Strain-relaxed bulk InGaN enables wavelength-stable red LEDs

Blue-shift in wavelength constrained to 6.2nm between 1mA and 100mA injection current.

Peking University in China and Saudi Arabia's King Abdullah University of Science and Technology (KAUST) have claimed the first use of high-indium-content red phase-separated bulk indium gallium nitride (InGaN) as the active region for red light-emitting diodes (LEDs) [Zuojian Pan, Optics Express, v33, p27245, 2025]. The structures achieved wavelength-stable red InGaN LED performance with just 6.2nm blue-shift between 1mA and 100mA injection current. At this preliminary stage, the efficiencies were less than impressive, at around 0.3%.

The bulk InGaN was grown at 800°C, around 100°C higher than usual for high-indium-content InGaN quantum wells typically used for red LEDs. The indium incorporation at higher-temperature growth was enabled by an underlying multiple quantum well (MQW) region grown at low temperature, resulting in spontaneous trench structures that relaxed the strain in the subsequent bulk InGaN. Along with enabling higher indium incorporation, the material underwent phase separation into high- and low-indium-content regions.

The team comments: "To the best of our knowledge, this study presents a new epitaxial strategy for red InGaN LEDs."

The researchers see their work as feeding into the recent interest in red InGaN micro-LEDs. These devices have reached efficiencies around 5%, and could challenge the more established aluminium gallium indium phosphide (AlGaInP) devices, which suffer more efficiency impacts at the micro-scale. Also, with the established green and blue InGaN LEDs, red InGaN could offer full-color display operation, particular if wavelength-stability is achieved.

The researchers used metal-organic vapor phase epitaxy (MOVPE) on sapphire to prepare InGaN LED material samples (Figure 1). Although the structures contained green MQWs, unusually the active red-light-emission material was the bulk InGaN grown on top.

The pure GaN layers were grown with trimethyl-Ga, while the precursor for the InGaN- and MQW-containing material was triethyl-Ga. The carrier gases were also changed: hydrogen for the bulk GaN, and nitrogen for the InGaN/MQWs.

The unintentionally-doped (u) buffer and n-type silicon-doped contact layers were 1 μm and 2μm, respectively. The MQW region consisted of six 2.5nm InGaN wells separated by GaN (3nm cap, 7nm barrier). The growth system heater temperature for the well and cap was 850°C and 760°C for samples A (characterization reference) and B (red LED), respectively.

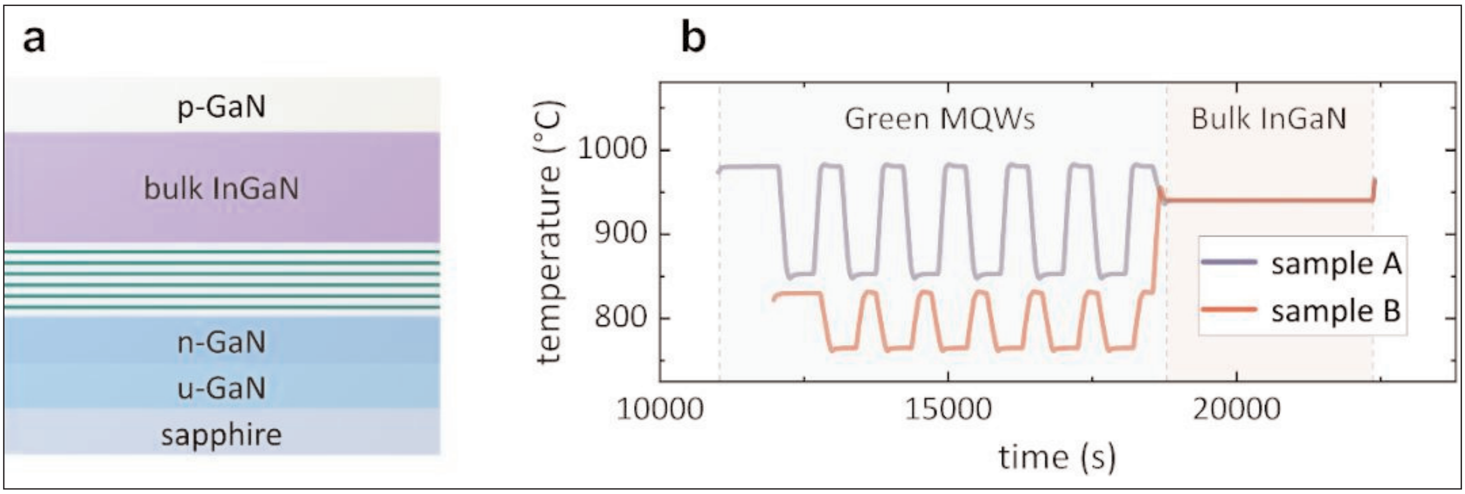

Figure 1. (a) LED structure based on bulk InGaN active region. (b) Heater temperature profiles during growth stages from green MQWs to bulk InGaN for samples A and B.

