

InGaN/GaN Nanowire LEDs and Lasers

Chao Zhao¹, Tien Khee Ng¹, Shafat Jahangir², Thomas Frost², Pallab Bhattacharya², and Boon S. Ooi^{1,*}

¹Photonics Laboratory, King Abdullah University of Science and Technology, Thuwal 23955-6900, Saudi Arabia

²Center for Photonics and Multiscale Nanomaterials, Department of Electrical Engineering and Computer Science, University of Michigan, Ann Arbor, Michigan 48109-2122, USA

*Email: boon.ooi@kaust.edu.sa

Abstract—The large specific surface, and the associated high density of surface states was found to limit the light output power and quantum efficiency of nanowire-array devices, despite their potential for addressing the “green-gap” and efficiency-droop issues. The phonon and carrier confinement in nanowires also led to junction heating, and reduced heat dissipation. In this paper, we will present our studies on effective surface states passivation in InGaN/GaN quantum-disks (*Qdisks*)-in-nanowire light-emitting diodes (LEDs) and lasers grown on silicon (Si), as well as our recent work on nanowires LEDs grown on bulk-metal, a non-conventional substrate.

Index Terms—InGaN/GaN quantum-disks-in-nanowire, light-emitting diodes, laser, Molecular Beam Epitaxy

I. INTRODUCTION

Group-III nitride based materials have been intensively studied for solid-state lighting and display applications. However, the performance of LEDs suffers from the lack of native substrates, high dislocation density, the existence of polarization fields, the related quantum-confined Stark effect (QCSE), and efficiency droop, *etc.* [1, 2].

Defect-free group-III nitride nanowires on silicon substrates, and green and red nanowire light-emitting diodes (NW-LEDs) have been developed in recent years, which demonstrated the potential of nanowires emitters for practical applications, beyond basic research. Compared to the planar LEDs, NW-LEDs were found to have reduced efficiency droop, reduced piezoelectric polarization field, and light extraction enhancement [3], which make them highly attractive visible light emitters. Yong-Ho Ra *et al.* reported coaxial InGaN/GaN quantum-well structures on n-GaN core NW-LEDs without polarization [3]. Zetian Mi *et al.* demonstrated NW-LEDs with high internal quantum efficiency and nearly zero efficiency droop [4]. Moreover, InGaN/GaN NW-LEDs emitting at long wavelength and white light were also demonstrated [5, 6]. For nanowire lasers, Chennupati Jagadish *et al.* reported lasing in optically pumped single nanowires made of GaAs and InP [7, 8], electrically-injected ultraviolet random lasing in AlGaIn nanowires on Si has recently been demonstrated by Zetian Mi *et al.* [9]. Besides NW-LEDs, Pallab Bhattacharya *et al.* have demonstrated electrically pumped edge-emitting, green, red and near-infrared lasers using InGaN/GaN *Qdisks* in nanowires on silicon substrates. Previous integration of lasers and Si was achieved through wafer bonding [10], and growth of epitaxy on Si using buffer layers [11]. The nanowire lasers on Si we reported have performance surpassing or comparable to those of devices grown on GaN, which can address various applications such as displays, solid state lighting, and silicon photonics [12-14].

Despite the achievement of high-quality nanowires and demonstration of nanowire devices, the high density of surface

states was found to limit the output power and quantum efficiency of nanowire devices. It is noted that ammonium sulphide $(\text{NH}_4)_2\text{S}_x$ has been commonly used for the surface passivation of III-V semiconductors. Organic sulfides, such as octadecylthiol (ODT), were used in passivating InAs materials [15]. Nevertheless, systematic studies of the passivation mechanism and the comparison of chemicals used for passivation of nitride nanowires and devices are required. Moreover, phonon and carrier confinement in these laterally discontinuous nanostructures led to reduced heat dissipation and increased junction heating. This requires further exploration into unconventional substrates.

In this paper, we will present our work on approach in surface states passivation in InGaN/GaN *Qdisks* in nanowire LEDs, as well as enhancing heat dissipation by growing high-quality nanowires on bulk-metal substrates.

