*Spring 2019 Purdue University*

# ECE 255: L5

# The PN Junction

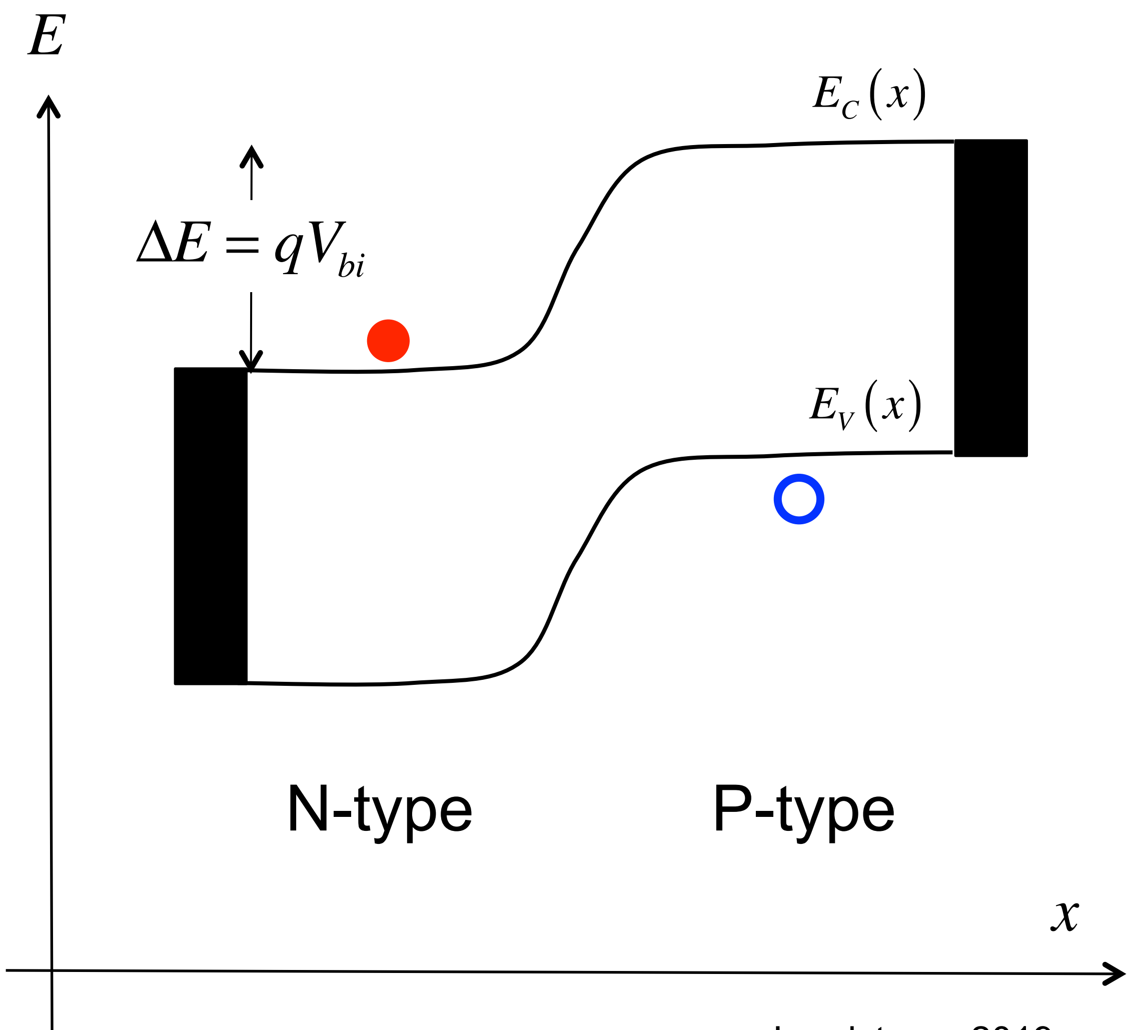
(Sedra and Smith, 7th Ed., Secs. 3.4-3.6)

Mark Lundstrom
School of ECE
Purdue University
West Lafayette, IN USA

# The PN junction

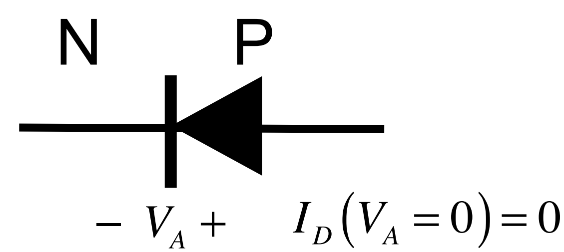
1) Equilibrium
2) IV characteristics
3) Saturation current
4) Capacitance

