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Optimization of GaN Nanorod Growth Conditions for Coalescence Overgrowth

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14. ABSTRACT
The growth and fabrication of GaN nanorod (NR) light-emitting diode (LED) arrays have attracted much attention because of their advantages of higher crystal quality, larger sidewall emission area, and non-polar or semi-polar quantum well (QW) formation. This report describes development of regularly-patterned GaN NR LED arrays grown on a patterned template with either continuous or pulsed growth mode using metal-organic vapor-phase epitaxy (MOVPE). Such an array device is expected to be useful for practical lighting application. Usually, with the pulsed growth mode, by switching group-III and V sources on and off alternatively, the NR geometry can be more uniform over an array. InGaN/GaN QWs can be deposited on the c-plane top face, m-plane sidewalls, and {1-101}-plane slant facets on a c-axis-oriented NR with the highest (lowest) growth rate in the c-plane ({1-101}-plane). After the overgrowth of p-GaN on an NR with n-GaN core and QW deposition, an NR LED array can be implemented by covering the NRs with a transparent conductor. It has been demonstrated that the optical and electrical performances of an NR LED array can be comparable to those of a planar LED. Further developments in NR LED growth and process techniques can lead to an outperforming LED device with the NR structure.

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Abstract:
The growth and fabrication of GaN nanorod (NR) light-emitting diode (LED) arrays have attracted much attention because of their advantages of higher crystal quality, larger sidewall emission area, and non-polar or semi-polar quantum well (QW) formation. In this report, we describe the development of regularly-patterned GaN NR LED arrays grown with metalorganic vapor-phase epitaxy. Such an array device is expected to be useful for practical lighting application. A regularly-patterned NR array is grown on a patterned template with either continuous or pulsed growth mode. Usually, with the pulsed growth mode, by switching group-III and V sources on and off alternatively, the NR geometry can be more uniform over an array. InGaN/GaN QWs can be deposited on the *c*-plane top face, *m*-plane sidewalls, and {1-101}-plane slant facets on a *c*-axis-oriented NR with the highest (lowest) growth rate in the *c*-plane ({1-101}-plane). After the overgrowth of p-GaN on an NR with n-GaN core and QW deposition, an NR LED array can be implemented by covering the NRs with a transparent conductor. It has been demonstrated that the optical and electrical performances of an NR LED array can be comparable to those of a planar LED. Further developments in NR LED growth and process techniques can lead to an outperforming LED device with the NR structure.

Introduction

A semiconductor nanorod (NR) perpendicularly extending from a template surface forms a three-dimensional (3-D) structure for providing us with larger device varieties in the applications to light-emitting diode (LED), solar cell, photodetector, sensor, etc. For LED application, GaN NRs have been widely grown for gaining the following advantages. First, with a GaN NR grown from a randomly formed nucleation center or a designated seed area of a couple hundred nm in size, a threading-dislocation-free NR structure can be obtained [1]. In other words, GaN NRs of high crystal quality can be grown on a template of low crystal quality or a high dislocation density. When an overgrowth process is applied onto an NR array, the crystal quality of the coalesced GaN layer can be significantly higher than that of the GaN template used for NR growth [1-3]. Therefore, an NR array can be used for converting a GaN layer of low crystal quality into another layer of high crystal quality. Second, InGaN/GaN quantum wells (QWs) can be grown on the sidewalls of such a NR structure to increase the emission area. When the NR height is large enough in an NR array, the total sidewall area can be larger than the basal planar area for enhancing the overall emission area of an LED device. Therefore, an NR array has the potential for fabricating a high power LED device. Third, on a *c*-axis-oriented GaN NR, QWs can be grown on the non-polar, *m*-plane sidewalls and the semi-polar, {1-101}-plane slant facets. In the QWs grown on a non-polar or semi-polar plane, the quantum-confined Stark effect (QCSE) can be eliminated or reduced. With the QCSE minimized, the QW potential tilt is reduced leading to a larger overlap integral between the electron and hole wave functions and hence higher emission efficiency. Also, the blue-shift behavior of the emission spectrum of such an LED in increasing injection current due to the screening of the QCSE can be weakened [4, 5]. Therefore, a GaN NR array provides us with a platform for developing non-polar and semi-polar LEDs. The crystal quality and emission efficiency of a non-polar or semi-polar LED with a planar structure are still not as high as those of a planar, polar LED on the c-plane, unless expensive freestanding *m*- or *r*-plane GaN substrate is used [6-8]. The growth of sidewall QWs on a *c*-axis-oriented GaN NR can be a less expensive approach for achieving a high-quality non-polar LED device.

GaN NRs have been widely grown with the molecular beam epitaxy (MBE) and metalorganic vapor-phase epitaxy (MOVPE) techniques. With either growth technique, randomly-distributed and regularly-patterned GaN NR arrays have been formed. Randomly-distributed NRs are formed based on the self-organized GaN nucleation centers on a substrate. The regularly-patterned growth of GaN is based on the selective growth behavior of GaN at the designated regions on a patterned template. Although NRs on *a*-plane substrate or template have been demonstrated [9-11], most efforts were made on the growth of *c*-axis-oriented GaN NRs. With MBE growth, InGaN/GaN QWs are usually grown along the NR axis, i.e., the formation of disk-like QWs in an NR. Although the growth of disk-like QWs in an NR was reported, the growth of sidewall QWs is more attractive with MOVPE. So far, sidewall QW growth with MBE is still quite difficult. In the effort of LED device fabrication, both NR-array and single-NR devices have been reported. In literature, numerous publications can be found demonstrating the growths of randomly-distributed [e.g., 12-17] and regularly-patterned [e.g., 18-22] GaN NRs with or without QW structure based on the MBE technique. Also, quite many journal publications can be found on the growth of randomly-distributed GaN NRs with or without QW structure based on the MOVPE technique [e.g., 23-30]. From the viewpoint of practical solid state lighting application, the growth of regularly-patterned GaN NR array with sidewall QWs based on the MOVPE technique is more attractive because such a structure provides us with the advantage of a uniform NR distribution for controllable emission and electrical behaviors, when compared with a randomly-distributed NR structure.

