EEE105
“Electronic Devices”

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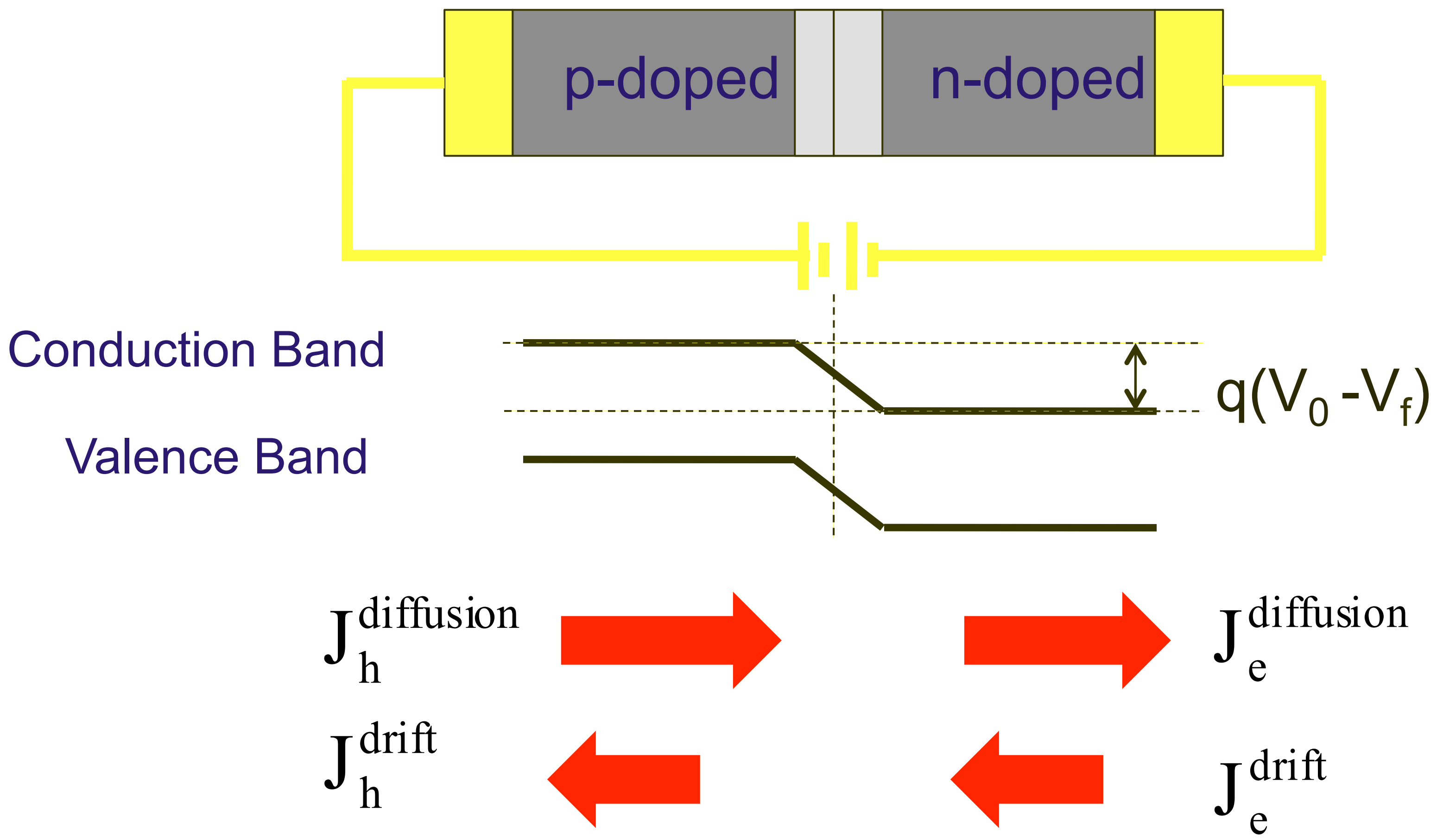
Lecture 14

