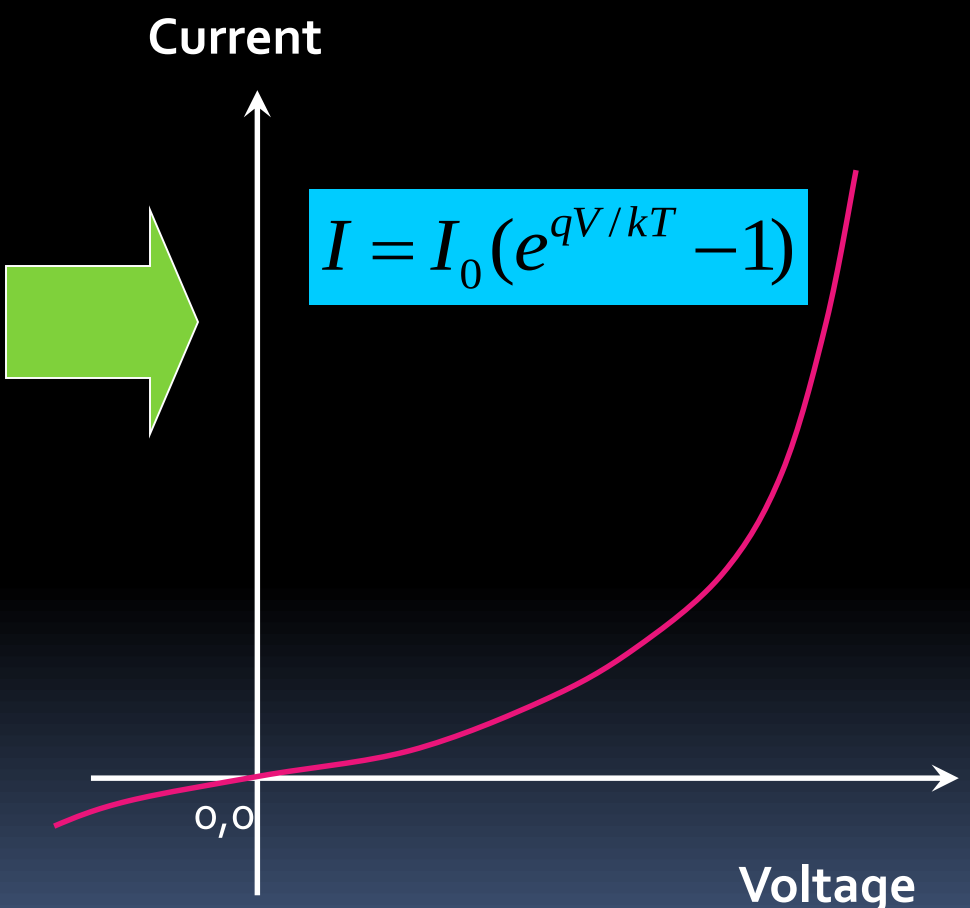
WHAT HAPPENS TO KIRCHOFF'S VOLTAGE LAW IN THE SHORT CIRCUIT CONDITION ?



The Built-in-Potential is compensated by the metal to semiconductor contact potentials !

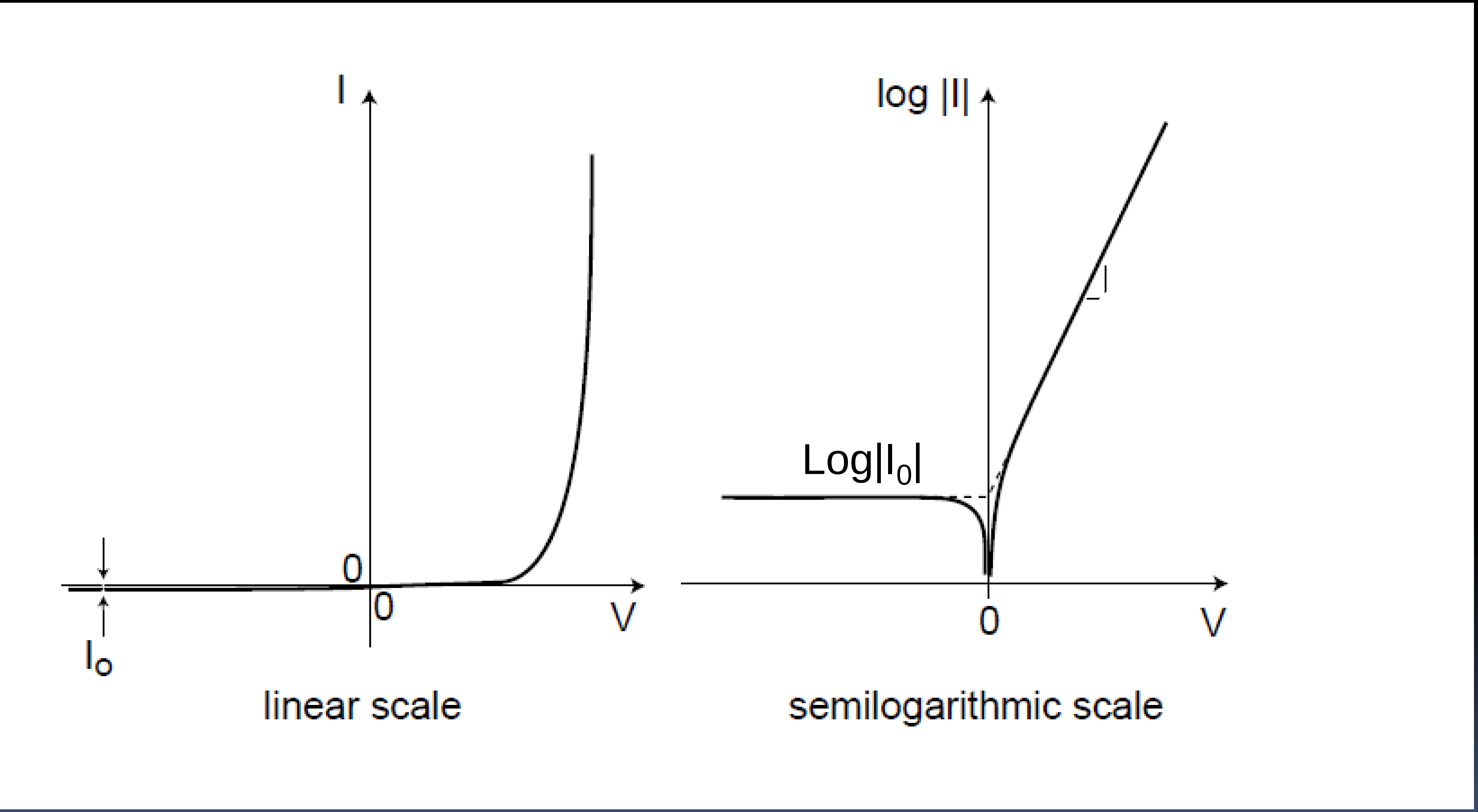
CURRENT VOLTAGE CHARACTERISTICS OF P-N JUNCTION





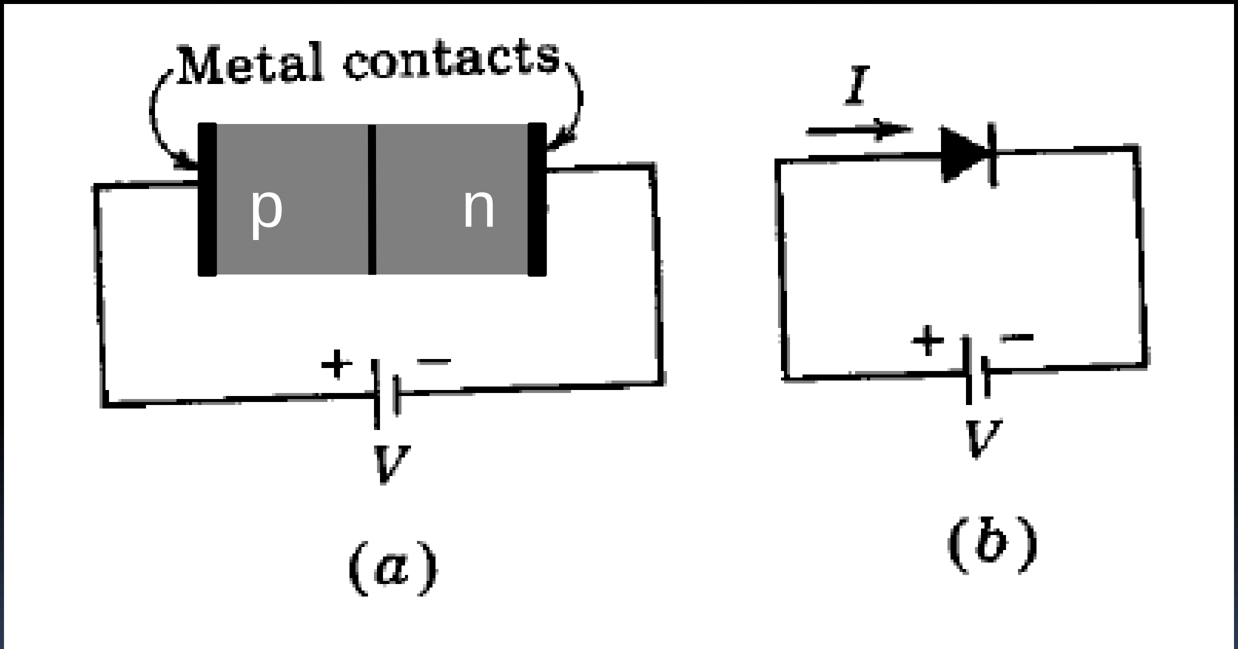
p-n junction allows the easy flow of current in one direction but blocks the flow in the opposite direction !

