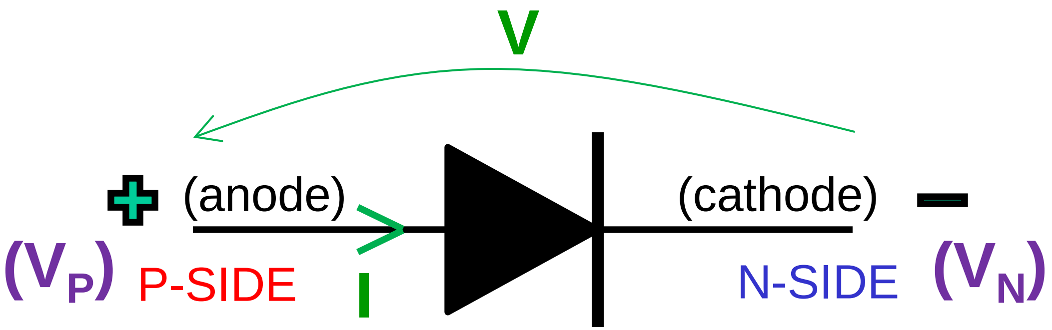
Chapter 8

Bias and Current Flow in the PN Junction

Biased PN Junction

- The term ‘bias’ in electronics refers to the application of one or more steady or “DC” voltages (or sometimes currents) to a semiconductor device;
- In the case of a PN junction which has just two terminals, we forward bias the junction when the potential on the P-side (anode) is higher than the potential on the N-side (cathode) (i.e. voltage across the device = $V > 0$)
- The opposite condition is referred to as reverse bias, where the potential on the anode is lower than that on the cathode (i.e. $V < 0$).
- Under conditions of DC bias, note that thermal equilibrium no longer applies.

Reference Senses and Notation



Forward Bias:
$V > 0, I > 0$
Reverse Bias:
$V < 0; I < 0$

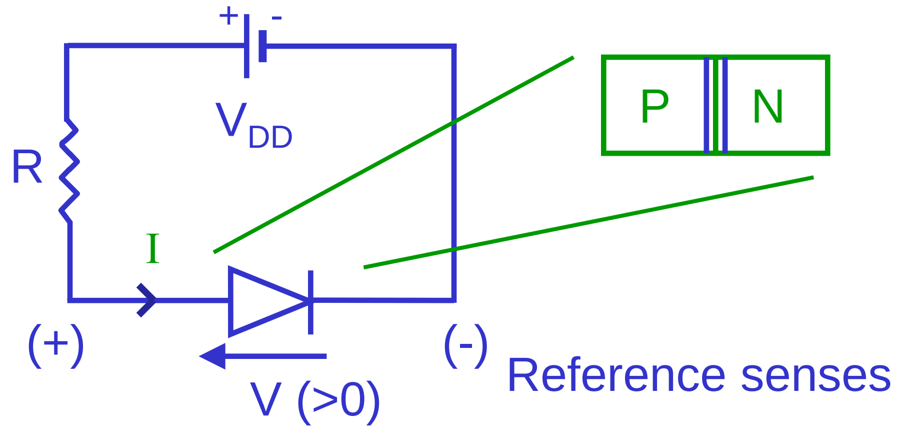
- We will adopt the notation that capital letters (perhaps with capital subscripts) always represent steady or DC voltages or currents
- For example, if V_P is the absolute DC voltage on the P-side (relative to 0V or Ground) and V_N is the equivalent DC voltage on the N-side, then from KVL above:

$$V = V_P - V_N$$

- Note that e.g. the current does not *have* to flow in the direction of the reference arrow, its just that *if it does* so then it is taken as a *positive* quantity.

Forward Bias of the PN Junction

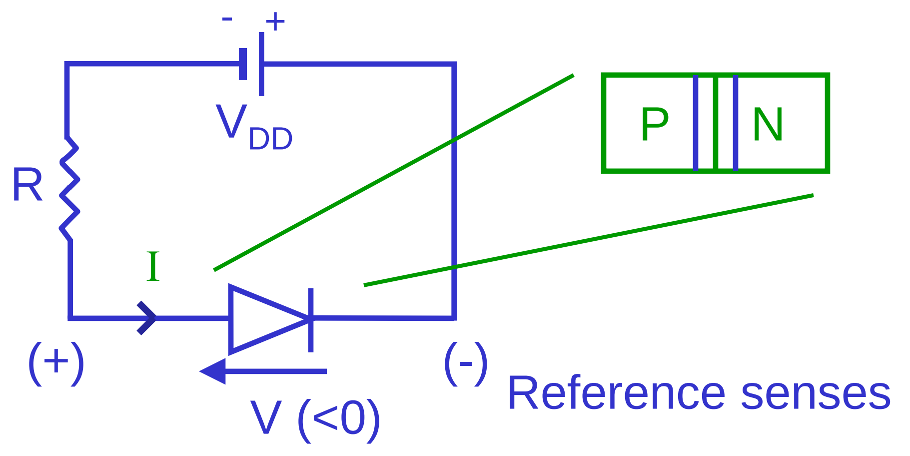
Connect positive terminal of DC voltage to anode of PN junction



- In thermal equilibrium, the internal N-side is at a voltage (ϕ_i) higher than the P-side.
- As a result of applying the DC bias, a (positive) voltage V exists across the terminals of the device as shown in the diagram, and therefore the N-side becomes only (ϕ_i-V) higher than the P-side, i.e. the potential barrier has been reduced by the forward bias.

Reverse Bias of the PN Junction

Connect negative terminal of DC voltage to anode of PN junction



- Again, thermal equilibrium no longer applies;
- In this case the V shown in the diagram is negative. It thus adds in magnitude to the higher potential on the N-side in thermal equilibrium. The potential on the N-side now becomes ($\phi_i + |V|$) higher than the P-side, i.e. the potential barrier has been increased by the reverse bias.

Extending from Thermal Equilibrium to the Non-equilibrium (Biased) Case

- We can simply re-use the formulas derived earlier that assumed thermal equilibrium, e.g. for the depletion layer width and penetration of the depletion layer into the P-side or N-side;
- All that needs to be done is everywhere to replace (ϕ_i) with (ϕ_i-V), where it is understood that V> 0 means forward bias and V< 0 means reverse bias. We should also remove any zero subscripts that indicated thermal equilibrium.

Depletion Layer Width with Bias

- For example, in thermal equilibrium we found previously that the equilibrium depletion layer width is given by:

$$W_o = \sqrt{\frac{2 \cdot \varepsilon \cdot \varphi_i}{q} \cdot \left(\frac{N_A + N_D}{N_A \cdot N_D} \right)}$$

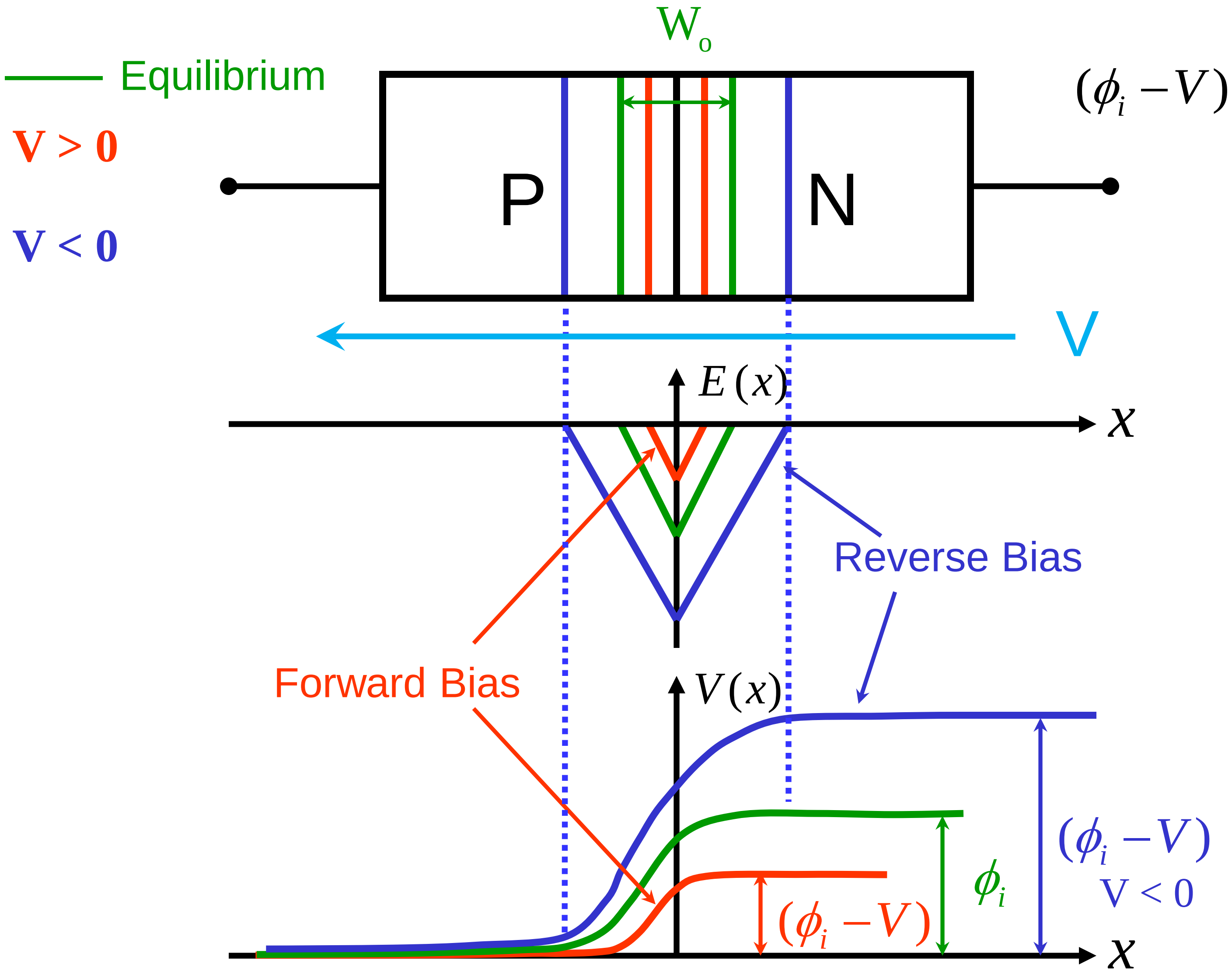
- Under biased conditions with a voltage V, this now reads:

$$\boxed{W = \sqrt{\frac{2 \cdot \varepsilon \cdot (\varphi_i - V)}{q} \cdot \left(\frac{N_A + N_D}{N_A \cdot N_D} \right)}}$$

This is the version of the formula given in the Formula Sheet

- Similarly, we can modify the formulas for x_{no} and x_{po} to get general expressions for x_n and x_p under biased conditions.

Effect of DC Bias on Depletion Layer Width, Electric Field E(x) and Potential V(x)



Example 8.1

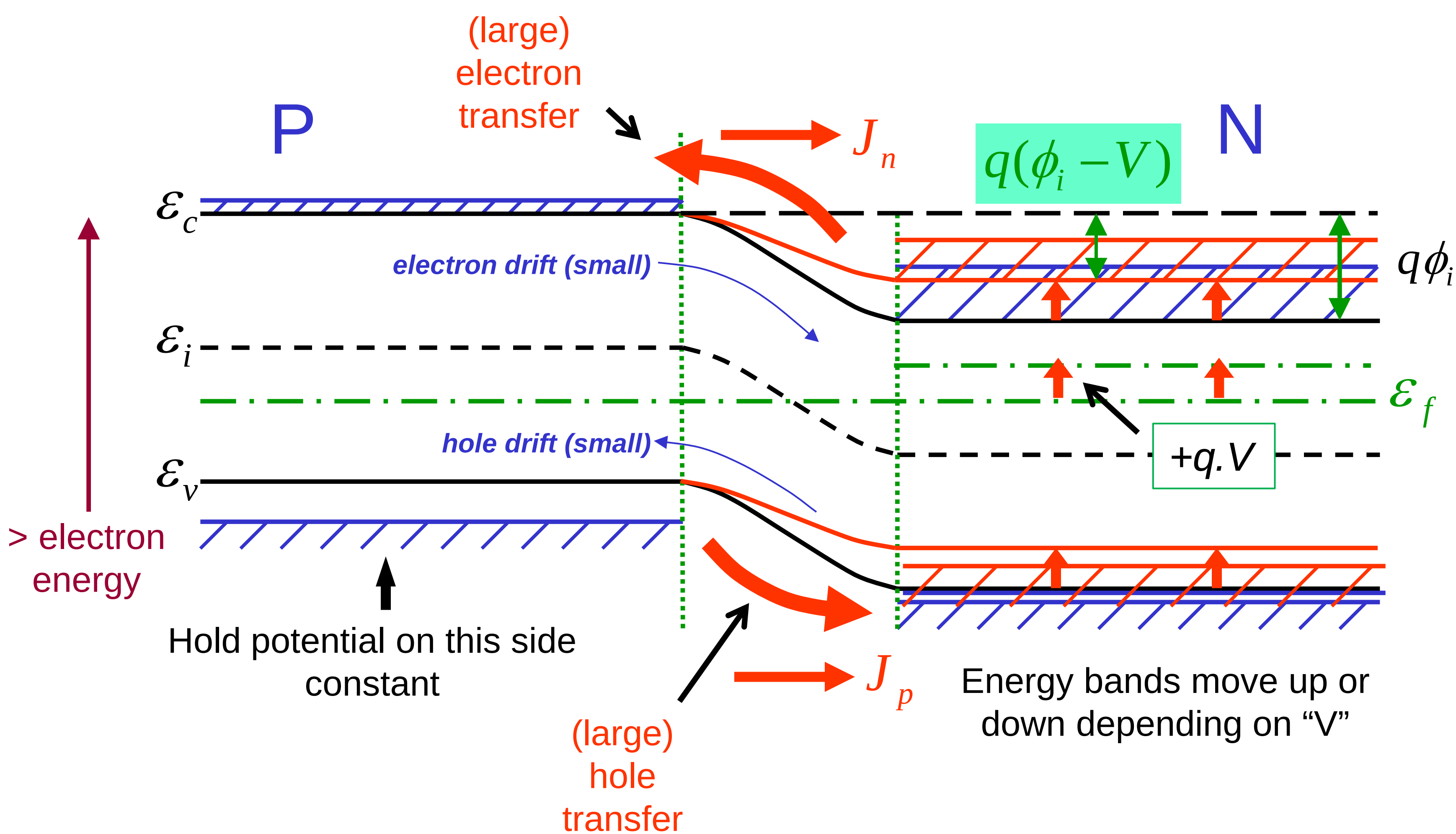
Current Flow in the PN Junction

- With a DC voltage V applied, it is possible for a current I to flow in the PN junction
- We now first consider *qualitatively* what happens within the structure under forward and reverse bias, respectively. This discussion is based on the energy band picture with the junction energy barrier modified from the value **$q.(\phi_i)$** in equilibrium to **$q.(\phi_i\text{-}V)$** with bias
- Following this, we use the basic semiconductor device equations to derive an *analytical formula* that allows us to predict I for any V in a PN junction, subject to certain approximations

Energy Bands Under DC Bias Conditions

- Since thermal equilibrium no longer applies, there is no requirement for the Fermi energy to be everywhere uniform;
- Earlier we took the neutral P-region as our reference for potential. Hence, we can take account of the effect of an applied DC bias V (equivalent to an energy shift q.V) by fixing or "pinning" the energy band diagram on the P-side and simply moving the band structure on the N-side, either up (Forward Bias) or down (Reverse Bias) by |q.V|;
- Note that technically the depletion layer width should also change on the energy band diagrams as the bias V changes, but this makes the drawings very complex so we will ignore this effect for the moment;
- Under **Forward Bias**, the potential barrier opposing large-scale electron diffusion from N-side to the P-side is **reduced by q.V**. A large unbalanced electron diffusion current can then flow from N → P.
- In exactly the same way, a large hole diffusion current can flow from P-side to N-side. Both of these current components add together.

