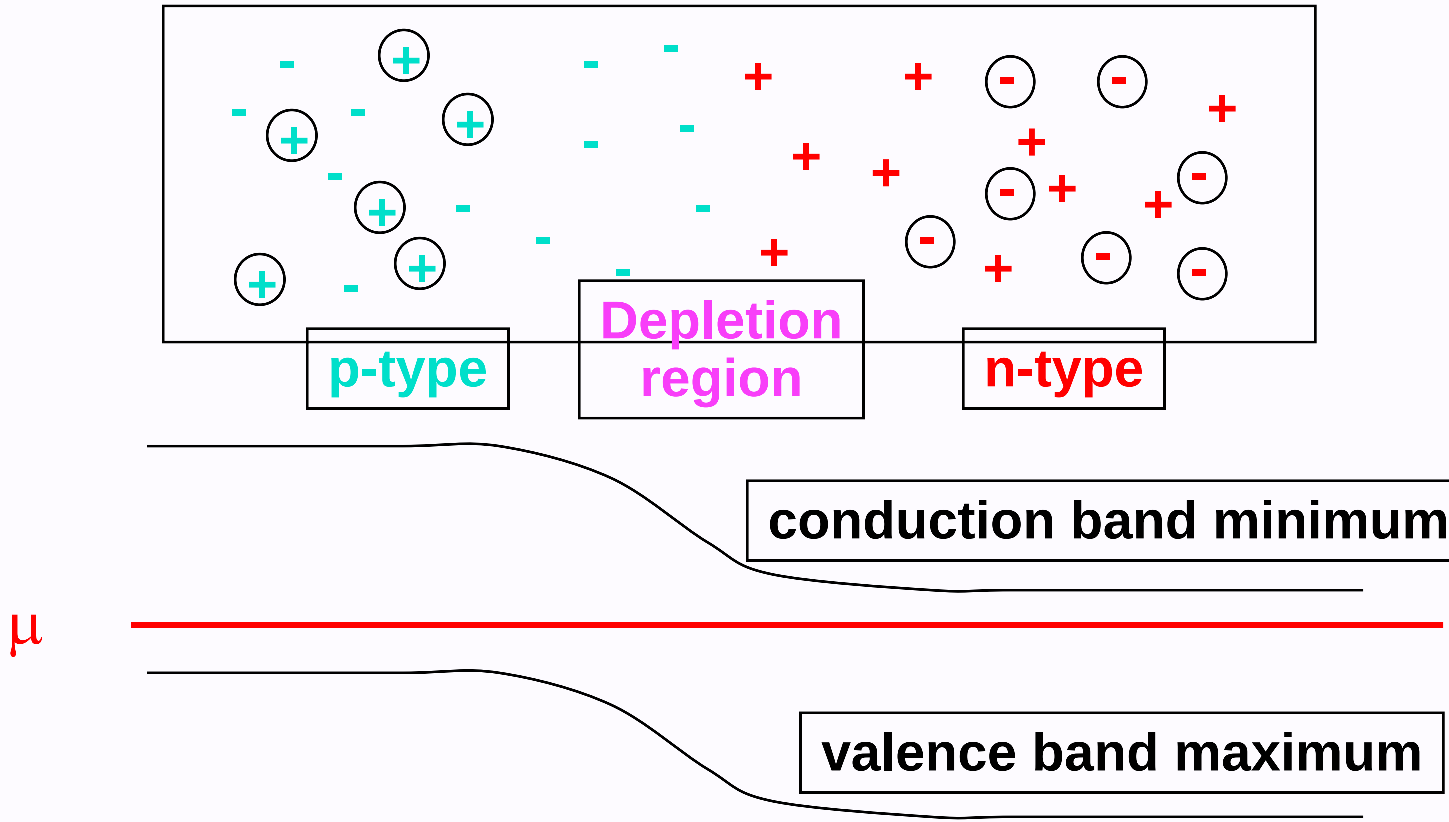
Lecture 19: Semiconductor Devices
Kittel Ch. 17, p. 503 - 512
+ extra material in lecture notes



Comment

- If the universe were a homgeneous crystal, it would be a very dull place
- It is the inhomogeneities that create our interesting world
- Sun - earth - …
- Metals - insulators together to make useful circuits
- The power of semiconductors is the ability to control their electrical (and optical) properties to make devices

Outline

- **What is a semiconductor device?**
- **Key point 1 - Bands and Fermi energy**
  Bands Relative to Fermi energy
- **Key point 2 - inhomogeneous material or doping**
  Variation in concentrations of electrons and holes by controlled doping profiles
- **p-n junctions - rectification- forward - reverse bias**
- **Metal-semiconductor junctions**
  Schottky barriers - rectification
- **Solar Cells**
- **Light emitting diodes**
- **Bipolar transistor n-p-n p- n-p**
- **Kittel Ch. 17, p. 503 - 512 + added materials in the lecture notes**

What determines the Band Energies and the Fermi Energy?

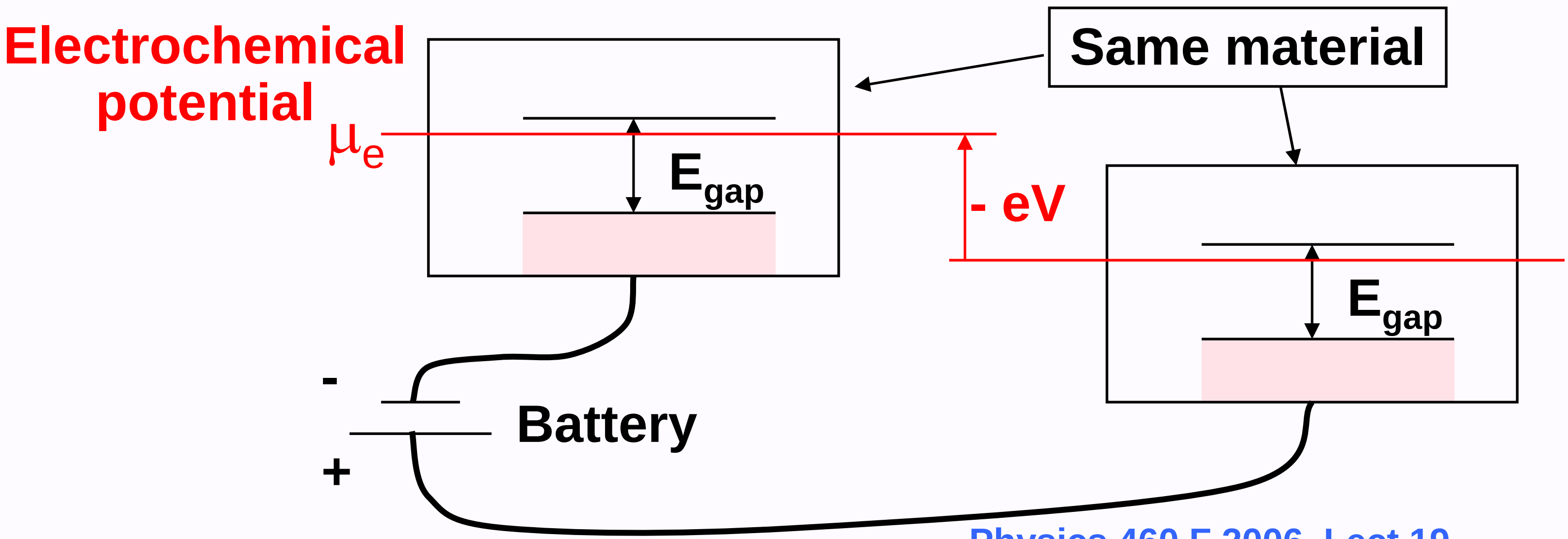
- Recall that the product
  $n\, p = 4\,(k_B T/ 2\pi^2)^3 (m_c m_v)^{3/2} \exp(-(E_c - E_v)/k_B T)$
  is independent of the Fermi energy
- BUT the concentrations n and p vary depending on the Fermi energy relative to the band energies

- $n = 2(m_c k_B T/ 2\pi^2)^{3/2} \exp(-(E_c - \mu)/k_B T)$
  $= N_0 \exp(-(E_c - \mu)/k_B T)$

- $p = 2(m_v k_B T/ 2\pi^2)^{3/2} \exp(-(\mu - E_v)/k_B T)$
  $= P_0 \exp(-(\mu - E_v)/k_B T)$

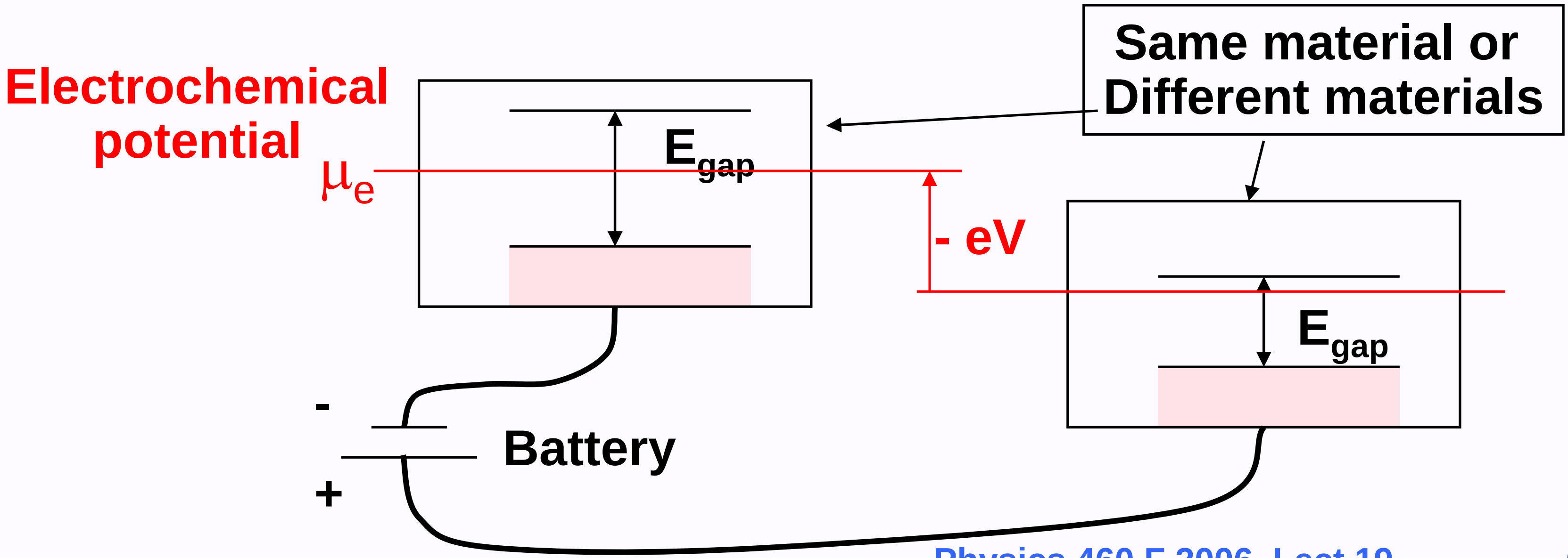
Band Energies and the Fermi Energy

- Key Points:
- 1A: Band energy differences, e.g., $E_{gap} = E_c - E_v$ are intrinsic properties of a material
- 1B: The absolute energy of the bands is NOT an intrinsic property. The electron band energies all shift by -eV(r) due to an electrostatic potential V(r).



Band Energies and the Fermi Energy

- Key Points:
- 1C: The Fermi energy μ is the energy to add or remove an electron, which is everywhere the same if the system is in equilibrium. One can either work with μ or with the "electrochemical potential" $\mu_e = \mu + eV(r)$ due to an electrostatic potential V(r).



What determines the Band Energies and the Fermi Energy?

