High output power density from GaN-based two-dimensional nanorod light-emitting diode arrays

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Here we propose and realize a scheme for making a direct contact to a two-dimensional nanorod light-emitting diode (LED) array using the oblique-angle deposition approach. And, more importantly, we demonstrate highly efficient electrical carrier injection into the nanorods. As a result, we show that at a 20 mA dc current injection, the light output power density of our nanorod LED array is 3700 mW cm^{-2}. More general, this contact scheme will pave the ways for making direct contacts to other kinds of nanoscale optoelectronic devices. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3119192]

The developments of advanced gallium nitride (GaN)-based (light-emitting diode) LED structures are critical to a wide range of applications that include intelligent interior lighting and optical communication module in automobiles, backlighting units for liquid crystal displays, and general lighting.[1,2] For energy-saving reasons, a LED structure must be designed to yield high internal quantum efficiency and light extraction efficiency. For a GaN-based blue LED, the internal quantum efficiency is determined primarily by growth and the associated defect formation.[3] On the other hand, the light extraction efficiency is limited by total internal reflection at the interface of GaN and air.[4] Recently, a GaN-based nanorod LED array with dislocation-free and large sidewall-surface-area characteristics was demonstrated.[5] The nanorod LED array showed an enhanced internal quantum efficiency and light extraction efficiency. However, the major challenge of making electrical contacts to nanorod LEDs having a typical diameter of 10–100 nanometer size has remained unsolved. The main difficulty of making such an electrical contact is related to depositing a continuous layer of electrode on top of nanorod LEDs without creating an electrical short between the *p*- and *n*-regions. Hence, most researches are constrained to use optical pumping to study the optical properties of nanorod LEDs.[6–8] However, for practical day-to-day use of LEDs, a feasible scheme for electrical pumping is essential. So far, a common approach is to use polymers, such as spin-on glass (SOG),[5] SU-8,[9] and polymethyl methacrylate,[10] to isolate individual nanorod LEDs, especially in the *n*-contact and the quantum well region. Subsequently, a planar conductive layer is deposited to form *p*-contacts to the *p*-type nanorods. This approach has several drawbacks. First, since the typical thickness of the *p*-type nanorod region is only 100–200 nm due to the difficulty in achieving high carrier density in *p*-type GaN, it is demanding to control both the thickness and uniformity of the polymer. Second, the filling of the polymer is often not complete when the rod-to-rod interval is smaller than 80–100 nm, thus creating an undesirable leakage electrical path. Finally, an additional coating process of polymer will not only add fabrication cost but also reduce production yields in the LED industry. Therefore, a much improved method for making a direct electrical contact to the nanorods is necessary. Here we demonstrate a general strategy involving oblique-angle deposition growth that makes a direct and selective contact to the top surfaces of a two-dimensional (2D) nanorod LED array. This method allows us to overcome the limitations of using a polymer as mentioned above.

The 2D nanorod LED array was fabricated by using self-assembled nickel (Ni) cluster as inductively coupled plasma dry etching hard mask. The fabrication detail for nanorod LED arrays is described elsewhere.[11] Figure 1(a) presents a scanning electron microscopy (SEM) image of our 2D nanorod LED array. The filling fraction (FF) of the nanorod array is 20% ± 4% and is determined by the spatial arrangement of

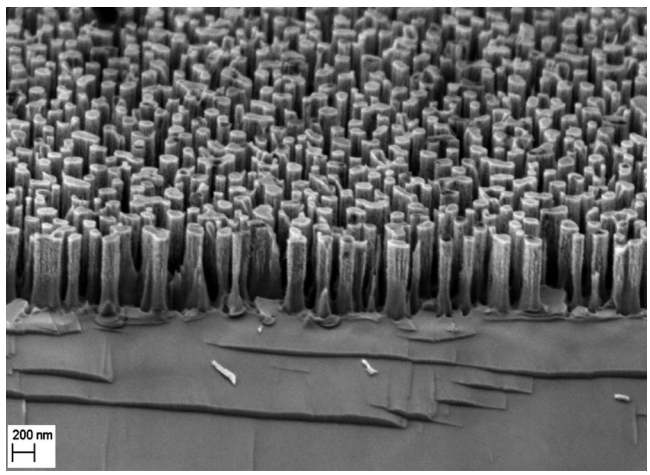

FIG. 1. A SEM image of randomly arranged 2D nanorod LED array.

