III-Nitride Nanowire LEDs for Enhanced Light Technology

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Abstract – Epitaxially grown GaN-based nanowire heterostructure arrays on (111) sapphire substrates have special characteristics and the ability to create practical devices. InGaN disks are often used as the active light-emitting device in nanowire heterostructures. By adjusting the composition of indium, the emission wavelength can be modified. In this paper, we have addressed the development of nanowire light-emitting diode for better performance in the light industry. We have designed green and yellow InGaN/AlGaN nanowire LEDs that exhibit remarkable efficiency using quantum dots grown on sapphire (111) substrate. The substrate temperature and the width of InGaN/GaN layers are the two growth parameters modified to impact the peak emission wavelengths. When compared to the results recorded at 5K, the devices exhibit comparatively higher (>40%) internal quantum efficiency at ambient temperature. A minimal blue-shift in the peak emission spectra with no efficiency droop is also observed when injection current is pushed up to 710 A/cm^2.

I. Introduction

The development of light emitting diodes (LEDs) with excellent efficiency and great brightness was made possible in recent years because of the group III-nitride materials [1]–[6]. LEDs have many advantages over conventional light sources due to their low power consumption, small size, and lengthy lifespan [7]. Because of their broad range of tuneable bandwidths, III-nitrides have a wide variety of uses including lighting, displays, sensing, recording data at a very high density, UV curing, document authentication, light therapy, different healthcare, and medicinal uses, and many more [7]. With energies ranging from 0.7 eV (InN), 3.4 eV (GaN) to 6.2 eV (AlN) III-nitrides and their alloys are particularly well suited for visible and ultraviolet LEDs [8]. GaN and its alloy-based blue light emitting diodes are the most well-known example and they have completely changed modern light technology [9]. Nitride semiconductors are the best materials for realizing optical devices in the UV, visible and infrared (IR) regime. Additionally, Group-V elements are the smallest and most electronegative elements with metal-N bond that have far higher iconicity than other III-V bonds [9].

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The paper is organized as follows: the details of III-nitride nanowire LEDs are presented in Section II. The device structure and simulation model framework are discussed in Section III followed by results and discussion in Section IV. Finally, the conclusion is drawn in Section V.

II. III-Nitride Nanowire LEDs

A potential substitute for the planar counterparts has emerged in the form of InGaN nanowire structures which exhibit a number of advanced features. In order to create visible LEDs and lasers, an imminent nanostructured technology called III-nitride based nanowires and quantum-confined heterostructures has evolved. Due to the efficient strain relaxation, the nanowires exhibit almost free dislocations and reduced piezoelectric polarization [10, 11]. Additionally, the InGaN nanowires have shown excellent heat dissipation [12], high light extraction efficiency [13], and superior p-type doping [14]. As a result, InGaN nanowire white LEDs with excellent efficiency are possible [15]. In contrast, because of the high surface-area-to-volume ratio, surface states like dangling bonds [16] and fermi-level pinning on the nanowire surface [17,18] significantly contribute to high surface non-radiative recombination [19,20], which eventually lowers the performance of the AlGaN nanowire UV LEDs [21]. White LEDs devoid of phosphorus have undergone extensive research and are highlighted as a potential platform for the upcoming solid-state applications. However, it is vitally crucial to produce highly effective LEDs with emission wavelengths in the deep green to yellow spectral region [22, 23]. Due to the high dislocation densities and polarization field present in the standard InGaN/GaN quantum well (QW) heterostructures, creating such devices has been proven challenging [24]. The Auger recombination [25], poor hole transport [26, 27], and carrier decentralization [28] in the InGaN/GaN heterostructures have all been used to explain their efficiency droop. This explains why InGaN-based nanowire heterostructures have been extensively studied; they offer a platform that has almost negligible defect, strain, and polarization for the development of nanoscale electronics [29-32]. Using InGaN/GaN nanowire heterostructures, tuneable emission has also been reported [33-35]. High efficiency nanowire LEDs, however, have remained unattainable despite such advances in the technological field. III-nitride nanowires can be produced either using the bottom up or the top down technique. Nanoscale designs are frequently used in conjunction with an etching procedure while using the top-down technique [36–40]. Additionally, post-etching annealing and/or wet chemical treatment have frequently been employed to reduce and/or cure surface flaws and damages [41-46]. However, a significant portion of current research on III-nitride nanowires is based on the bottom-up approach. A greater degree of freedom in manipulating device topologies is provided by the bottom-up approach. When using the bottom-up technique, the active layer of the electronic components can be positioned either on the sidewalls of nanowires or along the path of nanowire growth, resulting in radial or axial devices, respectively. The bottom-up category has seen the development of a variety of synthesis methods, including chemical vapor deposition (CVD), metal organic chemical vapor deposition (MOCVD), molecular beam epitaxy (MBE), and chemical beam epitaxy (CBE). The underlying mechanisms can be best represented by either the vapor-liquid-solid (VLS) or diffusion-driven development process, despite the fact that these methodologies differ from one another. As of present, a lot of the III-nitride nanowires produced by MBE spontaneously develop in nitrogen-rich environments. Despite the fact that the growth mechanism is still not completely understood, it is typically thought of as a diffusion-driven mechanism. The adatoms that impact on the substrate surface disperse and migrate along the sidewall of the nanowire, encouraging vertical growth, because of the anisotropy of surface attributes, such as chemical capacity and sticking coefficient. This growth model is confirmed by the data that thinner nanowires develop more slowly as substrate temperature rises and that greater nanowire vertical rate of development (along the upward axis) are seen [47,48].