- If there are inhomogeneous variations in the concentrations n and p as a function of position, the relations can be written

- $n = N_0 \exp(-(E_c - eV(r) - \mu)/k_B T) \quad = \quad N_0 \exp(-(E_c - \mu_e)/k_B T)$

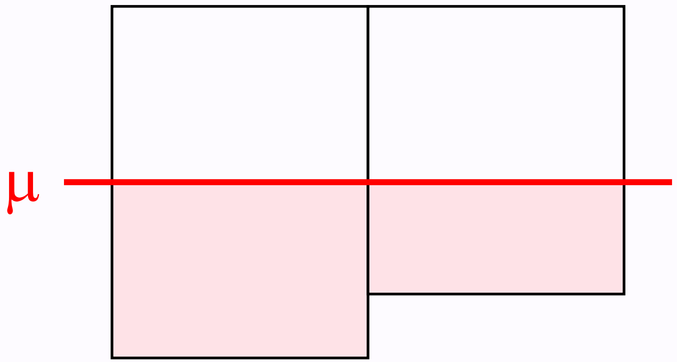
- $p = P_0 \exp(-(\mu - E_v + eV(r))/k_B T) \quad = \quad P_0 \exp(-(\mu_e - E_v)/k_B T)$

- Either form is correct and the relations obey the law of mass action:

$$n\, p = N_0 P_0 \exp(-(E_c - E_v)/k_B T) = N_0 P_0 \exp(-E_{gap}/k_B T)$$

Band Energies and the Fermi Energy

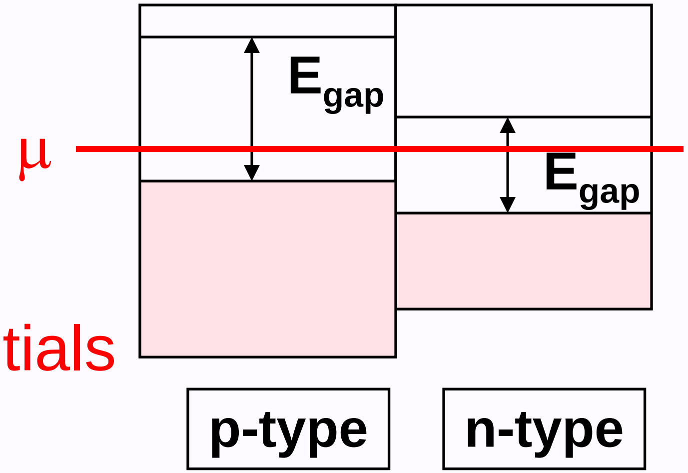
- Examples
- Line up of Fermi energy of two metals in contact



- Two semiconductors in contact

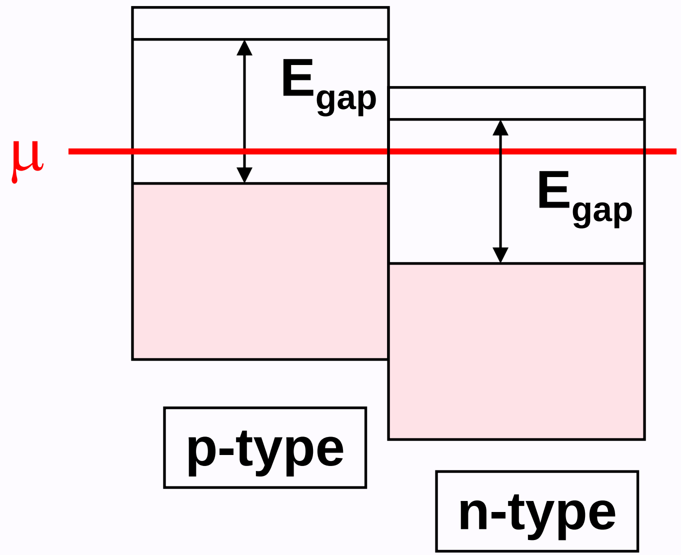
- Band are shifted by -eV(r) so that is the same.

  This means that there must be electrostatic potentials V(r) to make this happen



Inhomogeneous Semiconductors

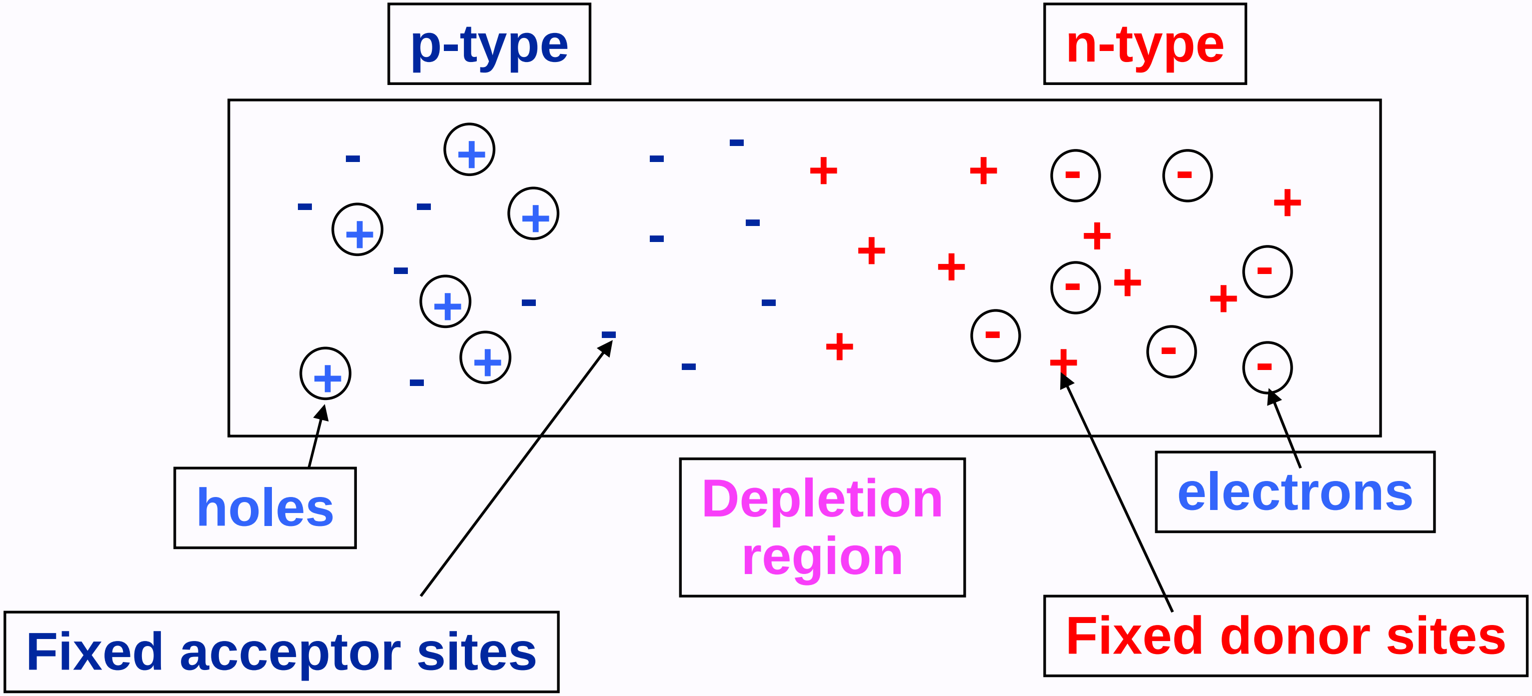
- First Example: one material doped differently in different regions



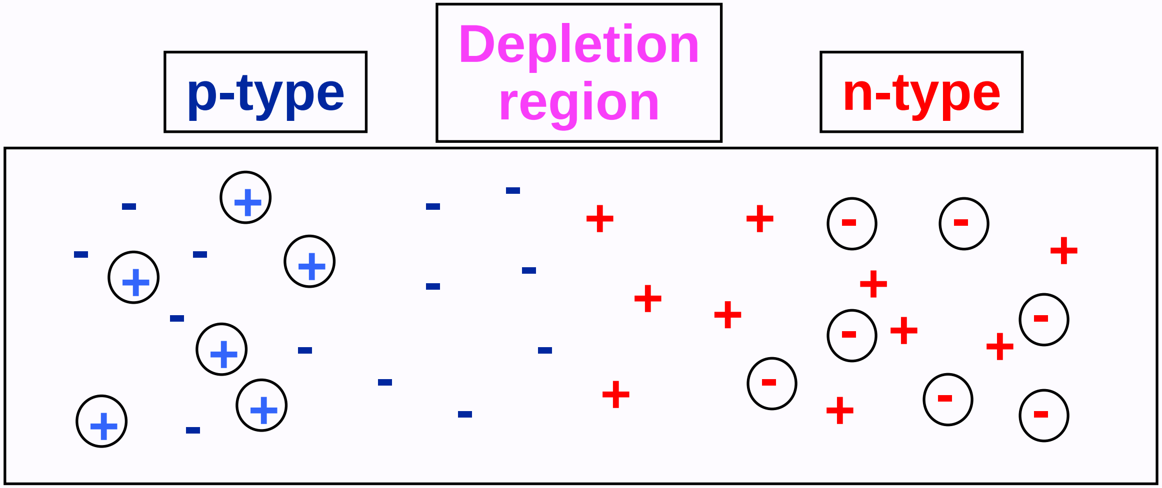
- How can this happen?
- Key assumption:
  variations are slow on
  the atomic scale
  - can treat as smoothly varying

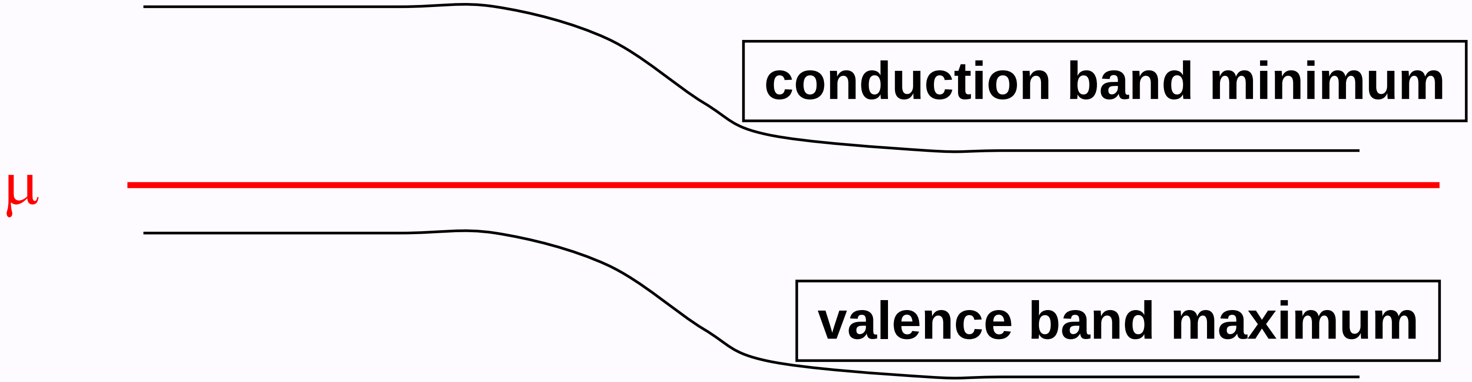
Inhomogeneous Semiconductors

- First Example: one material doped differently in different regions
- Looking more closely at the doping near the boundary:



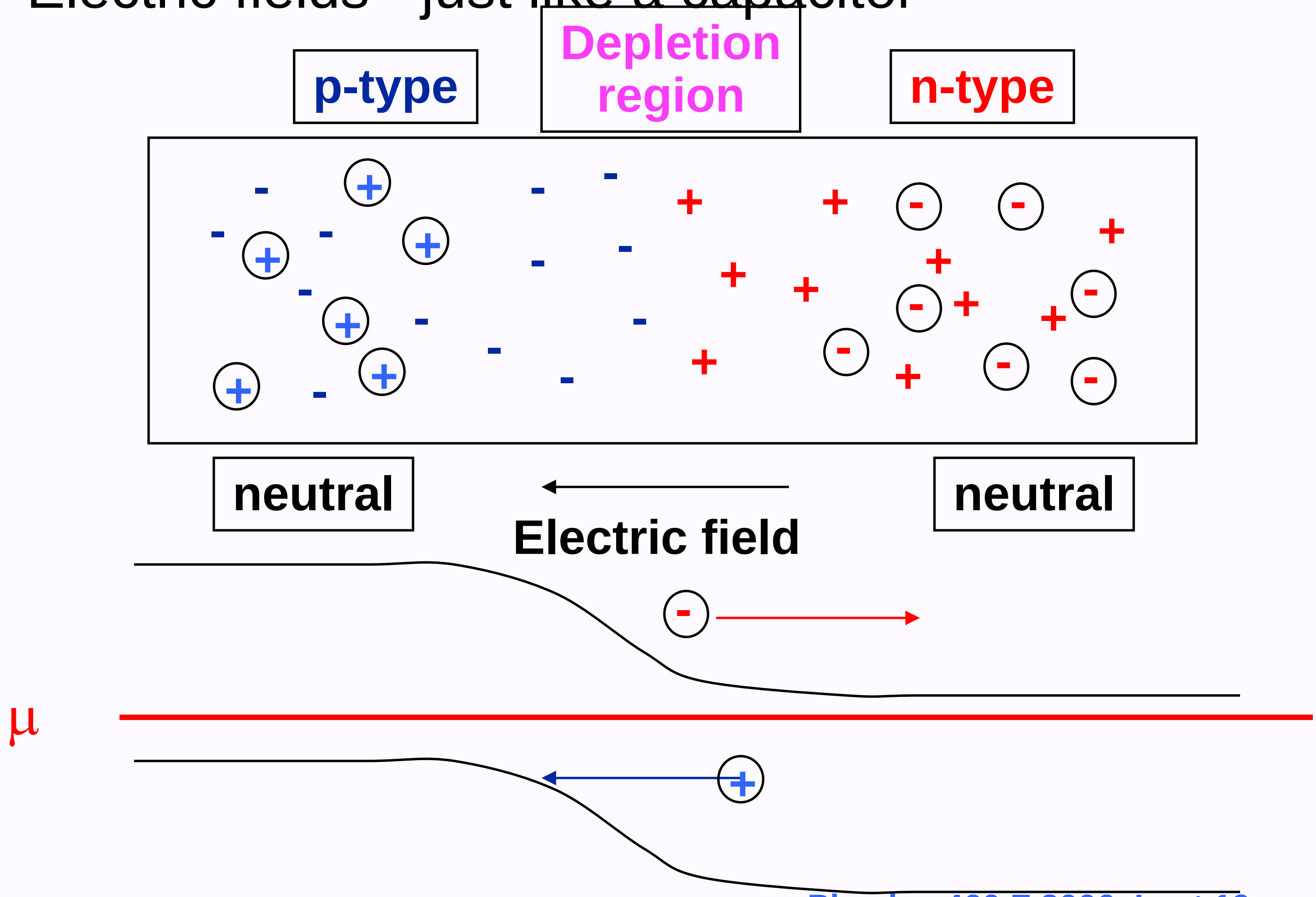
p-n junction


p-type
Depletion region
n-type


conduction band minimum
μ
valence band maximum

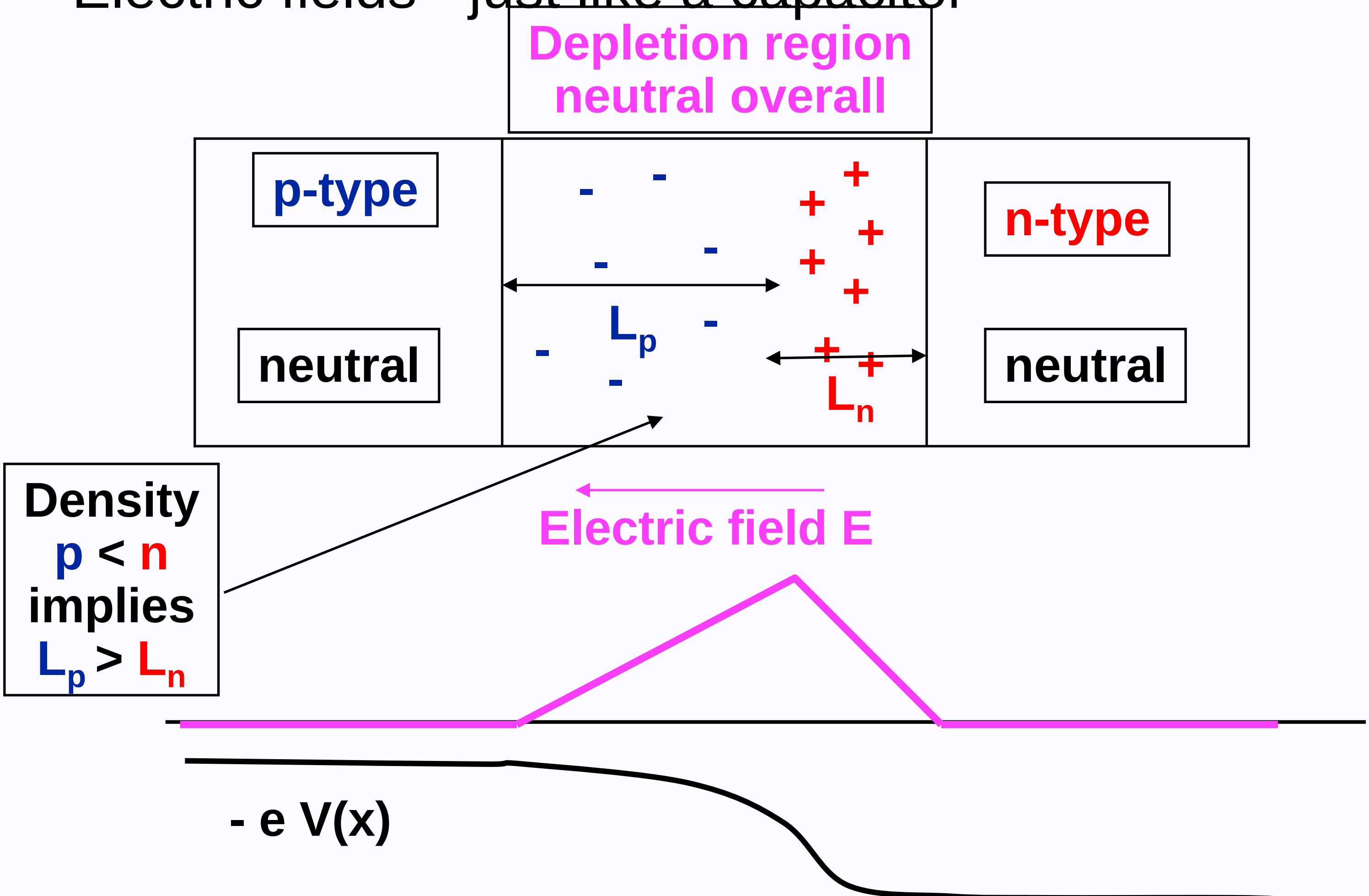
What causes bands to shift?

- Electric fields - just like a capacitor



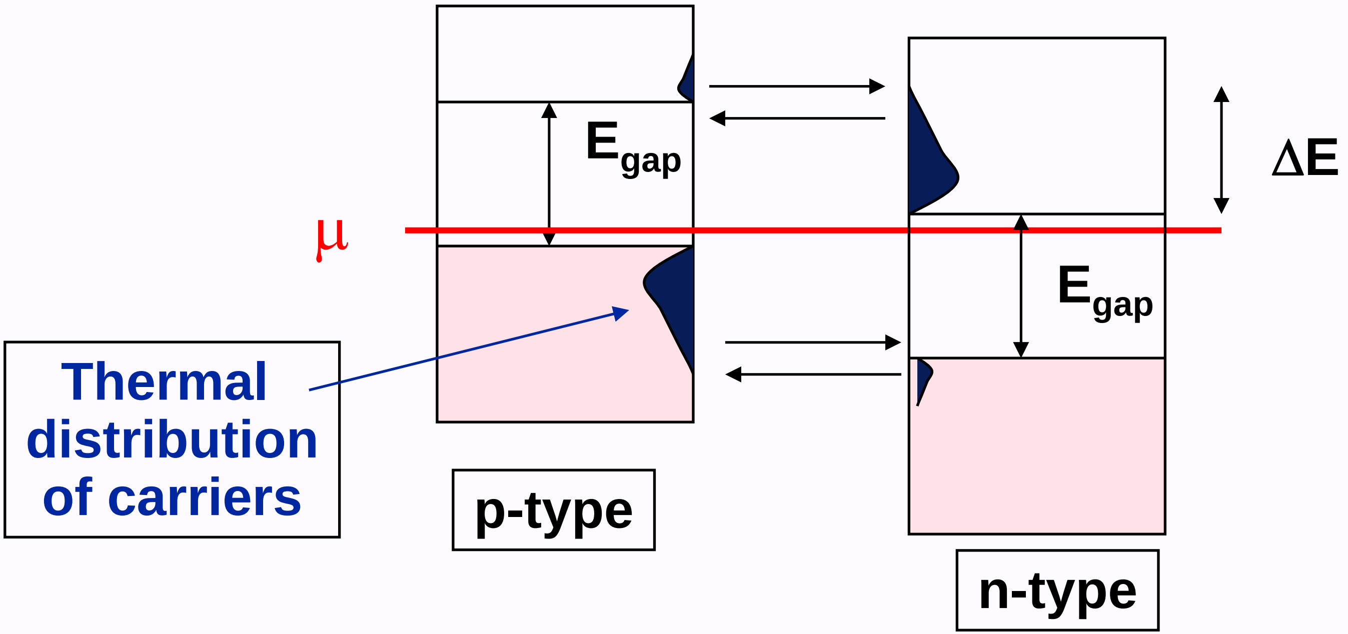
What causes bands to shift?

- Electric fields - just like a capacitor



Equilibrium

- In equilibrium with no applied voltage there is no net current, but there is always a generation and absorption of holes and electrons across the interface.
- Electrons on p side (n_p) easily go to n side at rate An_p
- Electrons on n side go to p side at rate $C \exp(-\Delta E/k_B T)$