The barriers were grown at the corresponding higher temperatures of 980°C and 830°C. Emission wavelength of the green MQWs was equalized for the two samples by adjusting the In/Ga ratio of the precursors.

The bulk InGaN was grown at 940°C in both samples with a high In/Ga precursor ratio to maximize indium incorporation, as needed for long-wavelength red light emission. The bulk InGaN also had a graded silicon-doping profile designed to reduced LED turn-on voltages.

The p-type layers consisted of 920°C magnesium-doped GaN, 1050°C more heavily doped GaN, and 810°C doped InGaN contact layers.

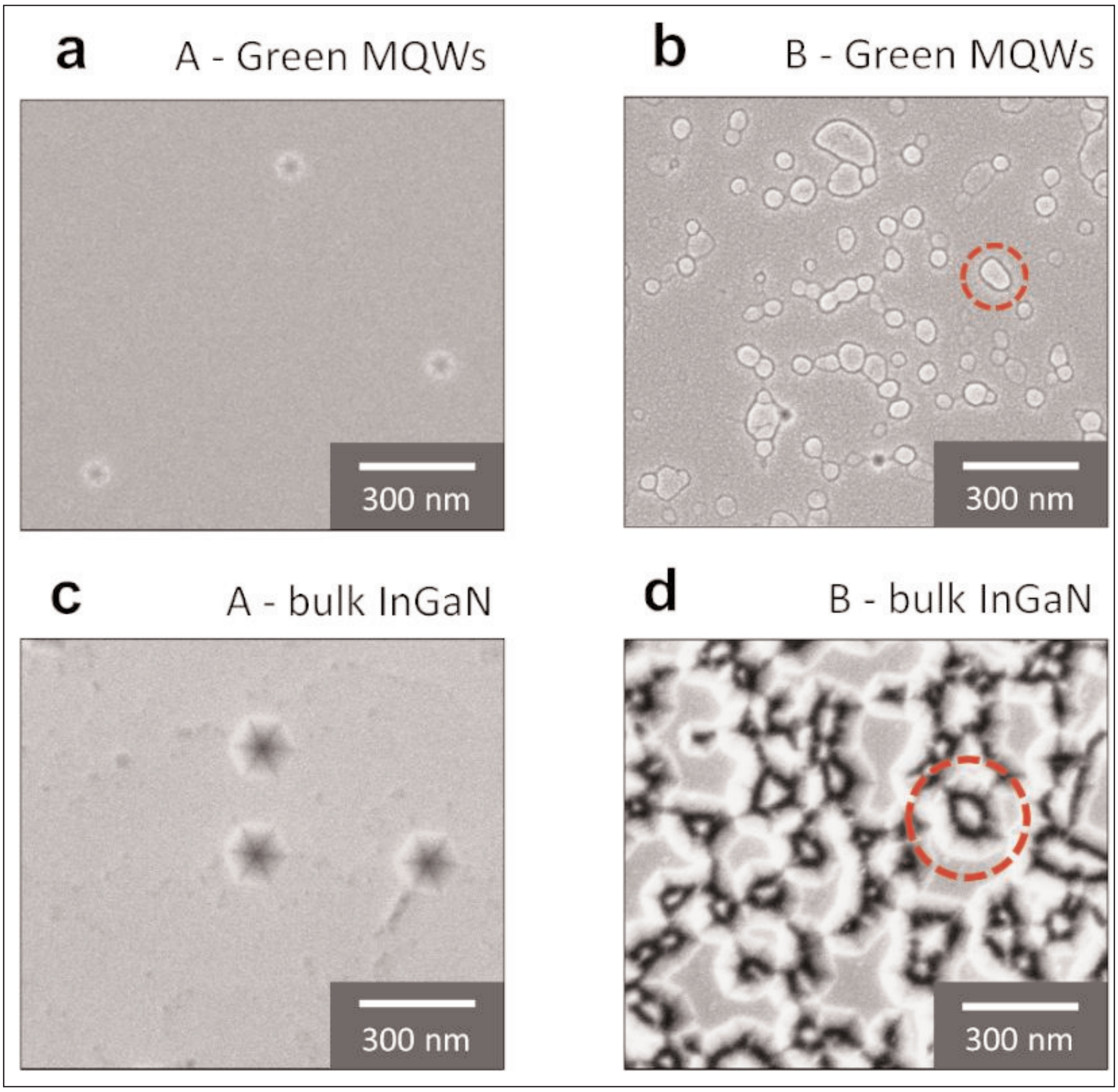

Figure 2. Scanning electron microscope (SEM) images of samples A and sample B after growth interruptions of green MQWs (a and b, respectively), and of bulk InGaN (c and d). Red dashed circles in (b) and (d) show corresponding locations of trench structures on green MQW and bulk InGaN surfaces.

