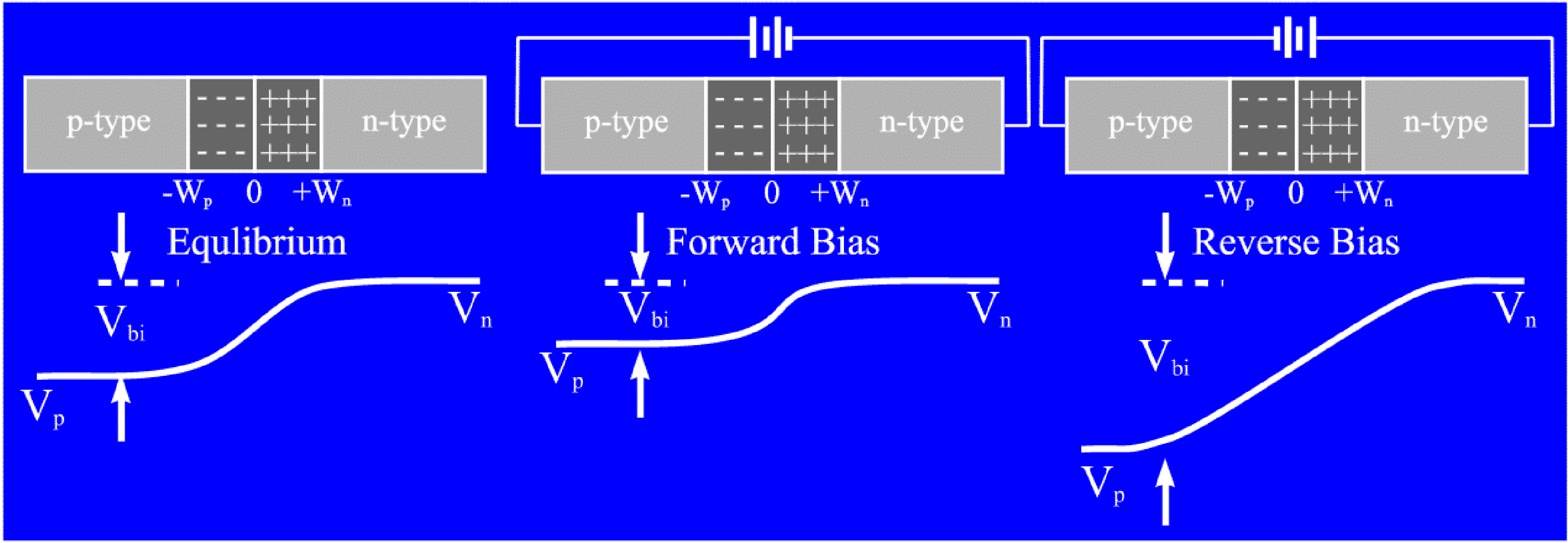
Lecture 6: PN Junctions under bias

- P-N junction under forward and reverse bias
  - Examples
- The Diode equation
- Current-voltage characteristics
- High voltage effects
- Modulation and switching
- P-N junction device response

P-N junction under bias

- If an external potential is applied across the p and n regions, the balance between the drift and diffusion currents no longer exists and a **net current will flow**.
- With the following assumption we can study the biased diode:
  - Assume that in the depletion region the electron and hole distributions are described by a Boltzmann distribution.
  - Across the depletion region the mobile carrier density is low and the external potential drops mainly across this region.
  - We assume the P-N junction is described by n- and p- regions and a depletion region.