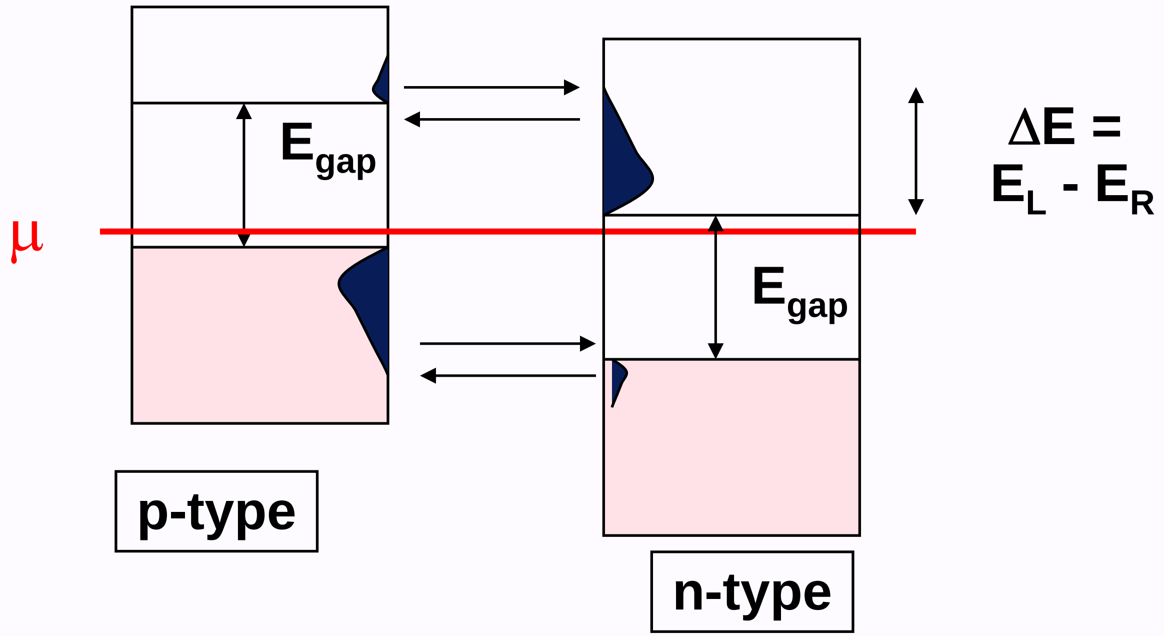


Equilibrium

- In equilibrium the current density of electrons is given by the difference of terms for left ⇒ right and right ⇒ left

$$j = C\exp(-\Delta E/k_BT) - An_p = 0$$

- Similarly for holes

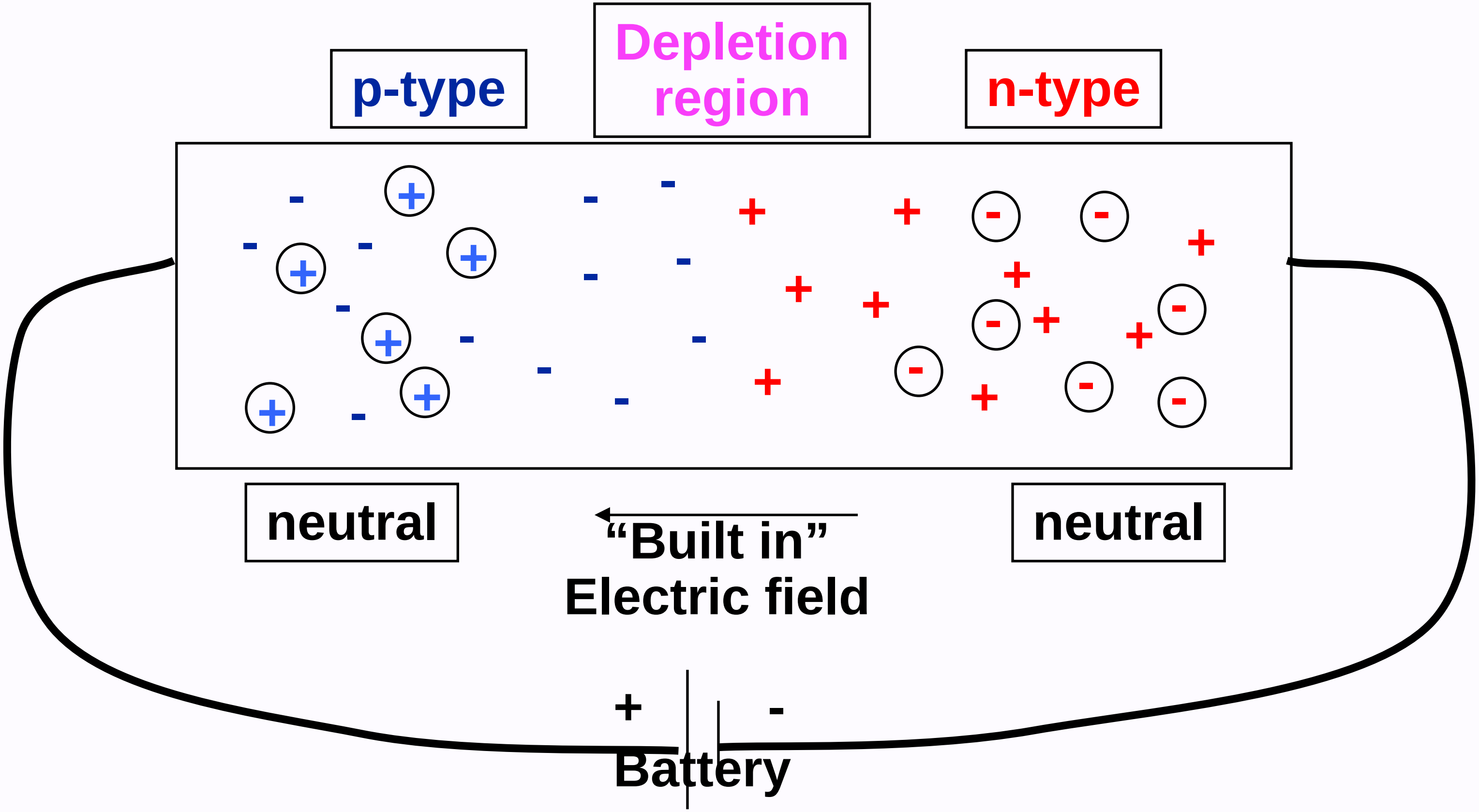


How can a pn junction be used to make a diode?

- A device that passes current easily in one direction
- Low resistance for voltage applied in one direction (the forward direction)
- High resistance for voltage applied in the other direction (the reverse direction)

Forward bias

- Apply a voltage V to reduce the difference between the two sides to $\Delta E - e\Delta V$ ($\Delta V > 0$) ($\Delta E = E_L^0 - E_R^0$)

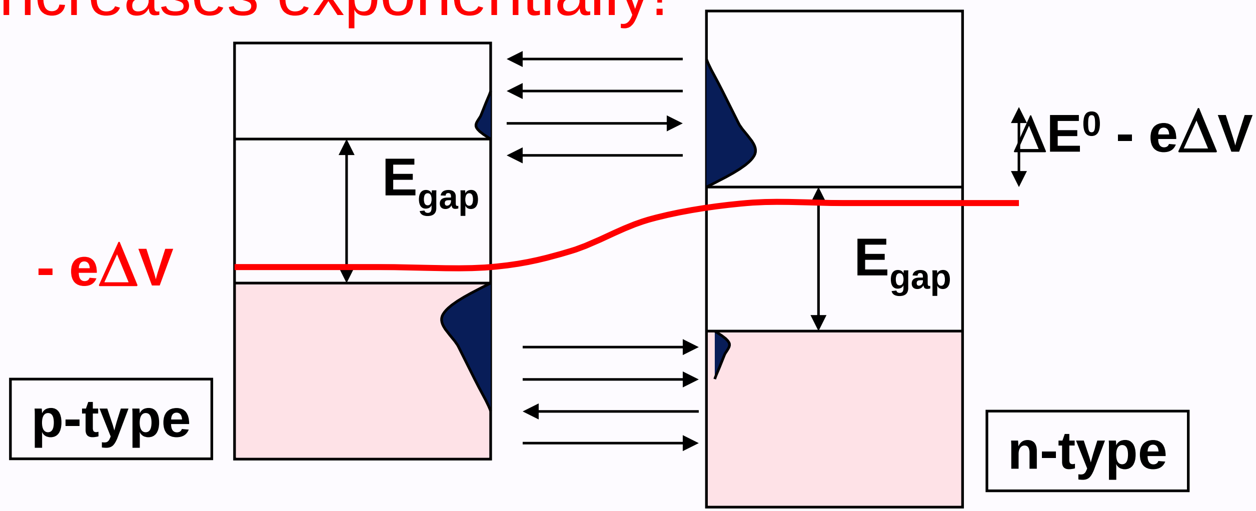


Forward bias

- Reduce the difference between the two sides to
  $\Delta E = E_L^0 - E_R^0 - e(V_L - V_R) = \Delta E^0 - e\Delta V$ (with $\Delta V > 0$)
- The net electron current is

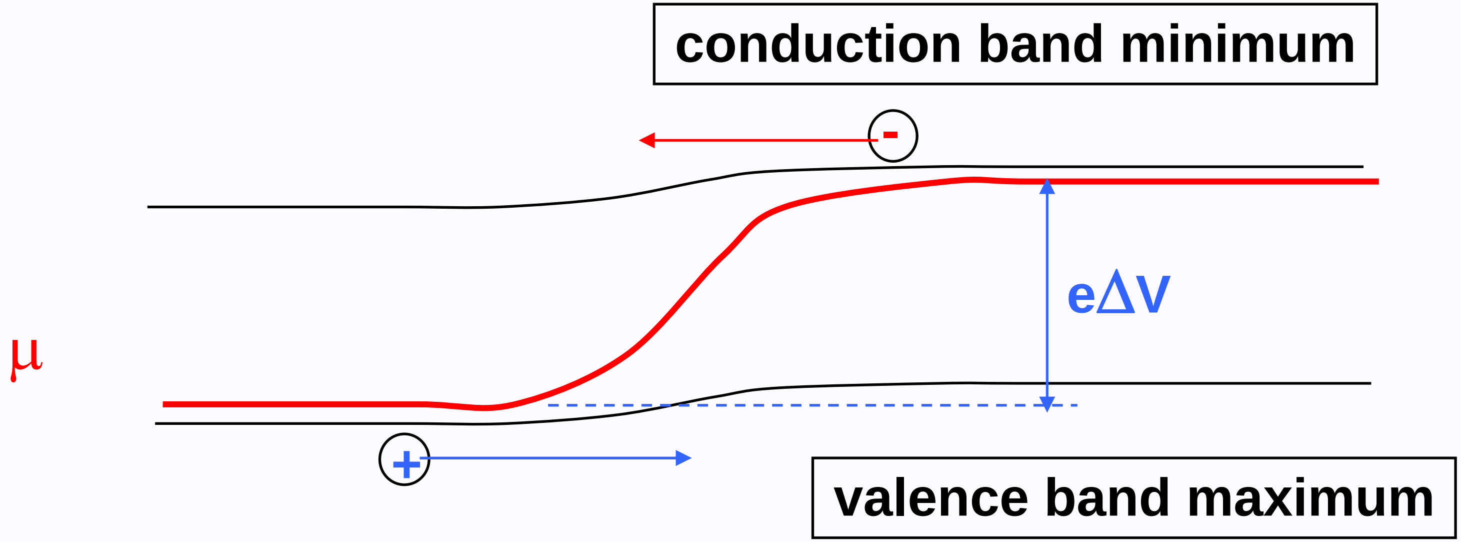
$$j = C\exp(-(\Delta E - e\Delta V)/k_B T) - A n_p$$
$$= A n_p [\exp(+e|\Delta V|/k_B T) - 1]$$

- Similarly for holes
- Current increases exponentially!



