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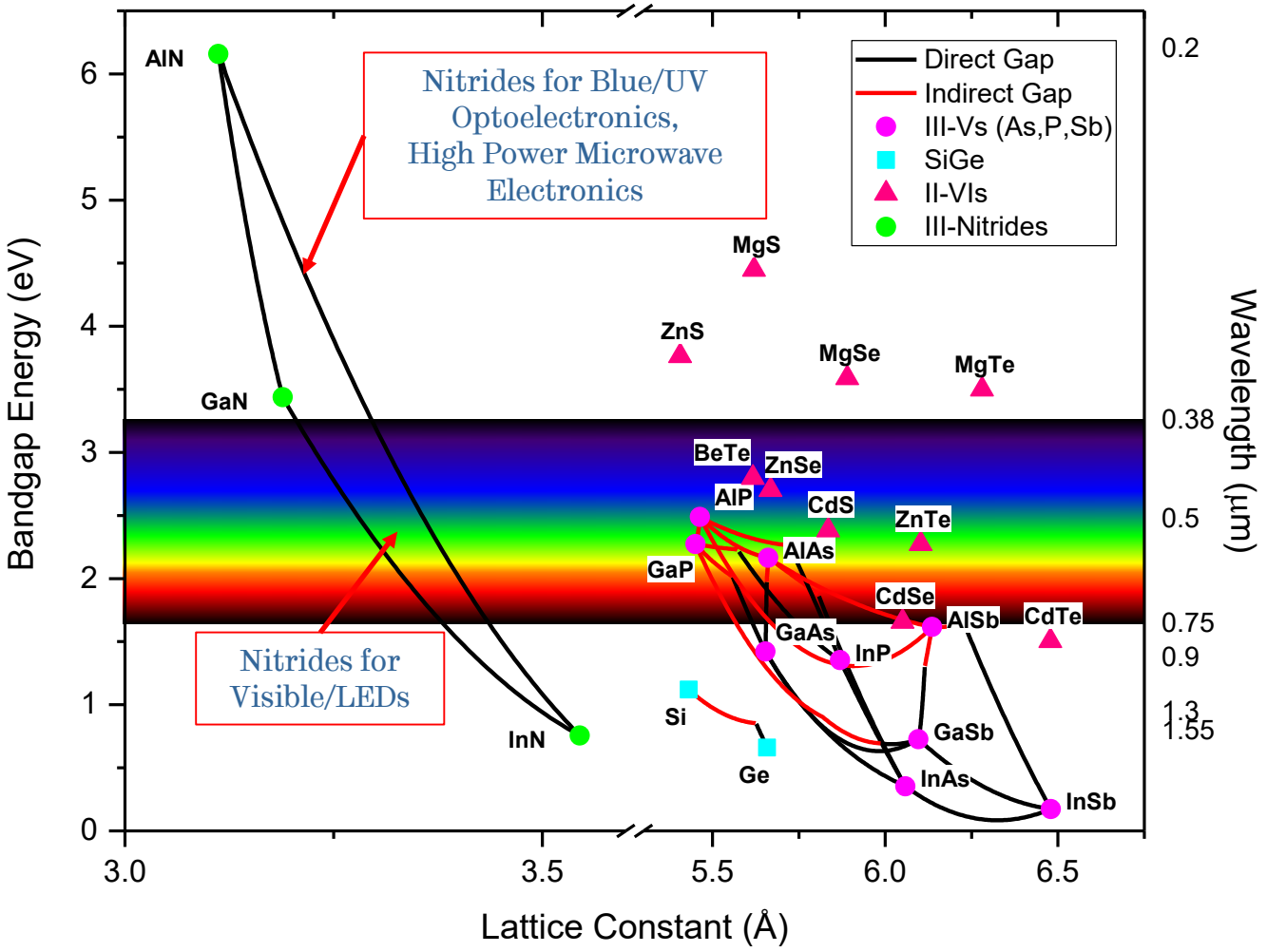
Semiconductor Materials



Data from "Semiconductor Band Parameters" (Kyle Montgomery) http://www.kmontgomery.net/resources/semiconductor-band-parameters
Colors in eV by Vojtěch Hála and Gringer - Wikimedia Commons - https://commons.wikimedia.org/wiki/File:Colors_in_eV.svg
http://www.sandia.gov/mstc/services/images/III-V-epitaxial-growth.gif

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Now and next … ?

Over Easter…

- You **need** to be working on the Practical Lab assignment – so far no one has contacted me suggesting they are ready to fit their data?!
- Remember the hand in date for your report is Friday 22nd April
- I am available on afternoon of Tuesday 16th March, morning of Thursday 17th March, all day on Thursday 24th March and then away until Monday 4th April…

After Easter… Lectures restart on 11th April

- Had the bulk of the lectures now only a few more to go…

- p-n junctions and diodes
- Transistors
- Photo-detectors
- Nanotechnology – Growth, Fabrication, Applications etc.
- Tutorials / Revision

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EEE6212 Lecture 17
"Conductivity and Conduction"

Dr Ian Farrer
E153a Mappin Building
Email – i.farrer@sheffield.ac.uk

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Outline

- Polarisation, Permittivity and Susceptibility
- Polarisation mechanisms
- Capacitors and Dielectrics
- Scattering of Free Electrons
- Drift and Diffusion Currents
- Built-in Electric Fields

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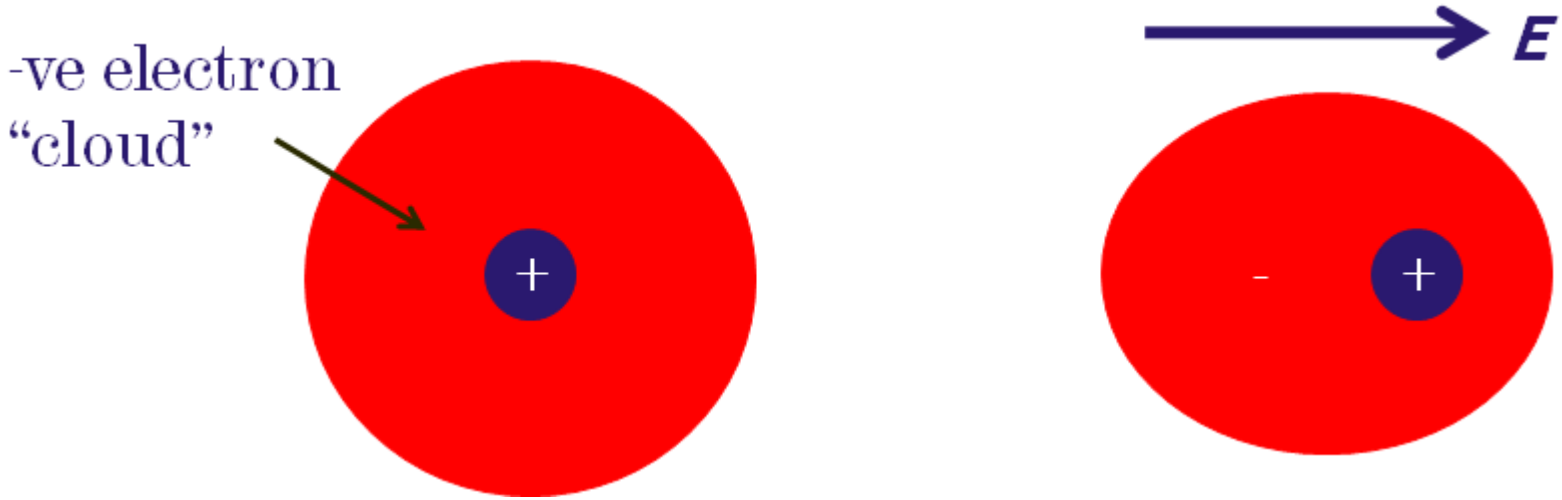
Polarisation



When a system is subject to an electric field $\boldsymbol{E}$ there is a tendency for the positive and negative charges to displace relative to one another

This produces an electric dipole moment

The dipole moment per unit volume is the polarisation $\boldsymbol{P}$ defined as

$$\boldsymbol{P} = \epsilon_0 \chi_e \boldsymbol{E}$$

Where ϵ_0 is the permittivity of free space and χ_e the electric susceptibility

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Permittivity and Susceptibility

Electric susceptibility χ_e – a measure of how easy it is to polarise a dielectric in response to an electric field

Electric Permittivity ϵ – a physical property of a solid (dielectric medium). Measure of the ability of the material to polarise in response to the field and thereby reduce the total electric field in the material. It as a measure of how easily the material "permits" the electric field to propagate

We usually compare the permittivity of a material to that of free space (a vacuum) $\boldsymbol{\epsilon_0} = 8.8 \times 10^{-12} F/m$ through the **relative permittivity ϵ_r**

The permittivity of air ~ permittivity of free space so $\epsilon_r = 1$ for air

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Polarisation Mechanisms

Electronic or Induced Polarisation (previous slide).

All dielectric materials – fast frequency response $\sim 10^{15} s^{-1}$

Ionic Polarisation

In ionic crystals (e.g. NaCl) the electric field can shift the sublattice of the Na^+ and Cl^- ions. Moderate frequency response $\sim 10^{9} s^{-1}$

Orientational Polarisation

Can have a dipole within a molecule (polar molecule e.g. HCl, H_2O)

The charge distribution is skewed in these molecules. E-field aligns randomly oriented dipoles causing a net polarisation. Important for liquids and gases. Slow frequency response $\sim 10^{4} s^{-1}$

Moving charge and molecules requires energy – loss appears as a resistive component to the impedance

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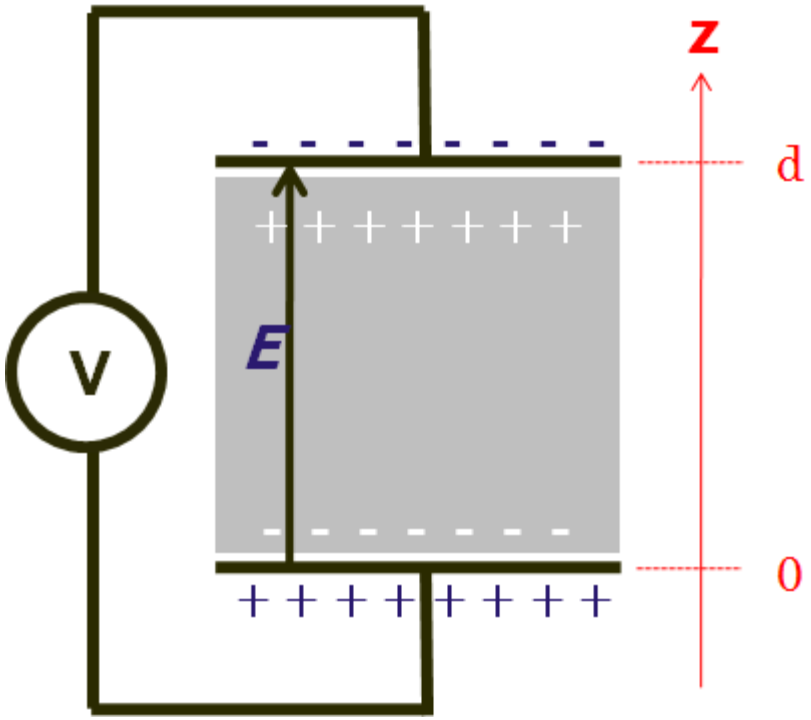
The Capacitor