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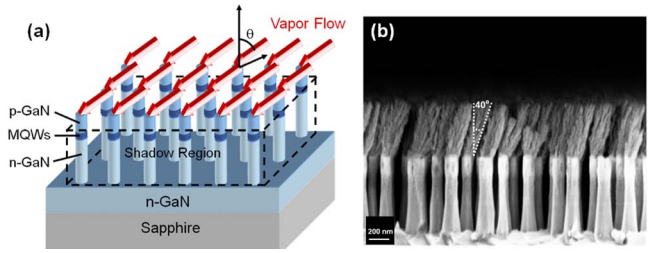

FIG. 2. (Color online) (a) A schematic of incident vapor flow selectively growing on top surfaces of nanorod array. (b) A cross-sectional view SEM images of ITO grown on the 2D nanorod array by oblique-angle deposition with a tilt angle of 40°.

the Ni cluster. Due to the self-assembly nature of the Ni cluster, our 2D nanorod array is randomly arranged. The diameter of an individual nanorod is 100–150 nm, which may be controlled by varying the Ni film thickness. The nanorod has an etch depth of 700 nm, which exposes the active layer to the air, and thus allows for an easier coupling of LED light emission into the air. The nanorod has a large height-to-diameter aspect ratio (Fig. 1) and thus is ideal for achieving the so called "shadowing effect" by oblique-angle depositions.[12] In this work, we recognize the selective growth aspect of the method and grow the slanted indium tin oxide (ITO) to make contact to our 2D nanorod LED array. ITO is chosen because of its high electrical conductivity, low contact resistance with GaN, and high optical transparency. The slanted ITO was grown by oblique-angle deposition using electron beam evaporation. The apparatus used in our oblique-angle deposition has a sample stage, on which the substrate is loaded, with controllable polar-angle rotation. For each layer, the sample stage is at a fixed polar angle so that the substrate has a certain tilt angle with respect to the vapor-flow direction.

The vapor flow (the red arrows) is incident at an angle θ, which is defined as the angle between the surface normal and the incident flow direction, as shown in Fig. 2(a). The incident vapor flow is to be deposited preferentially on top of p-GaN nanorod. Due to the shadowing effect, no vapor flow is allowed to be deposited on the sidewall, i.e., the multiple-QWs region and the n-GaN regions. This approach provides for a more effective way to bring p-GaN nanorod in contact with a p-electrode without involving polymer processing. In Fig. 2(b), we show an SEM side-view image of ITO grown on the 2D nanorod LED array. The incident angle of vapor flow is $\theta=70°$ and the deposited ITO thickness is 500 nm. Indeed, the ITO branch was selectively grown on top of the 2D nanorod array with a tilt angle of ~40°. The sidewall of the nanorods is clean and free from ITO deposition, indicating a successful implementation of a direct nanocontact scheme.

Next, we apply the oblique-angle-deposition to realize an electrically injected 2D nanorod LED arrays. In Fig. 3(a), we show a schematic cross section of our proposed slanted ITO multicontact layers to the 2D nanorod LED arrays. The advantage of this contacting scheme is that it is compatible with standard chip process widely adopted in the LED industry. The oblique-angle deposition process was repeated three times, having incident angles of $\theta=85°$, $-85°$, and 0°, respectively. This repeated deposition is needed to join together the individual ITO branches, to form a continuous blanket ITO film. In Fig. 3(b), we show a cross-sectional

