A decade of solid-state lighting R&D highlights at ISCAS

Here we present a summary of the progress made in solid-state lighting by the Institute of Semiconductors, Chinese Academy of Sciences over the last 10 years.

Over the last decade, China has made great progress in solid-state lighting (SSL). R&D has undoubtedly played a key role in supporting China's SSL industry, with more than 50 institutes and universities involved in SSL R&D. In particular, there is one institute that should not be overlooked when discussing China's SSL R&D: the Institute of Semiconductors, Chinese Academy of Sciences (ISCAS). ISCAS proposed that the Chinese government support SSL R&D as early as 2003. It is now China's biggest institute in SSL R&D, with numerous achievements. Here we present its most important SSL R&D highlights.

VLED with low operating voltage and thermal resistance

Constrained by poor thermal and electrical conductivity of the widely used sapphire substrate, vertical-injection gallium nitride (GaN)-based light-emitting diodes (VLEDs) have recently been investigated extensively. Fabricated by removal of the insulating sapphire substrate and transferred to a new thermal and electrical conductive substrate, VLEDs have a lower operating voltage, lower thermal resistance and higher saturation currents, so they have been considered as the candidate for future high-power and high-efficiency LED devices.

Considering thermal dissipation, a method for manufacturing GaN-based LEDs with a back-side via hole structure has been adopted. By introducing the back-side via hole technique of silicon-based microelectronics processing into this method, the silicon oxide insulation layer in the

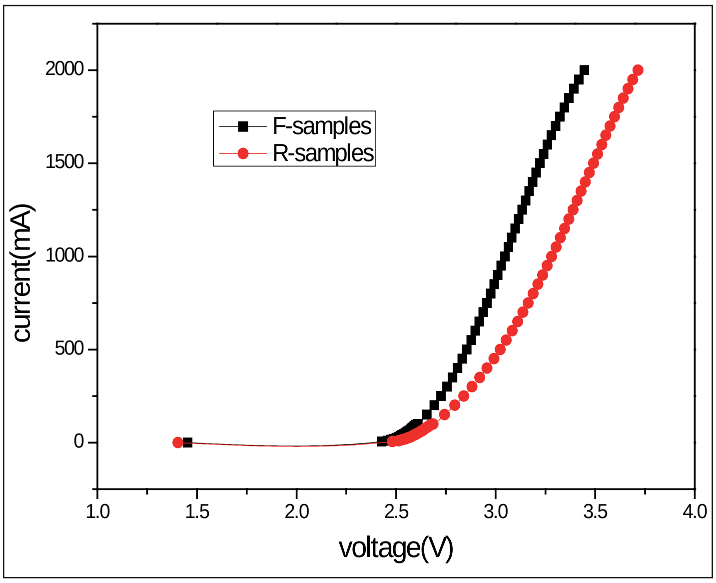

Figure 1. I–V curves of VLEDs with flat (F-samples) and roughed N contacts.