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

Forward Bias, V_f



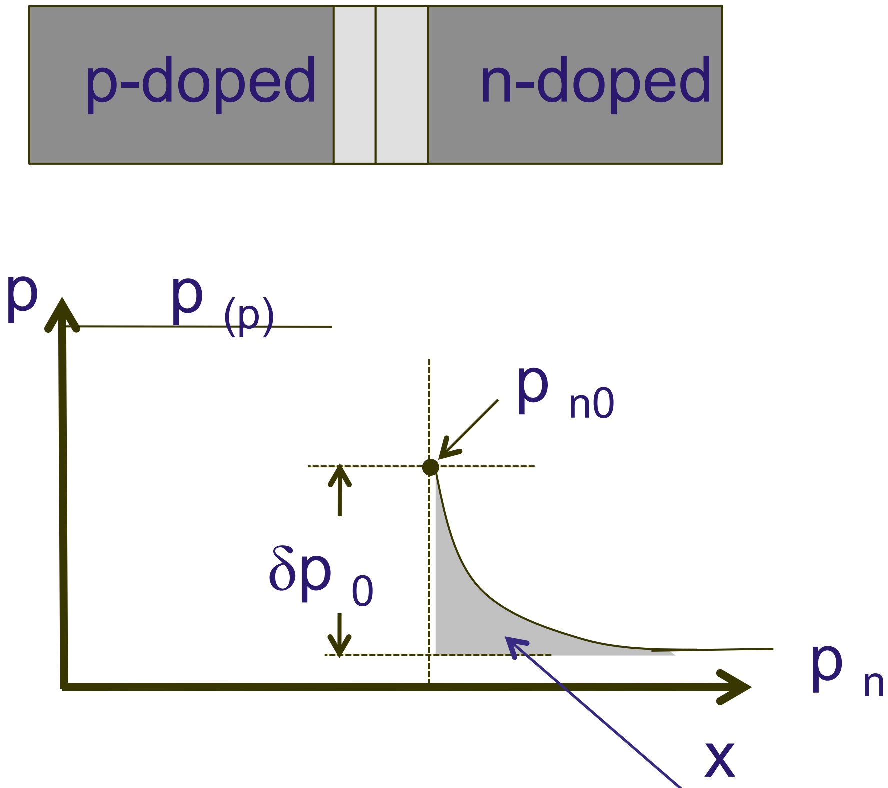
Forward Bias, V_f

- Applied voltage changes the potential barrier and thus E-field within junction region - as 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 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



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

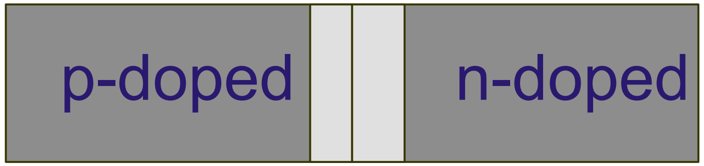
Holes Diffusing over barrier become excess minority carriers where they diffuse away from junction and recombine with majority electrons

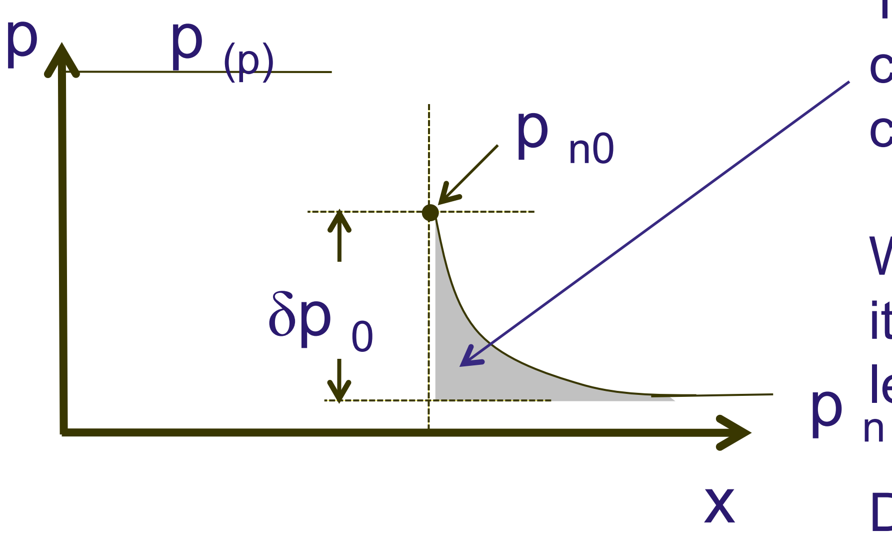
If continually biased we will maintain an exponentially decreasing excess hole (minority carrier) concentration