In response to the Electric field a dielectric produces a polarisation

Displaced surface charge opposite the capacitor plates

Charge on the plates maintains the Electric field

Capacitance $C = Q/V$ where

$Q = Charge$

$V = Voltage$

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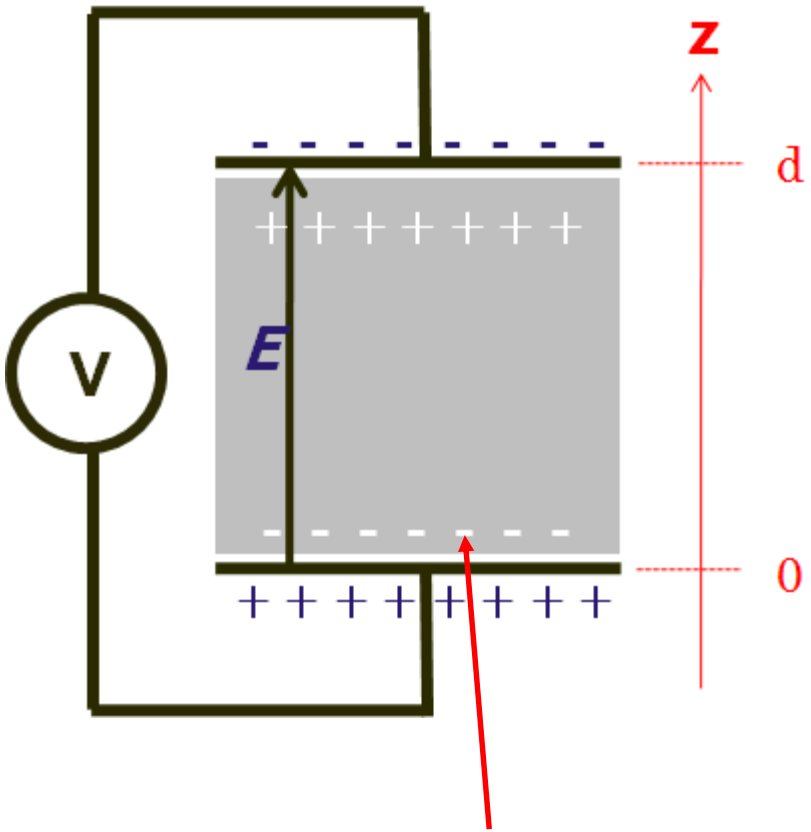
The Capacitor



Charge per unit area $\rho = \frac{Q}{a}$

$$V = \int_0^d E\, dz = \int_0^d \frac{\rho}{\epsilon}\, dz$$

$$= \frac{\rho d}{\epsilon} = \frac{Qd}{\epsilon a}$$

Inserting $C = \frac{Q}{V}$

Gives

$$C = \frac{\epsilon A}{d}$$

Where $\epsilon = \epsilon_r \epsilon_0$

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Dielectric Breakdown

Sudden increase in current above a critical electric field

Limitation of the dielectric – capacitor or insulator becomes ~ a short circuit

Can be reversible or non-reversible (i.e. catastrophic)

Breakdown Electric Field can be $\sim 10^9 V m^{-1}$

Ideally want this as high as possible

By Bert Hickman - http://www.capturedlightning.com, Attribution, https://commons.wikimedia.org/w/index.php?curid=205440

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Ideal Capacitor Dielectric

High ϵ_r – can store a lot of charge for the same applied voltage

Breakdown only at very high fields – can withstand large voltages

Low cost

Good manufacturability for thin films – gate insulators are extremely thin in modern devices, low defects required

Reliable

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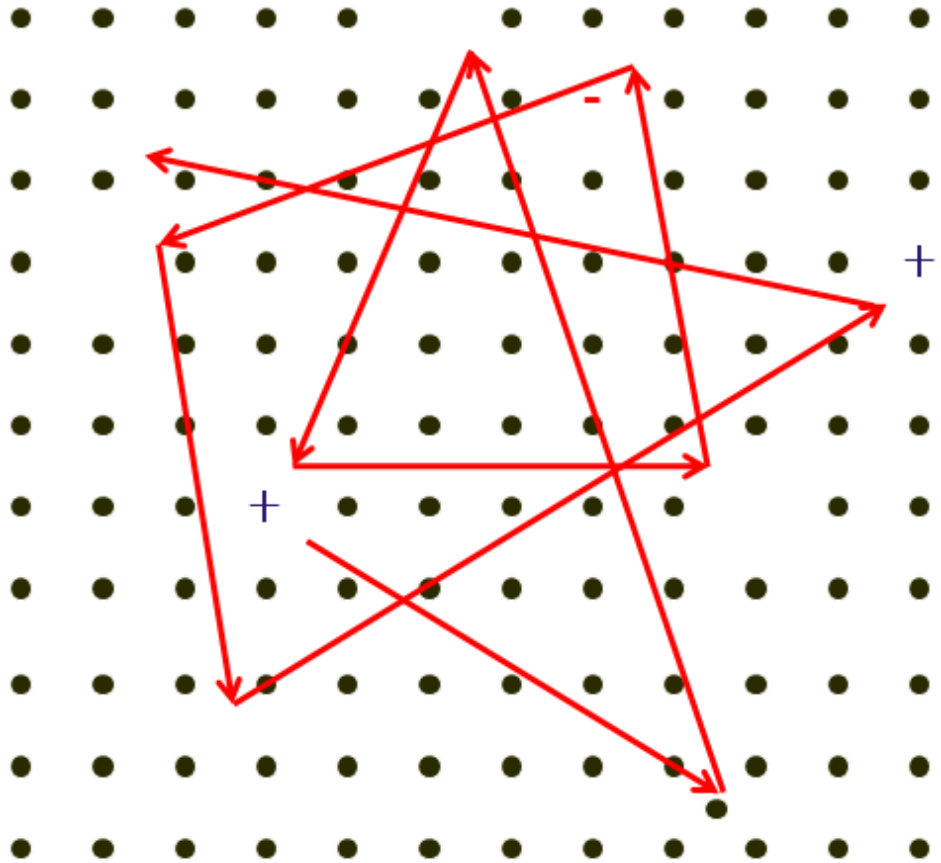
Free Electron - Scattering



Imagine for a moment that we can "see" the motion of the electrons

Free electrons – have thermal energy c.f. Brownian motion

If we observe enough carriers then we would see no net movement of charge – therefore no net current

Collisions arise from imperfections in the crystal lattice

- Ionised impurities
- Interstitial and Vacancy defects
- Phonons

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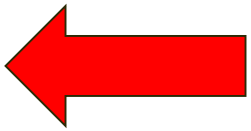
What causes a current?

Three causes of a net flow of current

- An electric potential gradient (i.e. An Electric Field)

$$\frac{dV}{dx}$$



- An electron density gradient (i.e. a difference in concentration)

$$\frac{dn}{dx}$$

- A temperature gradient

$$\frac{dT}{dx}$$

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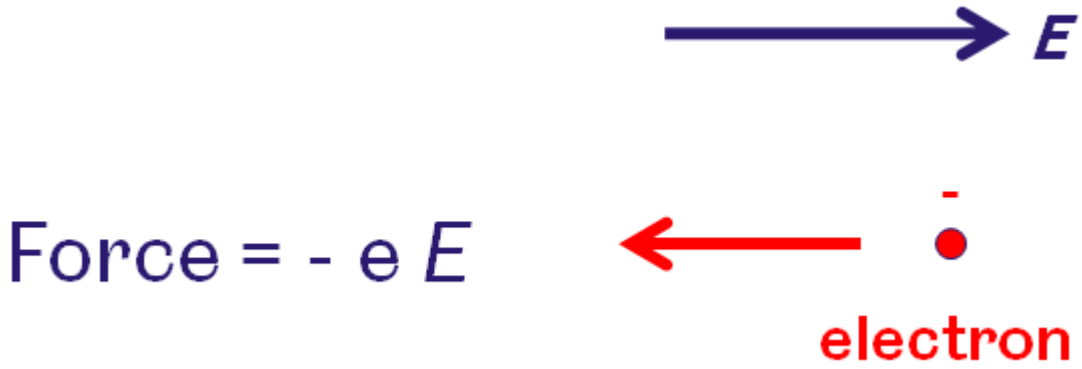
Application of an E-Field



Electron accelerates in ***opposite*** direction due to negative charge

In a vacuum we just use Newton's laws $F = m_e \times a$

In a semiconductor we just apply effective mass $F = m^* m_e \times a$

Where a = acceleration

n.b. the mass will commonly be written as m^* and it is assumed that you know $m^* = m^* m_e$

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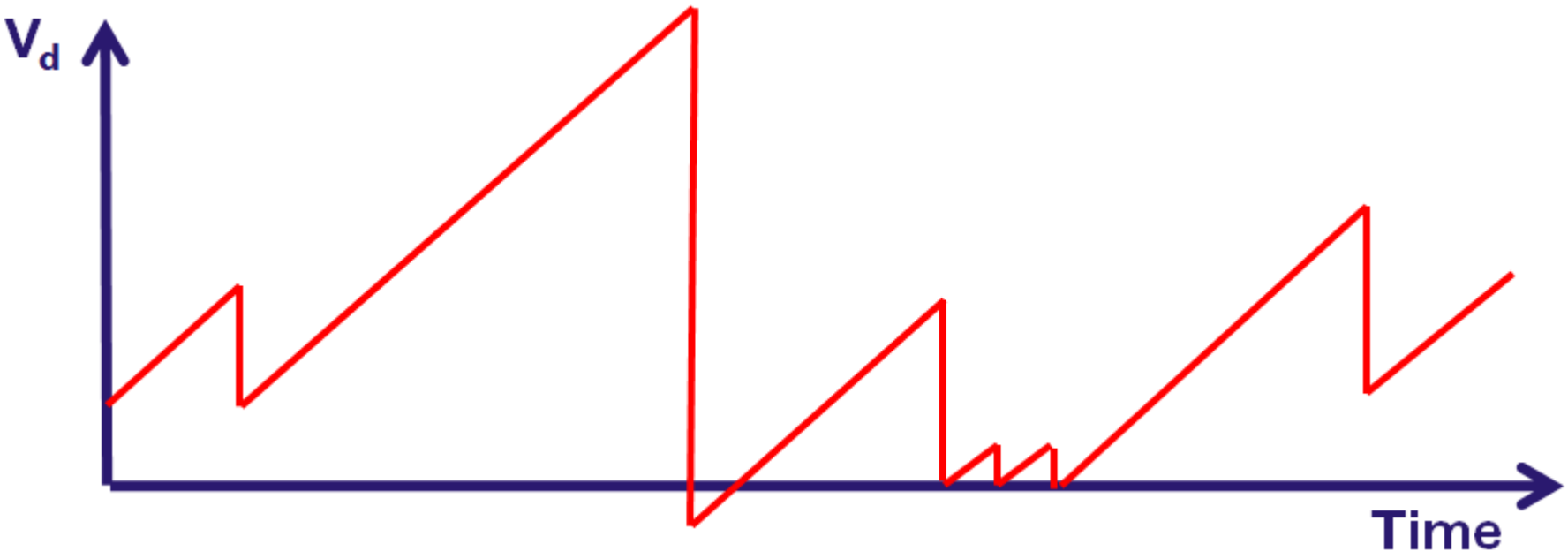
Drift Velocity

The electron gains velocity as it is accelerated by the Electric Field

The electron can lose velocity when scattered

Further complications when we consider ***all*** electrons not just ***one***



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Deriviation

Consider a solid with a free electron concentration of $n\ /m^3$

When an electric field $\boldsymbol{E}$ is applied the electrons will accelerate

$$a = -\frac{q\boldsymbol{E}}{m^*}$$

Acceleration so both velocity and momentum are changing

Rate of change of momentum with time for each electron

$$\frac{dp_e}{dt} = \frac{d(m^* v_d)}{dt} = m^* \frac{dv_d}{dt} = m^* a = F = -q\boldsymbol{E}$$

Rate of change of momentum p of all n electrons

$$\left(\frac{dp}{\mathrm{dt}}\right)_{drift} = -q\boldsymbol{E}n$$

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Assume electrons will accelerate until scattered

Chance (probability) that a particular electron will be scattered in unit time is a number between 0 and 1.