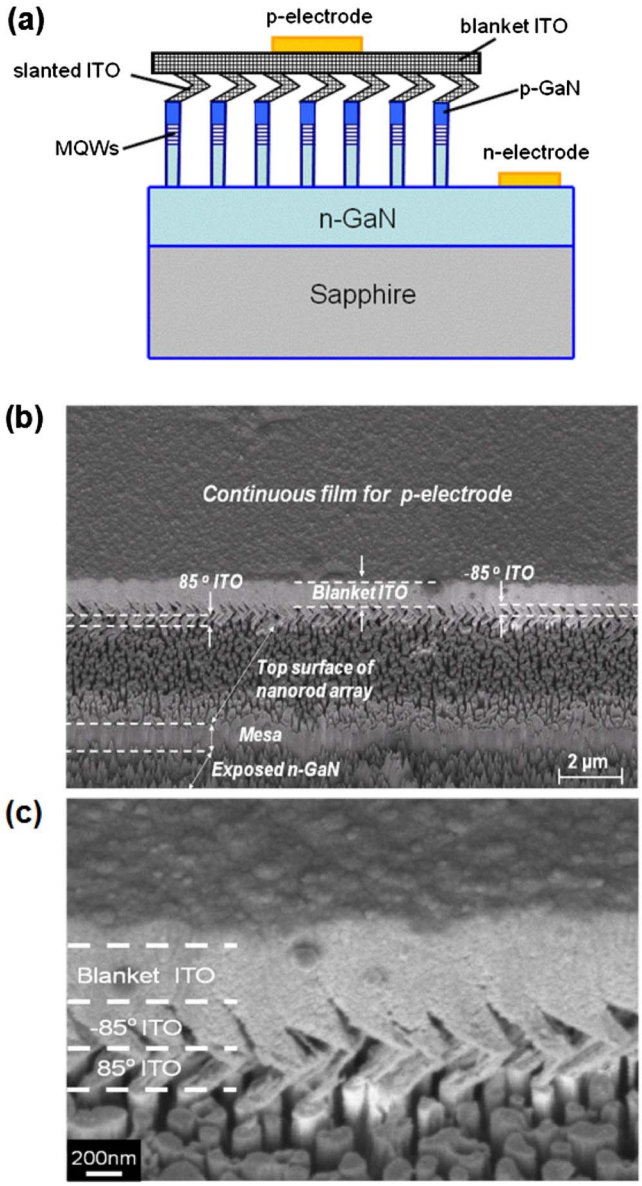

FIG. 3. (Color online) (a) The cross-section schematic of our proposed slanted ITO multicontact layers to 2D nanorod LED array. (b) A cross-sectional view SEM image of an ITO stack grown on the mesa of 2D nanorod LED array by oblique-angle deposition with incident angles of 85°, −85°, and 0°, respectively. (c) An enlarged SEM image of the ITO stack.

SEM image of the completed ITO stack grown on the mesa of 2D nanorod LED arrays, i.e., the 85°-ITO, the −85°-ITO, and the 0°-ITO film, respectively. An enlarged SEM image of the ITO stack was shown in Fig. 3(c). The function of the intermediate layer (−85°) is to prevent the successive blanket layer (0°) from filling into rod-to-rod intervals and thus causing undesirable electrical short circuits. The slanted ITO layers (85°/−85°) connect with each other well. And, more importantly, a flat and continuous surface morphology was observed on the top surface of the blanket ITO layer. This planar surface serves as a platform for a subsequent deposition of the p-electrode. As a result, the electrical current from p-electrode is spread out uniformly within the blanket ITO layer and injected evenly into each individual nanorod LED through slanted ITO layers.

As a result of our new electrical contact scheme, we are able to inject up to $I=100$ mA of bias current into a chip-size scale (300×300 μm^2) 2D nanorod LED array. In the

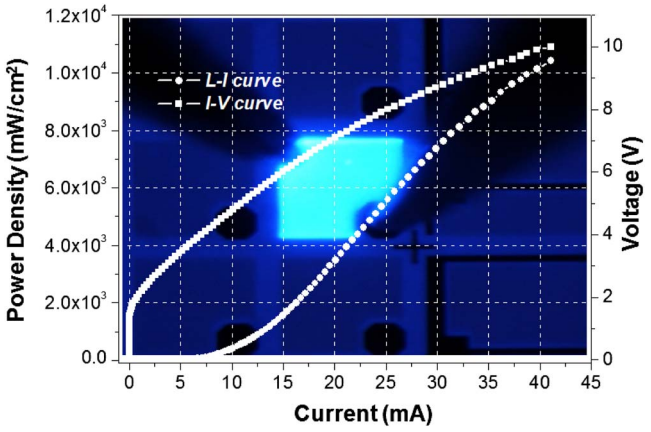

FIG. 4. (Color online) The light output power density (mW/cm^2) vs forward current and current vs voltage of 2D nanorod LED array. Background: A photograph image taken under an injection current of 20 mA.