The substrate was crucial to the functioning as well as that of electrical and optical characteristics of III-nitride nanowire LEDs because of the high surface-to-volume ratios [49, 50]. Fermi-level pinning had been theoretically predicted and empirically seen on the (111) plane [51, 52], which justified the lateral surfaces GaN nanowire LEDs, depending on the energy levels of the substrate states and the surface stoichiometry. The surface non-radiative recombination that resulted and the lateral electric field that followed have a severe negative impact on the performance of GaN-nanowire LEDs.

In this context we have recently created InGaN/AlGaN nanowire heterostructures using quantum dots, which can offer improved carrier confinement and carrier injection, thus resulting in high emission efficiency [53]. In this article, we have concentrated on creating high-efficiency green and yellow LEDs for their utilization in high-power light technologies. The altering of sizes and/or compositions of the indium allows us to vary the emission wavelengths from green to yellow spectral range. Additionally, with GaN-nanowire yellow LEDs, significant internal quantum efficiency (IQE>40%) has been observed for higher temperatures. For injection currents that exceeded 710 A/cm^2 at room temperature, no efficiency droop is recorded.

III. Device Structure and Simulation Model

In this work, the commercially available Silvaco TCAD tool is utilized to examine the effects of InGaN interlayer with varied indium composition on the efficiency enhancement of the LED. To study the impact of substrate temperature and width of the nanowire layers, the n-type GaN layer is grown on sapphire (111) substrate. This layer is then followed by dot-in-a-wire heterostructure region comprising of four periods of quantum wells (InGaN of 4 nm and 20% indium composition) and barriers (AlGaN with thickness of 9 nm) as depicted in Fig. 1. On top of this layer, p-type GaN is grown. Silicon (Si) and magnesium (Mg), respectively, are used to dope n- and p-type GaN regions. Four InGaN dots have been vertically aligned and spaced 3 nm apart by AlGaN barrier layers to form the device's active region. To improve the integration of Indium, the InGaN/AlGaN quantum dot heterostructure are produced at comparatively low temperatures (450-500 ºC). For characterization, LED devices with an overall area of 250×250 μm^2 have been used in our simulation model.

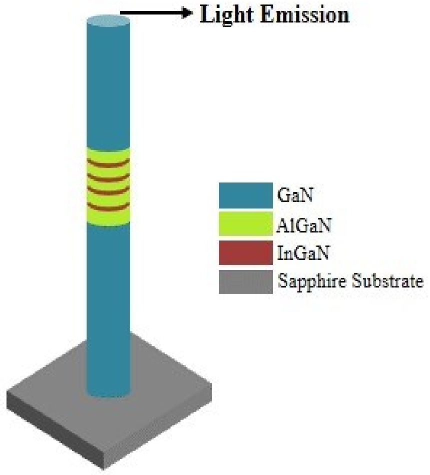


Fig. 1. Schematic diagram of InGaN/AlGaN dot-in-a-wire LED nanowire.

A 6×6 k.p model is used to estimate the energy band diagrams of the LED structures. InGaN and AlGaN bending parameters are set at 1.18 eV and 0.94 eV, respectively, and the band offset value of the III-nitride materials used in this study is 0.67/0.33. The SRH recombination lifespan, radiative, Auger recombination coefficient, and light extraction efficiency are all adjusted to 10 ns, 2.42×10^{-11} cm^3/s, 3.01×10^{-30} cm^6/s, and 12%. The polarization charges owing to both spontaneous and piezoelectric polarization effects are evaluated using Fiorentini *et al.* approach, and only 60% of the estimated value is considered in our model.