In this report, different growth techniques, including the continuous and pulsed growth modes, and their advantages and disadvantages will be discussed. Then, the growth method and results of the NR LED arrays of this research team are demonstrated with scanning electron microscopy (SEM) and transmission electron microscopy (TEM) images. The fabrication and performance of an LED device based on such a regularly-patterned NR array are discussed.

Experiment 1: Techniques for growing regularly-patterned GaN NR arrays

For the growth of a regularly-patterned GaN NR array, a patterned template needs to be prepared first. The patterning methods include electron-beam and focused ion-beam writings, holography, and nano-imprint lithography. For mass production, nano-imprint lithography is becoming the most widely used technique. Regularly-patterned GaN arrays can be grown with either continuous or pulsed growth mode. In the continuous growth mode, both group-III (normally TMGa) and V (usually NH_3) sources are supplied continuously with H_2/N_2 mixed carrier gas and a small V-III ratio [31-40]. In the pulsed growth mode, the supply of either group-III or V source is switched on and off alternatively [1, 2, 41-52]. In a modified pulsed growth mode, only the supply of group-V source is modulated while the supply of group-III source is continuous [53]. The major advantage of using the continuous growth mode is the higher growth rate. However, with the continuous growth mode, normally the NR uniformity in an array is relatively poorer unless the NR cross-sectional size is increased to the micron scale. On the contrary, the NR geometry in an array can be more uniform based on the pulsed growth mode. In particular, the control of the NR geometry can be more flexible when the pulsed growth mode is used. Most GaN NRs were grown with Ga polarity. All the reported GaN NR arrays grown with the pulsed mode so far are Ga-polar. However, it has been demonstrated that with N polarity based on the continuous growth mode, the NR geometry in an array can be more uniform [31-35, 37-39, 40]. In growing n-GaN NRs for eventually forming an LED structure, it has been found that a higher silane flow rate or Si-doping concentration can help in increasing the along-axis growth rate of an NR. This behavior was attributed to the formation of a thin SiN_x layer on the sidewalls of an n-GaN NR [28]. This SiN_x layer hinders lateral growth and hence increases the along-axis growth rate. However, it also makes the growth of a sidewall QW difficult. Therefore, when a high silane flow rate is used in growing n-GaN NRs, a process of buffered oxide etching for removing this SiN_x layer on the sidewalls is required before sidewall QW deposition. Nevertheless, the etching duration needs to be well controlled; otherwise, the SiO_2 or SiN_x growth mask on the template can also be removed, leading to current leakage when an NR LED array is fabricated.

InGaN/GaN QWs are usually deposited on a GaN NR with the ordinary 2-D growth mode, i.e., the growth condition the same as that for forming a planar QW structure. Depending on the growth condition of a GaN NR, three crystal planes can be exposed for QW deposition, including the top-face *c*-plane, the sidewall *m*-plane, and the slant-facet {1-101}-plane (or named *r*-plane). Among the three planes, the nitride deposition rate on the *c*-plane is the highest, followed by the *m*-plane and then the {1-101}-plane. In a *c*-axis-oriented NR, when a flat top-face is formed, *c*-plane QWs can be easily deposited [44-47, 50, 52, 54]. Meanwhile, QWs on the sidewall *m*-plane can usually be formed. Therefore, it is not difficult to grow a core-shell structure with the InGaN/GaN QW shell on the n-GaN core [34, 36, 44-48, 50, 52, 54, 55]. Although the growth rate is low, InGaN/GaN QWs on the {1-101}-plane have been observed [34, 50, 52]. Regarding the emission wavelength of the formed QWs on an NR, although the disk-like QWs grown with MBE can emit light in the green-red range, the emission spectra of the QWs on the *m*-plane sidewall and {1-101}-plane slant facet of an NR array grown with MOVPE are usually limited to the blue-green range. When NR height is large, the QW geometry and indium content can vary significantly with height on a sidewall, leading to an emission-spectrum variation along the sidewall height [44]. The deposition of sidewall QWs relies on two supply channels of the constituent atoms, including those directly from the top in the projected planar region around an NR and those migrating from the NR bottom along the sidewall surface after fallen to the bottom in the gap regions [44, 45]. The upward migration kinetics depends on the chamber temperature during growth. A higher chamber temperature results in more deposition at a larger height on a sidewall. Usually, a sidewall QW portion near the NR top has larger well and barrier widths and higher indium content, leading to a longer-wavelength emission, when compared with a QW portion near the NR bottom. The uniformities of QW geometry and indium content along the height on a sidewall can be improved when the NR separation or pattern pitch is increased. In this situation, the overall indium content of the sidewall QWs is expected to be enhanced and their emission wavelength can be elongated.