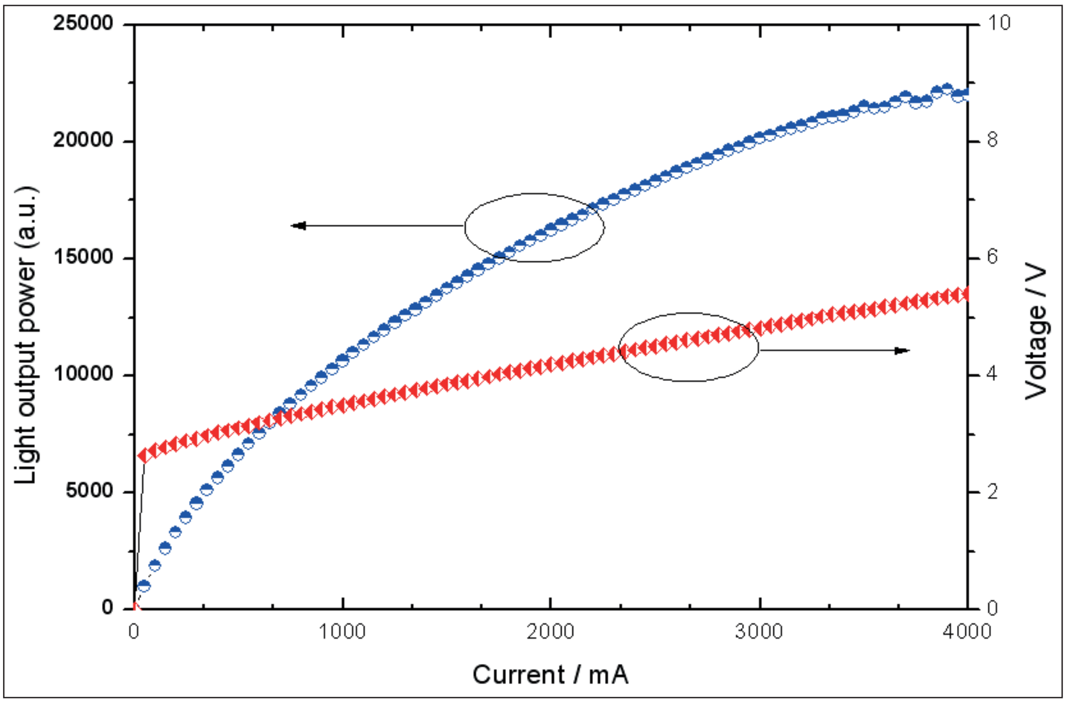

Figure 2. Transient saturation measurement of VLEDs.

heat-conducting path can be removed, and the silicon can be replaced by copper (whose heat conductivity is almost three times that of silicon). This enables the heat produced in the active region of the LED die to be conducted directly to the heat-sink through the metal, which is an excellent heat conductor, and the whole heat dissipation path includes no poor heat conductor, reducing thermal resistance as much as possible and realizing heat dissipation with 'sub-zero' thermal resistance. This method not only enables the LEDs to work at a larger operating current, but also improves the ability to work continuously for a long duration and enhances performance and reliability, facilitating the realization of power LEDs for illumination.

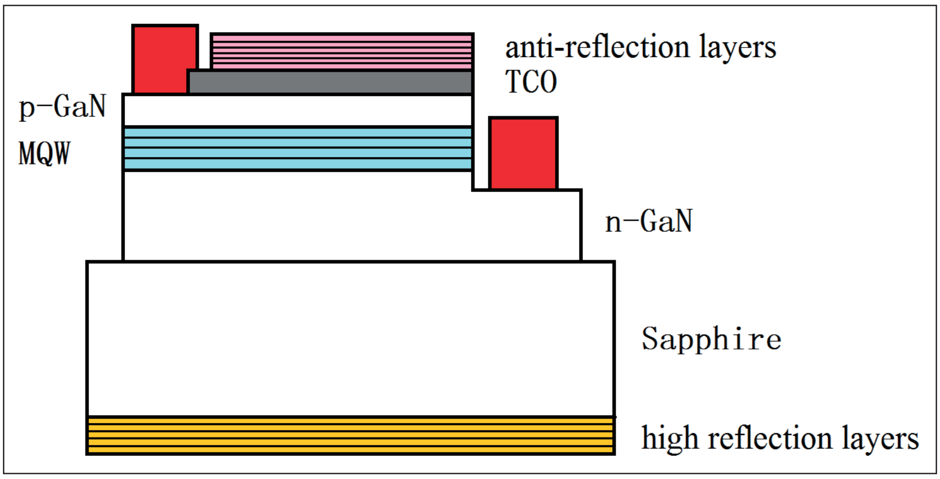

Fig. 3. Composite optical coatings used in LEDs.

As a p-type contact, nickel-silver (NiAg)-based metal layers were used, since they have high reflectivity in the visible light region. The p-type ohmic contact resistance was reduced through optimized p-GaN growth conditions and p-metal annealing. To reduce the n-type ohmic contact resistances, a new scheme for depositing metallization contacts was developed. This includes chemical cleaning, selectively wet etched surface roughing, and multiple Al-based metal layers were deposited on the n-type GaN. Chemical cleaning is effective in reducing the contact resistance.

These methods were used to fabricated VLEDs that showed extremely low operating voltage (2.75V@350mA), low reverse leakage current (0.015μA@-5V), low thermal resistance (2.5 K/W) and high saturation current.

