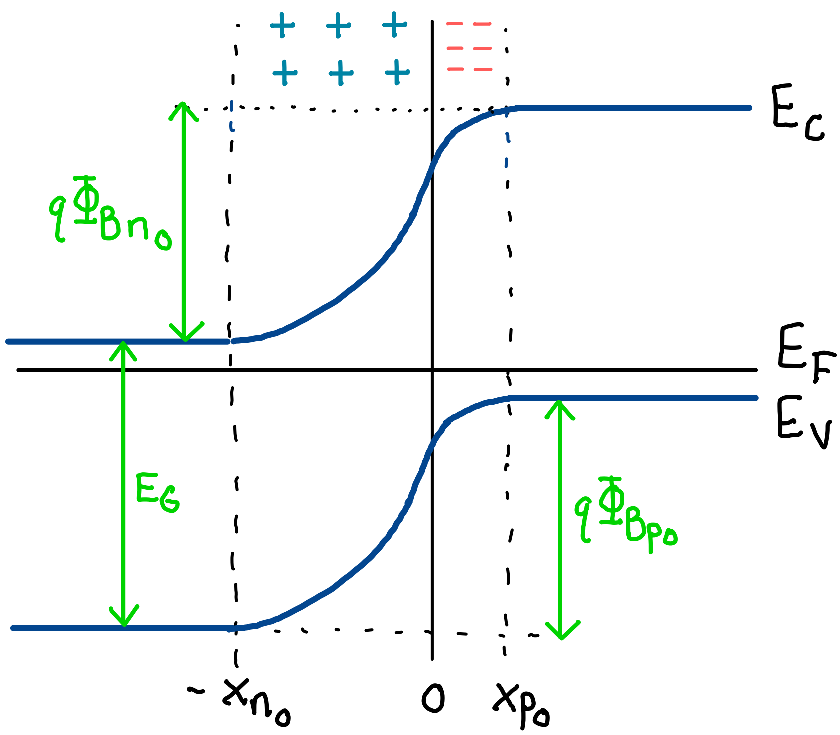
Currents in p-n Heterojunctions

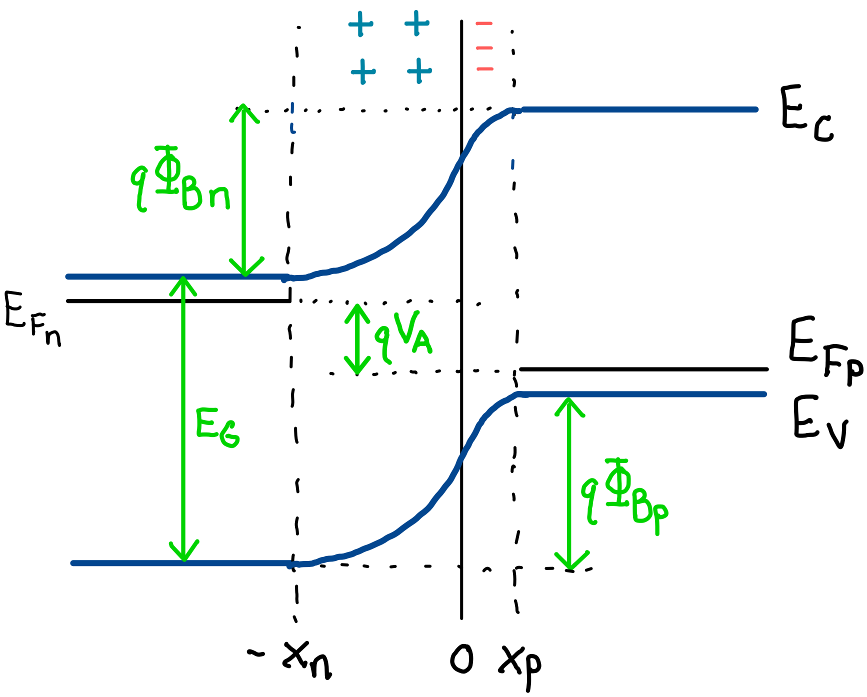
Homojunction ($N_D << N_A$):

