

## Research Article

# Enhanced Light Extraction from a GaN-based Light Emitting Diode with Triangle Grating Structure

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**Abstract:** We propose a simple method to improve the light extraction in GaN based light emitting diode. Conventional light emitting diode has an extraction limitation due to the total internal reflection which occurs at the interface between GaN and air. By using periodic grating etched at the GaN layer, we can couple more emitting light out of the active layer. Tapering the grating structure would facilitate the impedance matching between GaN light emitting diode and air, which can enhance broadband light extraction. We use finite difference time domain method to numerically find the best tapering grating structure. The numerical experiment demonstrate an enhance factor 4 of our proposed structure compared with the conventional one over broad band spectrum.

**Keywords:** Grating, LED, impedance matching

## INTRODUCTION

Illumination revolution is now on the way to shape the conventional way that we light up our life. Being one of the important semiconductor material, Gallium nitride (GaN) based Light Emitting Diode (LED) receives a lot of attention due to its applications in digital system, flat panel displays, signal transformation and optical interconnects in optoelectronic system (Nakamura *et al.*, 1994; Nakamura *et al.*, 1995; Nakamura *et al.*, 1997; Choet *et al.*, 2006; Kojima *et al.*, 2007; Kimet *et al.*, 2007; Wang *et al.*, 2009; Wierer *et al.*, 2009). As a particular and important application, using GaN based LED to realize general illumination become popular for its long-life time, robust and energy conservation properties of GaNLED (Schubert, 2006).

Although GaN based LED has several advantages compared with other material, it, however, also suffers from some limitations. On the early stage of GaN based LED's development, the rapidly reduction of output efficiency is because the degree of transparency become worse along with the increasing of the device's temperature. It is well know that the ultraviolet radiation, which arises together with the interbandradiative recombination of GaN material, would degrade the transparency degree of polymer. Metal electromigration is also a crucial factor which could even destroy the working device. There are other factors which would degrade the performance of the GaN based LED, such as P type ohmic contact degradation and deep level and the radiation recombination center increase etc. All the mentioned factors are electric properties of the device which instinctively has an effect on the efficiency of the LED.

On the other hand, the high dielectric constant (5.76) of the p-GaN would pose a limitation on the optical extraction efficiency of GaN based LED. For the general LED device, air is the medium of the output region. Therefore, the high dielectric constant contrast between p-GaN (5.76) and air (1) would result in a critical angle at the interface between p-GaN and air. It means that most of the radiations whose direction of emitting does not locate inside the cone with the critical angle of the total internal reflection are suffered from reflected at the interface. Large amount of the energy is confined at the p-GaN layer. As a result, the External Quantum Efficiency (EQE) of the conventional p-GaN based LEDs is as low as a few percent (Sheu *et al.*, 2007).

There were certain efforts to enhance the extraction ratio of the LED. Modification of the emitting surface (Huh *et al.*, 2003; Fujii *et al.*, 2004; Jin *et al.*, 2012) could be the most convenient way to improve the efficiency. The mechanism of improvement is to enhance the interaction between guided modes inside the LED and the outer space. With the grating attached with the LED, outside propagating waves could be coupled into the LED more easily. Because of the time reversal symmetry, the radiation inside the LED should obtain extraction ratio enhancement due to the presence of the grating.

At the same time, attached tapering structure on the top of the LED could facilitate the impedance matching between the LED and the free space. In this study, we investigate the effect of different grating structure fabricated at the surface of LED.

**METHODOLOGY**

Finite Difference Time Domain (FDTD) method is based on the finite difference method. It uses finite difference to represent derivative and solves the electromagnetic boundary problem which can realize the discrete sampling of spatial and temporal derivative.

