Improving LED luminous efficiency by surface-plasmon-enhanced waveguide

Ma Lijie[1], Zhao Junfeng[2]

(1. Inner Mongolia Electronic Information Vocational Technical College, Hohhot 010070, China;
2. College of Computer, Inner Mongolia University, Hohhot 010021, China)

Abstract: Surface-plasmon-enhanced GaN-LED was proposed based on the multilayered rectangular nano-grating, which was deposited by periodic raster silver thin film in the gas material. A model was theoretically established, which was enhancing the internal luminous efficiency of LED, the SPPs radiant matching and the SPPs radiant declining. The experiment shows that the structure of the deposited silver thin film can improve the luminous efficiency because of the SPPs enhancement. Polarized mode of the emergent light has no effect on the luminous efficiency of LED; Metal raster absorptivity will achieve the peak if the duty ratio is about 0.87; SPPs potentiation can dramatically improve the luminous efficiency and nonlinear process. The research on the improvement of the LED luminous efficiency has theoretical and practical significance.

Key words: luminous efficiency; SPPs enhancement; periodic grating; nonlinear process

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表面等离子波导改进 LED 发光效率的研究

马丽洁[1],赵俊锋[2]

(1. 内蒙古电子信息职业技术学院,内蒙古 呼和浩特 010070;
2. 内蒙古大学 计算机学院,内蒙古 呼和浩特 010021)

摘　要: 设计了在氮化镓材料上淀积周期光栅银薄膜的结构，利用 SPPs 增强作用提高 LED 的发光效率。理论上建立了增强 LED 的内部发光效率、SPPs 辐射匹配以及 SPPs 辐射衰减模型。实验结果表明:淀积银薄膜的 LED 结构由于 SPPs 的增强可以显著提高出光效率;出射光的偏振模式对 LED 出光效率没有影响；金属光栅的吸收率在占空比达到 0.87 左右达到峰值;SPPs 的增强作用可以显著改善弱光致发光的发光效率和非线性过程。这一研究对于 LED 发光效率的改进具有明显的理论和实际意义。

关键词: 发光效率； SPPs 增强； 周期光栅； 非线性过程

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作者简介:马丽洁(1976-),女,副教授,硕士,主要从事嵌入式技术与应用方面的研究。Email:329314391@qq.com

0 Introduction

Recently, the development in high-brightness gallium nitride (GaN) -based light-emitting diodes (LEDs) has made more possible for the LEDs to be used in many technologies, including traffic signals, cell-phone backlight and especially solid-state lighting. However, limited by the growth quality of GaN crystals, the internal quantum efficiency at room temperature is only several tens of percentage[1-3]. To further enhance the performance of these LEDs, there is always a great need to improve the internal quantum efficiency in order to increase their light output power[4-5]. In the year of 2000, N.Nakada et used Distributed Bragg Reflector(DBR) to improve the external quantum efficiency of LEDs[6-9]. The author fabricates 15 pairs of the GaN/AlGaN Bragg reflector between the substrate and the active area. It can make the light launched to the substrate reflects back to surface or side, and then, it can also reduce the absorption which is substrate to light and improve the efficiency of the light[10-11]. In 2003, Harvard University reported that they successfully developed a nanometer amplifier, which can automatically control the switch in "Nature", and install it on the microchip[12-14]. The nanometer amplifier can greatly improve the information storage capacity of the computer disks and photon computer. This phenomenon is using the conditions of nanometer structure local field and external light field resonated. Making the boson inherits the stimulated radiation by SP stimulation, amplification, radiation, and causes the resonance confined in the nanoscale[15]. While F.A.Fish et. chose the corrosive method to rust the GaAs substrate. With the action of the hyperthermal uniaxial press, it can make the epitaxial wafer bond to the GaP of transparent "N" type. The made-up device is sandwich structure, which is GaP substrate-active layer -GaP window. It allows light to emit from six faces, thereby enhancing the emergent efficiency. R. Windisch et al from German physics technological institute conductted further experiment by using the 430 nm′ polystyrene balls and discovered the better results than predecessor. In addition, it owns simple process, the higher light extracted efficiency advantages to use the two-dimensional photonic crystals to improve the extraction efficiency of LED, and now it become one of the research hotspot in improving the external quantum efficiency of LED. It also has some related reports in the two-dimensional photonic crystal appled to the LED. There are various technology in preparating the two-dimensional photonic crystal lattice, such as photolithographic corrosion, electrochemical, selective oxidation and so on[16-17]. Research group, based on the above-mentioned devoloped backgroud, design a structure,which is deposited by periodic raster silver thin film in the gaas material, and using the potentiation of SPPs to improve the luminous efficiency of LED. The model of improved structural bright dipping and enhanced theory was established. The experimental results for the improvement of the LED luminous efficiency has theoretical and practical significance.

