Lecture 3

- Effective Mass of Electron (m^*)
- Drift Velocity, (v_d)
- Mobility, (μ)

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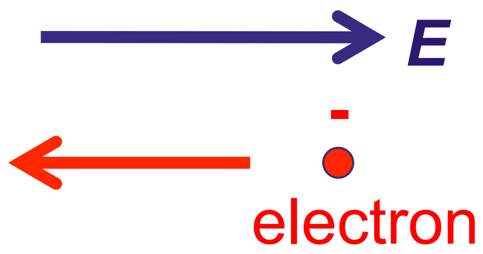
Application of E-field



Force $\boldsymbol{F} = - e\, \boldsymbol{E}$

e is the electronic charge

$\boldsymbol{E}$ is the electric field

In a vacuum we use Newton’s laws

i.e. Force = mass x acceleration, $F = ma$

Electron motion in a Crystal

- Complicated in a crystal – we need to include the effects due to other electrons and periodic atoms of the crystal
- Empirically (i.e. from various experiments) we know we can assume an "*effective mass*" for a group of electrons which takes account of this interaction with the crystal lattice
- Using an *effective mass* allows us to use simpler equations (such as Newton's laws) even though the reality is very complicated involving many forces and interactions the electron has.
- Effective mass can be calculated, but not in this module

Effective Mass

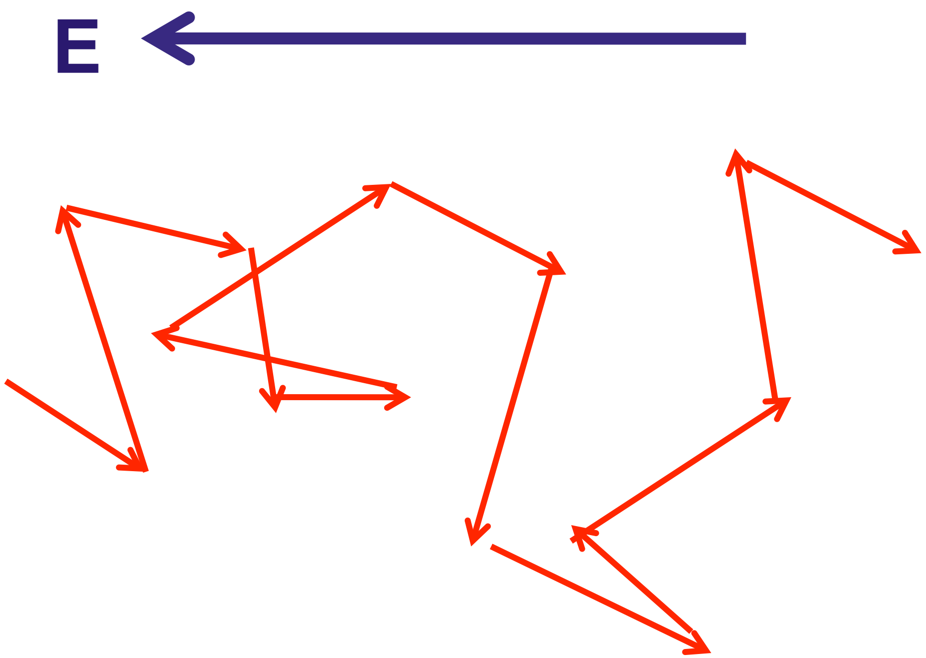
Electron effective mass, m^* (factor listed below multiplied by the free electron mass, m_e)

Si	Ge	GaAs	InP	InSb
0.97	0.22	0.07	0.08	0.013

e.g. for Si, $m^* = 0.97m_e$

- Effective mass in a semiconductor can be ***smaller*** than in vacuum - due to the internal periodic energy potentials of the crystal – the crystal fields tug on the electron which makes it look lighter.
- Ultimate speed of electronic devices and Integrated Circuits (ICs) governed by this parameter
- High frequency electronics – need lowest possible m^*

