EEE105
“Electronic Devices”

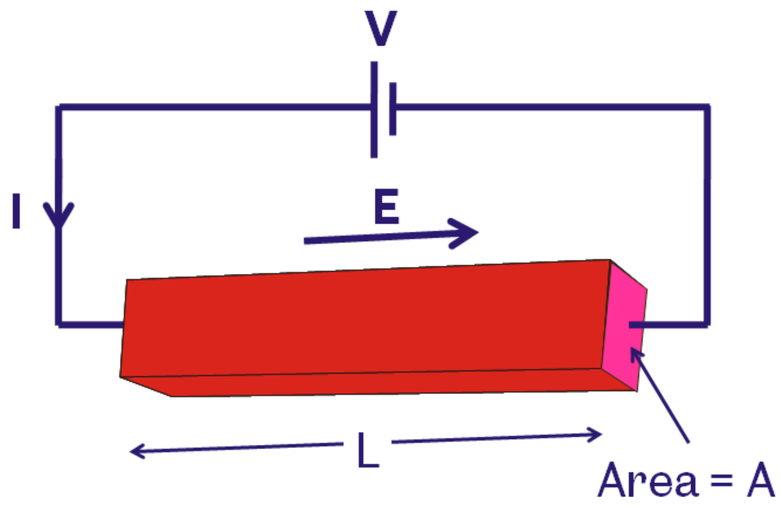
Professor Richard Hogg,
Centre for Nanoscience & Technology, North Campus
Tel 0114 2225168,
Email - r.hogg@shef.ac.uk

Lecture 20

- Junction field effect transistor - JFET
- Metal oxide semiconductor field effect transistor – MOSFET
- Review p-n junctions

Conductivity

The conductivity is governed by the carrier density



$$J = n\,q\,\mu\,E \qquad J = \sigma E$$

$$\sigma = nq\mu$$

If we can modulate the carrier density we can vary the resistance of a semiconductor