SEM inspection after the MQW and bulk InGaN growth steps showed dramatically different surface morphologies (Figure 2). Sample B had a high density of trench structures (about $5.6x10^9/cm^2$ and $4.9x10^9/cm^2$ before/after bulk InGaN layer, respectively), while sample A presented a smooth surface punctuated with a few V-pits that grow in size during the bulk InGaN growth. The bulk InGaN rough surface of sample B had almost no continuous c-plane.

The researchers comment: "In sample B, both the green QWs and QBs are grown at low temperatures. The reduced QW growth temperature promotes the formation of indium-rich clusters, while the low-QB growth temperature restricts the migration of Ga adatoms. The combination between indium-rich clusters and the limited Ga adatom mobility result in the formation of high-density trench structures."

X-ray analysis showed that the bulk InGaN in sample A had an indium content of 8.5% and the strain was relaxed by about 3%. The B sample contained 11.9% indium, and strain relaxation was around 96%. The team explains: "The deep and densely distributed trenches facilitate strain relaxation in the bulk InGaN layer. Under a relaxed strain state, the strain energy required for In–N bond formation decreases, thereby promoting indium incorporation."

The x-ray study also suggested that the range of indium compositions and strain state was wider in sample B than in sample A.

STEM showed that the indium content also varied within local bulk InGaN regions, increasing from 11.3% at the base to 23.2% at the top (Figure 3). The researchers comment: "This trend is attributed to the upward extension of V-pits, which gradually enhances strain relaxation, resulting in a compositional pulling effect. Consequently, the top region of the bulk InGaN in sample B exhibits a higher indium content and greater strain relaxation, making it more susceptible to phase separation."

Cathodoluminescence from a 10kV electron beam showed different spectral profiles for the two samples. ➤

