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ENHANCEMENT OF BLUE LIGHT EMISSION USING SURFACE PLASMONS COUPLING WITH QUANTUM WELLS

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Abstract—3-dimension finite-difference time-domain (FDTD) method is used to simulate the enhanced blue light emission of gallium nitride light emitting diode (GaN-LED) using the surface-plasmons (SPs) coupling with the quantum wells. The numerical simulation results demonstrate that when the silver film is coated on GaN-LED, the excited SPs play a key role in the enhanced blue light emission, and the enhancement depends on the geometries of GaN-LED and silver film. An enhancement factor is given to describe the enhancement effect of light emission. By changing the structure parameters of GaN-LED and silver film, the enhanced peak of the light emission in the visible region can be controlled. Under the optimal parameters, about 17 times enhancement at 460 nm can be obtained, and the enhancement effect is evidently demonstrated by the SPs field distribution.

1. INTRODUCTION

In recent years, great attention has been paid to the enhancement of light emission of light-emitting diode (LED), especially for gallium nitride light emitting diode (GaN-LED), because it has the advantages of high efficiency and long lifetime in comparison with the traditional light source [1–8]. The light emission can be strongly improved when the quantum wells (QWs) of LED is surrounded by the materials of different compositions and shapes, as it was predicted by Purcell and later corroborated experimentally [9–11]. Theoretical proposals along this direction have been made, and some of them consist in

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surrounding the QWs by different kinds of dielectrics and metals, such as photonic crystals [12–15], optical cavity [16], left-handed materials [17], mirrors [18–20], etc. Since 1990, surface plasmon (SP) has also received great interests when used in LED [21–26]. SP is formulated by Zenneck in 1907, which is a special surface wave solution to Maxwell's equations and demonstrated theoretically [27]. The surface waves occur at the boundary of two media when one medium is a "loss" metal with the negative real part of dielectric constant, and the other is a "loss-free" medium with the positive real part of dielectric constant [28–30], in which the absorption of light in molecules can be enhanced, and the Raman scattering intensities can be increased [31]. When the QWs are placed in the vicinity of metal, the strong emission enhancement effects are demonstrated due to the coupling between the emission of QWs and SPs modes in some of these geometries associated with the excitation of SPs [9, 32–37]. The presence of quantum wells has been demonstrated to influence both dispersion and damping of surface plasmon in silver films [38–41]. By employing the smooth or grating metal film, the light emission enhancements in the experiments have been observed, and some related 2-dimension (2D) numerical simulations have been reported. However, there are few reports on the 3-dimension (3D) numerical simulation by the smooth metal film coated on GaN-LED to enhance the light emission. In comparison with 2D FDTD simulation, 3D simulation requires more memory and computation time so that much higher performance of computation devices is needed. Although the interesting results can be obtained with 2D FDTD simulation, 3D simulation is a better approach for the actual excitation sources and structures. Furthermore, 3D simulation results will be more suitable for guiding experiments.

In this paper, a detailed analysis on SPs coupling with QWs to enhance the light emission is presented, and the geometric parameter influencing the light emission is discussed. The enhancement factor of light emission in different structures is calculated by 3-dimension finite-difference time-domain (3D-FDTD) method [42–44], and the structure parameters are optimized. A great enhancement peak at the blue light emission caused by SPs coupling with QWs is obtained, and the enhancement tendency is in agreement with the reported experimental results.

2. MODEL AND METHODOLOGY

The 3D and 2D views of our simulation models are shown in Fig. 1, in which (a) is the 3D view of the simulation model, and (b) is the y-z cross section of 2D view. The simulation space size is