(Related publications: Liancheng Wang, et al. 'Interface and Transport Properties of Metallization Contacts to Flat and Wet-Etching Roughed N-Polar n-Type GaN', ACS Applied Materials & Interfaces Vol. 5, Issue 12, pp5797 (2013).)

Composite optical coatings used in LEDs

The light extraction efficiency of GaN-based LEDs is quite low due to total internal reflection, Fresnel reflection, and absorption by GaN and electrodes. In lateral structure LEDs, the p-electrode is made of composite optical coatings with high transparency and high electrical conductivity. Another composite optical coating with high reflectivity is formed on the bottom surface of the sapphire substrate. When the light emitted from the active region transmits into the sapphire substrate, it is mostly be reflected back into the GaN epilayers and then mostly escapes from the top composite optical coatings into the free space, since the top composite optical coatings are anti-reflection layers.

To increase the extraction efficiency of the light emitted from a power GaN LED, a fabrication method has been developed for GaN flip-chip LEDs with both p-type and n-type electrodes formed by composite optical coatings. Since the contact electrodes for both p-GaN and n-GaN are formed from a composite optical coating comprising a transparent and electrically conductive film and an optical anti-reflection film, the light loss between the GaN medium and the transmission medium (e.g. air) can be reduced. Consequently, luminous efficiency is greatly improved.

As for a vertically structured chip, an optical composite electrode with high transparency on the top surface of the GaN LED epilayers is formed, and an optical composite electrode with high reflectivity is buried under the bottom surface of the GaN LED epilayers. In this LED structure, the light emitted from the active region mostly escapes from the top transparent electrode into space, and so light loss is reduced.

(Related publications: Xiaoyan Yi, et al. 'Research and Fabrication of High Power LEDs with Transparent Electrodes', Proc. of SPIE Vol. 6841, 68410B, (2007); Liancheng Wang, et al. "Combined transparent electrodes for high power GaN-based LEDs with long life time", 9th International Conference on Solid-State and Integrated-Circuit Technology, Vol. 1-4, p1051 (2008).)

Polarization-induced 3D hole gas

P-type conductivity has always been a technical difficulty for wide-bandgap III-nitride semiconductor materials. In 2010, a p-type doping method called polarization-doping was proposed by Simon in an N-face graded AlGaN layer (Science 327, p60, 2010). However, N-face GaN-based structures tend to have poor surface morphology and high impurity concentration, whether grown by metal-organic chemical vapor deposition (MOCVD) or molecular beam epitaxy (MBE). By using polarization-doping, researchers at ISCAS have achieved a three-dimensional hole gas (3DHG) in (0001)-oriented graded AlGaN. The hole concentration in the graded AlGaN layer is as high as ~10^{18}/cm^3 at room temperature (RT) and shows a weak tempera-