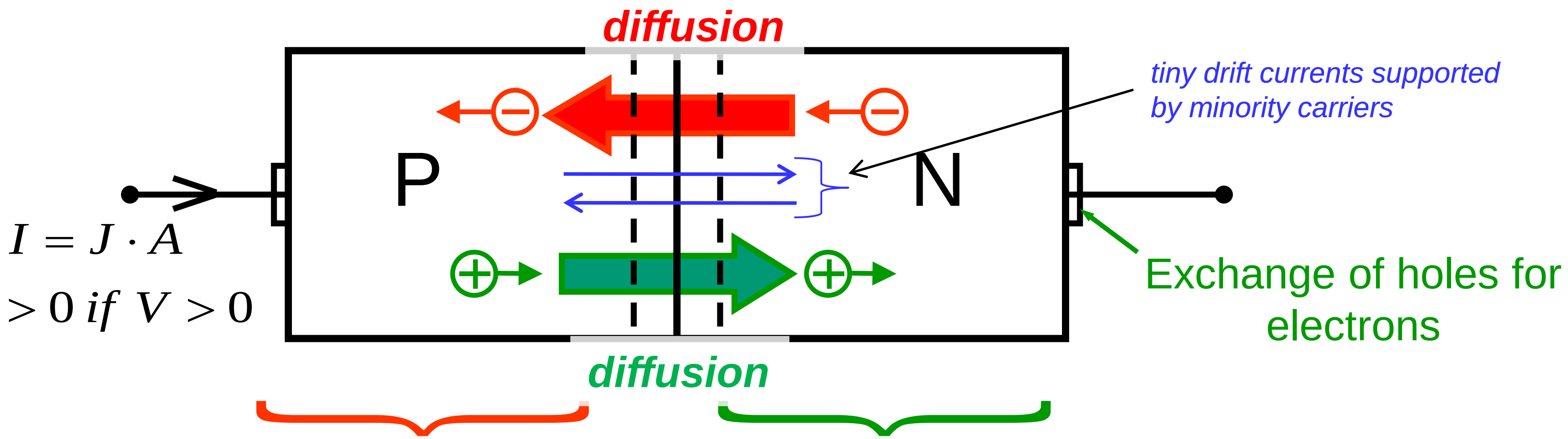
DC Current Flow in **Forward Bias**



See: http://jas.eng.buffalo.edu/education/pn/biasedPN/index.html

DC Current Flow in Forward Bias

- The result is that the total current density $J = J_p + J_n$ becomes large as V is made increasingly positive;
- Note that the small (now unbalanced) drift currents that oppose diffusion are ≈ unaffected by the presence of the forward bias.

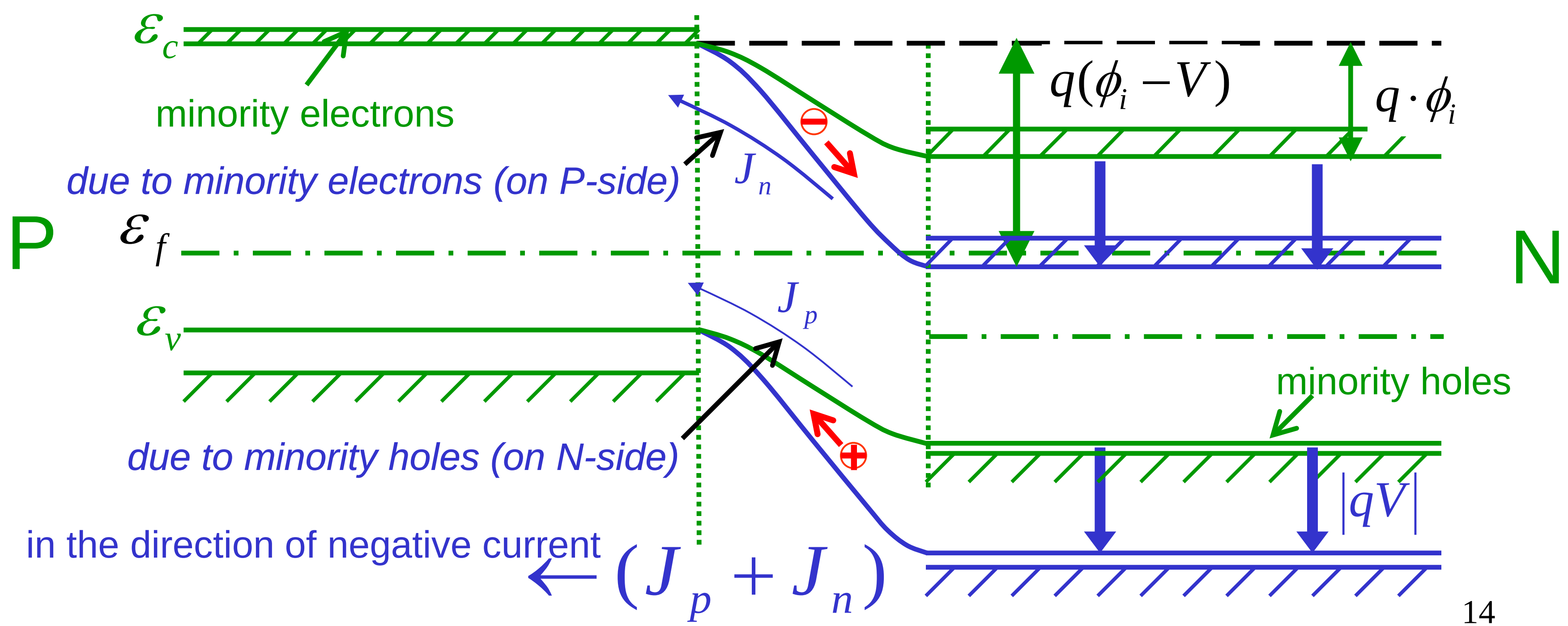


electrons are injected into neutral P-region and diffuse across to ohmic contact. These **are excess minority electrons $\Delta n_p(x)$**

holes are injected into neutral N-region and diffuse across to ohmic contact. These are **excess minority holes $\Delta p_n(x)$**

DC Current Flow in **Reverse Bias**

- Under reverse bias, the potential barrier opposing large-scale electron diffusion from N-side to the P-side is **increased by q.V**. The result is that diffusion current is quickly killed off almost entirely
- All that is left is a tiny drift current of electrons from P -> N and a drift current holes from N -> P. This current is limited by the very small minority carrier concentrations and is largely **independent of V**.



Analytical Formula for Current Flow in a Biased PN Junction

- The previous qualitative discussion of the biased PN junction suggests that a large and rapidly growing current may be expected under forward bias, while a very small and essentially constant current will flow in the opposite direction under reverse bias.
- We now analyse the current flow in the PN junction making several important approximations:
    1. 1-D structure, with zero electric field in the neutral regions
    2. Uniformly doped, abrupt PN junction
    3. The excess carriers injected into both neutral regions under forward bias correspond to *low-level* injection conditions
    4. We neglect Generation and Recombination in the depletion layer

Consequence of Neglecting G-R in the Depletion Region

- The result of this assumption is that the DC electron current density $J_n(x)$ and the hole current density $J_p(x)$ must be **separately constant** across the depletion layer,
- Proof: use the continuity equation for holes in the region $x \varepsilon [-x_p, x_n]$:

$$\frac{\partial p(x,t)}{\partial t} = -\frac{1}{q} \cdot \frac{\partial J_p(x,t)}{\partial x} + G - R \qquad \text{DC (static)} \Rightarrow \frac{\partial}{\partial t} = 0$$

$$0 = -\frac{1}{q}\frac{d\,J_p(x)}{dx} + \underbrace{G - R}_{\text{zero in depletion layer}} \qquad \Rightarrow \frac{d\,J_p(x)}{dx} = 0$$

$$\Rightarrow J_p(x) \quad \text{is constant,} \ \forall\ x \in [-x_p, x_n]$$

(Similar proof can be done for $J_n(x)$)

Minority Carrier Concentrations at the Edges of the Depletion Layer

Earlier (in developing an expression for ϕ_i) we proved that in thermal equilibrium :

$$\phi_i = \frac{kT}{q} \cdot \ln \left| \frac{p_{po}}{p_{no}} \right|$$

As before, we propose that in the case where a voltage "V" is applied (non-equilibrium conditions), this can simply be modified to :

$$(\phi_i - V) = \frac{kT}{q} \cdot \ln \left| \frac{p_p}{p_n} \right| \quad = \quad \frac{kT}{q} \cdot \ln \left| \frac{p_p(-x_p)}{p_n(x_n)} \right|$$

$$\Rightarrow p_n(x_n) = p_p(-x_p) \cdot \exp\left[-\frac{q(\phi_i - V)}{kT} \right]$$

Minority Carrier Concentrations at the Edges of the Depletion Layer

We can write, using the 'low-level' injection assumption:

$$p_p(-x_p) = p_{po} + \Delta p_p(-x_p) \approx \underline{p_{po}}$$

(i.e. excess holes have negligible effect in P neutral region)

Also:

$$p_n(x_n) = p_{no} + \underline{\Delta p_n(x_n)}$$

excess (minority) holes
in neutral N-region
produced by "V"

$$\Rightarrow p_{no} + \Delta p_n(x_n) = \underbrace{p_{po} \cdot \exp\left[-\frac{q\phi_i}{kT}\right]}_{= \; p_{no}} \cdot \exp\left[\frac{qV}{kT}\right]$$

Minority Carrier Concentrations at the Edges of the Depletion Layer

$\Rightarrow$

"Boundary Condition on N-side"

$$\boxed{\Delta p_n(x_n) = p_{no}\left[e^{qV/kT} - 1\right]}$$

This gives the minority hole concentration at the depletion layer edge of the neutral N-region as a function of bias "V".