# NP Junction in equilibrium



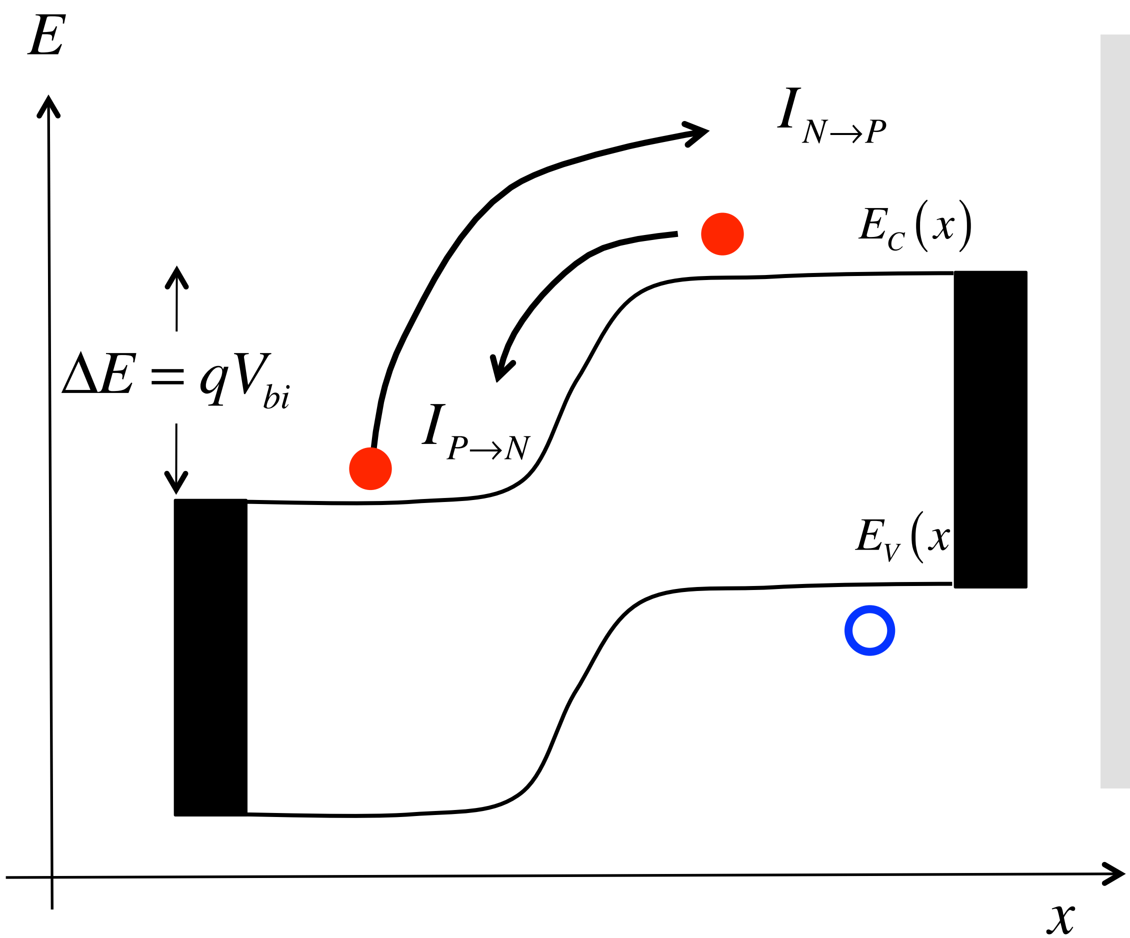

$$V_{bi} = \frac{k_B T}{q} \ln\left(\frac{N_A N_D}{n_i^2}\right)$$

$$V_{bi} < E_G/q$$




circuit symbol

# Current components in equilibrium




$$I_D(V_A) = I_{N\to P}(V_A) - I_{P\to N}$$

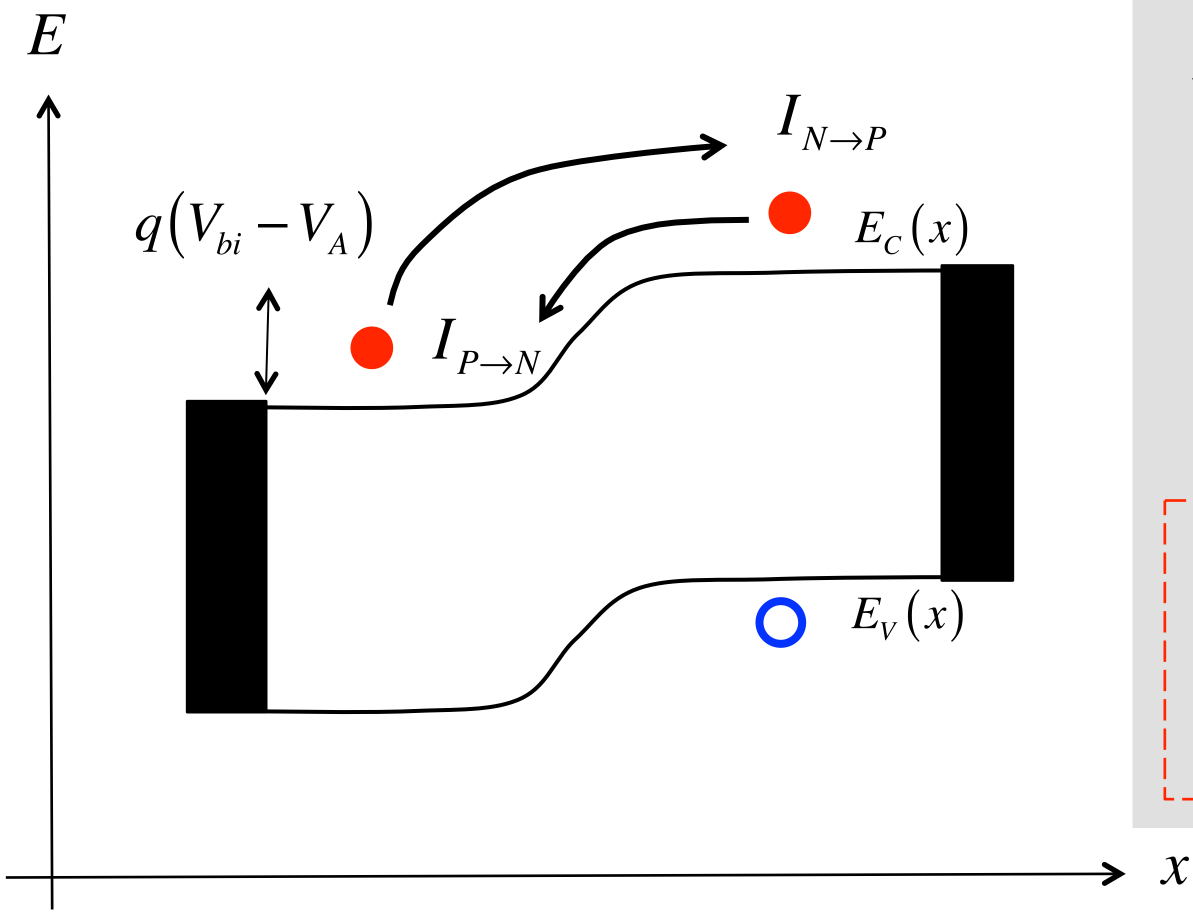
In equilibrium:

$$I_D(V_A = 0) = 0$$

$$I_{N\to P}(V_A = 0) = I_{P\to N} = I_S$$

$I_S$: saturation current

# NP Junction under forward bias



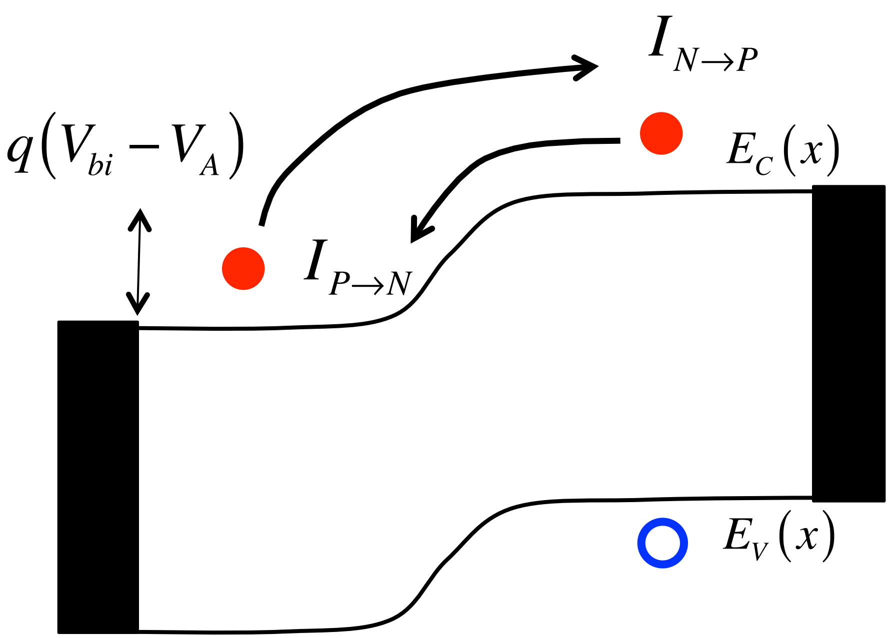

$$I_{N\to P} \propto e^{-\Delta E/k_BT}$$
$$= e^{-q(V_{bi}-V_A)/k_BT}$$
$$\propto e^{qV_A/k_BT}$$

