# Improving transport, reducing polarization in nitride LEDs

**Mike Cooke** reports on research aiming to increase LED efficiency for LCD and general lighting applications.

Nitride semiconductor LEDs are being developed for white light applications such as liquid-crystal display backlights and general illumination with reduced power consumption. However, these devices suffer from a degradation of efficiency at higher currents, also known as 'droop'. Researchers have tried various methods to overcome this droop to allow higher-efficiency operation of these devices at higher currents. Solving the problem would enable wider use of LEDs at lower cost both through more efficient operation and the need for fewer devices in a module.

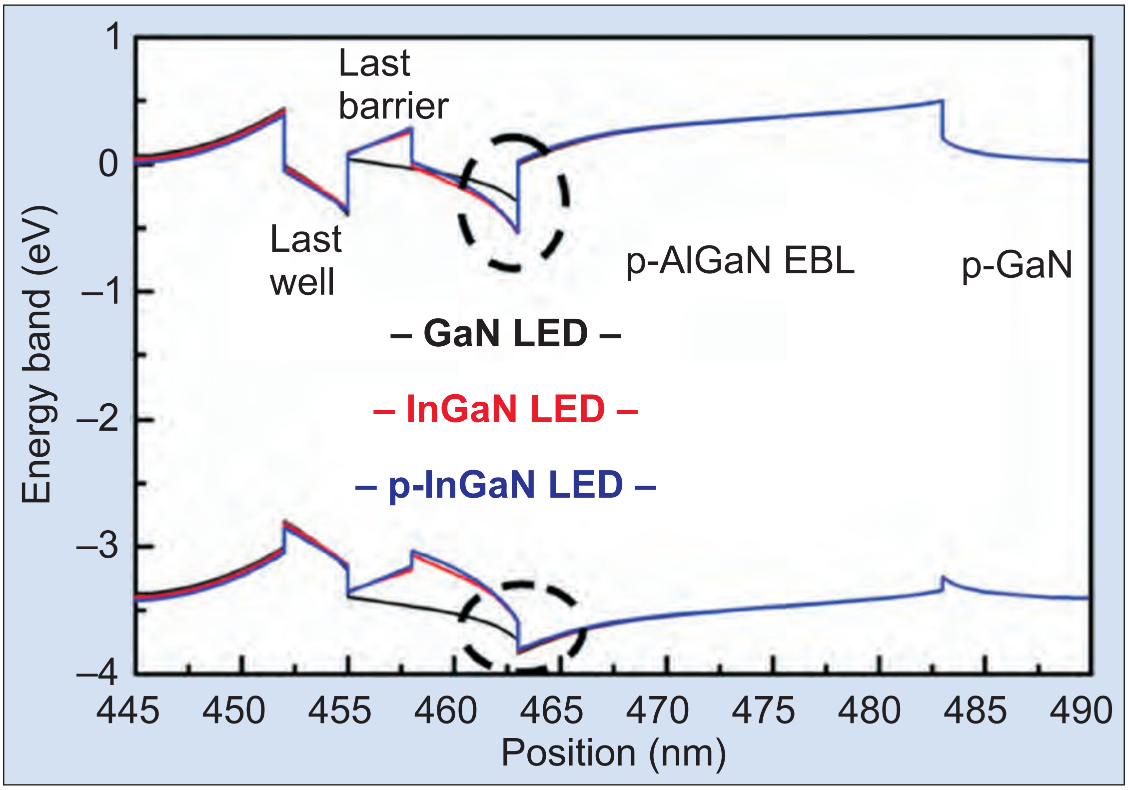

**Figure 1. Calculated band diagrams for GaN, InGaN, and p-InGaN LEDs at forward current of 20mA.**

A variety of explanations have been offered for the droop behavior. These tend to focus on the recombination process, carrier transport into the device, and the large spontaneous and strain-dependent (piezoelectric) polarization due to the more strongly ionic nature of the III-nitride bond compared with other semiconductor materials.