- we have done this with a p-n junction

Concept -

Make contacts like this –

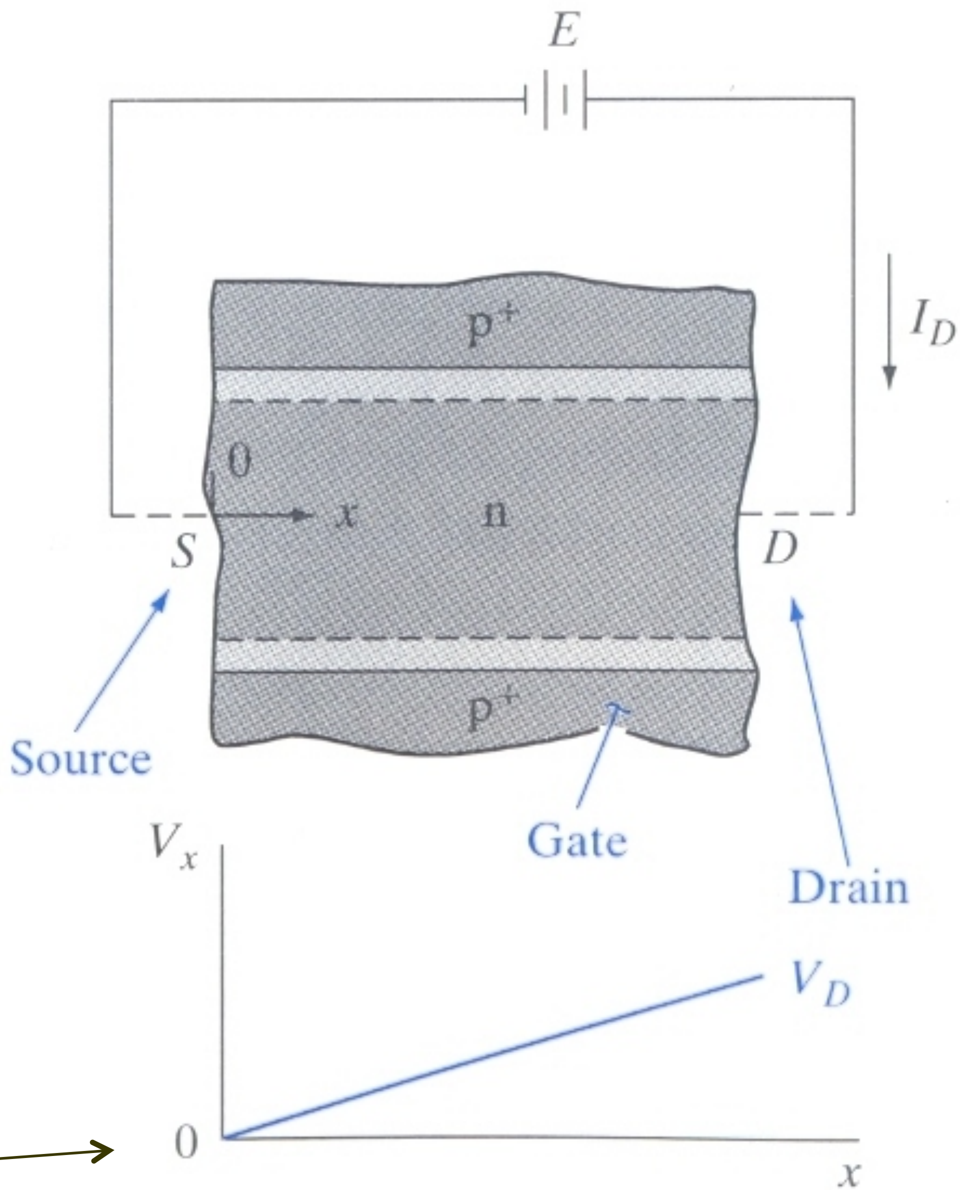
Electron drift in the n-type channel

Electrons flow from the source to the drain

Channel acts as a distributed resistor

Resistance governed by carrier density and volume of un-depleted n-type material

If current is low



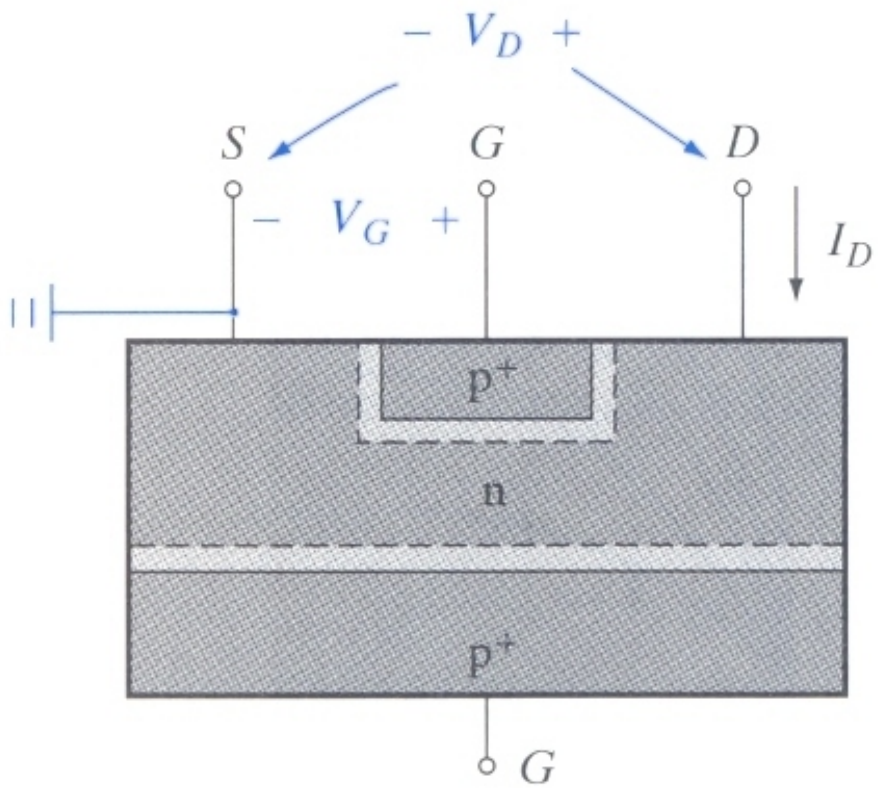
Junction Field Effect Transistor

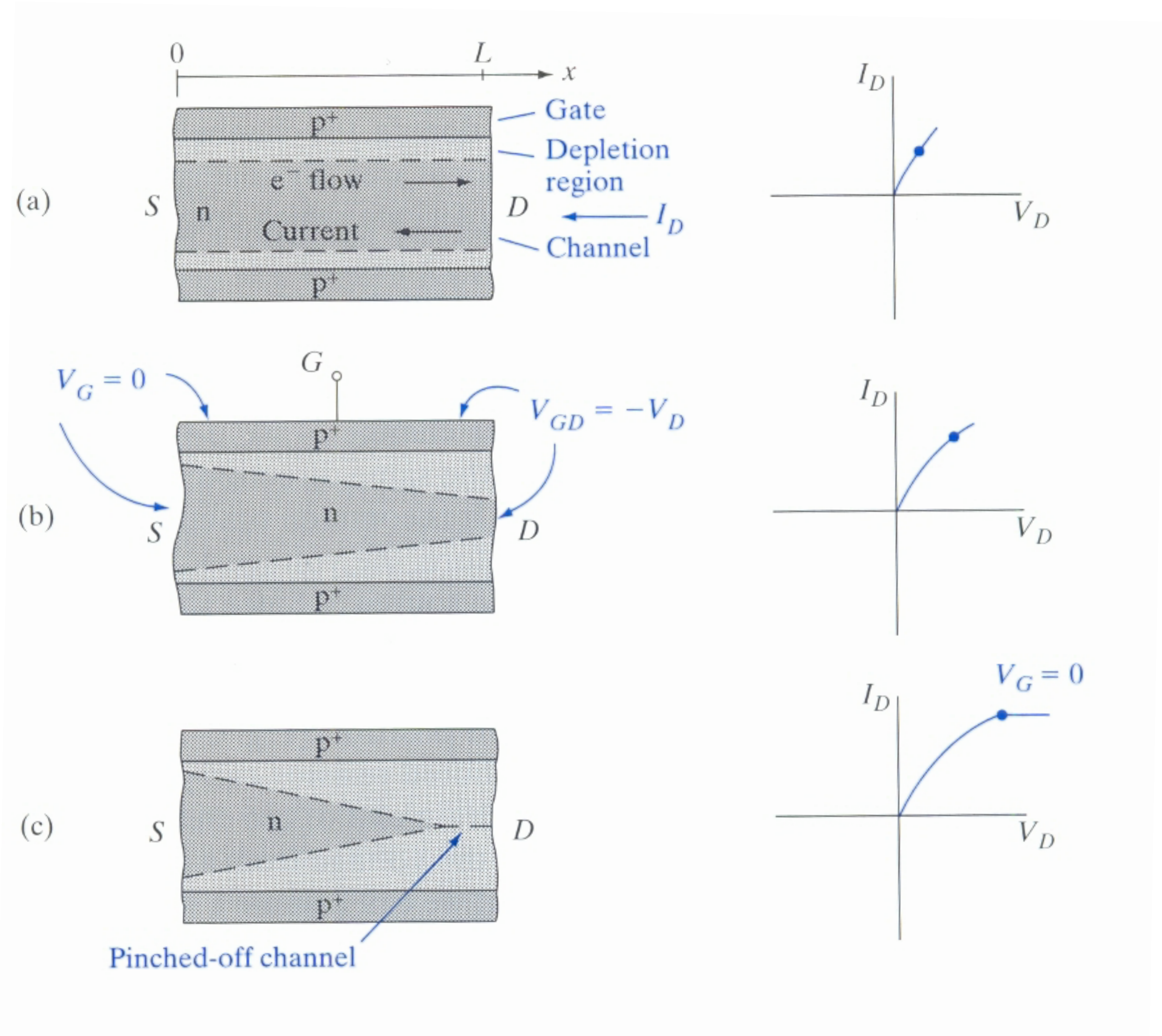
Can make contacts to p-regions

Forming a “gate”

This allows the application of a voltage to

Most of the deletion region is in the lower doped n-type material – varying gate voltage varies the area of the n-type material and so it’s conductivity