$V_A = 0$:



- $\Phi_{Bp_0} = \Phi_{Bn_0} = V_{bi}$

$V_A > 0$:



- $\Phi_{Bp} = \Phi_{Bp_0} - V_A$
- $\Phi_{Bn} = \Phi_{Bn_0} - V_A$

From Law of the Junction:

$$p_n(-x_n) = N_A e^{-q\Phi_{Bp}/kT} = \underbrace{N_A e^{-q\Phi_{Bp_0}/kT}}_{p_{n_0}} e^{qV_A/kT}$$

$$p_n(x \le -x_n) = N_A e^{-q\Phi_{Bp_0}/kT}\left(e^{qV_A/kT} - 1\right)\cdot \exp\left[\frac{-(-x_n - x)}{L_p}\right] + N_A e^{-q\Phi_{Bp_0}/kT}$$

$$J_p(x \le -x_n) = qD_p \frac{dp_n}{dx} = \frac{qD_pN_A}{L_p} e^{-q\Phi_{Bp_0}/kT}\left(e^{qV_A/kT} - 1\right)\cdot \exp\left[\frac{-(-x_n - x)}{L_p}\right]$$

$$J_p(-x_n) = qD_p \left.\frac{dp_n}{dx}\right|_{-x_n} = \frac{qD_pN_A}{L_p} e^{-q\Phi_{Bp_0}/kT}\left(e^{qV_A/kT} - 1\right)$$

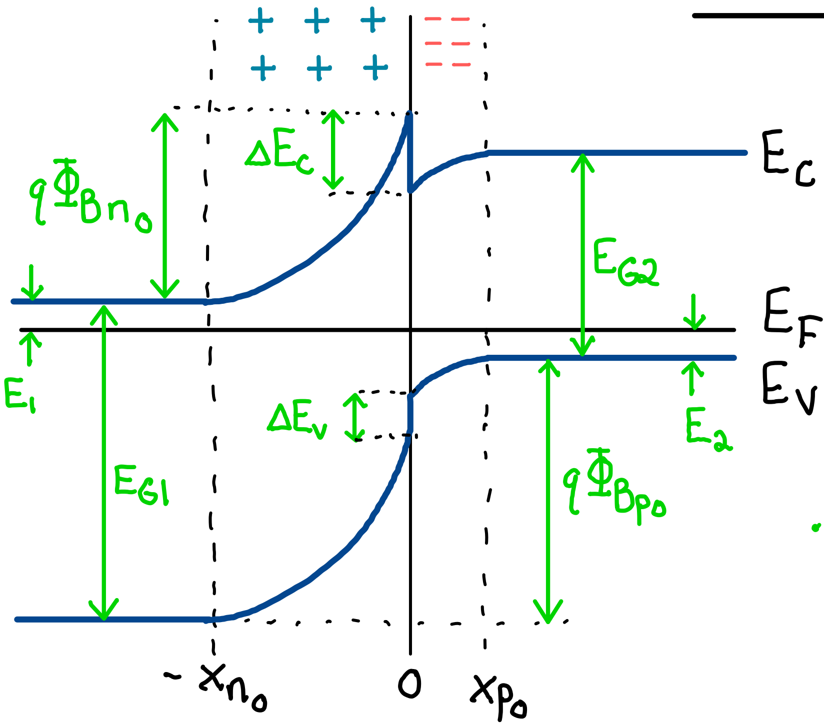
Similarly for J_n:

$$J_n(x_p) = \frac{qD_nN_D}{L_n} e^{-q\Phi_{Bn_0}/kT}\left(e^{qV_A/kT} - 1\right)$$

$$\frac{J_p}{J_n} = \frac{D_pL_nN_A}{D_nL_pN_D} e^{-q(\Phi_{Bp_0} - \Phi_{Bn_0})/kT} = \boxed{\frac{D_pL_nN_A}{D_nL_pN_D}}$$