The distributions of electric and magnetic field are restricted to the Yee unit cell, which is the basic form for numerically solving the Maxwell equation using FDTD method. Let's consider the Maxwell equation in the medium without the electric current and magnetic current.

$$\begin{aligned} \nabla \times E &= -\frac{\partial \vec{B}}{\partial t} \\ \nabla \times H &= \frac{\partial \vec{D}}{\partial t} \\ \nabla \times E &= -\frac{\partial \vec{B}}{\partial t} \\ \nabla \times H &= \frac{\partial \vec{D}}{\partial t} \end{aligned}$$

For the isotropic medium, we have  $\vec{D} = \epsilon \vec{E}$ ,  $\vec{B} = \mu \vec{H}$ . In the Cartesian coordinates, we can write Eq. (1) as:

$$\begin{aligned} \frac{\partial E_z}{\partial y} - \frac{\partial E_y}{\partial z} &= -\mu \frac{\partial H_x}{\partial t} \\ \frac{\partial E_x}{\partial z} - \frac{\partial E_z}{\partial x} &= -\mu \frac{\partial H_y}{\partial t} \\ \frac{\partial E_y}{\partial x} - \frac{\partial E_x}{\partial y} &= -\mu \frac{\partial H_z}{\partial t} \\ \frac{\partial H_z}{\partial y} - \frac{\partial H_y}{\partial z} &= \epsilon \frac{\partial E_x}{\partial t} \\ \frac{\partial H_x}{\partial z} - \frac{\partial H_z}{\partial x} &= \epsilon \frac{\partial E_y}{\partial t} \\ \frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y} &= \epsilon \frac{\partial E_z}{\partial t} \end{aligned}$$

For the two dimensional (x-y plane) case where  $\partial E_{x,y,z}/\partial z$  and  $\partial H_{x,y,z}/\partial z$ , we can obtain two sets of decoupled equations:

$$\begin{aligned} \frac{\partial E_z}{\partial y} &= -\mu \frac{\partial H_x}{\partial t} \\ -\frac{\partial E_z}{\partial x} &= -\mu \frac{\partial H_y}{\partial t} \\ \frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y} &= \epsilon \frac{\partial E_z}{\partial t} \end{aligned}$$

Which is referred to the transverse magnetic polarization and the other one is the transverse electric polarization with electric fields laying in the two dimensional plane (x-y plane).

$$\begin{aligned} \frac{\partial H_z}{\partial y} &= \epsilon \frac{\partial E_x}{\partial t} \\ -\frac{\partial H_z}{\partial x} &= \epsilon \frac{\partial E_y}{\partial t} \\ \frac{\partial E_y}{\partial x} - \frac{\partial E_x}{\partial y} &= -\mu \frac{\partial H_z}{\partial t} \end{aligned}$$

It means that in the two dimensional case, the polarization states can be represented by two kinds of polarization: transverse electric polarization (TE) and transverse magnetic polarization (TM). The combination of these polarizations can be used to qualitatively present the three-dimensional effect. These two sets of equations can be solved by applying difference method in space and time domain. The finite difference scheme is shown in the Fig. 1. As can be seen from Fig. 1, there is displacement between electric field and magnetic field which facilitates the calculation of the finite difference. And the sampling time between electric field and magnetic field is shifted by half time step. The grids of TE and TM polarization are similar, where electric field is substituted by the magnetic field. The discretization of arbitrary function is denoted as:

$$f(x, y, t) = f(i\Delta x, j\Delta y, n\Delta t) = f^n(i, j)$$

Therefore the derivative of function f(x, y, t) can be represented by the central difference method:

$$\begin{aligned} \frac{\partial f(x, y, t)}{\partial x} \Big|_{x=i\Delta x} &\approx \frac{f^n(i+\frac{1}{2}, j) - f^n(i-\frac{1}{2}, j)}{\Delta x} \\ \frac{\partial f(x, y, t)}{\partial y} \Big|_{x=j\Delta y} &\approx \frac{f^n(i, j+\frac{1}{2}) - f^n(i, j-\frac{1}{2})}{\Delta y} \\ \frac{\partial f(x, y, t)}{\partial t} \Big|_{x=n\Delta t} &\approx \frac{f^{n+\frac{1}{2}}(i, j) - f^{n-\frac{1}{2}}(i, j)}{\Delta t} \end{aligned}$$

