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

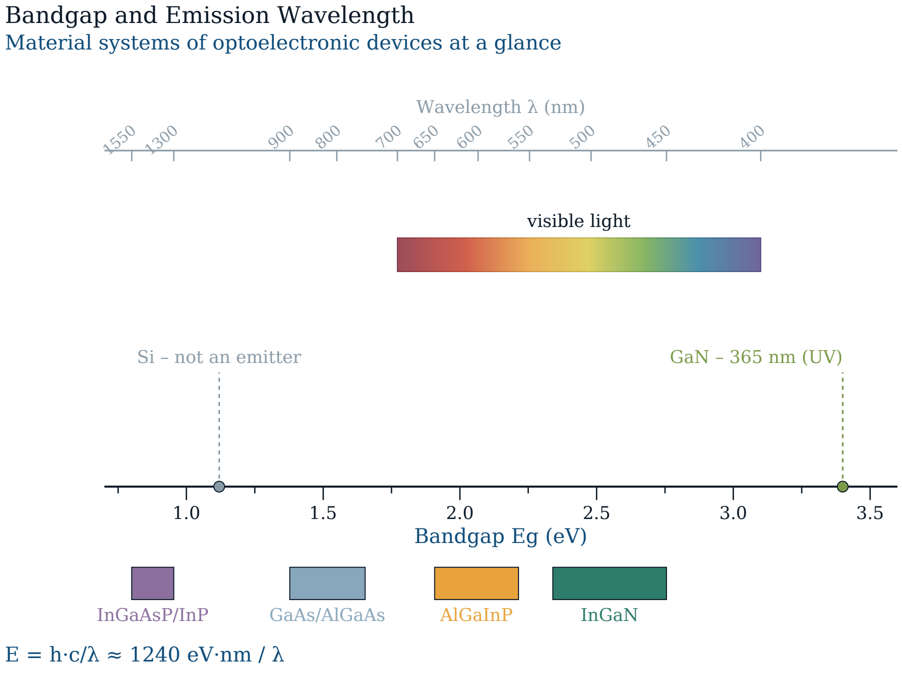
Whether a semiconductor can emit light efficiently is decided by its band structure in k-space – energy plotted against the crystal momentum of the electrons. In a direct semiconductor like GaAs, the conduction band minimum and valence band maximum occur at the same k-value. An electron can recombine 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.

Light-Emitting Diodes (LED)

Structure and Operating Principle

An LED is fundamentally a forward-biased pn junction made from a direct-bandgap semiconductor. Applying a forward voltage lowers the potential barrier of the depletion region, and electrons from the n-side and holes from the p-side are injected across it – this is known as minority carrier injection. In the active region, both carrier types meet and recombine radiatively, as described in the fundamentals chapter; the photon energy roughly corresponds to the material's bandgap, slightly reduced by the thermal energy distribution of the carriers (which is why the emission spectrum isn't a sharp peak but has a spectral width of typically 20–30 nm at room temperature). Unlike the Si pn junction, which is primarily used as a diode or solar cell, light emission in an LED is the actual purpose, not a side effect.

An LED's forward voltage correlates directly with the bandgap: a rule of thumb is $V_f \approx E_g/e$, slightly increased by series resistance and contact losses. A red AlGaInP LED ($E_g \approx 2$ eV) therefore has a typical forward voltage around 1.8–2.2 V, while a blue InGaN LED ($E_g \approx 2.7$ eV) sits at 2.8–3.4 V – markedly higher than a conventional Si diode (≈0.7 V), which directly affects the operating voltage required by LED circuits. Efficiency depends critically on how many carriers actually recombine radiatively rather than non-radiatively – governed by doping quality, defect density, and interface states in the crystal, which act as recombination centers and "swallow" carriers without emitting a photon.

Material Systems by Color

Emission color follows directly from the material's bandgap, which is why each LED color has its own established system. Red and yellow LEDs are based on AlGaInP heterostructures on GaAs substrate, lattice-matched by choice of the aluminum-gallium ratio. Infrared and simple red LEDs have historically also used GaAsP or AlGaAs. Blue and green LEDs use InGaN on sapphire or SiC substrate – despite substantial lattice mismatch to the substrate (up to 16% for GaN-on-sapphire), which produces high dislocation densities that long limited material quality.