CURRENT VOLTAGE CHARACTERISTICS OF P-N JUNCTION



$$I_0(e^{qV/kT} - 1)$$

FORWARD BIAS : CURRENT BY MAJORITY CARRIERS FLOW ACROSS THE P-N JUNCTION AND BECOME MINORITY CARRIER

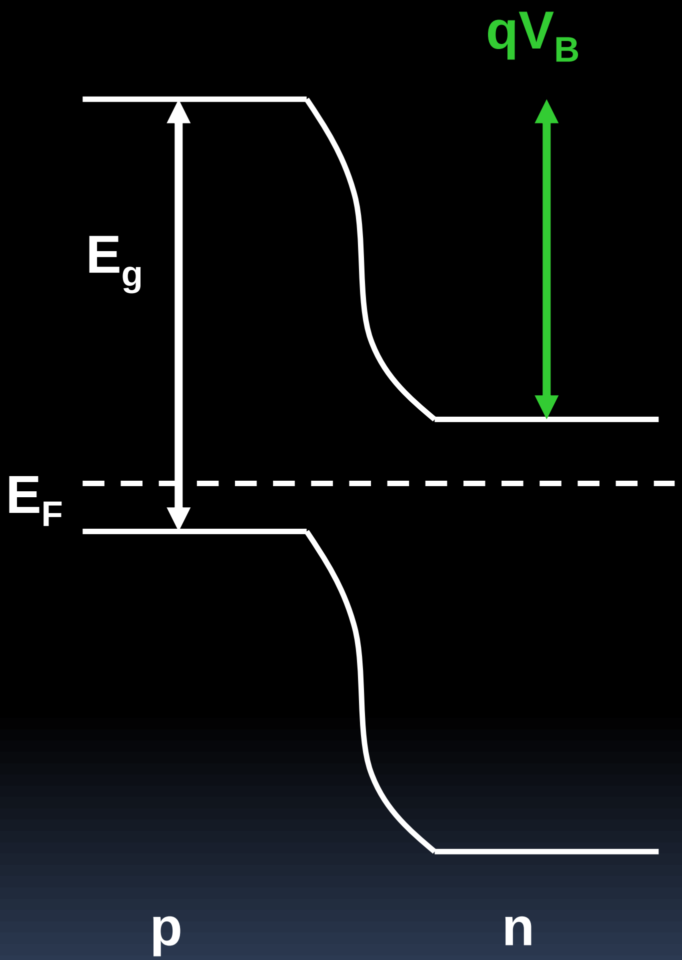


Minority Carrier Injection @ Forward Bias from Opposite sides

Fig 3.3, Milman & Halkias, Integrated Electronics

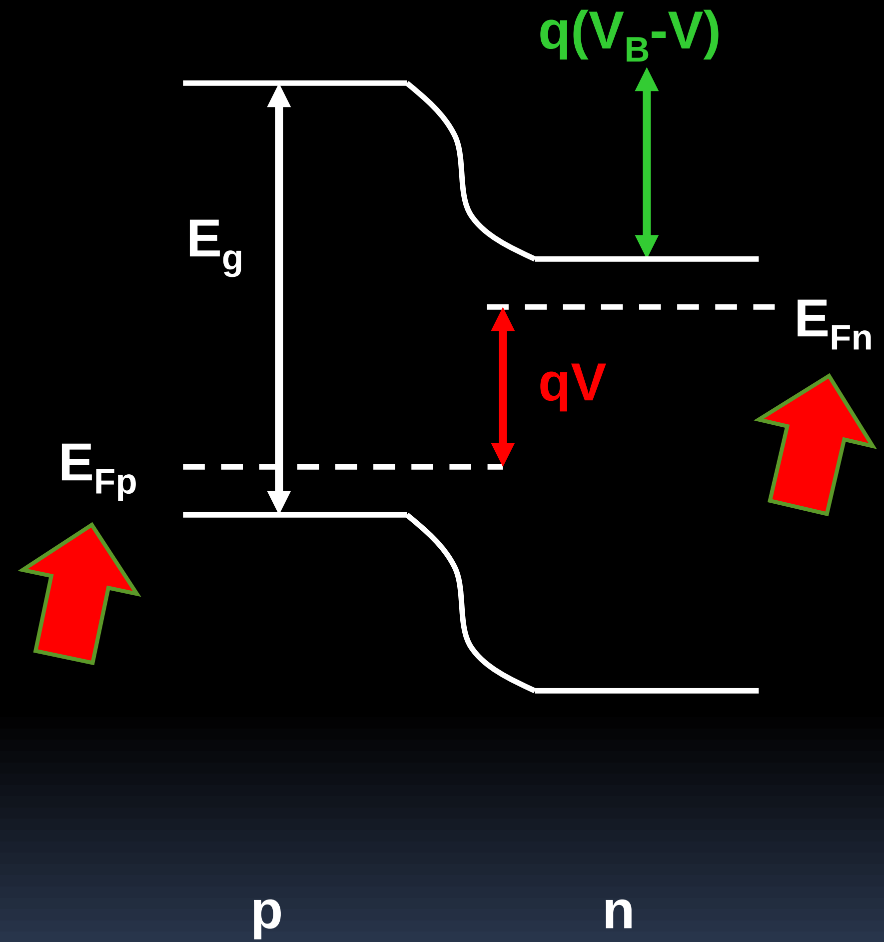
FORWARD BIAS

No Bias



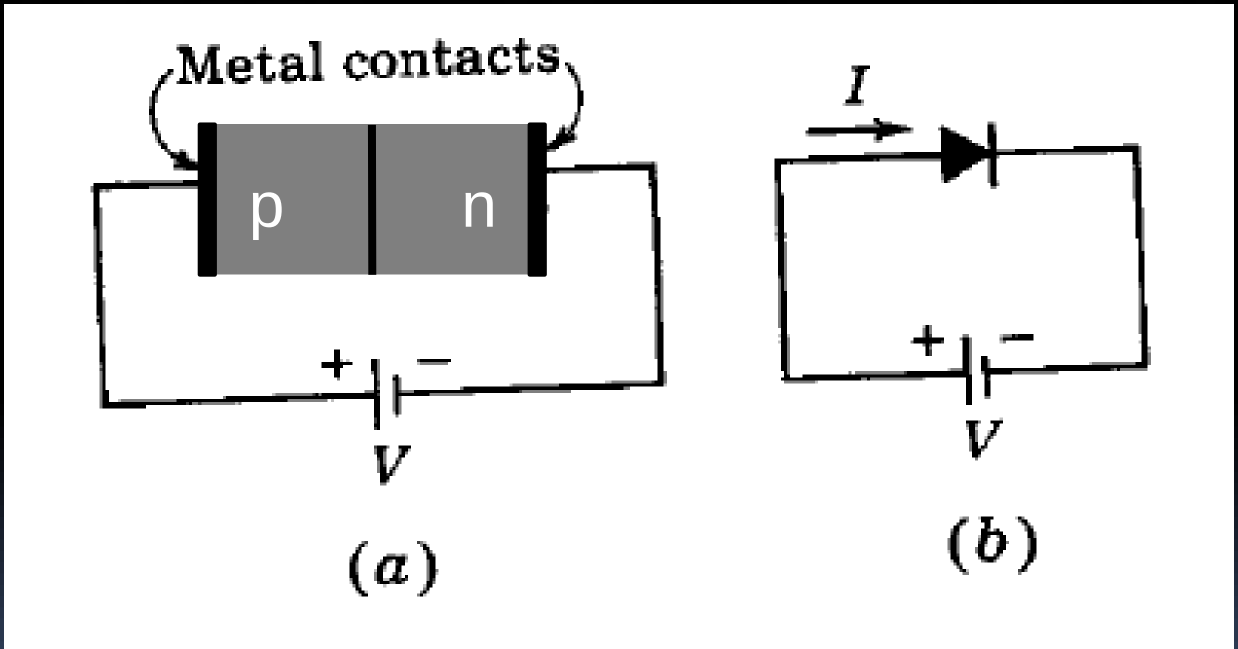
$$I_0^{\ L} - I_0^{\ R} = 0$$

Forward Biased



$$I_0(e^{qV/kT} - 1)$$

FORWARD BIAS : RESULTANT CURRENT CROSSING THE JUNCTION IS SUM OF THE "INJECTED" ELECTRON & HOLE MINORITY CARRIER CURRENTS