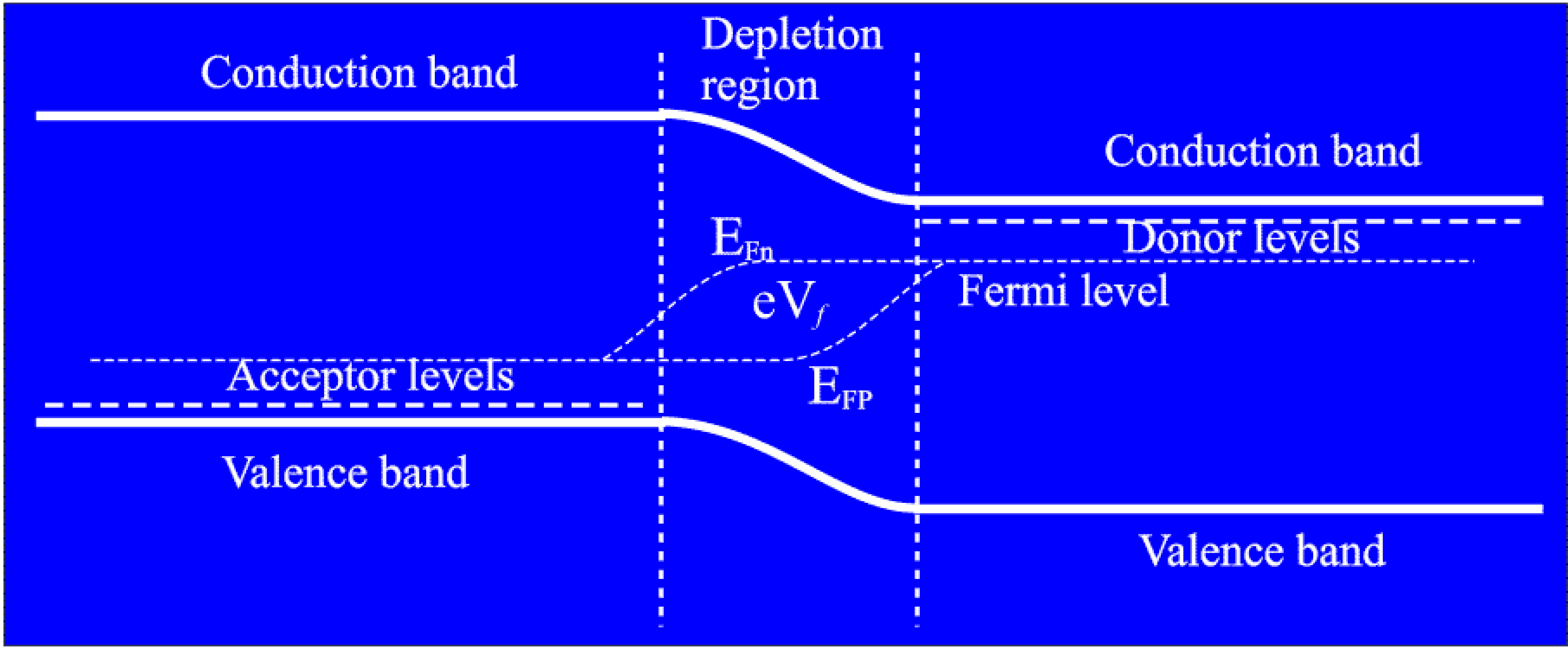
P-N junction under bias



- The biasing of a p-n junction.
- The equilibrium, forward and reverse bias cases are illustrated.
- Notice the voltage profile with the indication of the built in potential.