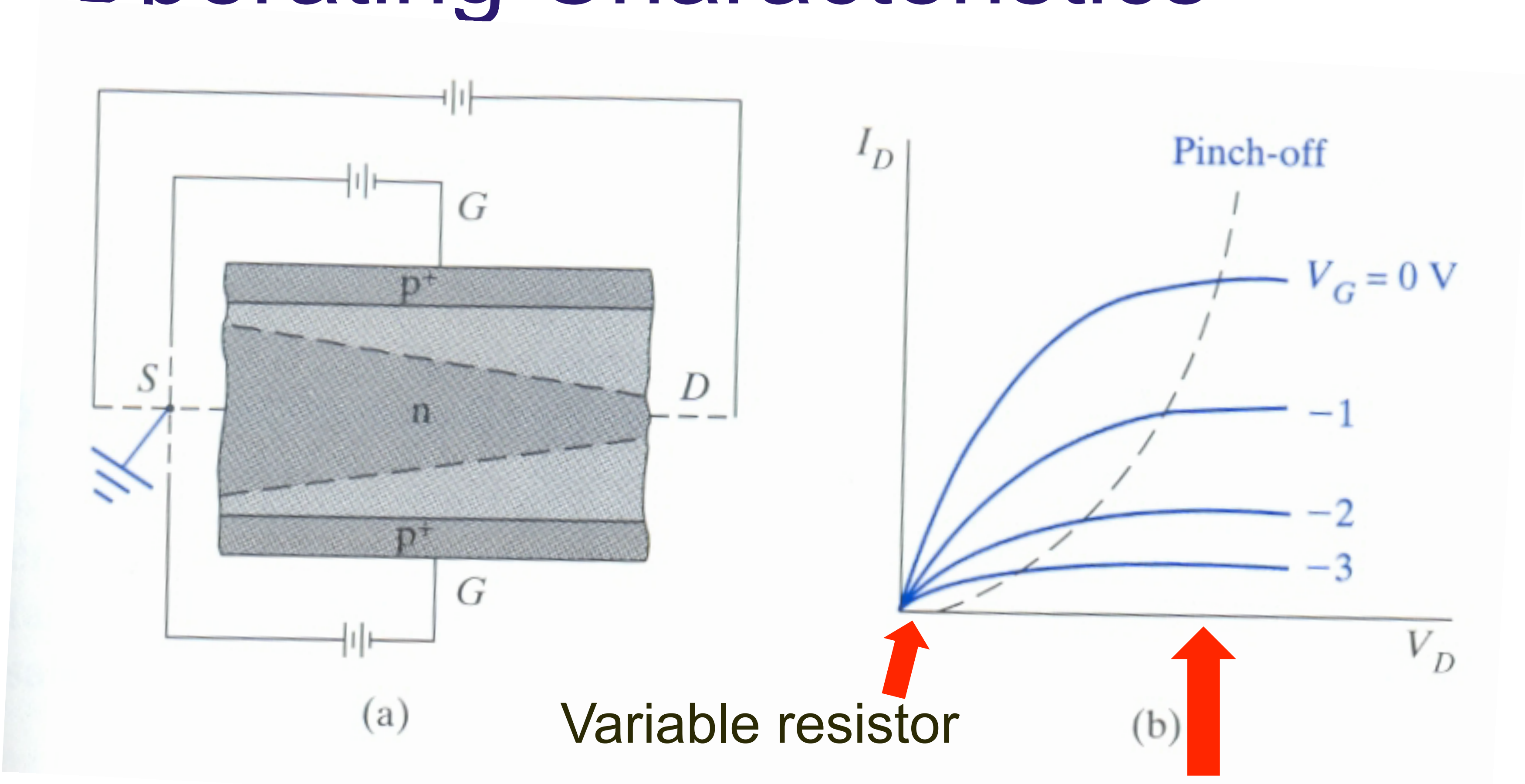

0
L
x
Gate
Depletion region
(a)
S
n
e⁻ flow
Current
D
I_D
Channel
p⁺
p⁺
I_D
V_D
$V_G = 0$
G
$V_{GD} = -V_D$
(b)
S
n
D
p⁺
p⁺
I_D
V_D
$V_G = 0$
I_D
(c)
S
n
D
p⁺
p⁺
V_D
Pinched-off channel

(a) No gate voltage – voltage between source and drain gives drift. At high I_D the voltage is large near the drain end and small at source end.

(b) As I_D increases the voltage increase at the drain puts the p-n junction at this end in reverse bias – increasing the depletion width and so constricts the channel. As the resistance of the constricted channel is higher – IV plot is no longer linear.

(c) At higher V_D the depletion regions can meet – the current I_D cannot increase with increasing V_D

Operating Characteristics



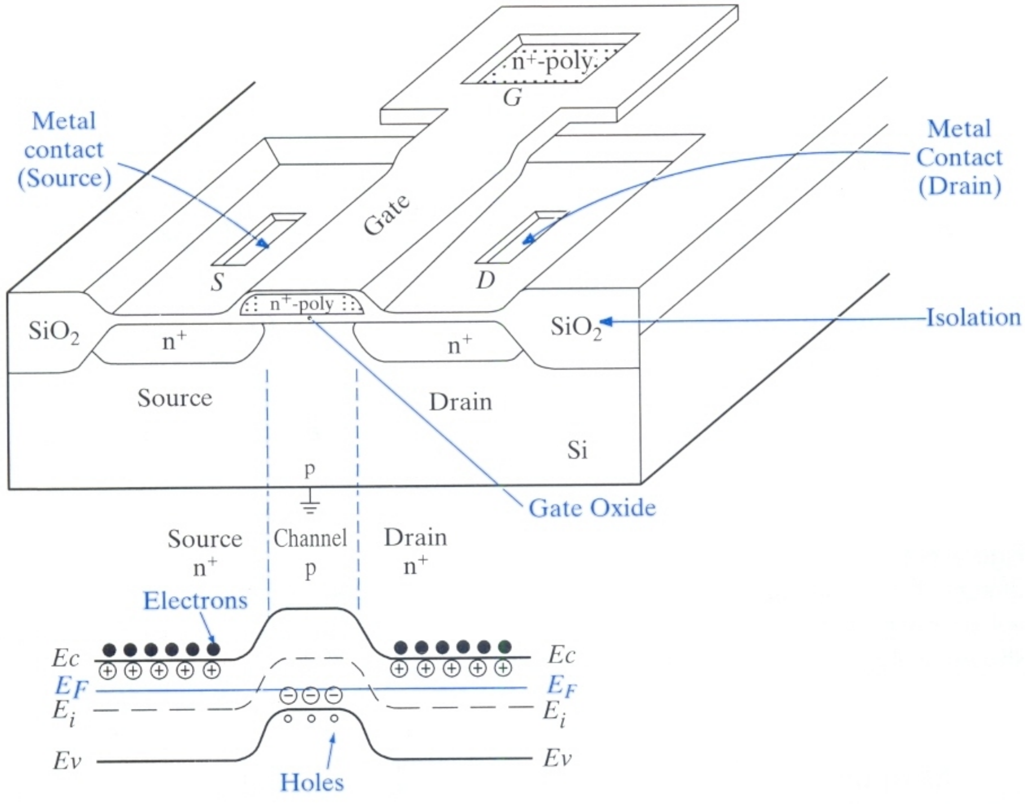
Variable resistor

Amplifier (c.f. BJT transconductance)