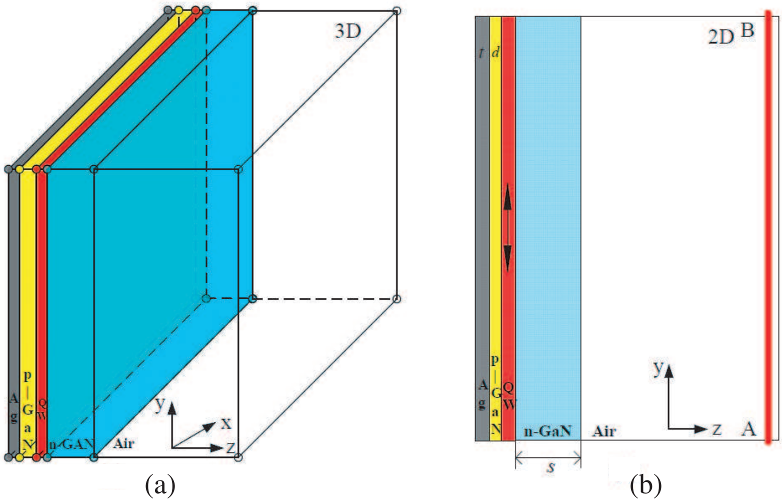


Figure 1. 3D and 2D views of the simulation model. (a) is 3D view. (b) is the y-z cross section of 2D view. The brown, red, yellow, blue, and white parts are silver film, QWs, n/p-GaN, and air, respectively. The polarization direction of single dipole is along y axis and is parallel to the silver film.

$2\,\mu\text{m}(x) \times 2\,\mu\text{m}(y) \times 2\,\mu\text{m}(z)$. The silver film is coated on GaN. The single dipole as QWs in GaN is located at the origin, and its polarized y axis is parallel to the silver film. The line A-B in 2D view indicates the detection plane, and the distance away from the GaN/Air interface is $1\,\mu\text{m}$. d is the distance between the silver film and QWs. s is the thickness of n-GaN between the silver film and GaN/Air interface, and t is the thickness of the silver film.

By using the FDTD method, which is simply a space and time discretization of the Maxwell's curl equations, three-dimensional field distributions are calculated. For saving memory and calculation time, the mesh of our calculations has to be set in different densities with different refractive indexes and dielectrics. However, the mesh density is large enough to insure the stability and accuracy. The FDTD mesh is terminated with the absorbing boundary conditions of perfectly-matched-layer (PML) that is employed around the entire simulation domain to absorb the outgoing waves and avoid non-physical reflections.

The refractive index for QWs and n/p-GaN is 2.5–2.6 according to different doping concentrations. The permittivity of silver film is described by the modified Drude model:

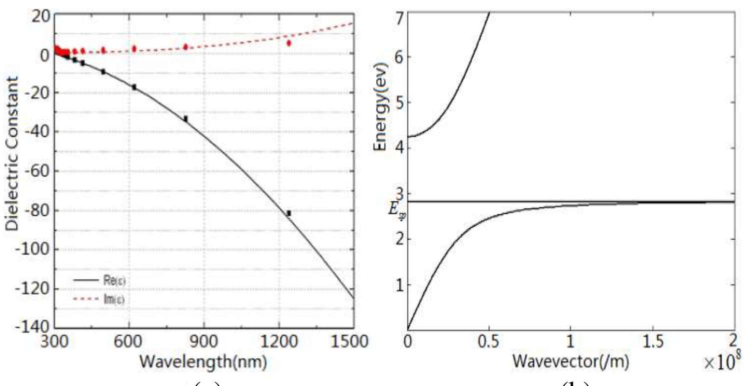
$$\varepsilon_{Ag}(\omega) = \varepsilon_{\infty} - \frac{\omega_p^2}{\omega^2 + j\omega\gamma} \tag{1}$$

where ε_{∞}, ω_p and γ are the dielectric constant at the infinite frequency, bulk plasma frequency, and damping constant, respectively. These parameters can be obtained by fitting the modified Drude model to Johnson and Christy bulk dielectric data [45]. For silver material, the fitted parameters are $\varepsilon_{\infty} = 5$, $\omega_p = 1.44 \times 10^{16}$ rad/s and $\gamma = 2.388 \times 10^{13}$ Hz. A comparison of our fitted parameters with the modified Drude model to the bulk dielectric data for silver is shown in Fig. 2(a). Obviously, in the wavelength regions of 300–900 nm, our model agrees well with the experimental data.

By solving Maxwell's equations and matching Ag/GaN boundary conditions at the interface, the following dispersion relation $\omega(k)$ for the SPs can be obtained:

$$k = \frac{\omega}{c}\sqrt{\frac{\varepsilon_{GaN}\varepsilon_{Ag}}{\varepsilon_{GaN} + \varepsilon_{Ag}}} \tag{2}$$

The surface plasmon energy ($E_{sp} = \hbar\omega_{sp}$) at Ag/GaN interface is lowered to around 2.787 eV (445 nm), which the dispersion curve $\omega(k)$ asymptotically approaches (Fig. 2(b)). Thus, the silver film is suitable for enhancing blue light emission of GaN-LED.



