High Output Power Density and Low Leakage Current of InGaN/GaN Nanorod Light Emitting Diode with Mechanical Polishing Process

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Abstract

We improve our fabrication of nanorod LED with mechnical polishing method. Our nanorod LED can achieve 6807mW/cm^2 of output power density at 32A/cm^2 of injection current density. The reversed-bias leakage current has also been reduced to nA level with the mechanical polishing process. Moreover, the investigation of the droop effect for such a nanorod LED array reveals that junction heating is responsible for the sharp decrease at the low current.

INTRODUCTION

The crisis of energy is an inevitable problem in our future not faraway. Solid-State lighting device can provide a new way of human illumination which consume much less energy compared to conventional lamps. It is imperative that LED becomes the most important role in this revolution. The field of high power SSLD has been ruled by GaN based LED over a decade. Recently, many studies of GaN based nanorod structured LED has been reported. Not only the higher surface to volume ratio of nanorod structure could increase the light extraction efficiency of LED, but also the low-dimensional characteristic of nanorod intrigue us to study the physical confinement effect of carriers, photons and phonons.

The crucial issue of nanorod LED fabrication is to prevent the P-N short circuit while making the P-type contact. There are several solutions and achievements, including our previous work which realized nanorod LED by inserting space layer [1], photo-enhanced wet (PEC) chemical oxidation of GaN to reduce reversed bias current to the level of µA [2] and oblique indium tin oxide(ITO) deposition [3] can achieve output power density of 3700mW/cm^2 at the current density of 22.22A/cm^2.

In this study, we present a new method to fabricate GaN nanorod structured LED easily which leads to lower reversed bias current, uniform light emission and high out put power density.

FABRICATION

The GaN based LED sample is grown by metal organic chemical vapor deposition (MOCVD) on c-plane sapphire substrate. The epi-structure is composed of a 25nm GaN buffer layer, a 2µm Si doped n-type GaN layer, a five period of $In_xGa_{1-x}N$/GaN multiple quantum well (MQW) structure in which each period is 17nm, and a 160nm Mg doped p-type GaN layer. The average composition x of indium is around 0.2 with the quantum well thickness 3nm. The nanorods are defined on the planar LED structure by spin coating a monolayer of silica nano-particles as the etch mask. The detail of nanorod LED fabrication was reported in our previous work[1]. Figure 1. is The SEM (scanning electron microscopic) image which shows the nanorod structures with 100nm in diameter and about 300nm in depth.

In order to prevent the P-N short circuit while the fabrication of metal contact, 100nm SiO_2 is deposited on the nanorod surface by plasma enhanced chemical vapor deposition (PECVD) as the passivation layer.

Next, we use mechanical polishing process to remove SiO_2 on the top of nanorods. This is similar to the chemical mechanical polishing (CMP) process which is known well in the IC fabrication industry but here we only choose the mechanical part of polishing effect. Figure 2. is the macro sketch of this method, we attach our sample on a copper column then put it on a rotational platen. As we know the surface microhardness of GaN is between 1200-1700 kg mm^{-2} which is more harder than 790 kg mm^{-2} of SiO_2 [4,5], so we can remove SiO_2 layer without damaging GaN by controling the force properly on the copper column. We use Al_2O_3 particles slurry to perform the mechanical polishing process which is shown in figure 2. The particles size of Al_2O_3 is about 800nm. Figure 3. shows the micro sketch of this process. After the top area of SiO_2 layer is removed, we put on thin metal Au/Ni (5nm/5nm) as current spreading layer and Au/Ti (120nm/10nm) on both p-mesa and n- mesa as metal pad. Figure 4. shows the sketch of our nanorod LED.

RESULTS & DISCUSSION

As shown in Figure. 5., the device show a well-rectified diode behavior with a current ratio 3983 at +-5V and the leakage current at -5V is about 4.77nA..

