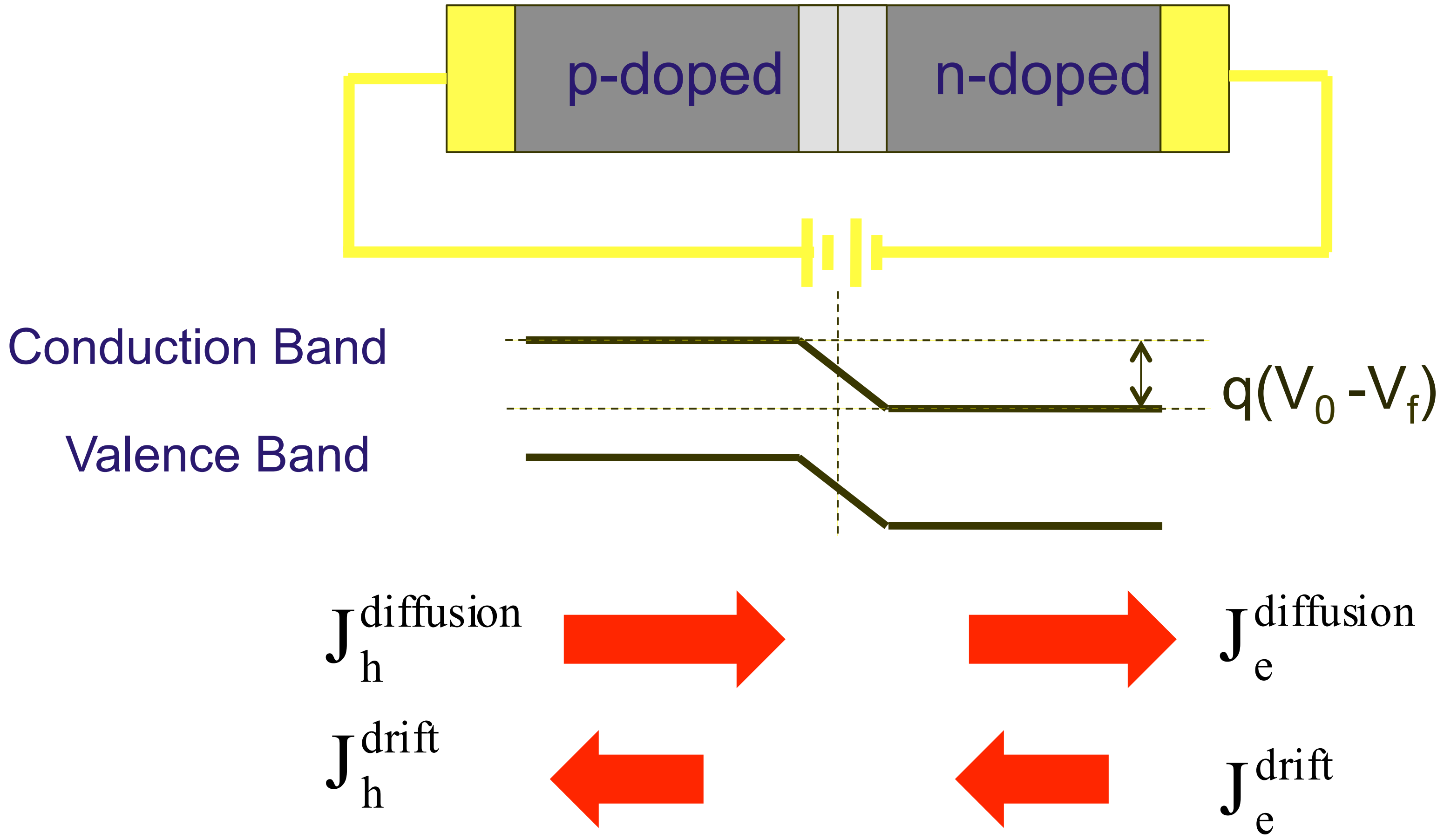
# Lecture 12

- Forward Bias in p-n Junction – Qualitative
- Quantitative - derivation
- Diode equation