The technological maturity of InGaN in the 1990s (Shuji Nakamura, Nobel Prize in Physics 2014) was the decisive prerequisite for efficient white LEDs, since previously only red and yellow were available with sufficient efficiency – the so-called "green gap" (the efficiency shortfall of green LEDs between the well-mastered InGaN/blue and AlGaInP/yellow systems) remains an active research topic today. White light today is mostly produced not by additive RGB mixing but by a single blue InGaN LED (peak ≈ 450–460 nm), part of whose light is converted by a yellow phosphor (usually Ce:YAG, cerium-doped yttrium aluminum garnet) via photoluminescence into longer-wavelength light (peak ≈ 560 nm). The combination of transmitted blue and excited yellow produces a white color impression for the human eye; phosphor blend and thickness can be tuned to set color temperature (warm white to cool white) and color rendering index (CRI).

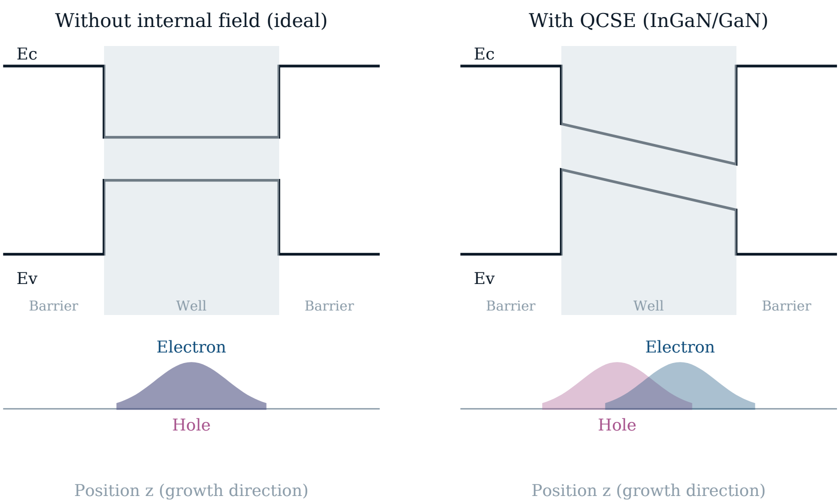
Quantum Wells for Improved Efficiency

Modern LEDs don't use a simple homogeneous pn junction but an active region made of multiple quantum wells (MQW): thin layers (typically 2–5 nm) of a smaller-bandgap material embedded between barrier layers of larger bandgap – in InGaN/GaN LEDs, thin InGaN wells between GaN barriers. Carriers are quantum-mechanically confined within these potential wells (quantum confinement), which changes the density of states from a continuous 3D distribution to a stepped 2D one. This substantially increases the effective carrier density in the active volume and thus the radiative recombination rate compared to a thick, unstructured junction.

Well thickness and material composition allow fine-tuning of the effective bandgap and thus the emission wavelength – in InGaN/GaN systems typically via indium content (a higher In fraction lowers the bandgap, shifting emission toward green) combined with well width. A material-specific complication in InGaN/GaN is the quantum-confined Stark effect (QCSE): since GaN is piezoelectrically and spontaneously polarized along the c-axis, strong internal electric fields (several MV/cm) arise at the well interfaces, spatially separating electrons and holes within the well. This reduces the overlap of their wavefunctions and thus the radiative recombination probability – an effect that's especially pronounced at high indium content (green LEDs) and a contributing factor to the green gap mentioned above. This heterostructure design is in principle the same technique used in HEMTs, just aimed at carrier confinement for recombination rather than high lateral mobility.

Quantum Well Without and With QCSE

Spatial separation of electron and hole due to the internal field in InGaN/GaN



Strong overlap → high radiative recombination rate;
separated wavefunctions → reduced efficiency.

Droop and Extraction Efficiency

Two effects limit an LED's real-world efficiency independent of internal material quality. Droop refers to the efficiency drop at high current densities, as described by the so-called ABC model: the recombination rate is composed of a defect-related Shockley-Read-Hall term (A·n, linear), the desired radiative term ($B \cdot n^2$, quadratic), and a non-radiative Auger term ($C \cdot n^3$, cubic). At low carrier densities n, the radiative B term dominates, but as current density rises, the Auger term (a three-particle process in which the recombination energy is transferred to a third carrier instead of a photon) grows disproportionately faster – internal quantum efficiency therefore peaks at moderate current density and declines again beyond it, right in the operating range needed for high brightness. The precise physical origins of the Auger contribution in InGaN remain a subject of active research.