Let's take the first equation of Eq. (4) as an example. By using the FDTD, this equation is read as:

$$\frac{H_z^{n+1/2}(i+\frac{1}{2}, j+\frac{1}{2}) - H_z^{n+1/2}(i+\frac{1}{2}, j-\frac{1}{2})}{\Delta y} = \epsilon(i+\frac{1}{2}, j) \frac{E_x^{n+1}(i+\frac{1}{2}, j) - E_x^n(i+\frac{1}{2}, j)}{\Delta t}$$

Equation (7) takes the form:

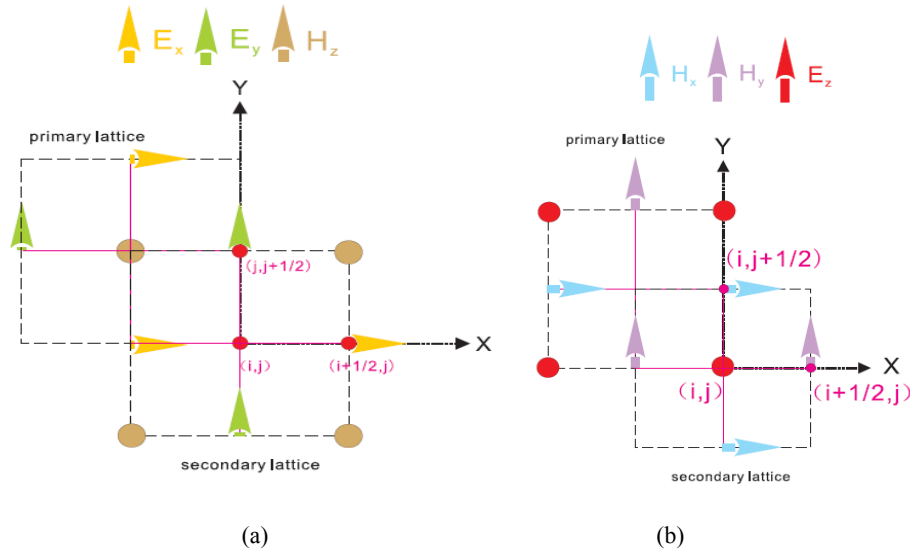


Fig. 1: Yee unit cell for the two-dimensional FDTD scheme of transverse electric polarization and transverse magnetic polarization.  $(i, j)$  stands for the location of the spatial grid. And the components of the electromagnetic field are indicated by the insets

$$E_x^{n+1}(i + \frac{1}{2}, j) = E_x^n(i + \frac{1}{2}, j) + \frac{\Delta t}{\epsilon(i + \frac{1}{2}, j)} \frac{H_z^{n+1/2}(i + \frac{1}{2}, j + \frac{1}{2}) - H_z^{n+1/2}(i + \frac{1}{2}, j - \frac{1}{2})}{\Delta y}$$

The other equations of Eq. (4) can be written as the similar form:

$$E_y^{n+1}(i, j + \frac{1}{2}) = E_y^n(i, j + \frac{1}{2}) - \frac{\Delta t}{\epsilon(i, j + \frac{1}{2})} \frac{H_z^{n+1/2}(i + \frac{1}{2}, j + \frac{1}{2}) - H_z^{n+1/2}(i - \frac{1}{2}, j + \frac{1}{2})}{\Delta x}$$

$$H_z^{n+1/2}(i + \frac{1}{2}, j + \frac{1}{2}) = H_z^{n-1/2}(i + \frac{1}{2}, j + \frac{1}{2}) - \frac{\Delta t}{\mu(i + \frac{1}{2}, j + \frac{1}{2})} \left[ \frac{E_y^n(i + 1, j + \frac{1}{2}) - E_y^n(i, j + \frac{1}{2})}{\Delta x} - \frac{E_x^n(i + \frac{1}{2}, j + 1) - E_x^n(i + \frac{1}{2}, j)}{\Delta y} \right]$$

