EEE105 "Electronic Devices"

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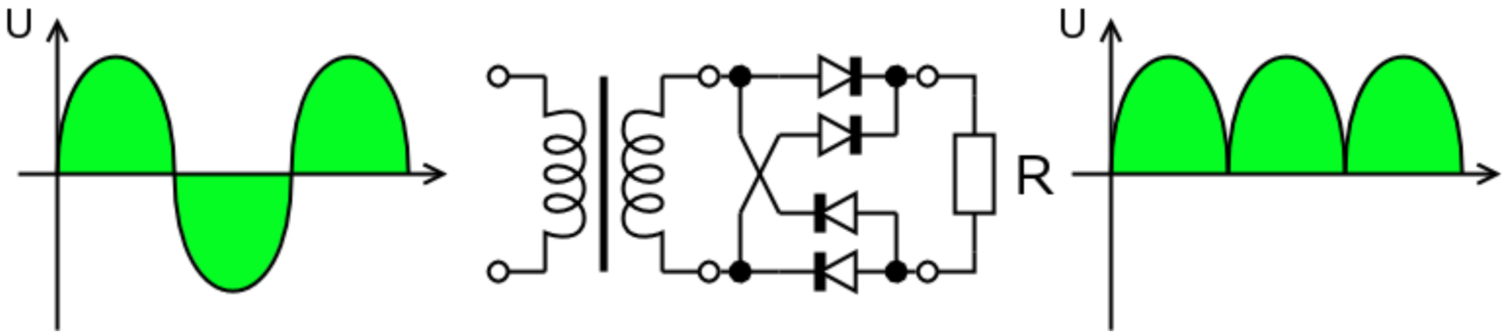
Lecture 16

- Ideal diode for rectification
- Real diodes & Trade –offs for a rectifying diode
  - Forward Resistance
  - Saturation current
  - Built in voltage
  - Reverse Breakdown
  - Capacitance

Rectification

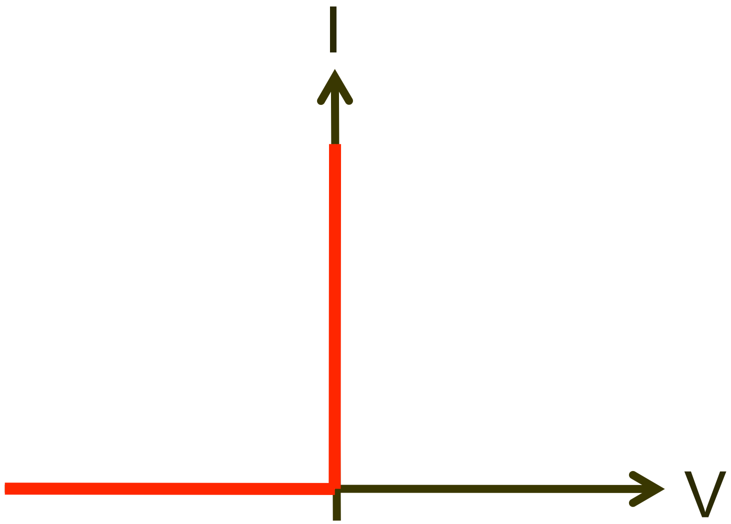


Most obvious use of diodes

Unidirectional nature of I under applied V

Rectification – What is ideal diode for rectification?