The main explanation based on recombination is the Auger process, where the energy release by electron transitions into hole states is transferred to a third carrier rather than producing a photon. Some researchers believe the Auger effect is too small at the relevant carrier densities to be dominant. Others suggest that there is an enhancement due to a resonance with higher excitation bands, particularly in the green wavelength range of the spectrum [reviewed in Mike Cooke, Semiconductor Today May/June 2011, p112].

Here we look at structures developed in Taiwan and China that aim to tackle transport and polarization aspects.

Carrier transport affects the distribution of the electrons and holes in the active light-emitting region of diode structures. While electrons often flow beyond the active region of the device into the p-contact, holes barely make it beyond the first well. The electron overflow also reduces efficiency by reducing the number of holes available for injection into the active region. Nitride LEDs frequently have an electron-blocking region of

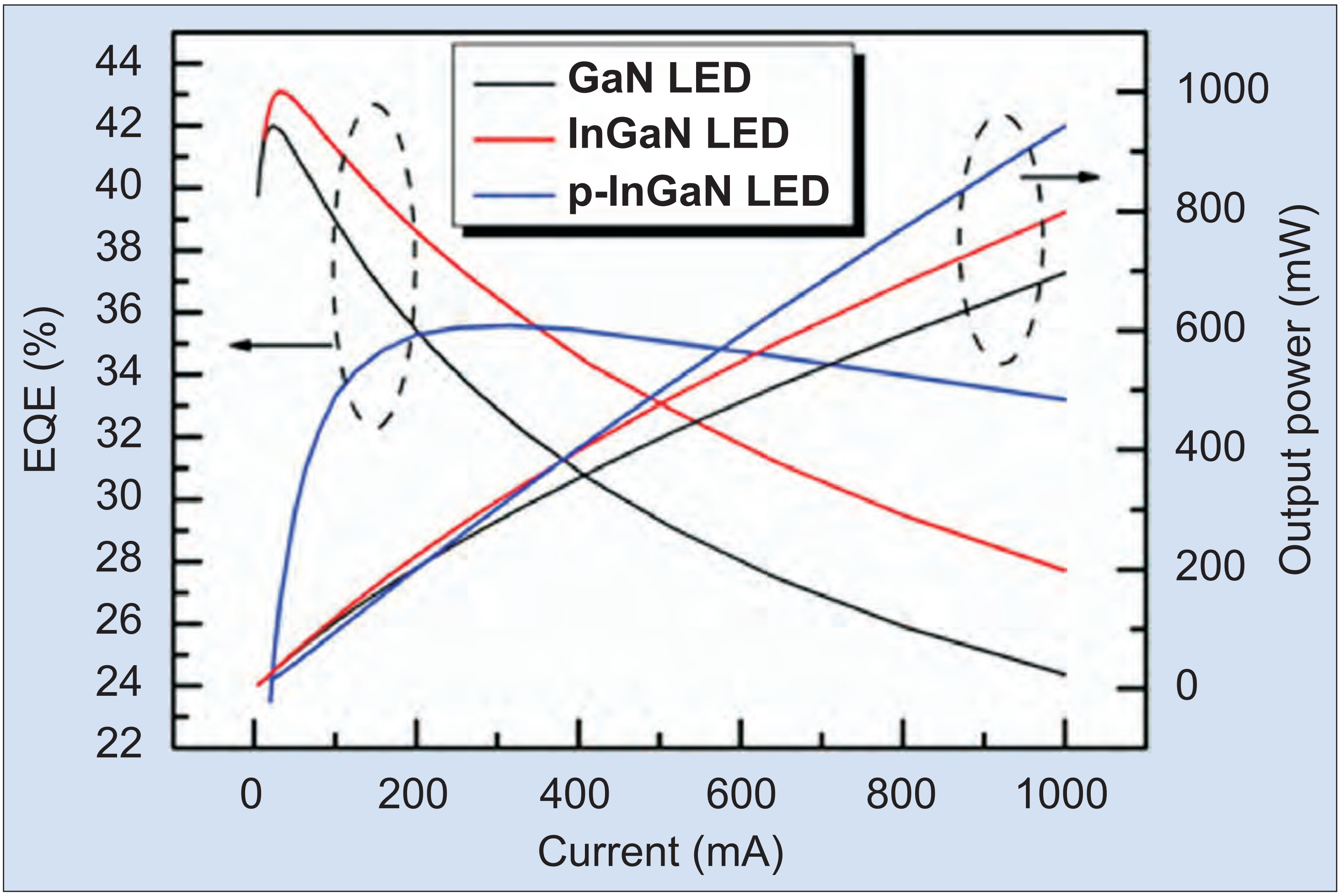

**Figure 2. External quantum efficiencies (EQEs) and output powers of GaN, InGaN, and p-InGaN LEDs plotted with respect to forward current.**

aluminium gallium nitride (AlGaN) to reduce electron overflow, but this then further impedes the flow of holes.

Strong polarization arises in indium gallium nitride (InGaN) MQW structures due to strain effects with large differences in lattice constant of the well and barrier materials. The resulting electric field in the active region makes it difficult for electrons and holes to recombine as photons/light, since the field tends to pull carriers of opposite charge apart.