Equation (8-10) shows the case of FDTD realization of the transverse electric polarization. Using the formulism, we can numerically calculate the electromagnetic dynamics of the two dimensional system. The transverse magnetic polarization case is similar as follow:

$$H_x^{n+1/2}(i, j + \frac{1}{2}) = H_x^{n-1/2}(i, j + \frac{1}{2}) + \frac{\Delta t}{\mu(i, j + \frac{1}{2})} \frac{E_z^n(i, j + 1) - E_z^n(i, j)}{\Delta y}$$

$$H_y^{n+1/2}(i + \frac{1}{2}, j) = H_y^{n-1/2}(i + \frac{1}{2}, j) + \frac{\Delta t}{\mu(i + \frac{1}{2}, j)} \frac{E_z^n(i + 1, j) - E_z^n(i, j)}{\Delta x}$$

$$E_z^{n+1}(i, j) = E_z^n(i, j) + \frac{\Delta t}{\epsilon(i, j)} \left[ \frac{H_y^{n+1/2}(i + \frac{1}{2}, j) - H_y^{n+1/2}(i - \frac{1}{2}, j)}{\Delta x} - \frac{H_x^{n+1/2}(i, j + \frac{1}{2}) - H_x^{n+1/2}(i, j - \frac{1}{2})}{\Delta y} \right]$$

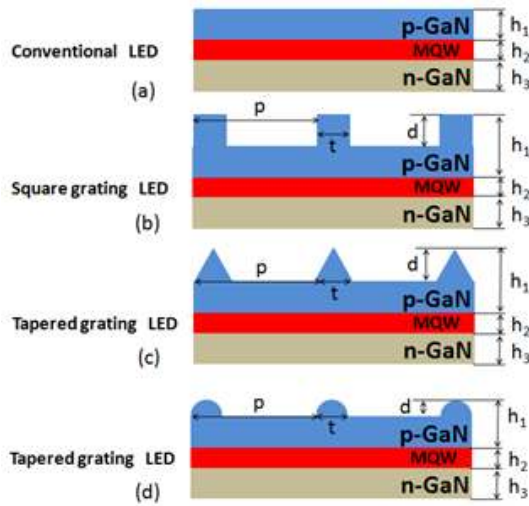
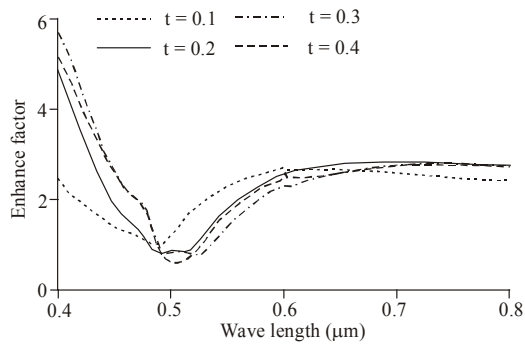
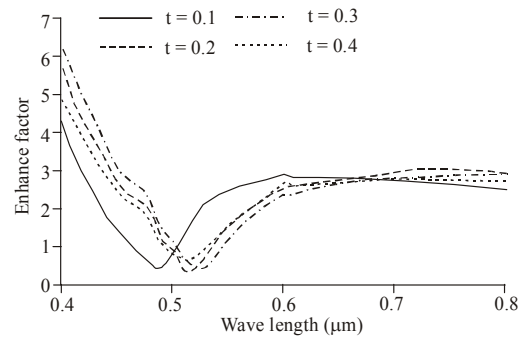


Fig. 2: Cross section views of the conventional LED, square grating LED and tapered grating LED. The thickness of MQW is  $h_2=150$  nm while the thicknesses of p = GaN and n-GaN layer are  $h_1= h_3 = 500$  nm. We can change the grating period  $p$  and the thicknesses of square, triangle and sphere to optimize the extraction ratio