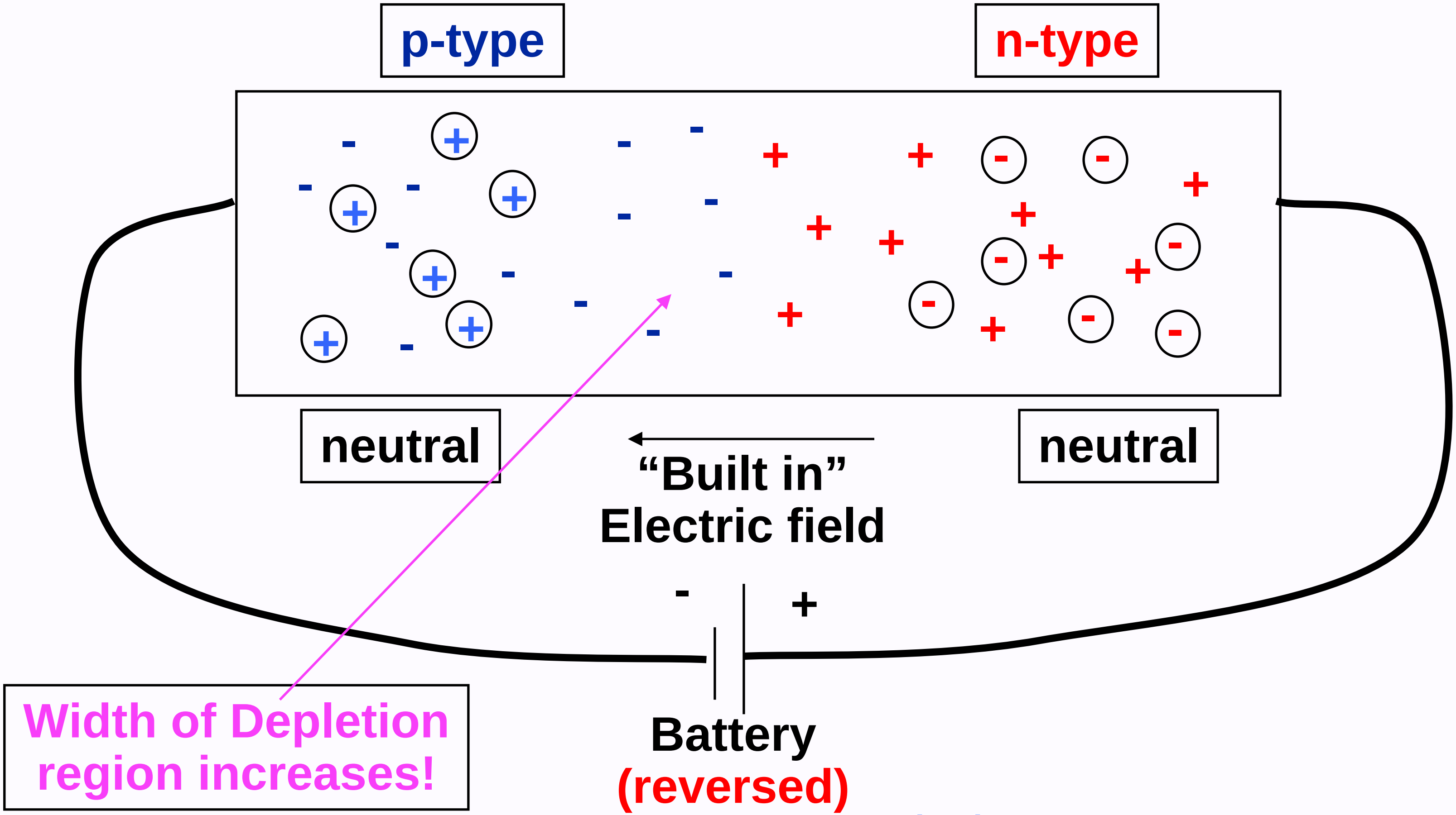
Forward bias

- The difference between bands on the left and right increases
- Below is figure of band energies near the "flat band" condition
- Current flows easily



Reverse bias

- Apply a voltage V to increase the difference between the two sides to $\Delta E + eV$ $(V > 0)$

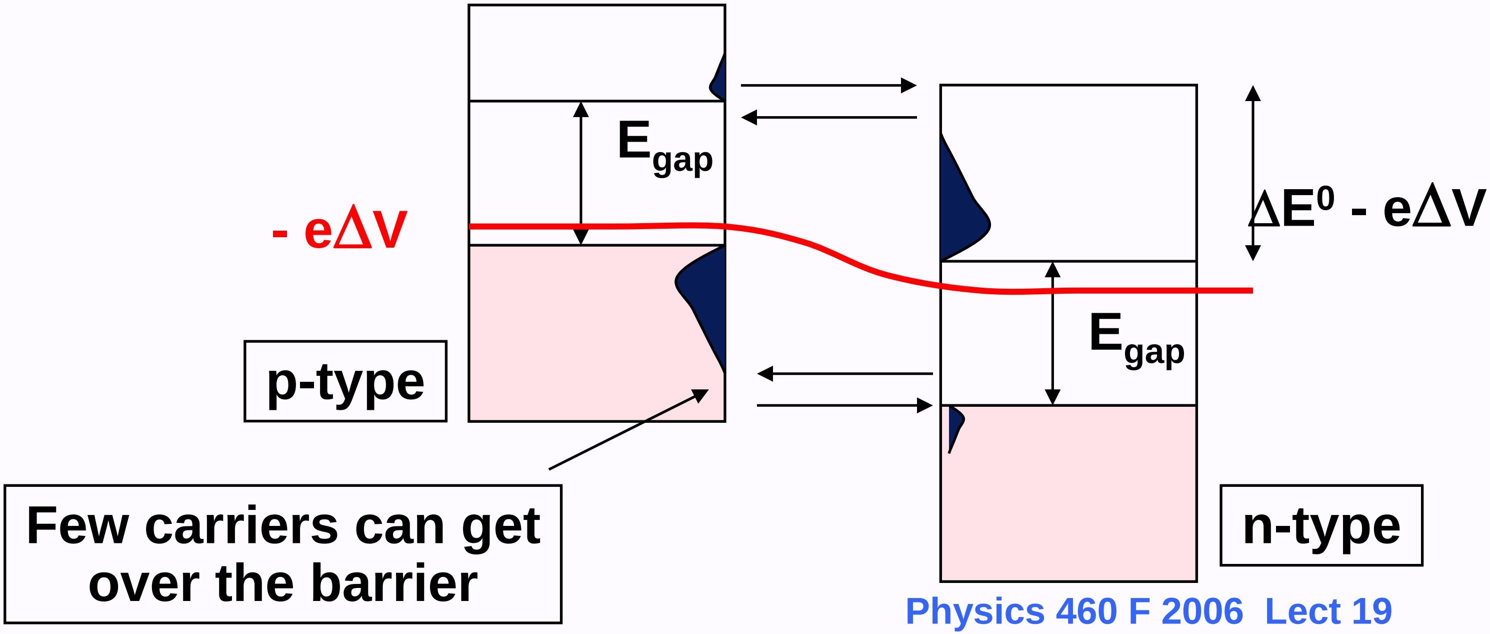


Reverse bias

- Current obeys same formula but with with $\Delta V < 0$
- Now the net electron current is (Similarly for holes)

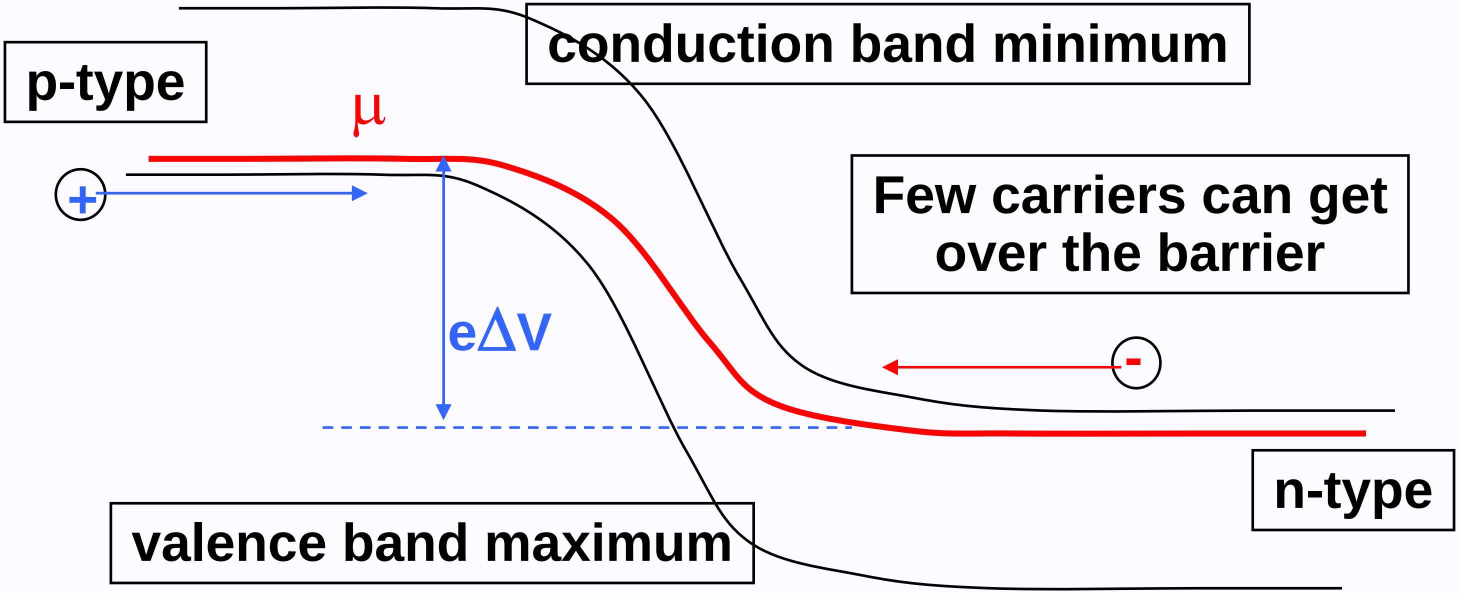
$$J = A n_p \left[\exp(- e|\Delta V| / k_B T) - 1 \right]$$

- Current saturates at small value!
- Acts like capacitor with increased depletion width



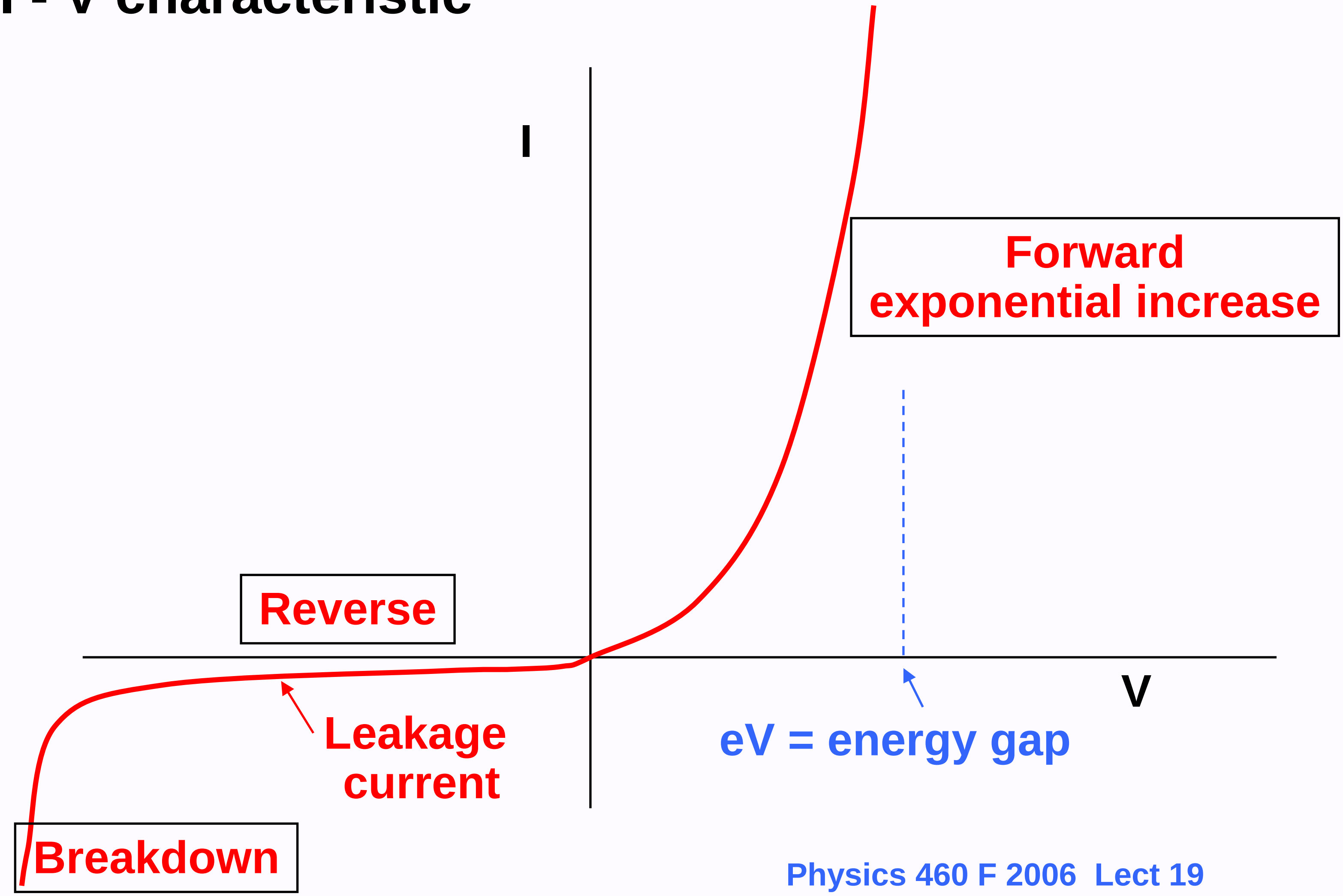
Reverse bias

- The difference between bands on the left and right increases
- Current saturates at small value!
- Acts like capacitor with increased depletion width