## Layer insertion

Taiwan researchers have reduced efficiency droop from 42% to 7% by inserting p-type indium gallium nitride (p-InGaN) between the active light-emitting and electron-blocking layers of a nitride semiconductor LED [Ray-Ming Lin et al, Appl. Phys. Lett., vol101, p081120, 2012]. The researchers were based at Chang Gung University, National Cheng Kung University, and MOME Business Development Group (LED Division). The researchers see their p-InGaN insertion as a way to overcome the asymmetry between electron and hole transport in nitride LEDs.

The InGaN-based blue LEDs were produced from material grown on c-plane sapphire with an SR2000 metal-organic chemical vapor deposition (MOCVD) reactor supplied by Taiyo Nippon Sanso. The layer sequence consisted of 25nm GaN nucleation layer, a 1μm undoped GaN buffer, 3μm of Si-doped n-GaN, two pairs of 3nm InGaN (10%-In) and 12nm GaN strain relaxation layers, a multi-quantum well (MQW) of four pairs of 3nm InGaN (16%-In) wells and 12nm GaN barriers followed by a 3nm last well and 3nm last barrier, 5nm GaN, an InGaN (7%-In) or p-InGaN insertion layer, a 20nm p-AlGaN (20%-Al) electron-blocking layer, and a 100nm p-GaN contact. The active region was designed to emit 440nm-wavelength blue light. The LEDs were formed from 1mm x 1mm chips of the material.

Based on simulations (Figure 1), the researchers believe that the effect of the InGaN insertion is to block electron overflow and increase hole injection into the LED structure, increasing external quantum efficiency (EQE). By doping InGaN as p-type, there is also the benefit of a lower activation energy for hole generation compared with p-GaN. The simulation suggested a reduction of almost three orders of magnitude in electron overflow and more than one order of magnitude increase in hole concentration in the last well when LEDs with p-InGaN insertion were operated at 1A injection current.