(a) (b)

Figure 2. (a) Comparison of the Johnson and Christy bulk dielectric data for silver (the square dots are the real part and the round ones are the imaginary part) and our fitted parameters with modified Drude model (the solid line is the real part and the dashed line is the imaginary part). (b) Dispersion relation diagram of SPs on Ag/GaN interface. Horizontal axis is wave vector, and vertical axis is the energy.

In order to describe the enhancement effect of light emission, an enhancement factor F is given, which is defined as the total power flow P across the x-y detection plane when the silver film is coated on GaN-LED divided by a similar total power flow when the system does not contain the silver film:

$$F = \frac{\iint P_{Ag}(x,y)dxdy}{\iint P_{noAg}(x,y)dxdy} \tag{3}$$

The greater the value of F, the stronger the light emission enhancement will be.

3. RESULT AND DISCUSSION

By using the above-mentioned 3D-FDTD calculation approach, the enhancement effect of light emission is simulated. Especially for simplicity, we fix the position and orientation of the emitter and focus on the effect of d, s, and t on SPs coupling with the QWs.

Figure 3 shows the emission intensity integral at the detection plane versus the wavelength. From Fig. 3, we can see that the emission intensity of GaN-LED at the surface plasmas wavelength around 460 nm with the silver film for three cases are 9.23, 9.59, and 14.12 times higher than that in GaN-LED without silver film. We consider that although the metal mirror reflects the emitted light that contributes to the enhancement effect, the emission enhancement of GaN-LED with silver film mainly results from SPs coupling with QWs.

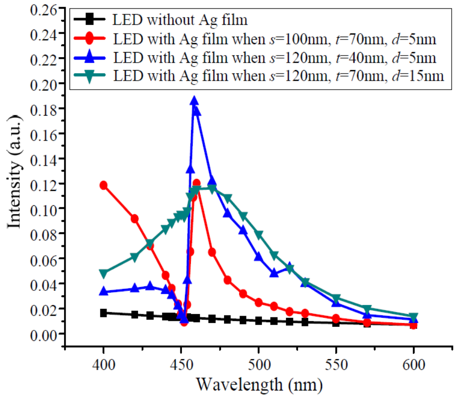


Figure 3. Spectra of emission intensity at the detection plane of the LED without and with silver film when $s = 100$ nm, $t = 70$ nm, $d = 5$ nm; $s = 120$ nm, $t = 40$ nm, $d = 5$ nm and $s = 120$ nm, $t = 70$ nm, $d = 15$ nm.

It can also be seen that the emission intensity varies greatly with s, t and d. The influences of s, t and d on the emission intensity will be discussed as follows, respectively.

Figures 4–7 demonstrate the influence of different structural parameters on the enhancement factor. Fig. 4 gives the enhancement factor versus d at 460 nm with $s = 120$ nm and $t = 70$ nm, in which the scattered points are the simulated values, and the solid line is exponentially fit. From Fig. 4, it can be seen that the enhancement factor decreases exponentially with increasing d, and when d is around 45 nm, there is no enhancement effect. This distance dependence maybe results from the SPs coupling with QWs, as the SPs are evanescent waves that exponentially decay with distance from the metal surface. When the distance d is longer than the penetration depth of the SPs fringing field into the GaN, the enhancement effect cannot occur. This penetration depth of the SPs fringing field into the GaN can be calculated by: $c/\omega\sqrt{(\varepsilon'_{GaN} - \varepsilon'_{Ag})/\varepsilon'^{2}_{Ag}}$, where ε'_{GaN} and ε'_{Ag} are the real parts of the dielectric coefficients. The calculated penetration depth is about 40 nm, which is close to our simulated value 45 nm in Fig. 4, in which there is no coupling enhancement effect when $d = 45$ nm. Fig. 4 also shows that only when the QWs is located within the near-field ($d < 45$ nm) of the SPs, can SPs be coupled to the QWs, which demonstrates that the emission intensity is strongly dependent