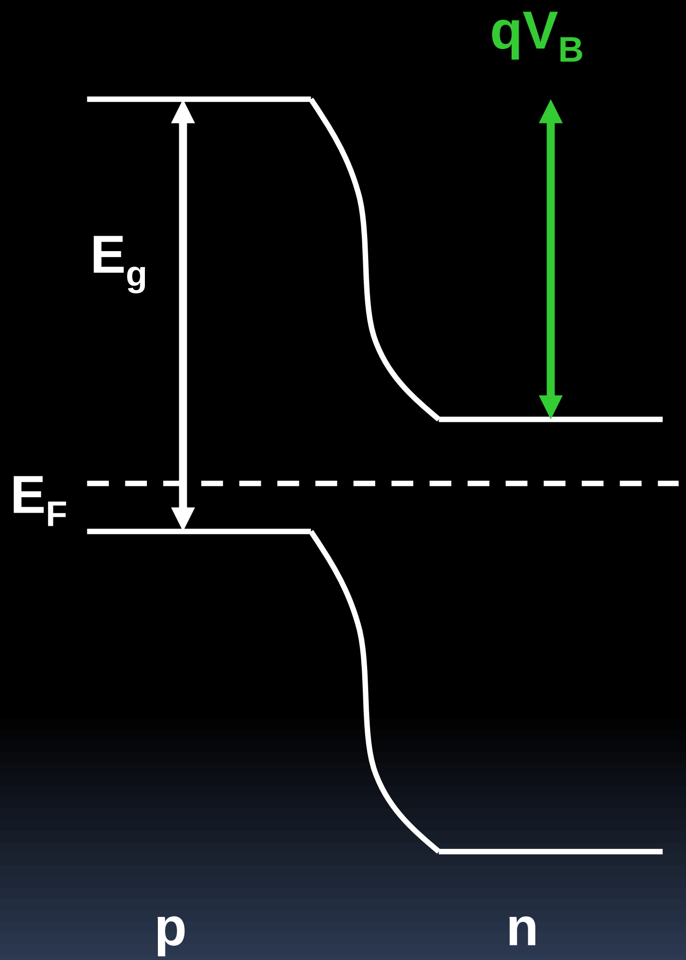


Minority Carrier Injection @ Forward Bias from Opposite sides

Fig 3.3, Milman & Halkias, Integrated Electronics

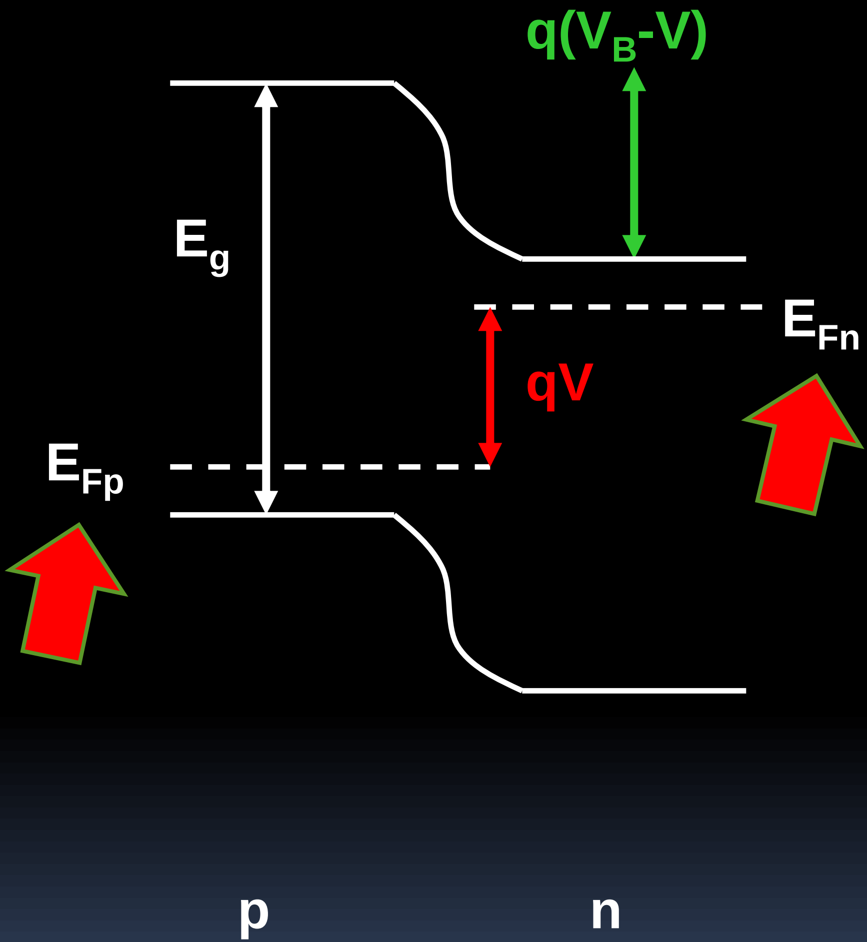
E_{Fp} & E_{Fn} IS QUASI FERMI LEVELS

No Bias



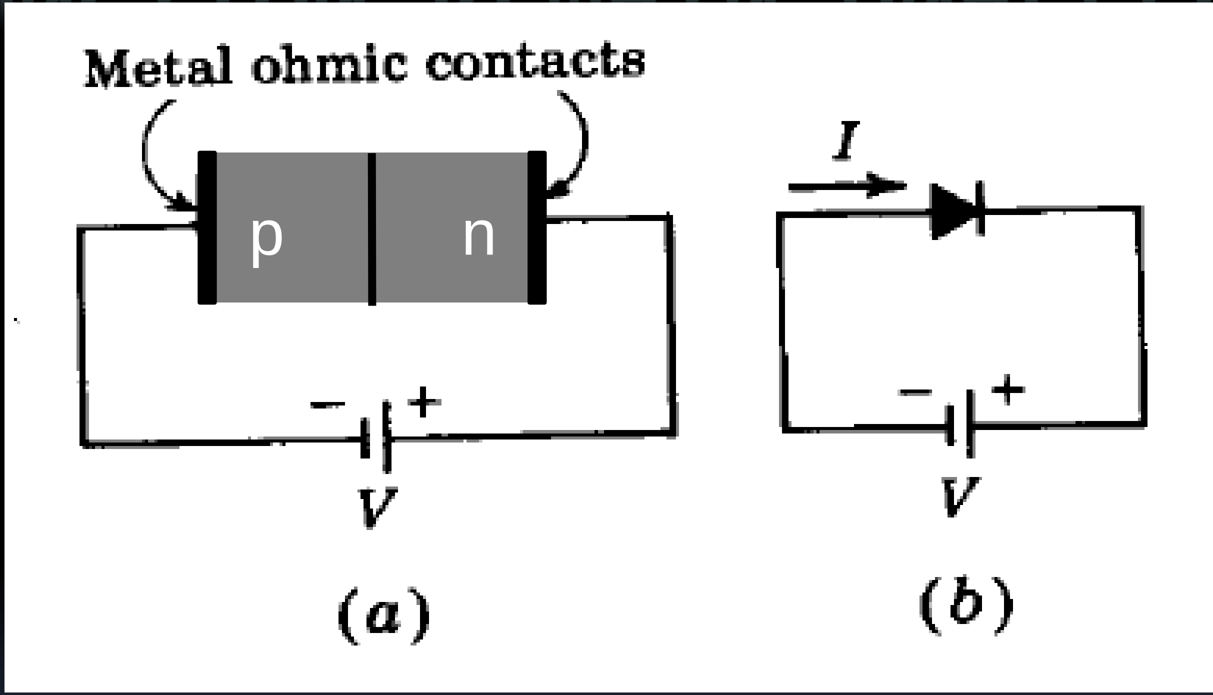
$$I_0{}^L - I_0{}^R = 0$$

Forward Biased



$$I_0(e^{qV/kT} - 1)$$

REVERSE BIAS : CURRENT BY MINORITY CARRIER ACROSS THE P-N JUNCTION REMAIN UNAFFECTED

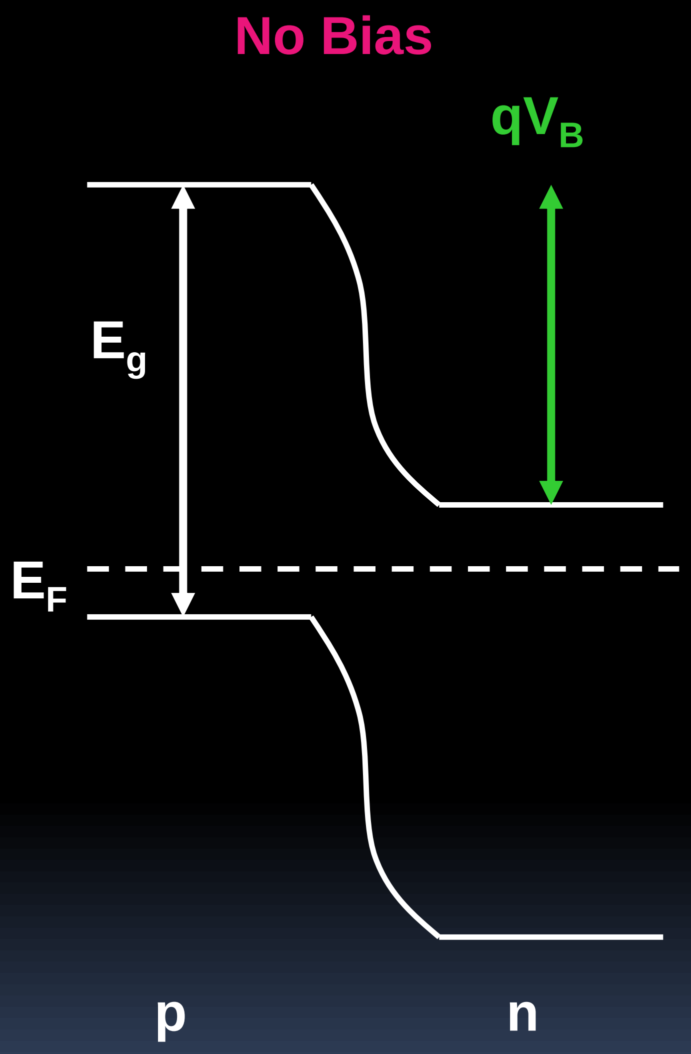


$$I = -I_0$$

