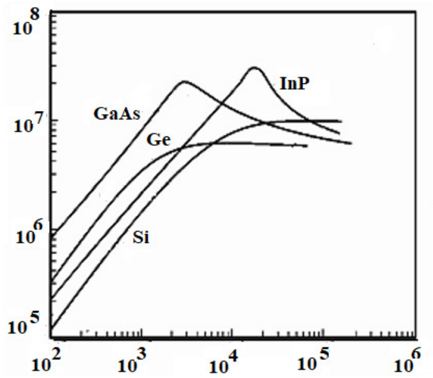
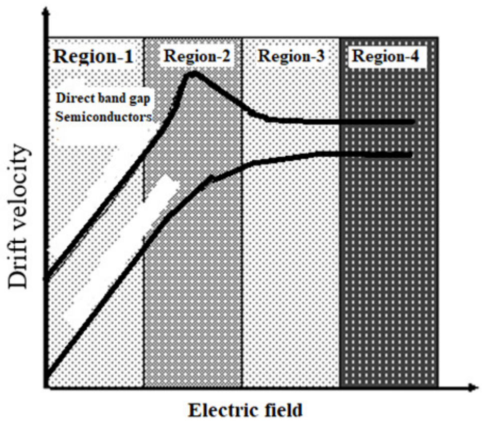
Drift velocity of charge carriers versus the applied electric field in semiconductors

Electrons and holes are the charged particles in a semiconductor. Their motion driven by external electric field leads to a current. This transport mechanism is termed **carrier drift**. The adjacent figure represents the drift velocity response of some important direct and indirect semiconductors, under the influence of electric field. We can notice from the figure that the drift of the carriers is remarkably different from direct band gap materials to indirect band gap materials. We can qualitatively explain this behavior by dividing the total region in to low, high and very high field regions as shown in the following figure.



Drift velocity-Electric field response of semiconductors at 300K.



Schematic representation of region-wise velocity-field response

(I) low field (II) High Field (III) saturation and (IV) impact-ionisation region

1. **Carrier transport by Drift at Low applied electric field (Linear region)**

In the region-1, the drift velocity is directly proportional the electric field and both carriers and lattice atoms are at thermal equilibrium. This is same for both direct as well as indirect band gap materials. The drift velocity is given by the equation

$$v_d = \frac{-eE\tau_r}{m^*} = \mu_e E$$

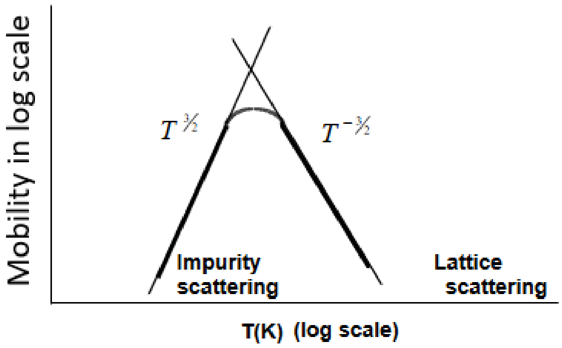
When the applied electric field is low, the drift velocity strongly depends on

- Scattering due to lattice
- Scattering due to impurities
- Effective mass

Scattering by lattice waves includes the absorption or emission of either acoustics or optical phonons. These phonons represent quanta of mechanical waves that travel through the semiconductor crystal. Since the density of phonons in solid increases with temperature, the scattering time due to this mechanism will decrease with temperature. Also, the mobility of charge carriers and the drift velocity decrease with temperature in the same way. Theoretical calculations reveal that the mobility in semiconductors like silicon and germanium is dominated by acoustic phonon interaction.

Parameter	Germanium	Silicon	Gallium Arsenide
Electron mobility	$\propto T^{-1.7}$	$\propto T^{-2.4}$	$\propto T^{-1.0}$
Hole mobility	$\propto T^{-2.3}$	$\propto T^{-2.2}$	$\propto T^{-2.3}$

Impurities are foreign atoms in the semiconductor. They are efficient scattering centres especially when charged like ionized donors and acceptors in a semiconductor. The amount of scattering due to electrostatic forces between the carrier and the ionized impurity depends on the interaction time and the number of impurities. At lower temperatures, carriers move more slowly, so there is more time for them to interact with charged impurities. Therefore, as the temperature decreases, impurity scattering increases, and the mobility decreases. Larger impurity concentrations result in a lower mobility. This is just the opposite of the effect of lattice scattering. The mobility of charge carriers in semiconductors due to impurity scattering is proportional to $T^{3/2}/N_I$, where N_I is the density of charged impurities. The total mobility then is the sum of the lattice-scattering mobility and the impurity-scattering mobility. Figure 1 shows how the total mobility has a temperature at which it is a maximum. The approximate temperature dependence of mobility due to lattice scattering is $T^{-3/2}$, while the temperature dependence of mobility due to impurity scattering is $T^{+3/2}$.



2. **Carrier transport by Drift at High applied electric field**

In high fields (typically up to $100kVcm^{-1}$), electron get more thermal energy and their temperatures go much higher than the lattice temperatures. The linear relationship between the average carrier velocity and the applied field breaks down when high fields are applied.