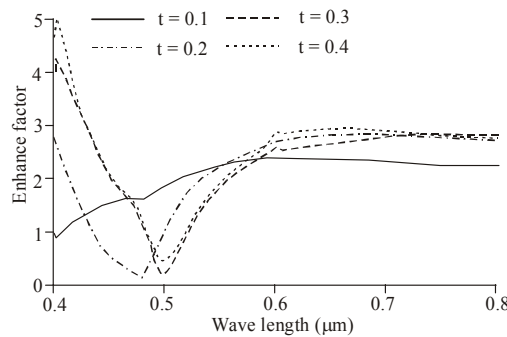
By summing up the results of two polarizations, we can get the qualitative result of the three dimensional



(a)



(b)



(c)

Fig. 3: (a) Enhanced factor vs different  $t$  which is corresponding to Fig. 2b, square grating structure; (b) Enhanced factor vs different  $t$  which is corresponding to Fig. 2c, triangle grating structure; (c) Enhanced factor vs different  $t$  which is corresponding to Fig. 2d, sphere grating structure; the unit of  $t$  is nm

case. We use the Perfect Matching Layer for simulating infinite system, which can absorb any radiation wave from the source and scatter. The FDTD scheme should obtain the Courant stable condition:

$$c \Delta t \leq \frac{1}{\sqrt{\frac{1}{(\Delta x)^2} + \frac{1}{(\Delta y)^2}}}$$

And the dielectric constant can be averaged over the nearest spatial grid when we come across certain dielectric boundary:

$$\varepsilon(i, j) = \frac{1}{4}[\varepsilon(i, +1j) + \varepsilon(i, j-1) + \varepsilon(i, j+1) + \varepsilon(i-1, j)]$$

$$\mu(i, j) = \frac{1}{4}[\mu(i, +1j) + \mu(i, j-1) + \mu(i, j+1) + \mu(i-1, j)]$$

### STRUCTURE DETAIL

The LED structure is shown in Fig. 2a. It is consisted a multi-quantum-well (MQW) structure where the active layer locates. The height of the p-GaN layer is denoted as  $h_1$  while the n-GaN is indicated as  $h_3$ .  $h_2$  represents the height of the MQW. In our interesting wavelength, the refractive index of the GaN

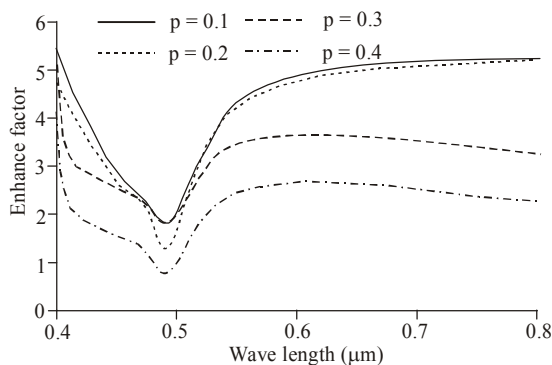


Fig. 4: Enhanced factor vs different period  $p$  which is corresponding to Fig. 2c, triangle grating structure. Here  $t = 100$  nm and  $d = 200$  nm. Here the unit of  $p$  is nm

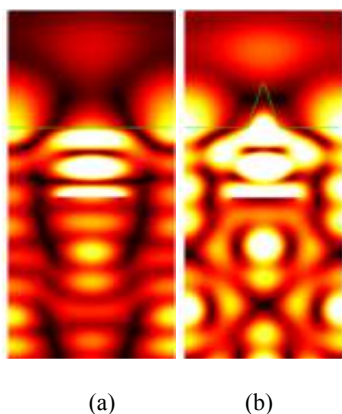


Fig. 5: Electric field distribution when  $t = 100$  nm,  $p = 500$  nm and working wavelength is 550 nm. The green lines outline the boundary of the grating structure. The LED is just shown by one period of the grating structure; both plots share the same color scale