1 Theoretical model

1.1 SPPs raster model

Figure 1 is the grating model for SPP coupling. Assuming that the incident electromagnetic wave can produce total reflection in the interface between the grating and medium, then there will be a part of evanescent wave passing through the dielectric close to the total reflection interface. When the metal grating is close enough to the surface of the distance plasma, there will be a part of the passing wave tunneling to the interface between glass medium and plasma (i.e., z=0), $k_x=k_{sp}=k_0\sqrt{\frac{\varepsilon_g\varepsilon_p}{\varepsilon_g+\varepsilon_p}}$. If the vector k_x belonging to the passing wave reaches the resonance coupling conditions, surface plasma can exist on the boundary . That is to say, boundary surface of the coupled plasma-glass prompts a lot of SPPs.

$$\frac{\omega}{c}\sin\theta_0 \pm vg = \frac{\omega}{c}\sqrt{\frac{\varepsilon_p}{\varepsilon_p+1}} = k_{sp} \quad (1)$$

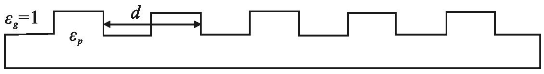

Fig.1 Metal grating

Using the boundary conditions of electromagnetic field where $z=0$ and $z=t$, we can get the answer which is not 0 in $(0,t)$.

Then the electromagnetic field satisfies the under dispersive condition:

$$(\varepsilon_2 k_{1z}+\varepsilon_1 k_{2z})(\varepsilon_3 k_{2z}+\varepsilon_2 k_{3z})+(\varepsilon_2 k_{1z}-\varepsilon_1 k_{2z})(\varepsilon_3 k_{2z}-\varepsilon_2 k_{3z})e^{i2k_{2z}t}=0 \quad (2)$$

At that time, the surface isoionic resonant frequency of the waveguide coupling is:

$$\omega=\frac{\omega_{ps}}{\sqrt{1+\omega_1}}\left(1\pm\frac{2\varepsilon_1}{1+\varepsilon_1}e^{-k_x t}\right) \quad (3)$$

For the medium surrounded by metal film, the surface plasmon resonance frequency produced by coupling effect will increase as the sheet thickness decreases.

1.2 Model of SPP increases the LED luminous efficiency

Figure 2 shows the structural model of SPPs enhances the LED luminous efficiency. The improving structure to enhance the LED adopts raster silver thin film and luminous layer(GaN) structure, the structural internal luminous efficiency is:

$$\eta_{rad}=\tau_{nrad}/(\tau_{nrad}+\tau_{rad}) \quad (4)$$

The radiation lifetime is mainly determined by the medium density. When the radiant light shed on the metal layer, it will enter into a degenerative channel. In the high SPPs structure, the degenerative efficiency is $\tau_{SPP}^{-1}=F_P\tau_{rad}$. It will increase with the increase of factor F_P, and the factor F_P is very big, the energy of the radiant source will transfer to the SPPs more effectively. But in order to make the energy to radiate in the form of light. It must be coupling the radiant model continuum by grating. Using the coupling strength k_{pr} to characterize the process of radiation, k_{pr} matches to the nonradiative loss caused by the ohmic loss among the surface plasmons excimer. While ohmic losses is determined by the imaginary part β_p'' of SPPs transmittal constant. When no radiant process plays a main role, the enhanced effect, SPPs to radiant efficiency, will severely weakened or even disappeared.

