Monolithic white LED based on $Al_xGa_{1-x}N/In_yGa_{1-y}N$ DBR resonant-cavity*

Chen Yu(陈宇)[1], Huang Lirong(黄黎蓉)[2,†], and Zhu Shanshan(朱珊珊)[1]

(1 College of Optoelectronics Science & Engineering, Huazhong University of Science and Technology, Wuhan 430074, China)

(2 Wuhan National Laboratory for Optoelectronics, Huazhong University of Science and Technology, Wuhan 430074, China)

Abstract: A monolithic white light-emitting diode (LED) with blue and yellow light active regions has been designed and studied. With the $Al_xGa_{1-x}N/In_yGa_{1-y}N$ distributed Bragg reflector (DBR) resonant-cavity, the extraction efficiency and power of the yellow light are enhanced so that high quality white light can be obtained.

Key words: monolithic; white light-emitting diode; distributed Bragg reflector; resonant-cavity

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1. Introduction

For conventional white light-emitting diodes (LEDs), an additional phosphor coating process is needed; furthermore, the performance and lifetime of white LEDs are limited by the degradation of phosphor, especially in the case of high current. As a kind of phosphor-free white LED, monolithic white LED is able to get rid of this disadvantage and has become a hot topic of increasing interest in recent years. A few methods have been proposed to obtain white-light emission in a single-chip without phosphor, e.g. by implanting carbon or by codoping Si and Zn into InGaN/GaN multiquantum well (MQW) active region[1,2], by stacking quantum dots or quantum wells with different sizes or composition[3−6], or by applying indium phase-separated InGaN active layers[7] etc. White light can be obtained by mixing the blue and yellow light. However, for a monolithic white GaN-based LED which has yellow InGaN/GaN quantum-well (QW) and blue InGaN/GaN QW, the internal quantum-efficiency of the yellow QW is usually much lower than that of the blue QW due to the large internal fields and poor crystal growth quality of the high indium-content yellow InGaN well[8], which is a big obstacle for monolithic LEDs to get high colour quality of white light. As it is well known that the extraction efficiency can be enhanced in a resonant-cavity LED (RCLED) owing to the directionality modification of spontaneous emission pattern, which has been widely used to get high-efficiency AlGaInP red LEDs and GaN-based blue, green, UV LEDs[9,10], we propose a new scheme of monolithic white LED based on $Al_xGa_{1-x}N/In_yGa_{1-y}N$ distributed Bragg reflector (DBR) resonant-cavity (RC). The extraction efficiency of the yellow light can be enhanced so that high quality white light can be obtained even if the internal efficiency of the yellow light is relatively lower.

2. Basic structure

The schematic diagram of the proposed monolithic RC-based white LED is shown in Fig.1, which has blue QW and yellow QW to emit blue and yellow light, respectively. The resonant-cavity (RC) is defined by the top and bottom DBR which are formed by stacking different periods of $Al_xGa_{1-x}N/In_yGa_{1-y}N$ alloys. The spontaneous emission from the active regions will be modified by the resonant effect.

In order to increase the proportion of the yellow light in the mixing light, we adjust the parameters of the bottom DBR and the top DBR so that they provide high reflectivity for the yellow light, but relatively low reflectivity for the blue light. Besides, we put the yellow QW in a proper position to maximize the coupling strength between cavity fields and spontaneous emission. Thus, the extraction efficiency of the yellow light is enhanced. Therefore, even if the yellow QW has low internal quantum efficiency, with the enhancement of extraction efficiency by DBR, the power of the emitting yellow light may be improved. So, white light of high color quality is accomplished. The optimal design will be discussed in details in the next section. Here we mainly discuss about the theoretical model for the proposed RC-based white LED.

According to the theoretical model for planer RCLED[9,11], the spontaneous emission is equivalent to an electric dipole. Assuming the refractive index of emitting medium is n_s and reflection coefficients for top DBR and bottom DBR are r_1, r_2 respectively. θ is the internal emission

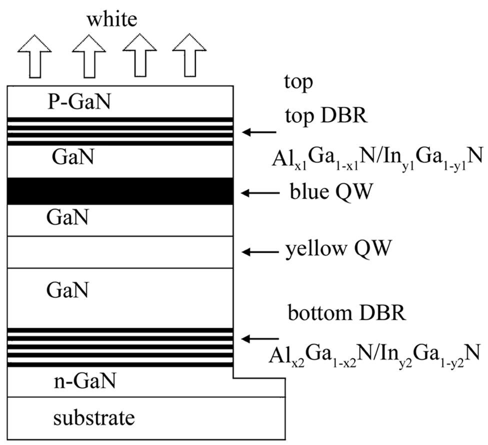

Fig.1. Schematic diagram of the proposed RC-based white LED.

