Nanorod photon management in nitride-based devices

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Nanostructures fabricated on nitride-based devices improve their performance, enhancing the output of LEDs and the absorption of solar cells.

The unique properties of indium gallium nitride (InGaN) alloys, including their wide electronic band gap spanning 0.7–3.4 eV, high absorption coefficient, high carrier mobility, and superior radiation resistance, make them ideal candidates for optoelectronic devices. Intense research efforts since the mid-1990s have led to remarkable successes in LEDs. More recently, the promising photovoltaic characteristics of InGaN have also attracted increasing research interest.

In the development of nitride-based optoelectronic devices, one of the main challenges is the difficulty of growing high-crystal-quality InGaN layers on GaN. GaN usually makes up p- and n-contacts. The lattice mismatch between InGaN and GaN can adversely affect device performance once the InxGa1−xN layer grows beyond a critical thickness on the GaN substrate. To address the issue, multiple quantum wells (MQWs) are used to form an active layer, ensuring excellent radiative recombination efficiencies for LEDs while also avoiding the undesired tradeoff between crystal quality and absorption efficiency for solar cells. Furthermore, the quantized energy levels in MQWs offer an additional level of control of solar absorption through proper selection of well and barrier widths without changing the indium content. Although progress has been made, many challenges still remain. For LEDs, the internal electrical field in MQWs that results from spontaneous and piezoelectric polarization leads to charge separation and reduces internal quantum efficiency. The great difference between the refractive index of GaN and that of air also prevents a high proportion of photons from escaping out of the device. In addition to the strong surface reflection caused by the large change in refractive index, the thin InGaN active layer also limits the absorption of solar energy, yielding suboptimal photovoltaic operation.

Figure 1. Process schematics for textured gallium nitride (GaN)-based LEDs. (a) SiO2/Ag (silica/silver) layers are deposited on indium tin oxide (ITO). (b) Material following thermal annealing at 270ºC for a few minutes and (c) following a reactive ion etching process. (d) The silver nanoparticles (NPs) are then removed by nitric acid.

Figure 2. Time-averaged, normalized transverse electric (TE) field distribution within GaN-based LEDs with two different surface conditions: (a) bare and (b) SiO2 nanorod arrays (NRAs)/roughened p-GaN. Ez: Electric field normal to the surface.

However, thanks to advances in nanofabrication techniques, the adoption of various forms of nanostructures onto nitride-based optoelectronic devices has been shown to improve their performance. For example, nanorod arrays (NRAs) can lead...
to enhanced light emission or absorption due to the refractive index gradient they create. In solar cells, this facilitates light traveling across the device interface between air and GaN.

In this work, we will show that antireflective NRAs (AR-NRAs) also yield improved performance, for example, in LEDs. As shown in Figure 1, we first deposited silica (SiO$_2$) and silver metal layers on ITO (indium titanium oxide) by electron beam evaporation. An etching mask of silver nanoparticles was then formed by thermally annealing the sample at 270°C for a few minutes. We obtained SiO$_2$ AR-NRAs by reactive ion etching. Figure 2 shows the steady-state distribution of electromagnetic fields for both flat surfaces and roughened p-GaN/SiO$_2$ NRA surfaces simulated by finite-difference time-domain (FDTD) analyses. We used Maxwell’s equations to calculate the propagation of the waves. It can be seen that the light intensity in the integrated regions for the roughened p-GaN/SiO$_2$ NRA surfaces is enhanced, compared with that for the flat surface. We attribute this result to the medium causing strong light scattering and thus increasing the external quantum efficiency (EQE).

We have also shown that ZnO (zinc oxide) AR-NRAs produced by a hydrothermal method hold great promise for InGaN-based MQW solar cells, requiring no lithography, operating well at low temperatures (<100°C), and exhibiting wafer-scale uniformity (>5in-diameter area). This layer exhibits superior AR performance when compared to conventional counterparts.

Figure 3(a–c) shows scanning electron microscopy (SEM) images of ZnO NRAs grown on MQW solar cells. The average length of the rods in the NRAs is 1μm, and their diameter is 85nm. According to the Figure 3(a), the area density of NRAs is around 2.6×10$^9$ cm$^{-2}$. In Figure 3(b), we can see that the space-filling ratio of NRAs is increased in the bottom region. We can also see that NRAs are terminated with ultrasharp tips, around 200nm in height, visible in Figure 3(c). To evaluate light propagation in MQW solar cells, we carried out FDTD analysis: see Figure 4(a–c). The wavelength chosen for all simulations is 415nm, where a noticeable enhancement of EQEs by ZnO NRAs is observed. The values of the steady-state optical power integrated over MQW regions is 0.72 for bare devices, 0.80 for flat-topped NRAs, and 0.83 for the syringe-like NRAs. These results indicate that the NRAs not only facilitate wave propagation across interfaces but also increase the lateral distribution of fields as they do so. Figure 5 shows the current density-voltage curves of solar cells measured when illuminated by an air mass 1.5 international-standard solar simulator at a power level of 100mWcm$^{-2}$. Compared with the bare surface, the syringe-like

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NRAs lead to an increase in the short-circuit current density \( J_{SC} \), indicating an enhanced solar absorption of the MQWs. The enhanced \( J_{SC} \) increases the conversion efficiency \( \eta \) up to 0.6\%, an improvement in \( \eta \) of \(~36%\) as compared with the bare surface.

In summary, we have described two situations in which nanostructures can effectively improve the efficiencies of both LEDs and solar cells. We incorporated SiO\(_2\) NRAs onto the surfaces of InGaN-based MQW LEDs to improve light extraction from the active regions, and used syringe-like ZnO NRAs to boost the light-collection efficiency of MQW solar cells. Simulations based on FDTD analysis reveal that light propagation across the air/device interface is greatly improved on the application of antireflective nanostructures. We attribute the superior photon management of NRAs to subwavelength dimensions and geometries, improving surface reflection via a graded index profile. The design concept and fabrication techniques adopted here provide a viable scheme for photon collection in a wide variety of optoelectronic devices. We continue to develop novel nanostructures and sophisticated fabrication techniques, and to explore the excellent optoelectronic performance of InGaN-based MQW devices.

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**References**


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