TABLE I

MATERIAL PARAMETERS USED IN THE SIMULATION MODEL OF THE NANOWIRE LEDS

Parameters	Symbol (Unit)	GaN	AlN
Lattice constant at 300 K	a_0 (A^0)	3.189	3.112
Lattice constant at 300 K	c_0 (A^0)	5.185	4.982
Crystal-filed split energy	Δ_{cr} (meV)	10	-169
Spin-Orbit split energy	Δ_{so} (meV)	17	19
Electron effective mass (*c*-axis)	m_e^c/m_0	0.2	0.32
Electron effective mass (transverse)	m_e^t/m_0	0.2	0.28
Hole effective mass	A_1	-7.21	-3.86
	A_2	-0.44	-0.25
	A_3	6.68	3.58
	A_4	-3.46	-1.32
	A_5	-3.40	-1.47
	A_6	-4.90	-3.40
Elastic stiffness constant	C_{11} (Gpa)	390	396
	C_{12} (Gpa)	145	137
	C_{13} (Gpa)	106	108
	C_{33} (Gpa)	398	373
	C_{44} (Gpa)	105	116
Mg-activation energy	(meV)	170	510
Piezo-electric constants	e_{33} (C/m^2)	0.73	1.46
	e_{31} (C/m^2)	-0.49	-0.60
Si-activation energy	(meV)	15	250
Hydrostatic deformation potential (*c*-axis)	a_z (eV)	-4.9	-3.4
Hydrostatic deformation potential (transverse)	a_t (eV)	-11.3	-11.8

IV. RESULTS AND DISCUSSION

To reduce the influence of junction heating, performance parameters of the dot-in-a-wire LEDs have been tested under pulsed bias circumstances with 1% duty cycle. The InGaN/AlGaN LED emits strong green and yellow emissions when operated at room temperature (Fig. 2). In Fig. 2(a) and (b), the electroluminescence (EL) spectra of the green and yellow nanowire LEDs are displayed, respectively with the injection current ranging from 50 mA to 350 mA. For green and yellow LED structures the peak emission wavelengths are 525 nm and 575 nm at injection current of 350 mA respectively.

Additionally, it should be noted that for the green and yellow emitting devices the spectral line-widths grow gradually with emission wavelengths starting at 65 nm and 115 nm respectively. This is a direct result of the improved In phase separation with rising In compositions, which causes In-rich nanoclusters to develop both the barrier layers and the dots. The compositions, dot sizes, and nanowire diameter all influence the emission characteristics of the nanowire LED. Strong emission at long wavelengths in the green to yellow region have been made possible due to the effective application of a core-shell nanowire heterostructure with integrated quantum dots. Maximum wavelengths of both green and yellow-emitting LEDs as shown in Fig. 2(a) and (b) are almost invariant with increasing current, pointing to the presence of a minor quantum-confined Stark effect [33, 54].

Further research has been done on the current-voltage (I-V) and light-current (L-I) properties of green and yellow LEDs at room temperature. In yellow LED (as shown in Fig. 3(a)) minimizing the defect density, polarization field, and the internal electric field create quantum-confined stark effect which also lead to excellent diode performances with extremely low leakage current of 0.5 mA at 4 V. The green LED also shows a minimal leakage current of 0.9 mA at 4 V (Fig. 3(a)). We have also verified that at room temperature the green and yellow dot-in-a-wire LEDs almost completely lack efficiency droop. The output power has risen linearly with current over the whole observational range (up to 710 A/cm^2), as shown in Fig. 3(b). According to the research, Auger recombination have been greatly decreased in InGaN/GaN nanowire heterostructures because of the lower defect density [37]. The application of the p-type modulating dopants in the device active region [35] and use of a self-distributed AlGaN multi-shell electron blocking layer [55, 56] has helped to reduce the issue of hole transportation. Finally, by contrasting the integrated electroluminescence intensity obtained at 300 K to that observed at 5 K under the same injection current, we have examined the IQE of the dot-in-a-wire LED. The IQE for the green and yellow-emitting LEDs, as shown in Fig. 3(c), has increased with input current and reached maximum values of 31.5% and 37.3% respectively at about 350 mA (about 383 A/cm^2). This indicate a minor or negligible efficiency droop over the relatively large current injection settings. By varying the substrate temperature of the nanowire devices from 280-360 K, the output parameters of the yellow nanowire LED are plotted in Figs. 4(a) and (b).