Experiment 2: Growth of NR LED arrays based on a pulsed growth technique

For forming a patterned template, we can first deposit a SiO_2 layer of a few tens nm in thickness on a GaN template to serve as the mask of selective growth. After nano-imprint lithography and a reactive ion etching process, a 2-D circular-hole pattern is formed on the GaN template. In Fig. 1(a), we show the plan-view SEM image of a typical n-GaN template for the growth of an n-GaN NR array. Here, at the hole bottom the n-GaN layer is exposed. The first step of NR growth is to fill the holes with GaN through an ordinary 2-D growth process. GaN can be deposited only in the holes due to the high growth selectivity. The hole filling process stops when the holes are completely filled with GaN and a hexagonal shape is about to be formed. In Fig. 1(b), we show the plan-view SEM image of a template when the hole filling process is completed. Depending on the hole depth or mask thickness, the hole filling process requires a duration between 5 and 20 sec. After the hole-filling process, a pulsed growth mode with TMGa and NH_3 supplies switched on and off alternatively is used for growing an un-doped or n-type GaN NR array. In Fig. 2(a), the flow patterns of TMGa and NH_3 are demonstrated with the supply durations of t_{III} and t_V, respectively. Between the first half-cycle for TMGa supply and the second half-cycle for NH_3 supply, a growth pause with the duration of t_p is applied. The durations, t_{III}, t_V, and t_p, can be adjusted for optimizing the growth results depending on the condition of the used MOVPE reactor. As an example, t_{III}, t_V, and t_p at 20, 30, and 0.5 sec, respectively, are used for growing the NR samples to be demonstrated in the following discussions. For eventually forming an LED structure, silane is supplied with NH_3 for growing n-type GaN NRs. A continuous silane flow also works for growing uniform n-GaN arrays. During the first half-cycle for TMGa supply, Ga droplets are formed at the designated locations for NR formation [45]. In Fig. 2(b), we schematically demonstrate a Ga droplet at the top of an NR of a hexagonal cross section. Such a melting Ga droplet at the high growth temperature serves as the catalyst for precipitating GaN below the droplet when its absorption of N atoms reaches the super-saturation condition. In this vapor-liquid-solid growth mode, a layer of GaN of the same cross-sectional size with the thickness in the range of 20-70 nm, depending on the growth condition, is added to the top of the grown NR. Therefore, by controlling the cycle or loop number in pulsed growth, we can obtain an NR array of a desired height. Normally, the cross-sectional size of the grown NR is larger than the diameter of the patterned holes on the template. In Figs. 3(a) and 3(b), we show the plan-view and tilted SEM images of an n-GaN NR array, respectively. Here, we can see the essentially uniform NR geometry across the array. The NR uniformity in an array also depends on the uniformity of the patterned holes on the template. A patterned hole with a significant eccentricity will result in an NR of an imperfect hexagonal cross section. A close-up look at an individual NR indicates that its top is flat except small slant facets at the edge. The tilted angle of the slant facets with respect to the *c*-plane is about 43 degrees, implying that the slant facets are in the {1-102}-planes.

After GaN NRs are formed, we can deposit InGaN/GaN QWs on an NR using the ordinary growth condition for forming planar QWs. In this process, a pointed- or truncated-pyramidal structure is formed at the top of an NR with the slant facets in the {1-101}-planes, which form a tilted angle of ~62 degrees with respect to the *c*-plane. Due to the low deposition rate in the {1-101}-planes, normally QWs can be formed only on the *c*-plane top face and *m*-plane sidewalls, as schematically shown in Fig. 4(a). In Figs. 4(b) and 4(c), we show the plan-view and tilted SEM images, respectively, of an NR array after QW deposition. If we grow a pointed-pyramidal GaN structure at the top of an NR before QW deposition, *c*-plane QW will not be formed. In this situation, only non-polar, sidewall *m*-plane QWs are deposited, as schematically shown in Fig. 5(a). In Fig. 5(b), we show the tilted SEM image of such a QW NR array. The pointed-pyramidal structure at the NR top can be formed by stepwise decreasing the TMGa supply duration during pulsed growth. For instance, the top structure shown in Fig. 5(b) is formed with 3 loops of 15-sec, 3 loops of 10-sec, and then 20 loops of 5-sec TMGa supplies on the n-GaN NR of a uniform cross section, which is formed with 20 loops of 20-sec TMGa supply. In the whole growth process before QW deposition, the NH_3 supply and growth pause durations are fixed at 30 and 0.5 sec, respectively. After QW deposition, p-GaN can then be grown on a QW NR.

In Fig. 6(a), we show the TEM image of a QW NR, including an n-GaN NR core with an essentially flat top, three top-face *c*-plane QWs in the truncated-pyramidal top structure, and three sidewall *m*-plane QWs. Figures 6(b)-6(d) show the magnified TEM images of the top portion, the sidewall QW portion near the top, and that near the bottom, respectively. As indicated by the (pink) arrows, the three QWs in each magnified TEM image can be seen. The thicknesses of the top-face QWs are larger than those on the sidewall. Also, no QW structure is found on the slant facets. These results confirm the highest growth rate in the *c*-plane, followed by those of the *m*-plane and then the {1-101}-plane (*r*-plane). In Fig. 7(a), we show the TEM image of an LED NR, in which a pointed-pyramidal n-GaN structure is formed at the top of the n-GaN NR core like the structures shown in Figs. 5(a) and 5(b) before QW deposition. In such a structure, QWs and then p-GaN can be formed mainly on the sidewalls of the NR. In Fig. 7(a), one can see that the thickness of the sidewall p-GaN layer increases with height on a sidewall. In Fig. 7(b), we show the magnified image of the circled portion in Fig. 7(a). Here, we can see the three QWs more clearly.