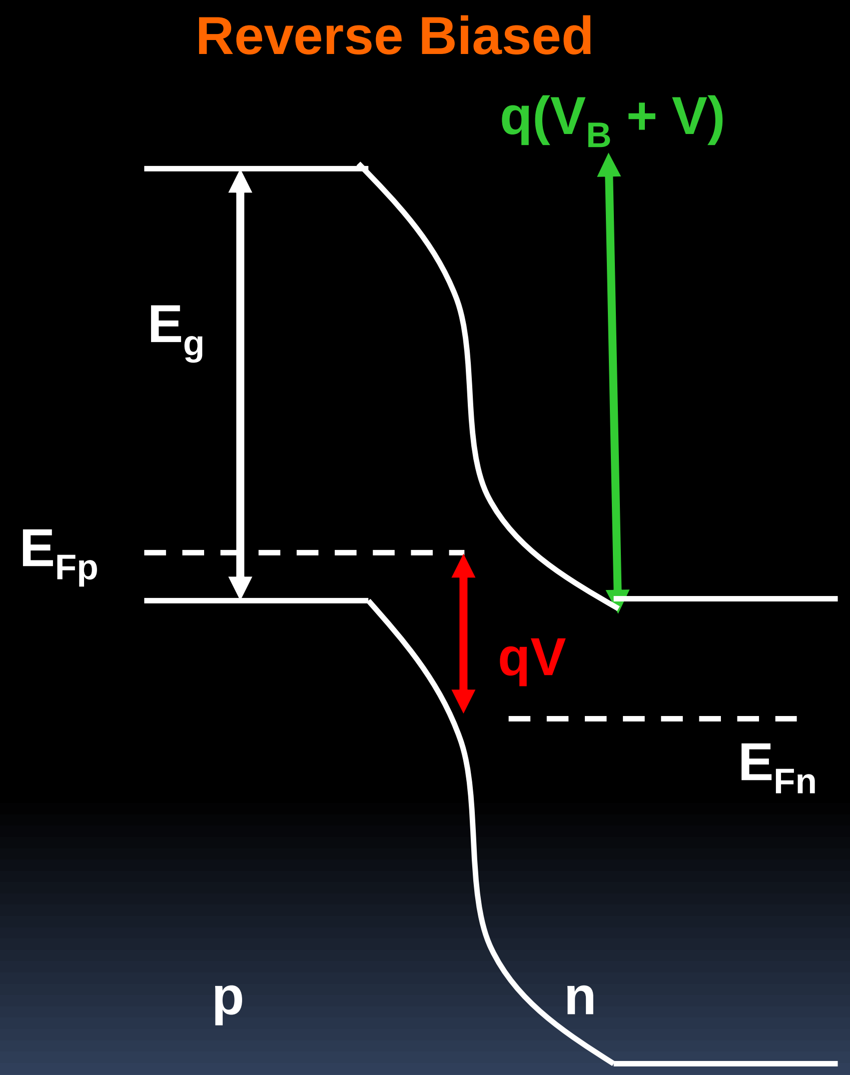
Origin of Reverse Saturation Current or Leakage Current : Small number of thermally generated electrons in the p type side and holes in the n type side cross the junction.

Fig 3.2, Milman & Halkias, Integrated Electronics

REVERSE BIAS



$$I_0^{\,L} - I_0^{\,R} = 0$$



$$-I_0$$

ASSUMPTION : THE METAL CONTACT TO BOTH P & N TYPE SIDE ARE OHMIC (V=RI)

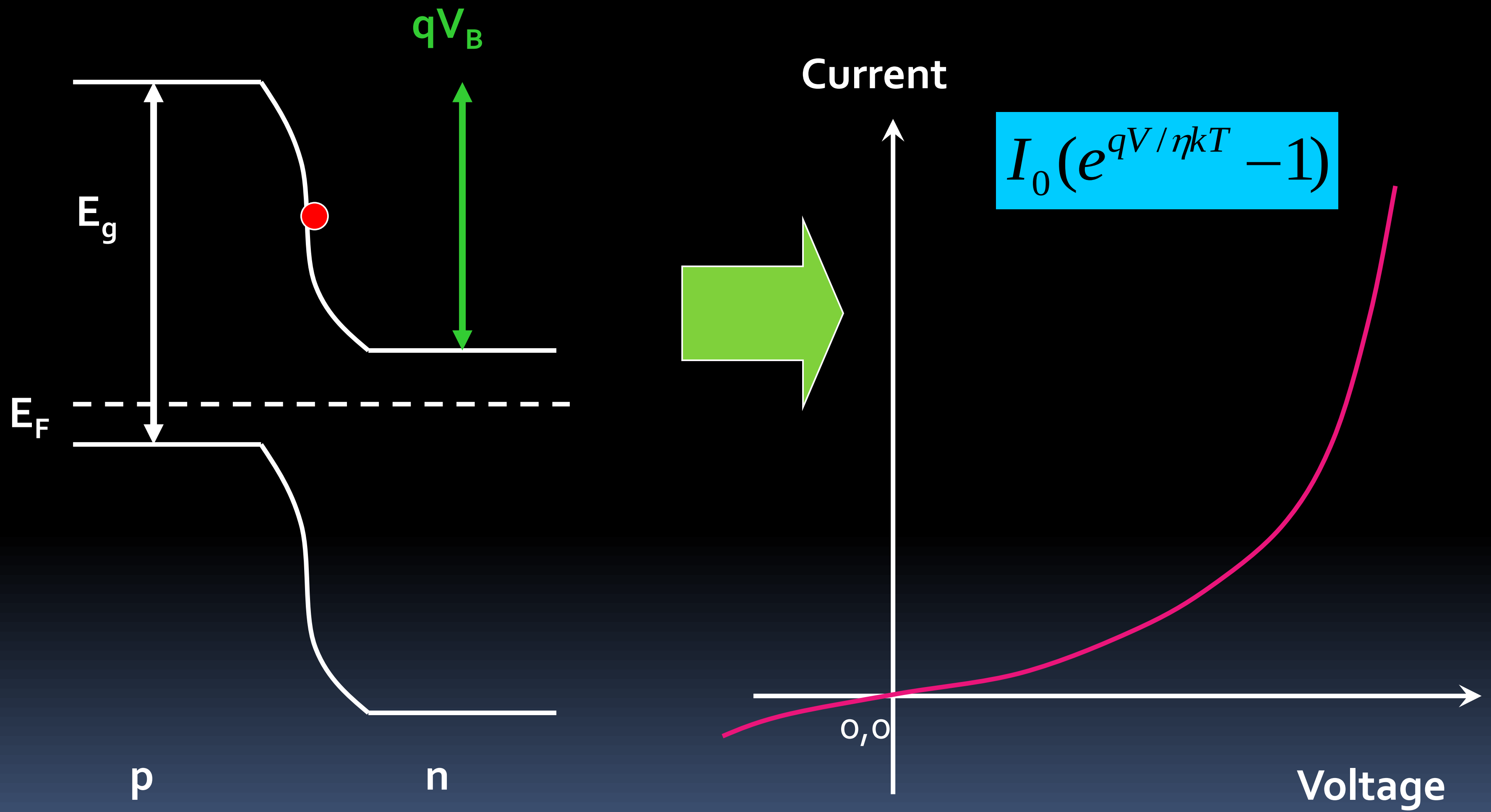
Usually, the metal semiconductor junctions are also diode like $\Rightarrow$ Schottky Diode !

