

Figure 3.2: Generation of an electron-hole pair.

Under thermodynamic equilibrium, generation and recombination events exactly balance one another, such that the electron and hole equilibrium concentrations remain constant with respect to time. Using an external source of energy such as illumination with light, one can, however, increase the carrier concentration and reach a state of non-equilibrium.

3.2. Direct and indirect transitions

In a semiconductor such as gallium arsenide (GaAs) the conduction band minimum (where free electrons are located) occurs at the same k -value (k is the wave vector) as the valence band maximum. The wave vector represents the momentum of the carriers. As shown in Figure 3.3 the value of that momentum is zero. Therefore, when an electron from the conduction band recombines with a hole in the valence band the law of conservation of momentum is obeyed. A semiconductor where the minimum of the conduction band and the maximum of the valence band occur at the same k -value is called a direct-bandgap semiconductor, and the "jump" of an electron from the conduction band into the valence band is called "band-to-band recombination".

Since momentum is conserved in this example of a recombination event, recombination requires nothing more than an electron with $k=0$ and a hole with $k=0$. Since most electrons occupy the conduction band at or near $k=0$, recombination is a very likely mechanism. When a recombination event takes place the law of conservation of energy also implies that a quantum of energy is released in the form of a photon. The energy of that photon is such that $h\nu=E_g$, where h is Planck's constant, ν is the frequency of the photon, and E_g is the bandgap energy. In most direct-bandgap semiconductors the photons emitted by recombination events have an energy corresponding to visible or near-infrared light. A recombination event where photons are emitted is called "radiative recombination" and is exploited in devices such as light-emitting diodes.

The relationship between the photon wavelength, λ , and the bandgap energy, E_g , is:

$$E = h\nu \text{ and } \nu = c/\lambda \Rightarrow \lambda (\mu\text{m}) = \frac{1.24 (eV \mu\text{m})}{E_g(eV)} \quad (3.2.1)$$

where ν , h and c are the photon frequency, Planck's constant and the speed of light, respectively.

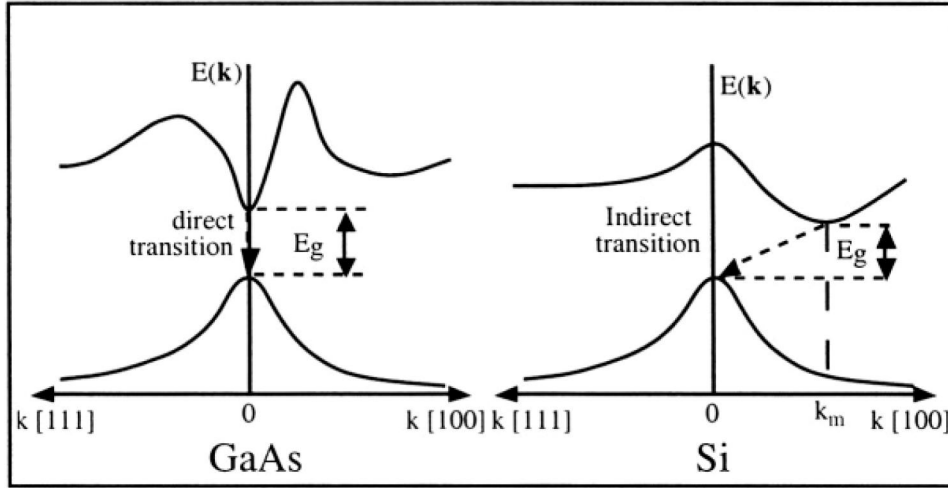


Figure 3.3: Band-to-band recombination in a direct-bandgap semiconductor (left) and in an indirect-bandgap semiconductor (right).

In silicon and germanium the minimum of the conduction band and the maximum of the valence band do not occur at a same k -value. A semiconductor where this is the case is called an "indirect-bandgap semiconductor". When recombination takes place in such a material an electron with a momentum $k=[k_m, 0, 0]$ recombines with a hole having a momentum $k=0$ (Figure 3.3). This can occur only if an appropriate momentum is transferred to the electron (or the hole) such that conservation of momentum is observed. This can happen through collision with a phonon or with several phonons. Since a precise value of momentum ($-k_m$ in Figure 3.3) must be transferred to the electron, band-to-band recombination is an extremely unlikely process in indirect-bandgap semiconductors. As a result there is no radiative recombination in silicon and germanium, and these materials cannot emit light. Rather recombination takes place via trap levels at various k -values within the band gap.

Gallium arsenide emits photons with a wavelength of $0.8 \mu\text{m}$, which corresponds to near-infrared, almost visible light. To fabricate semiconductor devices producing visible light more complex semiconductor materials are used, usually based on a combination of the

elements of columns III and V of the periodic table, such as Ga, Al, P, As, and N. Such semiconductors are called "III-V semiconductors".