# Forward Bias, $V_f$



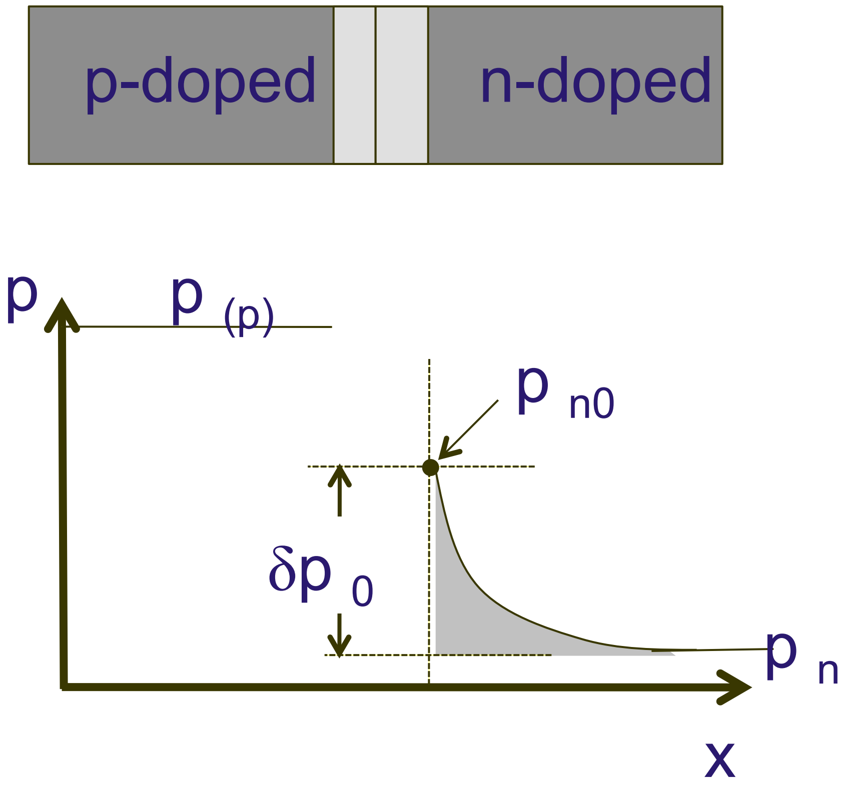
# Forward Bias, $V_f$

- Applied voltage changes the potential barrier and thus ***E***-field within junction region – since we have forward bias the potential barrier is reduced
- The electric field in the transition region reduces
- This reduces the transition region width (need fewer “exposed” ionized dopants to achieve this lower ***E***-field
- Diffusion Current – potential barrier smaller – so increased diffusion current
- Drift Current – essentially same as zero bias - very few minority carriers to contribute to drift–so very small

# Our Job Today…..

- Calculate diffusion current of carriers (electrons into p-doped, holes into n-type) at fixed bias
- Recall discussion on steady state injection of one (minority) carrier
- We will calculate current as a function of applied voltage
- We will calculate charge injected per unit time by electrons and holes - work on one charge carrier type and modify equations for other carrier