Similar story for electron diffusion

Current given by amount of charge injected per unit charge – need to calculate area under this curve

Calculate I (V_f)





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

Current given by amount of charge injected per unit charge

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 e.g. δp_0

Recall Equation for built-in potential (n.b. zero applied bias case)

$$V_0 = \frac{k_B T}{q} \ln\left(\frac{p_{(p)}}{p_n}\right) \quad \Rightarrow \quad p_{(p)} = p_n \exp\left[\frac{qV_0}{k_B T}\right]$$

Modifying to include the applied potential we get this in terms of p_{n0}

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

Continued

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

We have both of these from previously, so;

$$\partial p_0 = \frac{p_{(p)}}{\exp\left[\frac{q(V_0 - V_f)}{k_B T}\right]} - \frac{p_{(p)}}{\exp\left[\frac{qV_0}{k_B T}\right]}$$

$$\partial p_0 = \frac{\exp\left[\frac{qV_f}{k_B T}\right] p_{(p)}}{\exp\left[\frac{q(V_0)}{k_B T}\right]} - \frac{p_{(p)}}{\exp\left[\frac{qV_0}{k_B T}\right]}$$

Remember that

$$p_{(p)} = p_n \exp\left[\frac{qV_0}{k_B T}\right]$$

Continued (2)

So

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

And with a similar treatment for electron diffusion

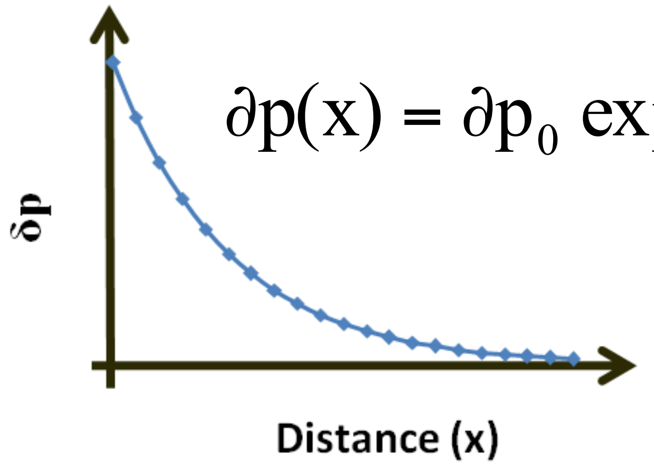
$$\partial n_0 = n_p\left[\exp\left[\frac{qV_f}{k_B T}\right] - 1\right]$$

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

...On with Deriving I (V_f)

We now need to include time and distances

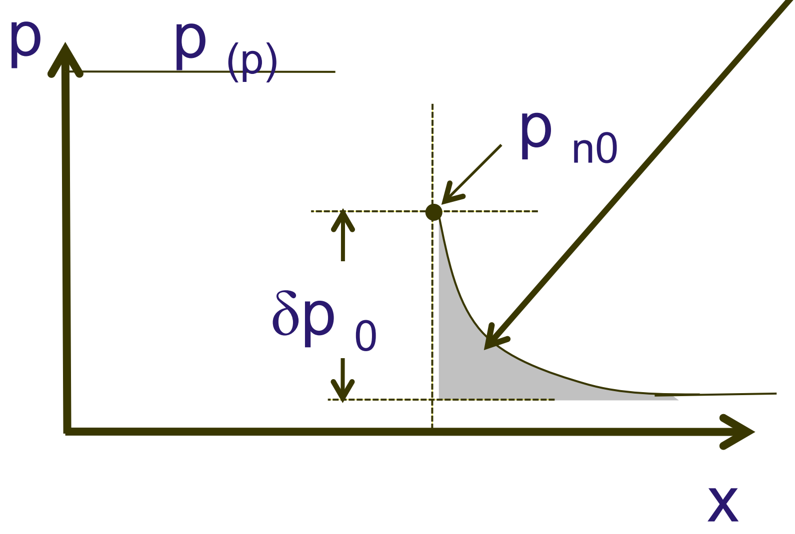
Remembering minority carrier diffusion length – we can relate distance to minority carrier lifetime