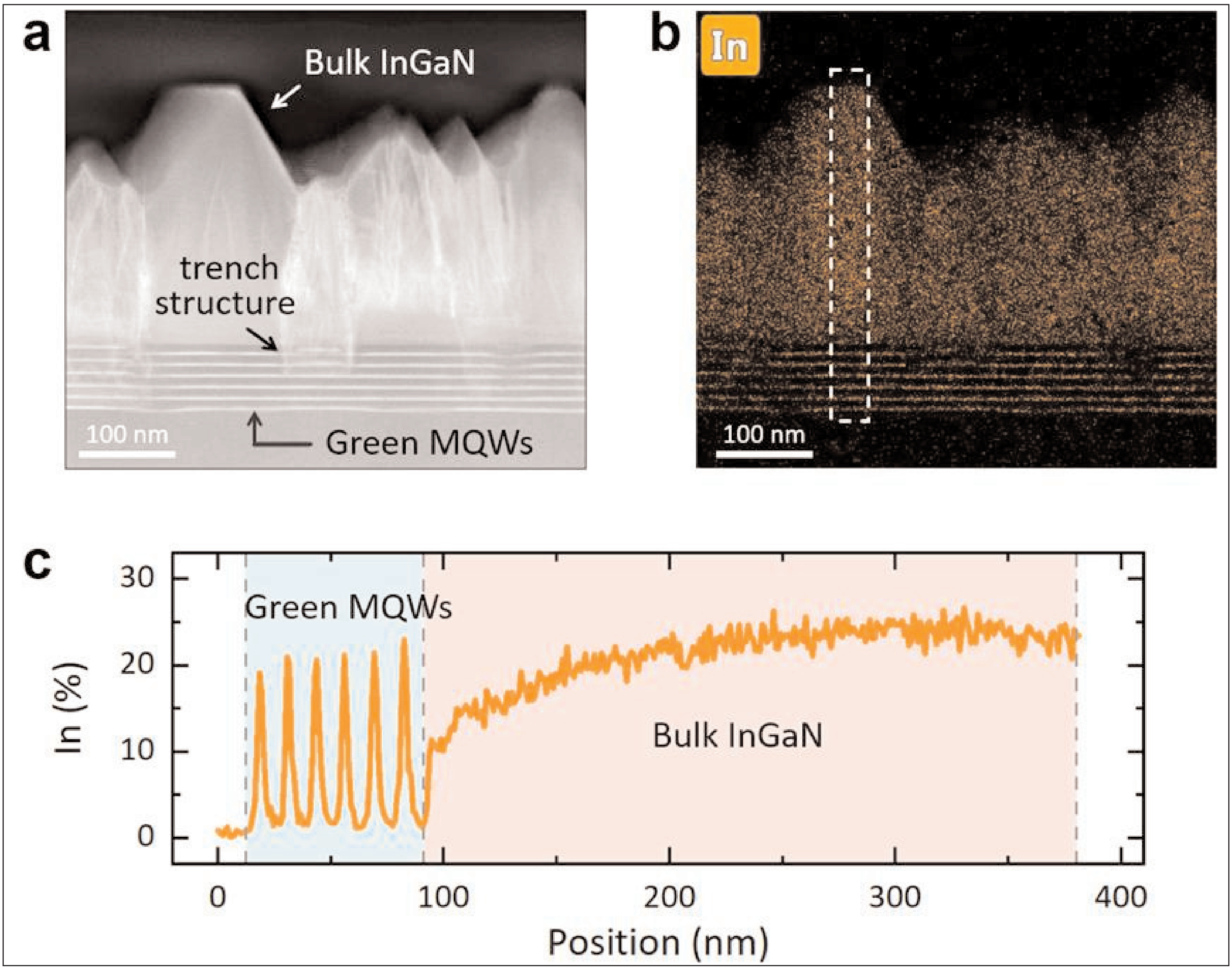

Figure 3. Scanning transmission electron microscope analysis (STEM). (a) High-angle annular dark-field (HAADF) image, (b) Indium elemental map obtained by combining STEM with energy-dispersive x-ray spectroscopy (EDX), and (c) indium composition profile along white dashed box in (b).

A had two peaks at 392nm (violet) and 506nm (green), associated with the strained bulk InGaN and green MQWs, respectively. B had three peaks: 443nm (blue-violet), 501nm and 635nm (red). The 501nm corresponded to the MQW structure, while the outer peaks were associated with low- and high-indium-content phase-separated regions of the bulk InGaN. The lower indium content naturally resulted in shorter-wavelength emission. The short-wavelength bulk InGaN emissions were little more than blips on the presented spectra. In sample B, the red 635nm-long wavelength peak was marginally higher than the 501nm green emission.

Observing that the 800°C bulk InGaN growth temperature is much higher than that typical for red InGaN QWs, the team comments: "The red emission at 635nm corresponds to an indium content exceeding 30%, which is unlikely to result from direct indium incorporation at 800°C. In a strain-relaxed state, InGaN tends to undergo phase separation, forming high-indium and low-indium phases. Therefore, the red emission most likely originates from phase separation in the bulk InGaN, rather than direct indium incorporation."

The phase separation is thought to encourage carrier localization, enabling higher radiative recombination efficiency and longer carrier lifetimes. "The high-indium (>30%) red phase likely forms three-dimensional (3D) nanostructures, similar to quantum dots," the team writes. "These regions, with narrower bandgaps than the surrounding low-indium phase, create potential wells for carrier localization."

Electroluminescence (EL) studies were performed on sample B using indium balls as contacts (Figure 4). The peak wavelength was found to have much reduced variation, compared with MQW-based LEDs. The peak blue-shifted just 6.2nm between 1mA and 100mA injection, decreasing from 648.6nm to 642.4nm.