Results and Discussions: Nanorod light-emitting diode array

Although NR LED arrays have been demonstrated by a couple companies, including Glo-USA and OSRAM, their detailed fabrication procedures are not published. Normally, to minimize current leakage in such a device, the NR gap regions are filled with certain insulating materials, such as SiO_2 and photoresist. During the growth of an NR array, NRs may not be perfectly formed at certain designated locations. Also, during device process, certain NRs can be broken. In this situation, current leakage can be produced through those "defects" in an array. By filling an insulating material in the gaps, such defects can also be covered for reducing leakage current. Then, usually, indium-tin-oxide (ITO) is deposited on the NR array as a transparent conductor for spreading injected current over the NR surface and electrically connecting individual NRs when the array pitch is not large. Contact metals are coated on the top and in a region without NR for forming the p- and n-contact. In such an LED-array structure, the injected current for exciting sidewall QWs near the bottom relies on the current flow along the sidewall p-GaN layer since it is usually difficult to cover the whole NR with ITO. However, because of the low current conductivity in p-GaN, the current injection efficiency and hence emission efficiency of the sidewall QWs are not high. In this research group, we use MBE-grown, highly Ga-doped ZnO (GaZnO) as the transparent conductor for spreading injected current over the whole sidewall of an NR. With MBE or MOVPE growth, a conformal GaZnO layer over the entire surface of an NR can be formed. Based on our MBE growth at 250 ^oC in substrate temperature, a highly-conductive GaZnO thin film can be formed with the resistivity, mobility, and electron concentration at 1.6 x 10^{-4} Ω-cm, 22 cm^2/V-s, and 1.5 x 10^{21} cm^{-3}, respectively [47]. It is essentially transparent in the visible range. In Fig. 8, we show the transmittance spectrum of a GaZnO layer of 250 nm in thickness grown on a sapphire substrate at 250 ^oC. Here, one can see that the transmittance is essentially higher than 90 % in the visible range.

In Fig. 9, we schematically demonstrate the structure of an NR LED array [48]. In this device, at the top of an n-GaN NR, we purposely form a pointed-pyramidal u-GaN structure. This top structure can hinder the growth of c-plane QW such that the output of this device is completely emitted from the non-polar sidewall QWs. Also, the u-GaN top structure can increase electric resistance of this portion such that injected current is guided to flow along the conformal GaZnO layer for effectively exciting sidewall QWs. In such an NR LED structure, the InGaN/GaN QWs and p-GaN layer are formed only on the NR sidewalls. However, the transparent conductor, GaZnO, can cover essentially the whole NR. The p-contact metals, Ni and Au, cover the top of the whole NR array and connect electrically individual NRs. As indicated by the pink arrows in Fig. 9, injected current flows along the GaZnO layer to excite the non-polar sidewall QWs. Because the top of the NR array is covered by metals, the device output is emitted from the sapphire substrate side. In Fig. 10, we show the relations between injected current density and applied voltage of an NR LED array and a *c*-plane planar LED. Because the two devices have different emission areas, current density is used in the vertical axis in Fig. 10 for a reasonable comparison. The NR LED array in the designed device mesa (50 x 50 μm^2) has the sidewall emission area of ~3000 μm^2 in total. The planar LED has a mesa dimension of 300 x 300 μm^2 and hence has an emission area of ~90000 μm^2. In Fig. 10, one can see that the leakage current up to -5 V in applied voltage is very small in either LED device. The turn-on voltages of the two devices are about the same although that of the NR LED array is slightly larger. The device resistance of the planar LED is 14.8 Ω. The overall device resistance of the NR LED array is as large as 336 Ω because of its smaller current flow cross-sectional area. However, as shown in Fig. 10, the electrical performance of the NR LED array is better than that of the planar LED. Because the supplied electric power per unit active area of an LED device is equal to $I^2R/A = J^2AR$, where *I, R, A, J* are the injected current, device resistance, active area, and injected current density, respectively, it is more appropriate to use the parameter *AR* for comparing the electrical performances between LED devices of different active areas. The *AR* values of the NR LED array and planar LED are 1.09 x 10^{-2} and 1.33 x 10^{-2} Ωcm^2, respectively, indicating that the electrical performance of the NR LED array is indeed better than that of the planar LED. In Fig. 11, we show the relations between the normalized output power per unit emission area and injected current density of the two LED devices. Here, one can see that the emission level per unit emission area of the NR LED array is slightly lower than that of the planar LED. This result can be attributed to the difficulty of collecting the whole emitted power from the NR LED array unless the device is well packaged. It can also be due to the relatively poorer QW quality on the NR sidewall. The growth condition for the sidewall QWs needs to be optimized. Also, the packaging technique for such an NR LED array needs to be developed.

Summary

In this report, we have described the development of regularly-patterned GaN NR LED arrays grown with MOVPE. Such an array device is expected to be useful for practical lighting application. A regularly-patterned NR array could be grown on a patterned template with either continuous or pulsed growth mode. Usually, with the pulsed growth mode, by switching group-III and V sources on and off alternatively, the NR geometry could be more uniform over an array. InGaN/GaN QWs could be deposited on the *c*-plane top face, *m*-plane sidewalls, and {1-101}-plane slant facets on a *c*-axis-oriented NR with the highest (lowest) growth rate in the *c*-plane ({1-101}-plane). After the overgrowth of p-GaN on an NR with n-GaN core and QW deposition, an NR LED array could be implemented by covering the NRs with a transparent conductor, such as ITO or GaZnO. It has been demonstrated that the optical and electrical performances of an NR LED array could be comparable to those of a planar LED. Further developments in NR LED growth and process techniques can lead to an outperforming LED device with the NR structure.