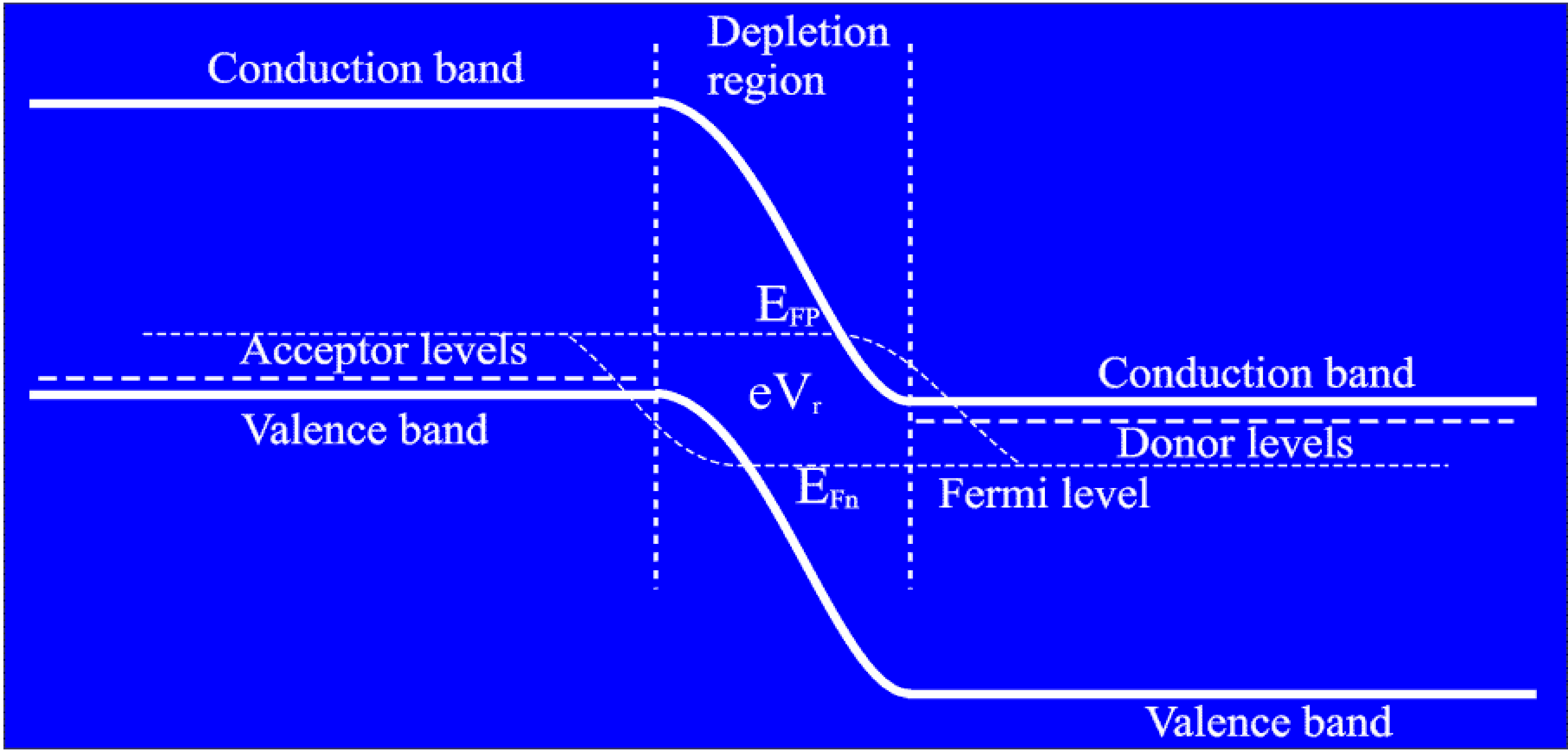
P-N junction under bias

- When a forward bias (V_f) is applied, the p-side is at a positive potential with respect to the n-side.
- The potential difference: $V_{Tot} = V_{bi} - V = V_{bi} - V_f$



P-N junction under bias

- In the reverse bias case the p-side is at a negative potential ($-V_r$) with respect to the n-side.
- The potential difference: $V_{Tot} = V_{bi} - V = V_{bi} + V_r$



P-N junction under bias

- Under the approximations given, the equations for electric field, potential profile and depletion widths are the same as shown in the previous lecture. The only difference is that V_{bi} is replaced by V_{tot}
- The important consequence is: The depletion width and peak electric field at the junction **will decrease under forward bias** and **increase under reverse bias**.

Example: Silicon Diode

- Consider a 20μm diameter silicon p-n diode. The donor density is 10^{16}cm^{-3} and acceptor density is 10^{18}cm^{-3}. What is the depletion width and E-field under the reverse biases of 0, 10 V and a forward bias of 0.5V.
- Start by calculating the built in potential is:

$$V_{bi} = \frac{k_B T}{e} \ln \frac{p_p}{p_n}$$

- The value of p_n is obtained by the law of mass action:

$$p_n = \frac{n_i^2}{n_n} = \frac{(1.5 \times 10^{10}\,\mathrm{cm}^{-3})^2}{10^{16}\,\mathrm{cm}^{-3}} = 2.25 \times 10^4\,\mathrm{cm}^{-3}$$

- The built in potential can hence be written:

$$V_{bi} = \frac{1.38 \times 10^{-23} \times 300}{1.6 \times 10^{-19}} \ln\left(\frac{10^{18}}{2.25 \times 10^4}\right) = 0.81\mathrm{V}$$

Example: Silicon Diode

- The depletion widths can hence now be calculated:

$$W_n = \left\{\frac{2\varepsilon V_{bi}}{e}\left[\frac{N_a}{N_d(N_a + N_d)}\right]\right\}^{1/2}$$

$$W_n(0.81) = \left\{\frac{2\times 11.9\times 8.85\times 10^{-12}\,\mathrm{F/m}\times 0.81}{1.6\times 10^{-19}}\left[\frac{10^{24}\,\mathrm{m}^{-3}}{10^{22}\,\mathrm{m}^{-3}\times(1.01\times 10^{24}\,\mathrm{m}^{-3})}\right]\right\}^{1/2}$$

$$= 0.32\,\mu\mathrm{m}$$

$$W_p(0.81) = 3.2\,\mathrm{nm}$$

$$W_n(10.81) = \left(\frac{10.81}{0.81}\right)^{1/2}\times 0.32\,\mu\mathrm{m} = 1.15\,\mu\mathrm{m}$$

$$W_p(10.81) = 11.5\,\mathrm{nm}$$

$$W_n(0.317) = 0.20\,\mu\mathrm{m}$$

$$W_p(0.317) = \left(\frac{0.317}{0.817}\right)^{1/2}\times 3.2\,\mathrm{nm} = 2\,\mathrm{nm}$$

Example: Silicon Diode

- The peak fields in the diode are given by:

$$E_m = -\frac{eN_dW_n}{\varepsilon}$$

$$E_m(0) = -\frac{1.6\times10^{-19}C\times10^{22}m^{-3}\times0.32\times10^{-6}m}{11.9\times8.84\times10^{-12}F/m}$$