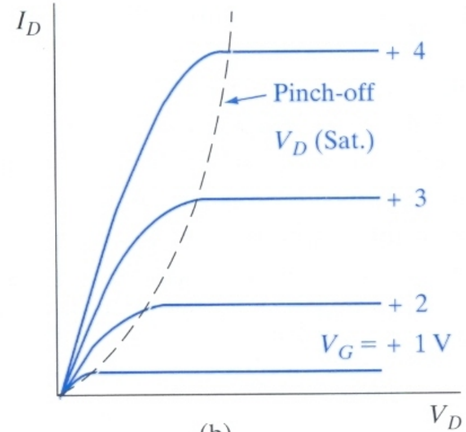
Other Transistors

- Metal/Insulator/Semiconductor structures
- Dealt with in future courses
- Most famous “MOSFET” – metal oxide semiconductor field effect transistor
- At the heart of the electronic age

- Metal/insulator interface allows the control of a sheet of charge below it
- This conducting channel links two heavily doped regions of semiconductor
- Transistor characteristics



(a)

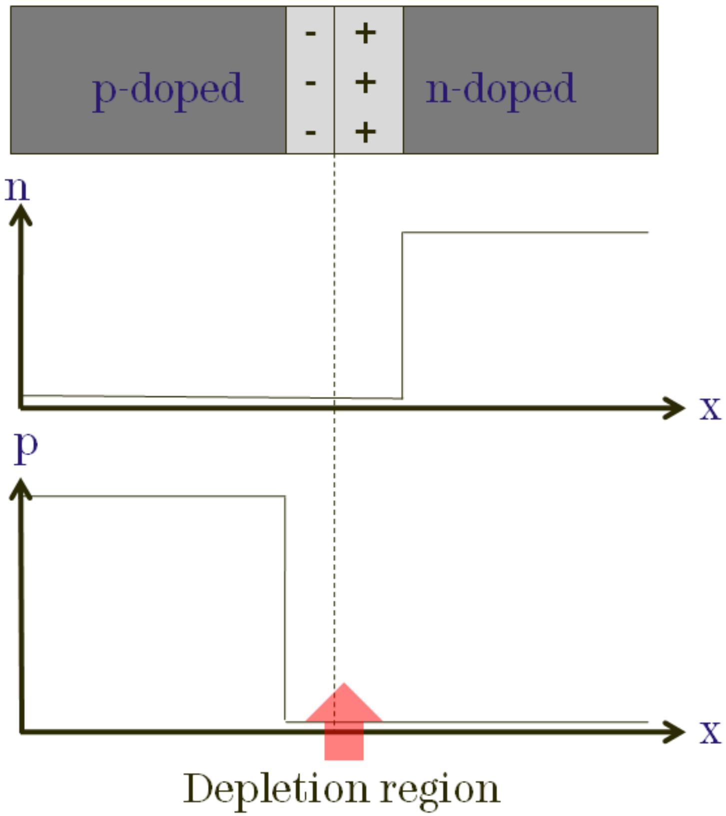


(b)

Summary

- Many types of semiconductor devices are possible
- JFET is a p^+-n-p^+ diode with contacts arranged to allow a bias to vary the depletion region width
- This device can operate as a variable resistor or as an amplifier
- Introduced MOSFET, dealt with (operation, manufacture, etc) in future courses

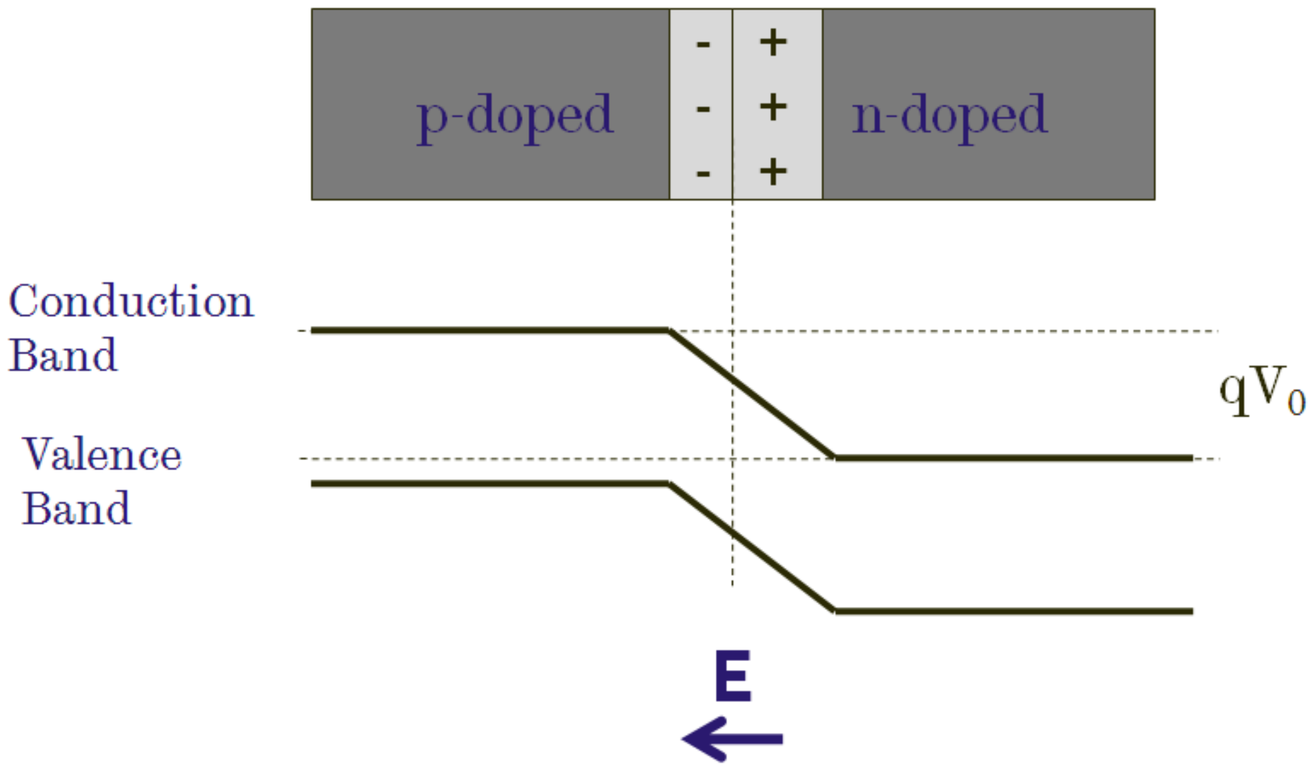
Review p-n junctions and BJTs



When p-type and n-type semiconductors are joined, the majority carriers diffuse into oppositely doped material.
They recombine making a region depleted of free carriers (depletion region).