A similar analysis gives: :

"Boundary condition on P-side"

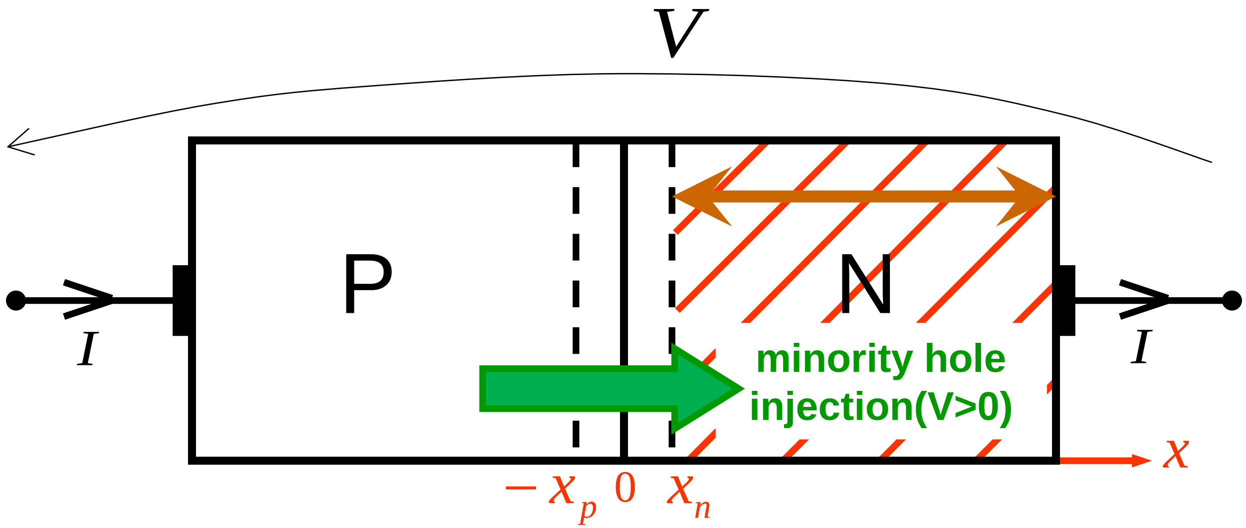
$$\boxed{\Delta n_p(-x_p) = n_{po}\left[e^{qV/kT} - 1\right]}$$

No Need to Remember: These important Boundary Condition equations for the PN Junction are given in the Formula Sheet

Static Analysis of the PN Junction

We are looking for a formula of the kind ***I = f(V)***.

1st consider neutral N-region:



Neutral region: $x \in [x_n, "\infty"]$ "long-based" on N-side

We wish to solve for the minority hole concentration: $\Delta p_n(x)$

Solution for $\Delta p_n(x)$ in the Neutral N Region

2 basic equations

- Continuity : $$\frac{\partial p(x,t)}{\partial t} = -\frac{1}{q}\frac{\partial J_p(x,t)}{\partial x} + G - R$$
- Current density : $$J_p(x,t) = q\,p(x,t)\mu_p E - qD_p\frac{\partial p(x,t)}{\partial x}$$

Can simplify these using the fact that this is DC $\Rightarrow \frac{\partial}{\partial t} = 0$ everywhere

The assumption of no electric field in neutral region means that there is no drift current carried so that current is carried entirely by diffusion :

$$0 = -\frac{1}{q}\cdot\frac{d\,J_p(x)}{dx} - \frac{\Delta p_n(x)}{\tau_p} \qquad (1)$$

$$J_p(x) = -q\,D_p\cdot\frac{d\,p_n(x)}{dx} \qquad (2)$$

Remember: τ_p is the ***minority hole lifetime***: the average time an excess hole survives in the neutral N-region before being eliminated through recombination

Solution for $\Delta p_n(x)$ in the Neutral N Region

But $p_n(x) = \underbrace{p_{no}} + \Delta p_n(x)$

this does not depend on "x" since the doping is uniform

$$\boxed{\Rightarrow \quad J_p(x) = -q\,D_p \frac{d\,\Delta p_n(x)}{dx} \qquad (2)}$$

Now substitute equation (2) into equation (1) on previous slide:

$$0 = -\frac{1}{q} \cdot \frac{d}{dx}\left(-qD_p \cdot \frac{d\,\Delta p_n(x)}{dx}\right) - \frac{\Delta p_n(x)}{\tau_p}$$

$$\Rightarrow 0 = D_p \cdot \frac{d^2 \Delta p_n(x)}{dx^2} - \frac{\Delta p_n(x)}{\tau_p}$$

Solution for $\Delta p_n(x)$ in the Neutral N Region

We re-write this equation as:
:

$$\frac{d^2 \Delta p_n(x)}{dx^2} = \frac{\Delta p_n(x)}{L_p^{\ 2}}$$

...where: $$L_p = \sqrt{D_p \tau_p} \quad (m)$$

L_p is defined as the ***hole diffusion length***

A solution to this second-order differential equation is :

$$\Delta p_n(x) = A \cdot \exp\left[\frac{x - x_n}{L_p}\right] + B \cdot \exp\left[-\left(\frac{x - x_n}{L_p}\right)\right]$$

Constants
of integration

(Exercise:
verify by substitution)

Boundary Conditions

- To eliminate the 2 unknown constants, A and B, we need 2 Boundary Conditions:
  - We know from the earlier derivation of the minority carrier concentration at the edge of the depletion layer (on the N-side)

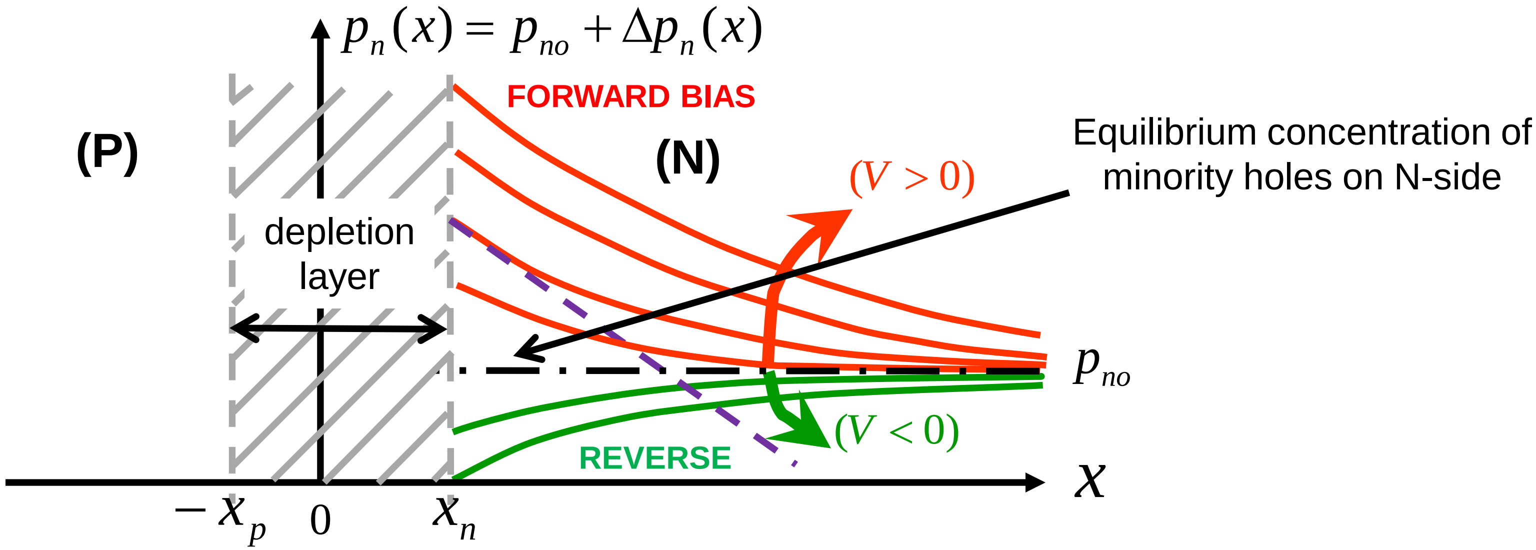
$$\Delta p_n(x_n) = p_{no} \cdot \left[e^{qV/kT} - 1 \right]$$