The second limiting factor is extraction efficiency. Since GaN's refractive index ($n \approx 2.4$) is markedly higher than air's ($n \approx 1$), Snell's law defines a narrow critical angle for total internal reflection – only light striking the interface nearly perpendicularly leaves the chip directly; the majority is reflected back, bounces multiple times within the chip, and is increasingly absorbed in the process. Measures such as surface roughening (photonic roughening), shaped chip geometries (e.g., beveled sidewalls), photonic crystal structures at the extraction surface, or flip-chip mounting with a reflective back contact deliberately break up this total internal reflection and substantially raise the externally usable light output – often from below 50% in untreated chips to over 80% in optimized designs.

From Emission to Usable Light Output

For a practical assessment of an LED, the chain of several efficiencies is decisive, combining multiplicatively into the so-called wall-plug efficiency (electrical power → visible light): internal quantum efficiency (radiative vs. non-radiative recombination in the crystal), extraction efficiency (chip → air, see above), and for white LEDs, additionally phosphor conversion efficiency. The latter is subject to Stokes loss: since a blue photon (high energy) is converted into a yellow photon (lower energy), the energy difference is inevitably lost as heat in the phosphor – a fundamental, unavoidable efficiency loss in phosphor-converted white LEDs.

Added to this is thermal droop: rising chip temperature during operation further reduces internal quantum efficiency, which is why efficient thermal management (submount material, thermal vias, package design) is just as important for real-world light output as the semiconductor physics itself. In total, modern commercial white LEDs achieve luminous efficacies of over 150–200 lm/W, compared to roughly 15 lm/W for conventional incandescent bulbs.

Laser Diodes

From LED to Laser: Population Inversion and Stimulated Emission

The fundamental difference between an LED and a laser diode lies not in the basic structure – both are based on a pn junction made from a direct-bandgap semiconductor – but in the emission mechanism. An LED generates light through spontaneous emission: an excited electron recombines with a hole at a random point in time, and the resulting photon has a random phase and direction. A laser, by contrast, relies on stimulated emission: a photon that already exists strikes an excited electron-hole pair and triggers its recombination – the newly generated photon is then identical in phase, direction, and wavelength to the triggering photon. This amplification mechanism (Light Amplification by Stimulated Emission of Radiation) produces coherent light, in contrast to the incoherent light of an LED.

For stimulated emission to dominate over absorption, the active medium must exhibit population inversion: more electrons must occupy the higher-energy conduction band state than the lower valence band state – a condition that never occurs in thermal equilibrium and must therefore be actively forced through high injection current density. In semiconductor lasers, the strongly forward-biased pn junction performs this role: above a certain threshold current, the ratio flips, optical gain sets in, and spontaneous emission increasingly gives way to stimulated emission.

The Optical Resonator and Mode Formation

Population inversion alone doesn't yet produce a laser – only an optically amplifying medium. The actual lasing effect additionally requires feedback: an optical resonator, usually realized as two parallel, partially reflective mirror facets on either side of the active region. In simple edge emitters, these mirrors form from the semiconductor's natural crystal cleavage planes (fracture surfaces along specific crystal planes), which already provide a reflectivity of 30–35% due to the refractive-index step to air – enough to circulate light repeatedly through the gain medium.

Only light whose wavelength forms an integer multiple of the resonator length (a standing wave between the mirrors) is amplified constructively – all other wavelengths interfere destructively and are suppressed. This produces a laser's characteristic longitudinal mode structure: instead of a broad, continuous spectrum as with an LED, a comb of sharp, closely spaced emission lines appears, with spacing set by the resonator length. Once the optical gain within the resonator exceeds the sum of all losses (mirror transmission, internal absorption, scattering), laser oscillation begins – the threshold current I_{th} marks exactly this transition point and is one of the most important parameters of any laser diode.

Edge Emitters: Fabry-Pérot and DFB Lasers

The simplest design is the Fabry-Pérot laser: two parallel cleaved facets serve as resonator mirrors, and light is coupled out sideways from the chip edge (hence "edge-emitting laser"). Since the resonator is usually several hundred micrometers long, it simultaneously supports multiple longitudinal modes, whose wavelength spacing is inversely proportional to the resonator length – a Fabry-Pérot laser therefore typically emits multimode, with several spectral lines spaced roughly 0.1–0.3 nm apart.