In this depletion region the fixed charges of the ionized dopants is revealed.

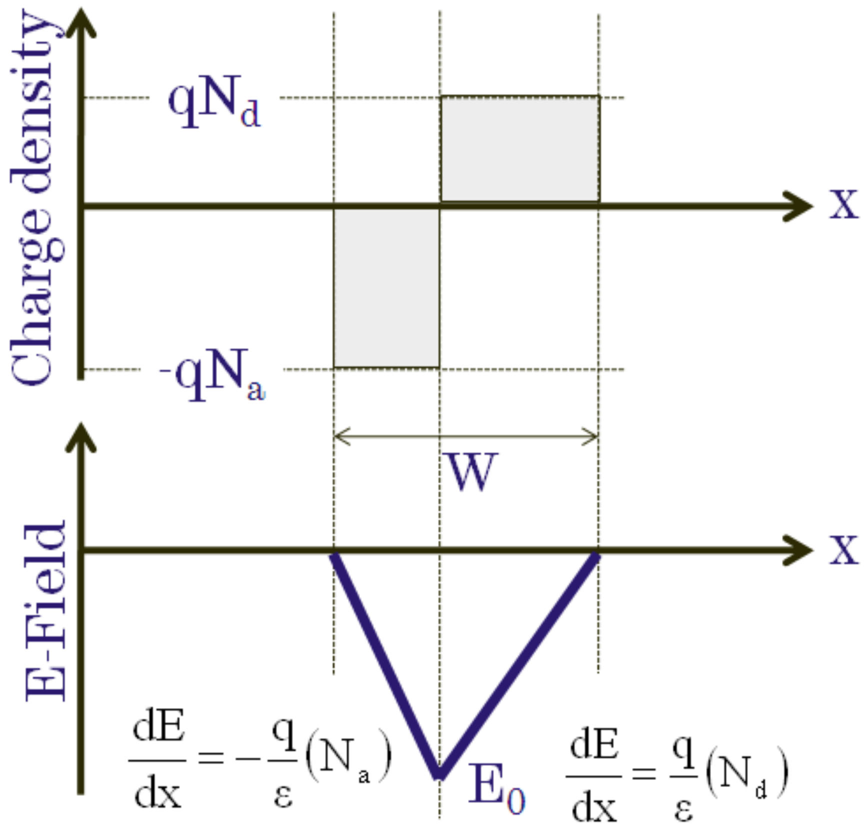
Charge is neutral in the regions with free carriers (e.g. same number of holes as ionized acceptors). The amount of revealed charge either side of the doping interface is equal.



Drift and diffusion currents equal $\Rightarrow$

$$V_0 = \frac{k_B T}{q} \ln\left(\frac{p_{(p)} n_{(n)}}{n_i^{\,2}} \right)$$

Electric Fields



$$\frac{dE}{dx} = \frac{\rho}{\varepsilon}$$

Integration

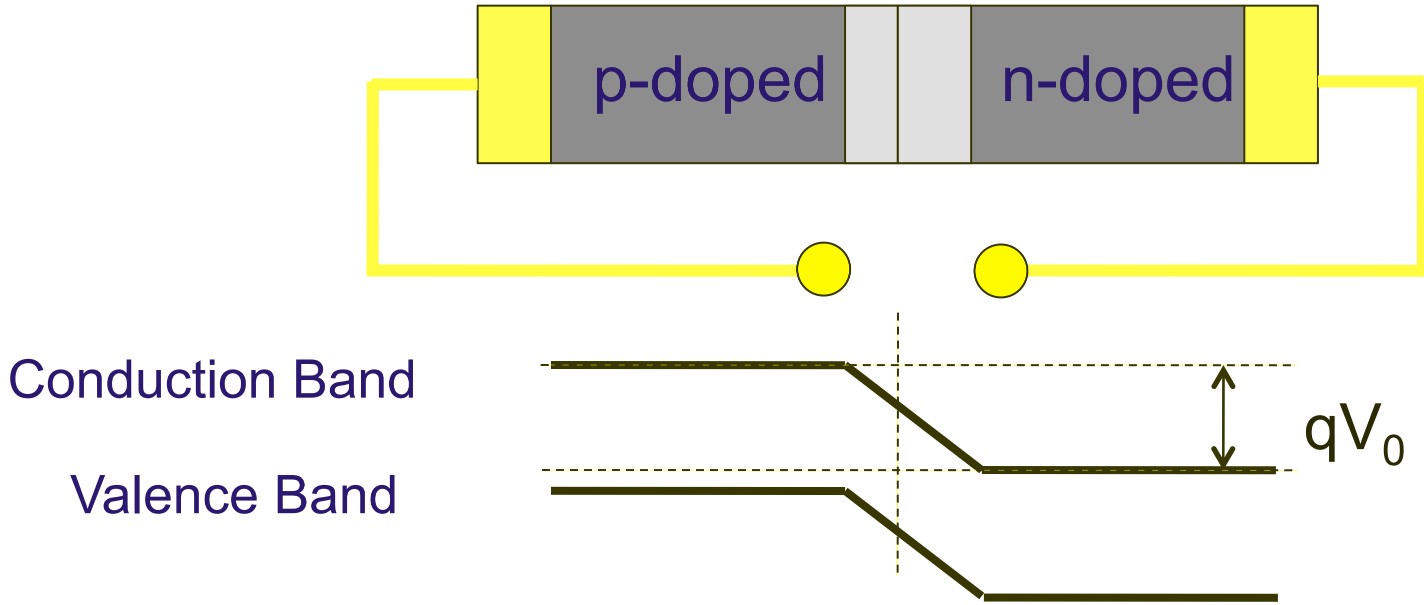
$$E_0 = -\frac{q}{\varepsilon} N_d x_{n0} = -\frac{q}{\varepsilon} N_a x_{p0}$$