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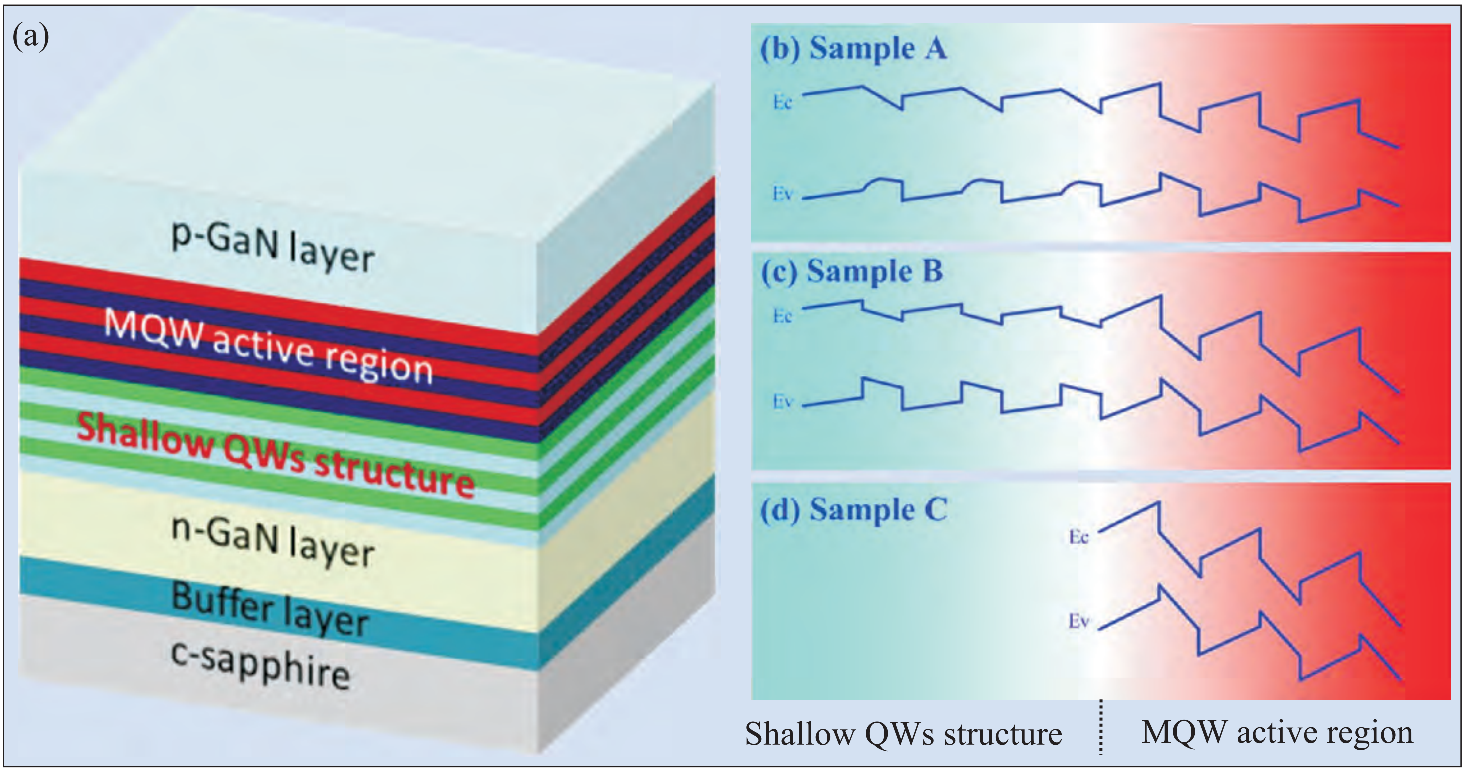

**Figure 3. (a) Schematic diagram of the epitaxial LEDs with shallow QW structure. (b) Schematic band profiles of shallow QW structure and active region of LEDs with shallow TQW (Sample A), (c) LEDs with shallow RQW (Sample B), and (d) conventional LEDs (Sample C). Diagram is not to scale.**

Processed devices were tested up to 1A using a 700μs 0.1%-duty-cycle, pulsed signal to avoid self-heating effects (Figure 2). The undoped InGaN insert provided the highest peak efficiency and a slight mitigation of the droop effect. The researchers comment: "We attribute this improvement to the enhanced hole injection efficiency and greater retardation of electron overflow as a result of the bandgap energy of $In_{0.07}GaN$ being lower than that of GaN."

The p-doping of the InGaN insert reduced the peak while pushing it out to higher current of about 316mA. The efficiency droop at 1A was 7% compared with the peak. The droop of the conventional device was 42%. "Accordingly, we observed a dramatic increase in the light output power from the p-InGaN LED because of its extremely low efficiency droop," the researchers write. The output power at 1A was 950mW, i.e. 1.35x that of the conventional LED.