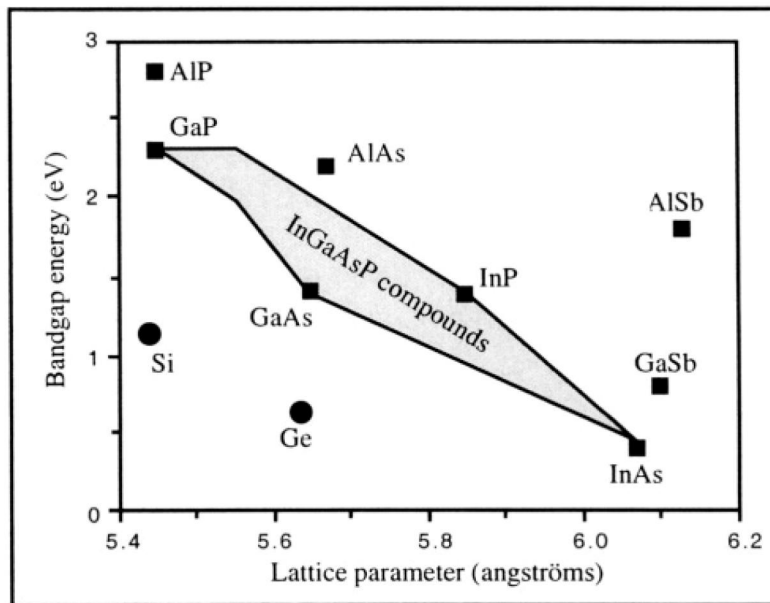


Figure 3.4: Energy bandgap in Si, Ge, and some III-V semiconductors. [1]

The main parameter that governs the electrical and optical properties of semiconductors is the bandgap energy, shown in Figure 3.4 as a function of the crystal lattice parameter. The use of ternary compound semiconductors, such as $\text{Ga}_x\text{Al}_{1-x}\text{As}$, or that of quaternary compounds, such as $\text{Ga}_x\text{In}_{1-x}\text{As}_y\text{P}_{1-y}$ allows one to tailor the bandgap energy in order to produce a desired light wavelength. The fabrication of a semiconductor material with an "engineered" bandgap energy is obtained, for example, by adjusting the x and y coefficients during the growth of a $\text{Ga}_x\text{In}_{1-x}\text{As}_y\text{P}_{1-y}$ crystal.

Semiconductors are transparent to photons that carry an energy, $h\nu$, smaller than the bandgap energy. Germanium, for instance, is used instead of glass to make infrared (IR) lenses for wavelengths larger than $2\text{ }\mu\text{m}$ since its bandgap energy is larger than the energy of $2\text{ }\mu\text{m}$ IR photons. Photons with an energy equal or greater than the semiconductor bandgap energy, on the other hand, can be absorbed to generate electron-hole pairs. Figure 3.5 shows the absorption coefficients in some semiconductors, as a function of wavelength. The absorption coefficient is a measure of the distance a light wave travels into the material before it is absorbed.

In addition to band-to-band recombination mechanisms, a free electron can recombine with a free hole through "recombination centers" located within the energy bandgap. These are permitted energy levels introduced

by contaminants, impurity atoms or crystal defects. A recombination center acts as a catalyst that enables an electron to recombine at k values differing from the k_m of the conduction band. This is especially true in indirect-bandgap semiconductors such as silicon or germanium, where band-to-band recombination events are very unlikely to occur.

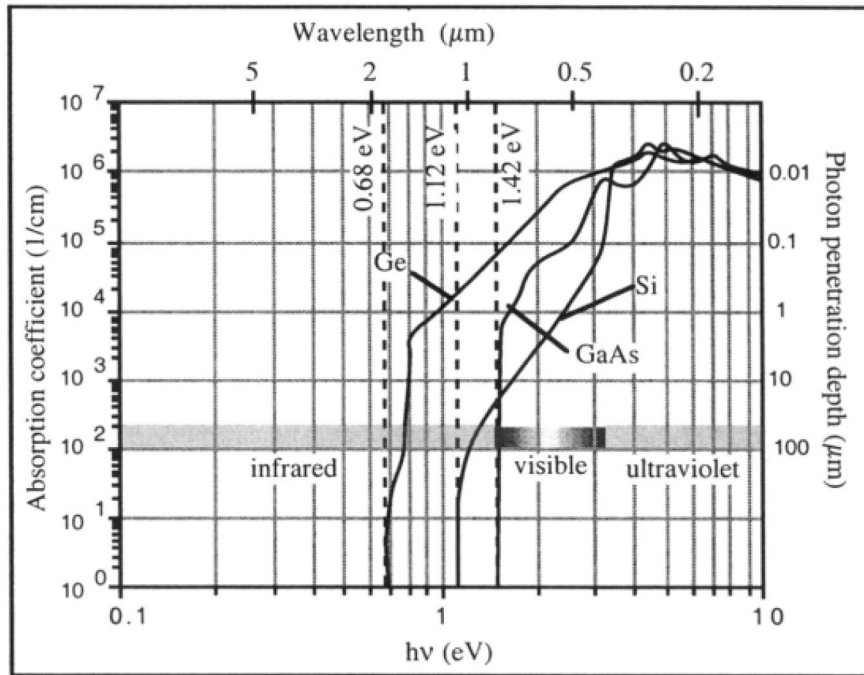


Figure 3.5: Absorption coefficient as a function of photon energy (and wavelength) in Ge, Si and GaAs, which have energy bandgaps of 0.68, 1.12 and 1.42 eV, respectively.[2]

3.3. Generation/recombination centers

Semiconductor crystals are of the highest purity and quality, but they are not perfect. They contain some crystal defects such as interstitials (excess semiconductor atoms in the crystal lattice), vacancies (missing semiconductor atoms in the crystal lattice) and dislocations (imperfections in the crystal structure), as well as traces of impurity elements such as metallic atoms or oxygen. These defects and impurities give rise to permitted levels within the energy bandgap. Let us consider one of these levels, having an energy E_t within the bandgap. This permitted level can receive an electron from the conduction band (case A in Figure 3.6), lose an electron to the valence band (case C), receive an electron from the valence band (case D), or lose an electron to the conduction band (case B). A level that is neutral if filled by an electron and positive if empty is called a "donor level", and a level that is neutral if empty and negative if filled by an electron is called an "acceptor level". Permitted levels inside the bandgap are called generation-recombination centers, or, in short, "recombination centers". In Figure 3.6 transitions A