II. EXPERIMENTAL DETAILS

The nanowires were prepared using *Veeco* plasma assisted molecular beam epitaxy (PAMBE) [6]. The NW-LEDs structures on Si have ~ 300 nm n-type GaN ($n \sim 4 \times 10^{18} \text{ cm}^{-3}$), 8 stacks of InGaN/GaN *Qdisks* and ~ 150 nm p-type GaN ($p \sim 7 \times 10^{17} \text{ cm}^{-3}$) grown at 750°C . To study the surface passivation of NW-LEDs on Si, a sample was soaked in ODT solution for passivation before the LED fabrication. As for the *Qdisks*-in-nanowire LEDs on polycrystalline-molybdenum (Mo) substrate, the structure consists of ~ 150 nm n-type GaN grown at 660°C , 8 stacks of InGaN-disks (~ 3 nm)/GaN-barrier (~ 12 nm) grown at 480°C with both Ga and In fluxes of 3×10^{-8} Torr. The p-GaN (~ 50 nm) was grown at substrate temperature of 570°C , with Ga flux of 3.9×10^{-8} Torr and Mg cell at 350°C . Detailed NW-LEDs fabrication process can be found in our previous report [16].

III. RESULTS AND DISCUSSION

A. Enhanced surface passivation in nanowire LEDs for mitigating Shockley-Read-Hall (SRH) recombination

We treated the nanowires with ammonium sulfide to reduce the p-contact resistance of GaN:Mg in the nanowire laser fabrication process [6], and further developed organic sulfide passivation process for LEDs. The passivation process results in the alteration of the surface dynamic charge, and recovered the band-edge emission, leading to a $\sim 4\text{X}$ increase in photoluminescence peak intensity, faster increasing trend in quantum efficiency and 50% increase in relative peak external-quantum-efficiency in these LEDs [17]. The is due to the reduction in SRH non-radiative recombination, a mono-molecular non-radiative recombination on the nanowires

surface, confirmed using a novel 4D scanning ultrafast electron microscopy technique [18].

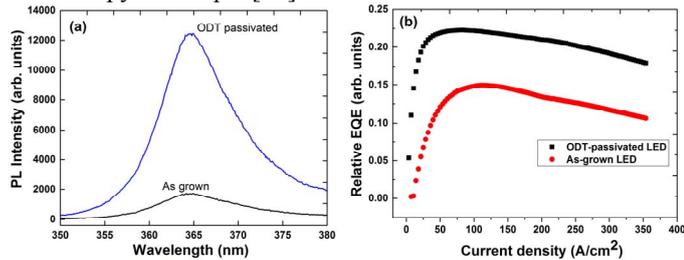


Fig. 1. (a) Room temperature GaN PL spectra of the sample without and with passivation; (b) the relative EQE of NW-LEDs without and with passivation.

B. High-quality InGaN/GaN Qdisks-in-nanowires on Bulk-Metal Substrates for High-power Light-emitters

Current planar LEDs have to be transferred to a heat sink via wafer bonding or laser liftoff. In addition, nanowire LEDs on Si suffers from the formation of SiN layer during growth, and significant light absorption from Si. We developed the first high-power red InGaN/GaN Qdisks-in-nanowire LEDs on Mo, which simultaneously implements buffer layer, n-metal contact, reflector and heat-sink, thus greatly simplifies the fabrication process [16]. The LEDs exhibited a low turn-on voltage of ~ 2 V without efficiency droop up to 1.6 kA/cm^2 . The light output power of 1.76 mW is higher than other reports on long wavelength (705 nm) LEDs, thus is promising for high-power device operation.

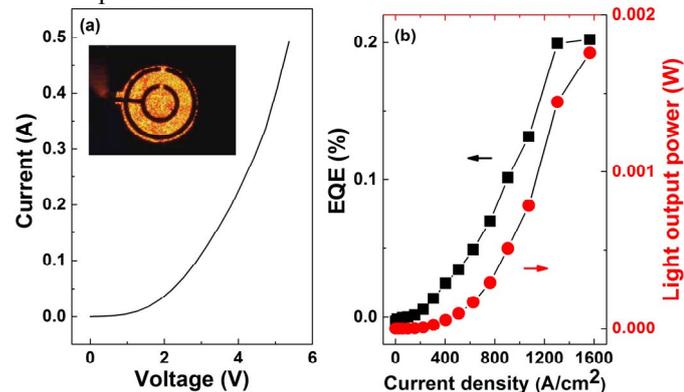


Fig. 2. (a) The measured I-V characteristics of a 200- μm diameter LED; the inset shows the optical microscope image of the NW-LED; (b) the EQE and L-I characteristics of the NW-LED.

IV. CONCLUSIONS

In conclusion, we demonstrated an effective chemical passivation treatment on nitride nanowires, leading to the reduction of SRH non-radiative recombination. We also reported the first nanowires growth process on metal substrates. The InGaN/GaN Qdisks-in-nanowires grown on Mo exhibited high crystal quality, and the fabricated device shows considerably low turn-on voltage of 2V, achieves high-power, and emits at peak wavelength of 705 nm. The InGaN/GaN nanowire lasers emitting at green-to-infrared wavelength range on Si were also demonstrated.

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