Technical White Paper – Light Extraction Aps

1. Abstract

A new way of compact periodic structures patterning without any costly material in the process is developed. This method can be used on LEDs with smooth surfaces. In the meanwhile, another method mainly based on dry etching technique has been invented to be applied to high power vertically structured LEDs with structured (or uneven) surfaces. Both methods result in an enhancement of more than 50% in photoluminescence (PL).

2. Introduction

Although the market for LED is booming, LED manufacturers are under great pressure to continually reduce prices and increase their competitiveness.

Nowadays, LED producers annually spend more than € 1 billion on R & D, most of which is estimated to be geared towards developing more efficient LEDs. The less effective the LED is, the less light it emits and the hotter it gets. Low efficiency also leads to greater energy needs and more heat creates the need for mechanisms to release it.

Suppression of total internal reflection loss (TIR), arising from the abrupt refractive index difference at the interface between LED surface and surroundings, is crucial for enhancing the light extraction efficiency. Surface patterning can effectively reduce TIR loss, thus increase LED efficiency. The usual patterning way in industry is quite simply, yet not very effective in enhancing LED efficiency due to the relatively large structures formed on the surface. Several research results have shown that it would be ideal if the surface texture size can be compared to or even less than the wavelength of the light emitted (400 nm for blue light LED). Before this project started, it is already possible to create such structures, but only with methods that are lengthy and thus costly. And time is a very important factor since the major manufacturers produce 4-5 billion LEDs per month.

With the support of EUDP project, we have developed two different nano-patterning methods in order to fabricate nanostructures on galiumnitrid (GaN) LED since most of the LED manufacturers are using GaN rather than other materials.

One method, based on UV lithography and dry etching, realizes periodic regular cone structures which can be used on LEDs with smooth surfaces. This method doesn't need any expensive material or metal and can be easily transferred to LED wafers of any size. The highest enhancement of PL for a certain size is 78%.

The other method is developed specifically for high power vertically structured LED which is commonly used in industry nowadays. Since the wafer of this type has uneven surface and can not be treated in high temperature or strong acid environments, fabrication mainly based on dry etching is deveoped. Compact stochastic nano pillar structures are formed and PL improvement of over 180% has been achieved.

3. Technical Results

- *Compact periodic cone-structure patterning*

For wafers with smooth surface, we have developed a surface compact periodic cone-structure forming method on GaN based on UV lithography and dry etching technique without any costly materials. Although it is only tested on small chips and 2” wafers, it can be easily transferred to 4” and even 6” wafers when they become commercially available. Moreover, test on other materials, e.g. SiC, has also been successfully done. The following are the results of this method.

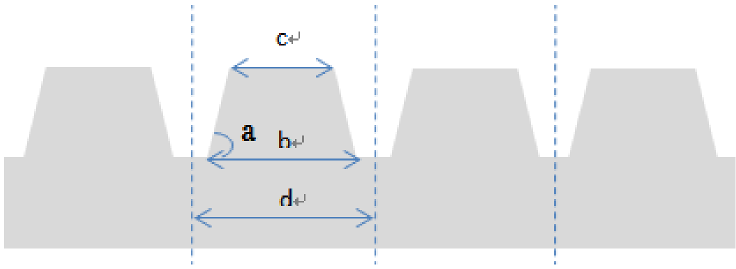

Fig 1. Schematic cross-sectional view of the chip with surface compact cone structures.

Figure 1 shows the schematic cross-sectional view of the chip with surface compact cone structures. According to the optimized simulation results, the dimensions and period of the cone structures should meet some requirements. As shown in Fig. 1, c and b are the diameters of the upper and lower surfaces of the cone structures, respectively. d and a are the periodic length and angle of the cones, respectively. Since the resolution of the aligner is 1 µm, the designed gap value “g” between two cones of the resist is designed to be 1 µm and 800 nm. Meanwhile, three different periodic lengths (d=1600 nm, 2600 nm and 3300 nm) were chosen in the fabrication.

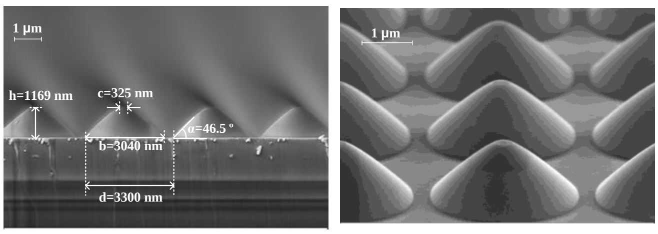

Fig 2. SEM picture of cross-sectional view of the chip with surface compact cone structures.