For a large number of electrons this fraction ***will be*** scattered.

Number scattered per unit time

$$= \frac{n}{\tau}$$

Where τ is a time constant (average time between scattering events)

Assume that on average each scattering event causes the electron to lose all momentum (at this instant momentum $= mv_d$)

Then the total change in momentum due to scattering events is

$$\left(\frac{dp}{dt}\right)_{scatter} = -\frac{n}{\tau} \times mv_d$$

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Where $\langle v_d \rangle$ is the average drift velocity of the electron population

At equilibrium the total momentum change of the population is zero

$$\left(\frac{dp}{dt}\right)_{drift} + \left(\frac{dp}{dt}\right)_{scatter} = 0$$

Hence

$$-q\boldsymbol{E}n - \frac{n}{\tau}m^*\langle v_d \rangle = 0$$

And so

$$\langle v_d \rangle = -\frac{q\boldsymbol{E}\tau}{m^*}$$

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Carrier Mobility μ

Drift velocity given by

$$\langle v_d \rangle = -\frac{q\boldsymbol{E}\tau}{m^*}$$

The important parameter is the average time between scattering events τ

Governed by impurity concentration, phonons, defects

Effective mass also important

Can simplify this to one (easily measurable) material dependent parameter, the mobility μ to give

$$\langle v_d \rangle = -\mu\boldsymbol{E}$$

Where

$$\mu = \frac{q\tau}{m^*}$$

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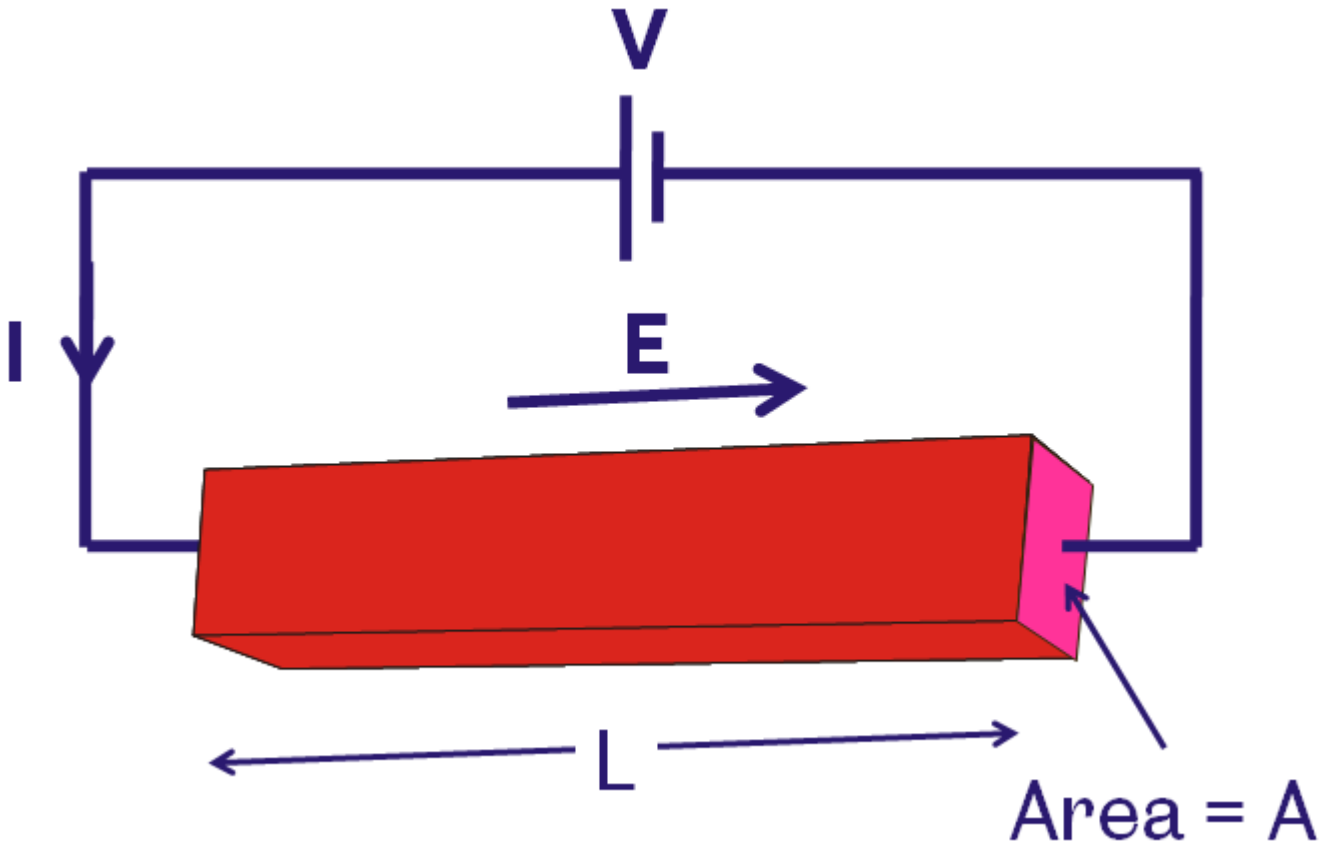
Solid with Free Electrons



Define a current density

$$J = \frac{I}{A}$$

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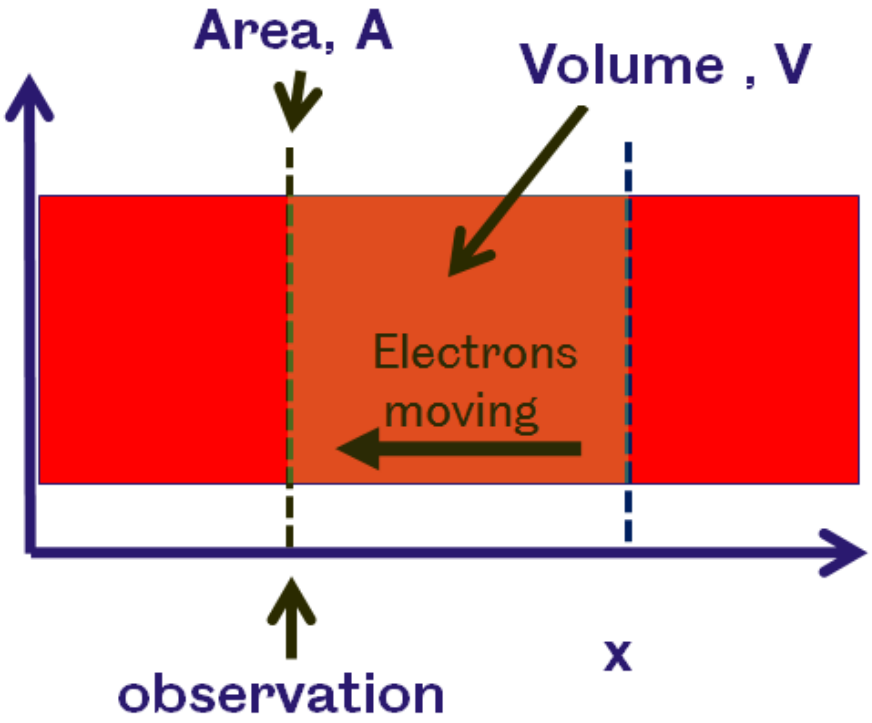
Longitudinal Slice



Average velocity of the electrons v_d and density of electrons n

In time t all electrons in the shaded region will have moved past the observation point

$$x = v_d t$$

Number of electrons in this volume

$$nV = nAx = nAv_d t$$

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Charge on each electron $= -q$ $(q = 1.6022 \times 10^{-19} C)$

So in unit time (1s) the amount of charge flowing past our observation point is the current

$$I = -nAqv_d$$

The current density

$$J = \frac{I}{A} = -nqv_d$$

n.b. J and I in opposite direction to the electron flow as expected (conventional current vs electron flow)

Sometimes drift velocity written as v or v_d

Sometimes charge on electron written as e or q

Often we use centimetres instead of metres … be very careful with units!!

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Eliminate v_d

The previous equation is only useful if we know the drift velocity

$$v_d = -\mu \boldsymbol{E}$$

Which gives us

$$J = nq\mu E$$

So the current density in our solid depends on

1) Carrier concentration – how many carriers
2) Electric Field – magnitude dV/dx
3) Mobility – how easily the carriers can move
4) The charge on the electron (non-negotiable!!!)

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Ohm's Law

Our expression for the current density

$$J = nq\mu E$$

Can be simplified to

$$J = \sigma E$$

Where the conductivity

$$\sigma = nq\mu$$

Conductivity is the inverse of resistivity

$$\rho = \frac{1}{\sigma}$$

This is the general form of Ohm's law

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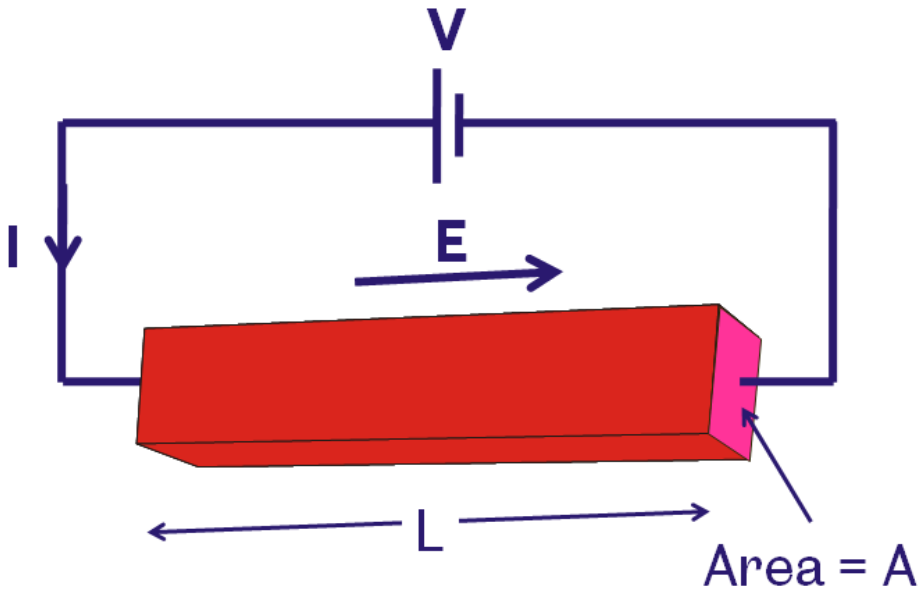

Given

$$J = \frac{I}{A}, \qquad E = \frac{V}{L}, \qquad J = \sigma E$$

$$\frac{I}{A} = \frac{\sigma V}{L}$$

$$I = \frac{\sigma A V}{L}$$

Ohm's Law is true if

$$R = \frac{L}{\sigma A}$$

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Extrinsic Semiconductor – Drift

Extrinsic Silicon

Made p-type by doping with Boron

$$p = 10^{21}\ m^{-3}$$
$$n \sim n_i = 10^{16}\ m^{-3}$$

$$\mu_e = 0.12\ m^2 V^{-1} s^{-1}$$
$$\mu_h = 0.05\ m^2 V^{-1} s^{-1}$$

$$\sigma = nq\mu_e + pq\mu_h$$

The hole drift current is 40,000x greater than the electron drift current

If the doping is high – can ignore the minority carrier *drift* current

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What causes a current?