    This means that $\Delta p_n(x_n) = A + B$

  - But it is also true from physical arguments that *$\Delta p_n(x)$ must $\rightarrow 0$ as $x \rightarrow \infty$. This forces $A = 0$. Thus $B = \Delta p_n(x_n)$.*
- The full solution for $\Delta p_n(x)$ in the range $[x_n, \infty[$ is thus:

$$\Delta p_n(x) = \underbrace{p_{no} \cdot \left[e^{qV/kT} - 1 \right]}_{= B} \cdot \exp\left[-\left(\frac{x - x_n}{L_p} \right) \right]$$

Minority Hole Distributions in Neutral N-Region



Knowing $\Delta p_n(x)$ we can find the current $J_p(x)$ using $J_p(x) = -qD_p \dfrac{d\,\Delta p_n(x)}{dx}$

$$\Rightarrow J_p(x) = \frac{qD_p}{L_p} \cdot p_{no} \left[e^{qV/kT} - 1 \right] \cdot \exp\left[-\left(\frac{x - x_n}{L_p} \right) \right]$$

Hence at $x = x_n$:

$$J_p(x_n) = \frac{qD_p}{L_p} \cdot p_{no} \cdot \left[e^{qV/kT} - 1 \right]$$

Final Analytical Result

A similar analysis can be carried out for minority electrons in the neutral P region giving the corresponding result for the electron current density at the opposite edge of the depletion layer:

$$J_n(-x_p) = \frac{qD_n}{L_n} \cdot n_{po} \cdot \left[e^{qV/kT} - 1 \right]$$

But since we assume no G-R in the depletion layer, we have seen that both $J_n(-x_p)$ and $J_p(x_n)$ must be constant within the depletion layer.

Hence the total current density (J) is :

$$J = J_p(x_n) + J_n(-x_p)$$

$$= \left[\frac{q D_p p_{no}}{L_p} + \frac{q D_n n_{po}}{L_n} \right] \times \left[e^{qV/kT} - 1 \right]$$

‘Ideal’ PN Junction Equation for DC Current

- Using $I = J.A$, we thus obtain a key formula for the DC current in a PN junction as a function of the terminal voltage V (that is valid for both forward and reverse bias):

$$\boxed{I = I_s \cdot \left[e^{qV/kT} - 1 \right]}$$

- Where I_s is the **saturation current** or the **reverse leakage** current.

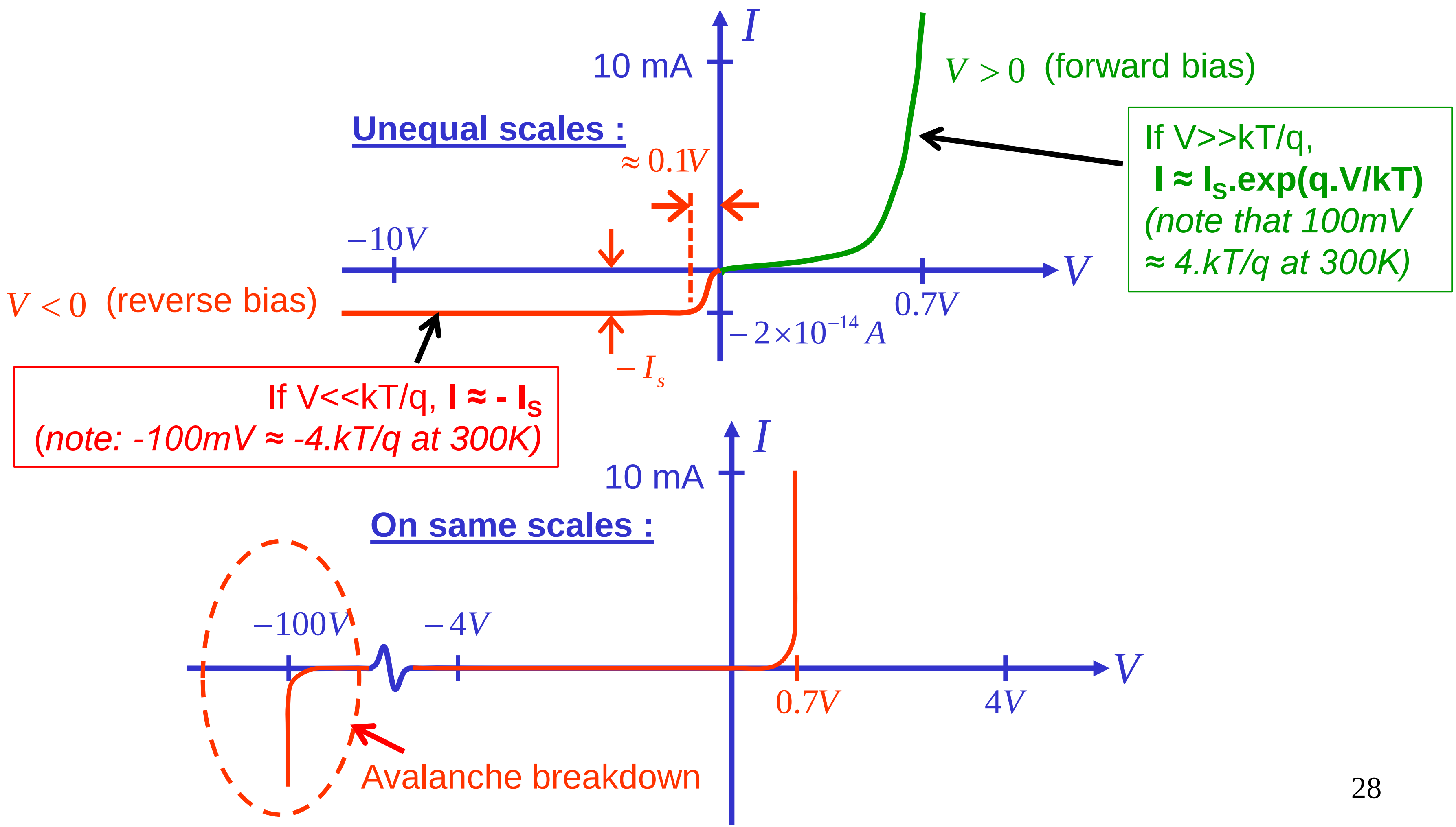
$$I_s = qA\left[\frac{D_p p_{no}}{L_p} + \frac{D_n n_{po}}{L_n}\right] \quad \underline{\underline{OR}} \quad I_s = qA\left[\frac{D_p n_i^2}{L_p N_D} + \frac{D_n n_i^2}{L_n N_A}\right]$$