$$I_{N\to P}(V_A) = I_{N\to P}(V_A = 0)e^{qV_A/k_BT}$$

$$I_{N\to P}(V_A) = I_S e^{qV_A/k_BT}$$

$$I_{P\to N} = I_S$$

# Forward biased current (electrons)



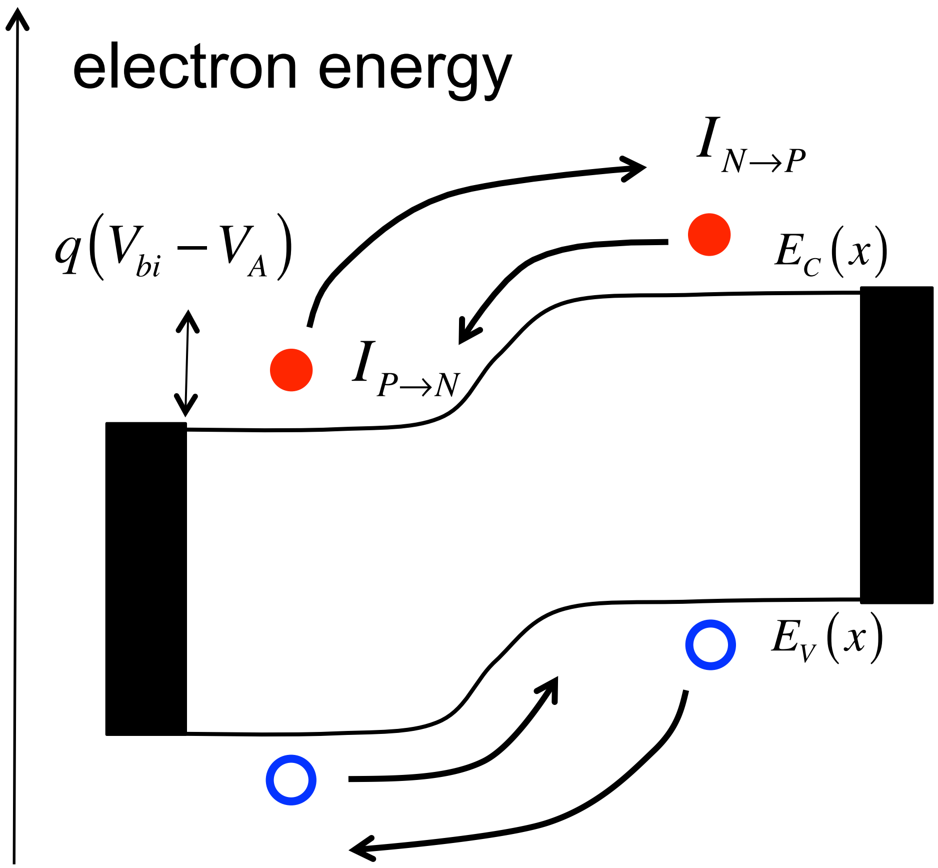

$$I_D = I_{N \to P} - I_{P \to N}$$

$$I_{N \to P} = I_S e^{qV_A/k_BT}$$

$$I_{P \to N} = I_S$$

$$I_D = I_S\left(e^{qV_A/k_BT} - 1\right)$$

# Forward biased current (electrons **and holes**)




$$I_D=\left(I^n_{N\to P}-I^n_{P\to N}\right)+I^p_{P\to N}-I^p_{N\to p}$$

$$I^n_{N\to P}=I^n_S e^{qV_A/k_BT} \qquad I^p_{P\to N}=I^p_S e^{qV_A/k_BT}$$

$$I^n_{P\to N}=I^n_S \qquad I^p_{N\to P}=I^p_S$$

$$I_D=I_S\left(e^{qV_A/k_BT}-1\right)$$

$$I_S=I^n_S+I^p_S$$

# Shockley diode equation

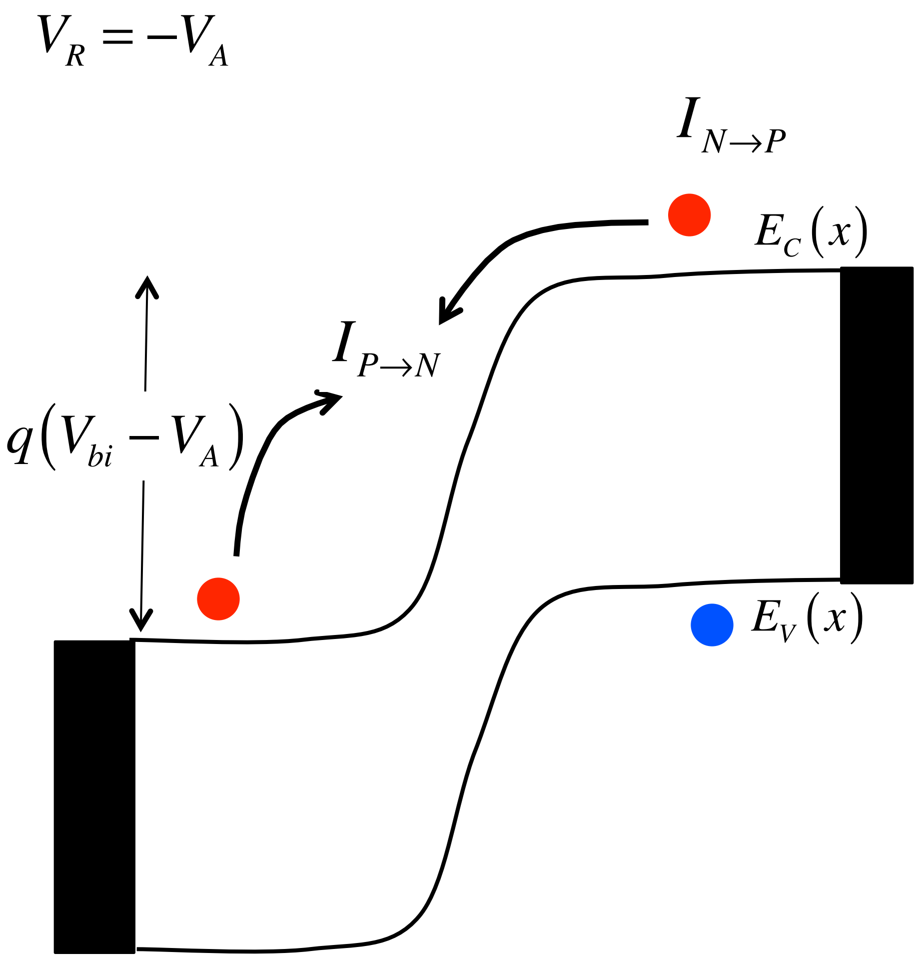
$$I_D = I_S\left(e^{qV_A/k_BT} - 1\right)$$

$$10^{-18} < I_S < 10^{-12}\ \text{A}$$

1) Why does the current increase exponentially with the applied forward bias?

2) Why is the reverse bias current independent of the reverse bias voltage?

# Reverse biased current




$$I_D = I_{N \to P} - I_{P \to N}$$

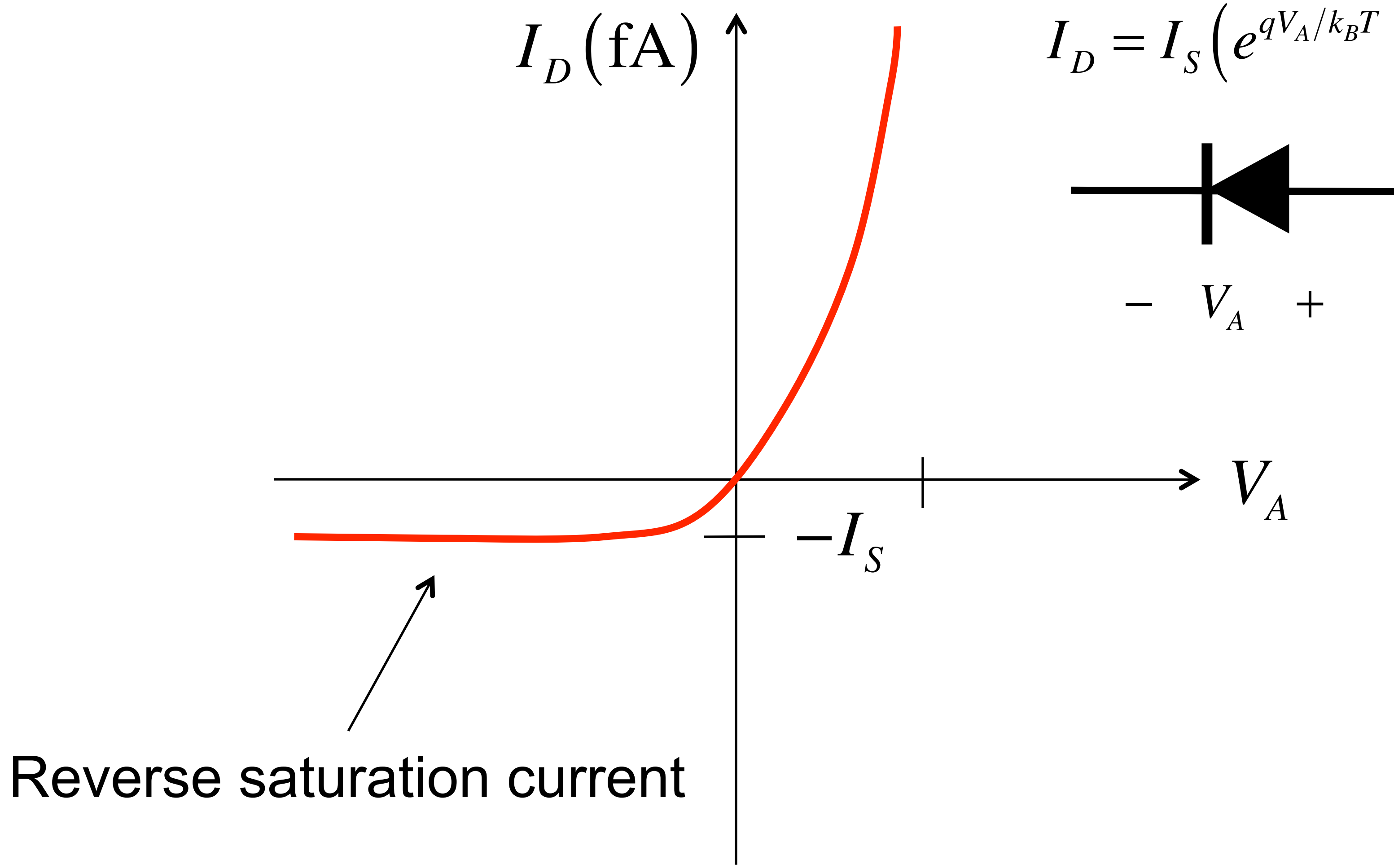
$$I_{N \to P} = I_S e^{qV_A/k_BT} = I_S e^{-qV_R/k_BT}$$