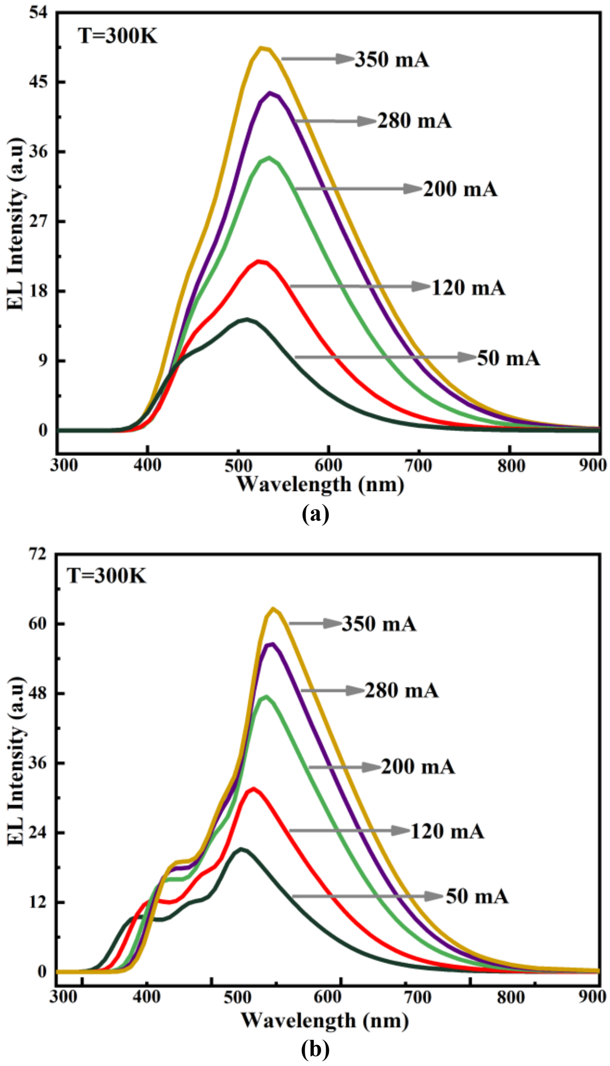


Fig. 2 The EL spectra under different currents for (a) green and (b) yellow nanowire LEDs at absolute room temperature.

In contrast to typical InGaN/GaN thin-film LEDs, which typically operate at 15-25 A/cm^2, the peak IQE is determined with a substantial injection current (383 A/cm^2). The nanowire LEDs have frequently reported a very slowly increasing IQE trend [57, 58], which is ascribed to the huge surface states and imperfections.

The strong carrier confinement offered by quantum dot heterostructures, the improved carrier injection, the decreased electron overflow, and other higher order effects on the device quantum efficiency are credited for the lower efficiency droop [59, 60]. The unique dot-in-a-wire heterostructure exhibit significantly higher IQE in comparison to the previously described InGaN/GaN nanowires [61-63] in the identical wavelength spectrum. This has been attributed to the higher effective carrier confinement along the radial direction of the wire, which has reduced the non-radiative carrier recombination on the lateral surfaces. Additionally, the significantly increased carrier confinement has decreased the non-radiative recombination brought on by the presence of surface states and improved carrier infusion to the device's active area. All these reasons are responsible for the significantly improved IQEs as observed in the dot-in-a-wire LED.