Ideal p-n Junction - Rectification

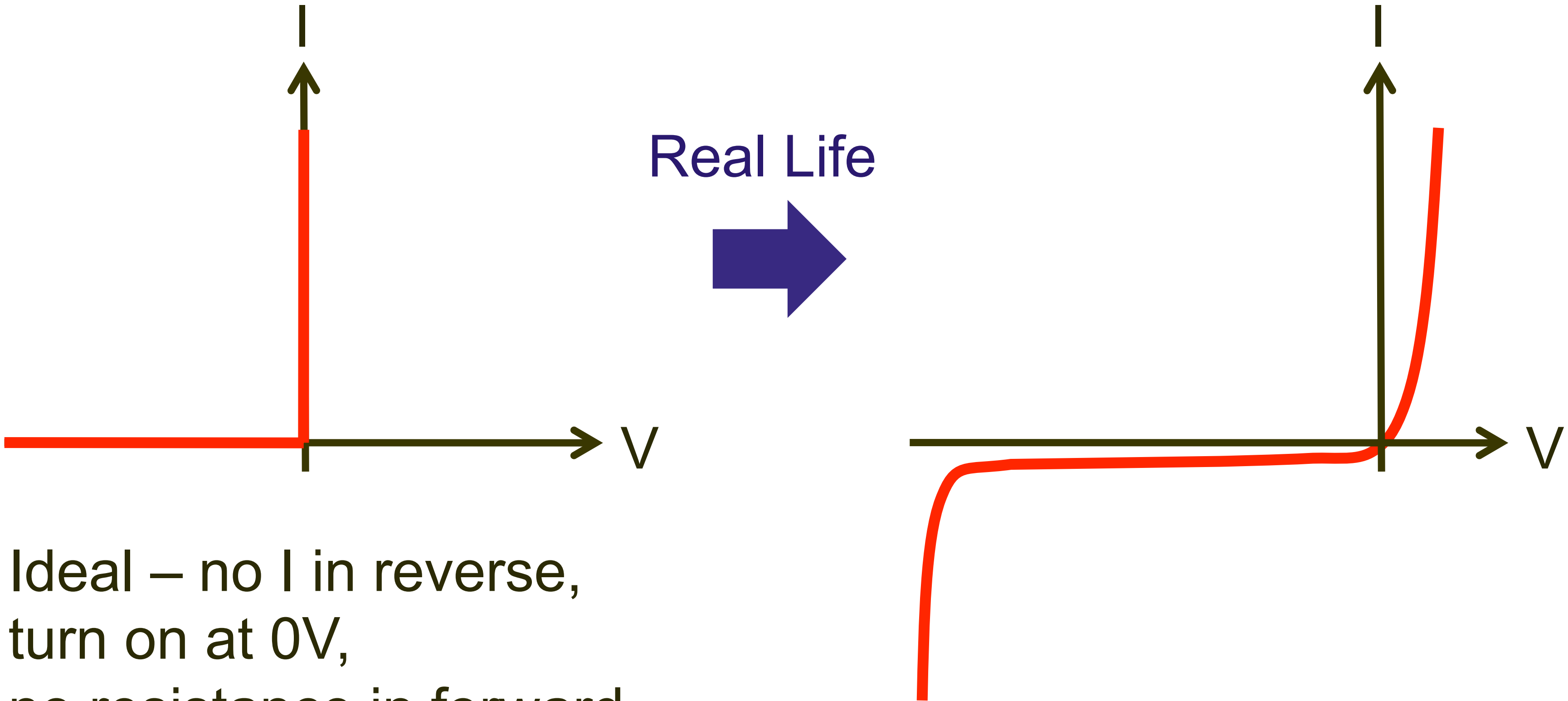


Generally we want -

- Low forward R
- I_0 is negligible
- Low V_0
- No reverse breakdown
- Thermally robust to large forward I & V
- Fast (enough) response to signals

Ideal Diode

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

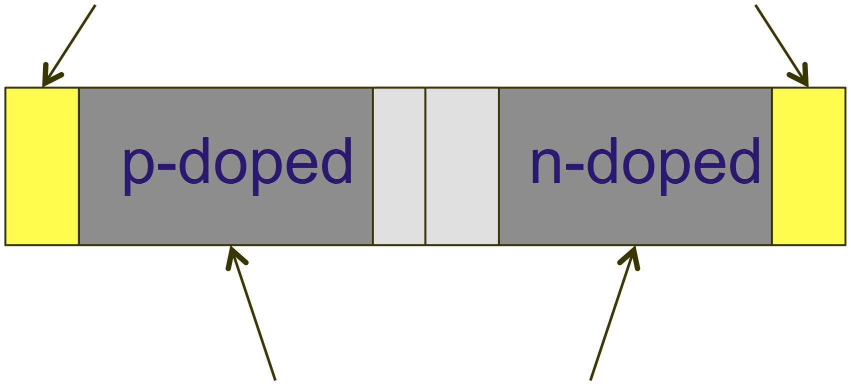


Ideal – no I in reverse,
turn on at 0V,
no resistance in forward

How to engineer to be as good as we can make it?