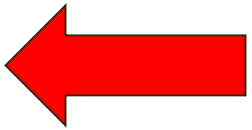
Three causes of a net flow of current

- An electric potential gradient (i.e. An Electric Field)

$$\frac{dV}{dx}$$

- An electron density gradient (i.e. a difference in concentration)

$$\frac{dn}{dx}$$



- A temperature gradient

$$\frac{dT}{dx}$$

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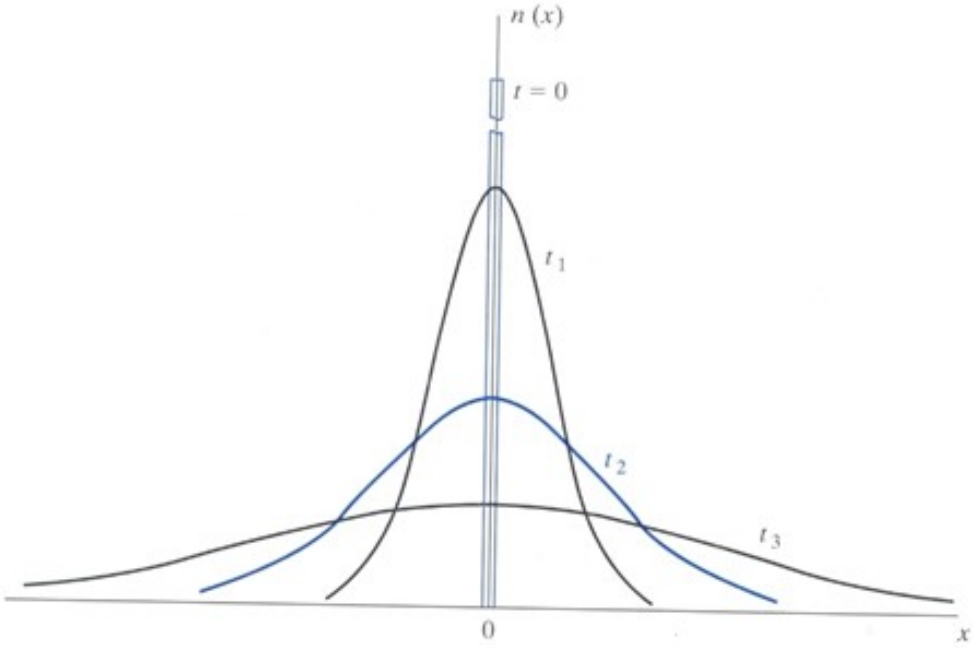
Diffusion – General

Diffusion has been studied for a long time – salts in liquids, dust particles in air, population dynamics in biology etc.

There will be a net flow (flux) of particles from a region of high concentration to a region of low concentration

Acts to cancel out a non-uniform concentration distribution

Governed by Fick's Laws



Fick's First Law: $J = -D\frac{\partial \phi}{\partial x}$

Fick's Second Law: $\frac{\partial \phi}{\partial t} = D\frac{\partial^2 \phi}{\partial x^2}$

$\therefore \phi = \phi(x, t)$

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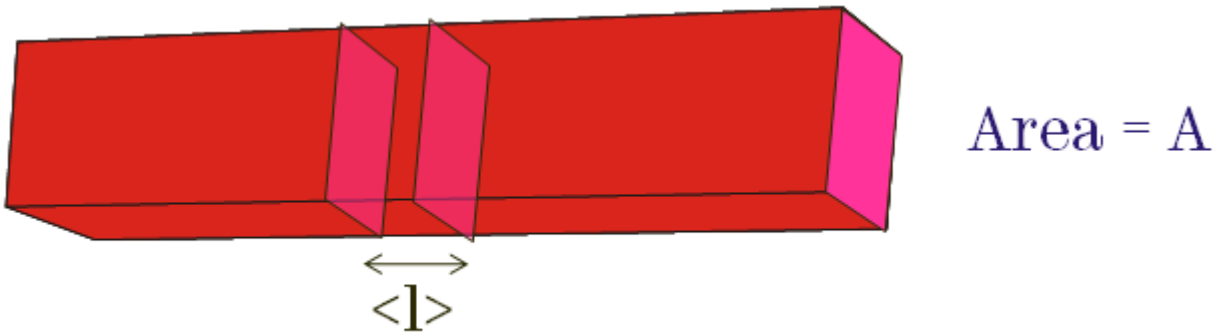
Mean Free Path

For a carrier population we have a mean velocity and a mean scattering time

There is a mean distance the carrier travels before scattering.

This is termed the “mean free path”

Imagine a bar or rod we split into segments $\langle l \rangle$ wide



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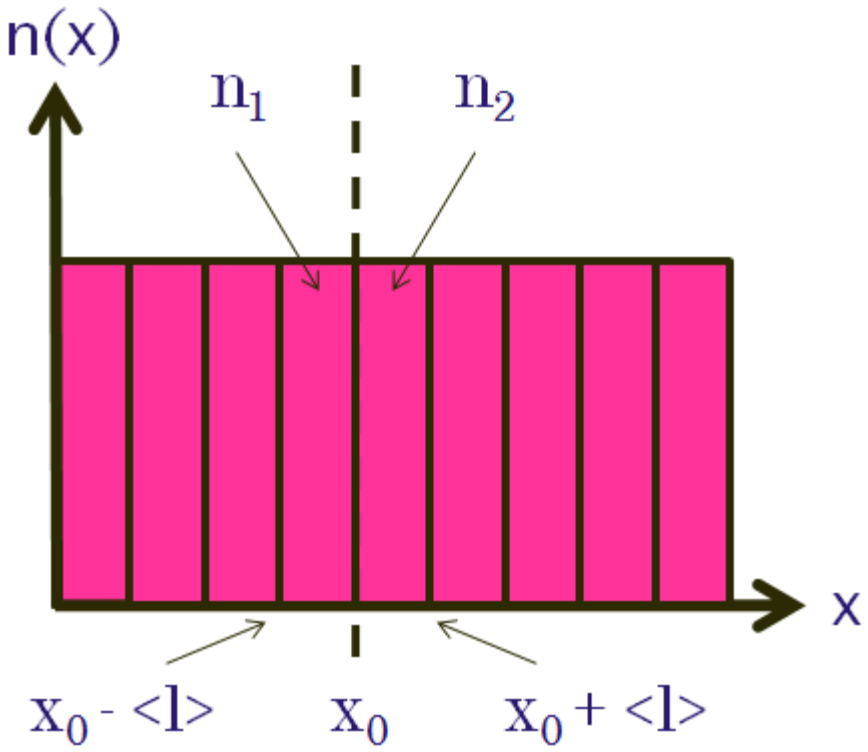
Case 1 – Uniform Carrier Distribution



Consider a 1-dimensional distribution

The neighbouring segments at x_0 have carrier concentrations n_1, n_2

Half of all carriers are moving in the positive direction and half in the negative direction

There is no net flow of charge – no current – As many carriers are moving from left to right as from right to left through x_0

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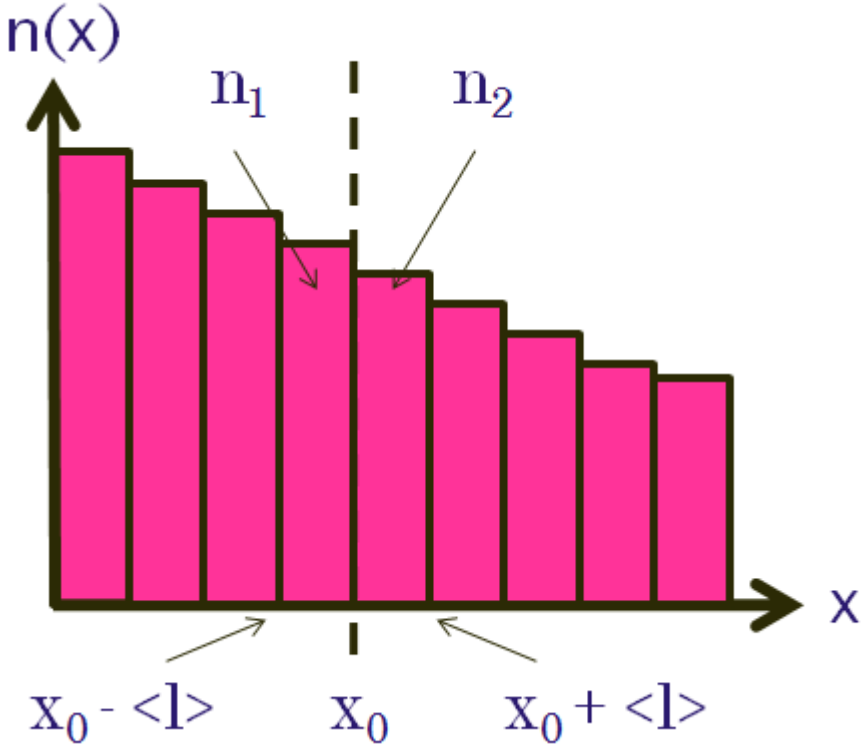
Case 2 – Carrier Distribution Gradient



Now consider a carrier flux passing x_0 from left to right (see e.g. Streetman)

$$\phi(x) = -D\frac{dn}{dx}$$

$\phi(x) =$ flux

$n =$ concentration

$x =$ distance

$D =$ Diffusion Coefficient

Negative sign as net motion is in the direction of decreasing n

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Electrons and Holes

Must consider both the electrons and holes in this case – electron and hole fluxes per unit area given by

$$\phi_e(x) = -D_e \frac{dn}{dx}, \qquad \phi_h(x) = -D_h \frac{dp}{dx}$$

Diffusion current is carrier flux times charge ($-q$ for electrons, $+q$ for holes)

$$J_e = qD_e \frac{dn}{dx}, \qquad J_h = -qD_h \frac{dp}{dx}$$

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The Diffusion Coefficient

$$D_{e,h} = \frac{k_B T \mu_{e,h}}{q}$$

"Einstein Relation"

Diffusion Coefficient (or Diffusivity) D is the measure of how easily carriers diffuse

D increases when T increases – as the carriers have more thermal energy

D increases as μ increases – as the carriers have less inhibition to motion

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Drift and Diffusion

Consider both an applied Electric Field ***and*** a carrier concentration gradient

$$J_e^{total}(x) = J_e^{drift} + J_e^{diffusion} = q\mu_e E_x n + qD_e \frac{dn}{dx}$$

$$J_h^{total}(x) = J_h^{drift} + J_h^{diffusion} = q\mu_h E_x p - qD_h \frac{dp}{dx}$$

Minority Diffusion

As drift current is proportional to the carrier concentration we know that minority carriers seldom provide much drift current and may often be ignored with little error

As diffusion current is proportional to the ***gradient*** of the carrier concentration, minority carrier diffusion current can therefore be large

Note: Here we have ignored Generation or Recombination of carriers

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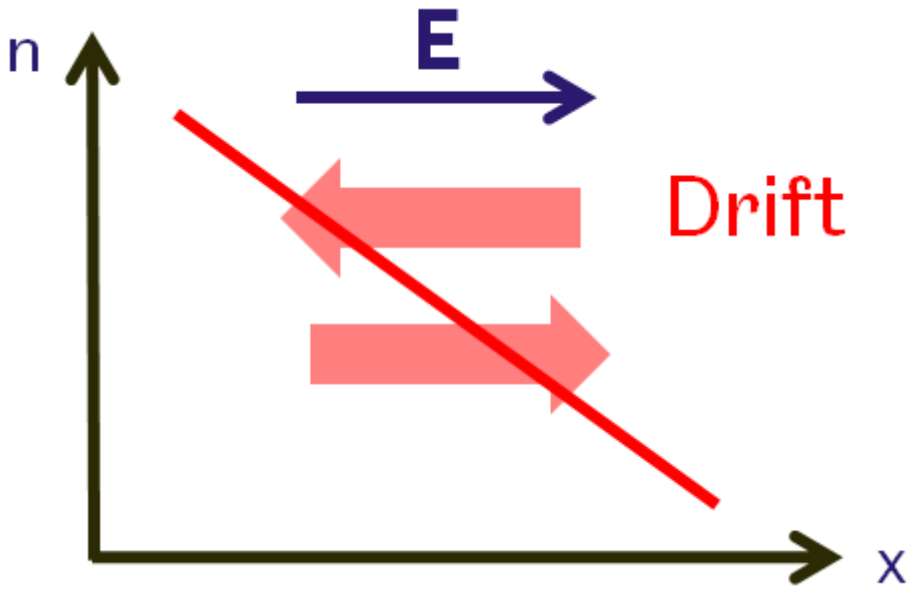
Drift vs Diffusion