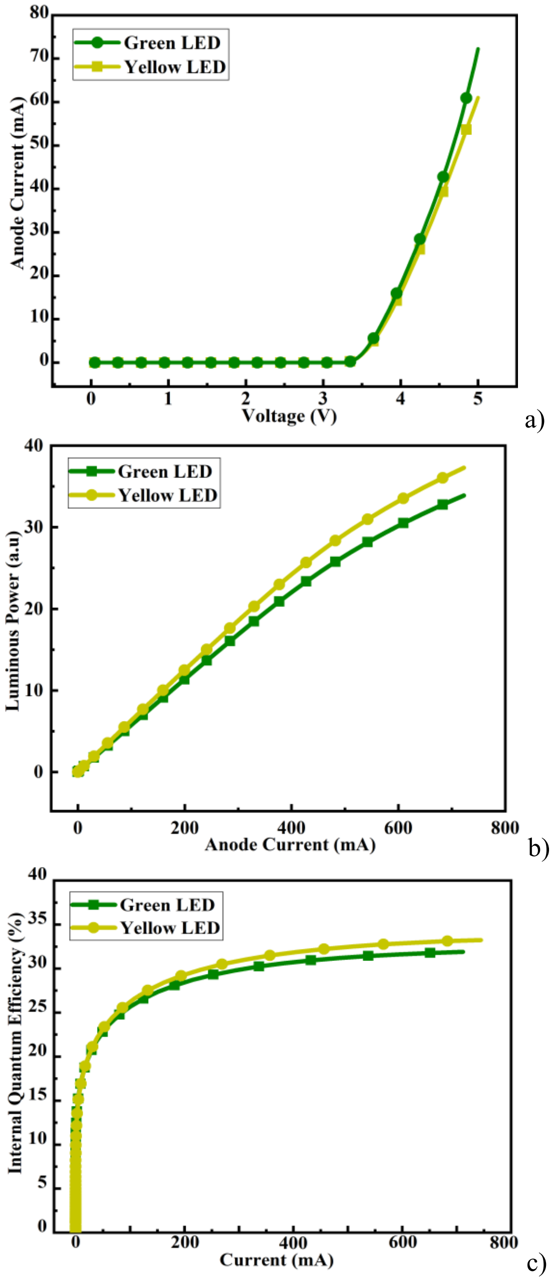
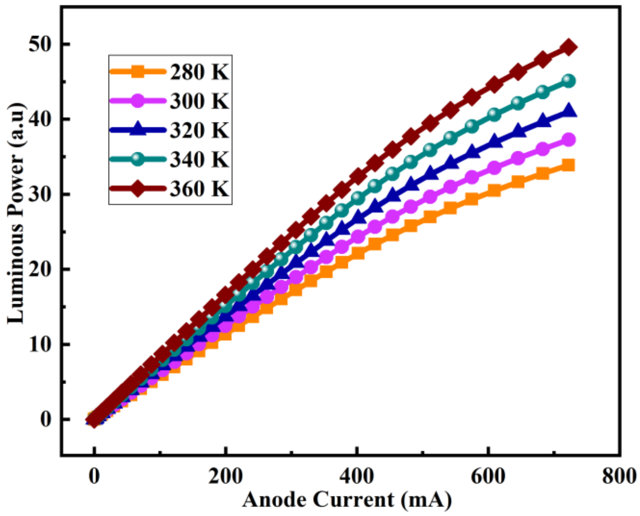
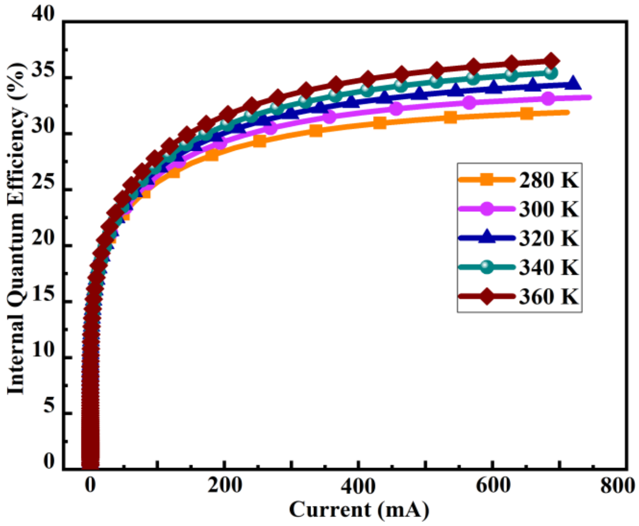


Fig. 3. (a) The I-V characteristic of green and yellow nanowire LEDs at room temperature, (b) The L-I characteristics of green and yellow nanowire LEDs under different injection currents at room temperature, (c) The internal quantum efficiency of green and yellow nanowire LEDs vs different current levels at room temperature.



a)



b)

Fig. 4. (a) The Internal quantum efficiency of typical yellow nanowire LED with varying temperature from 280-360 K, (b) The Luminous power of typical yellow nanowire LED with varying temperature from 280-360 K.

The performance of such nanowire LEDs can be further optimized for more effective light extraction efficiency in the practical lighting applications. As contrast to the small diameter wires, nanowire LED with larger diameters has improved carrier injection efficiency because of the minimized surface non-radiative recombination rate. Large dislocation density in the nanowire structures, however, can cause large diameter nanowires to acquire lower quantum efficiency.

V. Conclusion

In conclusion, we have shown that III-nitride nanowire LEDs can display relatively higher internal quantum efficiency and contribute tremendously in the advanced light industry. Precisely GaN-based nanowire has shown remarkable performance in the deep green to yellow wavelength region when electrical input is applied to the self-organized InGaN/AlGaN dot-in-a-wire heterostructure. Additionally, at relatively high injection circumstances (up to 383 A/cm^2), the devices exhibit highly steady emission characteristics with increasing current and essentially no efficiency droop. These findings mark a significant advancement for future solid-state lighting applications which results in LEDs of low price, great efficiency, and compact size. Such nanowire LEDs are ideal for high speed device in visible light communications as well as flexible wearable electronics.

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