$$I_{N \to P} \approx 0$$

$$I_{P \to N} = I_S$$

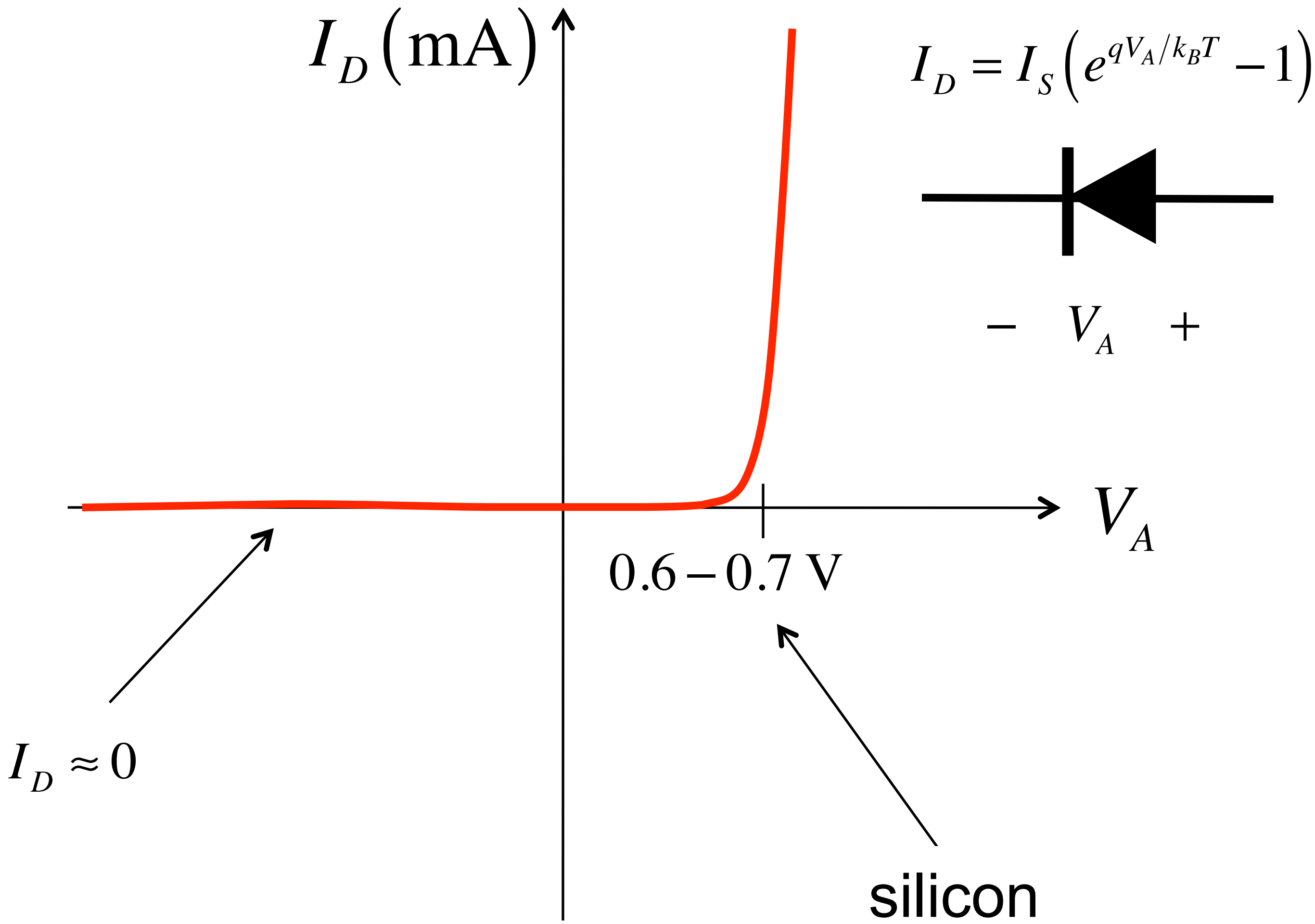
$$I_D = -I_S$$

# Diode IV characteristic

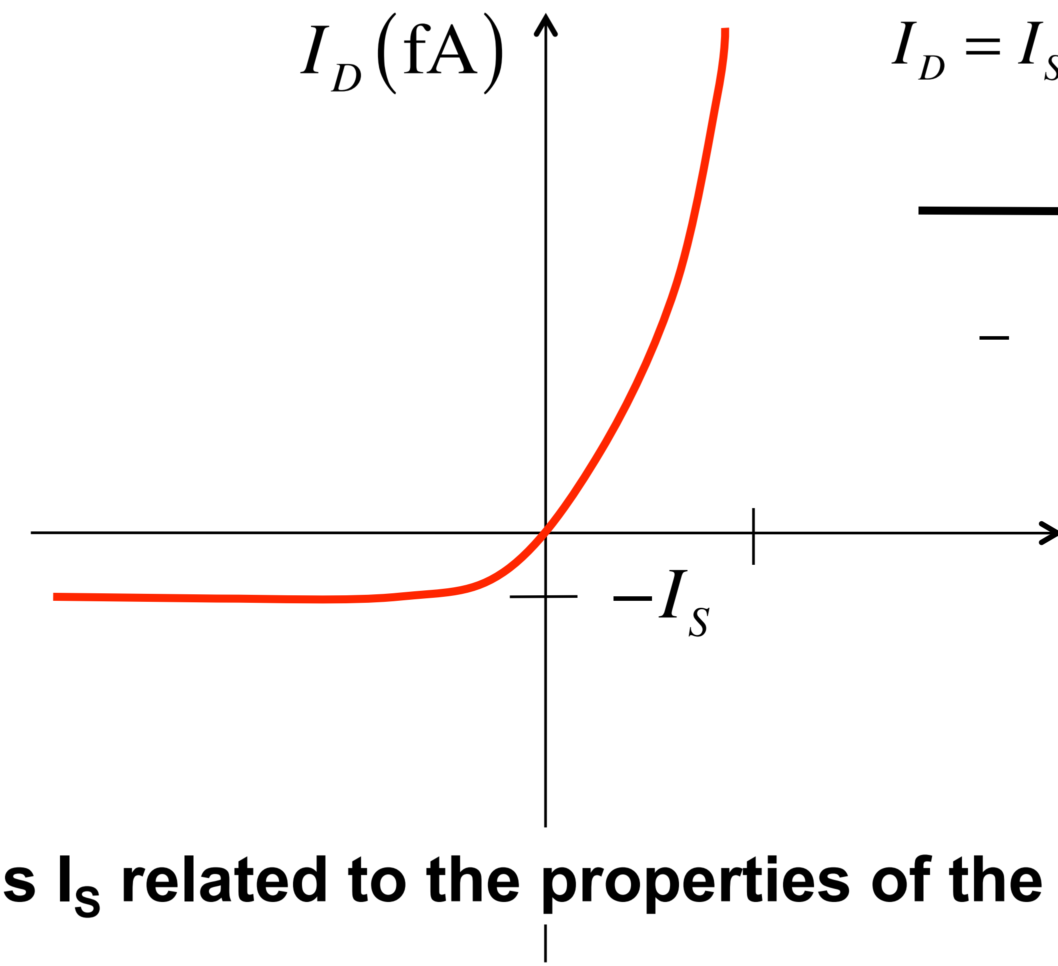



$$I_D = I_S\left(e^{qV_A/k_BT} - 1\right)$$

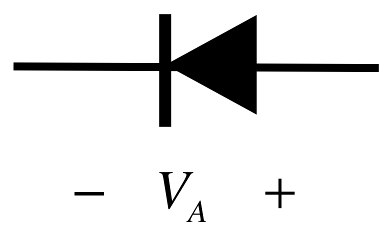
# Diode IV (mA scale)