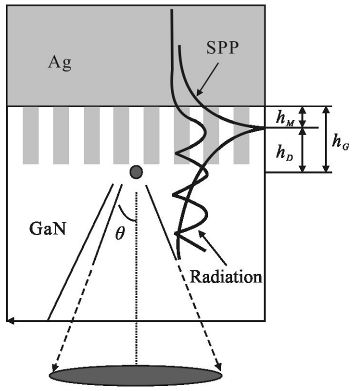

Fig.2 Structural model of SPPs enhancement

Assumes that the dielectric constant of metal layer is ε_M, the dielectric constant of luminous medium layer is ε_D. The electric field intensity in the interface can be represented as:

$$E_p(z,x)=A_p(z)e_p(\beta_p,x)e^{j(\beta_p z-\omega t)}$$

For the inherent model:

$$e_p(\beta_p,x)=\begin{cases}\frac{1}{\varepsilon}(\beta_p\hat{x}+q_M\hat{Z})e^{-q_M x}, & x>0\\(\beta_p\hat{x}-q_M\hat{Z})e^{-q_M x}, & x<0\end{cases} \quad (5)$$

where $\varepsilon=\varepsilon_M/\varepsilon_D$, the wave vector β_p, q_D and q_M are all having relationship with $\beta_p^2-q_D^2=1$ and $\beta_p^2-q_M^2=\varepsilon$, and all of them can be ruled $k_D=\sqrt{\varepsilon_D}\ \omega/c$. When the coordinates of the x axis and z axis are $1/k_D$, the answers are to be infinitesimal. The electric field intensity near the surface of the metal medium of TM radiant model can be represented as:

$$E_r(z,x)=A_r(z)e_r(\beta_r,x)e^{j(\beta_r z-\omega t)}$$

For the radiant inherent model:

$$e_r(\beta_r,x)=\begin{cases}(j\beta_r\hat{x}+q_r\hat{Z})e^{-q_r x}, & x>0\\ j\beta_r[\varepsilon\cos(k_r x)-(q_r/k_r)\sin(k_r x)]\hat{x}+[\varepsilon k_r\sin(k_r x)+q_r\cos(k_r x)]\hat{Z}, & x<0\end{cases} \quad (6)$$

Among them, $\beta_r^2+k_r^2=1$, $\beta_r^2-q_r^2=\varepsilon$.

In order to make the SPPs model coupled to the radiation model, both one-dimensional and two-dimensional medium need to match their internal transfer constant, namely $G=\beta_p-\beta_r$, (as shown in Fig.3).

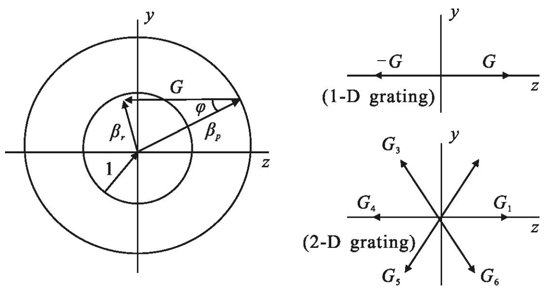

Fig.3 Calculation model

In order to make the SPPs coupled to the surface radiation model best, it must make G and β_p to be in the same order of magnitude. SPPs are located around the cylinder material, whose radius $\beta_p>1$, but the radiant model will be limited within a 1 μm radius ring. For making the continuous radiant wavelengths coupled with discreted state of SPPs, we should firstly grasp the SPPs coupling with one of the radiant pattern, then combined with one dimensional density radiant modes $\rho_r(\beta_r,\omega)=1/2\pi\omega\sqrt{1-\beta_r^2}$, you can gain the SPPs radiant attenuation equation:

$$\frac{\partial}{\partial z}|A_p(z)|^2=-k_{\rm pr}(\beta_p,\beta_r)|A_p(z)|^2 \tag{7}$$

The coupling strength is:

$$k_{\rm pr}(\beta_p,\beta_r)=\frac{\pi\omega^2\rho_r(\beta_r,\omega)}{8vg}f_G^2\left|\int\delta\varepsilon(x)e_p(x)e_r^*(x){\rm d}x\right| \tag{8}$$

For the Fourier amplitude, f_G is $1/\pi$ in the one-dimensional grating interface. For the two-dimensional grating $f_G=0.087$, $\delta\varepsilon(x)$ is the grating change of medium parameters on the vertical direction. Integral is used to calculate the grating. For the fixed model of SPPs, where the light is spreading in straight lines. The radiant efficiency is determined by medium incident angle φ, that is $\chi_{\rm pr}=k_{\rm pr}/(k_{\rm pr}+2\beta_p'')$.