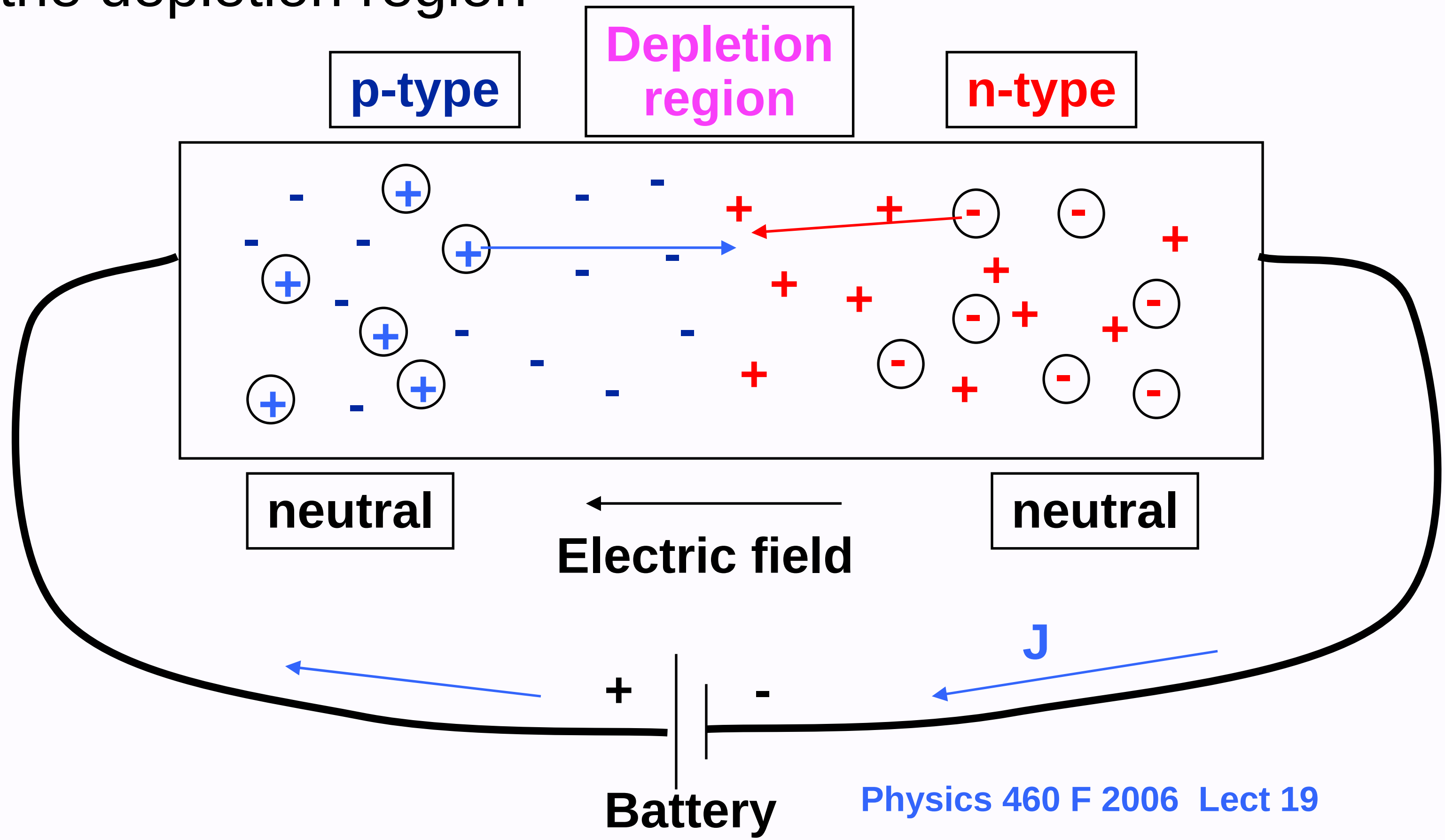
Rectification

- **I - V characteristic**



Forward bias (again)

- How does the current actually flow?
- Electrons flow from right, holes from left - combine near the depletion region

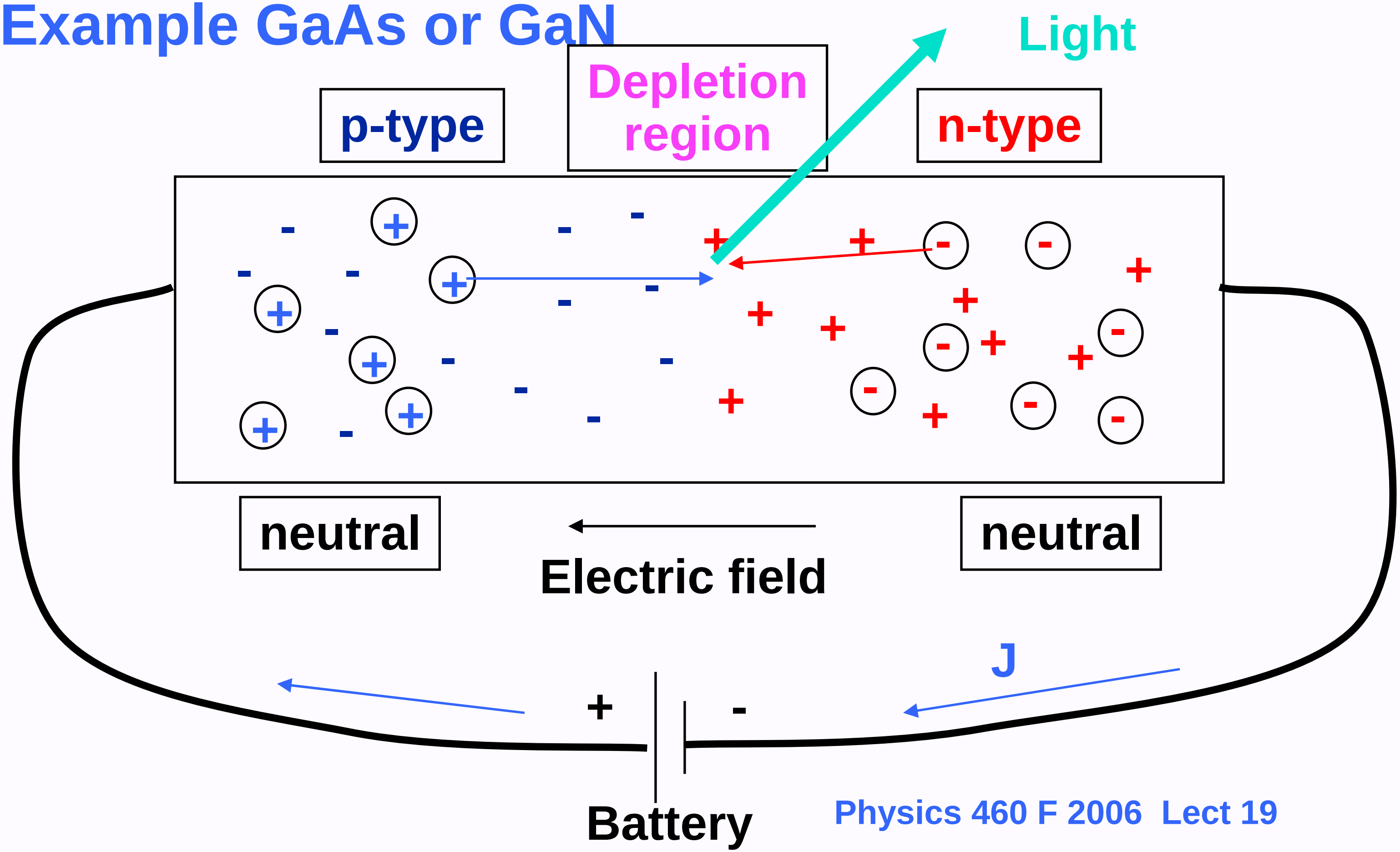


How can a pn junction be used to convert electric current into light?

- **A device in which a current leads to emission of light**

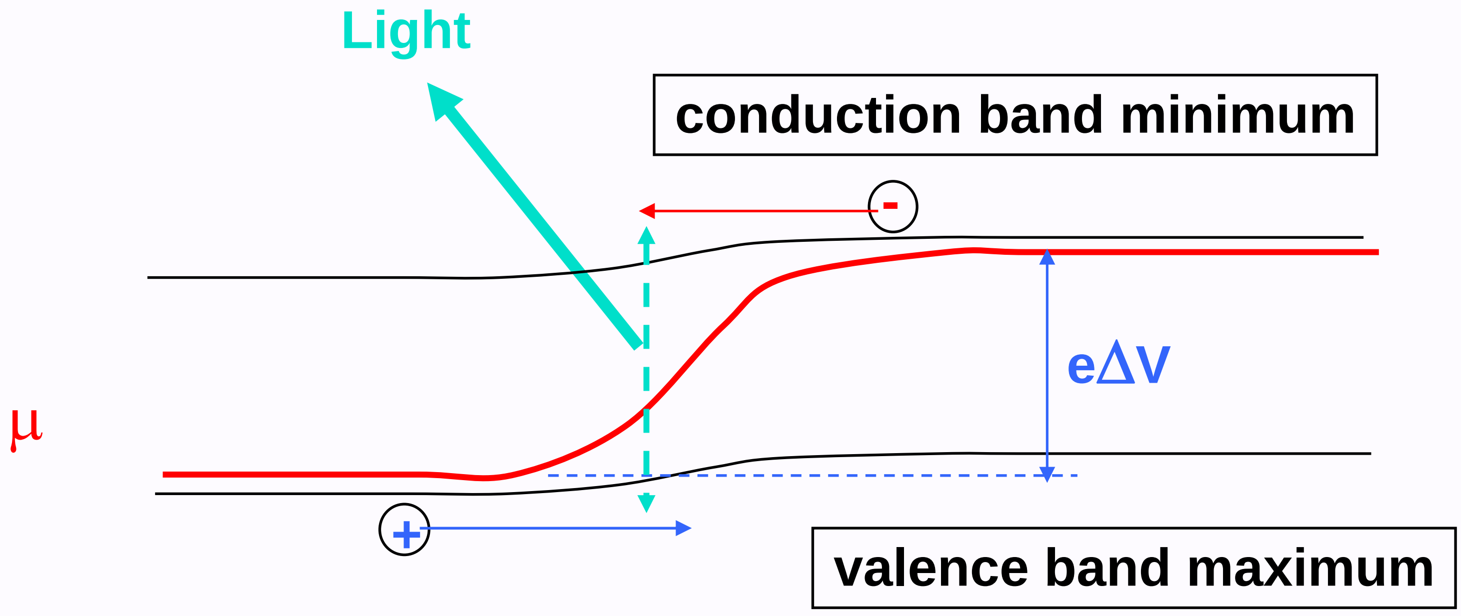
Light Emitting Diode

- Forward biased junction in a system where the combination of the electrons and holes creates light
- Example GaAs or GaN



Forward bias (again)

- Forward biased junction in a system where the combination of the electrons and holes creates light
- Example GaAs or GaN