layer is denoted as  $h_1$  while the n-GaN is indicated as  $h_3$ .  $h_2$  represents the height of the MQW. In our interesting wavelength, the refractive index of the GaN is set to be 2.4. Without loss of generality, we choose  $h_1 = h_3 = 500$  nm and  $h_2 = 200$  nm as a reference system and we neglect the conventional thin transparent ITO layer for the convenience of modeling. As can be seen from Fig. 2a, air is the output medium. It means that some light emitted from the active layer would undergo total internal reflection. Such part of light would be confined in the GaN layer which induces the reduction of extraction ratio. If we add some microstructure at the surface of the p-GaN, we can modify the condition of the total internal reflection.

In order to determine the extraction ratio, we calculate the electromagnetic problem by the FDTD method. We choose the source at the top of the MQW layer. And we choose the size of the source similar to a point source which mimics all the possible real-k vectors. The extraction ratio is determined by normalized the transmission of the structure of Fig. 2b

to  $d$  to the case of Fig. 2a, i.e., non-pattern one. As can be seen from the figure,  $h_1$  and  $h_2$  denote the thickness of the p-GaN and n-GaN, respectively. And  $h_1$  represents the thickness of the MQW. The period of the grating is set by  $p$  while the features of the grating unit are marked by  $t$  and  $d$ . For the case of fixed  $p = 500$  nm and  $d = 200$  nm, we calculate the enhanced factor when  $t$  is varying.

Fig. 3a to c show the results which are corresponding to the situation of Fig. 2b to d. As can be seen from these figures, the grating structure can definitely enhance the extraction ratio except for the wavelength near 500 nm. All of them can obtain broad and flat response of the enhancement when the wavelength is larger than 550 nm. We can also identify that the case when the triangle grating structure with feature  $t = 100$  nm is the best one for the enhancement over 530 nm. It can also be concluded from these figures that such grating structure can give an extraction ratio enhancement up to 6 times at the wavelength near 400 nm. It means that such surface texturing method can also be applied to the field of solar cell where the enhancement of light harvest near the ultraviolet is needed. The dips of the enhancement factor near 500 nm are due to geometry of this structure. The size of the source and the period of the grating  $p$  are related to this phenomenon.

The upper results show that by choosing suitable features of the grating structure, we can control the extraction ratio of the LED. As the next step, we consider the influence of the grating period. Fig. 4 shows the result when we fix  $t = 100$  nm and  $d = 200$  nm. As can be seen from the figure, the best period for the triangle grating structure is 100 nm which can obtain more than 4 times enhancement at the wavelength larger than 500 nm. The enhancement factor reduces together with the increasing of the period  $p$ .

## DISCUSSION

For a representative example, we show the electric field distribution when  $t = 100$  nm and  $p = 500$  nm in Fig. 5. As can be seen from the figure, the triangle grating structure can facilitate the impedance matching between the GaN layer and the free space. The enhancement of the near field electric field is also demonstrated.

Adding grating structure on the top of the LED can facilitate the enhancement of extraction ratio. However, it would impose a difficulty on the structure fabrication. At the same time, it would also raise the cost of topical LED. At this moment, electric lithography is the most precise method to fabricate such grating structure. However, it takes long time for fabricating large sample and it is expensive as well. Therefore, searching new

and simple method for texturing the surface of the LED is one of the important problems facing at this field.

### CONCLUSION

We propose a simple method to enhance the extraction ratio of GaN LED. The triangle grating structure is found to be the best candidate for extraction ratio enhancement among the square grating structure, triangle grating structure and sphere grating structure. By choosing suitable parameters, we can obtain more than 4 times enhancement at the wavelength larger than 550nm. The enhancement is due to the enhanced interaction between the guided mode and radiation. We expect this kind of method can be generalized to other fields such as solar cell etc.

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