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

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

In a minority carrier lifetime the minority carrier distribution is known



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

$$Q_p = qA \int_0^\infty \delta p(x)\delta x$$

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

$$Q_p = qA\, \delta p_0 L_h$$

Similarly for electrons diffusing into the p-type material, charge injected in time τ_e, Q_n, is ;

$$Q_n = qA\, \delta n_0 L_e$$

Definite Integral Step

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

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

$$\lim_{x \to -\infty} \exp(x) = 0 \qquad \lim_{x \to 0} \exp(x) = 1$$

$$Q_p = qA\,\delta p_0 L_h$$

Putting It All Together

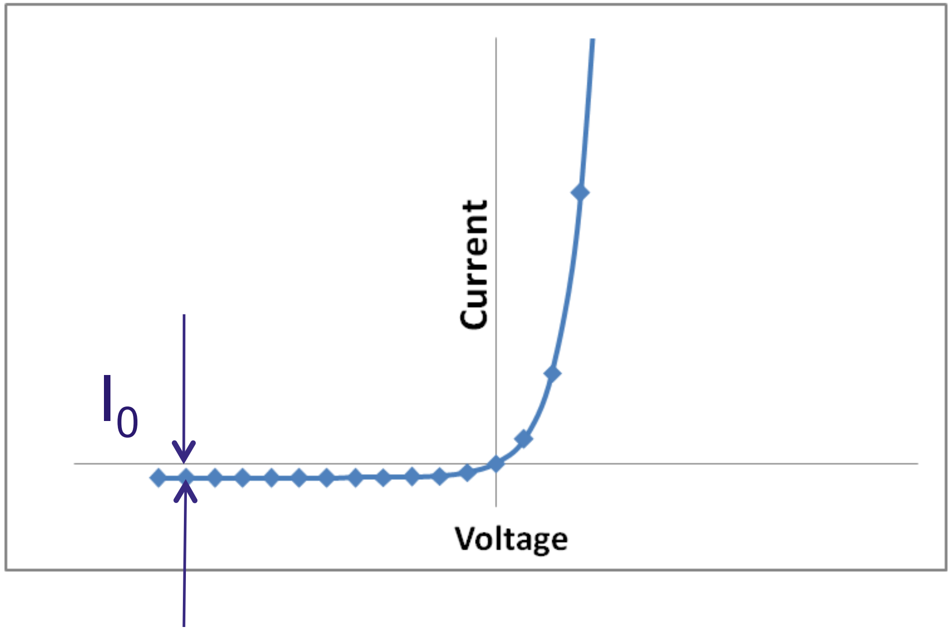
$$I = I_e + I_h = \frac{Q_e}{\tau_e} + \frac{Q_h}{\tau_h} = \frac{qAL_e\delta n_0}{\tau_e} + \frac{qAL_h\delta p_0}{\tau_h}$$

$$\partial p_0 = p_n\left[\exp\left[\frac{qV_f}{k_B T}\right] - 1\right] \qquad \partial n_0 = n_p\left[\exp\left[\frac{qV_f}{k_B T}\right] - 1\right]$$

$$I = \left[\frac{qAL_e n_p}{\tau_e} + \frac{qAL_h p_n}{\tau_h}\right]\left[\exp\left(\frac{qV}{k_B T}\right) - 1\right]$$

Diode Equation

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



Exponential increase in I with V_f

I_0 is the (reverse) saturation current

In J:

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

Saturation Current

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

Can be rewritten as

$$I_0 = qAn_i^2\left[\frac{D_e}{L_e N_A} + \frac{D_h}{L_h N_d}\right]$$

By substituting

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

$$n_i^2 = pn_p = N_A n_p$$

$$n_i^2 = np_n = N_d p_n$$

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 causes a current flow
- Current is exponential in applied bias - the diode equation