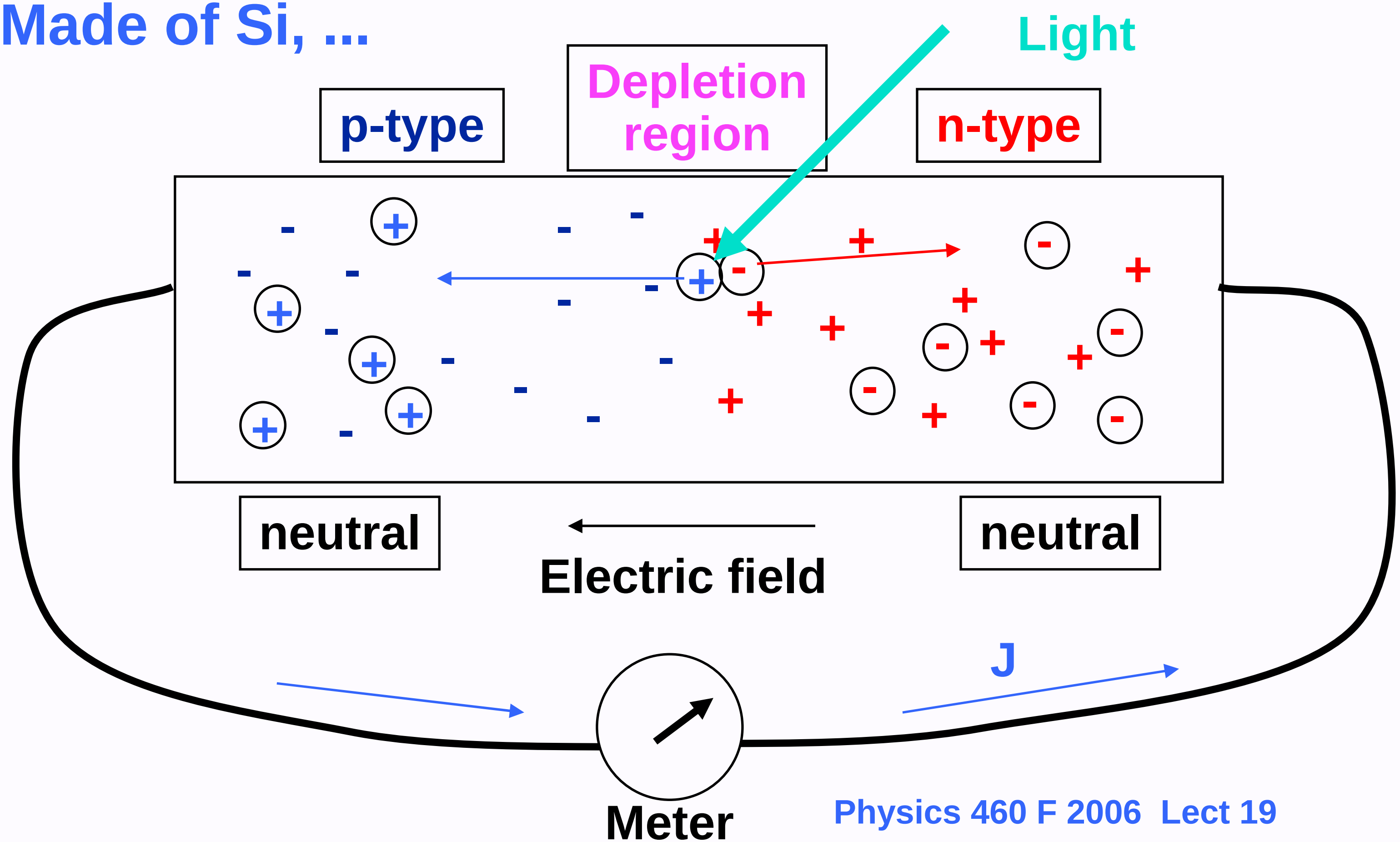


How can a pn junction be used to convert light into electric current?

- A device in which absorption current leads of electric current

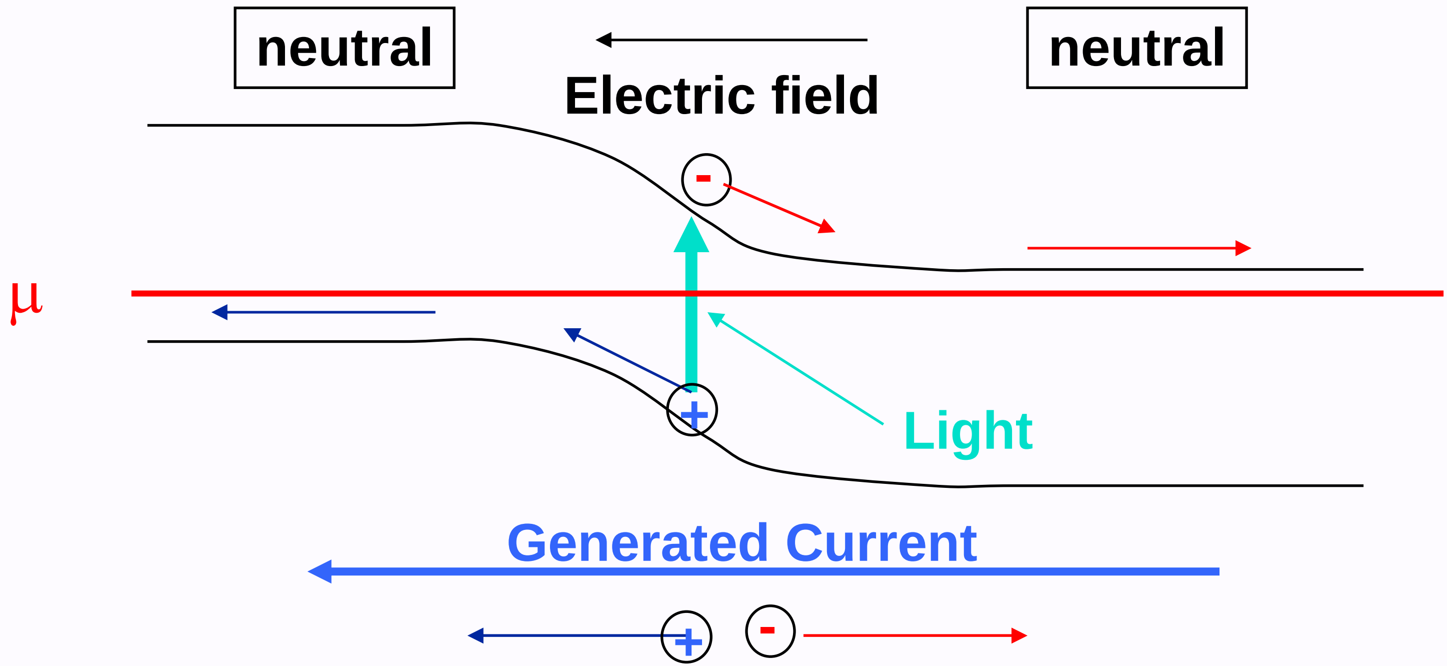
Solar Cell

- Light absorbed in depletion region creates electron-hole pairs
- Made of Si, ...

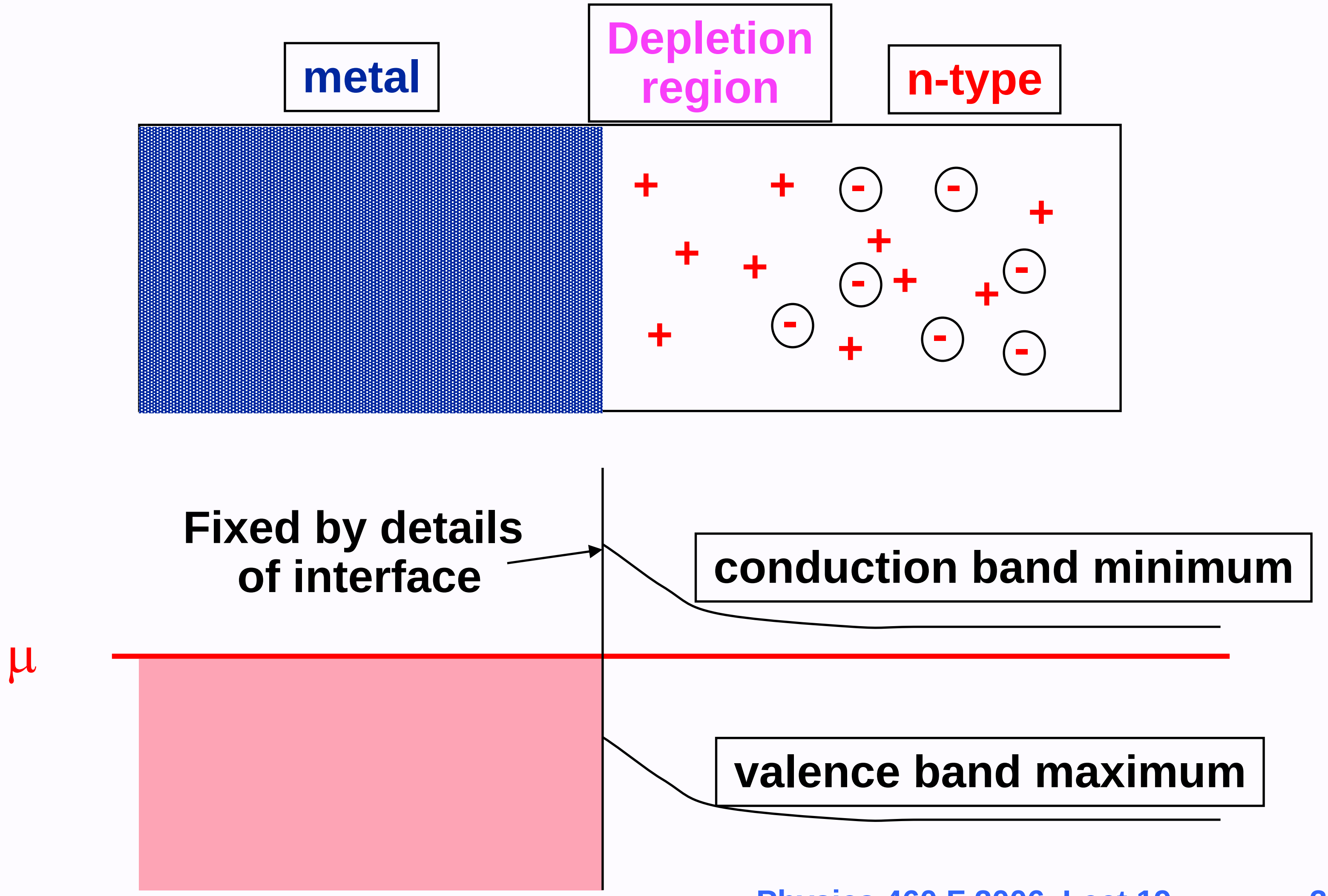


Solar Cell

- Light absorbed in depletion region creates electron-hole pairs



Shottky Barrier

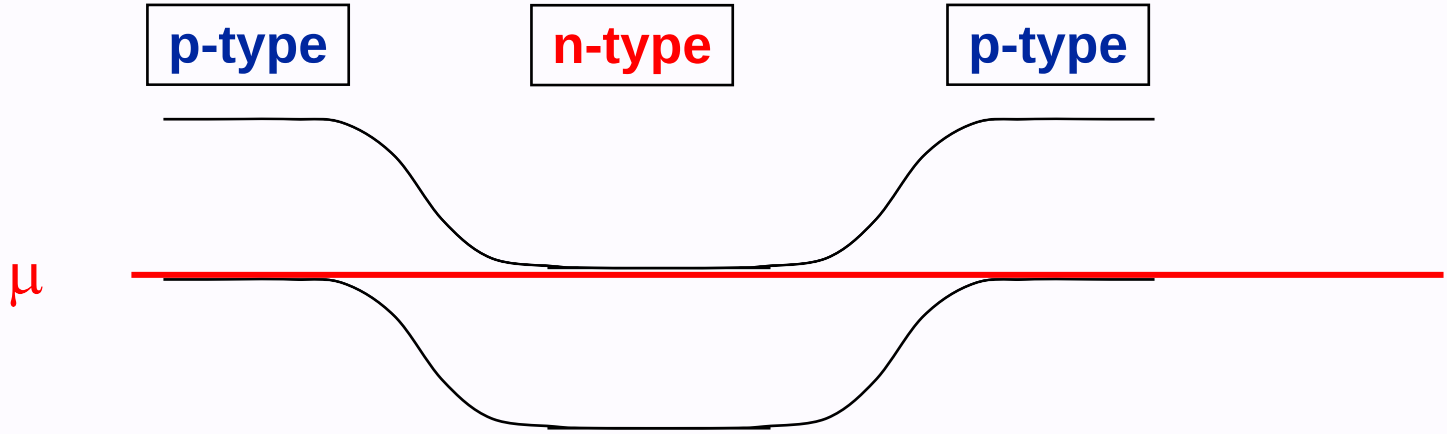


Rectification in Shottky Barrier

- Similar to p-n junction
- Current increases exponentially (until it saturates) for forward bias that tends to make the semiconductor bands bend less (in the case of n-type semiconductor the potential is negative on semiconductor)
- Reverse bias acts like capacitor with increased depletion width