$\Downarrow$

Special fabrication is needed to make it Ohmic

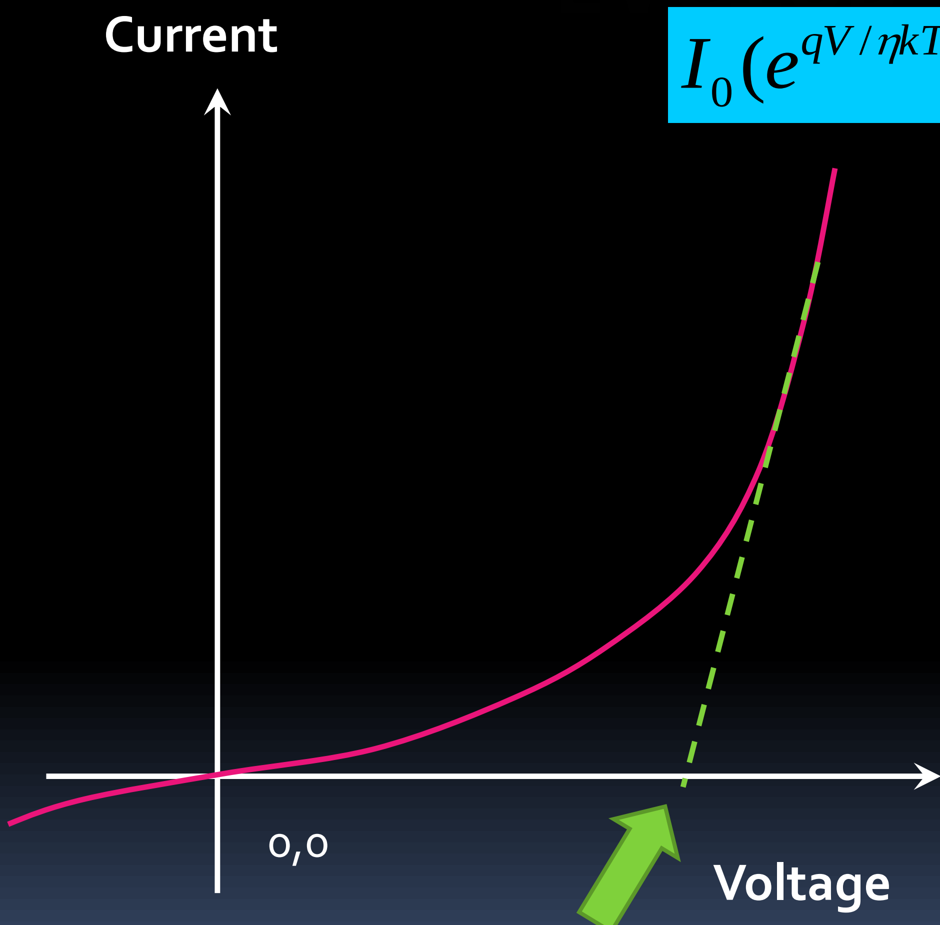
S. M Sze, Physics of Semiconductor Devices.

CURRENT VOLTAGE CHARACTERISTICS OF P-N JUNCTION



THRESHOLD VOLTAGE AND IDEALITY FACTOR

$$I_0(e^{qV/\eta kT} - 1)$$



$$V_{Threshold} \sim V_B$$

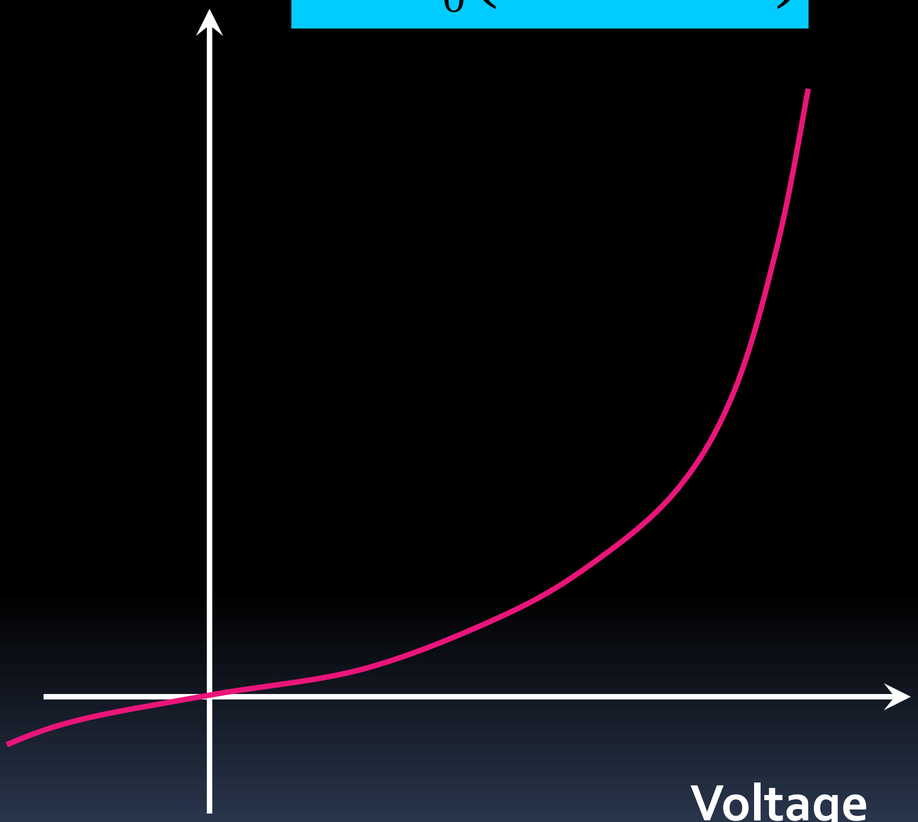
$$\eta_{Ideal} = 1$$

$$\eta_{Real} > 1$$

Near Ideal at Low Doping and at High Temperature

DIODE CONDUCTANCE : DEPARTURE FROM OHM'S LAW (V=IR)

$$I = I_0(e^{qV/\eta kT} - 1)$$



Incremental or Dynamic Resistance

$$r = \frac{dV}{dI}$$

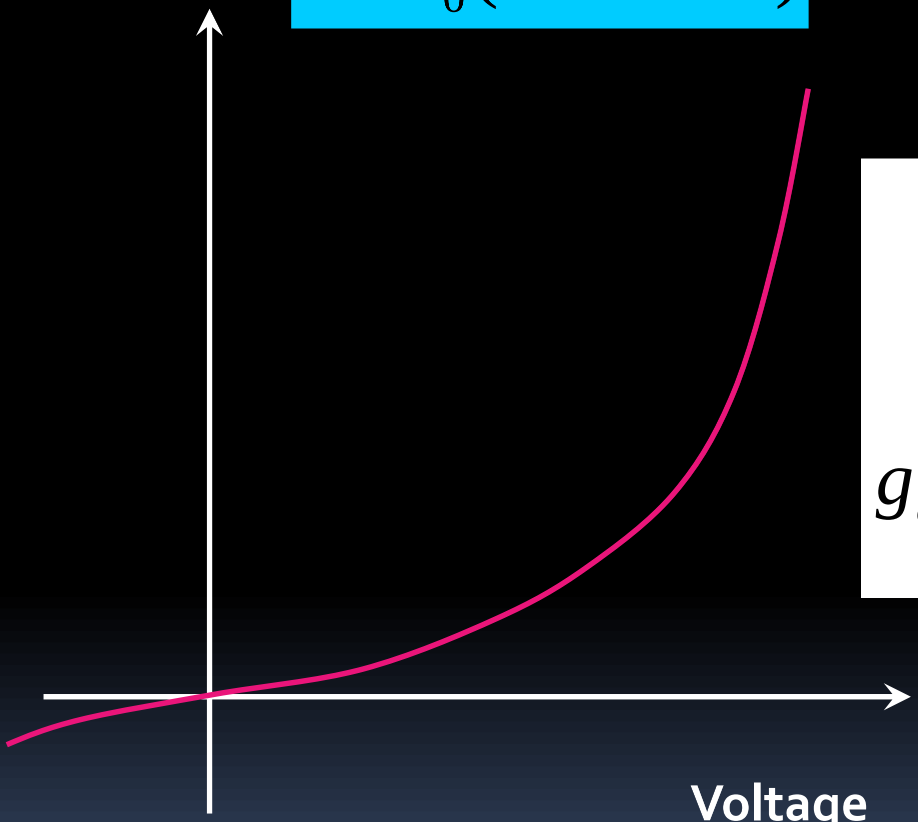
Dynamic Conductance

$$g_d = \frac{1}{r} = \frac{dI}{dV}$$

Milman & Halkias, Integrated Electronics

DIODE CONDUCTANCE : DEPARTURE FROM OHM'S LAW (V=IR)