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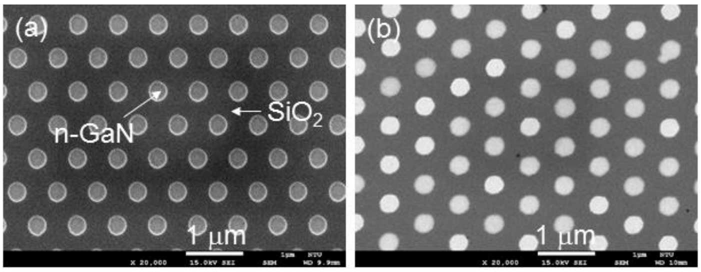

Fig. 1 (a): Plan-view SEM image of a GaN template for the growth of a GaN NR array. (b): Plan-view SEM image of a template after the hole filling process is completed.

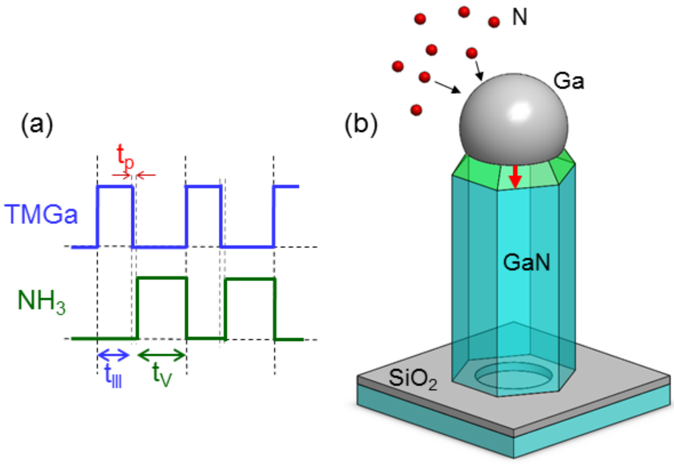

Fig. 2 (a): Flow patterns of TMGa and NH_3 with the supply durations of t_{III} and t_V, respectively, in a pulsed growth mode. Between the first half-cycle for TMGa supply and the second half-cycle for NH_3 supply, a growth pause with the duration of t_p is applied. (b): Schematic demonstrations a Ga droplet at the top of an NR of a hexagonal cross section and the incoming N atoms.

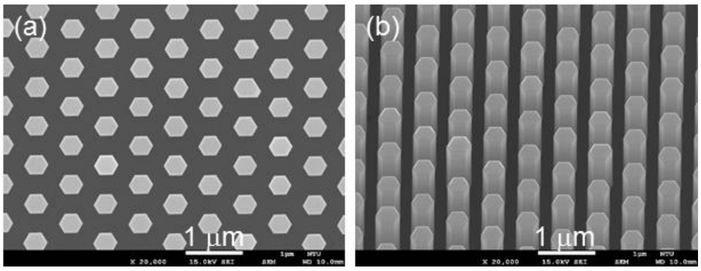

Fig. 3 (a) and (b): Plan-view and tilted SEM images of an n-GaN NR array, respectively.

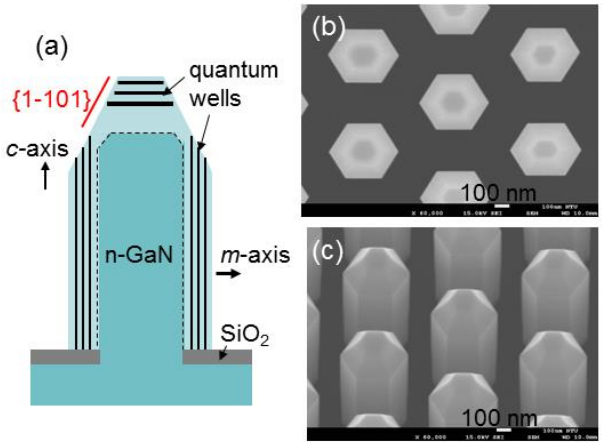

Fig. 4 (a): Schematic demonstration of an n-GaN NR with top-face *c*-plane and sidewall *m*-plane QWs. (b) and (c): Plan-view and tilted SEM images, respectively, of an n-GaN NR array after QW deposition demonstrated in part (a).

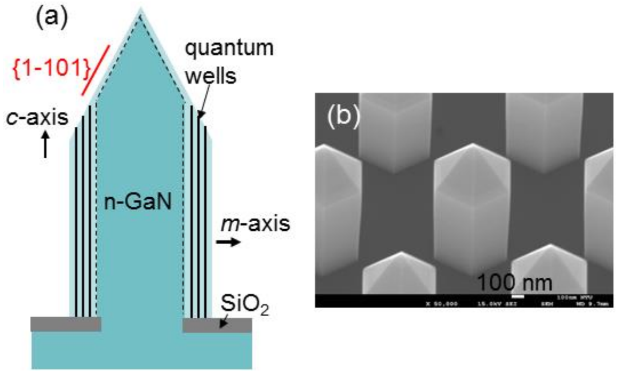

Fig. 5 (a): Schematic demonstration of an n-GaN NR with a pointed-pyramidal top structure and sidewall QWs. (b): Tilted SEM image of a QW NR array as depicted in part (a).