# Consider Hole Diffusion



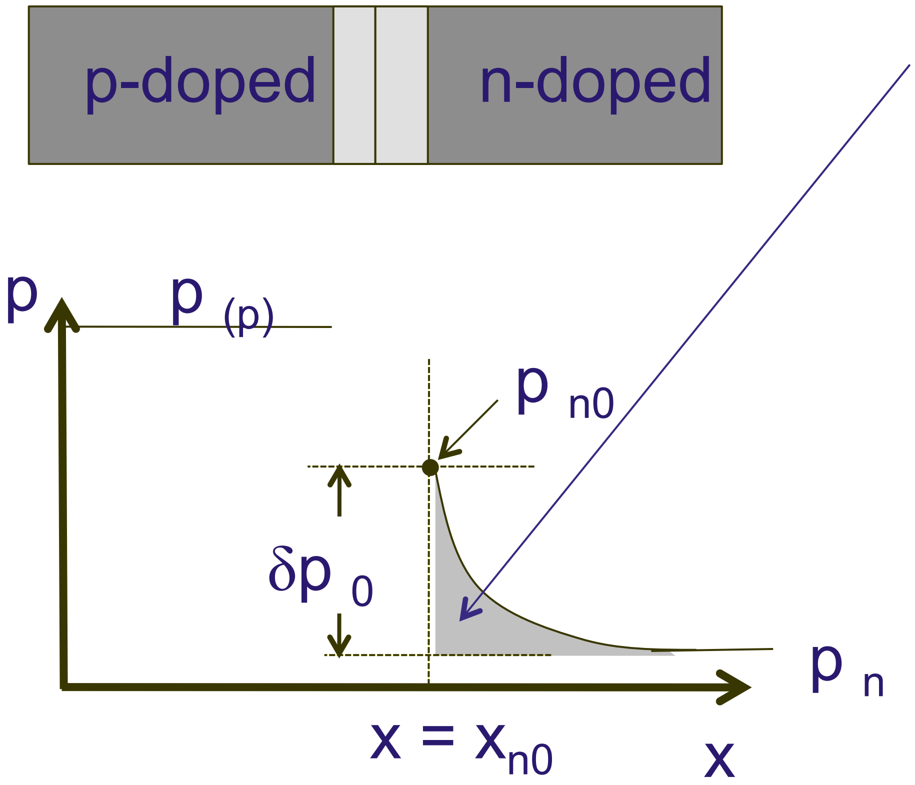

$$p_{n0} = p_n + \delta p_0$$

- Holes diffusing over barrier become excess minority carriers where they diffuse away from junction and recombine with majority electrons

- If bias is maintained we will achieve a continuous injection of minority holes (considered before) which will sustain an exponentially decreasing excess minority hole concentration

- Similar story for electron diffusion

# Calculate $I\ (V_f)$




$p_{n0} = p_n + \delta p_0$

- Need to calculate area under this curve to get the charge $Q_p$
- The diffused (excess minority) hole concentration is a function of hole concentration in p-type
- We will use minority carrier lifetime as it will describe characteristic diffusion length
- Do this for holes and electrons and add together

# Calculating $\delta p_0$

Recall Equation for built-in potential (NOTE: zero applied bias case)

$$V_0 = \frac{k_B T}{e} ln\left(\frac{p_p}{p_n}\right) \Rightarrow p_n = p_p exp\left[\frac{-eV_0}{k_B T}\right]$$

Modifying to include the applied forward bias, $V_f$, we get this in terms of $p_{n0}$, the minority carrier density at $x = x_{n0}$.

$$p_{n0} = p_p exp\left[\frac{-e(V_0 - V_f)}{k_B T}\right]$$

Note $p_{n0} > p_n$ due to bias forward bias $V_f$, The University Of Sheffield.

# Continued



$p_{n0}=p_n+\delta p_0$ so $\delta p_0 = p_{n0} - p_n$

We have seen both of these previously, so:

Using $$p_n = p_p exp\left[\frac{-eV_0}{k_B T}\right]$$

$$\partial p_0 = p_p \exp\left[\frac{-e\left(V_0 - V_f\right)}{k_B T}\right] - p_p \exp\left[\frac{-eV_0}{k_B T}\right]$$

$$\partial p_0 = p_p \exp\left[\frac{eV_f}{k_B T}\right] \times p_p \exp\left[\frac{-eV_0}{k_B T}\right] - p_p \exp\left[\frac{-eV_0}{k_B T}\right]$$

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# Continued (2)



