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# Nanoscale Ni/Au wire grids as transparent conductive electrodes in ultraviolet light-emitting diodes by laser direct writing

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ABSTRACT

Laser direct writing was applied for fabricating Ni/Au wire grid structure as transparent conductive electrode (TCE) of near ultraviolet (UV) light-emitting diodes (LEDs). Effect of period of Ni/Au wire grid on optical and electrical properties of UV LED was investigated. At the same wire width nearly 600 nm, the UV LED with small period of Ni/Au wire grid showed higher light output power (LOP) and lower forward voltage due to the lower sheet resistance and more uniform current spreading. Compared to Ni/Au wire grid, the UV LED with Ni/Au thin film TCE showed higher LOP and lower forward voltage because of better current spreading, which indicated that current spreading was more important than the light absorption of the metal materials. In addition, the UV LED with indium tin oxide (ITO) TCE exhibited a higher LOP than that of UV LED with Ni/Au thin film because of the high transmittance of ITO, which revealed that the transparency of material played a major role in improving the LOP when the Ni/Au thin film and ITO exhibited a similar current spreading.

## 1. Introduction

It is common sense that ultraviolet light has considerable potential applications such as medical equipment disinfection, water purification, medical treatments and tableware disinfection. Gallium nitride (GaN) based near ultraviolet (UV) light-emitting diodes (LEDs) could be a perfect light resource for these applications because of the high efficiency and long lifetime [1–7]. The light output power (LOP) of LED is closely related to light extraction efficiency. The forward voltage is a significant parameter to evaluate the current spreading that plays an important role in improving LOP [8]. For higher light output power (LOP) of the LED, silver nanowires [9,10] and copper nanowires [11–13] have been investigated, which have attracted much attention for fabricating transparent conductive electrode (TCE) because of the excellent electrical and optical characteristics. But the metal nanowire has some disadvantages such as poor adhesion to the substrate, easily to be oxidized and electrode failure due to the joule heat [14] that makes the metal nanowire cannot be widely applied before these drawbacks are solved. In addition, some special materials such as graphene [15–17] and carbon nanotube [18,19] have also been demonstrated for TCE. However, graphene and nanotube have high sheet resistance, leading to serious current crowding effect and poor device reliability.

To improve the light extraction efficiency of the LED, many methods such as surface roughness [20–22], patterned sapphire substrate [23,24], specific textured sidewalls [25,26], patterned ITO [27] and distributed Bragg reflector on the back of the chip [28,29] have been investigated. In addition, the metal wire grid structures have been developed for improving performance of optical device [30–32]. It is noted that the laser direct writing has shown great advantages to writing many kinds of micro and nano structures due to its high resolution and flexibility [33,34]. In this work, we applied laser direct writing technology to fabricate nanoscale Ni/Au wire grid with different periods to evaluate the light extraction efficiency of UV LED. With the laser direct writing technology, we investigated how the periods of Ni/Au wire grid affected the current spreading, forward voltage and LOP of the LED.

## 2. Experimental method

The GaN-based UV LEDs, which were grown on 25-nm-thick low temperature AlGaN nucleation layer in an AIXTRON Crius II_L close coupled showerhead reactor, were composed of a 2.75-μm-thick undoped GaN layer grown at 1025 °C, a 90-nm-thick n-AlGaN layer (Si doping = $2 \times 10^{18}$ $cm^{-3}$) at 970 °C, a 2.23-μm-thick heavily Si-doped n+-GaN layer (Si doping = $1.5 \times 10^{19}$ $cm^{-3}$) at 1025 °C, a

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30-nm-thick n-AlGaN layer (Si doping = $9 \times 10^{18}$ $cm^{-3}$) at 1025 °C, a 170-nm-thick lightly doped n-GaN layer (Si doping = $9 \times 10^{17}$ $cm^{-3}$) at 1025 °C, a 144-nm-thick InGaN/AlInGaN superlattice at 815 °C, an InGaN/AlInGaN multiple quantum wells (MQWs) active region including six pairs of 2.8-nm-thick InGaN well layers at 742 °C and 12-nm-thick AlInGaN barrier layer at 837 °C, a 19-nm-thick AlInGaN layer (last quantum barrier) at 837 °C, a 28-nm-thick p-AlInGaN layer (Mg doping = $1.7 \times 10^{20}$ $cm^{-3}$) at 920 °C, a 26-nm-thick p-AlInGaN/InGaN SLs (Mg doping = $1.7 \times 10^{20}$ $cm^{-3}$) at 920 °C, a 50-nm-thick p-GaN layer (Mg doping = $6 \times 10^{19}$ $cm^{-3}$) at 940 °C, and a 10-nm-thick heavily Mg-doped p+-GaN layer (Mg doping = $1.6 \times 10^{20}$ $cm^{-3}$) at 710 °C.