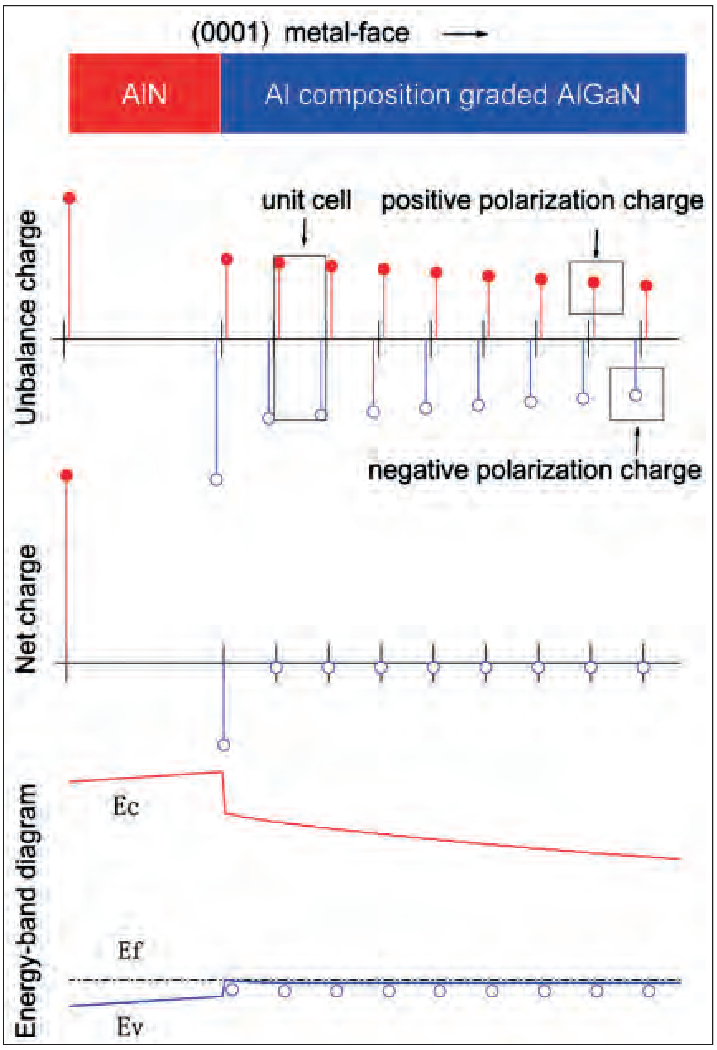

Figure 4. Schematic illustration of polarization-induced 3DHG in (0001)-oriented metal-face III-nitride structure.

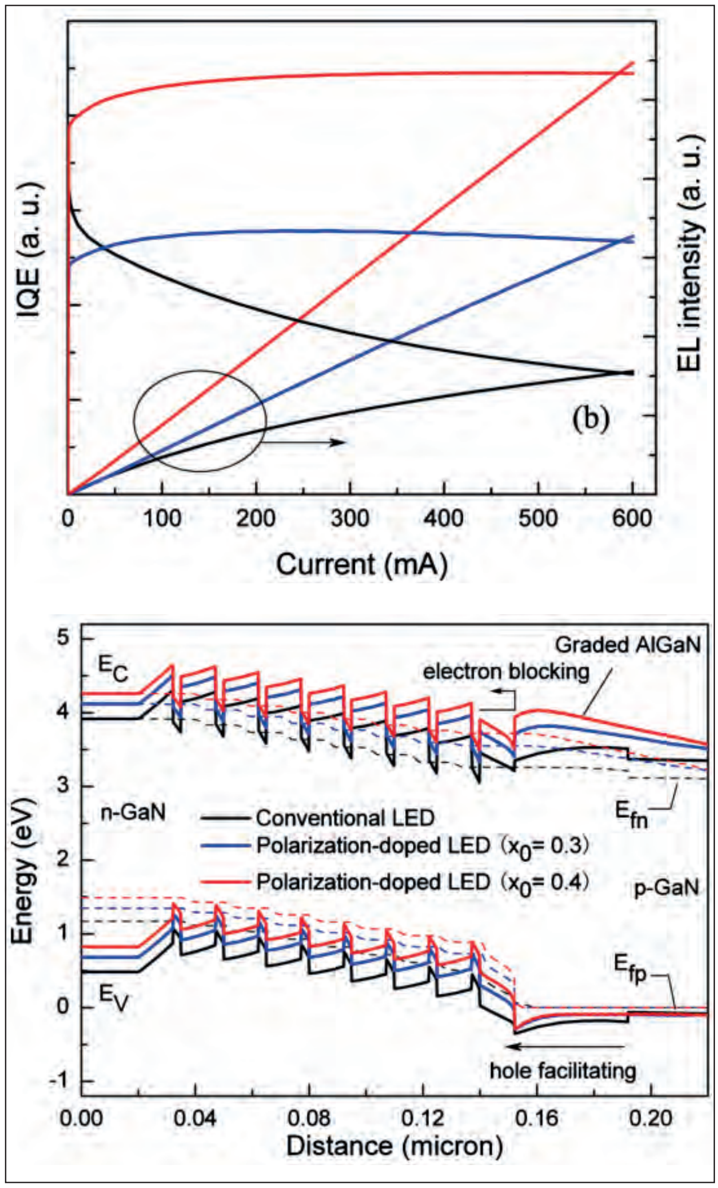

Figure 5. Optical performance and band diagrams of the polarization-doped LED and the conventional LED.

ture dependence.