Integration

$$V_0 = \frac{1}{2}\frac{q}{\varepsilon} N_d x_{n0} W$$

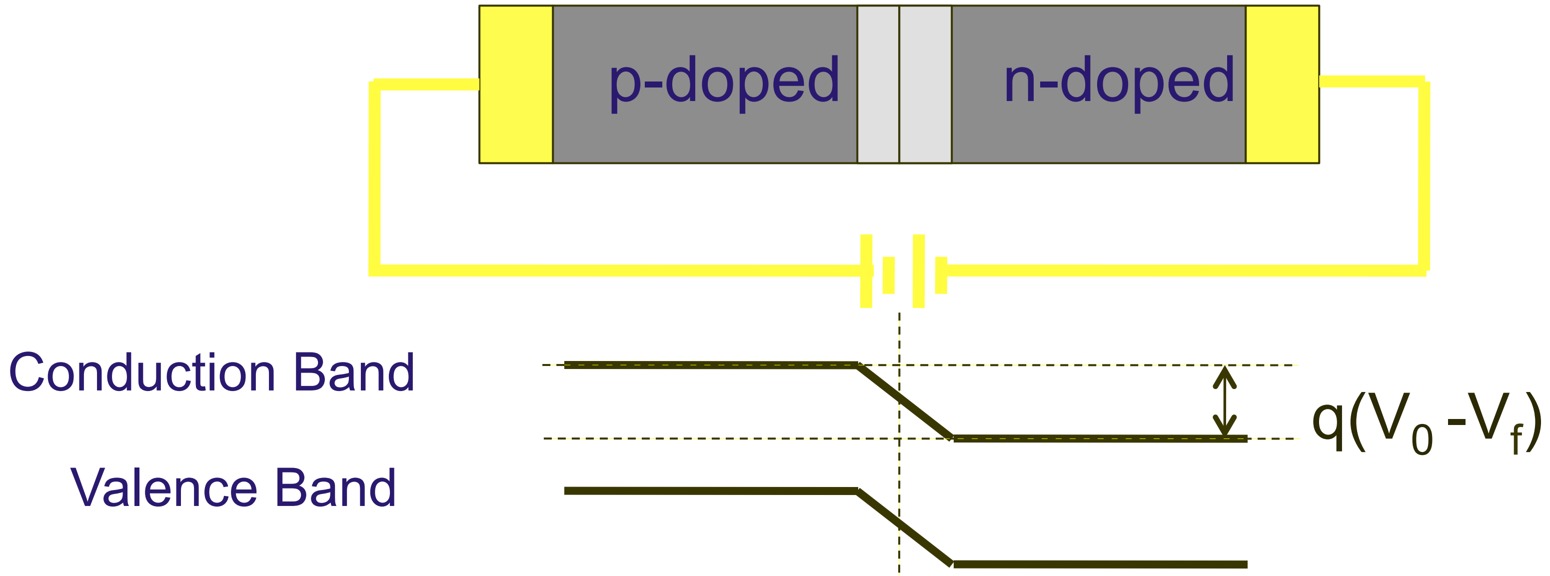
$$= \frac{1}{2}\frac{q}{\varepsilon}\frac{N_a N_d}{N_a + N_d} W^2$$

Zero Applied Voltage



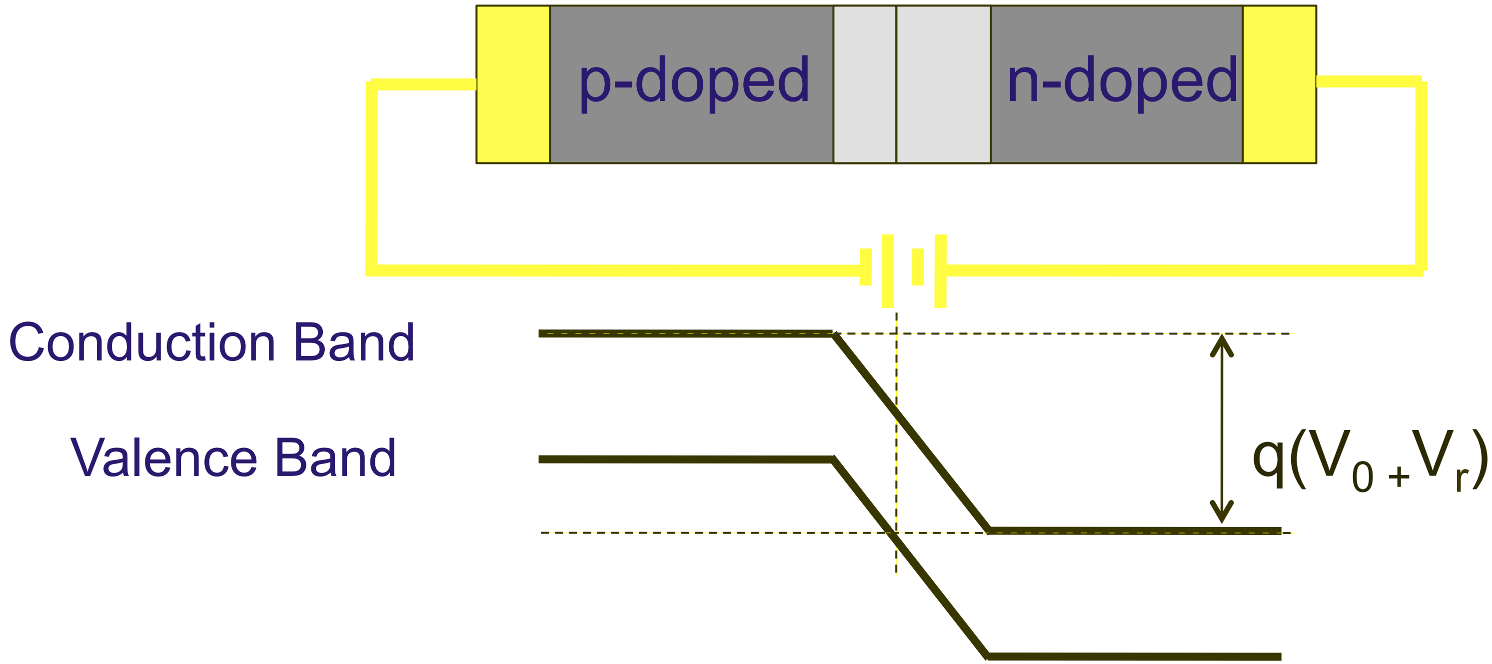
No current – drift and diffusion cancel
Diffusion is inhibited due to barrier to carrier motion
Drift is inhibited as low free holes in n-type, etc. – only thermally generated carriers in or close to depletion region contribute.

Forward Bias, V_f



Diffusion current increases as thermal barrier to conduction is reduced.
Drift is inhibited as low free holes in n-type, etc. – only thermally generated carriers in or close to depletion region contribute.