$$I = I_0(e^{qV/\eta kT} - 1)$$



Dynamic Conductance

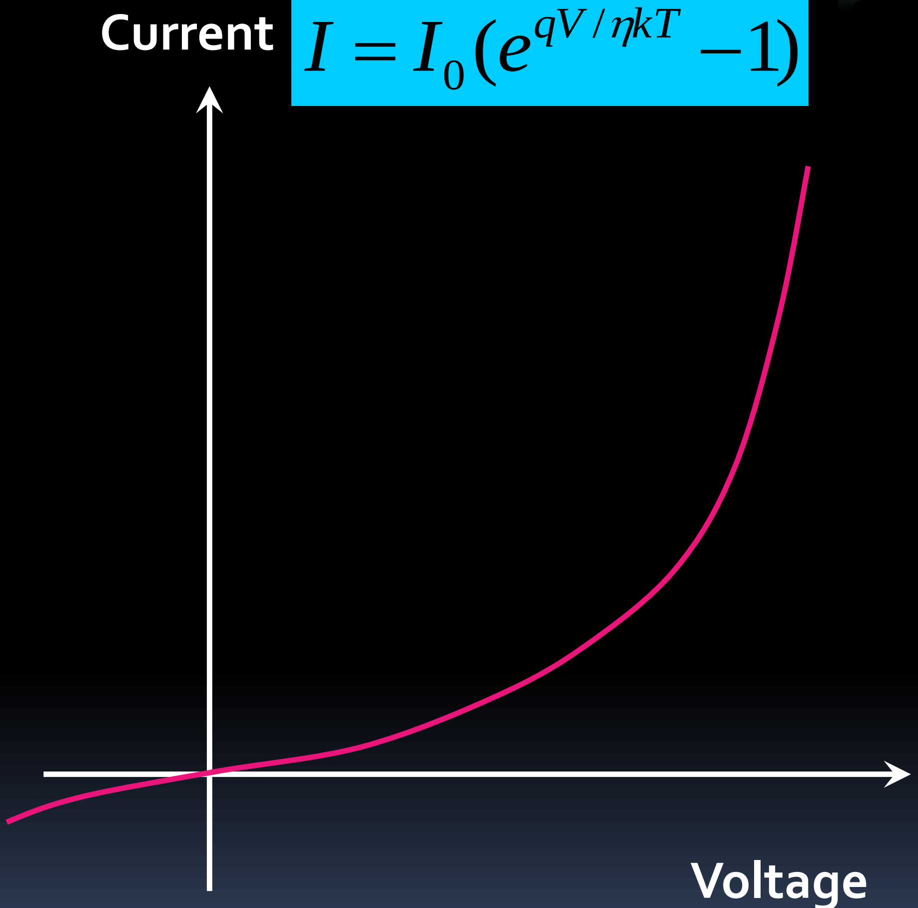
$$g_d = \frac{1}{r} = \frac{dI}{dV}$$

$$g_d = I_0 e^{\frac{qV}{\eta k_B T}} \left(\frac{q}{\eta k_B T} \right) = \frac{q(I + I_0)}{\eta k_B T}$$

Milman & Halkias, Integrated Electronics

DIODE CONDUCTANCE : DEPARTURE FROM OHM'S LAW (V=IR)

$$I = I_0(e^{qV/\eta kT} - 1)$$



Dynamic Conductance

$$g_d = \frac{1}{r} = \frac{dI}{dV}$$

$$g_d = I_0 e^{\frac{qV}{\eta k_B T}} \left(\frac{q}{\eta k_B T} \right) = \frac{q(I + I_0)}{\eta k_B T}$$

$$\text{For V} >> \eta \mathrm{k_B} T / q$$

$$\text{Reverse Bias : } \mathrm{g_d} \text{ is very small.}$$

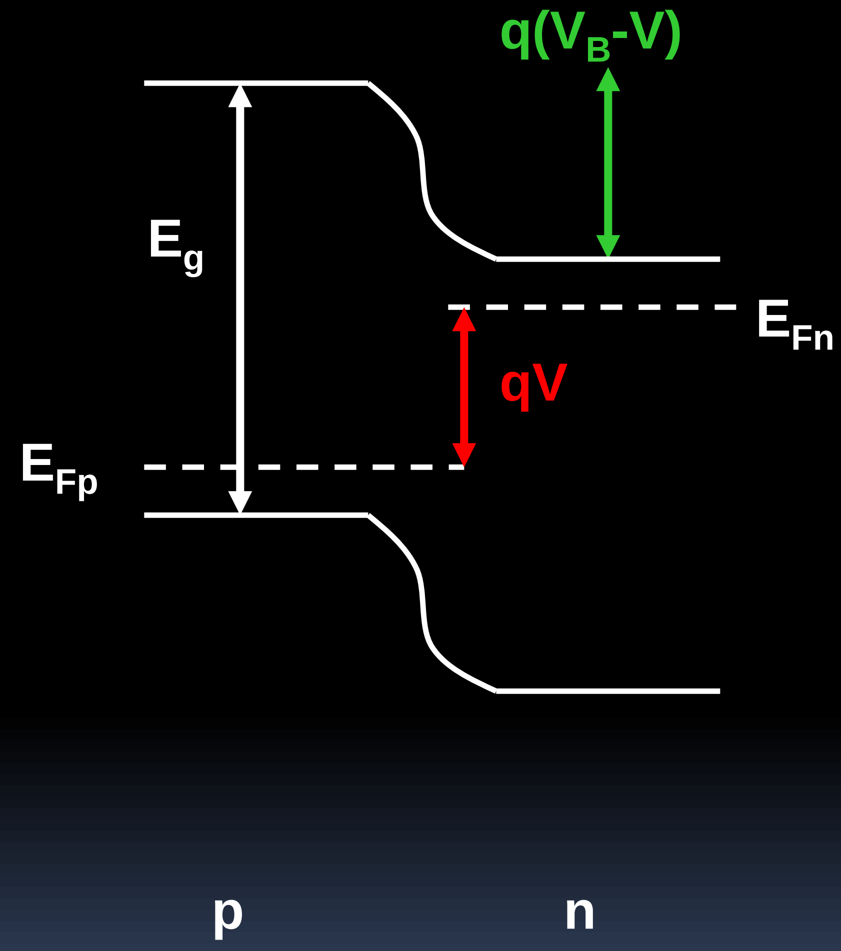
$$\text{Forward Bias : } \mathrm{g_d} \approx \frac{\mathrm{qI}}{\eta \mathrm{k_B} T}$$

Milman & Halkias, Integrated Electronics

LARGE FORWARD BIAS

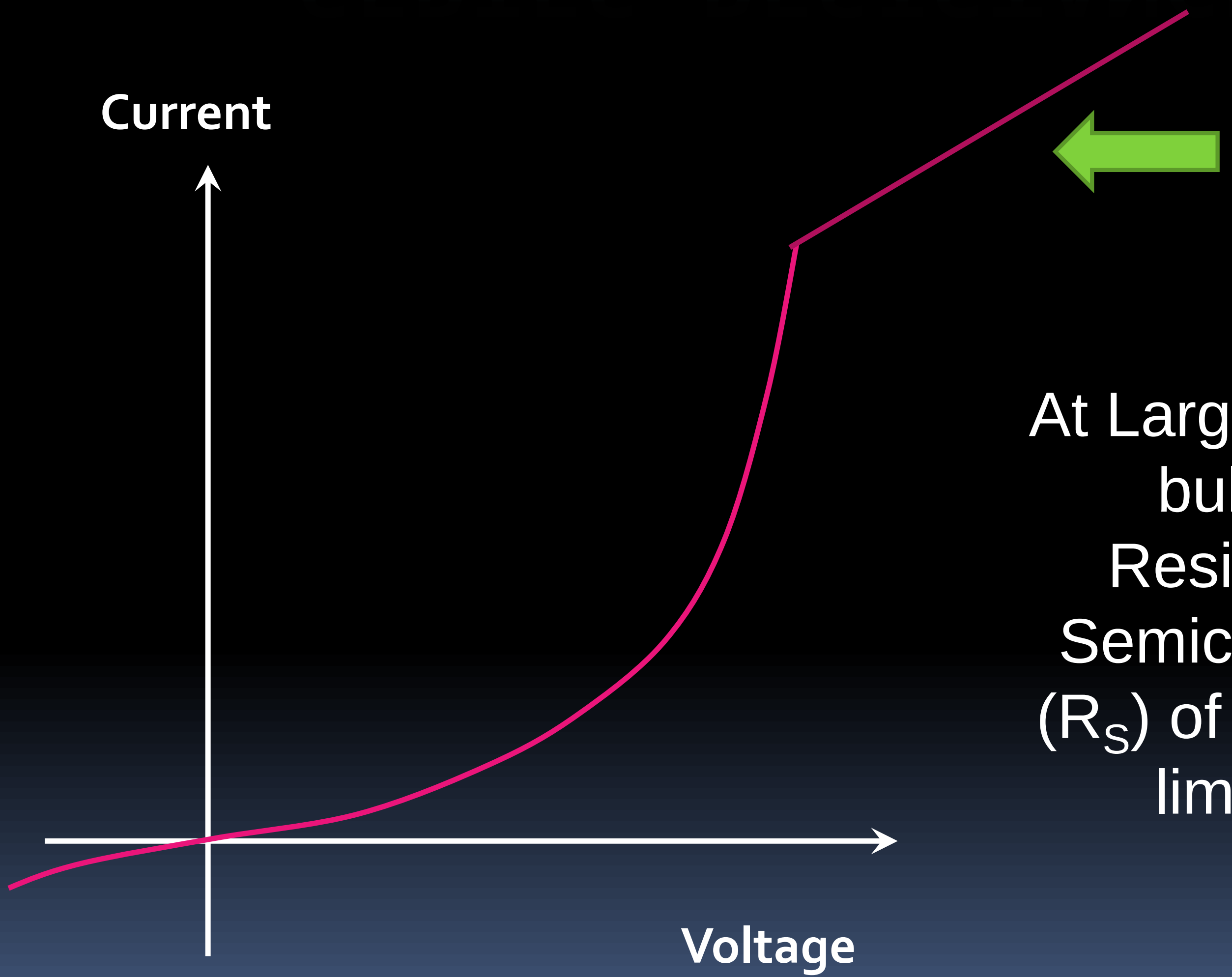
If V = V_B at all ?