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† Corresponding author. Email: hlr5649163.com

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angle in the emitting medium, and λ is the wavelength of spontaneous emission photon. Then, the emission intensity directed toward the top of the structure is given by[9]

$$I^{\mathrm{or,pol}}(\lambda,\theta)=(1-r_1^2)\times\frac{\left|A_{\uparrow}^{\mathrm{or,pol}}+A_{\downarrow}^{\mathrm{or,pol}}|r_2|\exp(-\mathrm{j}2\phi_{2\mathrm{eff}})\right|^2}{\left|1-|r_1r_2|\exp(-\mathrm{j}2\phi_{\mathrm{eff}})\right|^2},\quad(1)$$

where or=h,v represents the horizontal and vertical dipole, and pol=s, p represents s polarization (TE mode) and p polarization (TM mode); $A_{\uparrow}^{\mathrm{or,pol}}$, $A_{\downarrow}^{\mathrm{or,pol}}$ stand for the source terms for upward emission and downward emission, respectively, and they are both dependent on angle θ. ϕ,ϕ_{eff} and $\phi_{2\mathrm{eff}}$ are as follows,

$$\phi_i=\frac{2\pi}{\lambda}n_{\mathrm{s}}d_i\cos\theta,\quad(2)$$

$$\phi_{\mathrm{eff}}(\lambda,\theta)=\phi_1+\phi_2-\frac{1}{2}\arg r_1-\frac{1}{2}\arg r_2,\quad(3)$$

$$\phi_{i\mathrm{eff}}=\phi_i-\frac{1}{2}\arg r_i,\quad(4)$$

in which d_1 is the distance of electric dipole from the interface with the first layer of the top DBR, and d_2 is the distance of the electric dipole from the interface with the first layer of the bottom DBR; the resonant cavity has length of $L_{\mathrm{c}}=d_1+d_2$. arg r_1 and arg r_2 are the phases for complex reflection coefficients r_1 and r_2, respectively. For quantum well (QW) semiconductor materials, emitting dipoles are not isotropic, then, the angle-dependent and wavelength-dependent emitting intensity is given by[11]

$$I(\lambda,\theta)=\frac{1}{2}I^{\mathrm{h,s}}(\lambda,\theta)+\frac{1}{2}I^{\mathrm{h,p}}(\lambda,\theta).\quad(5)$$

Since spontaneous emission is not monochromatic radiation, the general Lorentzian function[11] can be used to describe the intrinsic spontaneous emission spectrum:

$$\mathrm{rspon}\,(\lambda)=\frac{A}{1+\left(\dfrac{\lambda-\lambda_0}{\sigma/2}\right)^2},\quad(6)$$

in which λ_0 is the peak-wavelength, σ is the full width at half maximum (FWHM) of the QW intrinsic spontaneous emission spectrum, and A is the peak intensity.

The power per unit solid angle and surface $II(\lambda,\theta)$ is then given by[11]

$$II(\lambda,\theta)=\mathrm{rspon}(\lambda)\times I(\lambda,\theta).\quad(7)$$

The overall optical intensity that can be extracted to the outside medium is:

$$P(\lambda)=2\pi\int_0^{\theta_{\mathrm{c}}}II(\lambda,\theta)\sin\theta\mathrm{d}\theta,\quad(8)$$

where $\theta_{\mathrm{c}}=\arcsin(n_{\mathrm{out}}/n_{\mathrm{s}})$ is the critical angle for total internal reflection, with n_{out} the refractive index of the external surrounding medium that usually is air or epoxy resin. Here we take it as air with n_{out} being 1.

For a given wavelength λ, its extraction efficiency $\xi(\lambda)$ is:

$$\xi(\lambda)=\frac{2\pi\int_0^{\theta_c}II(\lambda,\theta)\sin\theta\,\mathrm{d}\theta}{2\pi\int_0^{\pi}II(\lambda,\theta)\sin\theta\,\mathrm{d}\theta}.\quad(9)$$

The overall extraction efficiency η_{extr} is given by the ratio between the optical power emitting in the outside medium and the total optical power radiated by the source,

$$\eta_{\mathrm{extr}}=\frac{2\pi\int_0^{\infty}\int_0^{\theta_c}II(\lambda,\theta)\sin\theta\,\mathrm{d}\lambda\,\mathrm{d}\theta}{2\pi\int_0^{\infty}\int_0^{\pi}II(\lambda,\theta)\sin\theta\,\mathrm{d}\lambda\,\mathrm{d}\theta}.\quad(10)$$