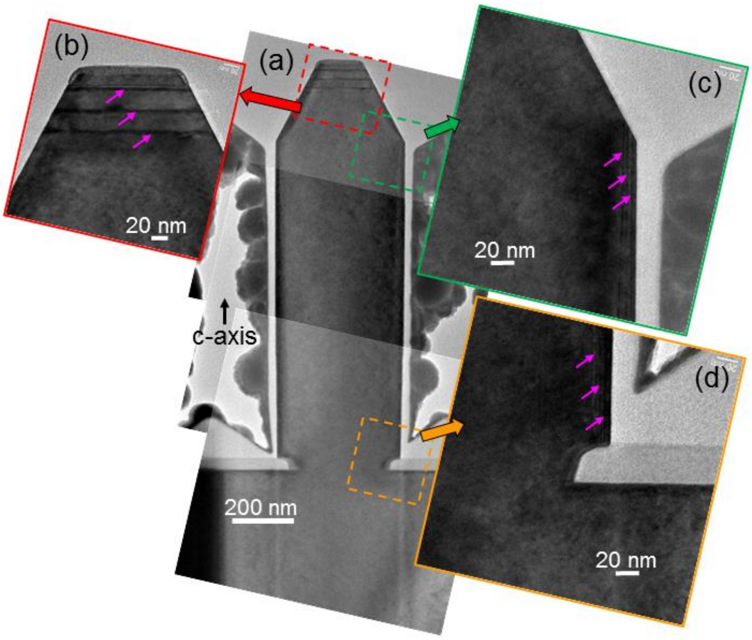

Fig. 6 (a): TEM image of a QW NR, including an n-GaN NR core with an essentially flat top, three top-face *c*-plane QWs in the truncated-pyramidal top structure, and three *m*-plane sidewall QWs. (b)-(d): Magnified TEM images of the top portion, the sidewall QW portion near the top, and that near the bottom, respectively. As indicated by the (pink) arrows, the three QWs in each magnified TEM image can be seen.

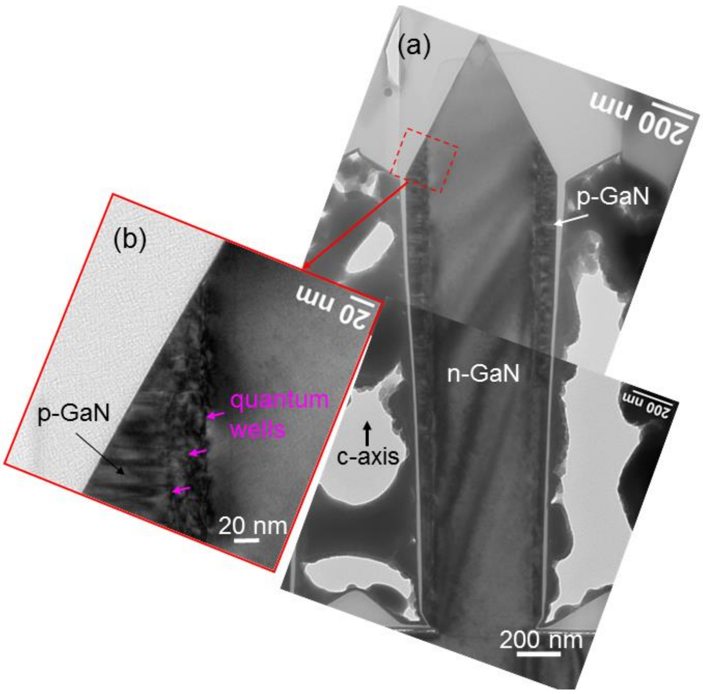

Fig. 7 (a): TEM image of an NR LED structure, in which a pointed-pyramidal n-GaN structure is formed at the top of the n-GaN NR core like the structures shown in Figs. 5(a) and 5(b). Here, QWs and p-GaN are formed mainly on the sidewalls of the NR. (b): Magnified image in the circled portion of part (a).

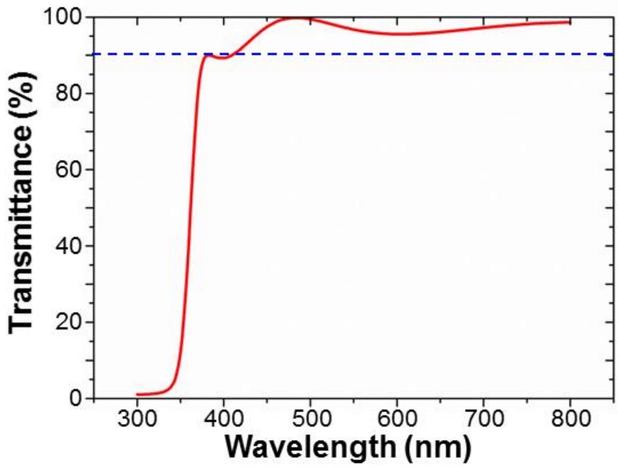

Fig. 8 Transmittance spectrum of a GaZnO layer of 250 nm in thickness grown on a sapphire substrate at 250 ^{o}C.

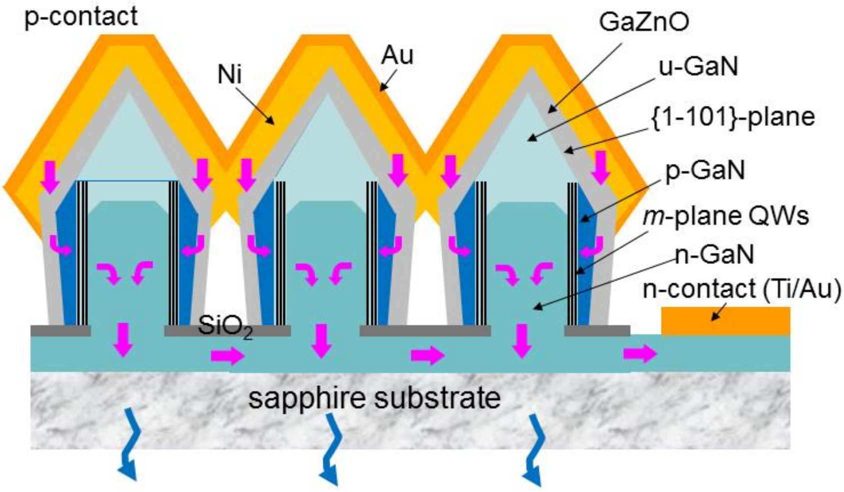

Fig. 9 Schematic demonstration of the structure of an NR LED array. The pink arrows indicate the flow of injected current.