An inductively coupled plasma (ICP) etching based on $BCl_3/Cl_2$ mixture gas was used to form GaN mesa [35]. The Ni (3 nm)/Au (3 nm) wire gird with different periods was formed on p+-GaN layer by laser direct writing. For comparison, a full area semi-transparent Ni (3 nm)/Au (3 nm) thin film and 230-nm-thick ITO TCEs were also deposited on p + -GaN layer. Cr/Pt/Au metallization was deposited as p-type and n-type electrodes. Finally, the UV LED wafers were diced into chips with size of 305 × 330 $\mu m^2$. The peak wavelength of UV LED is 395 nm. The light output power-current-voltage (L-I-V) characteristics of UV LEDs were measured using a semiconductor parameter analyzer (Keysight B2901A) and an integrating sphere.

Fig. 1 shows a schematic illustration of the laser direct writing process, including coating, exposure and developing. In addition, cleaning and hot bake are needed to get good results. Spin coating is the first step for laser direct writing. It is important to set the rotated speed and coating time that can determine the thickness of the photoresist layer. Then the hot baking that comprises baking temperature and baking time is required to bake the photoresist. After that, we use laser direct writer to expose the photoresist layer to obtain the wire grid structure, and the width of the wire grid structure is about 600 nm. The laser focus has two moving directions, including scanning direction and step direction. At the scanning direction, the scanning speed is 400 mm/s. At the step direction, the distance of moving one step is 40 nm.

Fig. 2 shows the image of PICO Master 100 laser direct writer (4PICO.BV, Netherlands) and its exposure module. After the exposure process, the LED wafer with photoresist layer was put into developing solvent to remove the photoresist of the exposed area. Then the grooves of the wire grid were obvious as shown in Fig. 1. After laser direct writing process, Ni/Au films were deposited on the wire grid structure. For lift-off process, the acetone was used

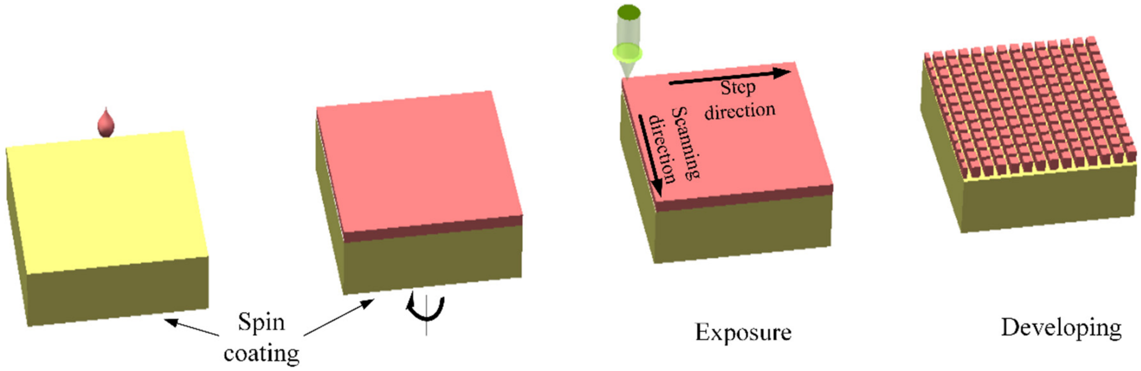

**Fig. 1.** Schematic illustration of laser direct writing. The moving direction of the laser focus consists of step direction and scanning direction. The scanning speed is 400 mm/s and the step distance is 40 nm.

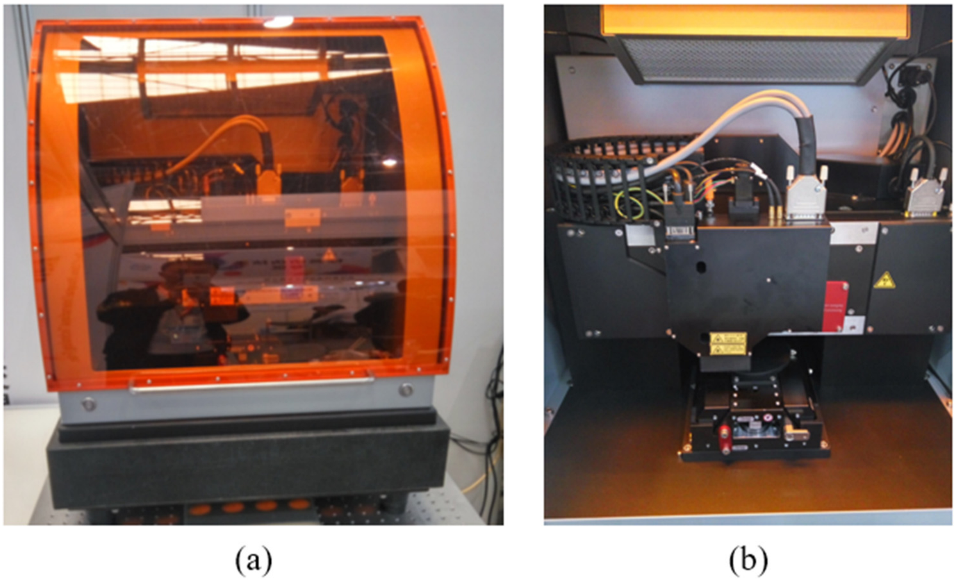

**Fig. 2.** Image of laser direct writer (a) and the details of the direct writing module (b). The maximal direct writing area is 100 mm × 100 mm.