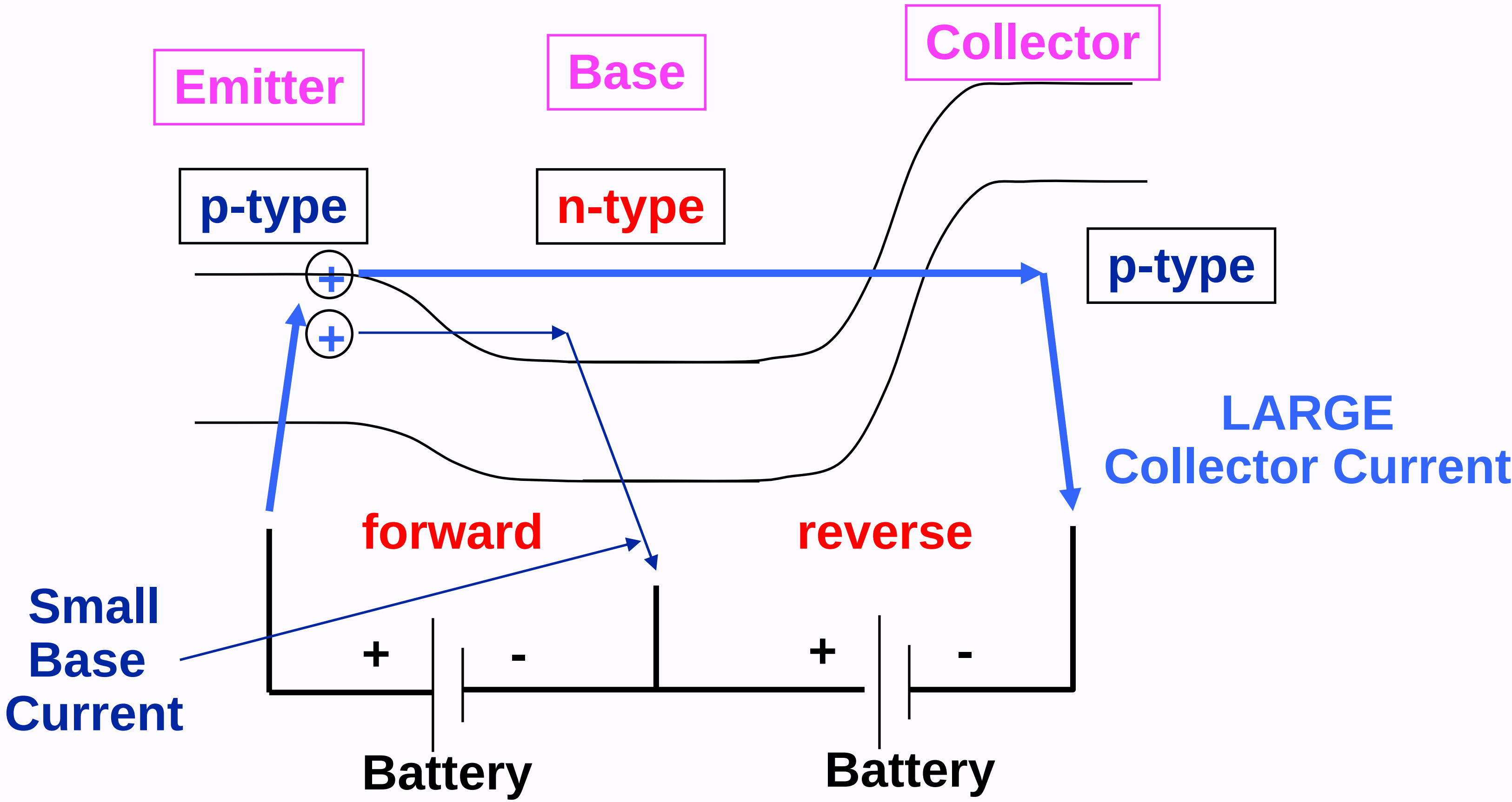
Transistor

- Invented in 1947 - Bardeen, Brattain, Schockley
- Equilibrium



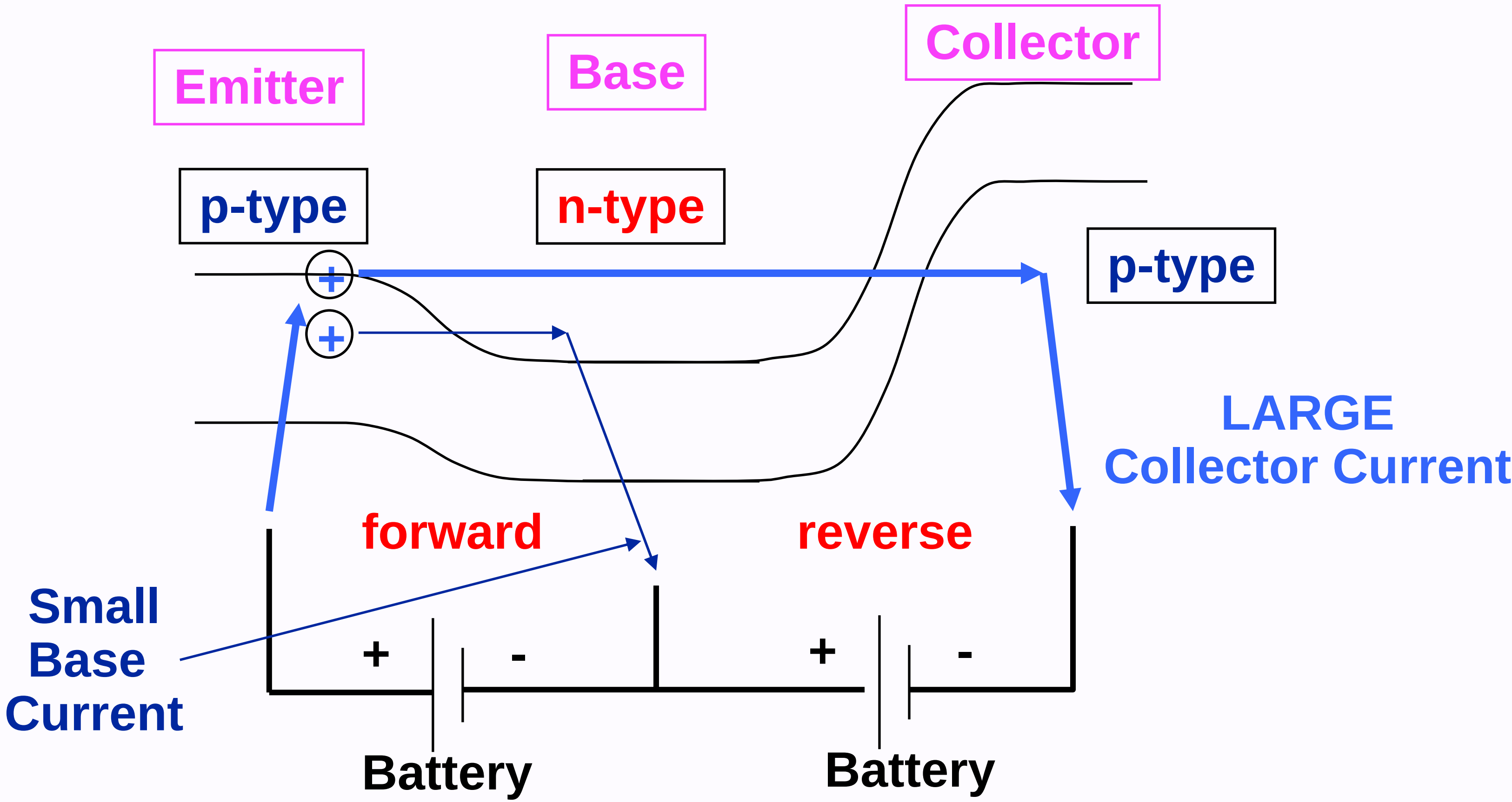
Transistor

- Applying voltages - one junction forward and the other reverse - (remember holes like to go uphill)



Transistor

- Amplifier - Small current controls LARGE current

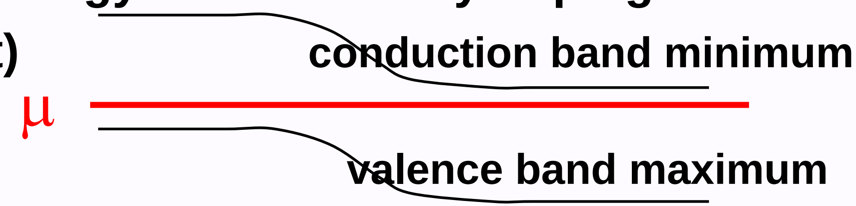


Summary

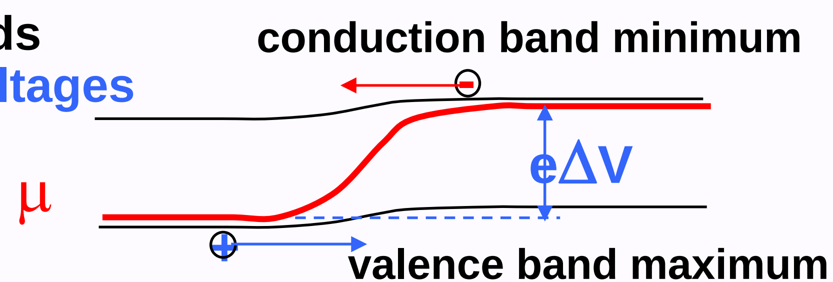
- **Semiconductor device – inhomogeneous doping to create a structure with electron and hole conduction that can be controlled**

Main points

- **Key general points:**
  - **Band gaps are fixed by the material Si, GaAs, …**
  - **Bands Relative to Fermi energy determined by doping**
  - **In equilibrium (no current) the Fermi energy μ is the same everywhere**



  - **Fermi energy and bands shift due to applied voltages**



Summary continued

- **Main points - continued**
- **p-n junctions - rectification- forward - reverse bias**
- **Light emitting diode: electron, hole ⇒ photon**
- **Solar Cell: photon ⇒ separated electron and hole**

Other points
(important but you are not responsible for these)

Metal-semiconductor junctions
Schottky barriers - rectification

- **Bipolar transistor n-p-n p- n-p**

- **Kittel Ch. 17, p. 503 - 512 + added materials in the lecture notes**

Next time

- Semiconductor structures
  Confinement of carriers
  by voltages and materials

- MOSFET Transistor

- Quantum Wells, Wires, Dots

- Carriers in Quantum Wells in a magnetic field
  Quantized Hall effect

- Covered briefly in Kittel Ch 17, p 494-503, 507- 511
  \- added material in the lecture notes