Giving

$$\partial p_0 = p_n \left[ exp\left[ \frac{eV_f}{k_B T} \right] - 1 \right]$$

And with a similar treatment for electron diffusion

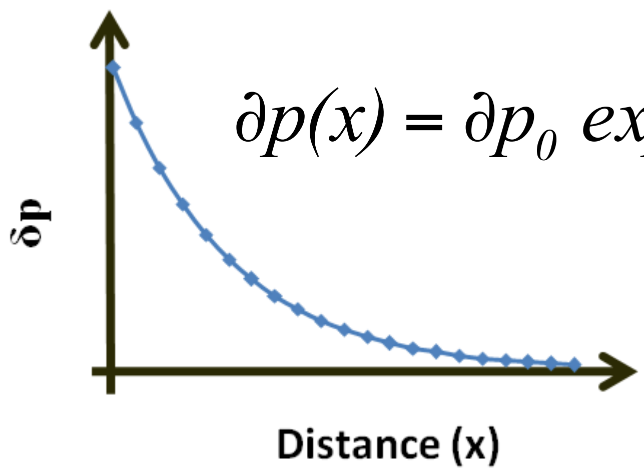
$$\partial n_0 = n_p \left[ exp\left[ \frac{eV_f}{k_B T} \right] - 1 \right]$$

These show that the excess minority carrier concentration injected across the junction increases exponentially with forward bias $V_f$ .

# Continue with Deriving $I\ (V_f)$

We now need to include time and distances

Remembering minority carrier diffusion length – we can relate diffusion distance to minority carrier lifetime




$$\partial p(x) = \partial p_0\ exp\left(-\frac{x}{L_h}\right)$$

$$L_h = \left(D_h \tau_h\right)^{1/2}$$

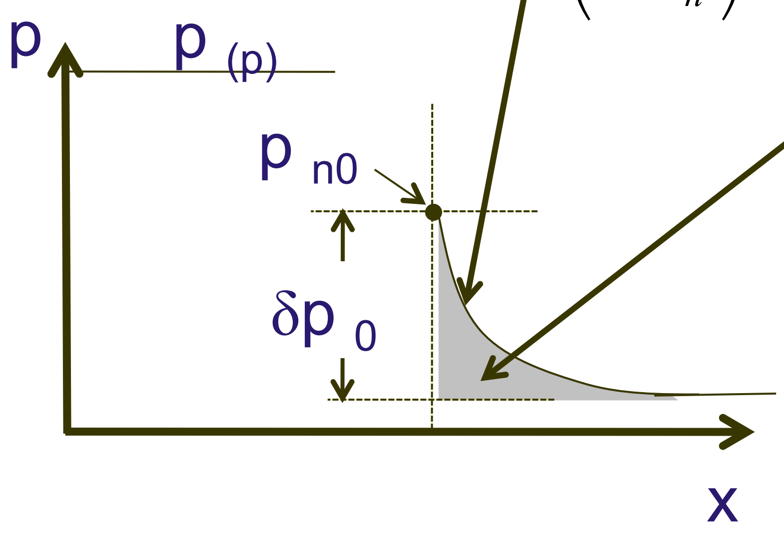
(Minority diffusion length)

The minority carrier distribution is thus known

## From a previous lecture

$$\partial p(x) = \partial p_0 \; exp\left( -\frac{x}{L_h} \right)$$




$p_{n0} = p_n + \delta p_0$

## Injected hole charge

$$Q_p = eA\int_0^{\infty} \delta p(x)\delta x$$

$$Q_p = eA \; \delta p_0 \int_0^{\infty} exp\left( -\frac{x}{L_h} \right) dx$$

$$Q_p = eA\,\delta p_o L_h$$

Similarly for electrons diffusing into the p-type material, charge injected, $Q_e$, is ;

$$Q_e = eA\,\delta n_o L_e$$

# Definite Integral Step

$$Q_p = eA\delta p_0 \int_0^{\infty} exp\left( - \frac{x}{L_h} \right) dx$$

$$Q_p = qA\delta p_0 \left( \left[ -L_h exp\left( - \frac{x}{L_h} \right) \right]_{x=\infty} - \left[ -L_h exp\left( - \frac{x}{L_h} \right) \right]_{x=0} \right)$$

$$\underset{x \longrightarrow -\infty}{Lim} \exp(x) = 0 \qquad \underset{x \longrightarrow 0}{Lim} \exp(x) = 1$$

$$Q_p = eA\delta p_0 L_h$$

# Putting It All Together

Diode current

$$I = I_e + I_h = \boxed{\frac{Q_e}{\tau_e} + \frac{Q_h}{\tau_h}} = \frac{eAL_e\delta n_0}{\tau_e} + \frac{eAL_h\delta p_0}{\tau_h}$$