The metal-face graded AlGaN is grown using a single-wafer home-made MOCVD reactor. Before growing the graded AlGaN layer, a 1µm-thick undoped AlN layer is deposited on the c-plane sapphire at 1200°C. Then a 100nm-thick Mg-doped graded $Al_xGa_{1-x}N$ layer (with Al composition ranging from x = 0.3 to 0) is grown on the AlN layer.

For the metal-face graded AlGaN layer grown on the AlN layer, it can be deemed as an N unit cells with an Al composition decreasing linearly from $x = x_0$ to 0. The unbalance bound sheet charge density is dependent on Al composition, which decreases as the Al composition decreases. The net bound sheet charge density at the interface of the ith and (i+1)th unit cell is then summed as $[(P_i^{sp}+P_i^{pe}) - (P_{i+1}^{sp}+P_{i+1}^{pe})]/q$. $P_i^{sp}\_P_{i+1}^{sp} < 0$ and $P_i^{pe}\_P_{i+1}^{pe} < 0$, so the net bound sheet charges are negative at the interface of each unit cell. Consequently, equivalent holes at the interface of each unit cell are induced from the acceptors (Mg) by the polarization field to neutralize the negative bound sheet charges. These holes spread over the graded AlGaN layer continuously, forming a mobile 3DHG.

The RT hole concentration of the graded AlGaN layer is $2.6\text{x}10^{18}\text{cm}^3$, which is one order of magnitude higher than that of the GaN layer ($2.5\text{x}10^{17}\text{cm}^3$). As the temperature decreases, the hole concentration of the GaN layer drops exponentially, caused by carrier freeze-out due to the high activation energy of Mg in GaN. While for the graded AlGaN layer the hole concentration shows weak temperature dependence, it is as high as $4.5\text{x}10^{17}\text{cm}^3$ when the temperature is down to 100K. This reveals that the holes in the graded AlGaN layer are induced by polarization, because the polarization doping does not need thermal ionization energy to activate. The RT resistivity of the graded AlGaN layer is 0.6Ωcm, lower than that of the GaN layer (1.8Ωcm), indicating enhanced p-type conductivity in the graded AlGaN layer. Besides, as the temperature decreases, the resistivity of the graded AlGaN layer increases more slowly than that of the GaN layer.