For applications requiring a single, extremely stable wavelength – chiefly fiber-optic communication, where chromatic dispersion would otherwise smear the signal – the DFB laser (Distributed Feedback) is used. Instead of simple end mirrors, a periodic diffraction grating is integrated directly into the layer structure near the active region (grating period on the order of a few hundred nanometers, typically fabricated by electron-beam lithography). This grating provides wavelength-selective reflection distributed along the entire resonator length rather than only at the end facets, forcing longitudinal single-mode operation with a side-mode suppression ratio typically above 30–40 dB. InGaAsP/InP-based DFB lasers at 1.55 µm are the industry standard for long-haul fiber-optic transmission.

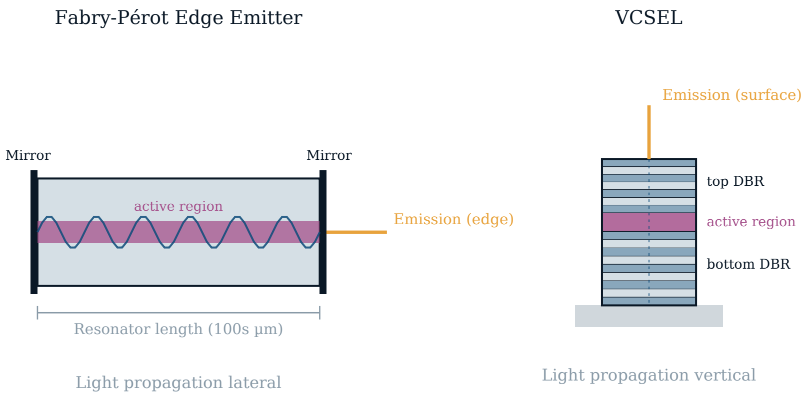
VCSEL: Structure and Advantages

The VCSEL (Vertical-Cavity Surface-Emitting Laser) follows a fundamentally different geometry: instead of coupling light out sideways from the edge, it emits perpendicular to the wafer surface. The resonator is vertical, formed by two DBR mirrors (Distributed Bragg Reflector) – stacks of alternating layers with different refractive indices, each a quarter-wavelength thick, which through constructive interference can achieve reflectivities above 99%, since a single semiconductor interface reflection would be far too low for a usable resonator. Because the active region is only a few micrometers long rather than several hundred micrometers as in edge emitters, extremely high mirror reflectivities are needed to reach the lasing threshold despite the short gain length.

The vertical design brings decisive practical advantages: VCSELs can be tested at the wafer level before being singulated (with edge emitters this is only possible after cleaving), they emit a round, low-divergence beam profile (instead of the elliptical beam of edge emitters, which simplifies fiber coupling), and they can be densely packed into two-dimensional arrays. These properties make

VCSELs the dominant technology for short datacom links (data centers, 850 nm GaAs VCSELs over multimode fiber) and, in high volume, for 3D sensing such as facial recognition and LiDAR illumination in smartphones, where arrays of thousands of VCSELs jointly project structured light.

Optical Resonator: Edge Emitter vs. VCSEL
Lateral resonator (Fabry-Pérot) vs. vertical DBR resonator (VCSEL)



Short gain length in a VCSEL requires mirror reflectivities > 99% – hence DBR stacks instead of simple cleaved facets.

Material Systems and Applications

Material choice follows the same principles as for LEDs, supplemented by resonator-specific requirements. GaAs/AlGaAs systems cover 780–980 nm (historically CD/DVD lasers, today mainly pump lasers for fiber lasers and VCSELs for datacom/sensing). InGaAsP/InP dominates at 1.3 µm and 1.55 µm for telecommunications, since these wavelengths coincide with the attenuation and dispersion minima of silica fiber. GaN-based laser diodes cover the blue-violet range around 405 nm and enabled high-density Blu-ray storage technology, since shorter wavelengths allow a smaller diffraction limit and thus higher storage density.

Beyond conventional data transmission, laser diodes have established themselves in three further fields: in materials processing, high-power diode laser bars (arrays of edge emitters) are increasingly replacing gas lasers for welding, cutting, and as pump sources for solid-state lasers, thanks to high electrical efficiency (conversion efficiency often above 50%). In sensing, LiDAR (Light Detection and Ranging) uses short laser pulses for time-of-flight distance measurement in automotive and robotics applications – here VCSELs are increasingly displacing conventional edge emitters. And in display technology, red, green, and blue laser diodes serve as light sources for laser projectors, where their high spectral purity enables a significantly wider color gamut than LED or lamp-based projectors.