However, the peak efficiency of the p-doped insert was significantly lower than the conventional and undoped-insert LEDs. It is frequently the case that measures taken to tackle droop also result in reduced peak efficiency.

In this case, secondary-ion mass spectroscopy (SIMS) of the epitaxial structures indicated the presence of magnesium (Mg) p-type dopant in the MQW region of the p-doped insert LED. Such diffusion of Mg into the active region would be expected to reduce efficiency from non-radiative recombination processes through material quality damage and ionized acceptor levels.

The researchers propose that improved LED performance would result from optimizing the doping profile of the Mg metal-organic source of bis(cyclopoentadienyl) magnesium ($Cp_2Mg$) and tuning the epi process condition to minimize the impact of back-diffusion of Mg atoms into the MQW active region.

## Triangular quantum wells

The State Key Laboratory of Optoelectronic Materials and Technology of Sun Yat-sen University in China has reduced the forward voltages and increased the device efficiency of nitride semiconductor LEDs by up to 80% by inserting a triangular quantum well region (TQW) before the usual MQW active region [Shanjin Huang et al, Appl. Phys. Lett., vol101, p041116, 2012].

The researchers ascribe the improved performance to weakening of the polarization field in the MQW active region induced by the TQW structure.

The epi material was grown on c-plane sapphire using MOCVD (Figure 3). The MQW region consisted of InGaN with GaN barriers (InGaN/GaN, 2.7nm/7.5nm, In-16%).

The shallow QW region was inserted before the MQW active region. Two types of shallow QW were created. Sample A had linearly increasing In-content (0% to 12%) due to decreasing growth temperature from 820ºC to 780ºC, giving TQWs (InGaN/GaN 3.78nm/7.53nm). Sample B had rectangular QWs (RQWs) of 6%-In InGaN grown at 800ºC (InGaN/GaN, 3.36nm/8.01nm). A further structure, Sample C, was produced without shallow QWs, representing a conventional LED material.