Will the current become arbitrarily large at large forward bias ?



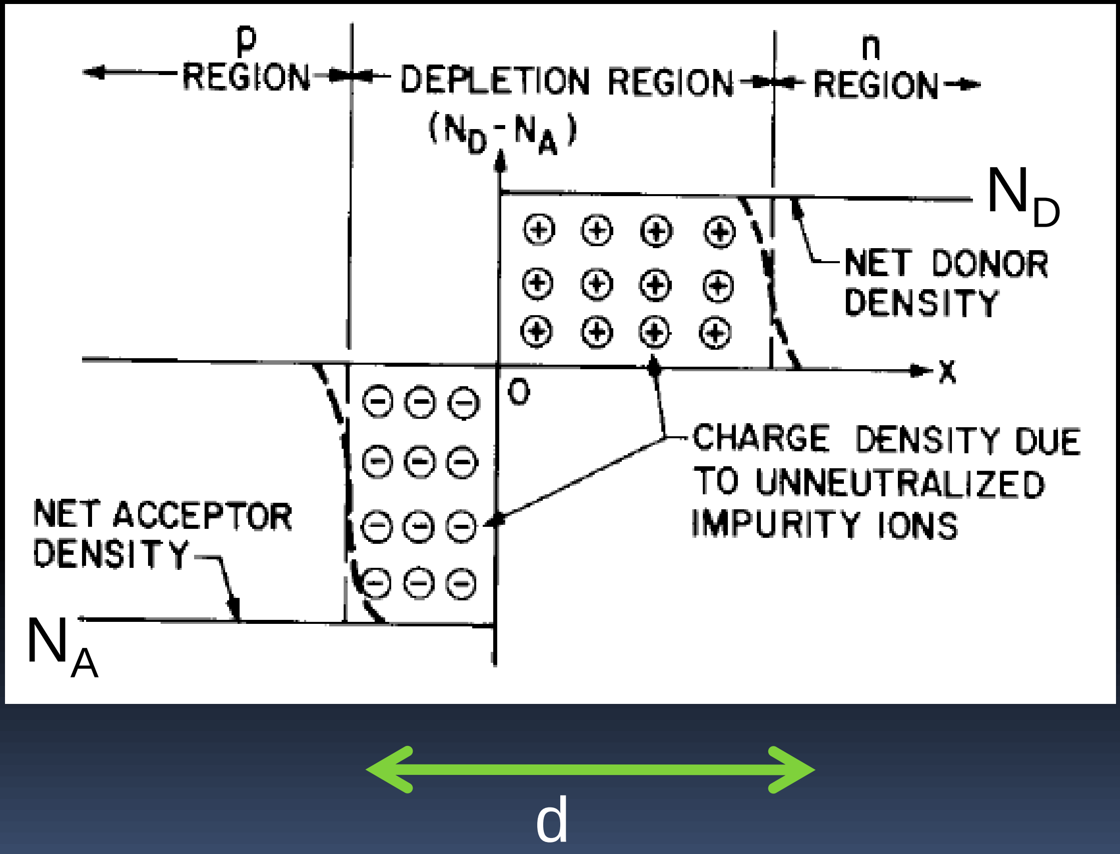
$$I_0(e^{qV/kT} - 1)$$

LARGE FORWARD BIAS & SERIES RESISTANCE (R_S)



At Large Forward Bias the bulk resistance + Resistance of Metal-Semiconductor contacts (R_S) of the semiconductor limits the current.

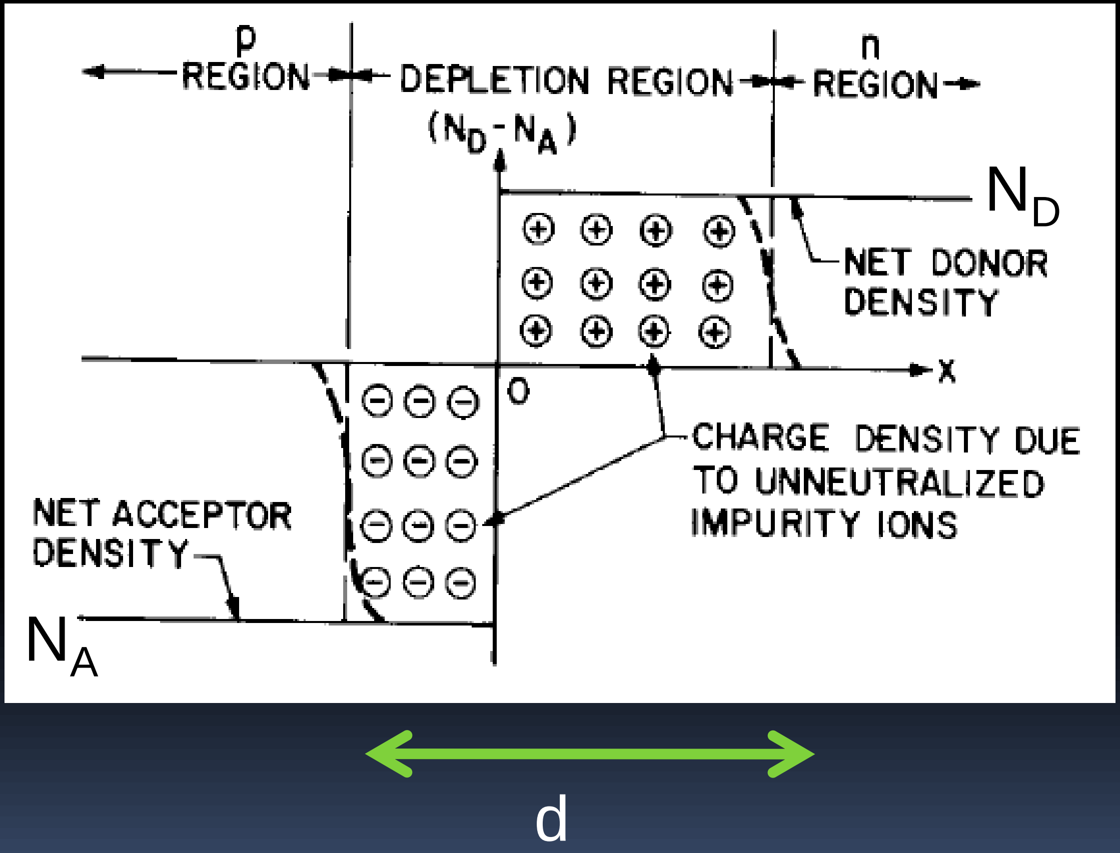
STATIC DEPLETION REGION :CHARGED IONS & NO FREE CARRIERS



No Applied Bias (V=0)