Consider the case where there is both a composition gradient ***and*** and Electric Field

$$J_e = q\mu_e E_x n + qD_e \frac{dn}{dx}$$

There is a case where these terms balance and $J_e = 0$

$$E_x = -\frac{D_e}{n\mu_e}\frac{dn}{dx}$$

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Carrier Concentration Gradients at Equilibrium

Imagine a sample with a carrier concentration gradient

e.g. Vary the doping in one direction

At equilibrium there must be no net flow of current

There is an internal field induced to ensure this is the case

Varying doping concentrations results in ***built-in*** Electric Fields and potentials

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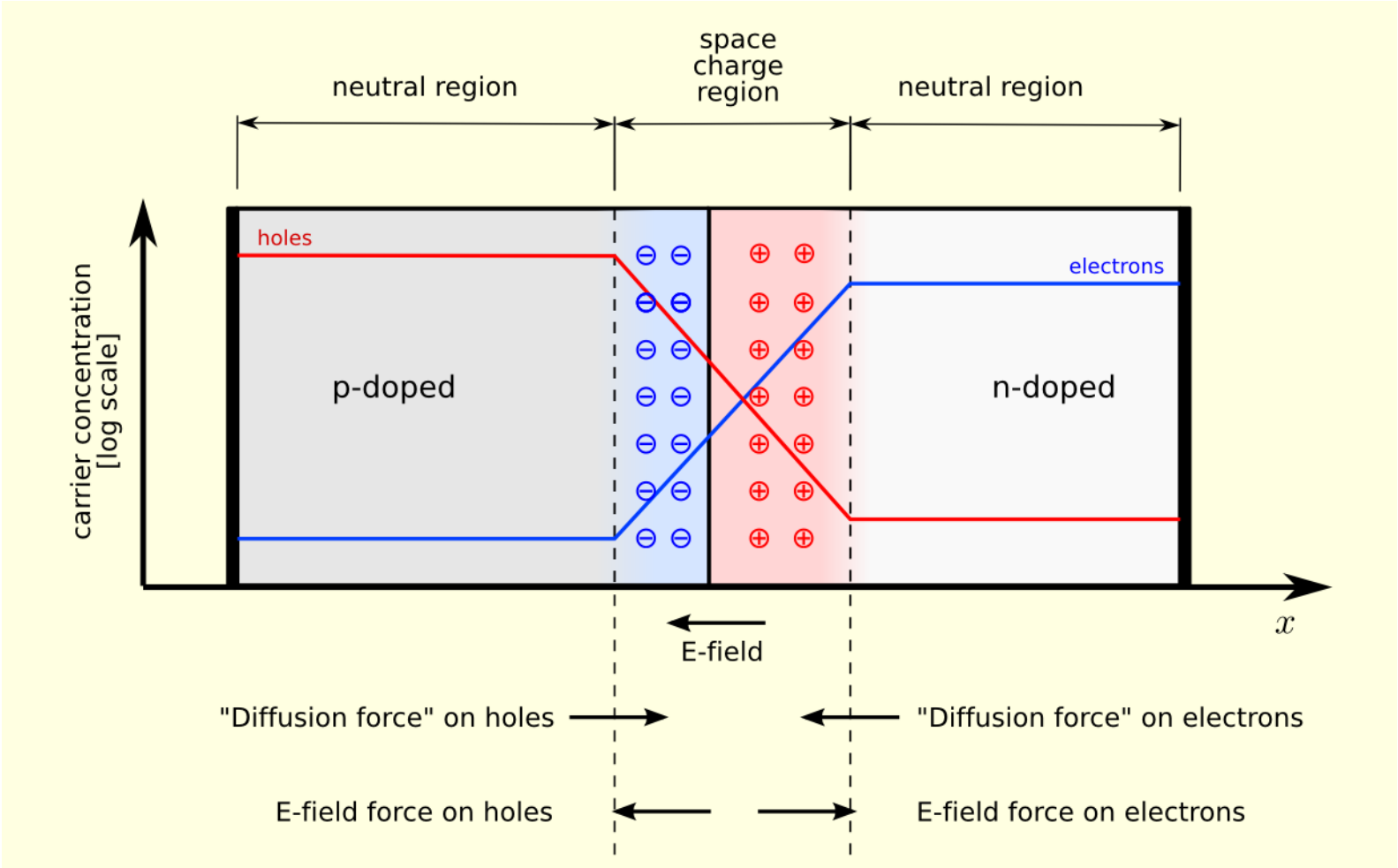
p-n junction



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Summary

- Discussed polarisation and capacitance
- Explored how a free electron is scattered within the crystal
- Discussed drift and diffusion currents
  - Drift – Driven by Electric Fields
  - Diffusion – Driven by Carrier Concentration Gradients
- Combination of Diffusion and Drift – gives rise to internal Electric Fields

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EEE6212 Lecture 18
"Carrier Lifetime and Recombination"

Dr Ian Farrer
E153a Mappin Building
Email – i.farrer@sheffield.ac.uk

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Outline

- Carrier Lifetime in the classical mobility model
- Debye Length
- Fermi's Golden Rule
- Radiative vs Auger Transitions
- Carrier Lifetime Model in Semiconductors:
  - Non – Radiative contributions by defects
  - Radiative Recombination
  - Auger Recombination
- Measuring Density and Mobility

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Classical Model of Charge Carrier in an Electric Field

Consider the differential equation for the drift velocity $\boldsymbol{v_d}$ of an electron of mass m and charge $-e$ in an electric field $\boldsymbol{E}$ with "friction" b

$$m\frac{\partial \boldsymbol{v_d}}{\partial t} + b\boldsymbol{v_d} = F = -e\boldsymbol{E}$$

Where the Relaxation Time $\tau = m/b$

$$\Rightarrow \quad \boldsymbol{v_d} + \tau\frac{\partial \boldsymbol{v_d}}{\partial t} = -\frac{e\boldsymbol{E}\tau}{m}$$

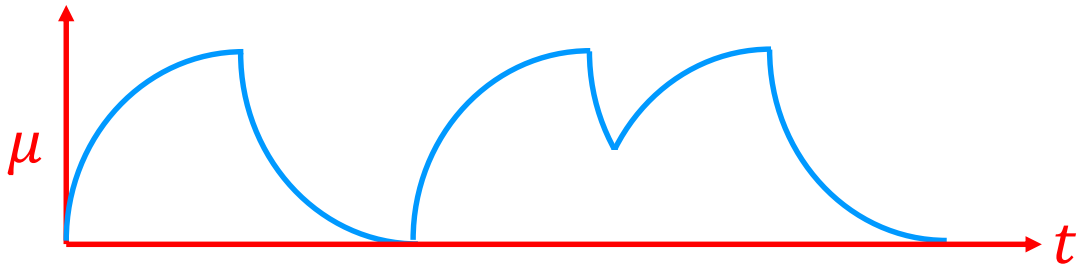
First order linear differential equation with separable variables

$$\Rightarrow \quad v_d = v_{d,\infty}\left[1 - e^{-t/\tau}\right]$$

Where $v_{d,\infty} = -\frac{eE\tau}{m} = -\mu E$

The carrier mobility $\mu = \frac{|\boldsymbol{v_{d,\infty}}|}{|\boldsymbol{E}|}$

or



Lifetime of individual electron in the CB: $\tau = \frac{\mu m}{e} = 10^{-14} - 10^{-13} s$

Temperature Dependence of Mobility

For bulk doped materials the scattering of carriers can be split into two regimes

At low temperatures scattering from the impurities (ionised donors/acceptors etc.) dominates the mobility

$$\mu \propto T^{+3/2}$$

At high temperatures scattering from phonons dominates

$$\mu \propto T^{-3/2}$$

As the impurity concentration is reduced the peak mobility shifts to lower temperatures

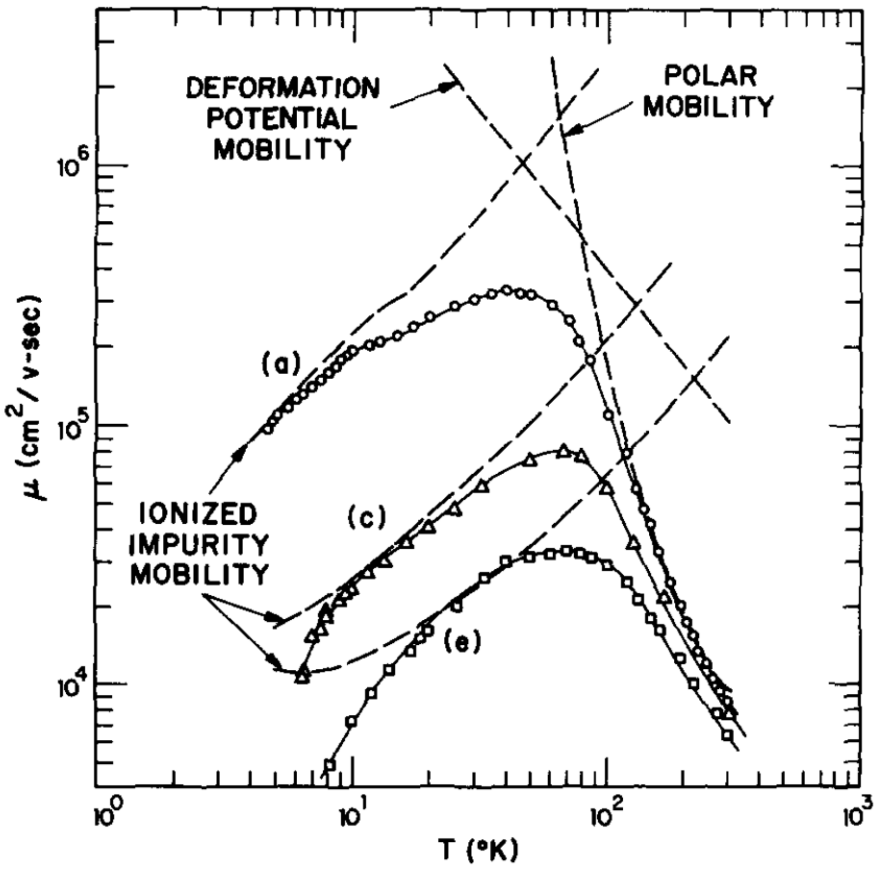


Fig. 2. Temperature variation of Hall mobility at 5 kG for three samples. In the temperature range from 300 to 77°K the mobility of sample (*a*) is dominated by polar mode scattering. Samples (*c*) and (*e*) show increased effects of ionized impurity scattering.