Note : $D_p = \frac{kT}{q}\mu_p$ $\qquad D_n = \frac{kT}{q}\mu_n$

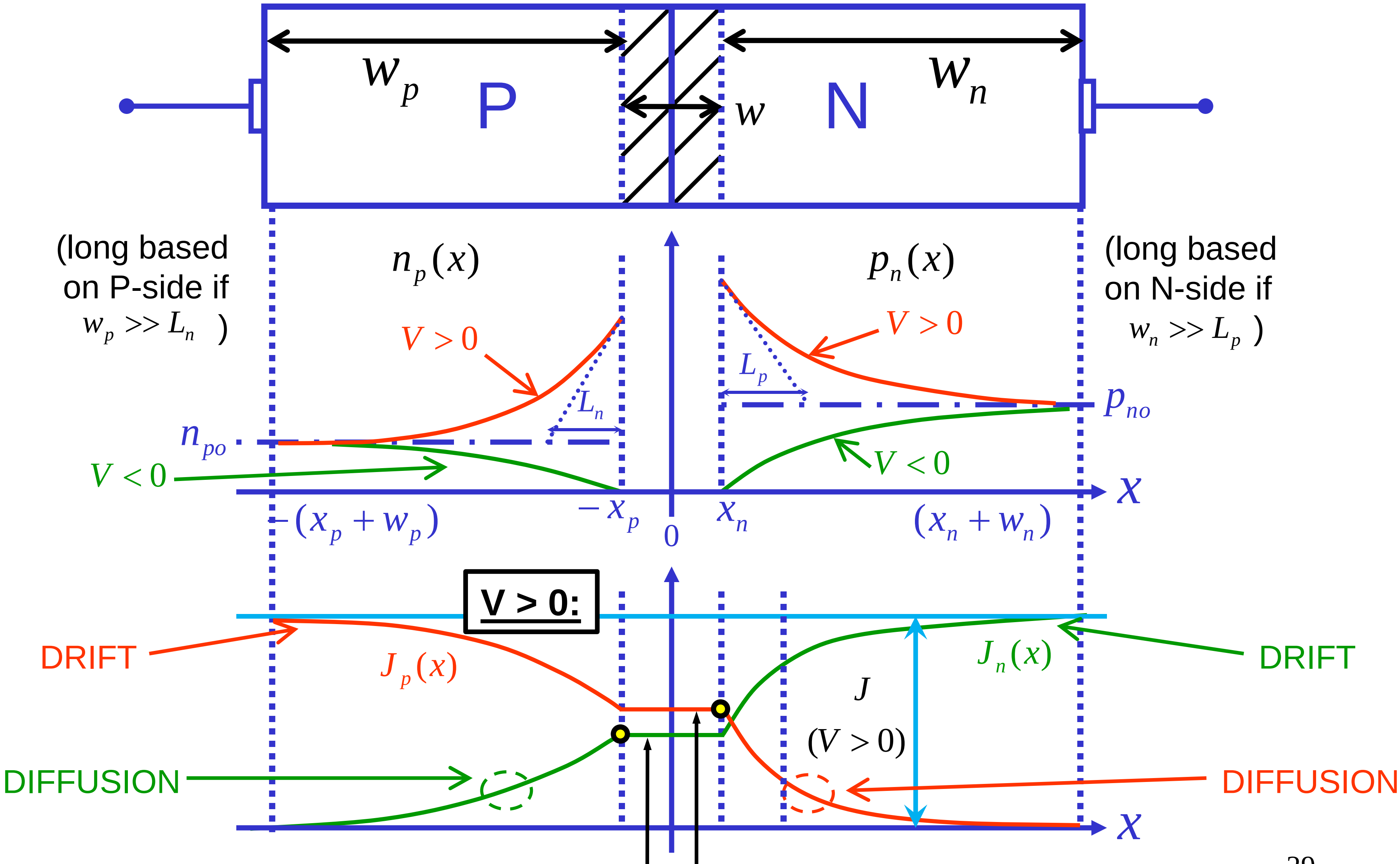
$$L_p = \sqrt{D_p \tau_p} \qquad L_n = \sqrt{D_n \tau_n}$$

$$\frac{kT}{q} = 0.0259V \text{ at } T = 300K$$

DC Current-Voltage Characteristic of PN Junction (typical values, Si at 300K)



Internal Current Distributions in PN Junction



Currents constant in the Depletion Region (no Generation/Recombination)

Temperature Dependence of Current in a PN Junction

- The current-voltage characteristic of a PN junction is quite sensitive to temperature
- This is obvious through the dependence on (qV/kT) but what is less obvious is the exponential increase of the reverse saturation current (I_s) with increasing temperature. This arises through the fact that I_s is directly proportional to the square of the intrinsic concentration n_i:

strongly temp. dependent $\propto n_i^2$

$$I = I_s\left[e^{qV/kT} - 1\right]$$

obvious

- Earlier we showed:

$$n_i = const\, T^{3/2} \exp\left[\frac{-\varepsilon_g}{2kT}\right]$$

- Note also that I_s will be much smaller in wider bandgap materials

Long-Based/Narrow-Based PN Junction Analysis

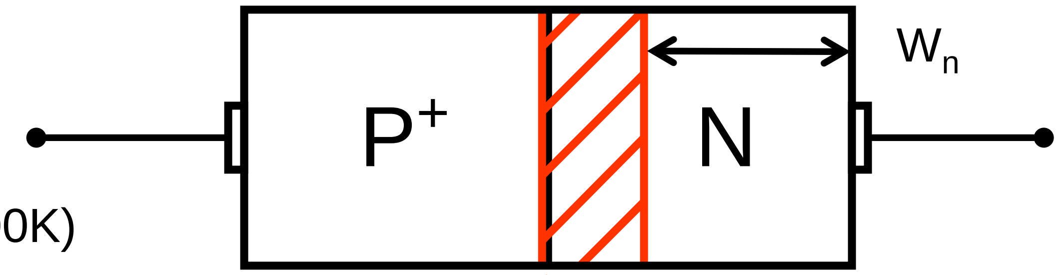
- One of the assumptions made in analysing the PN junction was the device could be considered “long-based” on both sides, meaning that the end-contacts were “far” from the depletion layer edges;
- More precisely, “long-based” means $W_p >> L_n$ and $W_n >> L_p$
- The opposite extreme is “narrow-based” whereby $W_p << L_n$ and $W_n << L_p$;. It turns out that the analysis in this case leads to a simple result for I_S: just replace L_p by W_n and by L_n by W_p:

$$I_S = \left[\frac{q D_p p_{no}}{W_n} + \frac{q D_n n_{po}}{W_p} \right]$$

- The intermediate case leads to a much more complicated solution involving hyperbolic functions (cosh, sinh etc).

"One-sided" (Long-Based) PN Junction

- This situation often arises in practical PN structures e.g. we could have a P^+N junction with $N_A = 10^{18}/cm^3$ and $N_D=10^{14}/cm^3$: :



(Si, 300K)

1/10,000 total width on P^+ side

$$p_{po} = N_A = 10^{18} / cm^3; \quad n_{po} = \frac{n_i^2}{p_{po}} = \underline{225 / cm^3}$$

$$\underline{n_{no}} = N_D = 10^{14} / cm^3; \quad \underline{p_{no}} = \frac{n_i^2}{n_{no}} = \underline{2.25 \times 10^6 / cm^3}$$

majority *minority*

i.e. simpler formula can be used

$$I_s = qA\left[\frac{D_p}{L_p} p_{no} + \cancel{\frac{D_n}{L_n} n_{po}}\right]$$

negligible

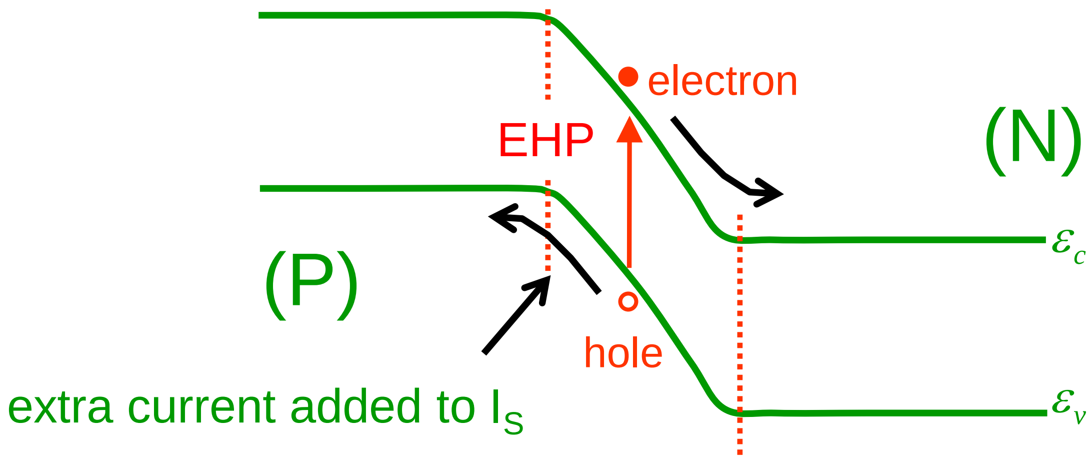
<u>One-Sided</u> $(P^+N): I_s = \frac{qAD_p\, p_{no}}{L_p} = \left(\frac{qAD_p n_i^2}{L_p N_D}\right)$

If one-sided <u>and</u> narrow-based, replace L_p by W_n

EXAMPLE 8.2

Generation and Recombination in the Depletion Layer

- We now re-visit the assumption of zero G-R in the depletion layer. In practice, thermally generated EHPs may be produced in this region, and, because of the intense electric field, they are quickly separated: electrons to the N-side and holes to the P-side. This results in an extra current component added to the saturation current I_S.