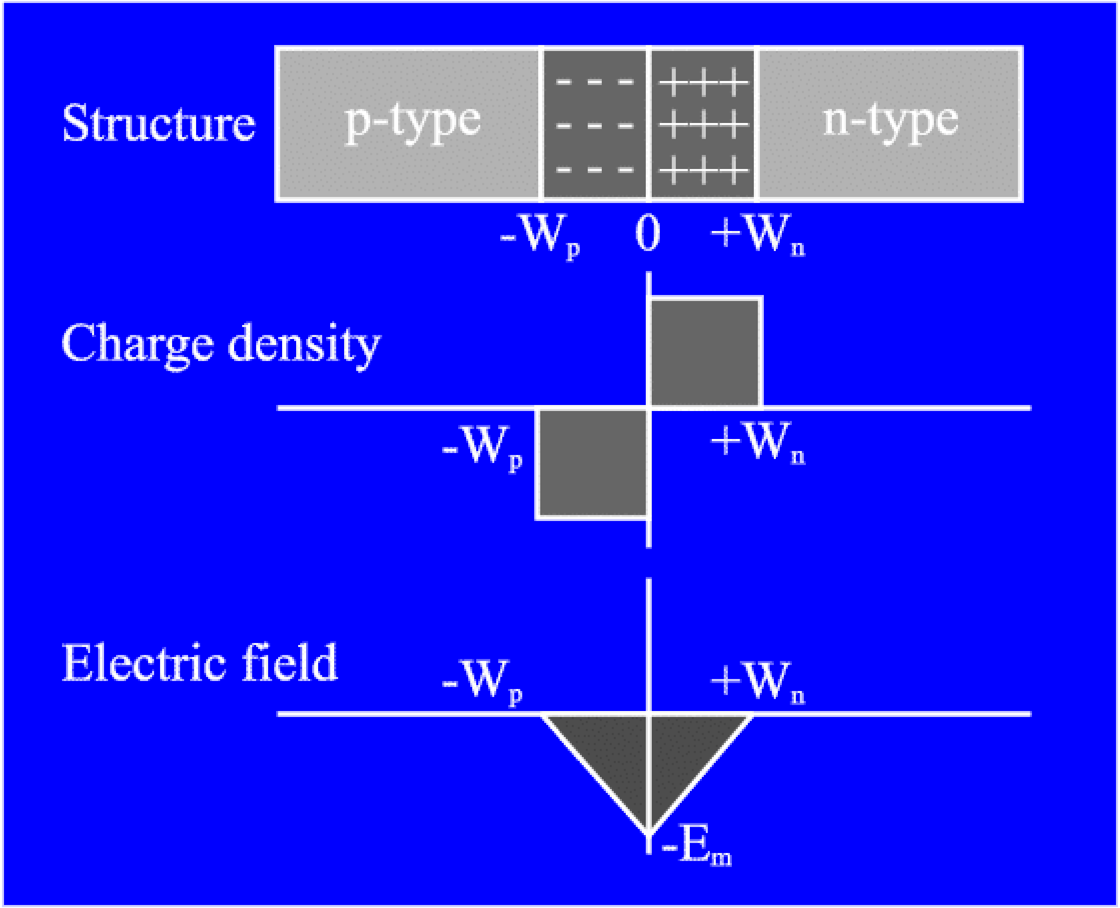
$$= -4.95\times10^{6}V/m = -4.95\times10^{4}V/cm$$

$$E_m(V_r10) = -1.78\times10^{5}V/cm$$

$$E_m(V_f0.5) = -3.14\times10^{4}V/cm$$

- At a reverse bias of ~10V, the peak field is beginning to approach the breakdown field for Si, which is around $3x10^5$V/cm.
- Note: the carrier density velocity remains unchanged, thus the drift current flowing in the depletion region is not affected by the bias conditions in a p-n diode.

Current components under bias



- We are interested in understanding the mobile carrier densities across the depletion region under bias.

Current components under bias

- How does the applied bias change the various current components in the p-n diode?
- The presence of bias increases or decreases the E-field in the depletion region.
- Under moderate bias (E>10kVcm^{-1}), the E-field in the depletion region is always higher than the field for carrier saturation.
- The change in the E-field does not alter the **drift** part of the electron or hole current in the depletion region. E-field in depletion region saturates v_d.
- The electrons or holes that come into the depletion region are swept out and contribute to the same current independent of the field.

Current components under bias

- The **diffusion** current depends on the gradient of the carrier density.
- The potential profile is considerably altered by the applied bias and the carrier profile will change accordingly, greatly affecting the diffusion current.
- The mobile carrier densities across the depletion region can be evaluated by recalling the relationship we have for no bias:

$$\frac{p_p}{p_n} = e^{eV_{bi}/k_B T}$$

- With an applied bias we can write:

$$\frac{p(-W_p)}{p_n} = e^{e(V_{bi}-V)/k_B T}$$

The Diode equation

- Under the assumption that in the ideal diode there is no recombination of the electron and hole injected currents in the depletion region.
- The **total current** can be obtained by adding the hole current injected across W_n and the electron current injected across $-W_p$.

$$I(V) = I_p(W_n) + I_n(-W_p)$$

$$= eA\left[\frac{D_p}{L_p}p_n + \frac{D_n}{L_n}n_p\right]\left(e^{eV/k_BT} - 1\right)$$

$$I(V) = I_0\left(e^{eV/k_BT} - 1\right)$$

- The diode equation gives the current through a *p-n* junction under forward and reverse bias.

The Diode equation

$$I(V) = I_0\left[e^{eV/k_BT} - 1\right]$$

- The diode equation gives us the current through a *p-n* junction under forward and reverse bias (recall $I=JA$).
- Under **forward bias** the current **increases exponentially** with the forward bias. Under **reverse bias**, the current simply goes towards **the $-I_0$ value**.