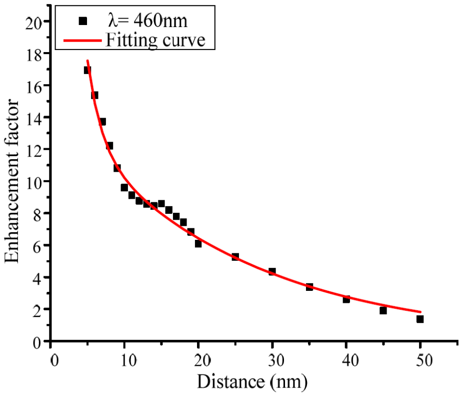


Figure 4. Enhancement factor versus the distance between the QWs and the GaN/Ag interface at 460 nm. The square dots are the simulated results and the curve is the exponential fitting line. When d is 45 nm, the enhancement factor is about 2, which means the enhancement is 100%, i.e., no enhancement effect when the metal mirror reflection is considered.

on the distance d.

Figure 5 gives the enhancement factor versus t at different wavelengths when $s = 120\,\mathrm{nm}$ and $d = 5\,\mathrm{nm}$. From Fig. 5, we can see that t is related to the enhancement factor. When t is very small, the silver film has no influence on the enhancement factor from 400 nm to 600 nm. Then the enhancement factor increases with increasing t at the resonant wavelength range of SPs. We attribute to that if the thickness of silver film is very thin or thinner than the skin depth, the back-emission light can penetrate the silver film, and the SPs cannot be excited. The back-emission light energy cannot be transferred to SPs, so it does not contribute to the front-emission light, resulting in the low enhancement factor. With the increase of t, the SPs can be excited, so more energy can be transferred to SPs and contribute to the front-emission by the coupling between QWs and SPs. When t is thicker than skin depth, the enhancement factor gradually approaches to a fixed value because the large part of energy is captured in the metal film.

Figure 6 gives the enhancement factor versus s with $t = 70\,\mathrm{nm}$ and $d = 5\,\mathrm{nm}$ for different wavelengths. From Fig. 6, we can see that the enhancement peaks alter periodically with changing s, and this periodic variation is insensitive to wavelength. However, different wavelengths have different periods. This phenomenon is induced by the constructive and destructive interferences of electromagnetic wave. For our simulation models, the optical path difference at Air/GaN

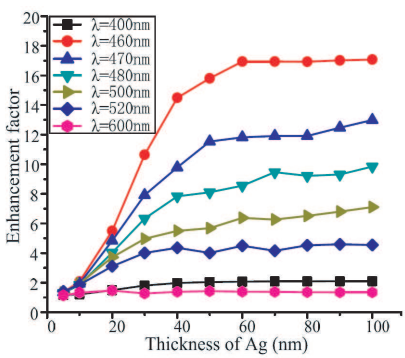


Figure 5. Enhancement factor versus the silver film thickness for 7 cases of wavelength from 400 nm to 600 nm. The enhancement factor near the resonant wavelength of SPs increases with increasing t.