Fig 3.1, Milman & Halkias, Integrated Electronics

DEPLETION (JUNCTION) CAPACITANCE



$$C_J = \frac{\varepsilon\varepsilon_0 A}{d}$$

Capacitance : The Space Charge or the depletion region stores charge

Fig 3.1, Milman & Halkias, Integrated Electronics

DEPLETION CAPACITANCE

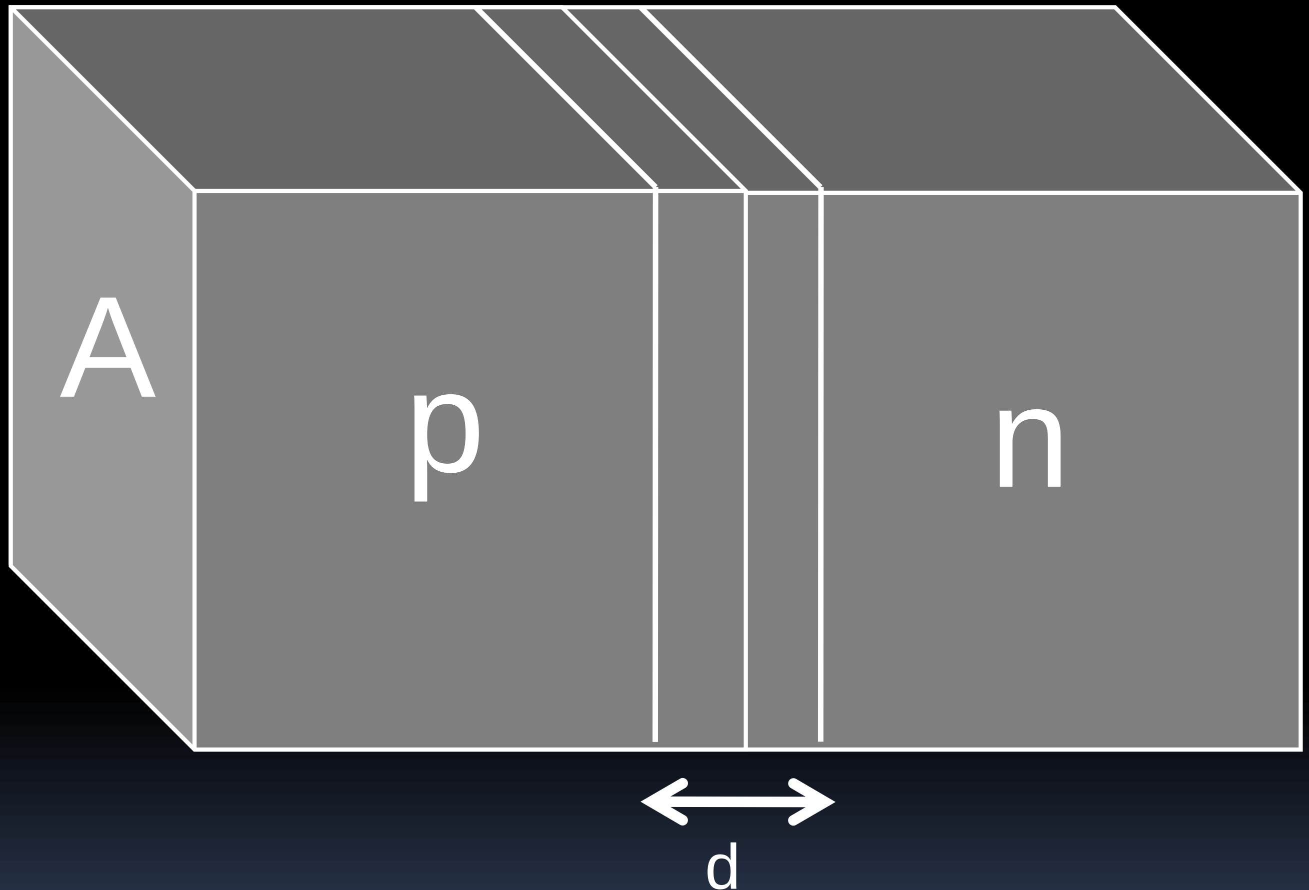


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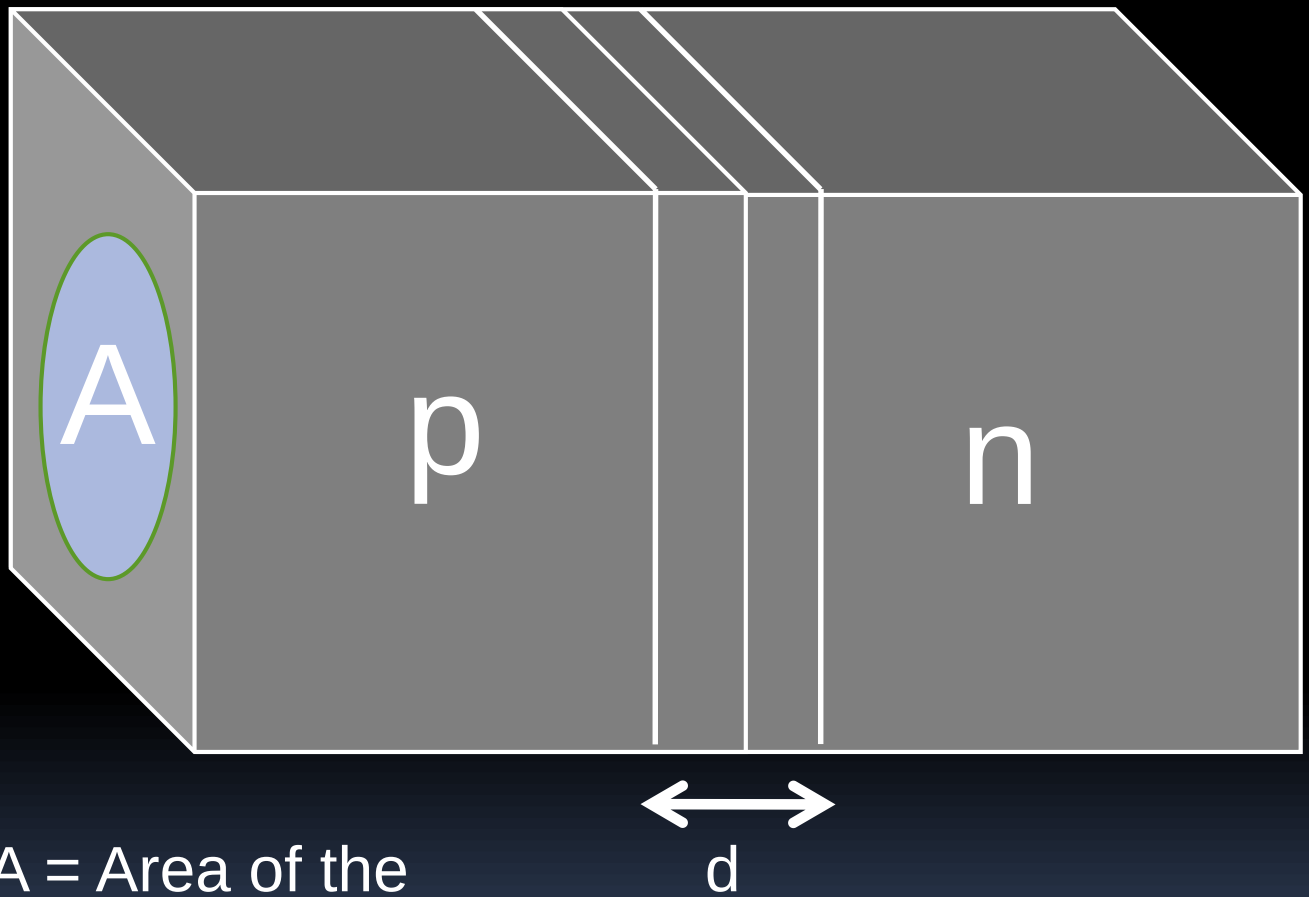
Fig 3.1, Milman & Halkias, Integrated Electronics

DEPLETION CAPACITANCE



$$C_J = \frac{\varepsilon\varepsilon_0 A}{d}$$

A = Area of the Metal Dot

C is not constant, it depends upon applied voltage, therefore it is defined as dQ/dV.

Fig 3.1, Milman & Halkias, Integrated Electronics

DEPLETION CAPACITANCE

$$C_J = \frac{dQ}{dV} = \frac{\varepsilon\varepsilon_0 A}{d}$$

$$C_J = \frac{1}{\sqrt{V_B - V}}$$

C is not constant, it depends upon applied voltage, therefore it is defined as dQ/dV.

Fig 3.1, Milman & Halkias, Integrated Electronics

DEPLETION CAPACITANCE UNDER FORWARD BIAS

Under Forward bias the capacitance is larger than the static value

The width (d) of the depletion region decrease under forward bias

$$C_J = \frac{\varepsilon \varepsilon_0 A}{d}$$

DEPLETION CAPACITANCE UNDER REVERSE BIAS

Under Reverse bias the width (d) of the depletion region increase

Under Reverse bias the capacitance is much smaller than the unbiased static value

$$C_J = \frac{\varepsilon \varepsilon_0 A}{d}$$

DIFFIUSION (DYNAMIC) CAPACITANCE UNDER FORWARD BIAS

Under Forward bias the capacitance is much larger (million times !) than the static Depletion Capacitance

Additional Contribution from he accumulation of injected minority carriers near the junction

In case of Reverse Bias C_d is negligible compared to depletion capacitance.

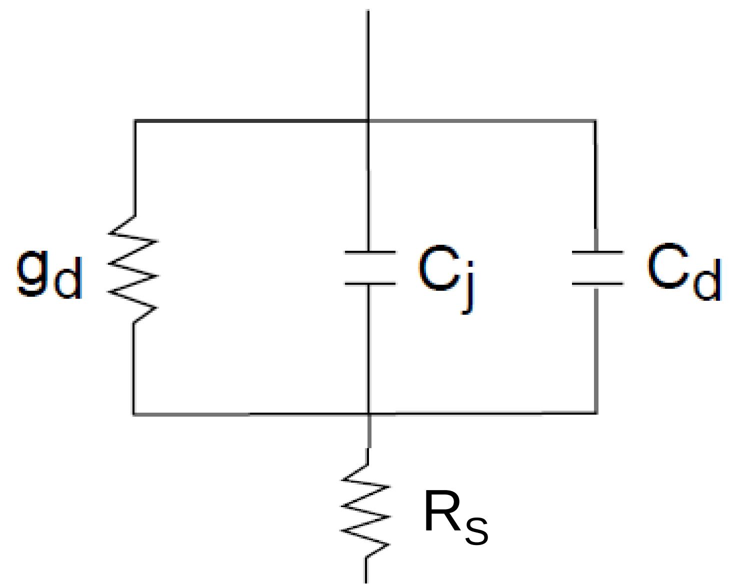
$$C_d \approx e^{\frac{qV}{\eta k_B T}} \approx I$$

C_d ($\sim 1/\omega^{1/2}$) is appreciable at Low Frequencies under forward bias.

Milman & Halkias, Integrated Electronics

EQUIVALENT CIRCUIT OF A P-N JUNCTION DIODE

Complete small-signal equivalent circuit model for diode:



SUMMARY

- FORMATION OF P-N JUNCTION DIODE.

- BUILT-IN-POTENTIAL V_B CAN NOT BE MEASURED WITH A VOLTMETER CONNECTED ACROSS DIODE TERMINALS.

- REVERSE & FORWARD BIAS.

- CAPACITANCE OF A P-N DIODE.

- EQUIVALENT CIRCUIT OF A P-N DIODE.