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.

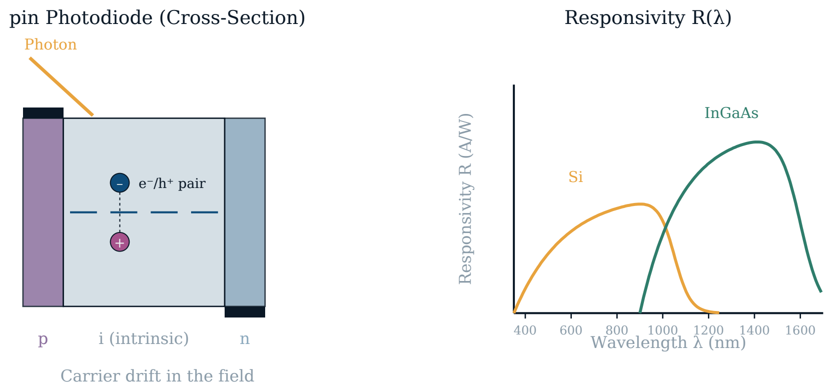
Key Parameters: Quantum Efficiency and Responsivity

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, $\lambda_g \approx 1240\ \text{nm}/E_g$), 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.

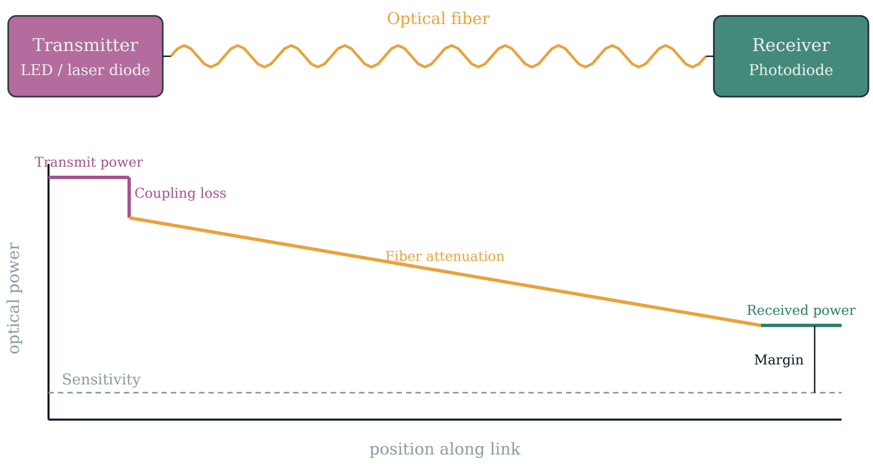
Integration & Applications

The Optical Transmission Chain

The previous three chapters treated the LED, laser diode, and photodiode as individual devices – in practice, however, they almost never work in isolation but as links in a transmission chain: transmitter (LED or laser diode) → transmission medium (optical fiber or free space) → receiver (photodiode). This chain clarifies why material choice in the previous chapters was so tightly coupled: an InGaAsP DFB laser at 1.55 µm only yields a working system if an InGaAs photodiode with matching responsivity sits at the other end, in exactly this wavelength window – transmitter and receiver aren't a random material pairing but a coordinated system component.

In system design, the efficiencies and losses of each stage add up: the transmitter's wall-plug efficiency, the fiber coupling efficiency (typically the lossiest step for edge emitters, one reason for the growing use of VCSELs with their round, easily coupled beam profile), fiber attenuation over the link length, and finally the photodiode's receiver sensitivity. The power budget (link budget) – transmit power minus all losses – must ultimately exceed the photodiode's minimum detectable power; if the margin isn't sufficient, intermediate amplifiers (optical fiber amplifiers) or more sensitive APD receivers are used.

Optical Transmission Chain and Link Budget
Transmitter, fiber and receiver as a coordinated system chain



The power budget — transmit power minus all losses — must exceed the photodiode's minimum detectable power.