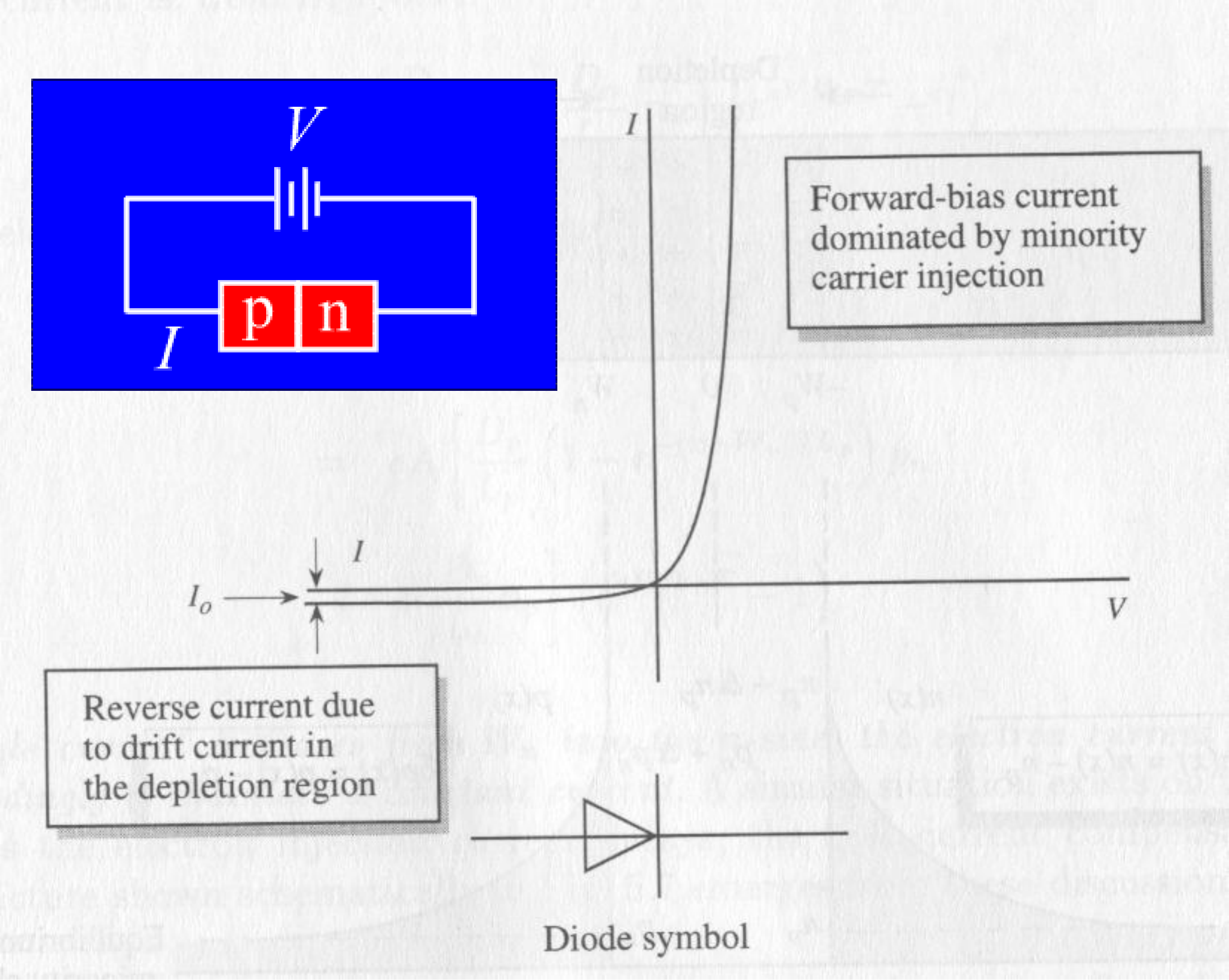
$$I_0 = eA\left(\frac{D_p p_n}{L_p} + \frac{D_n n_p}{L_n}\right)$$

- This strong **asymmetry** in the diode current is what makes the *p-n* diode attractive for many applications.

Current components under bias

- The current flow through a simple p-n junction has some interesting properties.
- There is no simple Ohm's law behaviour, but a strongly rectifying behaviour. The current saturates to a value I_0 (given by the diode equation), when a reverse bias is applied.
- When a positive bias is applied, the diode current increases exponentially and becomes strongly conducting.
- The forward bias voltage at which the diode current becomes significant (~10^3Acm^{-2}) is called the **cut-in voltage**.
- This voltage is ~0.8V for Si diodes and ~1.2V for GaAs diodes.