As the RC is formed by the top and bottom DBR, the reflection coefficients also vary with both the wavelength and emission angle. In order to calculate the reflection coefficients, we have to know refractive index first. We use improved refractive index formulas for the $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{N}/\mathrm{In}_y\mathrm{Ga}_{1-y}\mathrm{N}$ alloys proposed by Laws *et al.*[12]:

$$\begin{aligned}n(h\nu)=\Big\{&a(x)(\frac{h\nu}{E_g})^{-2}\Big[2-(1+(\frac{h\nu}{E_g}))^{0.5}\\&-(1-(\frac{h\nu}{E_g}))^{0.5}\Big]+b(x)\Big\}\end{aligned}\quad(11)$$

where E_{g} is the band gap of the material, ν is the frequency of the laser emission, h is the Planck's constant, and $a(x)$ and $b(x)$ are the fitting parameters,

$$\begin{aligned}&a(x)=9.82661-8.21608x+31.5902x^2\\&b(x)=2.73591+0.84249x-6.29321x^2\\&\quad 0<x<0.38.\end{aligned}\quad(12)$$

The reflectivity of the $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{N}/\mathrm{In}_y\mathrm{Ga}_{1-y}\mathrm{N}$ DBR is dependent on the layer thickness of $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{N}$ and $\mathrm{In}_y\mathrm{Ga}_{1-y}\mathrm{N}$, their refractive indices and the number of DBRs. By using transfer-matrix method[13], the reflectivity spectrum of the $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{N}/\mathrm{In}_y\mathrm{Ga}_{1-y}\mathrm{N}$ DBR can be calculated.

3. Optimal design for AlGaN/InGaN DBR

For an $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{N}/\mathrm{In}_y\mathrm{Ga}_{1-y}\mathrm{N}$ DBR, high reflectivity at a yellow light can be obtained by properly selecting content x, y and the number of periods. We need to carefully select contents of Al and In so that not only DBR provides high reflectivity for yellow light but also the lattice mismatch between $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{N}$ and $\mathrm{In}_y\mathrm{Ga}_{1-y}\mathrm{N}$ is small enough to avoid strain relaxation or dislocation. The lattice constant can be easily calculated by Vegard's law. Generally, the refractive index and lattice constant of $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{N}$ decrease when the aluminum content x increases, while those of $\mathrm{In}_y\mathrm{Ga}_{1-y}\mathrm{N}$ increase when the indium content y increases, as shown in Fig.2.

By using optical transfer-matrix method, we calculate the reflectivity spectra of the DBR. We set the Bragg wavelength at 560 nm, and the aluminum and indium content x, y are 0.15 and 0.06. The thickness of $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{N}$ and $\mathrm{In}_y\mathrm{Ga}_{1-y}\mathrm{N}$ is 60 and 59 nm respectively. The lattice constant of $\mathrm{Al}_{0.15}\mathrm{Ga}_{0.85}\mathrm{N}$ and $\mathrm{In}_{0.06}\mathrm{Ga}_{0.94}\mathrm{N}$ is 0.318 and 0.321 nm, so the lattice mismatch between the two alloys is as low as 1%. For the sake of smaller lattice mismatch, we cannot set the aluminium and indium contents too high. So, if we want a high reflectivity at

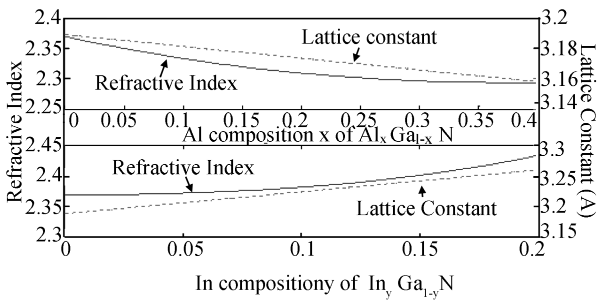

Fig.2. $Al_xGa_{1-x}N/In_yGa_{1-y}N$ refractive index (solid) and lattice constant (dashed) vary with x, y, for wavelength 560 nm.

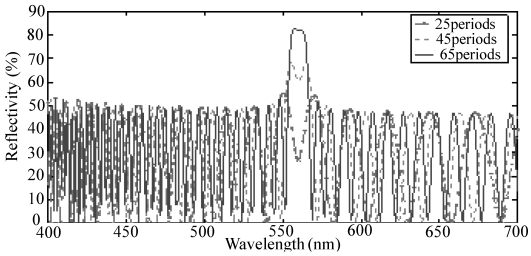

Fig.3. Reflectivity spectra of the DBR with different periods.