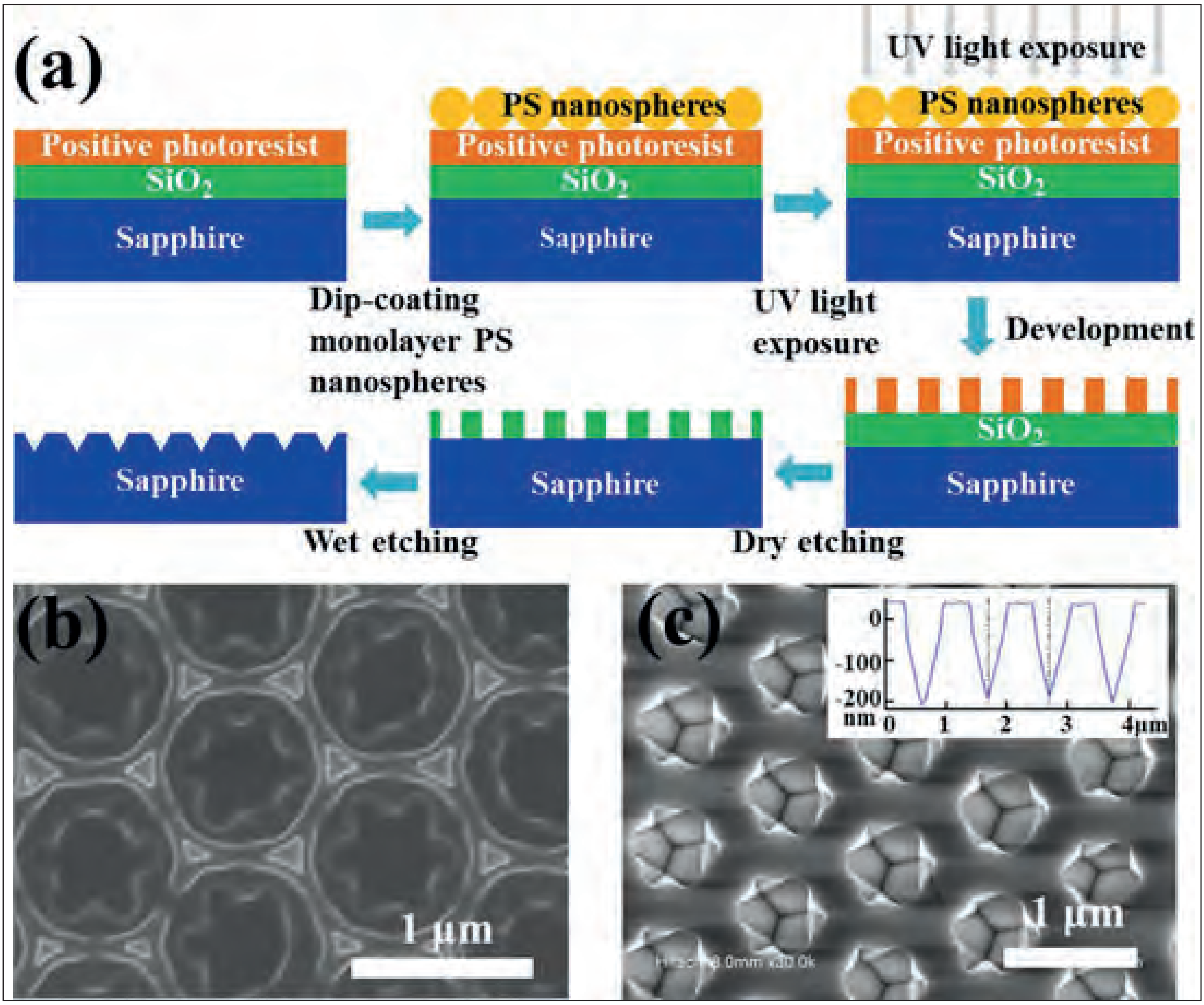

Figure 6. (a) Schematic of fabrication process flow to create nano-patterns on a sapphire substrate (NPSS). SEM images of the patterned photoresist (b) and wet-etched NPSS (c). Inset in Figure 6(c) shows line profile of patterns of NPSS by AFM measurement.

This p-type doping method overcomes the problem of high Mg activation energy in III-nitrides and paves the way for achieving high efficiency in wide-bandgap semiconductor light-emitting devices. The researchers studied the polarization-doped (0001)-oriented GaN-based LEDs by using APSYS software. The calculated results indicate that the electroluminescence (EL) intensity and the internal quantum efficiency (IQE) in the polarization-doped LEDs are enhanced significantly compared with the conventional LED due to the polarization-doped hole as well as the smooth valence band in the graded AlGaN layer, and consequently the enhanced hole injection. On the other hand, the efficiency droop in the polarization-doped LEDs is also improved compared with the conventional LED.

The influence of the degree of AlGaN gradation on polarization-doped LEDs has also been studied by the researchers. Because of the enhanced hole concentration caused by the increased degree of AlGaN gradation, the EL intensity and external quantum efficiency (EQE) of the polarization-doped LED are improved when x_0 is increased from 0.15 to 0.2. However, when x_0 is further increased to 0.25 and 0.3, the EL intensity and EQE are decreased due to the increased alloy scattering in the graded AlGaN and the larger strain in the MQWs, which reduce the hole injection and radiative recombination rate.

(Related publications: L. Zhang, et al. 'Three-dimensional hole gas induced by polarization in (0001)-oriented metal-face III-nitride structure', Applied Physics Letters 97, 062103 (2010); L. Zhang, et al. 'Theoretical study of polarization-doped GaN-based light-emitting diodes', Applied Physics Letters 98, 101110 (2011); L. Zhang, et al., Applied Physics Letters 98, 241111 (2011).)