# Saturation current

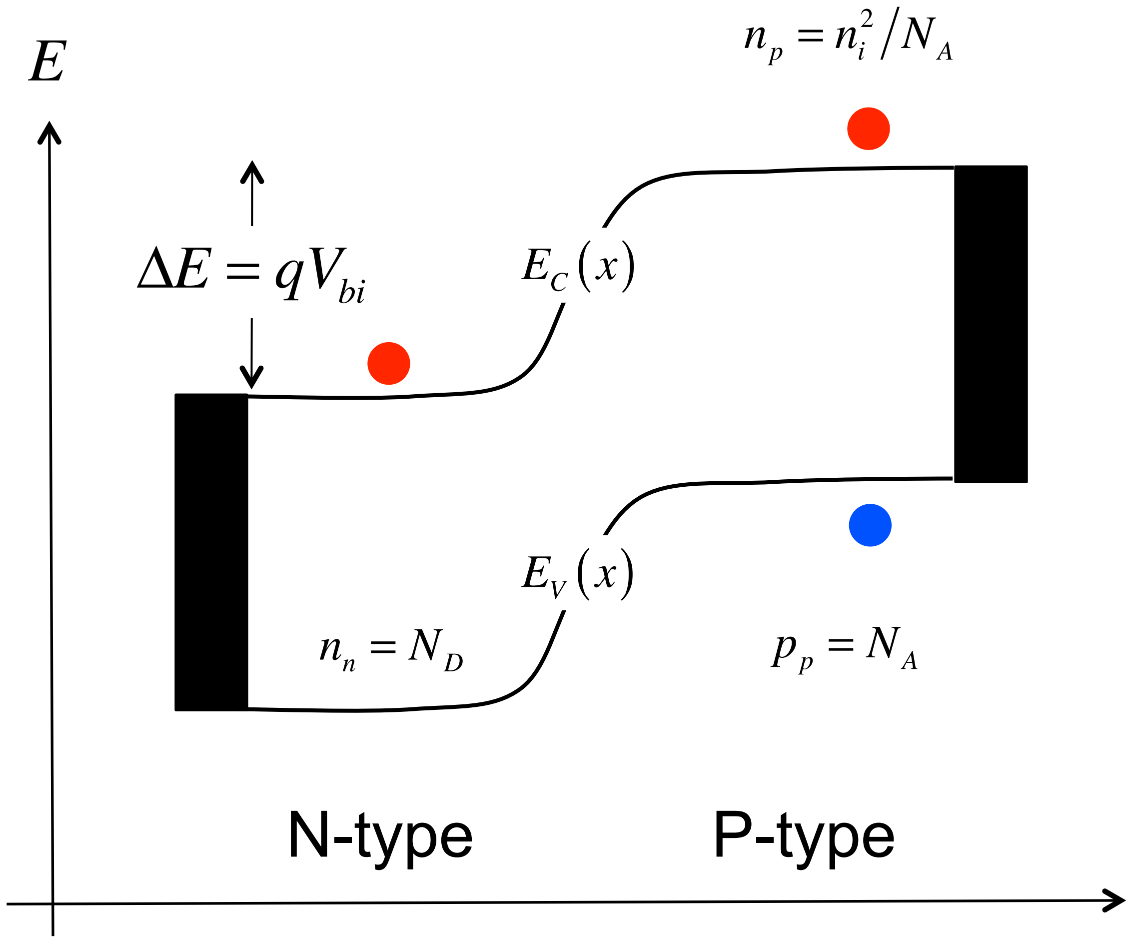



$$I_D = I_S\left(e^{qV_A/k_BT} - 1\right)$$

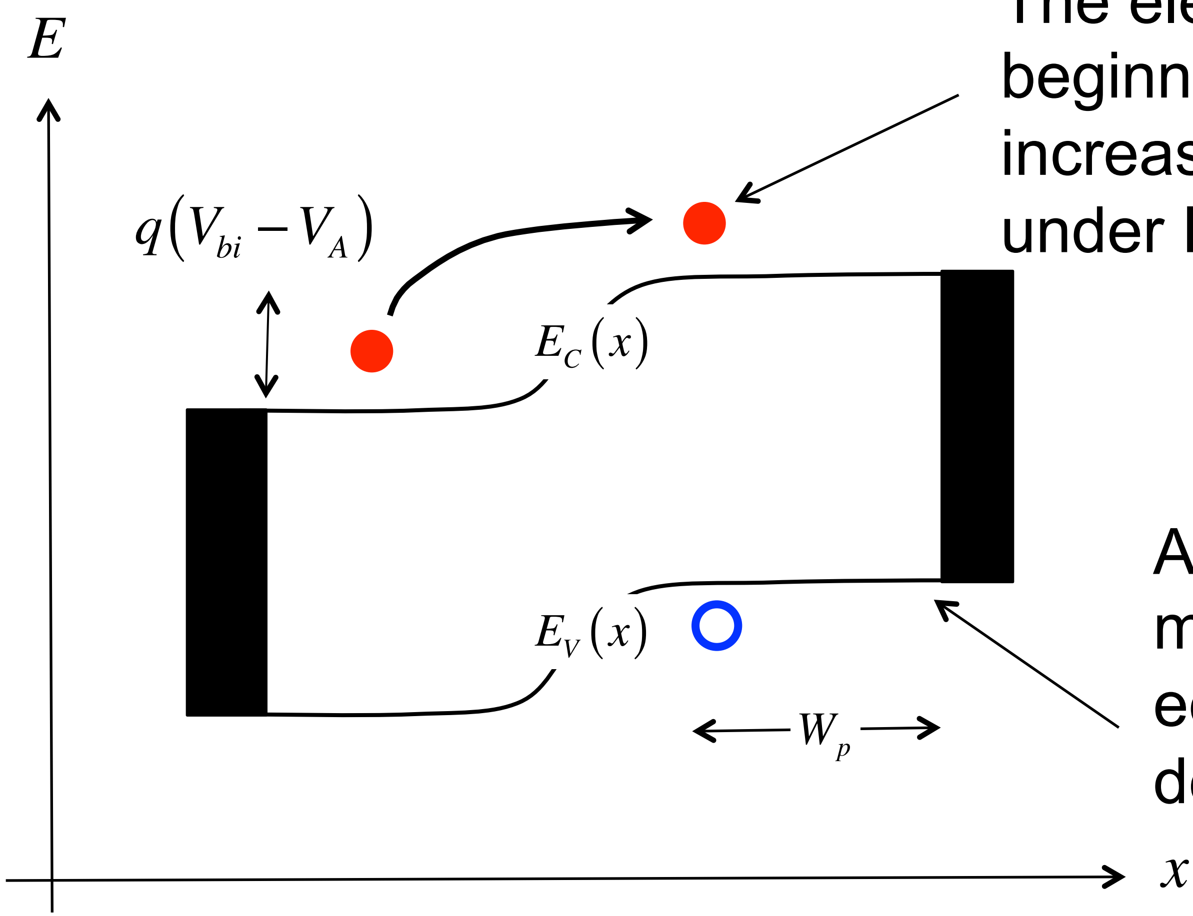



**How is $I_S$ related to the properties of the diode?**

# NP Junction in equilibrium



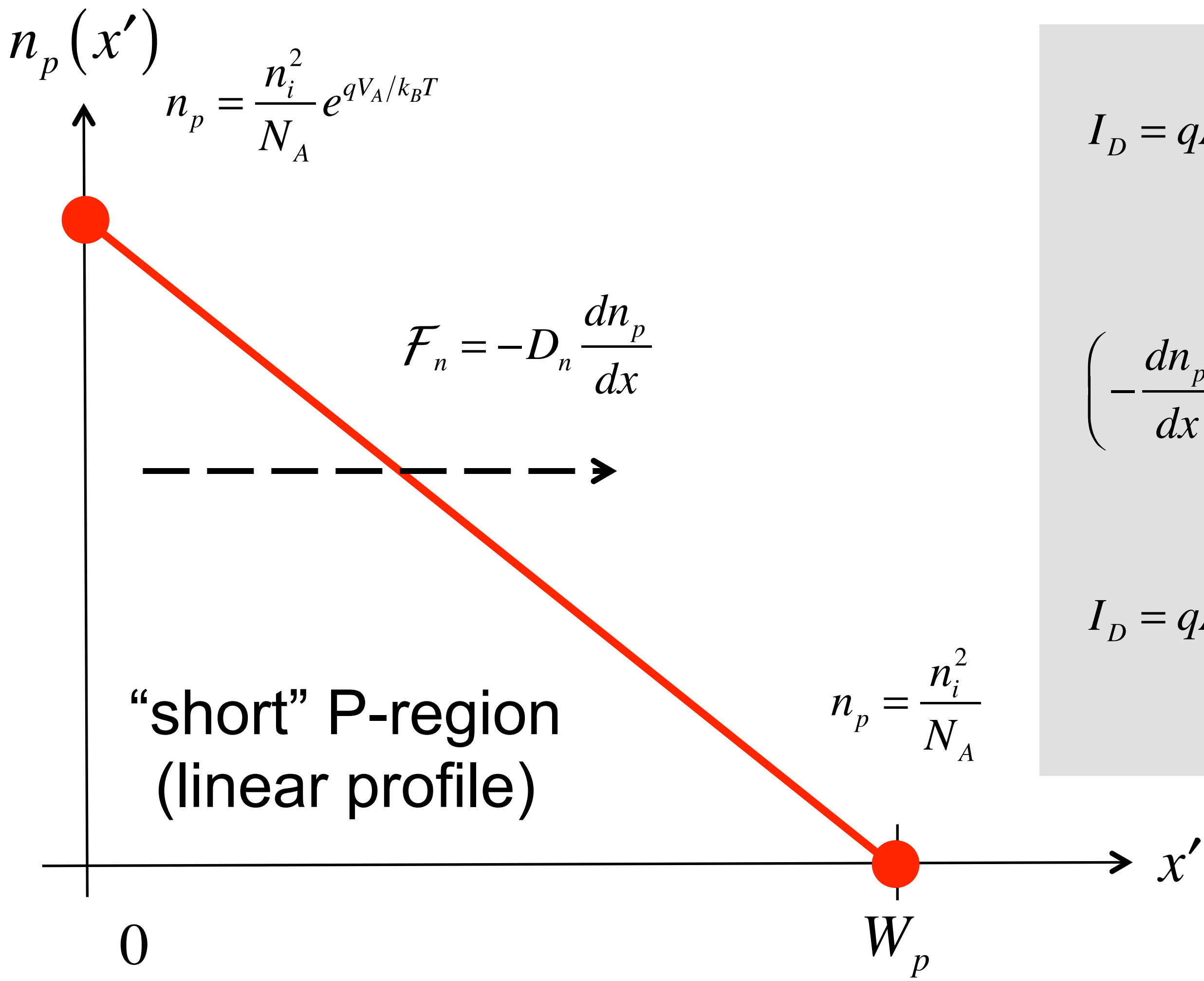
# NP Junction under forward bias




The electron density at the beginning of the P-region increases **exponentially** under FB.

An ideal contact maintains the equilibrium electron density at the contact.

# Neutral P-side only



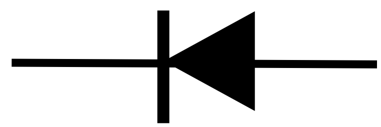