Reverse Bias, V_r

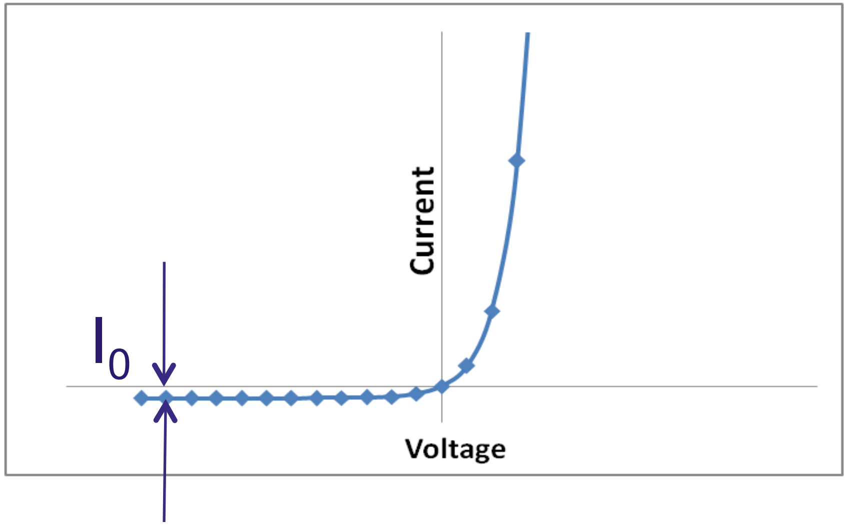


Diffusion current effectively zero as larger thermal barrier to conduction.

Only thermally generated carriers in or close to depletion region contribute to drift.

Diode Equation

Integration of diffused minority charge per unit time into p-type and n-type regions



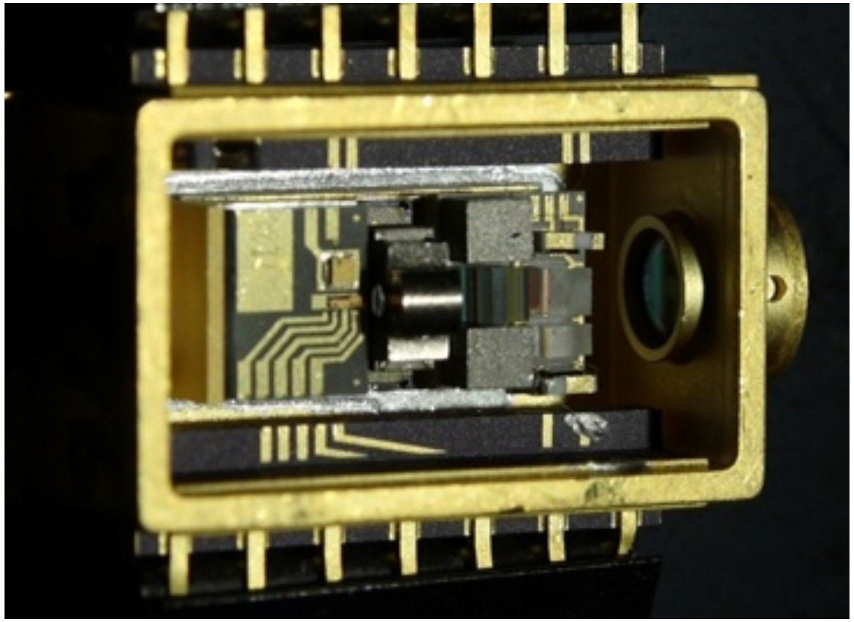
$$I = I_0\left[\exp\left(\frac{qV_f}{k_B T}\right) - 1\right]$$

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

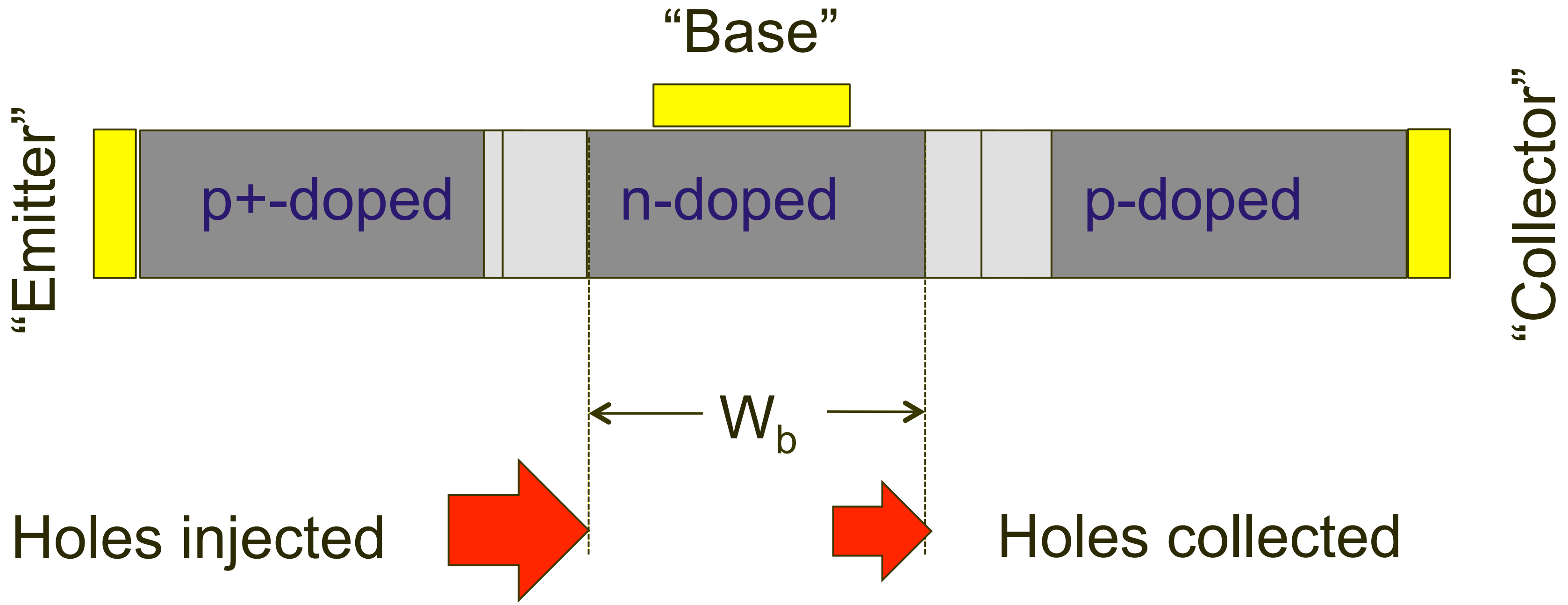
$$I_0 = qAn_i^2\left[\frac{D_e}{L_e N_A} + \frac{D_h}{L_h N_d}\right]$$

p-n junction

- Applications –
  - Rectifier
  - Variable capacitor
  - LED
  - Laser
  - Photodiode
  - Solar cell
  - *etc., etc.*