G. E. Stillman et al, "Hall coefficient factor for polar mode scattering in n-type GaAs," J. Phys. Chem. Solids, vol. 31(6), pp. 1199-1204, 1970

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Alternative Model

Consider the time during which a discontinuity in "space charge" is dissipated by electrical conductance

E.g. Injection of Δn electrons (of charge density $\rho = -e\Delta n$)

Gauss' Law	$\boldsymbol{\nabla . D} = \rho = -e\Delta n$
Electric Displacement (or flux Density)	$\boldsymbol{D} = \epsilon_0 \epsilon_r \boldsymbol{E}$
Ohm's Law	$\boldsymbol{j} = \sigma \boldsymbol{E}$
Continuity Equation for charge	$\boldsymbol{\nabla . j} = -\frac{\partial \rho}{\partial t}$

$$\frac{\partial \rho}{\partial t} = -\frac{\sigma}{\epsilon_0 \epsilon_r}\rho \Rightarrow \rho \propto e^{-t/\tau}$$

With $\tau = \epsilon_0 \epsilon_r / \sigma$

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Debye Length

Consider the current density through the electrodes into the semiconductor when electric current $\boldsymbol{j}$ due to $\boldsymbol{\nabla}.\boldsymbol{E} = \rho/\epsilon_0\epsilon_r$ compensates the diffusion current due to the concentration gradient….. (Einstein relations – previous lecture)

$$\sigma \boldsymbol{E} + eD_n \nabla(\Delta n) = 0$$

Where $D_n = \frac{\mu_n kT}{e}$

$$\frac{\partial E_X}{\partial x} = \frac{\rho}{\epsilon_0 \epsilon_r}$$

Differentiating first equation gives

$$\sigma \frac{\partial E_x}{\partial x} + eD_n \frac{\partial^2(\Delta n)}{\partial x^2} = 0$$

Substituting and recall that $\rho = -e\Delta n$

$$\frac{\sigma}{\epsilon_0 \epsilon_r} \Delta n(x) = D_n \frac{\partial^2(\Delta n)}{\partial x^2}$$

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Debye Length

Gives

$$\Delta n = \Delta n_0 e^{-x/L}$$

With Debye Length

$$L = \sqrt{D_n \tau}$$

And

$$\frac{\partial(\Delta n)}{\partial t} = -\frac{1}{\tau}(\Delta n)$$

$$\Rightarrow \Delta n \propto e^{-t/\tau}$$

Where $\tau = 10^{-10} s$ (doped Silicon) – $10^{-3} s$ (pure Silicon) for space charges

The Debye Length is the distance over which local electric fields affect the distribution of free charge carriers. It decreases with increasing charge concentration. (E.g. 0.1nm for 1E21/cm^3 and 100nm for 1E15/cm^3 in Silicon at 300K)

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Haynes-Shockley Experiment

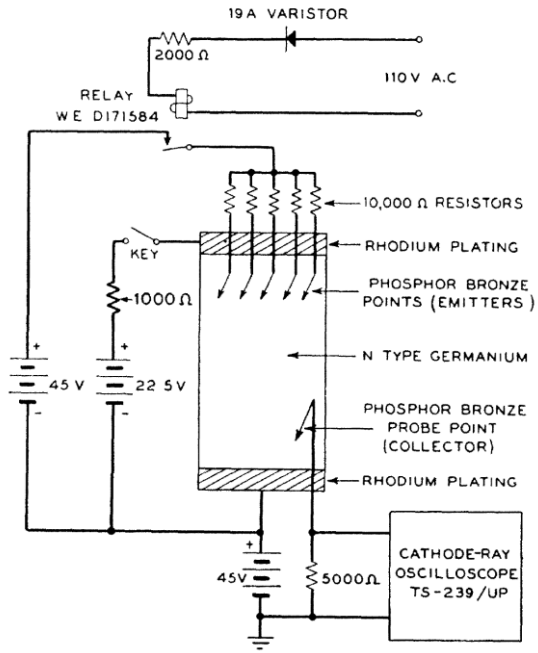
Consider the case of a long thin rod of n-type semiconductor where a short pulse of minority carriers (holes) is injected

There are now excess charges in the rod immediately after injection

Majority carriers flow to neutralise this excess charge (takes a few dielectric relaxation times)

If there is also an applied field then the holes move along the rod at a velocity determined by the hole mobility

Thus by observing the shape and position of the pulse after a time t this can be used to directly measure the mobility, diffusion constant and lifetime of the holes



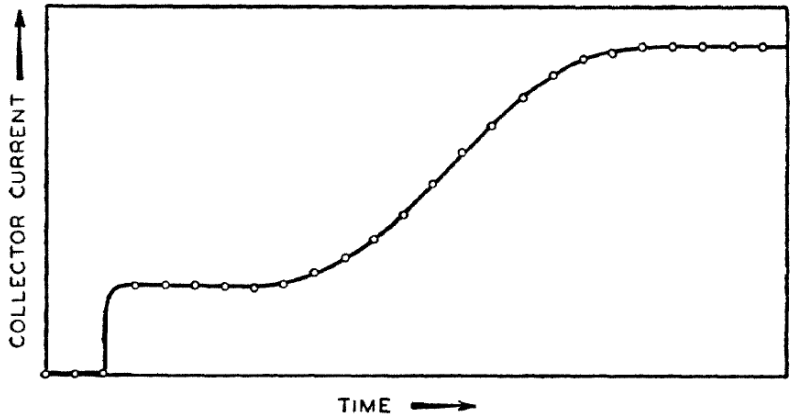


FIG. 2. Oscilloscope trace showing delay of holes in reaching collector.

Haynes and Shockley – Phys. Rev. 75 p691 (1949)

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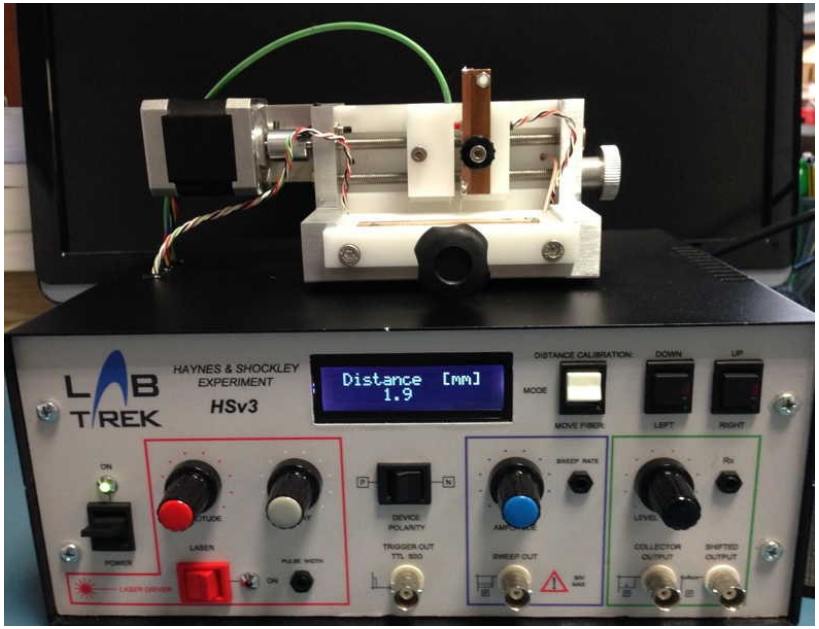
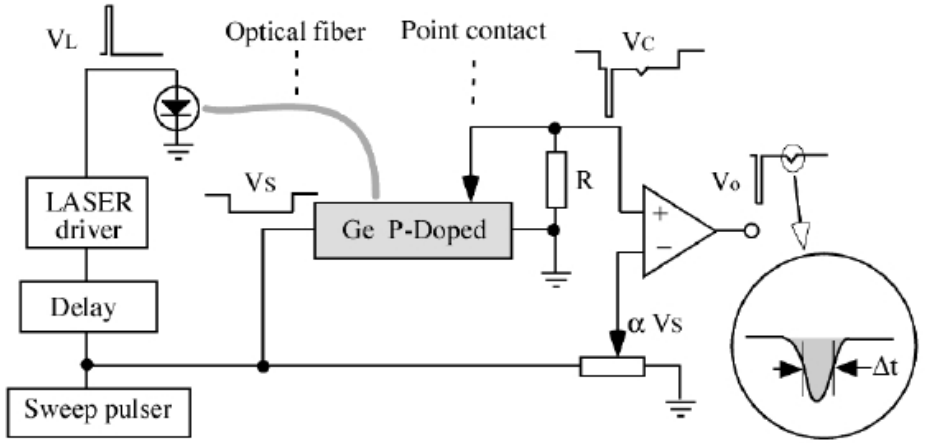
Improved Version

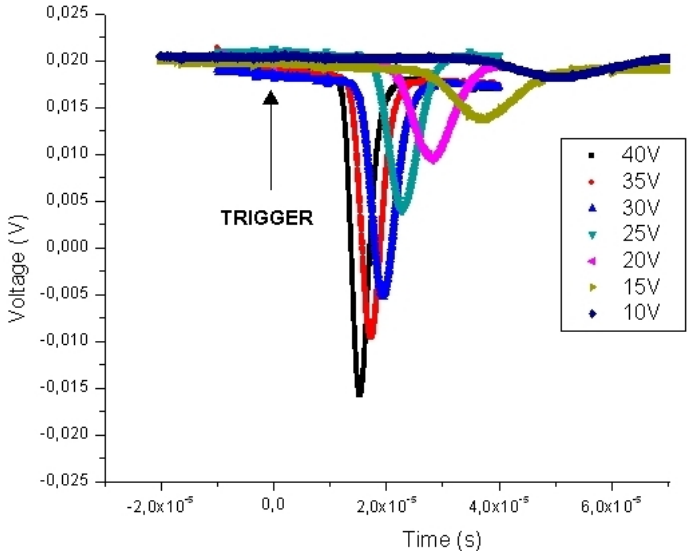
Now a pretty standard undergraduate experiment!

Use a laser pulse to inject the carriers and apply a bias

Width of the electrical pulse is related to the diffusion of the holes, time to the drift velocity







Sconza et al Am. J. Phys. 68 (2000)
http://www.labtrek.it/proHSuk.html

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Fermi's Golden Rule

Fermi's Golden Rule for Quantum Mechanically allowed transitions

$$Rate_{i\to f} \propto N_i(E) \times \left|M_{if}(E)\right|^2 \times N_f(E)$$

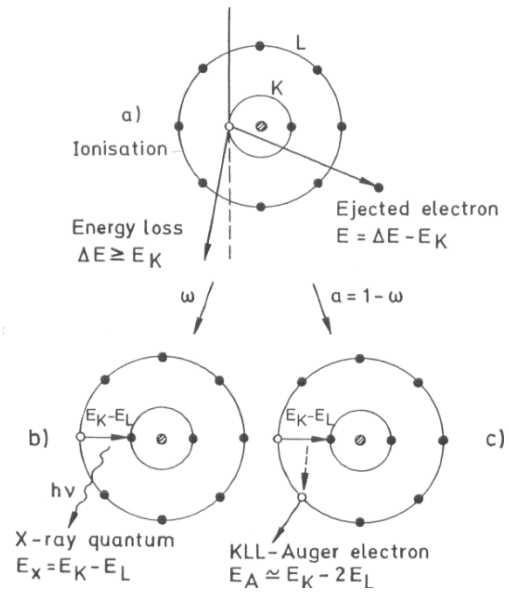
Density of initial states
(here: in conduction band)

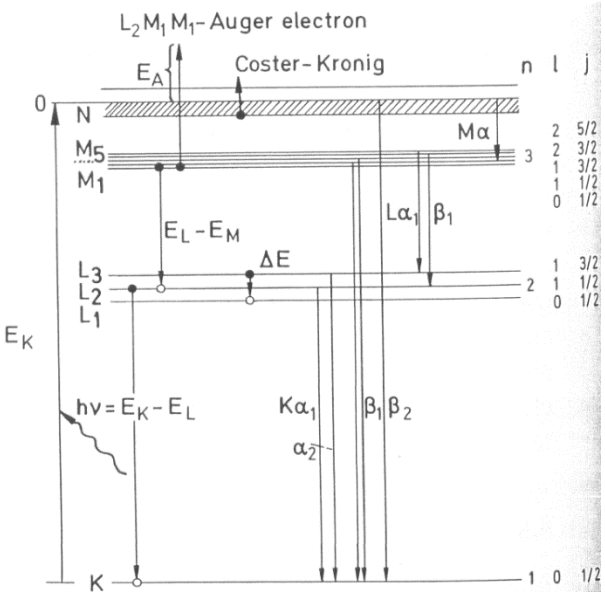
Transition Matrix with
Dipole Selection Rule