The dash line in Figure 5. shows 7.35 ideality factor of nanorod LED which is based on the diode equation

$I=I_0[\exp(Ve/nkT)-1]$, n is the ideality factor [6].
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The ideality factor of GaN based diode with multiple quantum wells is usually in the range between 5~7[7,8], which is higher than the n of common diode(n=1~2). Furthermore, the fabrication of nanorod structure diode will damage the surface of devices easily which also contribute to high ideality factor (10 and 18 [9,10]). For the relative low ideality factor of our MQW nanorod structured LED, we suggest that the SiO_2 layer passivated the surface damage through the whole fabrication process.

The luminescence-current (L-I) behavior of the nanorod LED array was measured at room temperature using an integrating sphere. Figure 6. is the luminescence-current density curve. It is shown that at $32A/cm^2$, the luminous intensity is $6807mW/cm^2$. The out put power of our device is the highest among similar devices reported so far. The inset of Figure 6. shows the uniform light emission surface picture of nanorod LED at 1mA which proves the great uniformity of the controlled mechanical polishing process over the whole device.

Next we want to discuss the external quantum efficiency (EQE), which is defined as the ratio between the photons extracted to free space and carriers injected to the device (assuming the same area size as the p-mesa). Usually, a so-called efficiency droop phenomena will be observed as the injection current increase. Such an interesting phenomenon leads us to study the droop effect in the nanorod LED array. Typically, for planar GaN based LED structure, the root causes of efficiency droop may be attributed to various device phenomena such as the Auger recombination, junction heating, and polarization induced carrier overflow [11-14].

In order to simplify the case, the EQE of nanorod device was extracted at both DC (100% duty cycle) and pulsed (1% duty cycle with the cycle period of 50ms) currents. The normalized EQE vs. injection current for both bias conditions are plotted in Figure 7.. Basically, the heating effect can be mitigated at the 1% duty cycle. The EQE curve at 1% duty cycle shows a nearly constant decreasing trend (with the slope $-7.69\ x10^{-3}\ (A/cm^2)^{-1}$), which is close to that of the 100% duty cycle case at the high current level (slope= $-6.45x10^{-3}\ (A/cm^2)^{-1}$)). As we compared both cases, the rapid EQE decrease between 1.6 and $8A/cm^2$ (slope= $-8.3\ x10^{-2}\ (A/cm^2)^{-1}$)) in Figure. 7 is mainly associated with the thermal effect, while the decrease beyond $8A/cm^2$ is related to other factors.

CONCLUSIONS

Nanorod LED array devices were fabricated using the technology of nanosphere lithography. By spin-coating a monolayer of silica nanospheres on top of the GaN based LED epi-structure, and followed by semiconductor etching, the MQWs nanorod structure was realized. The nanorod sidewalls were passivated by PECVD grown SiO_2 and the p-type GaN tips were exposed by chemical mechanical polishing. We achieve a reverse leakage current of 4.77nA at -5V, an ideality factor of 7.35, and an optical output intensity of $6807mW/cm^2$ at the injection current density of $32A/cm^2$ with very high nanorod light emitting uniformity. Moreover, the study of droop effect for such a nanorod LED array reveals that junction heating is responsible for the sharp decrease at the low current between $1.6A/cm^2$ and 8 A/cm^2.

FIGURES

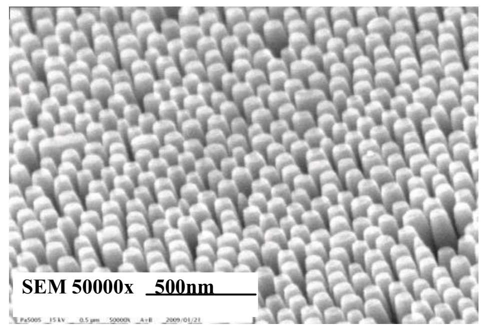

Figure 1. The SEM of nanorod structure with 100nm in diameter and 350nm in depth.

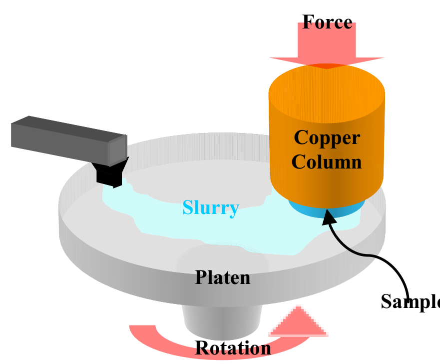

Figure 2. The macro schematic diagram of mechanical polishing process.