Current-voltage characteristics



Forward-bias current dominated by minority carrier injection

Reverse current due to drift current in the depletion region

Diode symbol

High voltage effects in diodes

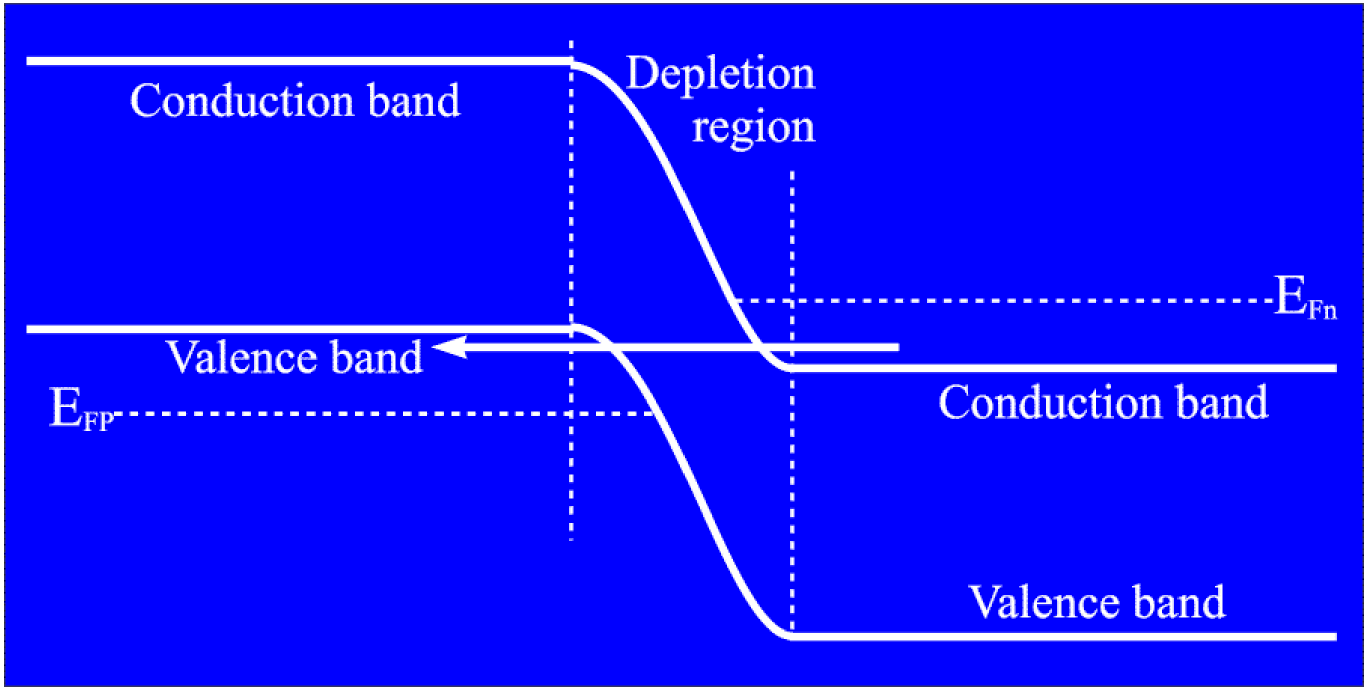
- As the forward bias is increased:
  - The injection of **minority carriers increases** and eventually the injected minority carrier density becomes comparable to the majority carrier density.
  - An increasing large fraction of the external bias drops across the undepleted region. The diode current will stop growing exponentially with the applied voltage, instead it will saturate.
  - The minority carriers inject move not only under diffusion effects, but also under the E-field that is now present in the undepleted region and the device has a more Ohmic behaviour.
  - At the high current densities involves the device may heat and suffer burnout.

High voltage effects in diodes

- Reverse Bias:
  - Impact Ionisation
  - Zener Tunneling
- Impact Ionisation:
  - Under very high E-fields the electron acquires so much energy that it can scatter from an electron in the valence band, knocking it into the conduction band – **Impact Ionisation**.
  - Once the applied bias becomes so large that $E_m=E_{crit}$. The impact ionisation process starts to become dominant and the current shows a runaway behaviour.

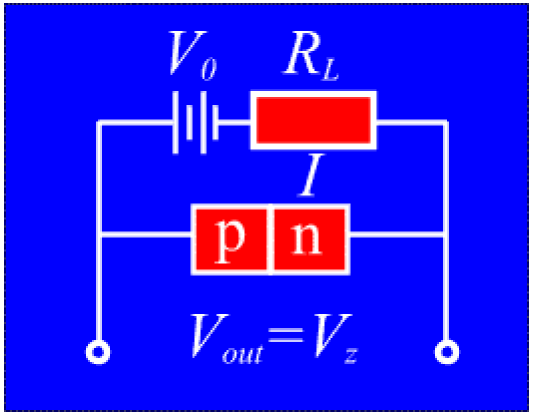
High voltage effects in diodes

- Reverse bias:
  - Quantum mechanical tunnelling allows electrons in the valence band to tunnel into the conduction band.
  - As the E-field in increased (reverse biased) the effective barrier that an electron in the valence band has to overcome to get to the conduction band starts to decrease.