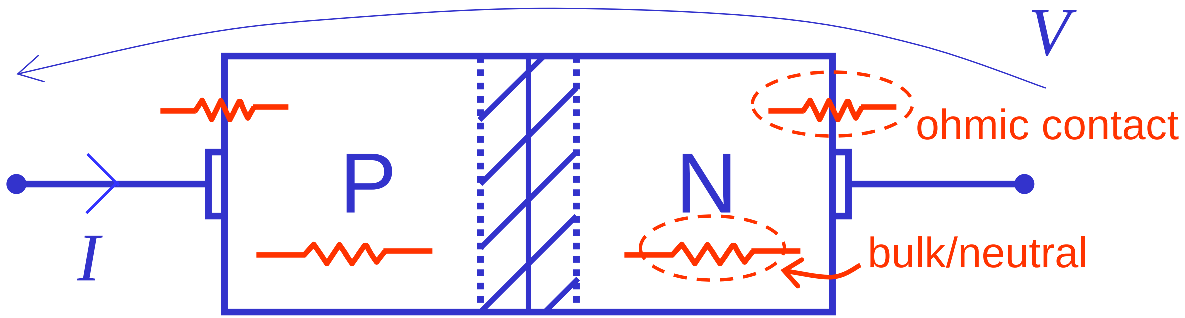
- The earlier analysis may be extended to take this into account.

$$I = I_s\left[e^{qV/kT} - 1\right] + I_{s1}\left[e^{qV/2kT} - 1\right]$$

don't remember

Extra term due to G-R

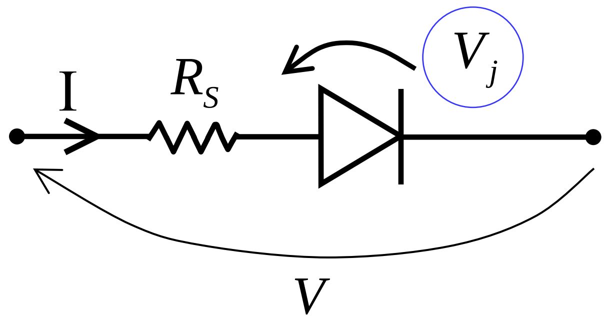
Effect of Parasitic Resistances



- Earlier we assumed zero electric field within each neutral region. In practice, there is 'ohmic' loss due to the finite conductivity of the semiconductor material in each region;
- In addition, the metal-semiconductor contacts are not perfect and this can be modelled by the introduction of a small series resistance at each contact;
- All of these can be lumped together into a single **parasitic resistance R_s** (~1Ω) in series with the 'ideal' PN structure.

DC Equivalent Circuit Model

- A simple DC equivalent circuit for the PN junction allowing for parasitic resistance effects can be constructed as follows:



- Although apparently a simple change, the introduction of R_S considerably complicates the task of solving this circuit (non-linear simultaneous algebraic equations involved):

$$I = I_s \cdot \left[e^{qV_j / kT} - 1 \right] \qquad V_j = V - I \cdot R_s$$

The Ideality Factor (n)

- In practical PN junctions, it is found that the ideal PN junction equation does a good, but not perfect, job of fitting the DC characteristics;
- A better result is obtained by introducing an empirical 'ideality factor' 'n' (this is a dimensionless number ≥ 1):

$$I = I_S \cdot \left[e^{\left(qV / n \cdot kT \right)} - 1 \right]$$

- In a perfect PN junction, n=1, while in a practical well-made Si junction we might find n = 1.04, for example;
- The ideality factor n, and saturation current I_S can be determined experimentally by plotting the $\log_e$ of the forward current against the voltage (i.e. $\ln|I|$ vs. V)

Determining 'n' and 'I_S'

- Assume a forward biased PN junction with V>>(kT/q) . Then we can use the approximation:

$$I \cong I_S \cdot e^{\left(qV / nkT \right)}$$

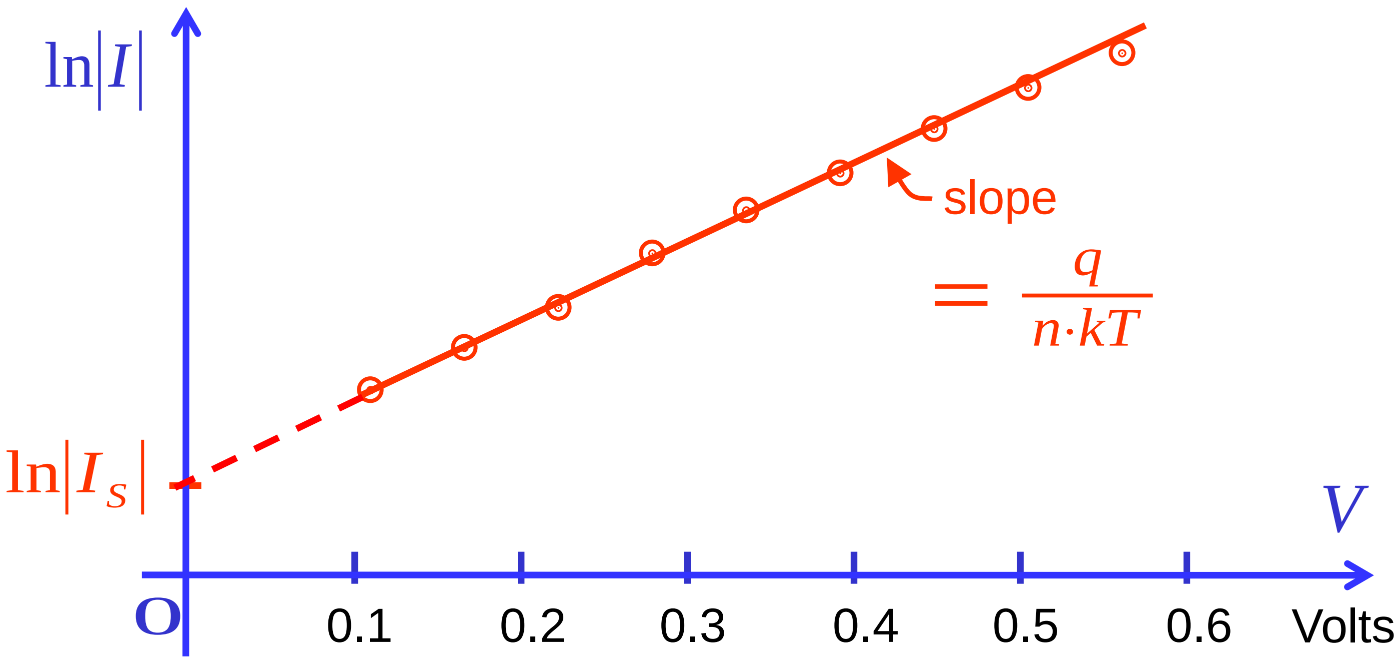
- Take the natural log of both sides:

$$\ln|I| = \ln|I_S| + \frac{qV}{nkT}$$

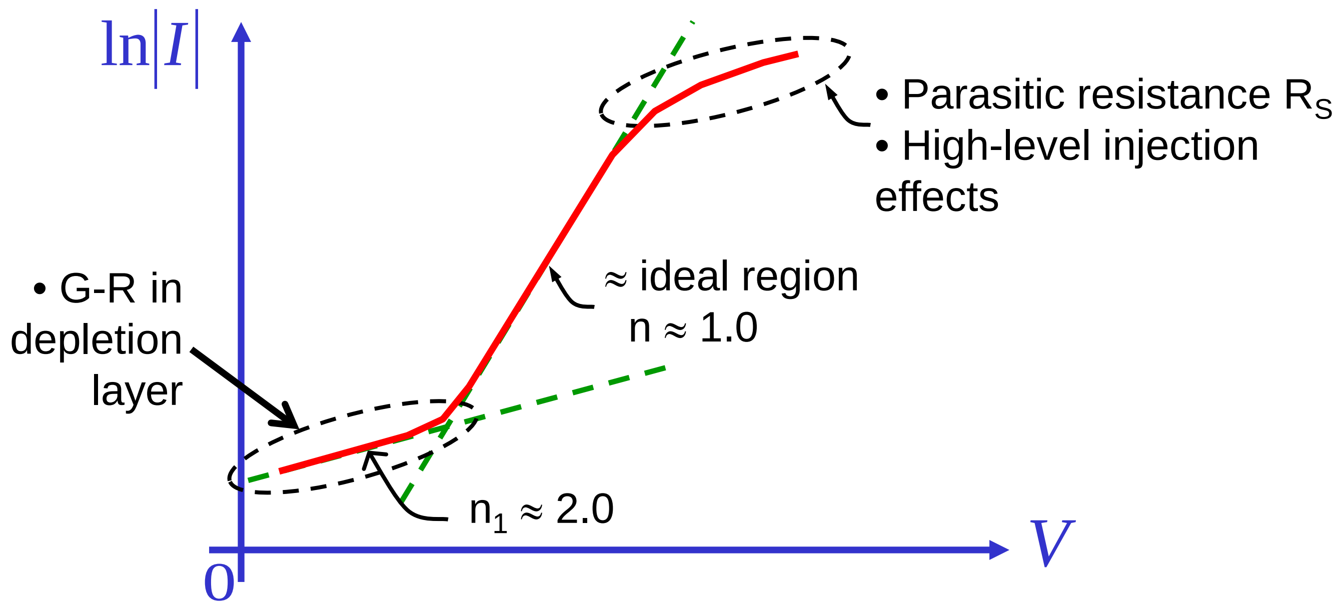
- This in the form of a straight line: " y = m.x +c" where "y" is *ln|I|* and "x" is *V*

Determining 'n' and 'I_S'

- By plotting $\ln|I|$ versus V (for V > ~100mV) we can find $\mathbf{I_s}$ from the y-axis intersection and then if the temperature T is known, we can estimate **n** from the slope.