As shown in Fig. 2, compact cone structures with designed dimensions of d=3300 nm and g=1 µm were fabricated on GaN. The diameters of the upper and lower surfaces of the cones are 325 nm and 3040 nm respectively. The cone height and angle are 1169 nm and 46.5° respectively.

Two other cone structures on GaN with designed dimensions of d=2600 nm and d=1600 nm were shown in Fig. 3(a)-(b) and (c)-(d), respectively. The dimensions and period of the above three cone structures were displayed in tab. 3 and they well fullfilled the requirements.

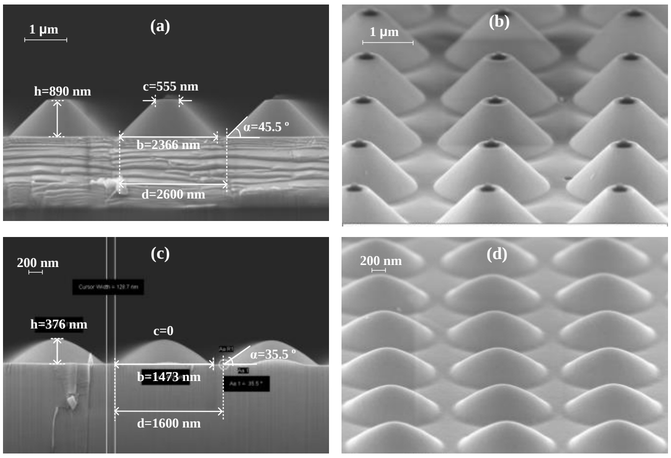

Fig 3. SEM pictures of compact cone structures with dimensions of (a) and (b) d=2600 nm, g=1µm; (c) and (d) d=1600 nm, g=800 nm.

Table 3. cone structures with different dimensions

Designed dimensions	period d (nm)	c & b length (nm)	a (degree)	height (nm)
G1000D3300	3300	325 & 3040	46.5	1169
G1000D2600	2600	555&2366	45.5	890
G800D1600	1600	0 & 1473	35.5	376

In order to evaluate the PL enhancement of the GaN chips after surface treatment using our method, cones with different etching depth were fabricated and the PL spectra of the chips were measured and compared. SEM pictures of compact cone structures with heights of 575 nm, 923 nm and 1169 nm were shown in Fig. 4(a)-(c), respectively. The designed period and gap were 3300 nm and 1 µm, respectively despite the different heights. Compared with the LED without any surface treatment, the measured PL at the peak wavelength of the ones with the above three cone heights structures were enhanced obviously by 47%, 78% and 68%, respectively, as we can see in Fig. 5. The optimized cone height in this case is about 900 nm.

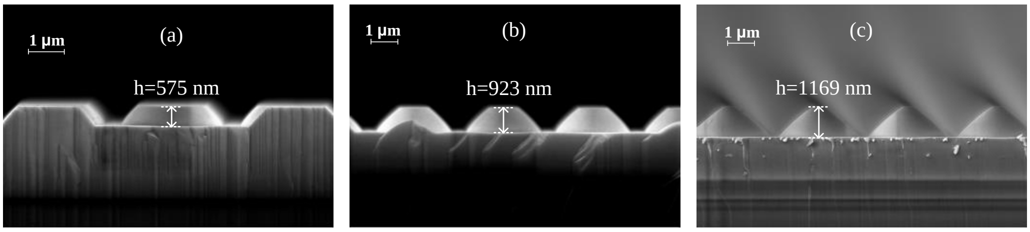

Fig 4. SEM pictures of compact cone structures with heights of (a) 575 nm, (b) 923 nm and (c) 1169 nm. The designed periods and gaps of the three cones are 3300 nm and 1 µm, respectively.

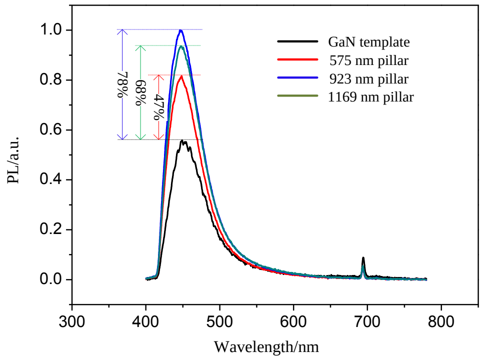

Fig 5. Measured PL spectra of the GaN chips with/without surface compact cones structures.

SEM pictures of compact cone structures with heights of 166 nm, 209 nm, 262 nm and 322 nm were shown in Fig. 6(a)-(d), respectively. The designed period and gap of the four different height cones were 1600 nm and 800 nm, respectively. Compared with the LED without any surface treatment, the PL of the ones with the above four cone structures were enhanced by 13%, 19%, 47% and 32%, respectively, as we can see in Fig. 7. The optimized cone height in this case is about 260 nm.