Display Technology: LED Backlighting, µLED, and OLED Compared

In display technology, LEDs serve in several, technically quite different roles. In conventional LCD screens, a row of white InGaN LEDs (see Chapter 2) merely serves as backlighting – the actual image is formed by downstream liquid crystal cells that transmit or block the LED light pixel by pixel. In OLED displays, by contrast, each pixel is itself a light emitter: organic semiconductor layers emit light directly, substantially improving contrast (true black by fully switching off individual pixels) and viewing-angle stability – though at the cost of maximum brightness and long-term stability compared to inorganic semiconductors.

µLED displays pursue a third approach: instead of organic emitters, tiny inorganic InGaN/AlGaInP LED chips (edge length often below 50 µm) are used directly as individually addressable pixels – the same semiconductor technology from Chapter 2, just massively miniaturized and transferred in extremely high volumes onto a carrier substrate ("mass transfer," one of the biggest manufacturing bottlenecks of this technology). µLEDs thereby combine the contrast advantages of self-emitting pixels with the brightness, lifetime, and material stability of inorganic III-V semiconductors, but due to manufacturing complexity are currently still limited to premium applications and large display diagonals.

Sensing: LiDAR and Time-of-Flight

LiDAR systems (Light Detection and Ranging) use the devices covered in Chapters 3 and 4 in a precise timing application: a laser diode – usually a VCSEL or edge emitter in the near infrared (905 nm or the more eye-safe 1550 nm) – emits a short light pulse, and a fast photodiode (often an APD, due to the weak return signal) registers the reflection from the target object. The time-of-flight Δt between emission and reception directly yields the distance via $d = c \cdot \Delta t/2$ – at the speed of light, this corresponds to picosecond-range timing resolution for centimeter-level distance accuracy, placing high demands on the switching speed of both the laser diode and the photodiode readout electronics.

Automotive LiDAR systems scan an entire field of view, either mechanically (rotating mirror) or increasingly solid-state via VCSEL arrays that address different angles electronically instead of mechanically – a direct application of the VCSEL array capability described in Chapter 3. In 1550 nm systems, the advantage of the InGaAsP/InP technology already established for telecommunications comes into play: this wavelength can be operated at substantially higher power than 905 nm without exceeding eye-safety limits, since it's absorbed by the cornea rather than focused onto the retina.

Sensing: Pulse Oximetry and Proximity Sensors

A medical application example combining the materials from Chapters 2 and 4 is pulse oximetry: a fingertip clip sensor shines two LEDs of different wavelengths (red, ≈660 nm, and infrared, ≈940 nm) through tissue and measures the transmitted light intensity with a photodiode behind it. Oxygenated and deoxygenated hemoglobin absorb these two wavelengths to different degrees; from the ratio of the pulsating absorption signals (caused by arterial blood volume with each heartbeat), the device calculates blood oxygen saturation, entirely without drawing blood.

Proximity sensors in smartphones work on a similar but simpler principle: an IR LED (usually GaAs-based, see Chapter 2) emits invisible light, and an adjacent silicon photodiode measures the reflection – if an object (such as an ear during a call) is close enough, the reflected intensity rises sharply and switches off the screen. The same basic architecture, extended with structured light from VCSEL arrays (see Chapter 3), also forms the basis for 3D facial recognition systems, which reconstruct a complete depth image of the scene instead of a simple yes/no proximity measurement.

Photonic Integrated Circuits (PICs) – Outlook

All the devices covered so far – lasers, photodiodes, and to some extent modulators – today exist predominantly as discrete, individually packaged components connected to each other via fiber or free space. Photonic integrated circuits (PICs) pursue the same miniaturization and integration philosophy that has shaped microelectronics for decades: several optical functions – lasers, waveguides, modulators, photodetectors – are combined on a single chip, connected by structured waveguides instead of discrete fibers.

Silicon photonics is currently the most important trend in this space: since silicon itself doesn't emit light (Chapter 1) but is excellently suited as a waveguide and detector material (combined with germanium, see Chapter 4) and can additionally be manufactured on established CMOS production lines, passive and detecting photonic functions can be integrated cost-effectively. The light source itself typically remains a separately fabricated III-V laser chip (InP-based), subsequently bonded onto the silicon chip or coupled via hybrid integration – an active research field that directly links the III-V material systems covered in this section with the silicon manufacturing world of the site's other chapters. The main application driver is data centers, where PICs are increasingly replacing electrical cabling between servers with optical links offering higher bandwidth and lower energy consumption per bit.