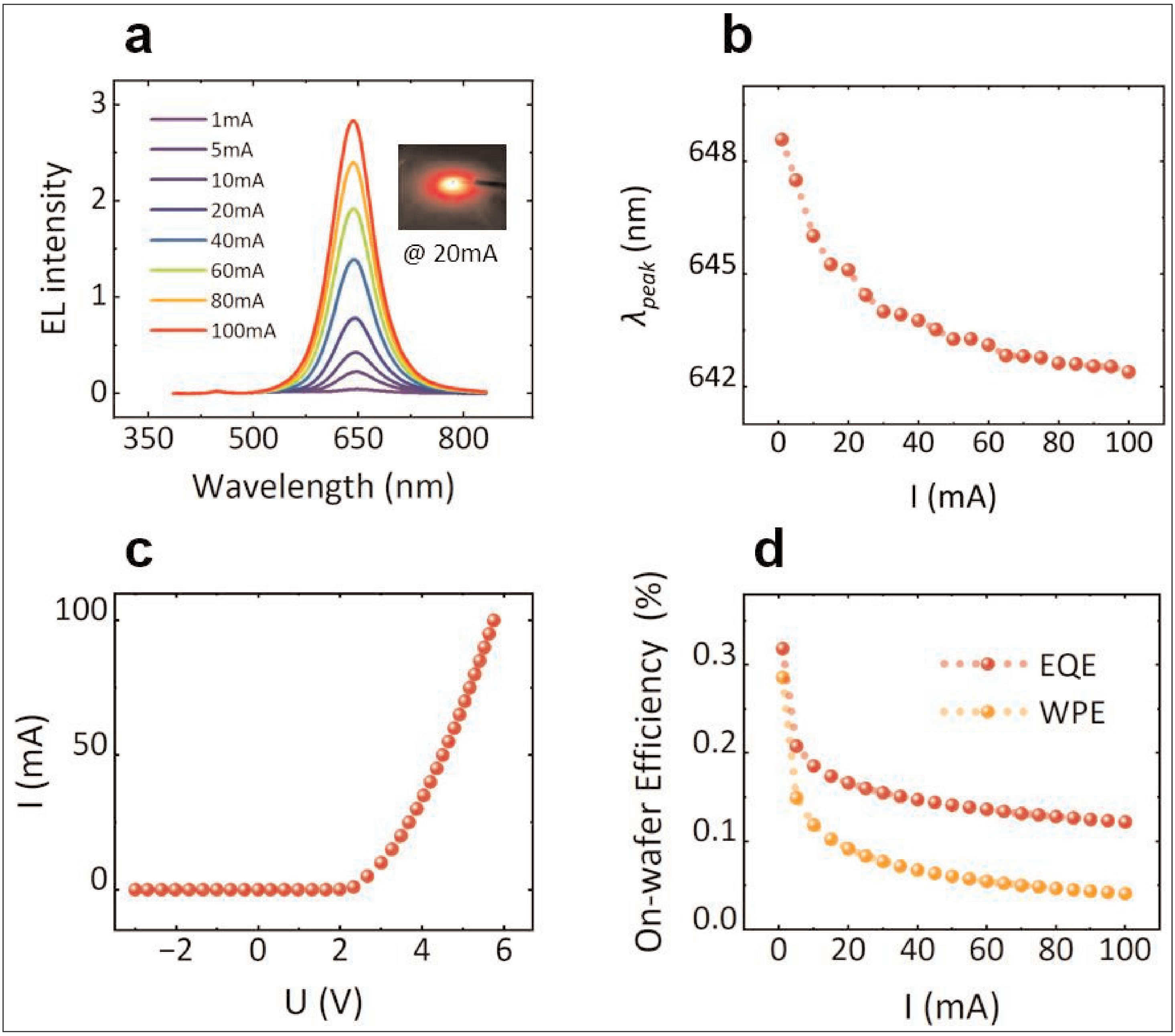

Figure 4. Sample B's electroluminescence (EL) performance: (a) EL spectra with corresponding EL image inset. (b) Peak wavelength variation with current. (c) Current (I)–voltage (U) curve. (d) On-wafer external quantum efficiency (EQE) and wall-plug efficiency (WPE) versus injection current.

MQW LEDs typically suffer blue-shifts of more than 30nm in wavelength.

InGaN QWs are usually in a highly strained state, reducing tendencies to phase separation. The strain also tends to enhance local electric fields due to the charge polarization of the chemical bonds of III–nitride semiconductors. These electric fields change as the current injection increases, Stark-shifting the energy levels and hence the emission wavelength to give the 'quantum-confined Stark effect' (QCSE).

The researchers comment: "In this study, high-density trench structures are intentionally introduced to promote strain relaxation in bulk InGaN, thereby facilitating phase separation and forming a high-indium red phase. Under strain-relaxed conditions, the polarization field is significantly reduced in the red phase, resulting in the observed minor wavelength shift."

The threshold voltage was around 3.2V. The peak external quantum efficiency (EQE) and wall-plug efficiency (WPE) at 1mA were 0.32% and 0.29%, respectively. The efficiency droop at higher current injection is blamed on the usual suspects, "Auger recombination and/or carrier overflow".

The team laments: "Inhomogeneous phase separation and the limited volume of the red phase may lead to low carrier injection efficiency, ultimately resulting in a low EQE. Further structural optimization is necessary to enhance the efficiency." ■

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Author: Mike Cooke