From Fig.3, SPPs corresponds to different coupling efficiency in different directions. It can be available to whole radiant efficiency:

$$\eta_{\rm pr}=N_G/2\pi\int_{-\varphi_m}^{\varphi_m}\chi_{\rm pr}(\varphi){\rm d}\varphi \tag{9}$$

For the one-dimensional grating, N_G is 2. For the two-dimensional grating, N_G is 6. In the end, we can get the integral luminous efficiency during the luminescence under the action of SPPs:

$$\eta_{\rm SPP}=\eta_{\rm pr}\frac{F_P\tau_{\rm rad}^{-1}}{F_P\tau_{\rm rad}^{-1}+\tau_{\rm nrad}^{-1}} \tag{10}$$

And under the action of SPPs, the magnification of optical radiant efficiency is:

$$F_{\rm SPP}=\frac{\eta_{\rm SPP}}{\eta_{\rm rad}}=\frac{\eta_{\rm pr}}{\eta_{\rm rad}(1-\eta_{\rm rad})F_p^{-1}}<\frac{\eta_{\rm pr}}{\eta_{\rm rad}} \tag{11}$$

Therefore, no matter how hig the factor is, magnification $F_{\rm SPP}$ which is SPPs of optical radiation efficiency is affected by the ratio of SPPs coupling of radiation efficiency and the source itself.

2 Experimental analysis of the improving structure

2.1 Analysis about light efficiency

Firstly, it needs to simulate the phenomenon, different structural metal gratings′ plasmons mode improves LED light efficiency. Then we simulate the modle of Fig.2, where the 20 nm silver nano film was deposited on the GaN material, and the software simulated structure is shown in Fig.4. Figure 5 shows the primary light and the light after increasing silver film(by SPPs enhanced), and the curve of absorption and reflected efficiency. Figure 6 is the analysis chart, which improved LED irradiance or illuminance. From Fig.5, compared with the two conditions, we can see the reflectivity of deposite silver film is decreased obviously. That is to say, at this time, the result, which the light efficiency plus the efficiency of the light energy absorbed by the metal, is surely greater than the light efficiency without owning deposited silver. Especially, when it is more than a critical angle, due to the absorbent effect of the metal film plasma, emergent light is not entirely reflected, but some of them is absorbed by the nanoparticles. Adopting the structure to make a part of the energy converting into light energy and launching them out, this will greatly improve the overall light efficiency

Fig.4 Simulation chart

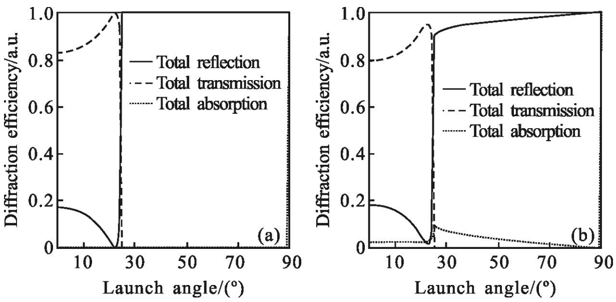

Fig.5 Light absorption and reflection efficiency curves before (a) and after (b) depositing a silver film

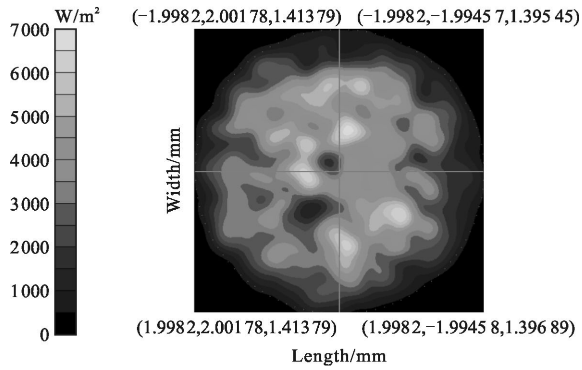

Fig.6 Analysis chart of the LED's irradiance illumination which is improved in structure