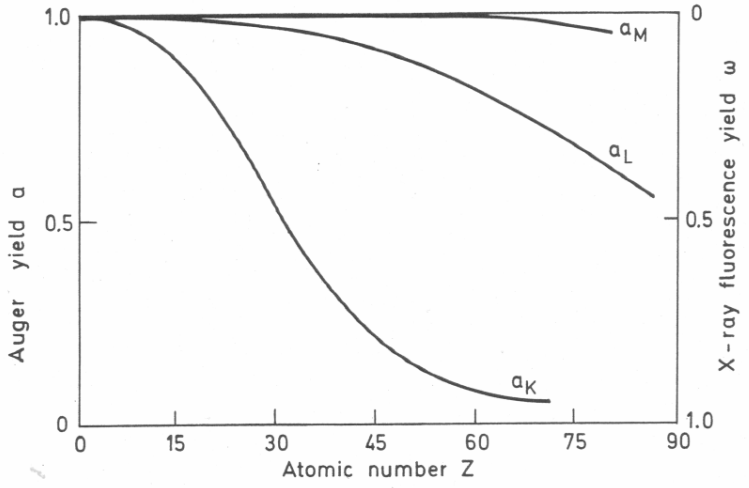
Density of final states
(here: in valence band)

Relevant as we need to consider recombination events too…

Radiative vs. Auger Transitions







Plot of Auger and X-ray fluorescence yield vs atomic number

a) Electron Energy Loss (EELS)
b) Energy Dispersive X-ray (EDXS)
c) Auger Electron emission (AES)

The "S" refers to Spectroscopy – the study of these emission processes
(e.g. in a SEM or TEM)

"Selection Rules" for allowed transtions

$$\Delta l = \pm 1, \qquad \Delta j = 0 \; or \; \pm 1$$

n = state

l = orbital angular momentum

j = total angular momentum $l + s$

s = spin

(Atomic Physics!)

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L. Reimer: Transmission Electron Microscopy, 2nd ed.(1989), Springer, Berlin, p.188-190

Recombination Probabilities

Consider the dependence of carrier lifetime on the **minority** carrier density n

Decay probability

$$\propto \frac{1}{\tau} = A + Bn + Cn^2$$

With some constants A, B, C

A – Non-Radiative contributions due to defects (e.g. Dislocations)

B – Radiative Recombination of electrons and holes across the band gap, produces light (or X-rays)

C – Non-Radiative Auger Recombination (3 electron process), produces free electrons

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Measuring n and μ

Carrier density and mobility are measured using resistivity or conductivity measurements.

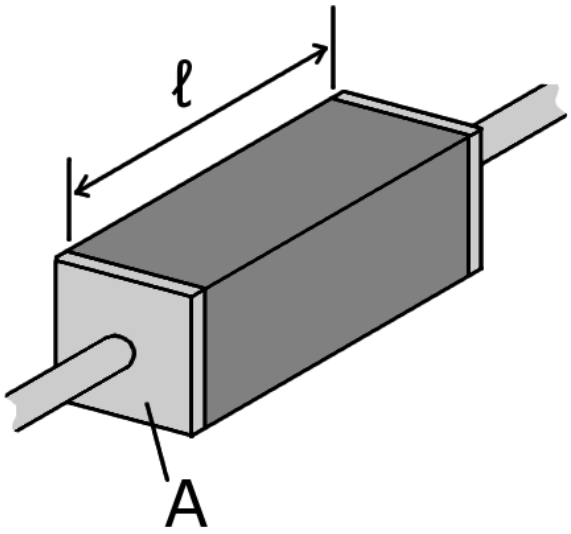
We know that

$$\sigma = nq\mu_e + pq\mu_h$$

And in the case where a material is doped one term usually dominates

For n-type material

$$\sigma = nq\mu_e$$



So if we know the dimensions of the sample we can calculate the mobility

$$R = \frac{V}{I}, \qquad \rho = R\frac{A}{l}$$

$$\rho = \frac{1}{\sigma}, \qquad \mu = \frac{1}{nq\rho}$$

But we don't know n?

 © The University of Sheffield By User:Omegatron - https://commons.wikimedia.org/w/index.php?curid=1699802

Perpendicular Magnetic Field

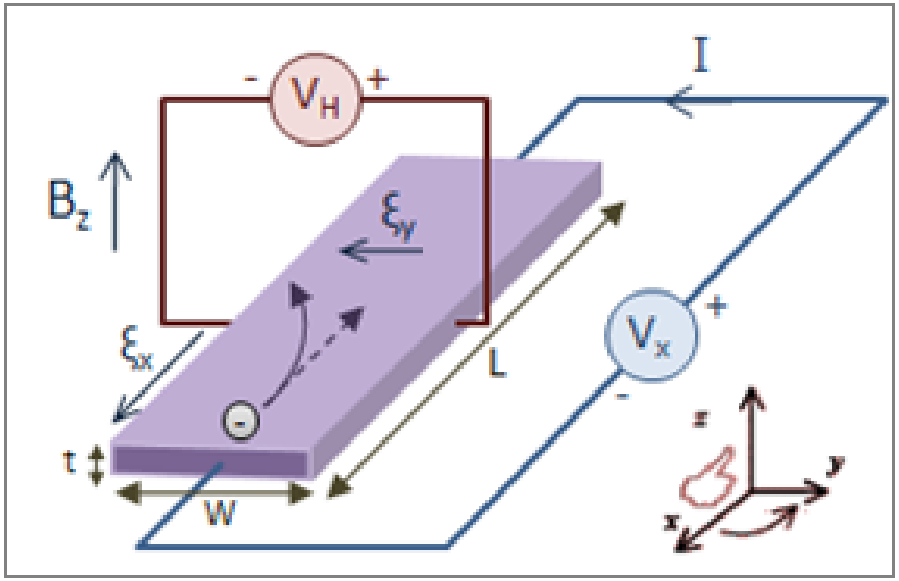
Applying a magnetic field perpendicular to the sample causes the electron path to bend due to the Lorentz force

$$\boldsymbol{F} = q[\boldsymbol{E} + (\boldsymbol{v} \times \boldsymbol{B})]$$

This causes a build up of charge (and hence an electric field) which opposes further charge → the Hall Voltage V_H

$$qE_y = qv_xB_z = \frac{J_xB_z}{N}, \qquad \frac{1}{qN} = \frac{E_y}{J_xB_z} = R_H$$

$E_x = V_H/w$, $J_x = I_x/wt$ so w cancels out



Hall coefficient (for electrons)

$$R_H = \frac{V_H}{I_xB_z}t = -\frac{1}{nq}$$

Thus n can be found and hence μ

Note that R_H has opposite sign for holes, if we know the directions of I and B we can determine the carrier type

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Public Domain, https://en.wikipedia.org/w/index.php?curid=22918777

How to increase the mobility?

Why bother? So devices can operate faster and resistances are lower

1) Reduce the number of impurities

- Use purer starting materials, grow better samples!
- Allows you to approach the physical limits of the material (phonons etc.)

2) Choose a different material

- Cheat! Well not quite…
- Industry continually focussed on what will replace Silicon…
- "Silicon chips" from Intel contained Si-Ge from as early as 2003!
- High speed devices based on GaAs or InGaAs used for HEMTs, HBTs
- Huge efforts in III-Vs (InGaAs and InSb) and new materials such as Graphene and Two-Dimensional Transition Metal Di-Chalogenides (2D-TMDCs) such as MoS_2/$MoSe_2$

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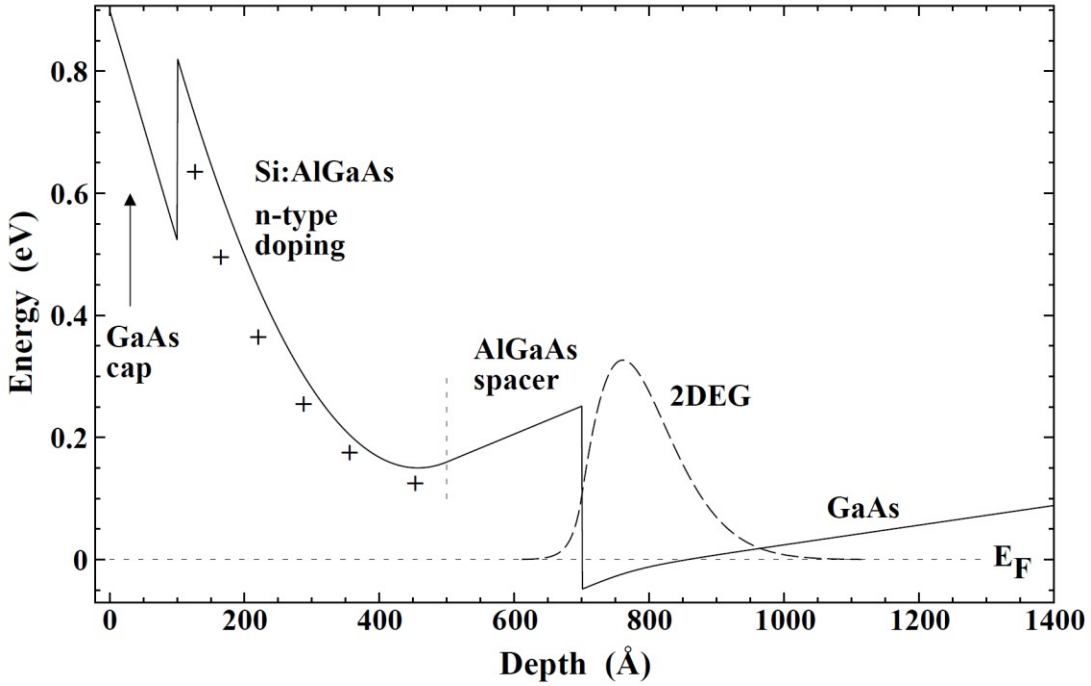
How to increase the mobility?

3) Spatially separate the donors from the generated electrons

When the electron is released from the donor it leaves behind a positive charge. Separating the electrons from these positive charges by a spacer layer "smoothes out" the potential and the electrons can also screen each other from it. This technique is known as "Modulation Doping". This routinely used in "High Electron Mobility Transistors" (HEMTs). It is an example of changing the *design* of the structure to improve mobility without necessarily changing the materials



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How to increase the mobility?

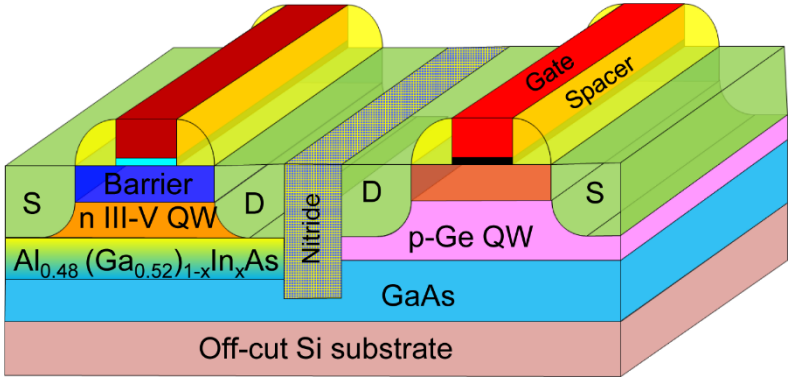
4) Use of strained layers to alter the effective mass

Si-Ge strains the Silicon decreasing it's effective mass.