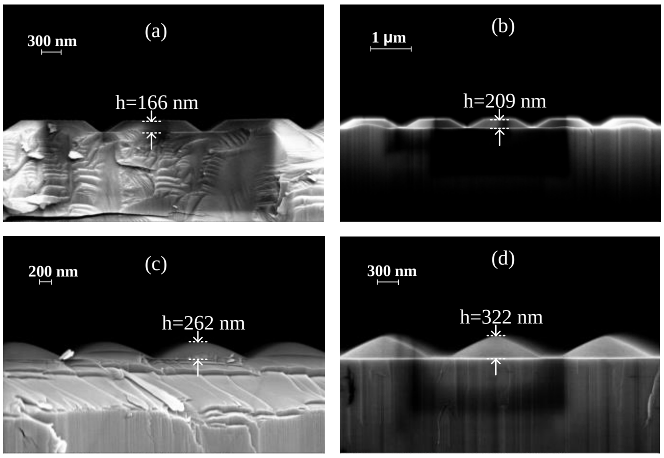

Fig 6. SEM pictures of compact cone structures with heights of (a) 166 nm, (b) 209 nm, (c) 262 nm and (d) 322 nm. The designed periods and gaps of the three cones are 1600 nm and 800 nm, respectively.

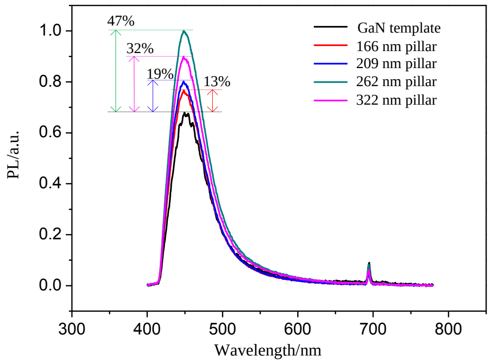

Fig 7. Measured PL spectra of the GaN chips with/without surface compact cones structures.

- *Compact stochastic nano pillar-structure patterning*

The other method was developed especially for vertically structured LED with uneven surface to form compact stochastic nano pillar structures because the first method could not be applied in this case. The height of the pillars varies from 100-200 nm and the width varies in dozens of nano meters, as shown in Fig 8. The measured PL spectral in Fig. 9 shows an enhancement of 185% at the peak wavelength.

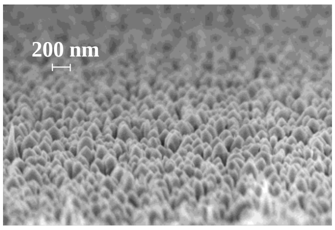

Fig 8. SEM picture of tilted view of compact stochastic pillar structures.

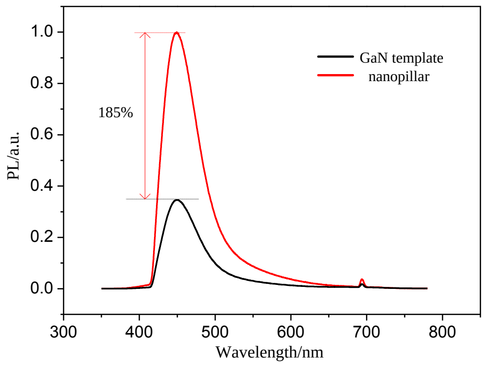

Fig 9. Measured PL spectra of the GaN chips with/without surface compact nanopillars.

4. Conclusion and perspective

Together with DTU Photonics, Light Extraction has invented two new methods of compact nano structure patterning on GaN wafer, resulting in an improvement of more than 50% in photo luminescence. The methods can be used, respectively, on LEDs with smooth surface and/or vertical structures. Both of them are suitble for large-scale production in industry.

The demand for more efficient LEDs come especially from producers' B2B-customers. These customers are partly manufacturers of various luminaries, partly manufacturers of televisions, tablets and phones etc., where LED are used to illuminate screens from behind. The higher the efficiency is, the less the LEDs to be used and the cheaper the products become. Moreove, LEDs with higher efficiency open the doors to new applications, such as car headlight, outdoor lighting and ultraviolet light emitting, which may be used in disinfection of air and fluids.

The demand for more powerful and cheaper LEDs can be clearly seen in the development, where the price of LED falls 30% per year while the efficiency increases.

There are over 50 LED manufacturers in the world, and although they each have their different ways of producing LEDs, they are all facing the same technical challenge in relation to the structure patterning of surfaces. Our technology can help them solve this problem and increase the efficiency of LED. Futhermore, technology development is always needed for the fast changing LED structures and packages to meet requirements for different applications from company to company.

Acknowledgement

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