2.2 Impact analysis of structure parameter on luminous efficiency

2.2.1 Analysis of the impact of polarizated direction of emergent light on LED luminous efficiency

Firstly, we change the light polarizated direction in dielectric materials, and analyse the effect of the different direction on the LED luminous efficiency. According to the different polarized direction of polarized light, we can divide the polarized light into two polarizated mode, TM and TE. Because the metallic surfacial plasma needs to stimulate the polarized light, we can choose the polarized light of TM and TE models. We get the simulation figure which is luminous efficiency, absorpted efficiency, reflected efficiency by GaN lighted (based on the 20nm silver namo film). From Fig.7, we can see that, changing the polarized model of luminous light has no obvious effect on the dielectric materials luminous efficiency, metal nanoparticles absorption efficiency and reflection efficiency.

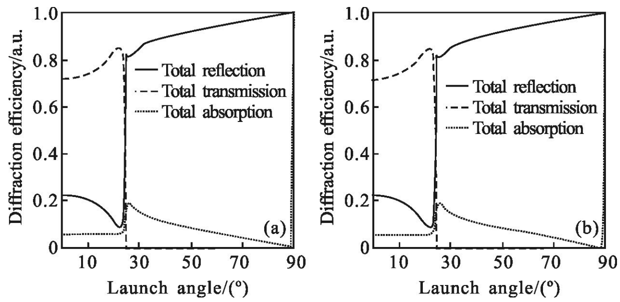

Fig.7 Emitted light mode is TM, the optical efficiency, absorption efficiency and the reflection efficiency of TE when the simulation graphics

2.2.2 Analysis of the impact of grating period to LED luminous efficiency

Next, the influence of grating period LED luminous efficiency was analyzed. Through changing the film duty ratio to seek out the only period, the LED luminous efficiency was improved. Figure 8 shows the curve of lumination, absorption and reflection efficiency, when the gap is 2,6,8, and the duty ratio is 0.87,0.66,0.5 (the first chart is the curve of not adding silver nano-particles). In order to get the characteristics, which the duty ratio affects the LED. Figure 9 shows the graph of lumination efficiency, absorption efficiency and their total changes with the change of duty ratio of the silver grating. We can draw three basic conclusions from Fig.9 obviously: The luminous efficiency decreases with the increase of the duty ratio of metal gratings. Firstly, the absorption of metal grating increases with the increase of the duty ratio, and it will reach peak at 0.87, then it will decline with the increase of the thickness. In the beginning, the sum of lighted quantity and absorpted quantity is increased with the increase of the size.When the duty ratio reach the peak 0.87, it will decrease, but it is always greater than the lighted quantity of no light silver nanoparticles.

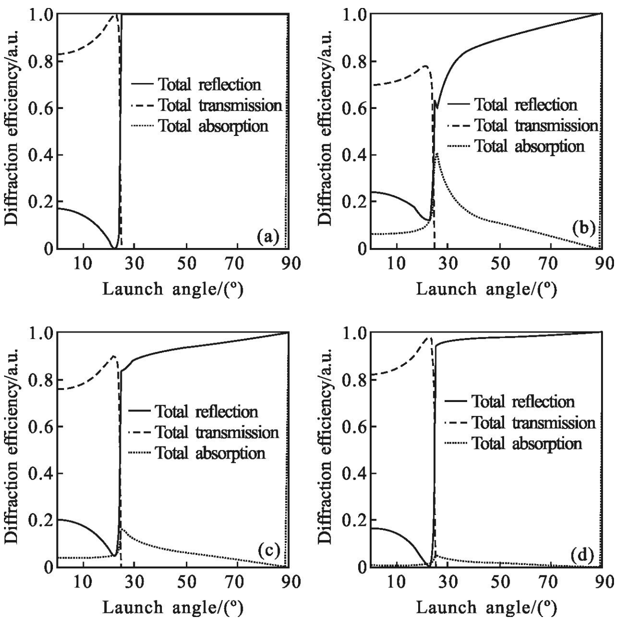

Fig.8 Curve of lumination absorption and reflection efficiency when the gap is 2,6,8 and the duty ratio is 0.87,0.66,0.5