Low Forward Resistance

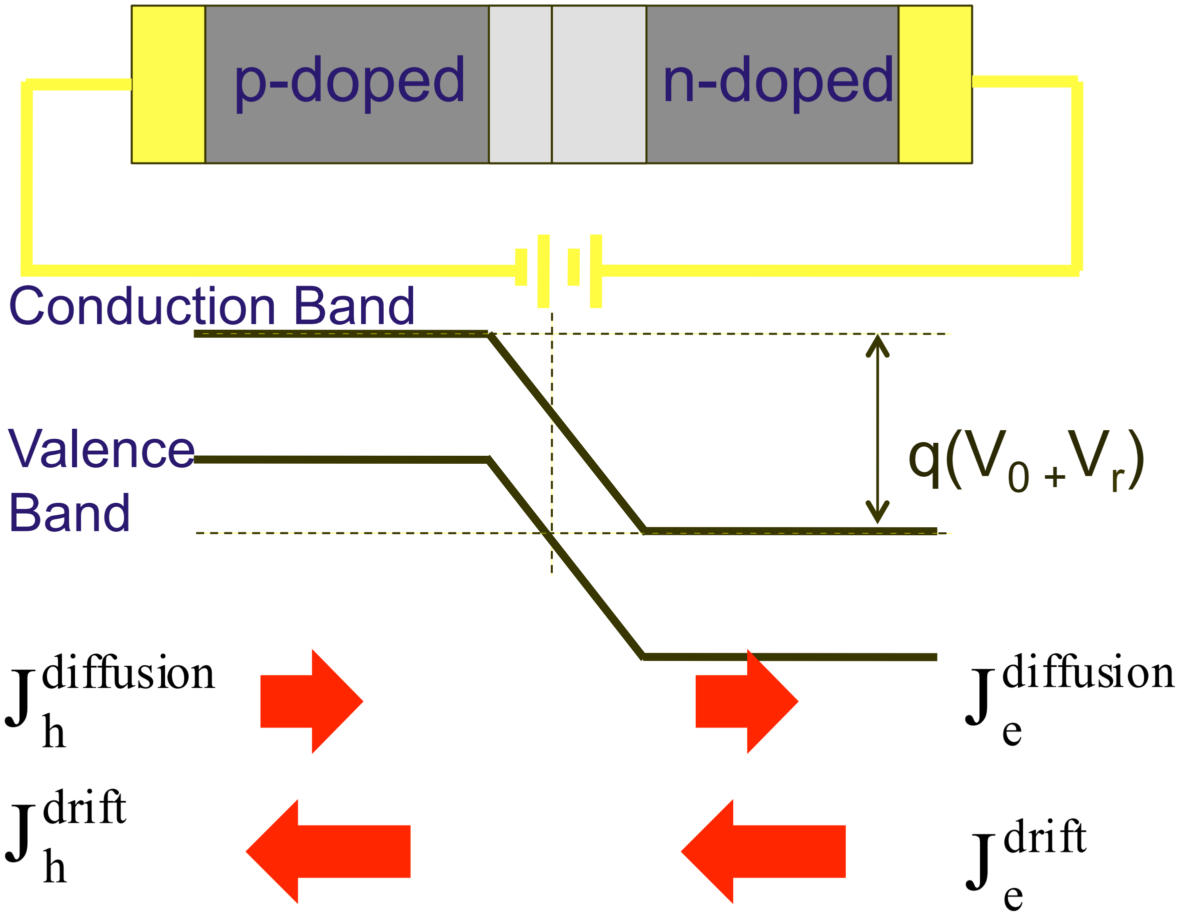
Low R Ohmic contacts



High doping in n and p-doped regions low R

(Highly doped semiconductors are best for making good ohmic contacts to)

Low I_0 ?