Wide-Range ln|*I*| versus *V* Plot



$$I = I_s \cdot \left[e^{qV_j / n \cdot kT} - 1 \right] + I_{s1} \cdot \left[e^{qV_j / n_1 \cdot kT} - 1 \right] \qquad V_j = V - I \cdot R_s$$

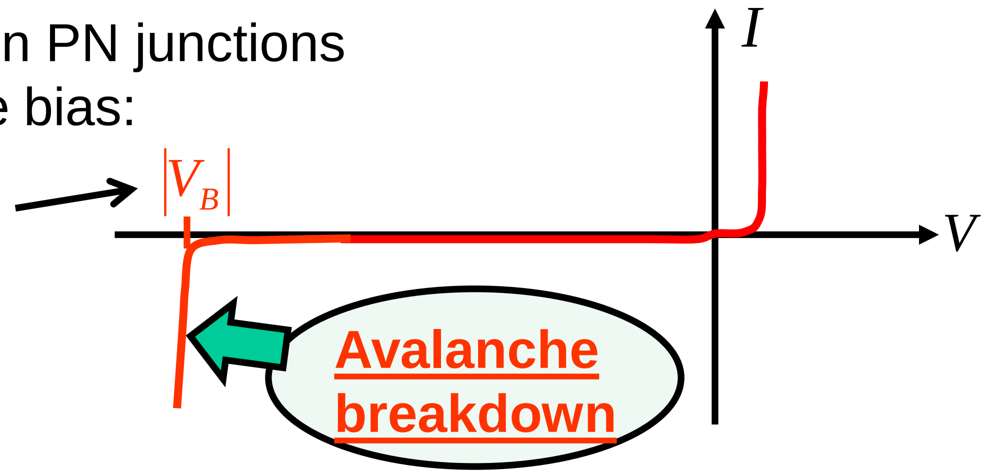
- Graphical plots like this are very useful for experimental **parameter extraction**, i.e. using measurements to identify critical parameters of device model: the above plot could be used to determine I_S, n, I_{s1}, n_1, R_S..

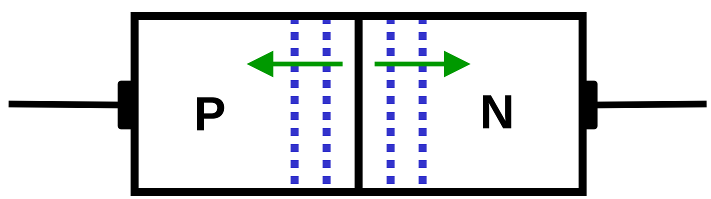
Example 8.3

Impact Ionisation and Avalanche Breakdown in PN Junctions

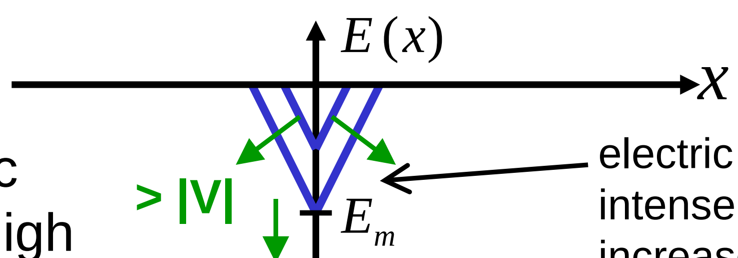
Experimentally we observe the following behaviour in PN junctions under strong reverse bias:

V_B: the **"breakdown voltage"**





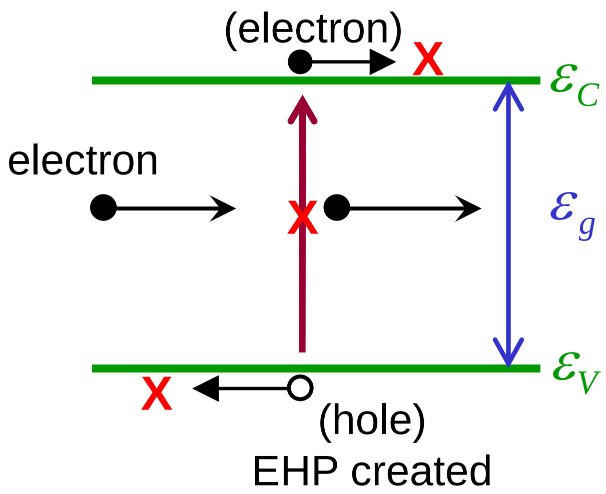
As |V| increases under reverse bias, the maximum electric field becomes very high



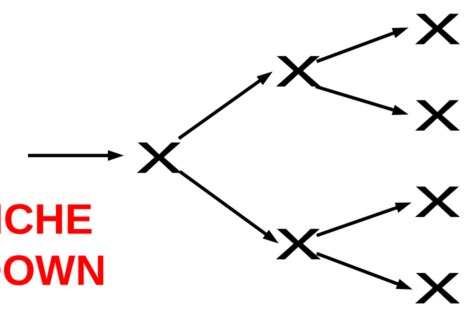
electric field becomes more intense as reverse bias increases

Impact Ionisation and Avalanche Breakdown

- At very high electric fields, the energy acquired by electrons between collisions can become so high that a collision with the lattice can transfer an electron from VB to CB (i.e. an EHP created). This is called **impact ionisation**
- The electron and hole thereby created are also accelerated by the field, and can acquire enough energy to create further EHPs – a chain reaction can then occur leading to a large increase in (reverse) current – **avalanche breakdown**



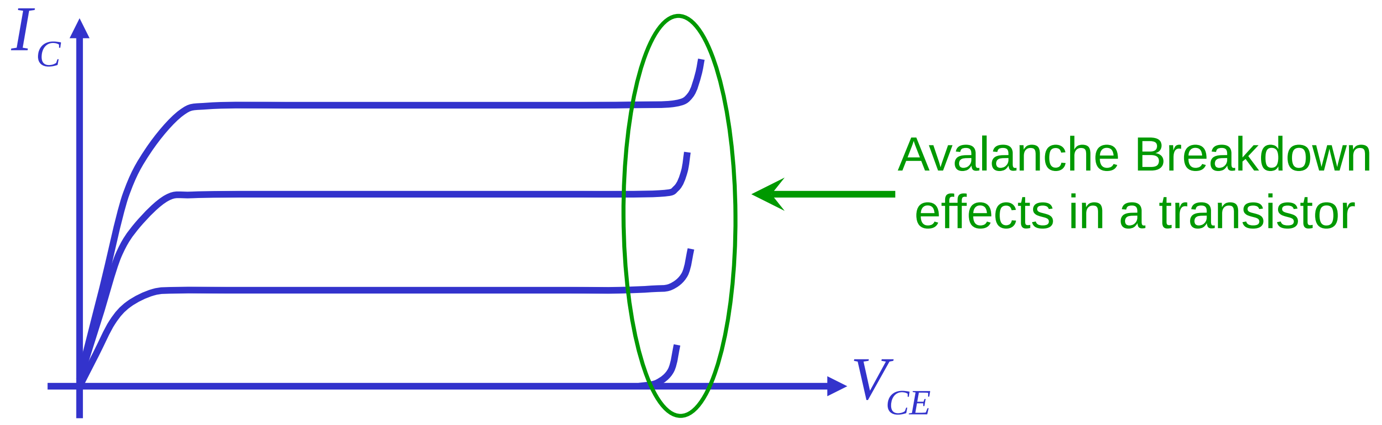
Chain reaction :



AVALANCHE BREAKDOWN

Avalanche Breakdown

- A sudden increase in current at high voltages due to avalanche breakdown is very commonly observed in semiconductor devices, e.g. transistor characteristics:



- Although it sounds catastrophic, it need not be if handled carefully and some kinds of device are even operated for years in continuous avalanche breakdown!

The Zener Diode

- When a PN junction is heavily doped on <u>both</u> sides (P^+N^+), the breakdown voltage can become quite low;
  - Diodes specifically designed to produce a stable, carefully-controlled reverse breakdown voltage often go under the general name of "Zener Diodes"
- Zener diodes are widely used as voltage references in electronic circuits