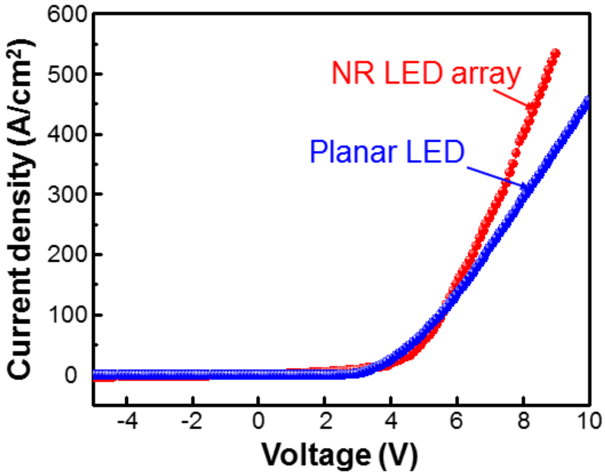

Fig. 10 Relations between injected current density and applied voltage of an NR LED array and a *c*-plane planar LED.

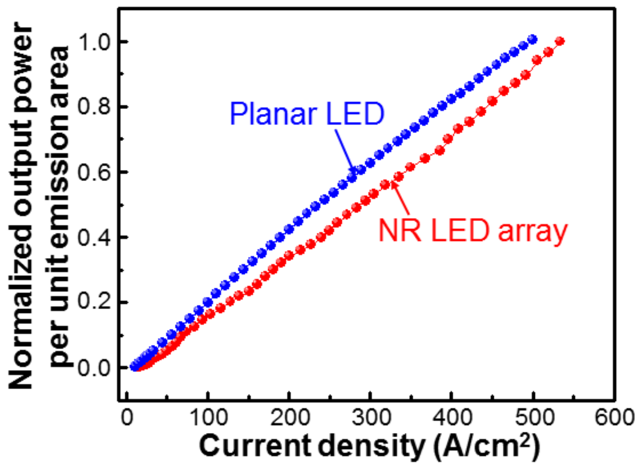

Fig. 11 Relations between the normalized output power per unit emission area and injected current density of the NR LED array and the *c*-plane planar LED.

List of Publications and Significant Collaborations that resulted from your AOARD supported project:

SCI Journal papers:

1. Charng-Gan Tu, Yu-Feng Yao, Che-Hao Liao, Chia-Ying Su, Chieh Hsieh, Chi-Ming Weng, Chun-Han Lin, Hao-Tsung Chen, Yean-Woei Kiang, and C. C. Yang, "Multi-section core-shell InGaN/GaN quantum-well nanorod light-emitting diode array," Optics Express, Vol. 23, No. 17, pp. 21919-21930, 24 August 2015.
2. Charng-Gan Tu, Chia-Ying Su, Che-Hao Liao, Chieh Hsieh, Yu-Feng Yao, Hao-Tsung Chen, Chun-Han Lin, Horng-Shyang Chen, Yean-Woei Kiang, and C. C. Yang, "Regularly-patterned Nanorod Light-emitting Diode Arrays Grown with Metalorganic Vapor-phase Epitaxy," Superlattices and Microstructures, Vol. 83, pp. 329-341, July 2015. **(Invited)**
3. Chun-Han Lin, Chia-Ying Su, Erwin Zhu, Chieh Hsieh, Charng-Gan Tu, Yu-Feng Yao, Hao-Tsung Chen, Che-Hao Liao, Horng-Shyang Chen, Yean-Woei Kiang, and C. C. Yang, "Thermally induced variations of strain condition and emission behavior in flat and bendable light-emitting diodes on different substrates," Optics Express, Vol. 23, No. 12, pp. 15491-15503, 15 June 2015.
4. Yu-Feng Yao, Charng-Gan Tu, Ta-Wei Chang, Hao-Tsung Chen, Chi-Ming Weng, Chia-Ying Su, Chieh Hsieh, Che-Hao Liao, Yean-Woei Kiang, and C. C. Yang, "Growth of Highly Conductive Ga-doped ZnO Nanoneedles," ACS Applied Materials & Interfaces, Vol. 7, No. 19, pp. 10525-10533, 20 May 2015.
5. David C. Look, Eric R. Heller, Yu-Feng Yao, and C. C. Yang, "Significant mobility enhancement in extremely thin highly-doped ZnO films," Applied Physics Letters, Vol. 106, No. 15, p. 152102, 13 April 2015.
6. Chun-Han Lin, Chia-Ying Su, Erwin Zhu, Yu-Feng Yao, Chieh Hsieh, Charng-Gan Tu, Hao-Tsung Chen, Yean-Woei Kiang, and C. C. Yang, "Modulation behaviors of surface plasmon coupled light-emitting diode," Optics Express, Vol. 23, No. 6, pp. 8150-8161, 23 March 2015.
7. Charng-Gan Tu, Che-Hao Liao, Yu-Feng Yao, Horng-Shyang Chen, Chun-Han Lin, Chia-Ying Su, Pei-Ying Shih, Wei-Han Chen, Erwin Zhu, Yean-Woei Kiang, and C. C. Yang, "Regularly patterned non-polar InGaN/GaN quantum-well nanorod light-emitting diode array," Optics Express, Vol. 22, No. S7, pp. A1799-A1809, 15 December 2014.
8. Duanjun Cai, Na Lin, Hongmei Xu, Che-Hao Liao, and C. C. Yang, "Extraordinary N atom tunneling in formation of InN shell layer on GaN nanorod m-plane sidewall," Nanotechnology, Vol. 25, No. 49, p. 495705, 12 December 2014.
9. Chun-Han Lin, Chia-Ying Su, Yang Kuo, Chung-Hui Chen, Yu-Feng Yao, Pei-Ying Shih, Horng-Shyang Chen, Chieh Hsieh, Yean-Woei Kiang, and C. C. Yang, "Further reduction of efficiency droop effect by adding a lower-index dielectric interlayer in a surface plasmon coupled blue light-emitting diode with surface metal nanoparticles," Applied Physics Letters, Vol. 105, No. 10, p. 101106, 8 September 2014.
10. Chieh Hsieh, Yu-Feng Yao, Chia-Feng Chen, Pei-Ying Shih, Chun-Han Lin, Chia-Ying Su, Horng-Shyang Chen, Chung-Hui Chen, Chih-Kang Yu, Yean-Woei Kiang, and C. C. Yang, "Localized Surface Plasmon coupled Light-emitting Diodes with Buried and Surface Ag Nanoparticles," IEEE Photonics Technology Letters, Vol. 26, No. 17, pp. 1699-1702, 1 September 2014.
11. Horng-Shyang Chen, Chun-Han Lin, Pei-Ying Shih, Chieh Hsieh, Chia-Ying Su, Yuh-Renn Wu, Yean-Woei Kiang, and C. C. Yang, "Thermal effects in a bendable InGaN/GaN quantum-well light-emitting diode," IEEE Photonics Technology Letters, Vol. 26, No. 14, pp. 1442-1445, 15 July 2014.
12. Che-Hao Liao, Charng-Gan Tu, Wen-Ming Chang, Chia-Ying Su, Pei-Ying Shih, Hao-Tsung Chen, Yu-Feng Yao, Chieh Hsieh, Horng-Shyang Chen, Chun-Han Lin, Chih-Kang Yu, Yean-Woei Kiang, and C. C. Yang, "Dependencies of the emission behavior and quantum well structure of a regularly-patterned, InGaN/GaN quantum-well nanorod array on growth condition," Optics Express, Vol. 22, No. 14, pp. 17303-17319, 14 July 2014.