AlGaN-based efficient DUV-LEDs on nano-patterned sapphire substrate

AlGaN-based UV-LEDs are promising for providing a good solution for SSL with high color rendering. It is also hoped that efficient deep UV LEDs would provide more energy-efficient compact solutions compared with existing fragile and hazardous mercury vapor lamps. Proposed applications of deep UV LEDs include disinfection, sensing, water purification, bio-medical, and communication. Key to achieving these aims is improved material quality.

Researchers at ISCAS have been developing nano-patterned sapphire substrates (NPSS), achieved with nano-sphere lithography (NSL), as a basis for the production of superior aluminium gallium nitride (AlGaN) semiconductor material for deep ultraviolet (UV) light-emitting diodes (LEDs) — see www.semiconductor-today.com/news_items/2013/AUG/LED_050813.html.

Sapphire patterning was achieved by photolithography through a mask consisting of polystyrene nanospheres that were then removed using deionized water (Figure 6). The pattern in the developed photoresist was transferred to an underlying hard mask layer of 200nm silicon dioxide using inductively coupled plasma (ICP) etch. Finally, the sapphire was wet etched using a mix of sulfuric and phosphoric acid solutions. The silicon dioxide was removed using hydrofluoric acid.

The pattern consisted of 230nm-deep concave triangular cones set in a hexagonal pattern of period 900nm. The unetched region between the cones was 400nm wide.

The growth of the UV LED epitaxial structure was through low-pressure metal-organic chemical vapor deposition (LP-MOCVD) with trimethyl-aluminium, trimethyl-gallium, and ammonia precursors, respectively, for the Al, Ga and N species. The structure began with 25nm of low-temperature 550°C AlN, before the whole 4μm AlN template was completed at 1200°C.

The AlN was found to coalesce after only 3μm. This is much sooner than other epitaxial layer overgrowth (ELOG) techniques using micro-stripe patterning that only coalesce after 10μm growth. Atomic force microscopy (AFM) over 5μm x 5μm fields gave a root-mean-square (RMS) roughness of 0.15nm. The AFM analysis also indicated a step-flow growth mode. X-ray analysis gave estimates for screw and edge dislocation densities of $1.6x10^7/cm^2$ and $1.2x10^9/cm^2$, respectively.

This AlN template material was used in further growth of the UV LED structure. The same structure was grown on flat sapphire with a 1μm AlN template layer. The n-AlGaN layer was found to have pure edge and mixed threading dislocation densities on NPSS and FSS substrates of $\sim 1.6x10^9/cm^2$ and $\sim 3.4x10^9/cm^2$, respectively. The reduced-density layer on NPSS was attributed to the higher-quality AlN template.