The direct band gap materials such as GaAs and InP contain multiple closely spaced conduction band minima. Such valleys have different effective mass contributions. Below a certain field, electrons are primarily in low effective mass ($m^*=0.067m_0$) and a high mobility G valley. As the field is increased, the electrons get transferred from the totally filled G valley to slightly higher L valley (valley containing charge carriers of low mobility and high effective mass $m^*=0.22m_0$). This is called inter-valley transfer. The difference between these two valleys is ~0.3eV. Since the density of states in the L valley minima is much higher, the probability that the electron transfers back into the G valley minimum is small because of the small number of available states. During this inter valley transfer, the velocity increases with increasing applied electric field and attains a maximum as shown in the fig.2. The applied electric field at which the maximum drift velocity occurs is called the peak field. The carriers in the L valley minima have higher effective mass. Even though, the applied electric field is increased further, the average mobility and carrier velocity decrease. This type of field behavior is desirable for some specific devices such as high-frequency microwave devices.

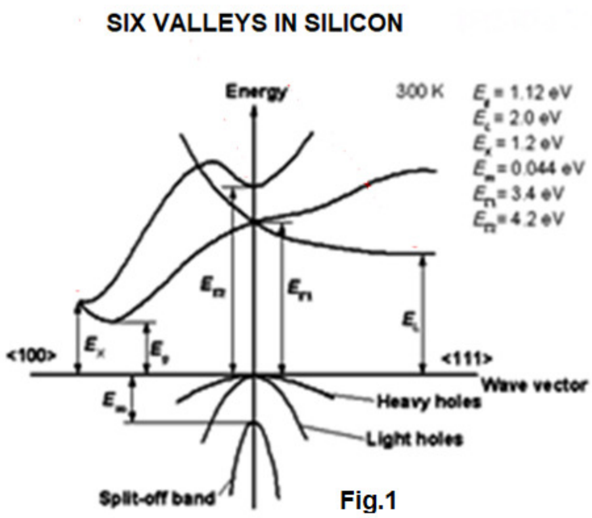


Fig.1

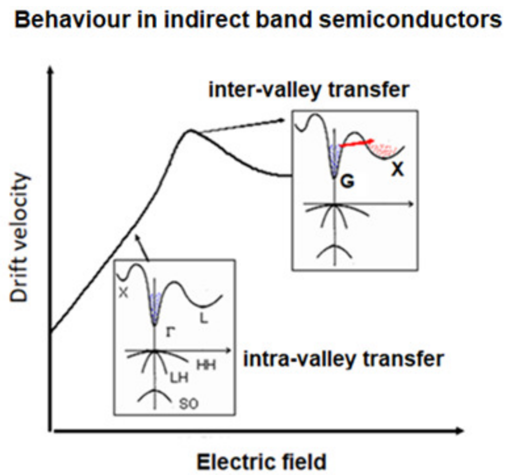


Fig.2

3. **Saturation drift velocity region**

Silicon is an indirect band gap semiconductor. It is having six-equivalent energy valleys. Therefore as the field increases, the electron gets more thermal energy and occupy first all six valleys simultaneously and then higher levels. Indirect band gap semiconductor materials such as silicon and germanium do not contain accessible higher bands. The velocity versus field relation increases monotonically as shown in fig.3. This transport mechanism is called intra-valley transfer. If the electric field is increased, the average carrier velocity and the average carrier energy increase as well. When the carrier energy increases beyond the optical phonon energy, the probability of emitting an optical phonon increases abruptly. This mechanism causes the carrier velocity to saturate with increasing electric field as shown in fig.4.

4. **Carrier transport by Drift at very high applied electric field (impact ionization) – Not shown in the graph.**

If the energy (typically >100kV/cm) supplied by the external field exceeds the band gap energy, very hot electrons in the conduction band knock out one electron from the valence band to the conduction band.

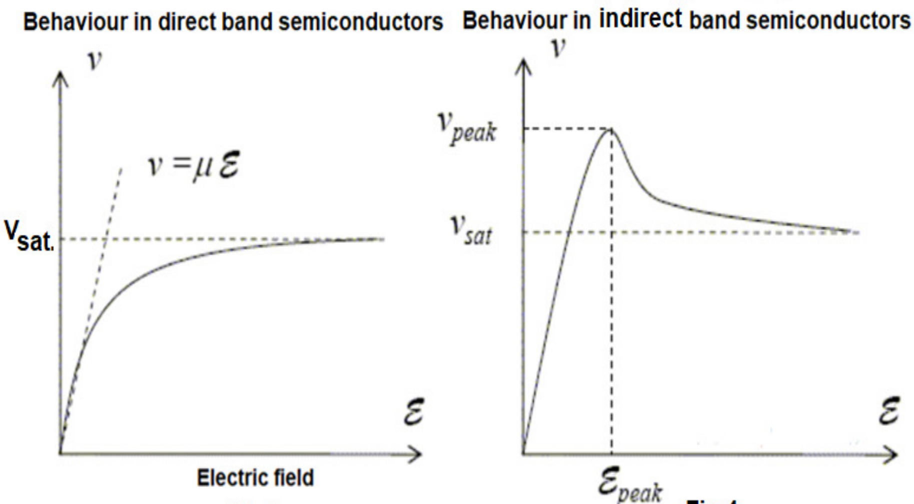


Fig.3 Fig.4

If the energy (>100kV/cm) supplied by the external field exceeds the band gap energy, very hot electrons in the conduction band knock out one electron from the valence band to the conduction band. Finally, we end up with two electrons and one hole! (But, the total number of electrons is always conserved). This *breakdown* rapidly increases the carrier multiplication rate and the process is called **impact ionization** or avalanche process. This process, keeps an important limitation to the devices, where due to carrier multiplication, control over device is completely lost. However, in particular devices such as photo-detectors, this behaviour is very useful to achieve high-gain detection.

Why does drift velocity change from electrons to holes?

The effective mass of holes in GaAs is normally greater than that of electrons in the same material. Therefore, the drift velocity due to electrons in conduction band of the material is greater than that due to holes for the same any applied electric field as shown in the following figure.