At high V_r

Current is entirely due to drift

This is due to thermally generated minority carriers in n and p-type material

"Generation current"

Low Saturation Current

In effect – the number of minority carriers making it to the high field intrinsic region in a given time

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

Can re-write in terms of intrinsic carrier density and other parameters more easily measured

$$n_i = C\ T^{3/2}\exp\left(-\frac{E_g}{2K_B T}\right)$$

For low I_0 need -
Small area
High E_g
High doping
Low mobility

$$L_e = \left(D_e \tau_e\right)^{1/2}$$

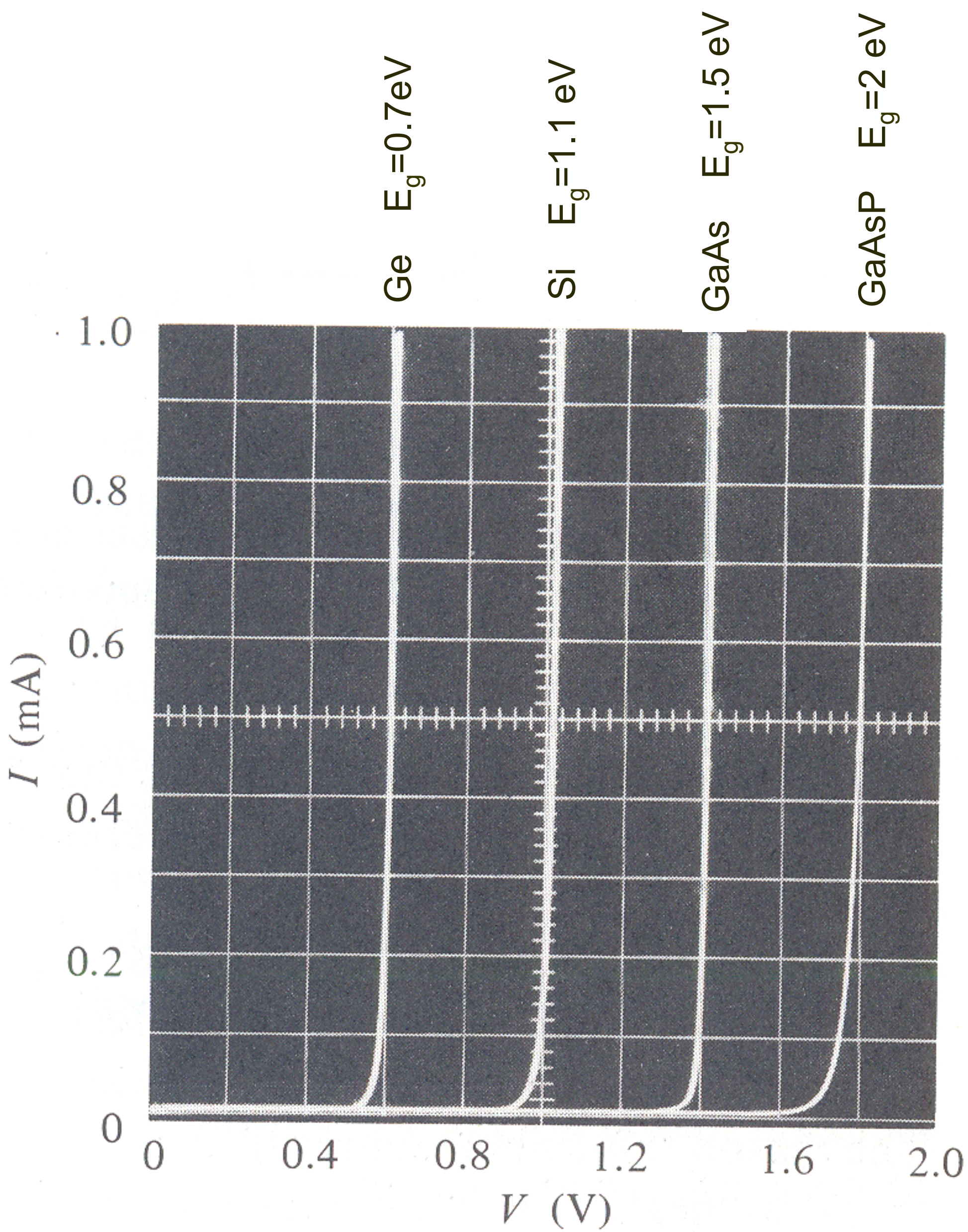