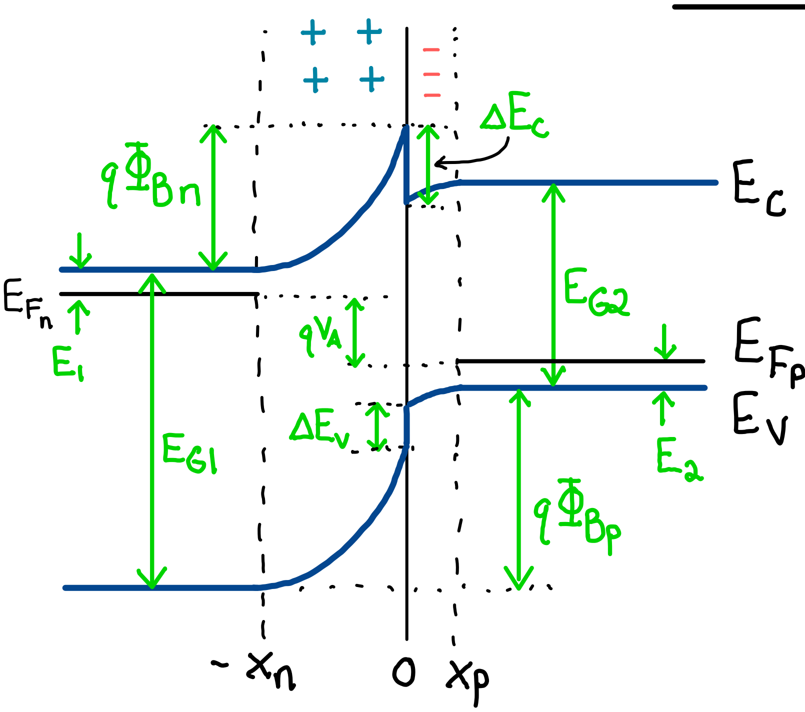
Abrupt Heterojunction ($N_D << N_A$):

$V_A = 0$:



- $q\Phi_{Bp_0} = E_{G1} - E_1 - E_2$
- $q\Phi_{Bn_0} \approx E_{G2} + \Delta E_c - E_1 - E_2$
- $q(\Phi_{Bp_0} - \Phi_{Bn_0}) = E_{G1} - E_{G2} - \Delta E_c$
  $= \Delta E_G - \Delta E_c$
  $= \Delta E_V$

$V_A > 0$:



- $\Phi_{Bp} = \Phi_{Bp_0} - V_A$
- $\Phi_{Bn} = \Phi_{Bn_0} - V_A$

From Law of the Junction:

$$p_n(-x_n) = N_A e^{-q\Phi_{Bp}/kT} = \underbrace{N_A e^{-q\Phi_{Bp_0}/kT}}_{p_{n_0}} e^{qV_A/kT}$$

$$p_n(x \le -x_n) = N_A e^{-q\Phi_{Bp_0}/kT}\left(e^{qV_A/kT} - 1\right)\cdot \exp\left[\frac{-(-x_n - x)}{L_p}\right] + N_A e^{-q\Phi_{Bp_0}/kT}$$

$$J_p(x \le -x_n) = q D_p \frac{dp_n}{dx} = \frac{q D_p N_A}{L_p} e^{-q\Phi_{Bp_0}/kT}\left(e^{qV_A/kT} - 1\right)\cdot \exp\left[\frac{-(-x_n - x)}{L_p}\right]$$

$$J_p(-x_n) = q D_p \left.\frac{dp_n}{dx}\right|_{-x_n} = \frac{q D_p N_A}{L_p} e^{-q\Phi_{Bp_0}/kT}\left(e^{qV_A/kT} - 1\right)$$

Similarly for J_n:

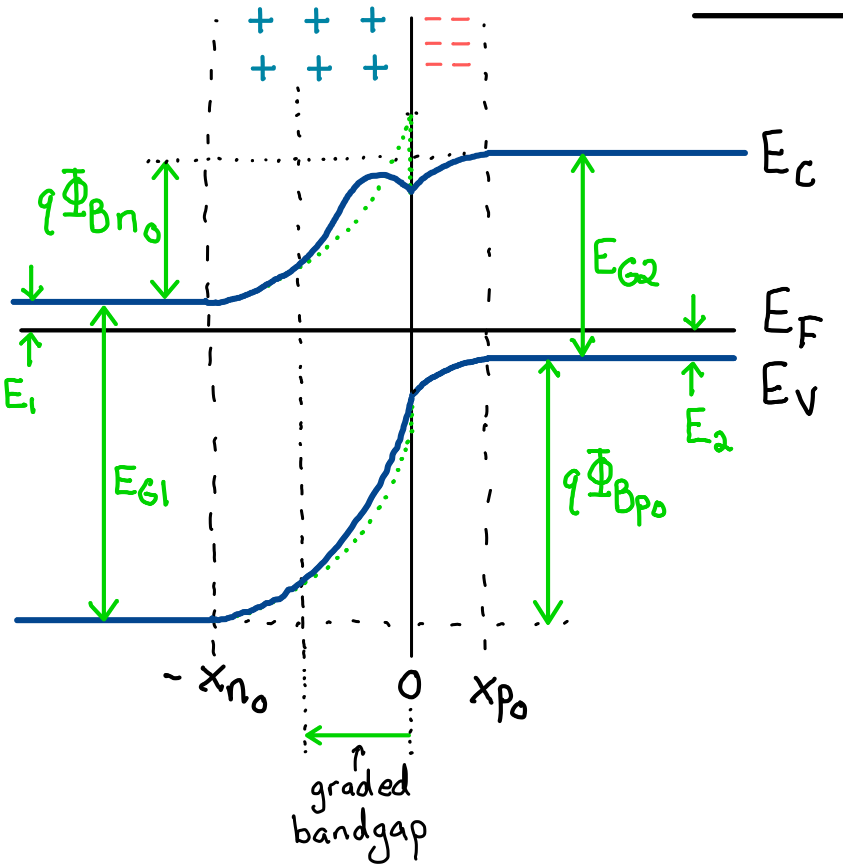
$$J_n(x_p) = \frac{q D_n N_D}{L_n} e^{-q\Phi_{Bn_0}/kT}\left(e^{qV_A/kT} - 1\right)$$

$$\frac{J_p}{J_n} = \frac{D_p L_n N_A}{D_n L_p N_D} e^{-q(\Phi_{Bp_0} - \Phi_{Bn_0})/kT} = \boxed{\frac{D_p L_n N_A}{D_n L_p N_D} e^{-\Delta E_v/kT}}$$

- J_p is suppressed relative to J_n by a factor $e^{-\Delta E_v/kT}$

Graded Heterojunction ($N_D << N_A$):

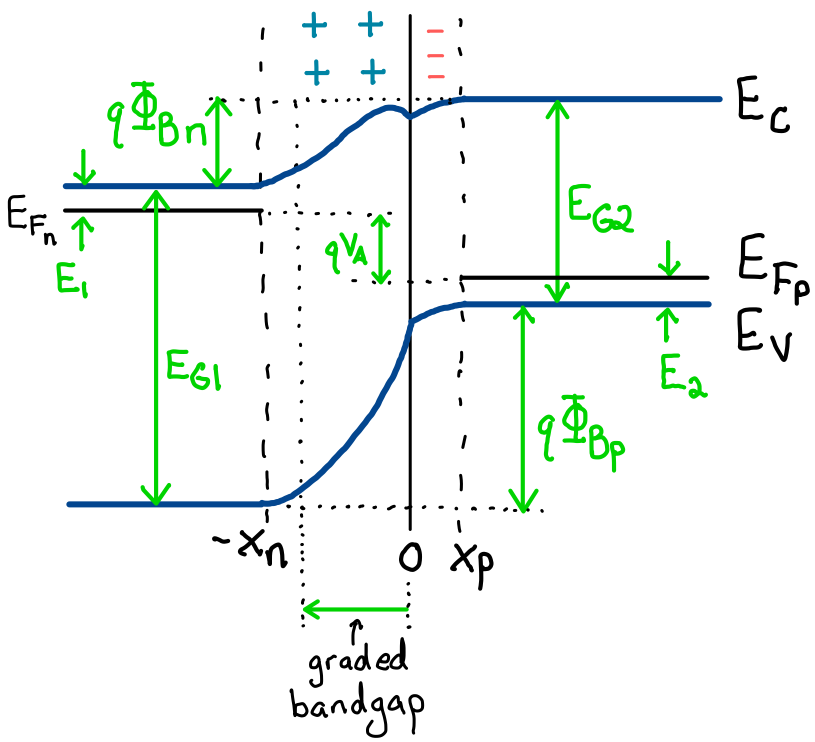
$V_A = 0$:



- $q\Phi_{Bp_0} = E_{G1} - E_1 - E_2$
- $q\Phi_{Bn_0} = E_{G2} - E_1 - E_2$
- $q\left(\Phi_{Bp_0} - \Phi_{Bn_0}\right) = E_{G1} - E_{G2}$

$$= \Delta E_G$$

$V_A > 0$:



- $\Phi_{Bp} = \Phi_{Bp_0} - V_A$
- $\Phi_{Bn} = \Phi_{Bn_0} - V_A$

From Law of the Junction:

$$p_n(-x_n) = N_A e^{-q\Phi_{Bp}/kT} = \underbrace{N_A e^{-q\Phi_{Bp_0}/kT}}_{p_{n_0}} e^{qV_A/kT}$$

$$p_n(x \le -x_n) = N_A e^{-q\Phi_{Bp_0}/kT}\left(e^{qV_A/kT} - 1\right)\cdot \exp\left[\frac{-(-x_n - x)}{L_p}\right] + N_A e^{-q\Phi_{Bp_0}/kT}$$

$$J_p(x \le -x_n) = q D_p \frac{dp_n}{dx} = \frac{q D_p N_A}{L_p} e^{-q\Phi_{Bp_0}/kT}\left(e^{qV_A/kT} - 1\right)\cdot \exp\left[\frac{-(-x_n - x)}{L_p}\right]$$

$$J_p(-x_n) = q D_p \left.\frac{dp_n}{dx}\right|_{-x_n} = \frac{q D_p N_A}{L_p} e^{-q\Phi_{Bp_0}/kT}\left(e^{qV_A/kT} - 1\right)$$

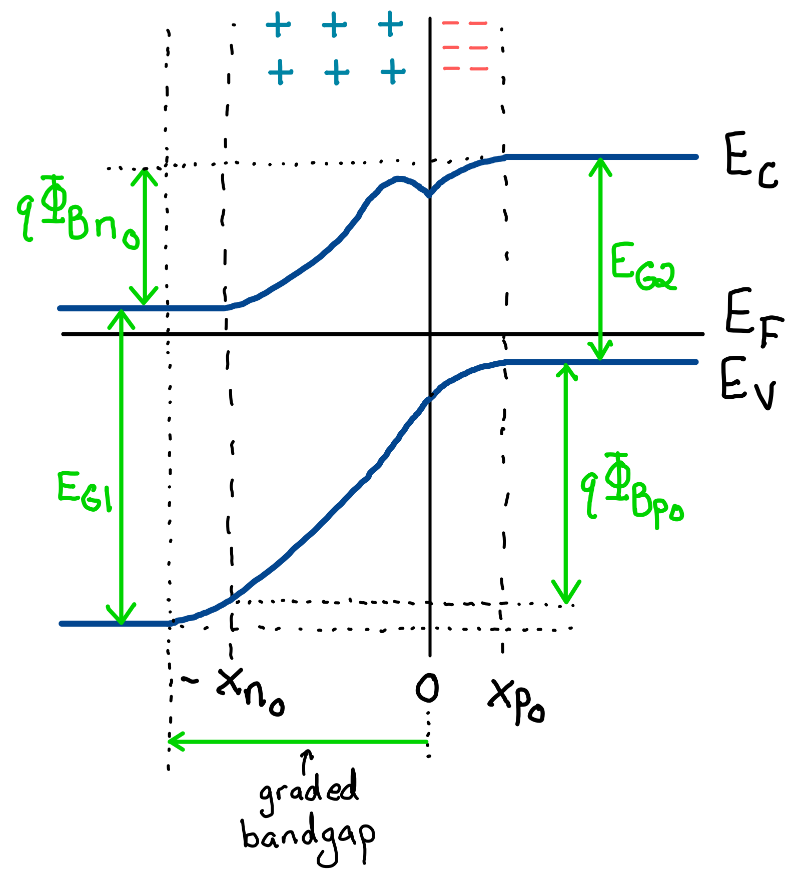
Similarly for J_n:

$$J_n(x_p) = \frac{q D_n N_D}{L_n} e^{-q\Phi_{Bn_0}/kT}\left(e^{qV_A/kT} - 1\right)$$

$$\frac{J_p}{J_n} = \frac{D_p L_n N_A}{D_n L_p N_D} e^{-q(\Phi_{Bp_0} - \Phi_{Bn_0})/kT} = \boxed{\frac{D_p L_n N_A}{D_n L_p N_D} e^{-\Delta E_G/kT}}$$

- J_p is suppressed relative to J_n by a factor $e^{-\Delta E_G/kT}$

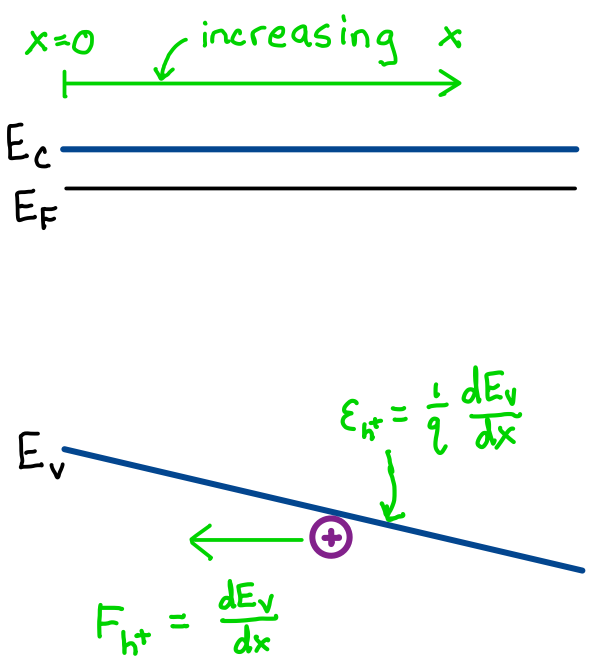
What if grade extends beyond the edge of the depletion region?



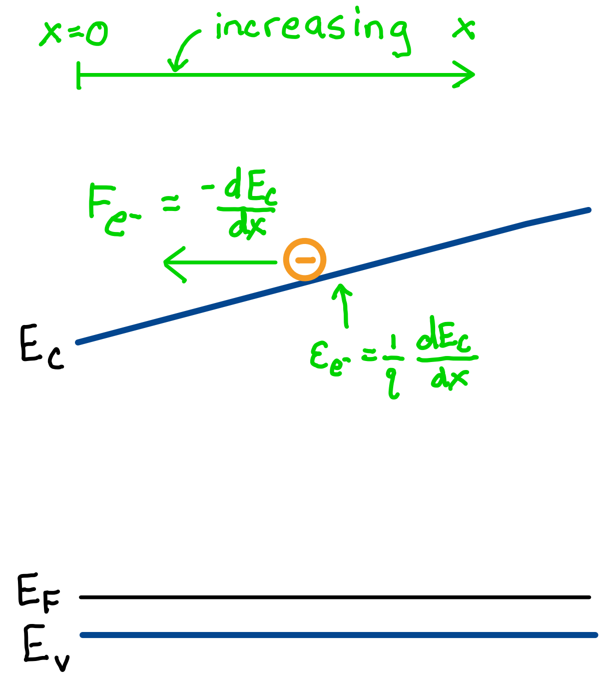
- Φ_{Bp_0} is reduced, Φ_{Bn_0} is unaffected
- Less suppression of J_p relative to J_n

Quasi-Electric Fields

n-type Graded $Al_xGa_{1-x}As$



p-type Graded $Al_xGa_{1-x}As$



Undoped Graded $Al_xGa_{1-x}As$