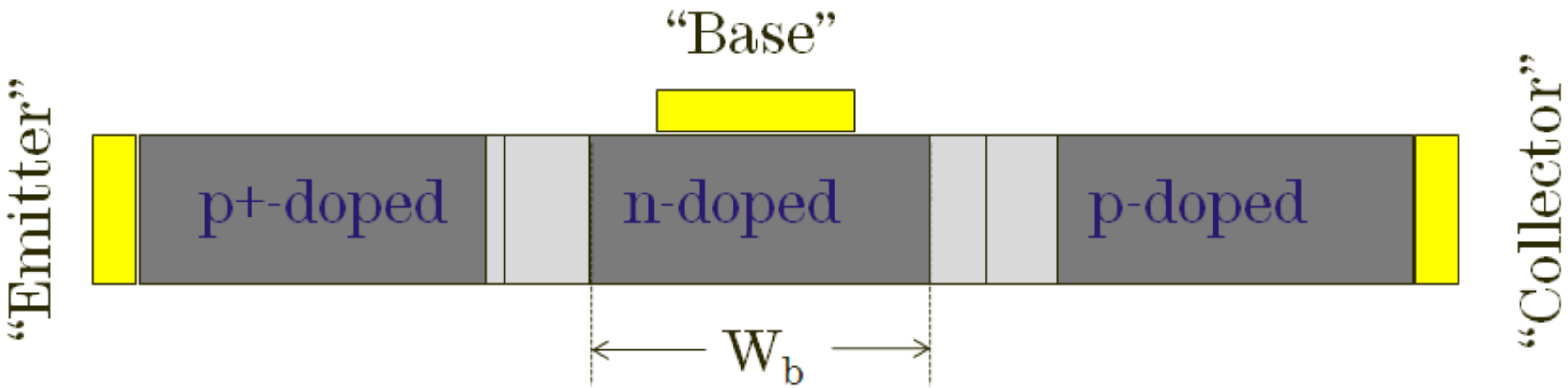


Bipolar Junction Transistor



Asymmetric doping of p-n-p or n-p-n structure – injection of one type of carrier from one p-n junction into another

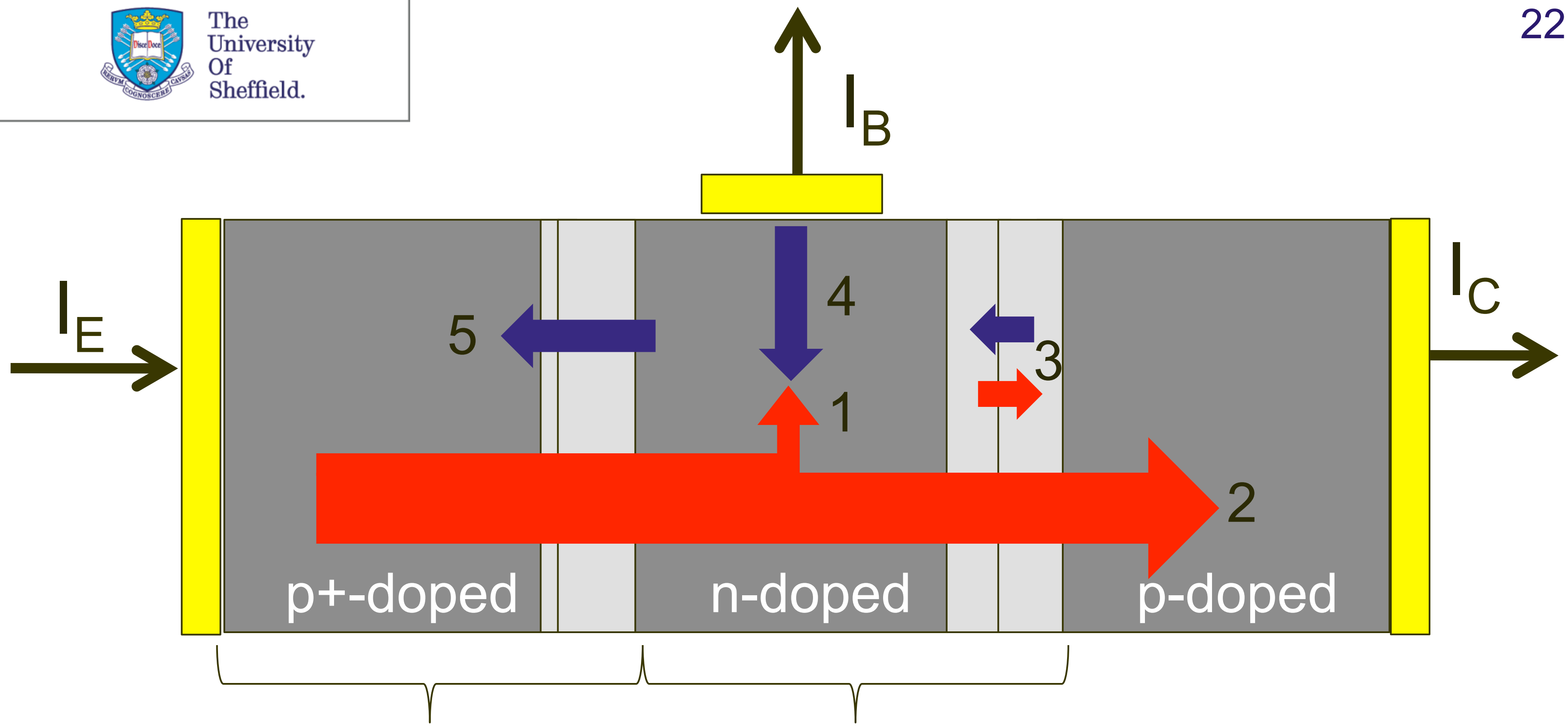
BJT – Key factors



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

$$\left(D_h = \frac{k_B T \mu_h}{q}\right)$$

The base width needs to be small so that the vast majority of injected minority carriers transit without recombination



Emitter efficiency

$$\gamma = \frac{i_{Eh}}{i_{Ee} + i_{Eh}}$$

$I_C = BI_{Ep}$

B - "Base transport factor"

Current amplification factor $=\beta$

$$\frac{i_C}{i_B} = \frac{B\gamma}{1 - B\gamma} = \frac{\alpha}{1-\alpha} \equiv \beta$$

BJT – Secondary Effects

- The Early effect describes base narrowing which tends to increase current amplification factor, β, due to an increase in base transport factor, B. The Early voltage needs to be used to predict β accurately.
- Avalanche breakdown may also occur of the reverse bias across the base-collector junction is high. The injection of majority carriers to the base can result in very large (possibly catastrophic) increases in collector current.
- The Kirk effect describes high current effects which alter the distribution of space charge in the depletion regions. At high collector currents the base width increases as the depletion region position is altered.