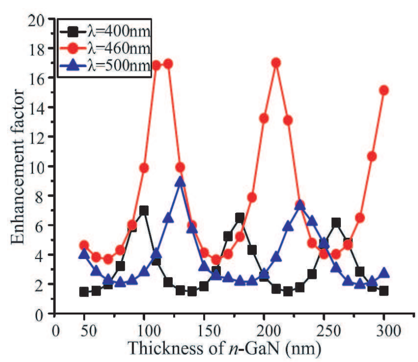
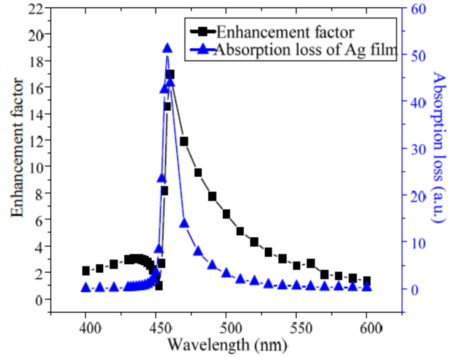
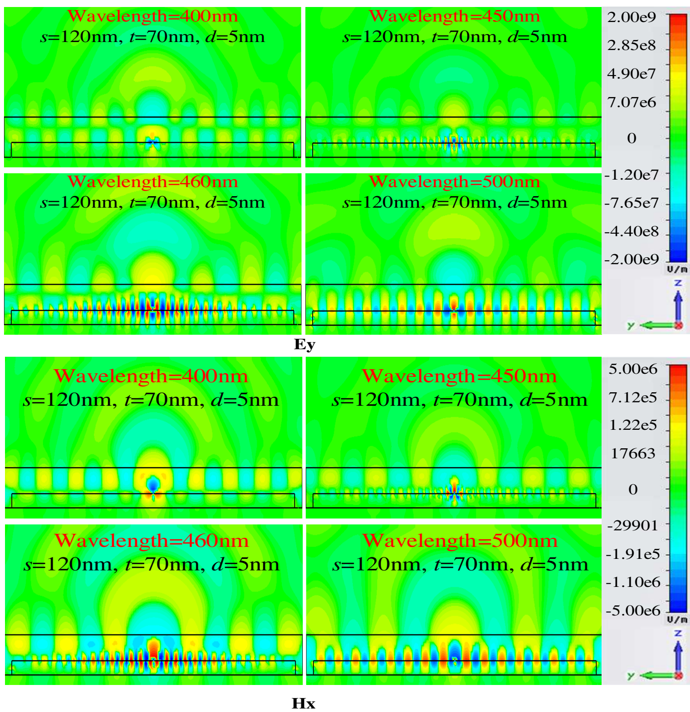


Figure 6. Enhancement factor versus the n-GaN thickness for 3 cases of wavelength from 400 nm to 500 nm. The enhancement peaks alter periodically with changing s.



(a)



(b)

Figure 7. (a) Spectra of enhancement factor and metal loss with optimal parameters ($s = 120$ nm, $d = 5$ nm and $t = 70$ nm). (b) Distribution of electromagnetic field under the same conditions as in (a) at 400 nm, 450 nm, 460 nm and 500 nm respectively.

interface is $2s\eta_{GaN}/\cos\theta$, and the period is $\lambda\cos\theta/2\eta_{GaN}$, here θ is the incident angle at the interface. It can be calculated that the period is proportional to wavelength, which is in accordance with our simulation result in Fig. 6. This interference phenomenon has great impact on the numerical simulation when a single dipole is used as an excitation source.

From the above simulation result, the optimal parameters of the geometries of GaN and silver film for the blue light emission enhancement should be $s = 120$ nm, $d = 5$ nm and $t = 70$ nm. Fig. 7(a) gives the diagrams of the enhancement factor and absorption loss versus wavelength in this case. From Fig. 7(a), we can see that about 17 times emission enhancement at 460 nm under the optimal parameters has been obtained, and the enhancement tendency is in agreement with the experimental result in [1]. It can be also seen that at 400 nm there is no enhancement effect because the SPs are not excited. At 450 nm, a trough of the emission curve occurs. The reason may be that 450 nm is the absorption wavelength of silver, but the resonance of SPs is not induced, resulting in the large part of energy absorbed by silver film. Because SPs depend on the absorption loss of silver film, according to the enhancement factor and loss curves, it can be concluded that SPs play a key role in the light emission enhancement. To further understand the contribution of SPs coupling with QWs to the light emission enhancement, we plot the distributions of electromagnetic field of E_y and H_x with the optimal parameters on the y-z cross section, shown in Fig. 7(b). It can be seen that the SPs field is not observed at 400 nm, very weak at 450 nm, the strongest at 460 nm, and gradually decreases with increasing wavelength, which evidently demonstrates that SPs make great contribution to enhance blue light emission when the silver film is coated on GaN-LED.

4. CONCLUSION

In conclusion, SPs coupling with QWs to enhance the blue light emission of GaN-LED is numerically simulated. The results demonstrate that the SPs play a key role in enhancing light emission. The light emission enhancement is dependent on a series of factors: the thickness and refractive index of dielectric, the geometry and dispersion model of silver film, and the positions of the QWs. Under the optimal parameters, about 17 times enhancement at blue light emission occurs, and the enhancement tendency is in agreement with the reported experimental results. Our work is of importance for designing and improving the GaN-LED.

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