background of Fig. 4, we show a photograph of our 2D nanorod LED arrays at a forward bias of $I=20$ mA. A uniform light emitting intensity was observed over the entire chip area. This observation indicates that we have achieved a good current spreading in the *p*-contact layers and, more importantly, an exceedingly uniform current-injection efficiency into all the nanorod LEDs. Previously, an electrically injected nanorod LED array was realized by using polymer to isolate individual nanorod LEDs and a planar conductive layer to form a *p*-contact. Because of the difficulty in achieving a uniform polymer filling, a localized current-injection often occurs. As a result, either severe leakage paths were observed[9] or an extremely low current was injected (approximately microampere) into the devices.[11]

We now examine the light output power characteristics of our 2D nanorod LED arrays. In Fig. 4, we show the light output power density L (the solid dots) and the bias voltage V (the square dots) versus the forward bias current I of our sample. Both the *L-I* and the *I-V* curve exhibit a typical functional dependence of a *p-n* junction, similar to that of a planar LED sample. We observe a slight increase in output power at I is increased to $I=5-10$ mA and a stronger and linear increase for $I>10$ mA. At $I=20$ mA, the light output power density of our 2D nanorod LED array is as high as 3700 mW cm^{-2}. The random arrangement of the nanorod array can alter the mechanism by which the emitted light is coupled into the free space.[13] Thus this extraction effect can also be a contributing factor to the large output power density of our electrically injected nanorod LED arrays. The low turn-on voltage (~ 2 V) in our work may be due to the collapse of nanorods in certain regions of the sample during device fabrication. Within these regions, the incident ITO vapor flow would be deposited directly to the *n*-type regions without shadowing. A more careful fabrication process will need to be designed in the future to overcome this issue.

In summary, we have demonstrated a scheme for the efficient injection of carriers into a 2D nanorod LED array by an oblique-angle deposition method. Cross-sectional SEM studies reveal that oblique vapor flow was selectively grown on the top surfaces of the *p*-type nanorod LED array. This 2D nanorod LED array exhibits an high light output power density of 3700 mW cm^{-2} at $I=20$ mA, and that is attributed mainly to the selective and nonleaky electrical contact to the 2D nanorod LED array, as well as light scattering due to the random arrangement of the nanorods.

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[1] M. R. Krames, O. B. Shchekin, M. M. Regina, G. O. Mueller, L. Zhou, G. Harbers, and M. G. Craford, J. Disp. Technol. **3**, 160 (2007).
[2] E. F. Schubert, *Light-Emitting Diodes* (Cambridge University Press, Cambridge, 2006).
[3] S. Nakamura, Science **281**, 956 (1998).
[4] M. Boroditsky and E. Yablonovitch, Proc. SPIE **3002**, 119 (1997).
[5] H. Kim, Y. Cho, H. Lee, S. Kim, S. R. Ryu, D. Y. Kim, T. W. Kang, and K. S. Chung, Nano Lett. **4**, 1059 (2004).
[6] Y. Sun, Y.-H. Cho, H. M. Kim, and T. W. Kang, Appl. Phys. Lett. **87**, 093115 (2005).
[7] Y. He, L. Chen, Y.-K. Song, A. V. Nurmikko, S.-R. Jeon, Z. Ren, M. Gherasimova, and J. Han, Phys. Status Solidi C **2**, 2740 (2005).
[8] S. Keller, C. Schaake, N. A. Fichtenbaum, C. J. Neufeld, Y. Wu, Y. McGroddy, A. David, S. P. Denbaars, C. Weisbuch, J. S. Speck, and U. K. Mishra, J. Appl. Phys. **100**, 054314 (2006).
[9] M. Y. Hsieh, C. Y. Wang, L. Y. Chen, M. Y. Ke, and J. J. Huang, IEEE J. Quantum Electron. **44**, 468 (2008).
[10] X. W. Sun, J. Z. Huang, J. X. Wang, and Z. Xu, Nano Lett. **8**, 1219 (2008).
[11] C. H. Chiu, M. H. Lo, C. F. Lai, T. C. Lu, H. W. Huang, Y. A. Chang, T. H. Hsueh, C. C. Yu, H. C. Kuo, S. C. Wang, C. F. Lin, and Y. K. Kuo, Nanotechnology **18**, 335706 (2007).
[12] K. Robbie, J. C. Sit, and M. J. Brett, J. Vac. Sci. Technol. B **16**, 1115 (1998).
[13] I. Schnitzer, E. Yablonovitch, C. Caneau, T. J. Gmitter, and A. Scherer, Appl. Phys. Lett. **63**, 2174 (1993).