Low V_0

- V_0 is roughly the band gap E_g

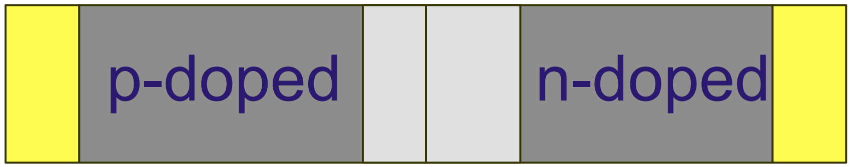
- Trade off here

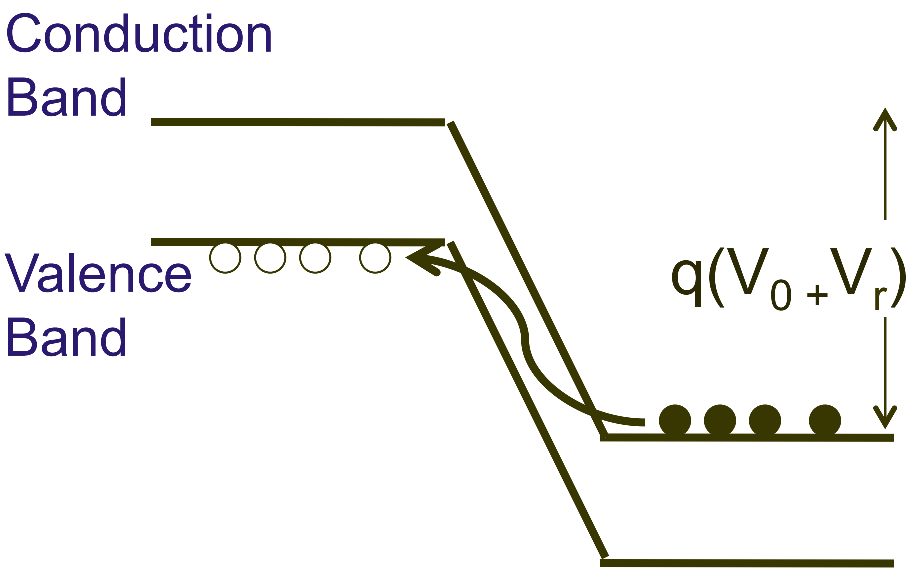
E_g low for low V_0,

but E_g large for low I_0



Zener Breakdown at High V_r





At high V_r (High E-field)

Electrons can tunnel through the band-gap filling empty valence band states (holes)

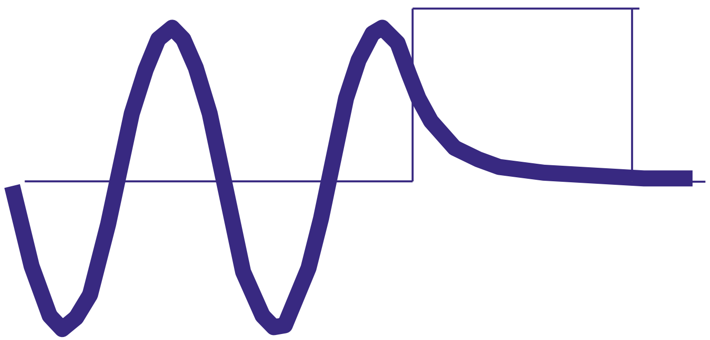
A current results – which increases in magnitude if there are mid-gap states

This is "Zener" breakdown

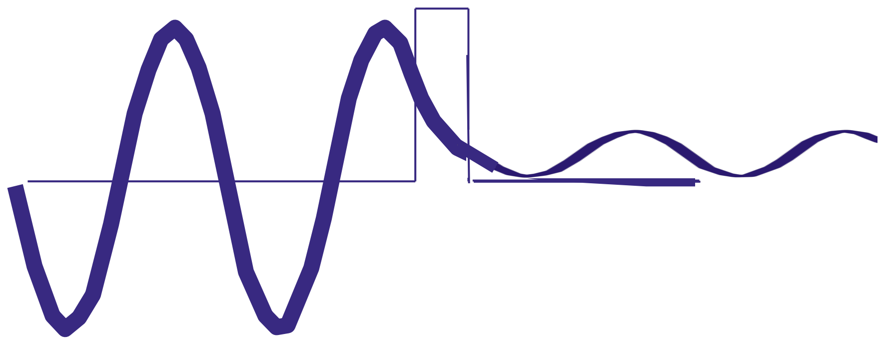
Need ultra-pure crystals and low E-field to rule out Zener breakdown