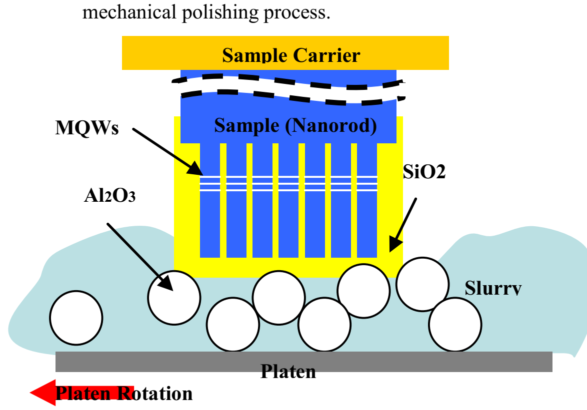

Figure 3. shows the micro schematic diagram of mechanical polishing process.

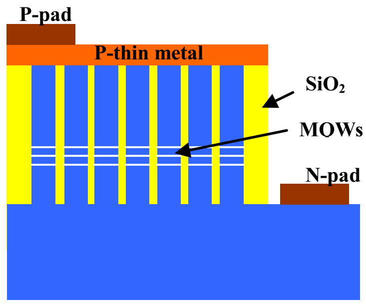

Figure 4. shows the schematic diagram of our nanorod LED.

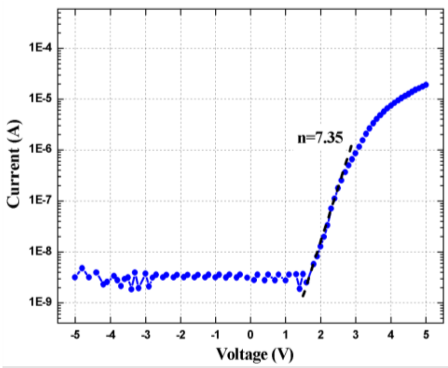

Figure. 5. The diode curve of nanorod LED ploted in semi-log scale. N is the ideality factor.

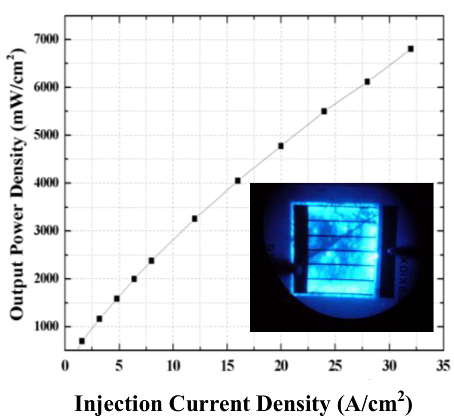

Figure. 6. The L-I curve of nanorod LED (Inset is the light emission picture at 1mA injection current).

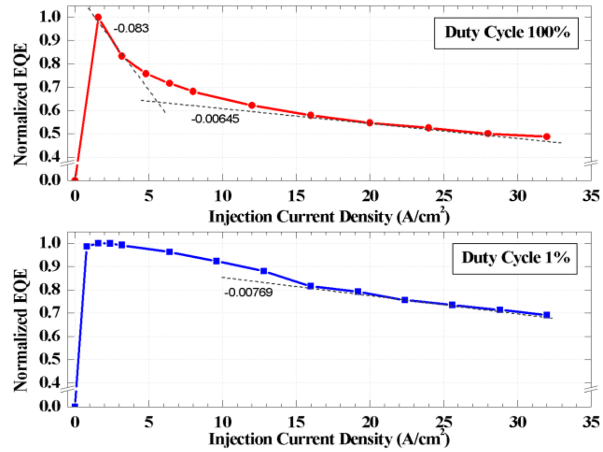

Figure. 7. Normalized EQE at (a)100% and (b)1% duty cycles.

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