InGaAs has a higher mobility at room temperature than GaAs.

Pseudomorphic HEMT (pHEMT) technology involves strained InGaAs channels in GaAs devices.

May require different solutions for electrons and holes (NMOS, PMOS devices)



5) Operate the device at lower temperatures

Reducing the effect of phonon scattering, can also improve noise performance

Cryogenic Amplifiers etc.

http://www.mdpi.com/1996-1944/7/3/2301/htm

Electron Mobility at the Extreme…

The Two Dimensional Electron Gas (2DEG) is used as a "playground" for fundamental physics experiments

Key requirement – long carrier lifetimes and large scattering lengths to allow the study of electron–electron interactions

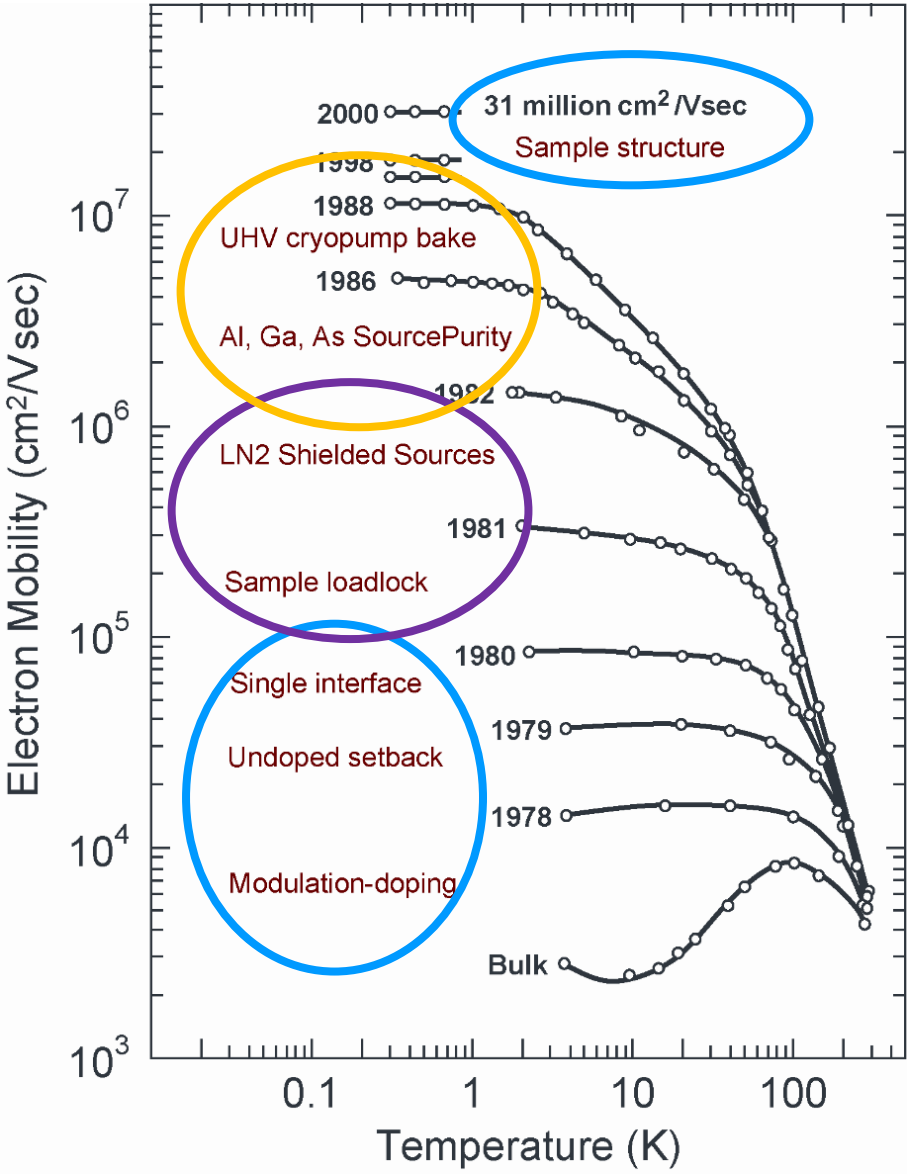
Purity, Structure Design and Technological Developments led to many orders of magnitude in electron mobility at low temperatures

→ The idea of "Ultra-High" Mobilities

Current world record $37 \times 10^6\ cm^2/Vs$

Corresponds to a lifetime $\tau = 14\ \mu s$!!

And a "mean free path" between collisions of over $300\ \mu m$ (in a solid!!)



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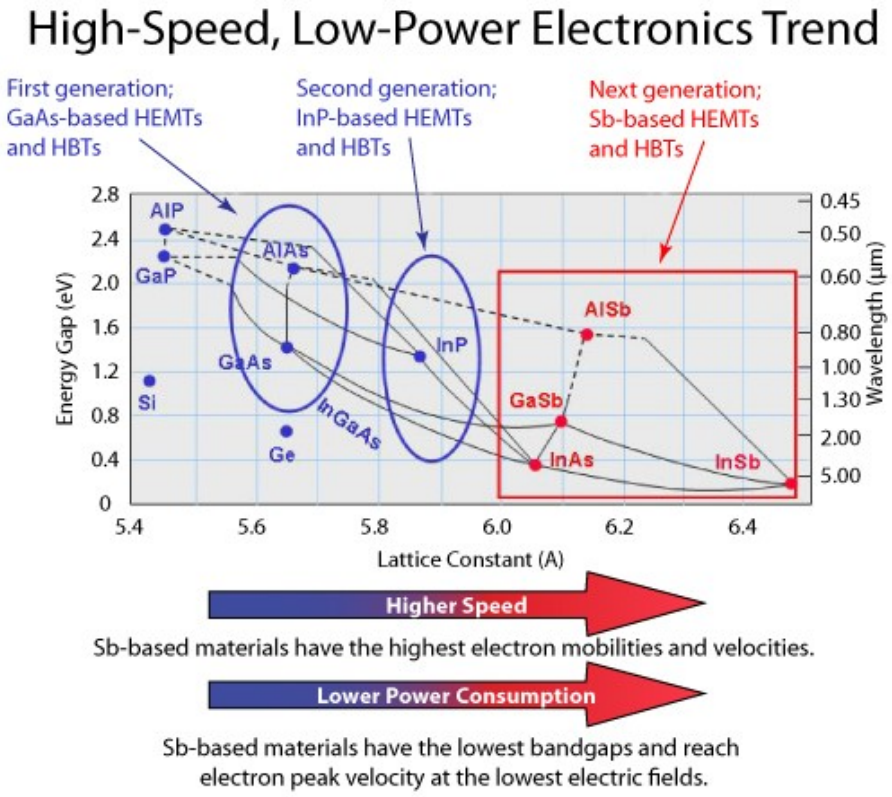
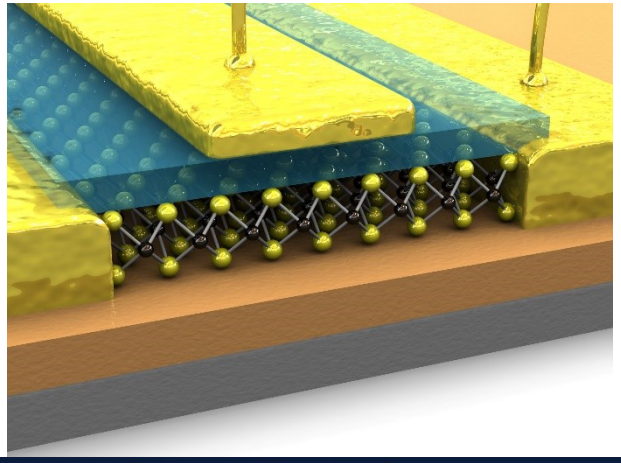
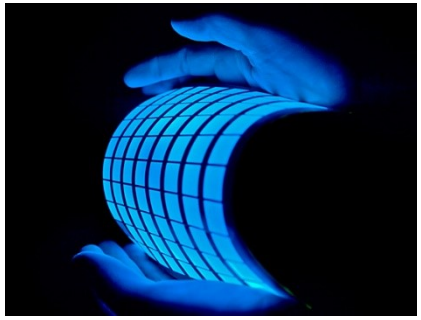
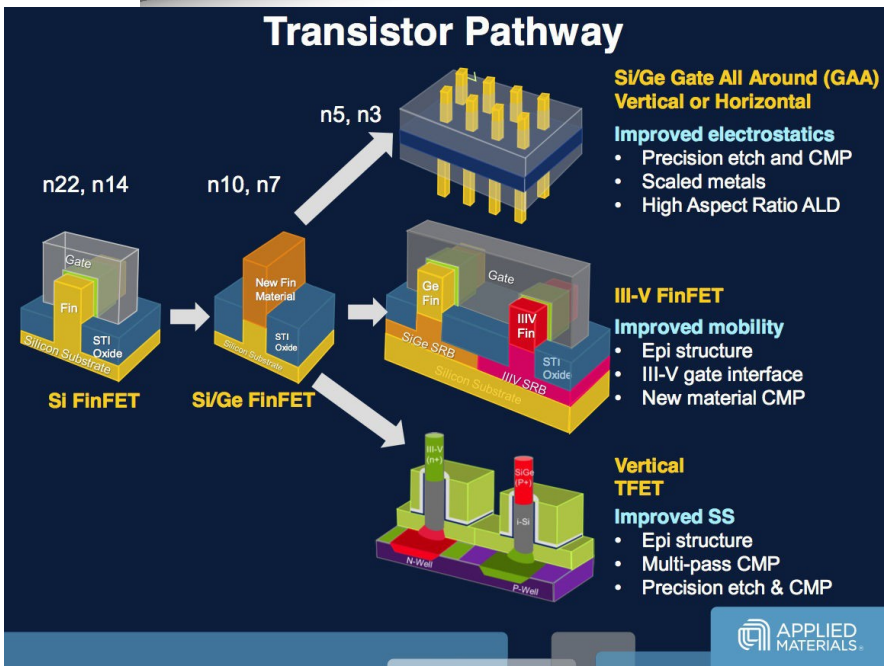
Physica E 20 (2003) 57 – 64 Loren Pfeiffer and K. W. West

Future Electronic Devices?









http://www.nrl.navy.mil/estd/branches/6870/6876 , http://lanes.epfl.ch/MoS2FET
http://www.theregister.co.uk/2013/07/25/proposed_semiconductor_transistor_possibilities/

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Summary

- Revisited Carrier Lifetime and Drift/Diffusion
- Debye length and relaxation time for non-equilibrium charge distributions
- Fermi's Golden Rule
- Radiative vs Auger Transitions
- Carrier Lifetime Model in Semiconductors:
  - Non – Radiative contributions by defects
  - Radiative Recombination
  - Auger Recombination
- Measuring Density and Mobility
- Looked at ways of increasing the mobility in semiconductor devices

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Now and next … ?

Over Easter…

- You **need** to be working on the Practical Lab assignment – so far no one has contacted me suggesting they are ready to fit their data?!
- Remember the hand in date for your report is Friday 22nd April
- I am available on afternoon of Tuesday 16th March, morning of Thursday 17th March, all day on Thursday 24th March and then away until Monday 4th April…

After Easter… Lectures restart on 11th April

- Had the bulk of the lectures now only a few more to go…

- p-n junctions and diodes
- Transistors
- Photo-detectors
- Nanotechnology – Growth, Fabrication, Applications etc.
- Tutorials / Revision

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