Semiconductor Technology from A to Z

Optoelectronics & Photonics

Fundamentals of Optoelectronics

Why Optoelectronics?

Optoelectronic devices exploit the interaction between light and semiconductors in both directions. In emission, LEDs and laser diodes convert electrical energy into photons: electrons from the conduction band recombine with holes in the valence band, releasing the energy as a photon. Detection runs the process in reverse – an absorbed photon lifts an electron into the conduction band, creating an electron-hole pair that shows up as photocurrent.

Together, these three device classes – LED, laser diode, photodiode – form the basis of virtually all optical data transmission, much of sensor technology, and modern display technology. Unlike the devices covered so far (MOSFET, bipolar transistor), the focus here isn't switching currents but the controlled conversion between electrical and optical energy.

Direct vs. Indirect Bandgap

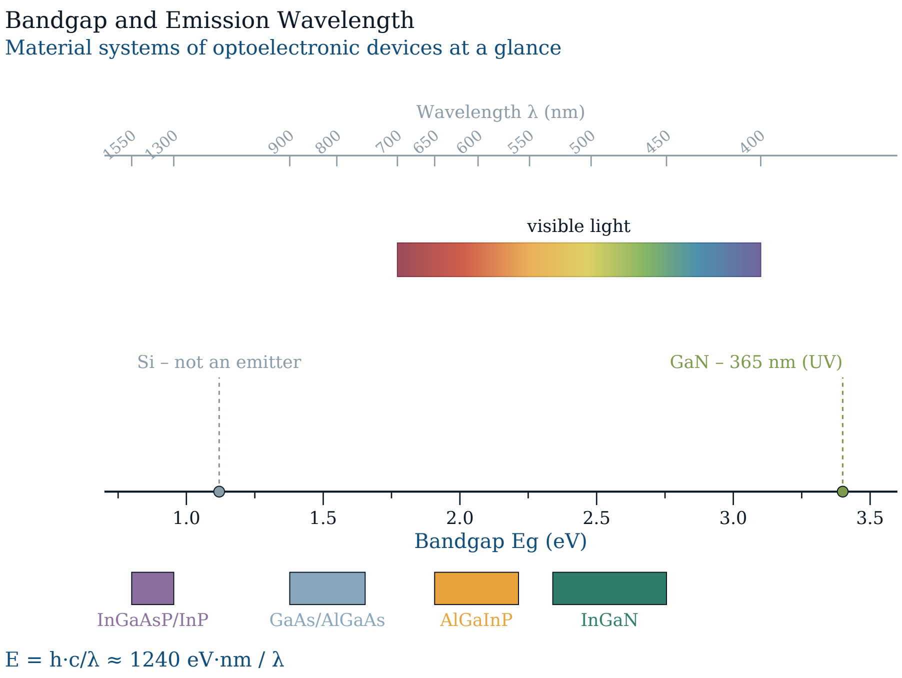
Whether a semiconductor can emit light efficiently is decided by its band structure in k-space – energy plotted against the crystal momentum of the electrons. In a direct semiconductor like GaAs, the conduction band minimum and valence band maximum occur at the same k-value. An electron can recombine into the valence band without needing to change its momentum – momentum conservation is handled entirely by the emitted photon, whose momentum is negligible compared to that of the electron.

In an indirect semiconductor like silicon, the conduction band minimum and valence band maximum sit at different k-values. Recombination then additionally requires a phonon to absorb or supply the momentum difference. Since a three-particle process (electron, hole, phonon) is far less probable than a two-particle process, the radiative recombination rate in silicon is several orders of magnitude lower than in GaAs – internal quantum efficiency is typically around 10^{-6} for Si, versus close to 1 for GaAs. This is the physical core of why Si LEDs essentially don't exist and III-V compound semiconductors are indispensable for light emission.

Photon Energy and Bandgap

The wavelength of emitted or absorbed light depends directly on the bandgap: $E = h \cdot c/\lambda$. A practical rule of thumb: λ [nm] $\approx 1240 / E_g$ [eV]. A larger bandgap means shorter-wavelength, higher-energy light. GaAs, with $E_g \approx 1.42$ eV, emits around 870 nm in the near infrared; GaN, with $E_g \approx 3.4$ eV, sits around 365 nm in the UV range.

Visible light requires bandgaps between roughly 1.8 eV (red) and 3.1 eV (violet) – a range no binary III-V material fully covers. Only through alloying, such as InGaN or AlGaInP, can the bandgap be tuned continuously between the values of the binary end compounds (Vegard's rule as an approximation) and thereby set precisely to the desired emission wavelength, without switching the underlying material system.



Material System Overview

Each wavelength range has its established material system, shaped by the respective application:

- InGaN – blue to green (450–530 nm), the basis of modern white LEDs combined with yellow phosphor
- AlGaInP – red to yellow (560–650 nm), complements InGaN for full RGB coverage
- GaAs / AlGaAs – near infrared (750–900 nm), standard material for simple laser diodes and IR LEDs (remote controls, proximity sensors)
- InGaAsP / InP – telecom wavelengths 1.3 µm and 1.55 µm, chosen for the attenuation and dispersion minima of silica fiber in this range
- Silicon / Germanium – not emitters, but important photodetector materials in the visible (Si) and near-infrared (Ge) range, since absorption, unlike

emission, doesn't require a radiative transition and therefore also works efficiently in indirect semiconductors

This material mapping runs through the following chapters as a common thread: which material suits an LED, laser, or photodiode is fundamentally a question of target wavelength and the associated bandgap.

Quantum Efficiency as a Metric

To make emitters and detectors comparable later on, a brief clarification of terms is worthwhile here. Internal quantum efficiency describes the fraction of injected electron-hole pairs that actually recombine radiatively, as opposed to being lost through non-radiative channels via crystal defects or surface states. External quantum efficiency additionally accounts for how many of the internally generated photons actually leave the semiconductor, rather than being lost to total internal reflection or reabsorption within the device.

This distinction returns in the LED chapter when discussing extraction efficiency and droop, and is also central to photodiodes, there expressed as responsivity.