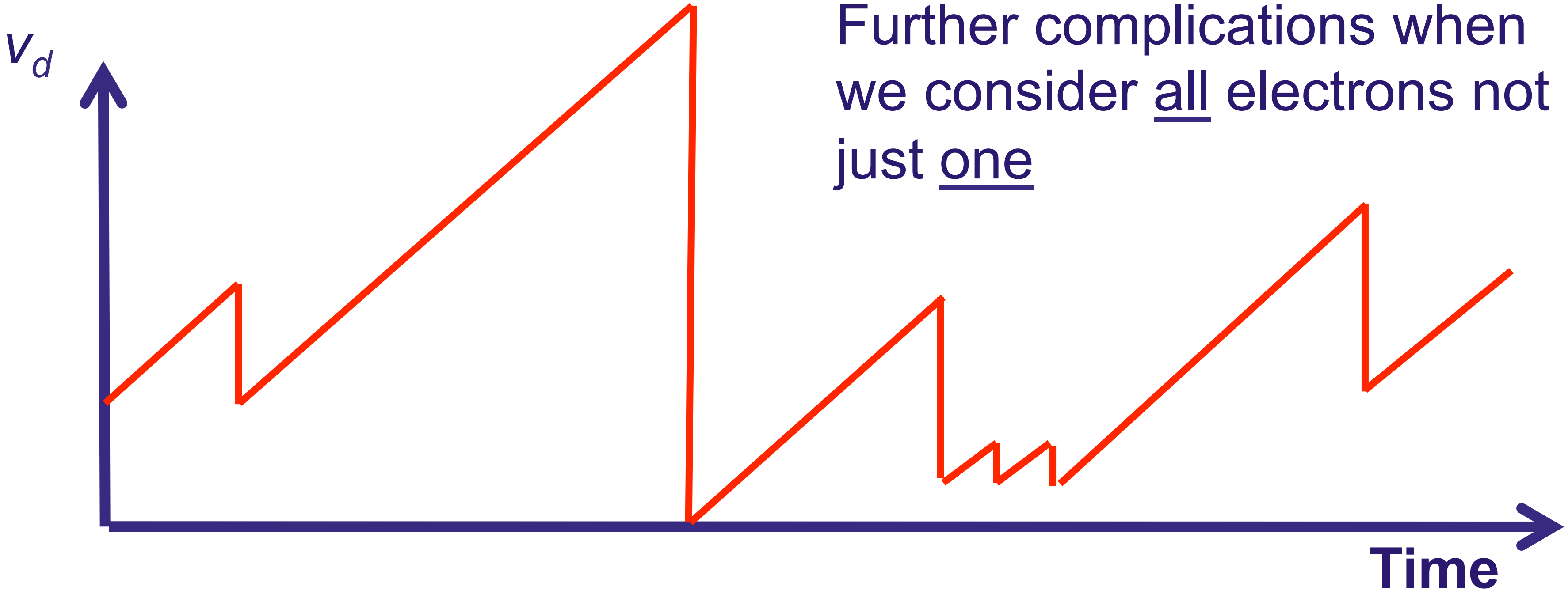
Drift Velocity



- Electron scatters from imperfections in the crystal lattice
- The time between scattering events affects the *drift velocity*, v_d, of the electron
- We need to think about v_d for one/all electrons