Quantum Tunnelling

Electron can be considered as a wave – potential barrier attenuates wave

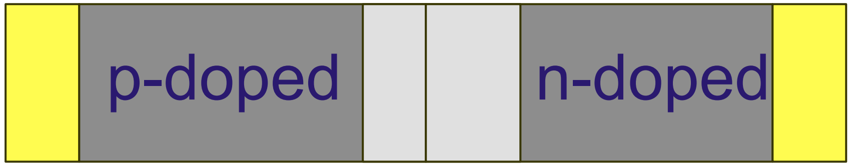


Thick Potential Barrier
Wave extinguished
-classical world
No tunneling

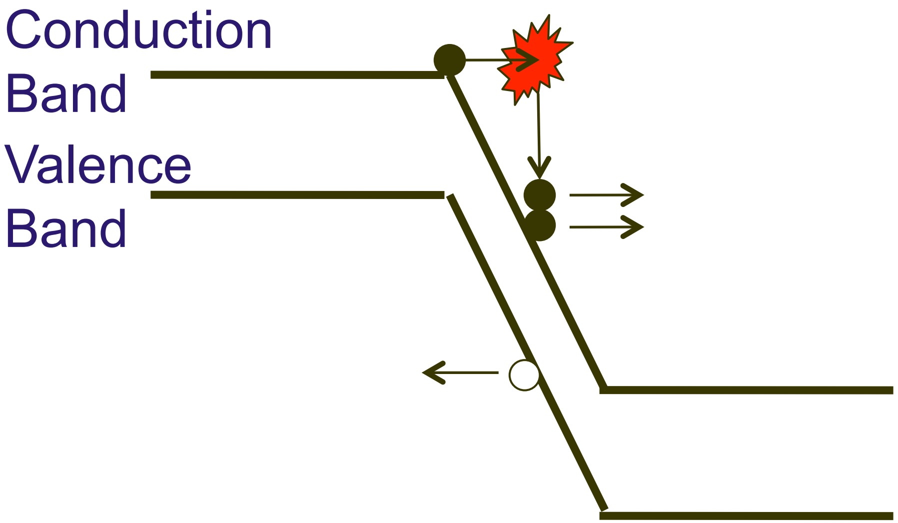


Thin Potential Barrier
Wave not extinguished at end of barrier
-quantum tunneling
- Fraction of electrons tunneling is ratio of amplitudes of incident and exiting waves

Avalanche Breakdown



A minority carrier which diffuses into the intrinsic region may accumulate potential energy due to the high E-field

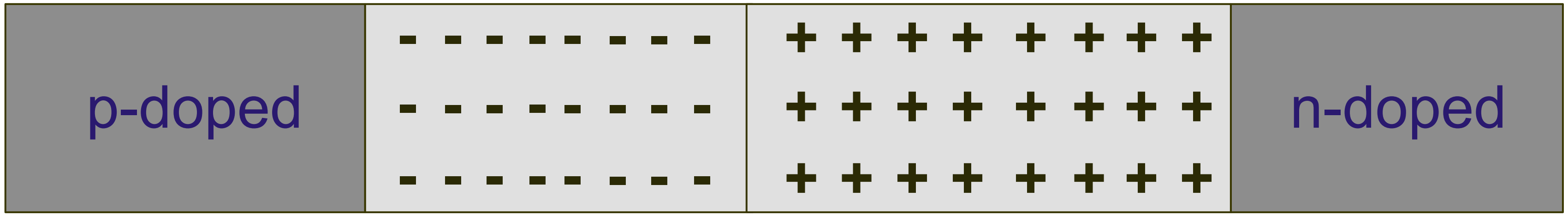


If this builds up to a large enough value ($>E_g$) this energy may be released by impact ionization – the carrier "impacts" with the lattice and creates an electron hole pair

This results in carrier multiplication and an avalanche effect – this is "avalanche breakdown"