$$I_D = qA\mathcal{F}_n = qAD_n\left(-\frac{dn_p}{dx}\right)$$

$$\left(-\frac{dn_p}{dx}\right) = \frac{\frac{n_i^2}{N_A}e^{qV_A/k_BT} - \frac{n_i^2}{N_A}}{W_p}$$

$$I_D = qA\frac{n_i^2}{N_A}\frac{D_n}{W_p}\left(e^{qV_A/k_BT} - 1\right)$$

# Diode IV characteristic

$$I_D = I_S\left(e^{qV_A/k_BT} - 1\right)$$

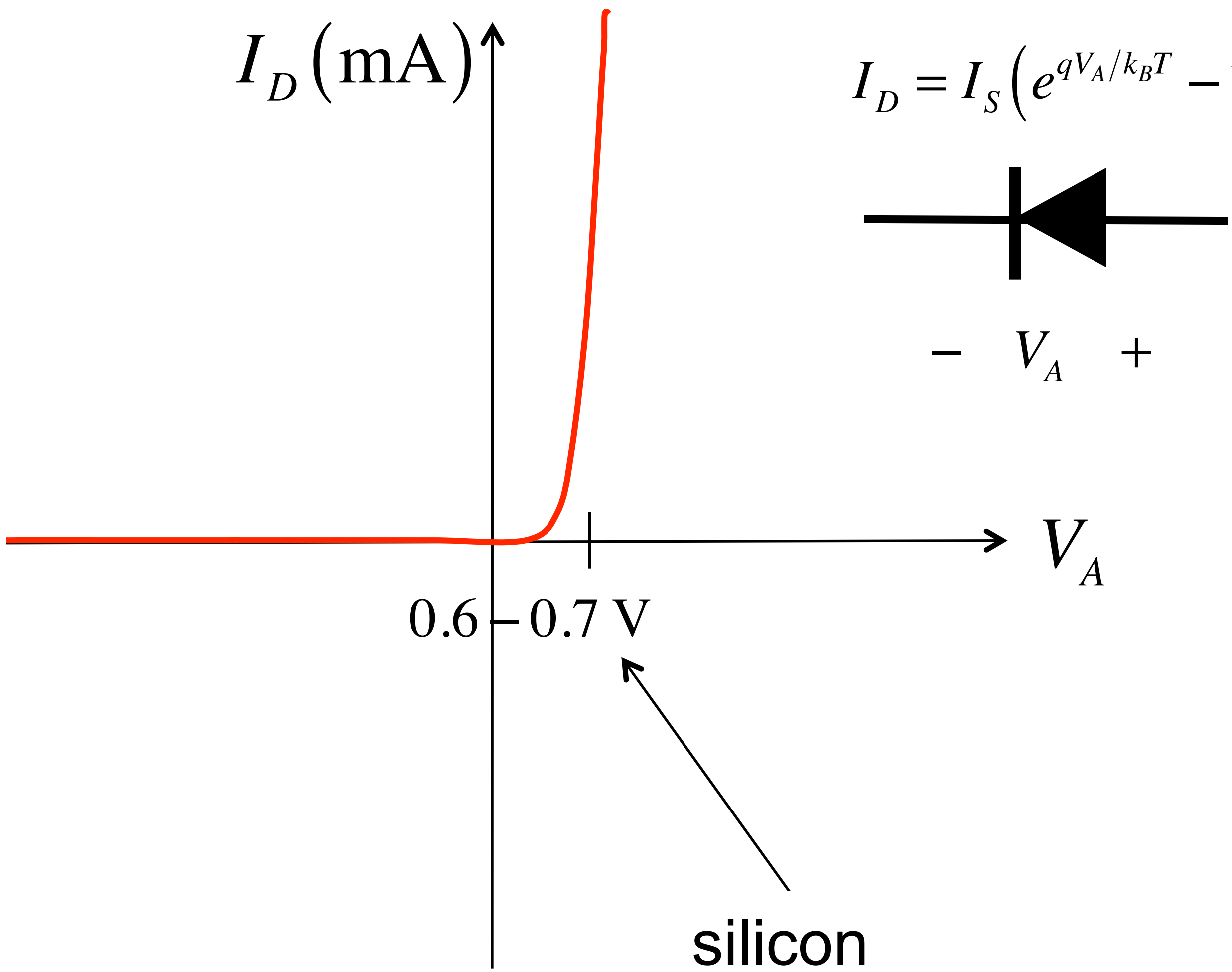


$- \quad V_A \quad +$

$$I_S = qA\left(\frac{n_i^2}{N_A}\frac{D_n}{W_p} + \frac{n_i^2}{N_D}\frac{D_p}{W_n}\right)$$

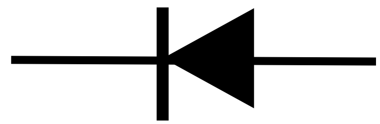
**Note:** $I_S$ is **very sensitive** to temperature.