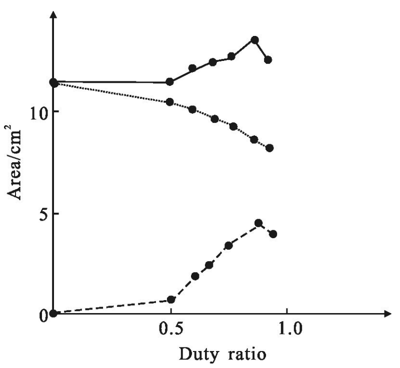

Fig.9 Graphs of lumination efficiency, absorption efficiency and their total changes with the change of duty ratio of the silver grating

2.3 Impact analysis of transmission coefficient on light extraction

In Fig.10(a), we shows the conditions of one-dimensional and two-dimensional gratings, when $\theta_m=\pi/2$. The amplification effect of SPPs changes with the transmission coefficient. Under the condition of fixed radiant efficiency of the emissive source itself. With the transmittal coefficient reach the optimal value $\beta_{p,\mathrm{opt}}'$, magnificated times reaches peak, at the same time, the optimal value of the transmittal coefficient is affected by η_{rad}. Because the Fourier amplitude of the one-dimensional grating F_G is smaller than two-dimensional grating, the optimal value is nearer 4 and behave better character. Due to the three different incident angles of the one-dimensional grating, the biggest magnificated times of SPPs to optical radiant efficiency can be expressed as:

$$F_{\mathrm{SPP,opt}}=\eta_{\mathrm{SPP}}(\theta_m,\beta_{p,\mathrm{opt}}')/\eta_{\mathrm{rad}}(1-\cos\theta_m)$$

It is mainly determined by the optimal value of the transmittal coefficient $\beta_{p,\mathrm{opt}}'$ with various η_{rad}. From different ways of optical excitation, we can get $\Omega/2\pi=1-\cos\theta_m$. The results of Fig.10 (b) clearly show that the enhanced effect, SPPs to medium light emitting, is obviously improving the structure of the LED luminous efficiency. The SPPs enhanced effect is obvious to improve the light-emitting efficiency caused by weak photo luminescence and nonlinear process. At the same time, the nonlinear process can be used to detect different substrate medium small amounts of radiation.

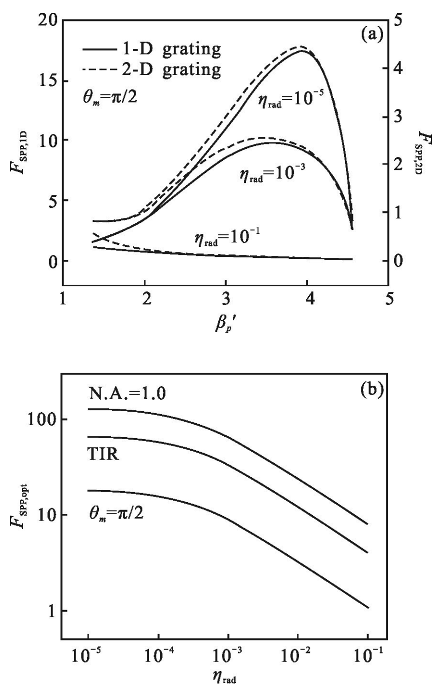

Fig.10 Transmission relationship

3 Conclusion

In this paper, the GaN-LED based on MRG is proposed and theoretically investigated. The fabrication and experiments about this structure are described. Adopting the LED improved structure of cycle grating silver film can significantly improve the efficiency of the light. The luminous efficiency of the SPPs enhanced structure decreases with the increase of the of metal gratings. The absorptivity of the metal grating increases with the duty ratio increases, and it will reach the peak at 0.87. The SPP enhanced effect is obvious to improve the light-emitting efficiency caused by weak photo luminescence and nonlinear process.

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