High voltage effects in diodes

- Once this tunnelling probability becomes significant, there are so many free carriers that the diode effectively starts to short out.
- If the junction is made from heavily doped materials, Zener tunnelling can start at the reverse bias of V_z (as low as a few tenths of a volt).
- The voltage across the junction is then clamped at V_{zm} and the current is controlled by the external circuit:



This clamping property is a very useful application for Zener diodes

$$I = \frac{|V - V_z|}{R_L}$$

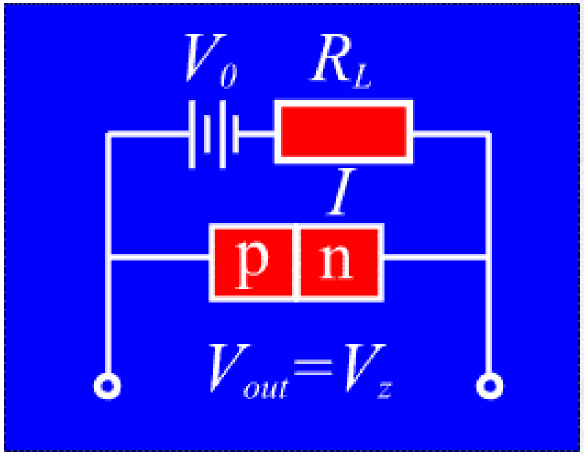
High voltage effects in diodes

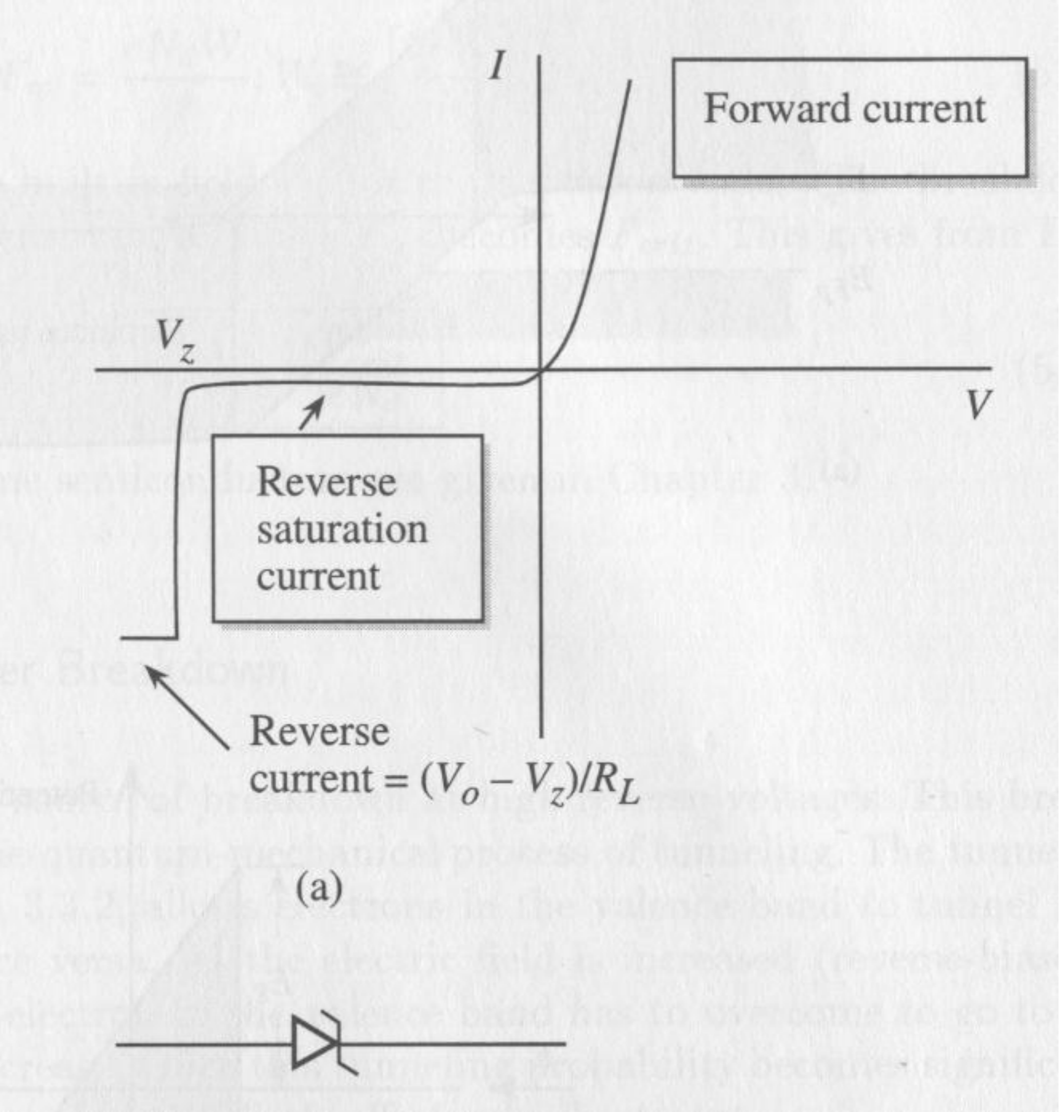
- The *Zener* tunnelling probability (lecture 4) is:

$$T \cong \exp\left(\frac{-4\sqrt{2m^*}E_g^{3/2}}{3e\hbar E}\right)$$

- The breakdown does not have to be catastrophic for the device if the external circuit is properly designed so that the current flow is not excessive.
- Which breakdown process dominates depends on the diode width, doping levels and the semiconductor material.