# Reverse breakdown




$$I_D = I_S\left(e^{qV_A/k_BT} - 1\right)$$

# Time varying voltages and currents



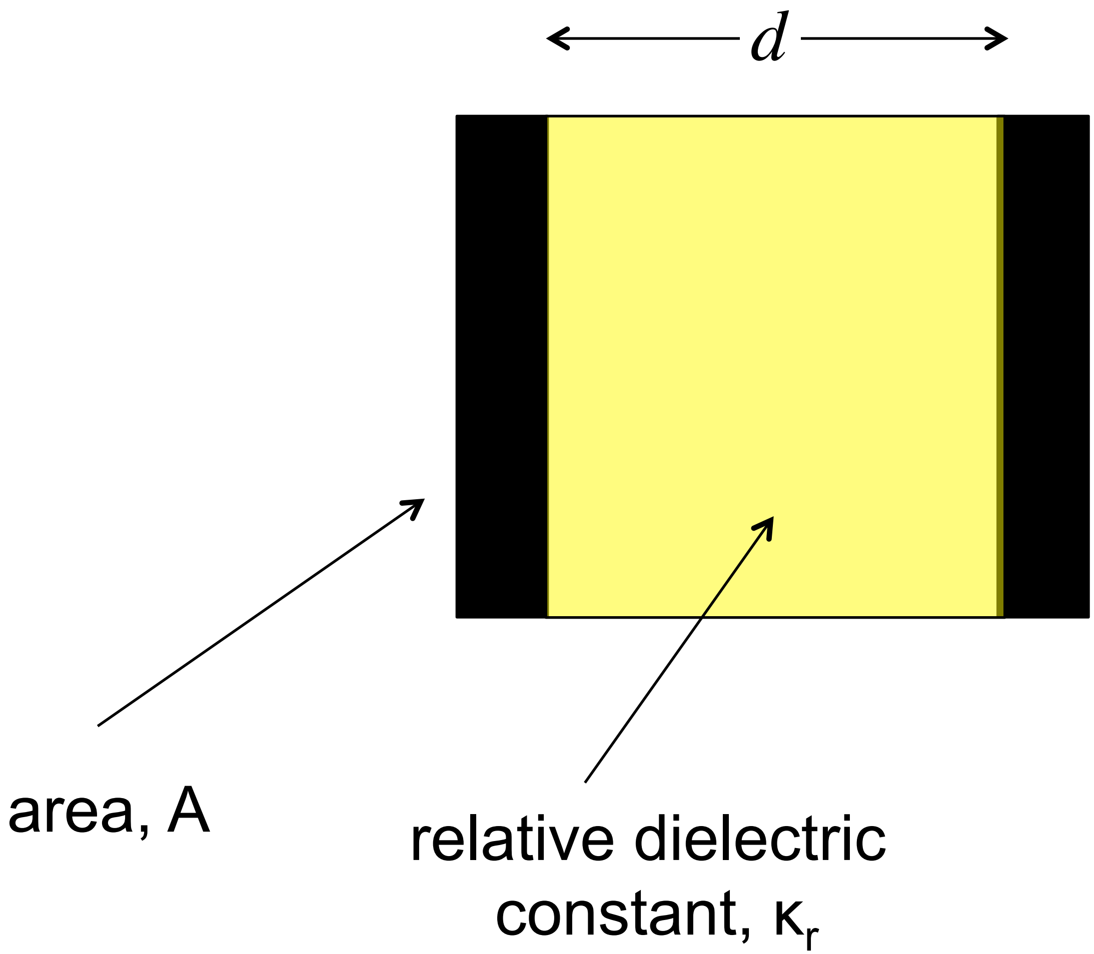
$$- \quad V_A \quad +$$

$$I_D = I_S\left(e^{qV_A/k_BT} - 1\right)$$

(D.C. applied bias and D.C. current.)

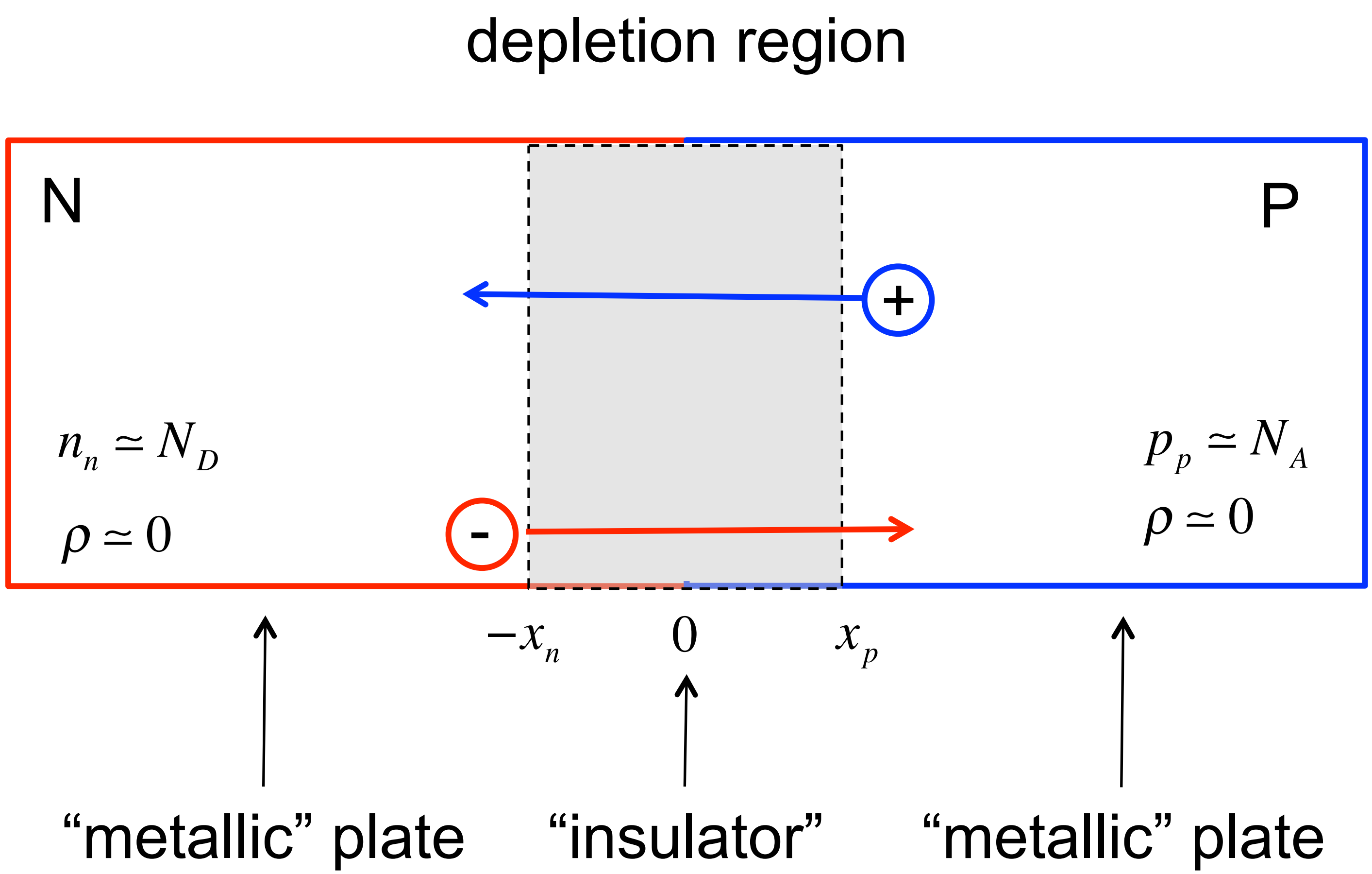
For time varying voltages and currents, we need to consider inductance and **capacitance.**