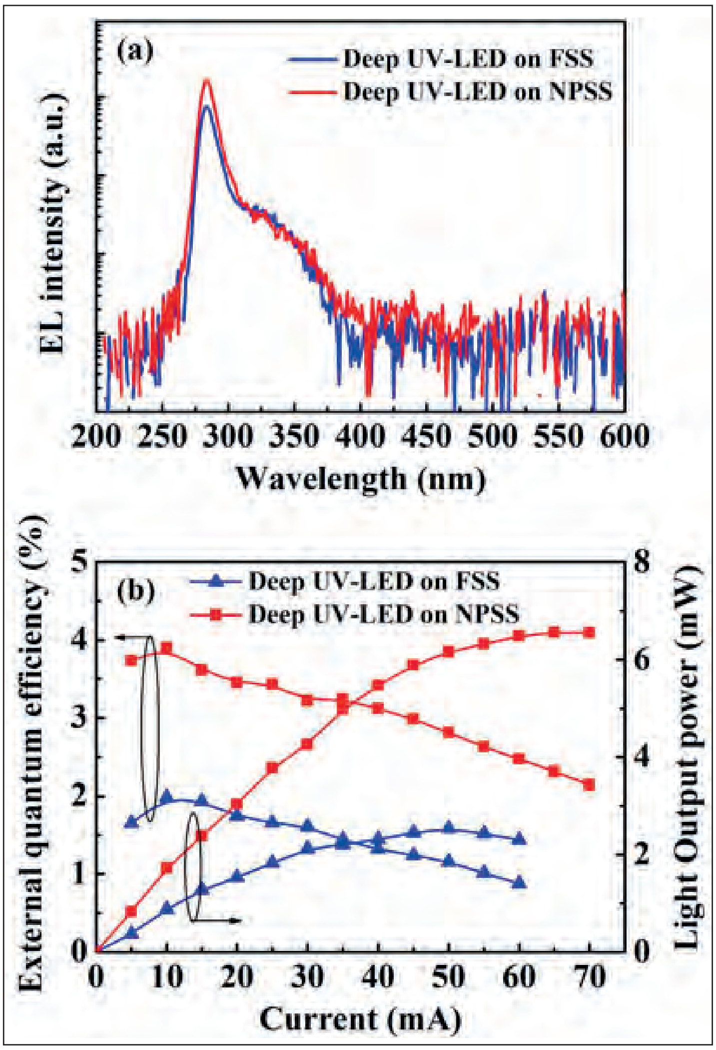

Figure 7. (a) EL spectra and (b) LOP-I-EQE curves of deep UV LEDs grown on NPSS and FSS.

Temperature-dependent photoluminescence studies at 10K and 300K suggested an internal quantum efficiency of 45% for the NPSS LED structure, compared with 28% for the FSS AlN template epitaxy.

The epitaxial materials were formed into 380μm x 380μm devices. The chips were flip-chip-mounted on silicon sub-mounts with gold-bump bonding. The majority of light in deep UV LEDs is expected to emerge through the sapphire substrate, since the p-GaN layer absorbs the radiation due to it having the narrowest bandgap in the structure. Device testing was performed with the sub-mounted chips attached to metal-core circuit boards with silver paste to improve heat dissipation.

The main EL peak occurred at 282nm with a weak shoulder peak near 330nm (Figure 7). It is thought that recombination in the electron-blocking layer was responsible for the shoulder peak. Hence, "further optimization of the electron-blocking layer is needed to suppress electron overflow into the p-cladding layer," the researchers write.

For the NPSS-based device, the light output power (LOP) at a current (I) of 20mA was 3.03mW, with EQE of 3.45%. This was almost double that of the FSS-based LED. The saturation LOP for the NPSS LED was 6.56mW at 60mA current. The FSS device saturated at 2.53mW with 50mA injection.

Since the internal quantum efficiency does not account for all the improvement in performance, the light scattering at the AlN/NPSS interface reduces the total internal reflection and absorption in the p-GaN layer, and increases the photon's escape opportunity from the sapphire backside.

(Related publication: Peng Dong, et al. '282-nm AlGaN-based deep ultraviolet light-emitting diodes with improved performance on nano-patterned sapphire substrates', Applied Physics Letters 102, 241113 (2013).)

Summary

To summarize the above SSL R&D highlights, low-operating-voltage VLEDs, composite optical coatings, polarization-induced p-type doping and NPSS-based UVLEDs, are the epitome of endeavors by ISCAS in III-nitride LEDs. These innovations offer possible solutions for future LEDs targeted at general lighting. In future, SSL is expected to replace conventional lighting applications, such as incandescent and fluorescent lamps. All the research work at ISCAS is carried out with this aim. By combining the novel technologies developed at ISCAS, high-power white LEDs with efficiency above 180lm/W have been achieved. This value is much higher than the efficiency of incandescent and fluorescent lamps.

ISCAS' aim is focused not only on novel lab-level research but also on applying R&D results to the SSL industry. In fact, this has been done through Yangzhou Zhongke Semiconductor Lighting Co and Hunan HuaLei Optoelectronic Corp (two of the main Chinese LEDs companies). Yangzhou Zhongke Semiconductor Lighting Co's LED epitaxy technique came almost entirely from ISCAS on the firm's foundation several years ago, and it now has more than 50 MOCVD systems. For Hunan HuaLei Optoelectronic Corp, ISCAS contributed greatly to the firm's device processing. ISCAS has also performed collaborative research with many other Chinese LED companies, including Xiamen San'an Optoelectronics Co and Foshan Nationstar Optoelectronics Co. Through close collaboration with the firms, ISCAS has transferred its novel techniques to industry. It is now more concerned with LED reliability, lifetime prediction, standards, etc, and is confident in overcoming these issues. ■

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