High voltage effects in diodes

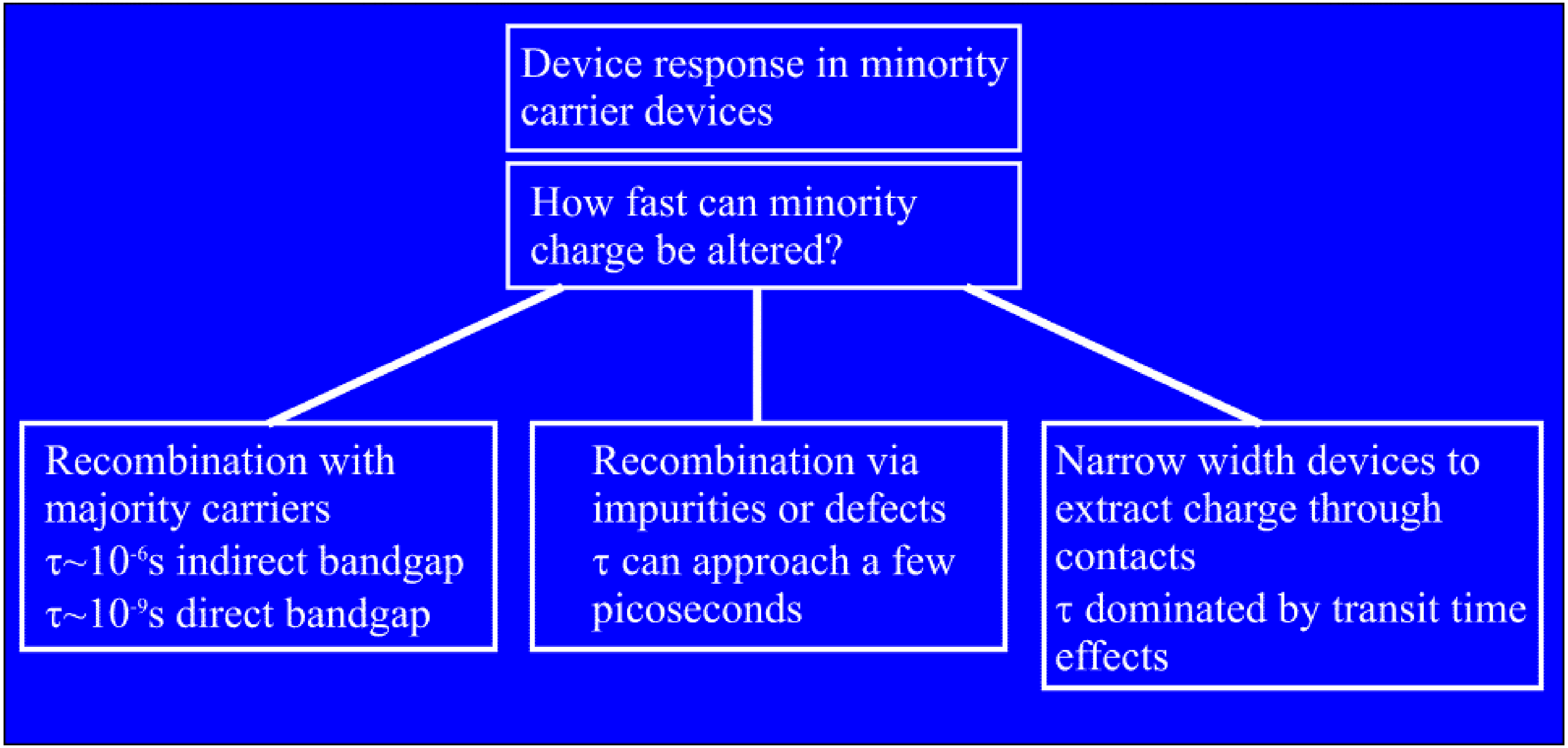




Modulation and switching

- Many important applications of the diode involve the AC properties of the diode. The transient properties of the diode are not very good, especially for high speed applications.
- This is one reason why diodes have been replaced by transistors and Schottky diodes in many applications.
- **The p-n junction is a minority carrier device**; it involves the injection of electrons into a p-type region and holes into an n-side region.
- In forward-bias where the diode is in a conducting state, the current is due to the minority charge injection.
- If this device is to be switched, this excess charge must be removed. The device time response depends on how fast the injected minority charge can be altered.

Minority carriers: Device response



Device response in minority carrier devices

How fast can minority charge be altered?

Recombination with majority carriers
$\tau \sim 10^{-6}$s indirect bandgap
$\tau \sim 10^{-9}$s direct bandgap

Recombination via impurities or defects
τ can approach a few picoseconds

Narrow width devices to extract charge through contacts
τ dominated by transit time effects

Device response characteristics for a minority carrier device.

Summary of lecture 6

- Current components
- The Diode equation
- Current-voltage characteristics
- High voltage effects
- Modulation and switching
- P-N junction device response