13. Chih-Yen Chen, Wen-Ming Chang, Wei-Lun Chung, Chieh Hsieh, Che-Hao Liao, Shao-Ying Ting, Kuan-Yu Chen, Yean-Woei Kiang, C. C. Yang, Wei-Siang Su, and Yung-Chen Cheng, "Crack-free GaN deposition on Si substrate with temperature-graded AlN buffer growth and the emission characteristics of overgrown InGaN/GaN quantum wells," Journal of Crystal Growth, Vol. 396, pp. 1-6, 15 June 2014.
14. Horng-Shyang Chen, Zhan Hui Liu, Pei-Ying Shih, Chia-Ying Su, Chih-Yen Chen, Chun-Han Lin, Yu-Feng Yao, Yean-Woei Kiang, and C. C. Yang, "Independent variations of applied voltage and injection current for controlling the quantum-confined Stark effect in an InGaN/GaN quantum-well light-emitting diode," Optics Express, Vol. 22, No. 7, pp. 8367-8375, 7 April 2014.
15. Yu-Feng Yao, Chen-Hung Shen, Wei-Fang Chen, Pei-Ying Shih, Wang-Hsien Chou, Chia-Ying Su, Horng-Shyang Chen, Che-Hao Liao, Wen-Ming Chang, Yean-Woei Kiang, and C. C. Yang, "Void Structures in Regularly Patterned ZnO Nanorods Grown with the Hydrothermal Method," Journal of Nanomaterials, Vol. 2014, Article ID 756401, 11 pages, doi:10.1155/2014/756401,19 March 2014.

Invited presentations at international conferences:

1. "MOCVD growth of III-nitride core-shell-structured nanorod with flexible geometry," ISPlasma 2015, Nagoya, Japan, March 26-31, 2015.
2. "Regularly patterned non-polar InGaN/GaN quantum-well nanorod light-emitting diode array," Photonics West 2015, San Franscico, US, February 7-12, 2015.
3. "Surface Plasmon Coupled Light-emitting Diode," OSA Light, Energy and the Environment Conference, Canberra, The Australian Capital Territory, Australia, December 2-5, 2014.
4. "Development of Nitride Nanorod Light-emitting Diode Array," AVS 61st International Symposium and Exhibition (AVS-61), Baltimore, US, November 9-14, 2014.
5. "Surface Plasmon Coupled Light-emitting Diode," AOM 2014 – The 4th Advances in Optoelectronics and Micro/nano-optics, Xi'an, China, September 17-20, 2014.
6. "Development of Nitride Nanorod Light-emitting Diode Array," International Nano-optoelectronic Workshop (iNOW), Luga and St. Petersburg, Russia, August 11-22, 2014.
7. "Surface plasmon coupling for reducing the efficiency droop effect of a light-emitting diode," The 5th International Conference on White LEDs and Solid State Lighting (WLED-5), Jeju, Korea, June 1-5, 2014.
8. "Multiple-section core-shell InGaN/GaN quantum-well nanorod light-emitting diode array," European Materials Research Society (E-MRS 2014) Spring Meeting, Lille, France, May 26-30, 2014.
9. "Surface plasmon coupled light-emitting diodes," Photonics West 2014, San Francisco, US, February 1-6, 2014.

Collaboration with Dr. Kent Averett:

(1) Delivering GaN nanorod and GaZnO nanoneedle samples to the collaborator at AFRL/RXAP, Dr. Kent Averett, on July 31, 2015.
(2) Meeting with Dr. Kent Averett at the conference of SPIE Photonics West 2015 (February 7-12, 2015) in San Francisco for discussion of collaborating research, including the results and future work.