Semiconductor Technology from A to Z

Optoelectronics & Photonics

Photodiodes & Photodetectors

Operating Principle: pn and pin Photodiodes

A photodiode reverses the LED principle: instead of injecting carriers to generate light, incident light is absorbed and converted into an electrical current. When a photon with sufficient energy ($E \geq E_g$) strikes the semiconductor, an electron is lifted from the valence band into the conduction band, creating an electron-hole pair. In the depletion region of a reverse-biased pn junction, the electric field present there immediately separates this pair before it can recombine – electron and hole drift to their respective contacts and generate a measurable photocurrent, proportional to the incident optical power.

In a simple pn diode, however, the depletion region is very thin (typically < 1 µm), so most of the light is absorbed deeper in the field-free bulk material, where generated carrier pairs must reach the contacts by slow diffusion rather than fast drift – this limits both sensitivity and switching speed. The pin photodiode solves this problem by inserting a thick, intrinsic (undoped) i-layer between the p- and n-layers. The electric field then extends over a substantially larger distance (often 10–50 µm), essentially all incident light is absorbed in the high-field region, and carriers drift rather than diffuse – this substantially increases quantum efficiency and enables bandwidths in the gigahertz range.

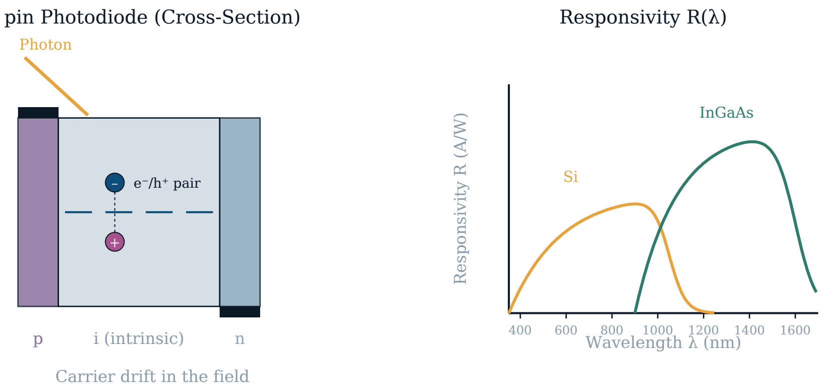
Key Parameters: Quantum Efficiency and Responsivity

Two quantities describe how efficiently a photodiode converts light into current. Quantum efficiency η indicates what fraction of incident photons actually generates a detectable electron-hole pair (values near 1 for well-designed devices). The more practically relevant quantity is responsivity $R = I_{ph}/P_{opt}$ in A/W, which directly relates the generated photocurrent to the incident optical power: $R = \eta \cdot e/(h \cdot f) = \eta \cdot \lambda / 1240$ nm (with R in A/W and λ in nm). A silicon photodiode typically reaches R ≈ 0.5–0.6 A/W at 850 nm, an InGaAs photodiode about R ≈ 0.9–1.0 A/W at 1550 nm.

Responsivity is wavelength-dependent and drops sharply above a material-specific cutoff wavelength (set by the bandgap, $\lambda_g \approx 1240$ nm$/E_g$), since photons below the bandgap energy can no longer be absorbed. Toward short wavelengths, responsivity also declines, since high-energy photons are already absorbed very close to the surface, where surface recombination destroys part of the generated carriers before they can be separated. Each material therefore has a characteristic responsivity window that defines its usable detection bandwidth.

pin Photodiode and Spectral Responsivity

Structure of the pin photodiode and material-dependent sensitivity over wavelength



The electric field spans the full thickness of the i-layer – carriers drift rather than diffuse, raising yield and bandwidth.

Avalanche Photodiode (APD)

For applications with very weak light signals – such as long-haul fiber-optic receivers or single-photon detection – the sensitivity of a simple pin photodiode is often insufficient, since the generated signal gets lost in the electronic noise of the subsequent amplifier stage. The avalanche photodiode (APD) solves this problem through internal gain: it's operated with a substantially higher reverse bias (typically 20–200 V, material-dependent), creating a very strong electric field in a high-field multiplication region of the photodiode.

Photogenerated carriers are accelerated so strongly in this field that, upon colliding with lattice atoms, they carry enough energy to generate additional electron-hole pairs through impact ionization – these in turn are accelerated and generate further pairs of their own. The resulting avalanche effect (hence the name) delivers an internal multiplication factor M typically ranging from 10 to over 100, before the signal even reaches the external amplifier. The multiplication factor can be finely tuned via the applied reverse bias, but must be carefully weighed against additional multiplication noise (excess noise, arising from the statistical nature of the avalanche process) – too high a gain factor degrades the signal-to-noise ratio again rather than improving it.

Material Choice by Wavelength Range

As with LEDs and laser diodes, the bandgap determines which material suits which spectral range – though with an important inversion of the logic: absorption doesn't strictly require a direct bandgap, since unlike radiative recombination, no photon needs to be emitted. Silicon (indirect bandgap, $E_g \approx$ 1.12 eV) is therefore, despite its unsuitability as a light source, an excellent, low-cost photodetector in the visible and near-infrared up to about 1000–1100 nm – the wavelength range also used by CMOS image sensors in digital cameras and smartphones.

For telecom wavelengths (1.3 µm and 1.55 µm), above silicon's cutoff wavelength, $In_{0.53}Ga_{0.47}As$ (lattice-matched to InP substrate) is used – the same material system also used in the corresponding DFB laser diodes, which makes transmitter and receiver of a fiber-optic link closely related in materials terms. Germanium covers a similar infrared range and is gaining importance, due to its CMOS compatibility, for monolithically integrated silicon photonics circuits. For UV and deep-blue detection, wide-bandgap materials such as GaN or SiC are used, whose large bandgap makes them essentially transparent to visible and infrared light, providing intrinsic blindness to stray light – advantageous, for example, in UV flame detectors.

Applications: Fiber-Optic Communication and Image Sensing

The economically most significant application of photodiodes is the receiver in fiber-optic communication: at the end of every fiber-optic link, an InGaAs pin or APD photodiode converts the optical signal back into an electrical one, which is then processed electronically – receiver sensitivity (the minimum detectable optical power at a given bit error rate) is, alongside transmitter power, the central parameter that determines the maximum reach of a fiber-optic system without intermediate amplification.

The second major application domain is image sensing: CMOS image sensors in cameras use millions of individual silicon photodiodes (pixels), each preceded by color filters (a Bayer pattern of red, green, and blue filters) for color resolution, combined with readout electronics integrated directly at the pixel. Photodiodes also serve as simple light sensors in countless everyday applications – automatic screen brightness, exposure metering, smoke detectors – as well as the basis of photovoltaics, where the same pn-junction physics is used for large-area energy harvesting instead of signal detection, though without reverse bias and with geometry optimized for power yield rather than speed.