# White paper: Introduction to the Green Gap Project: InGaN-GaN Multiple Quantum Wells for Green LEDs on Si

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III-V materials are widely used for LEDs. Depending on the material bandgap, InGaN and AlGaInP alloys are used for visible spectrum LEDs, while AlGaN alloys are used for UV LEDs. The external quantum efficiencies versus peak wavelength of LEDs are shown in figure 1. The state-of-art data shows that in the green spectral range (where human eyes are most sensitive to), the external quantum efficiency (EQE) of conventional LEDs drop for both families of materials. This phenomenon is known as 'green gap'.

EQE is defined as the product of internal quantum efficiency (IQE) and extraction efficiency (EXE). IQE is the ratio of the number of photons generated to the number of electrons ejected into the LED. It is determined by the materials properties and defects. While EXE is the ratio of number of extracted photons to the number of generated photons. It is mainly depends on the refractive index of materials and devices design.

InGaN based blue LEDs have relative high IQE. The bandgap decrease and wavelength shifts to green as the indium concentration increases. However, the IQE decreases dramatically as the indium concentration increases to 15-20%. There are various explanations [3]: 1) indium atoms are lager than gallium and the larger lattice mismatch introduces more defects and dislocations; 2) InGaN is grown at lower temperature to avoid indium decomposition, and this reduces the materials quality as well; 3) spontaneous and piezoelectric polarization increase the internal electric field and distort the quantum wells, which reduce the electron hole wavefunctions overlap (quantum-confined Stark effect). For AlGaInP based red yellow LEDs, its

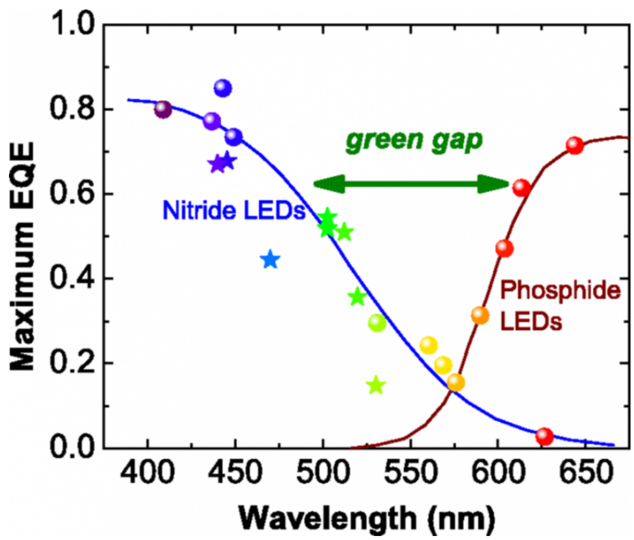


Figure 1: (Figure adapted from [1]) State-of-art external quantum efficiencies for visible-spectrum light-emitting diodes. Nitride LEDs refer to $In_xGa_{1-x}N$, while phosphide LEDs are $(Al_xGa_{1-x})_{0.52}In_0.48P$.[2]

efficiency drops significantly below 570nm due to a direct-indirect bandgap transition. [4]

Many approaches have been proposed to solve this 'green gap' challenge. Here we will mainly discuss the improvement of InGaN films' internal quantum efficiency. To give some examples here: 1) using non-polar or semi-polar GaN substrates to minimize the quantum-confined Stark effect; 2) use InGaN quantum dots as the active region; 3) use surface plasmon polaritons (SPPs) supported by metallic films or nanostructures.

I'll explain everything in a better way once I understand them myself...

# References

[1] der Maur, Matthias Auf, *et al.* "Efficiency drop in green InGaN/GaN light emitting diodes: The role of random alloy fluctuations." *Physical review letters* 116.2 (2016): 027401.

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[3] Moustakas, Theodore D., and Roberto Paiella. “Optoelectronic device physics and technology of nitride semiconductors from the UV to the terahertz.” *Reports on Progress in Physics* 80.10 (2017): 106501.

[4] Jiang, Yang, *et al*. “Realization of high-luminous-efficiency InGaN light-emitting diodes in the ”green gap” range.” *Scientific reports* 5 (2015): 10883.