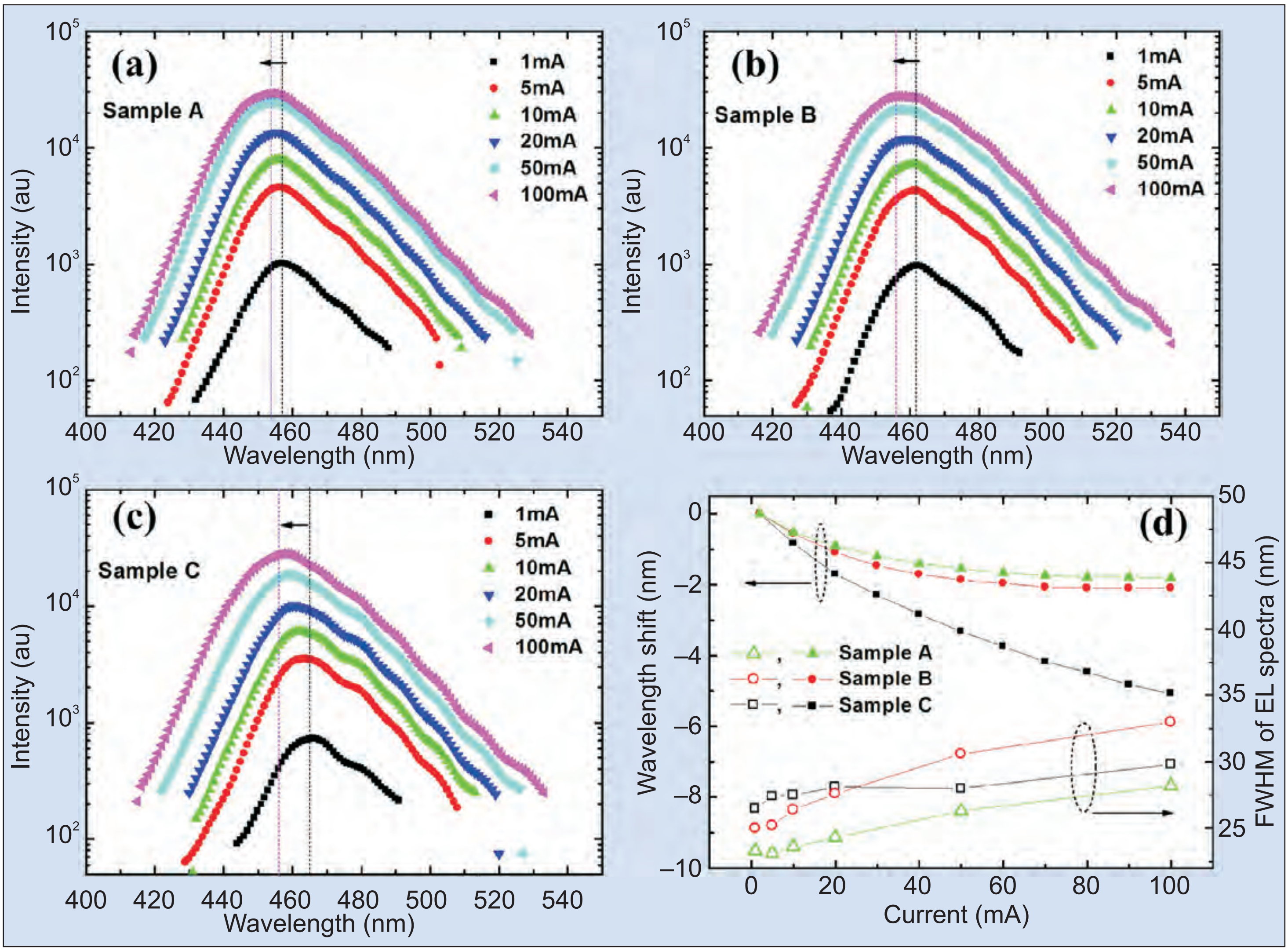

**Figure 4. Electroluminescence spectra of (a) Sample A (with shallow TQW), (b) Sample B (with shallow RQW), (c) Sample C (w/o. shallow QWs) at various injection currents. (d) Magnitude of blue-shift and FWHM of electroluminescence emission peak in the three samples as function of injection current.**

The materials were processed into 200µm x 250µm lateral LEDs. Pulse currents (10msecs) were used to test the devices to avoid self-heating effects.

The TQWs of Sample A gave the lowest forward voltage of 2.70V at 1mA. The respective values for samples B and C were 2.75V and 3.05V. The improved performance of Sample A was attributed to weakening of the polarization field, allowing carriers to overcome potential barriers and enhancing carrier transport in the active region.

At 20mA current injection, the light output from Sample A was 14% more than Sample B and 57% more than the conventional device based on Sample C. The lower forward voltage and increased light output indicated increased efficiency for Sample A devices of 80% over Sample C LEDs and 16% over Sample B LEDs.

X-ray diffraction analysis suggests that the inclusion of TQWs partially releases strain in the upper active MQWs. As a result the strain-dependent piezoelectric polarization field is reduced.

Another effect of introducing TQWs was to reduce the spectral blue-shift with increasing current (Figure 4). Between 1mA and 100mA, the peak wavelength shifted 1.8nm for LEDs based on Sample A, compared with 5.1nm for Sample C devices.

Such blue-shift can be due to combined effects of coulomb screening of polarization-induced quantum-confined Stark effects (QCSEs), and band filling of localized states under high carrier injection. The reduced polarization field of Sample A from reduced strain would lead to reduced QCSE effects. However, increased peak widths for all the LEDs also suggest the presence of band-filling effects. The full-width at half-maximum (FWHM) values for 100mA injection were increased over those at 1mA by 21%, 32% and 13%, for LEDs based on samples A, B and C, respectively.

The researchers suggest that the insertion of the TQW structure may result in both weakening of QCSEs and enhancement of band filling. ■

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