Semiconductor Technology from A to Z

Optoelectronics & Photonics

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.

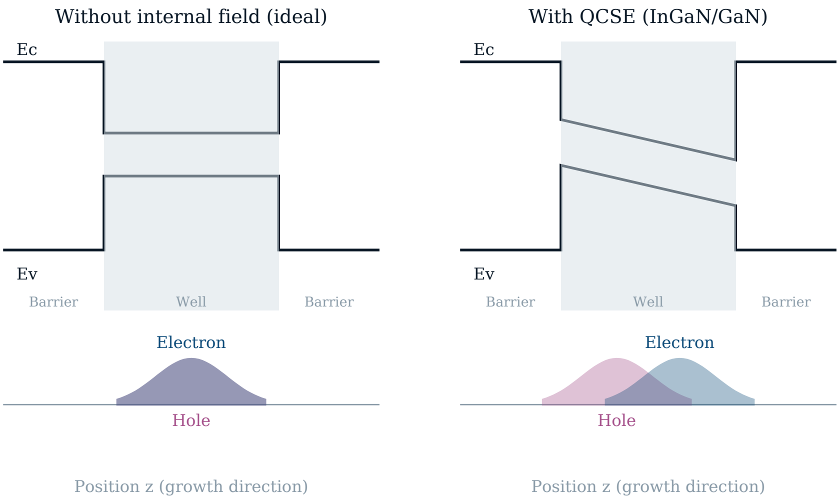
The technological maturity of InGaN in the 1990s (Shuji Nakamura, Nobel Prize in Physics 2014) was the decisive prerequisite for efficient white LEDs, since previously only red and yellow were available with sufficient efficiency – the so-called "green gap" (the efficiency shortfall of green LEDs between 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 ($A \cdot n$, 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.