Assumes excess charge replenished every $\tau_{e,h}$ seconds

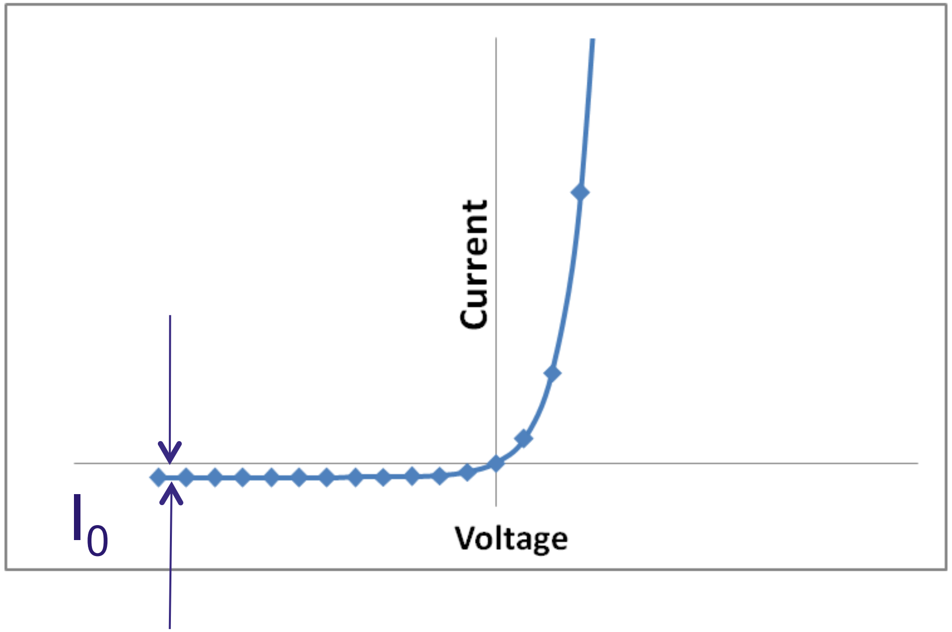
using $\partial p_0 = p_n\left[exp\left[\frac{eV_f}{k_BT}\right] - 1\right]$ and $\partial n_0 = n_p\left[exp\left[\frac{eV_f}{k_BT}\right] - 1\right]$

$$I = \left[\frac{eAL_e n_p}{\tau_e} + \frac{eAL_h p_n}{\tau_h}\right]\left[exp\left(\frac{eV_f}{k_BT}\right) - 1\right]$$

Can be + or - to reflect forward and reverse bias

# Diode Equation

$$I = I_0\left[exp\left(\frac{\boxed{eV}}{k_B T}\right) - 1\right]$$




- Exponential increase in $I$ with $V = V_f$
- For reverse bias $V \rightarrow -V >> k_BT$ (large and negative)

$I \rightarrow I_0$

- $I_0$ is the (reverse) saturation current

In terms of current density, $J$

$$J = J_0\left[exp\left(\frac{eV}{k_B T}\right) - 1\right]$$

# Saturation or Reverse Current

$$I_0 = I_{e0} + I_{h0} = eA\left[\frac{L_e n_p}{\tau_e} + \frac{L_h p_n}{\tau_h}\right]$$

Can be rewritten as $$I_0 = eAn_i^2\left[\frac{D_e}{L_e N_A} + \frac{D_h}{L_h N_D}\right]$$

using $L_h = \left(D_h \tau_h\right)^{1/2}$

$$n_i^{\,2} = p_p n_p = N_A n_p$$

$$n_i^{\,2} = n_n p_n = N_D p_n$$

# Summary

- The p-n junction under zero bias has a built-in potential preventing carrier diffusion
- Under forward bias the built-in potential is reduced, allowing carriers to diffuse more readily
- A continuous diffusion process across the junction is set up under a constant forward bias
- The recombination of diffusing excess minority carriers with majority carriers results in a current flow
- Forward current varies exponentially with applied bias - the diode equation
- Under reverse bias the (reverse or saturation) current is small and constant