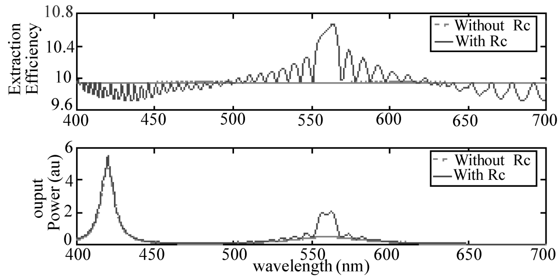

Fig.4. Extraction efficiency and emitting spectrum of the RC-based LED.

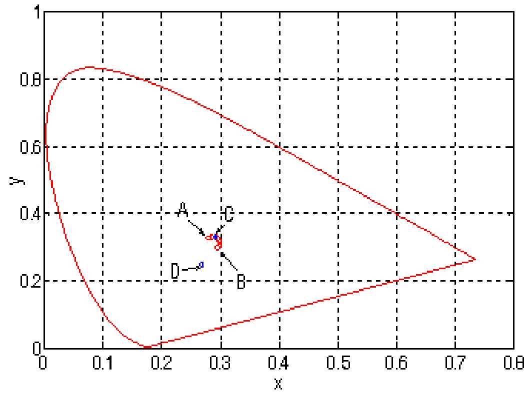

Fig.5. Color coordinates x, y in CIE 1931 for this RC-based LED. Dot C: original position with DBR; Curve AB: changing Bragg wavelength; Dot D: position of generated light without DBR.

yellow light, more periods of DBR are needed. The reflectivity spectra of DBR with different periods are shown in Fig.3. The more periods the DBR has, the higher reflectivity it offers.

Besides using the DBR to provide a high reflectivity for the yellow light, we put the yellow QW and blue QW in proper positions of the resonant-cavity to ensure the yellow QW locates in the antinode so that it has a maximal coupling length[9], therefore its output power can be enhanced.

In Fig.4, we compare the extraction efficiency and output power of the emission spectrum from LED with and without RC. The periods of the top and bottom DBR are 55 and 59, respectively. To simulate the intrinsic spontaneous emission spectrum, we use the general Lorentzian function as mentioned in Eq. (6). For the blue QW, the peak-wavelength is set at 420 nm and the FWHM is 10 nm; and for the yellow QW, the peak-wavelength is set at 560 nm and the FWHM is 60 nm. The intensity ratio A1/A2 (A1, A2 refers to blue and yellow respectively) is 10/1 because the internal quantum efficiency of yellow QW is much lower than that of the blue QW. We set the length of the RC at 500 nm, the yellow QW is located at the middle of the RC with a distance of 250 nm from the bottom cavity, and the blue QW is located in the position with a distance of 340 nm from the bottom cavity.

Figure 4 shows that with the help of DBR resonant-cavity, both the extraction efficiency and output power of the yellow light can be improved. So, in this DBR resonant-cavity based LED, the power of the yellow light may match with the blue light, which makes it possible to get white light.

After the optimal selection of the DBR and resonant-cavity parameters, the output power of the yellow light is improved greatly. So the generated light from the resonant-cavity based LED has a good white light position in the CIE 1931 chromaticity diagram with its color coordinate $x = 0.29$ and $y = 0.33$, as dot C shown in Fig.5. In contrast, in the case of LED without DBR, the emitting light locates in blue region in the CIE 1931 chromaticity diagram with its coordinate $x = 0.26$ and $y = 0.25$, as dot D indicated in Fig.5.

The effect of Bragg wavelength variation on the color quality is studied. When the Bragg wavelength of the DBR is changed from 550 to 580 nm, the position of the output light in CIE 1931 chromaticity diagram still remains in white zone, which is shown by curve AB in Fig.5. We also change some parameters such as the periods of DBRs, the position of the QW in the Resonant-cavity. The simulation results indicate that the color quality of RC-based LED has good tolerance to the above parameters variation.

4. Conclusion

We have designed a monolithic white LED based on $Al_xGa_{1-x}N/In_yGa_{1-y}N$ DBR resonant-cavity with blue and yellow QW. The content x, y are properly selected and the DBR reflectivity spectra is studied. After the optimal design of the DBR and RC parameters, the extraction efficiency and output power of the yellow light are prominently improved, which makes it possible to obtain high quality white light.

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