# Parallel plate capacitor



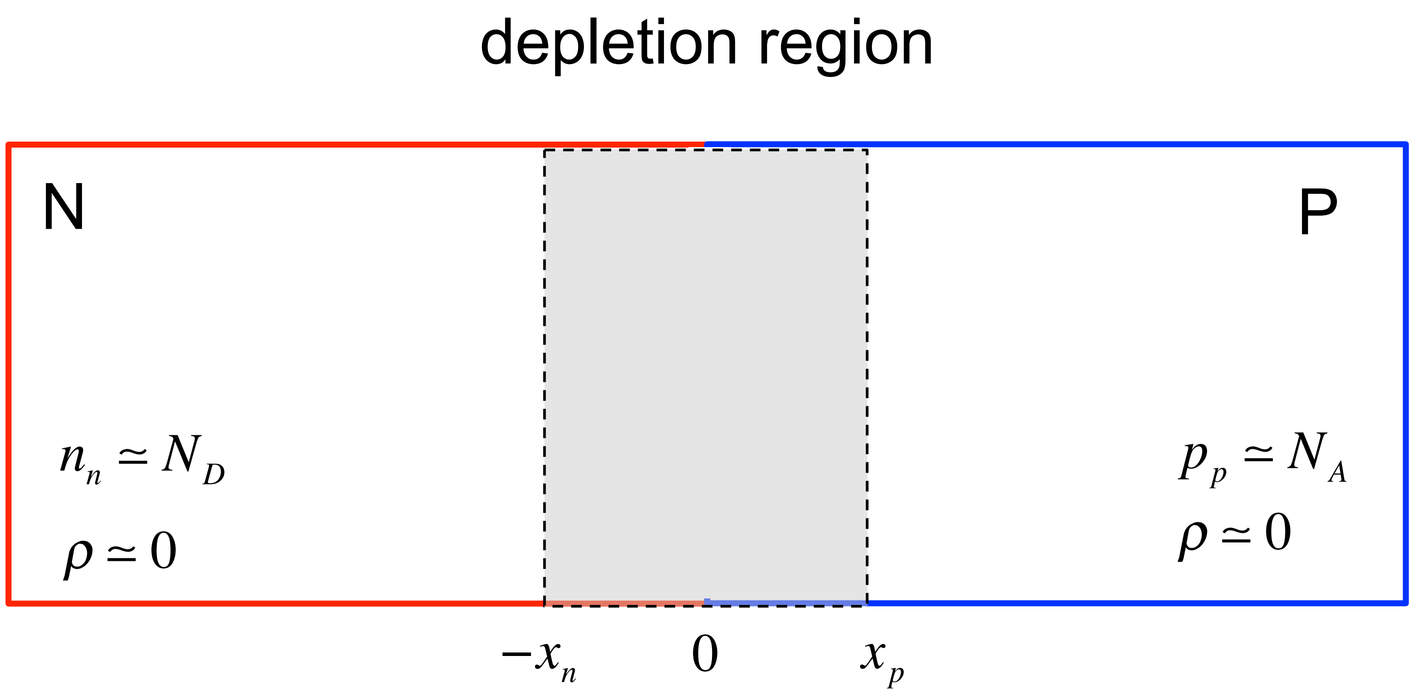

$$C = \frac{\kappa_r \varepsilon_0 A}{d} \quad \text{F}$$

# NP junction



depletion region
N
P
+
-
$n_n \simeq N_D$
$\rho \simeq 0$
$p_p \simeq N_A$
$\rho \simeq 0$
$-x_n$
0
$x_p$
“metallic” plate
“insulator”
“metallic” plate

# Junction capacitance

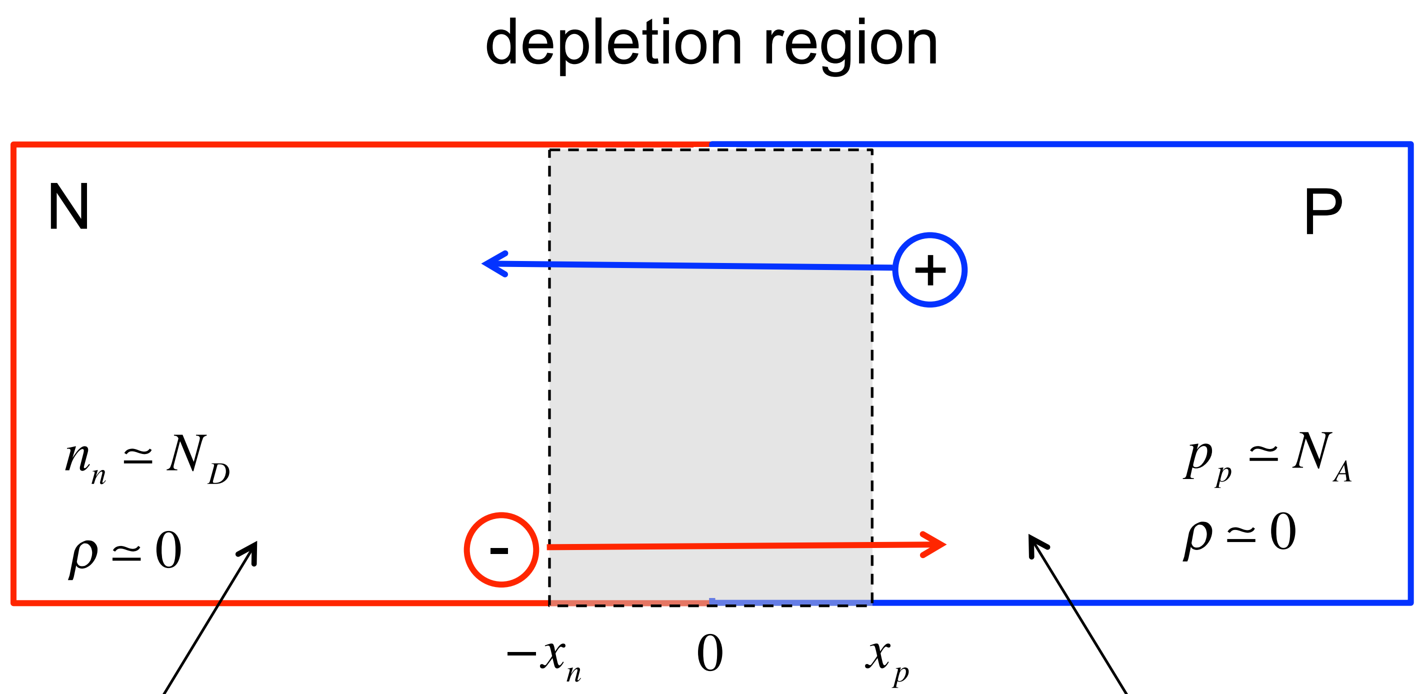



$$C_j = \frac{\kappa_r \varepsilon_0 A}{W(V_A)} \quad \text{F}$$

$$W = x_n + x_p$$

The junction capacitance is voltage dependent.

# Diffusion capacitance




Stored minority hole charge depends exponentially on FB.

Stored minority electron charge depends exponentially on FB.

# Diffusion capacitance (electrons)

$$C \equiv \frac{Q}{V} \qquad C_d \equiv \frac{dQ}{dV}$$

$$Q_n = \frac{1}{2} W_p n_p (x=0)$$

$$I_D = qA \frac{n_i^2}{N_A} \frac{D_n}{W_p} \left( e^{qV_A/k_BT} - 1 \right) \approx qA \frac{n_i^2}{N_A} \frac{D_n}{W_p} e^{qV_A/k_BT}$$

$$Q_n = \frac{1}{2} W_p \left( \frac{n_i^2}{N_A} e^{qV_A/k_BT} \right)$$

$$C_d = \left( \frac{W_p^2}{2D_n} \right) \frac{I_D}{\left(k_BT/q\right)} = t_t \frac{I_D}{\left(k_BT/q\right)}$$

$$C_d = \frac{1}{2\left(k_BT/q\right)} W_p \left( \frac{n_i^2}{N_A} e^{qV_A/k_BT} \right)$$

# Summary

Diode current increases exponentially with voltage in FB.

Diode current saturates at $-I_S$ in RB.

The above two features are readily understood with energy band diagrams.

The saturation current depends strongly on temperature.

The diode capacitances (junction and diffusion) become important for time-varying voltages and currents.

# The PN junction

1) Equilibrium
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