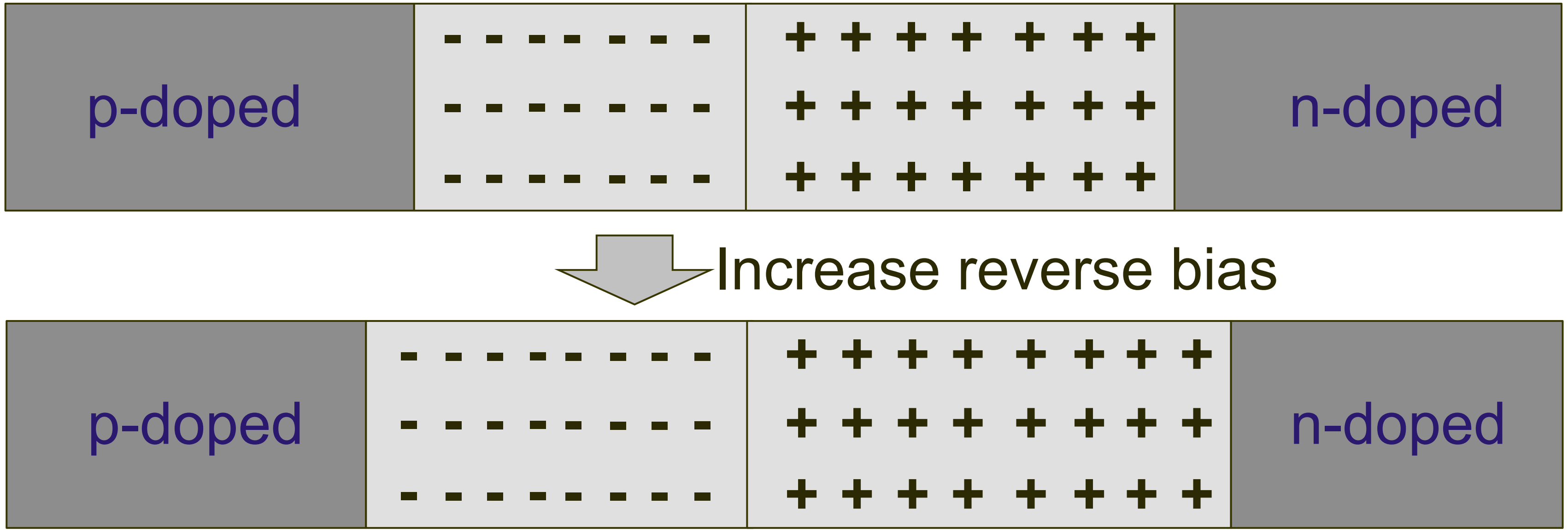
Low E-fields to inhibit avalanche & Zener breakdown

Capacitance of p-n Junction



Calculating capacitance looks tricky due to distributed charge in depletion region

Apply ΔV to p-n junction



The additional charge is added/removed from the edges of the depletion region – just like parallel plate capacitor

Capacitance

- Parallel plate capacitor with dielectric

$$C = \frac{\varepsilon A}{d} = \frac{\varepsilon A}{W_d} \qquad W_d = \left[\frac{2V_0\varepsilon}{q}\left(\frac{N_a + N_d}{N_a N_d}\right)\right]^{1/2}$$

Then need to make assumptions...

$N_a = N_d$, or $N_d << N_a$

$$C = A\left(\frac{q\varepsilon N_d}{2(V_0 - V_f)}\right)^{1/2}$$

For high switching speed – C must be small –
Small A, Low doping

Trade-offs - Rectifiers

Material (E_g) choice depends on operating temperature – power devices at room temperature are typically Si - Low n_i wins over V_0

Higher temperature operation – larger band-gap

For High V operation breakdown is an issue – usually one highly doped and one low doped region (two low doped can make resistance too high, make the device harder to manufacture reproducibly…)

Large area and short length of low doped region to reduce resistance

Summary

- The saturation current is due to the thermal generation of minority carriers which diffuse into the intrinsic region and contribute to drift current
- Two methods of reverse breakdown discussed
  - Zener – tunnelling through the band-gap – enhanced by high fields and mid-gap states
  - Avalanche – at high E-fields the carriers may not be able to shed excess energy quick enough – they may do this by impact ionization where a new e-h pair is created.
- Deviation of practical from ideal characteristics and trade offs for rectification discussed