Conduction Electron in E-field

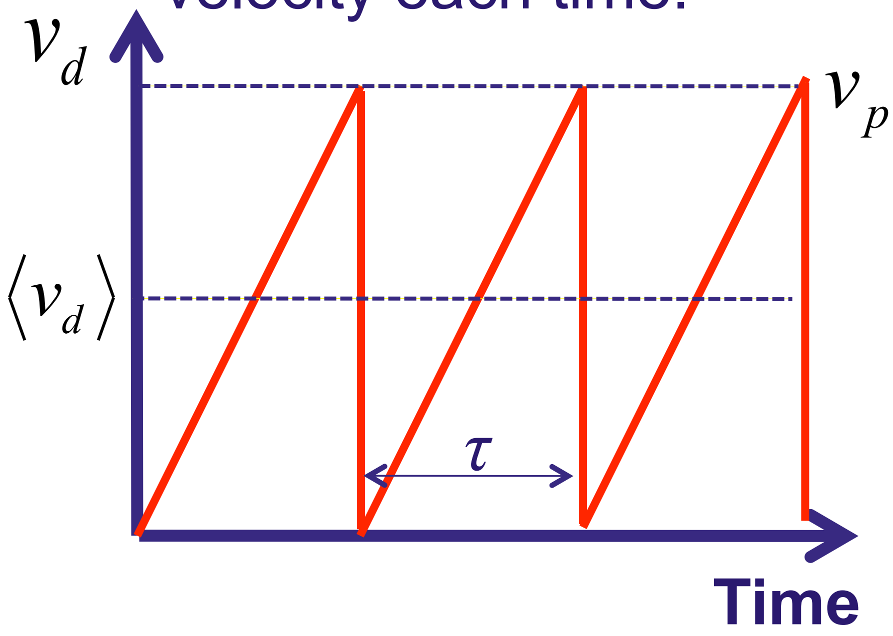
- Electron gains velocity in the opposite direction to that of the ***E***-field as it is accelerated
- It can loose all or some of this velocity when it is scattered



Further complications when we consider all electrons not just one

Simplification (helps visualise the process)

- Consider one electron scattering regularly (on average every τ seconds) from a peak velocity, $\boldsymbol{v_p}$, to zero velocity each time.



- Average velocity $\langle v_d \rangle = \dfrac{v_p}{2}$

- Peak velocity $v_p = a\tau = \dfrac{F\tau}{m}$

  acceleration

- Hence $\langle v_d \rangle = \dfrac{-eE\tau}{2m^*}$

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More Accurate Derivation of v_d

- A different and more accurate approach is to look at the balance between energy or momentum gained by the electrons from the field and that lost through scattering with crystal defects
- If this balance were not maintained then either the electrons would continue to gain energy to infinity or they would lose energy until their velocity is zero – neither of these is observed in practice, hence we must always have a balance
- Energy is gained by the electric field and given up to the lattice as heat through the scattering events
- Using the more accurate calculation based on energy/momentum balance we get the average velocity of electrons

$$\langle v_d \rangle = \frac{-eE\tau}{m^*}$$

Mobility, μ

- Drift velocity given by $$\langle v_d \rangle = -\frac{e\tau E}{m^*}$$
- The important parameter is the average time between scattering events, τ - governed by impurity and defect concentration and temperature (phonons)
- Effective mass also important – can simplify to one (easily measureable) material parameter - the mobility, μ, to give:

$$\langle v_d \rangle = -\mu E$$ where $$\mu = \frac{e\tau}{m^*}$$

- The mobility is a measure of how easily electrons move through a crystal lattice

Typical Mobilities

- Electron mobility depends on the effective mass (material dependent) and how pure and defect-free the crystal is
- Mobility is a key factor in how fast electronic circuits can 'switch' and how sensitive they are
- Typical electron mobilities at room temperature

Si	Ge	GaAs
1200 $cm^2V^{-1}s^{-1}$	3900 $cm^2V^{-1}s^{-1}$	8500 $cm^2V^{-1}s^{-1}$

GaAs Electronics
makes your smart phone work

Summary

- Electrons in a solid behave differently to those in vacuum – this can be accounted for fully by using an effective mass, m^*, for electrons in a crystal
- Electrons are scattered by random processes within a solid from imperfections of the crystal lattice – defects, impurities, phonons (temperature related)
- Due to the random nature of scattering, we cannot look at a single electron and extrapolate to the whole population. Hence, to derive the relationship between Electric field, $\boldsymbol{E}$, and drift velocity, $\boldsymbol{v}_d$, we need to consider the electron population as a whole
- We can simplify our result by introducing a new (easily measured) parameter, the mobility μ. The mobility includes the effect of scattering and effective mass to give a single parameter to describe conduction processes and is a measure of how easily electrons can move in a particular solid