Simulation Study on Surface Plasmon Coupled Light-emitting Diode

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***Abstract*-In this paper, we first review the theoretical model and numerical algorithm for the simulation study of the surface plasmon (SP) coupling with a radiating dipole in an InGaN/GaN quantum well to demonstrate the advantages of SP-coupled light-emitting diode (LED) in the visible range, including internal quantum efficiency enhancement, droop effect reduction, and modulation bandwidth increase. Then, we apply the similar method for investigating the SP coupling behavior in a deep UV LED for showing its functions of reducing p-GaN absorption and suppressing TM-polarized emission.**

I. Introduction

Although the technology of light-emitting diode (LED) has been widely developed and commercialized for solid state lighting and other applications, several key problems of nitride-based LED are still not solved yet. First, the low crystal quality of the InGaN/GaN quantum well (QW) with high indium content leads to the low emission efficiency in the green-yellow range. This issue is usually named as the problem of "green gap". Second, the low AlGaN crystal quality and poor p-AlGaN conductivity of high Al content results in the low emission efficiency of an AlGaN-based ultraviolet LED. Third, the efficiency droop behavior of a nitride LED at any wavelength is still a major problem for high-power application. The efficiency droop effect has been attributed to several causes, including the major ones of polarization field and Auger recombination. Many approaches have been demonstrated for reducing the effects of the polarization field and hence minimizing the droop effect. However, the Auger recombination is a fundamental physical process such that it is difficult to suppress its effect. Fourth, the emerging technology of visible communications requires a nitride LED of a high modulation bandwidth. Although a high modulation-bandwidth LED can be implemented by reducing the mesa size for decreasing its resistance-capacitance (RC) time constant. However, a small mesa implies a weak output power from such an LED. Other approaches are required for increasing the modulation bandwidth of an LED and meanwhile maintaining its high output power. Among the possible techniques, surface plasmon (SP) coupling can be an effective approach for solving all the aforementioned key problems. In this paper, we first review the theoretical model and numerical algorithm for simulating the coupling between an SP resonance mode induced on a metal nanostructure and a radiating dipole in a QW of an LED. Then, the simulated SP coupling results based on the numerical algorithm with an embedded Ag nanoparticle (NP), a surface Ag NP, and an Ag protrusion into GaN are demonstrated. Next, certain experimnetal results of SP-coupled LED are shown for comparing with the simulation results. Finally, the reduction of p-GaN absorption and the suppression of TM-polarized emission are illustrated with an embedded Al NP in the p-AlGaN layer of a deep UV LED.

II. Theoretical Model and Numerical Algorithm

In this coupling process, one or more SP modes are induced on a metal structure by a nearby radiating dipole. The induced SP can interact with the source dipole for changing its radiation behavior. Then, the changed radiation behavior of the source dipole further influences the SP resonance property and so on. A numerical algorithm has been developed for including such a feedback effect in the coupling process between an SP mode and a radiating dipole. In this algorithm, the unperturbed electromagnetic field emitted by a radiating dipole situated in a homogeneous spherical background medium of GaN is first evaluated with an analytical method or a numerical approach. Then, the total field is calculated in the real problem geometry, including the radiating dipole and the metal structure. By subtracting the unperturbed field from the total field, we can obtain the scattered field, which is to be used for evaluating the feedback effect on the dipole radiation behavior from the SP resonance on the metal structure. With the available scattered field, the optical Bloch equations are solved to find the resultant strength and orientation of the modified radiating dipole following an iteration procedure. Based on the modified radiating dipole, the final total electromagnetic field can thus be calculated numerically. We can then evaluate the total radiated power as well as the absorbed power in the metal region. This algorithm has been used for evaluating the coupling behavior of a radiating dipole with the LSP resonance modes on an Ag nanosphere embedded in GaN, a surface Ag NP on GaN, and an Ag protrusion into GaN. It is also used for studying the coupling behavior between an LSP mode on an Ag NP and two radiating dipoles simultaneously.

III. Simulated Surface Plasmon Coupling Results

In the coupling process with an embedded Ag nanosphere, it was found that the enhancements of radiated power of a radial and an orbital dipole (oriented with respect to the Ag nanosphere) were induced through the couplings with the localized surface plasmon (LSP) dipole and higher-order resonance modes, respectively. It was also found that both the LSP dipole resonance and higher-order resonance modes

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could make significant contributions to the radiated power enhancement of the QW-LSP coupling system even though the dipole resonance mode led to a relatively stronger coupling effect. In the coupling process with a surface Ag NP, it was found that the spectral peaks of radiated power enhancement corresponded to the substrate LSP resonance modes with the mode fields mainly distributed around the bottom of the Ag NP such that the coupling system radiated mainly into the GaN half-space. By moving the radiating dipole laterally away from the bottom of the Ag NP, the spectral peaks of radiated power enhancement red shifted and their levels diminished with increasing lateral distance. The radiation patterns in the GaN half-space showed more congregated radiation around the vertical direction, indicating that the light extraction efficiency could be enhanced in an LSP-coupled light-emitting device with surface metal NPs. In the coupling process between a radiating dipole and an Ag protrusion, two spectral ranges (400-570 and 570-800 nm) of radiated power enhancement could be observed. The radiated power enhancement in the long-wavelength (short-wavelength) range was generated through the coupling of the radiating dipole with the dipole and quadrupole (higher-order) LSP resonance modes induced on the protrusion. Because the LSP fields of those higher-order modes were mainly distributed around the tip of the protrusion, which was close to the radiating dipole, the radiated power enhancement was quite effective in the blue-green range even though the corresponding metal absorption could be higher than that of a lower-order LSP mode. Compared with the configurations of surface Ag NP and embedded Ag NP, the protrusion structure has the advantages of relatively higher radiated power enhancement in the blue-green spectral range.

IV. Surface Plasmon Coupled LED

When a metal film is coated on the p-GaN layer to form a smooth metal/GaN interface, at the interface SPP can be induced for coupling with the radiating dipoles in the QW. Also, a metal grating structure on the p-GaN layer can produce the momentum compensation effect for enhancing the radiation of SPP. For this purpose, normally the grating period needs to be smaller than 200 nm for a green LED and even smaller for a blue LED. With a larger period, LSP resonance can be formed within a period of the grating structure for coupling with the QW if the grating period and duty cycle are well designed. The simplest metal structure for inducing SP coupling is a surface metal NP array on the top of the p-GaN layer. The metal NPs can be fabricated through the thermal annealing of a thin metal film. With those three metal structures, to increase the SP field strength at the QW, the thickness of the p-GaN layer needs to be small, usually smaller than 70 nm. With a thick p-GaN layer, to make the distance between the metal structure and the QW short, we can fabricate a metal protrusion structure. In this situation, the distance between the hole bottom and the last-grown QW can be as small as ~30 nm. Then, the holes are filled with Ag to form the structure of Ag protrusion. With a liftoff process, we can form Ag NPs in the holes and cover the Ag NPs with SiO_2 NPs through the immersion of the sample in a SiO_2 solution. The SiO_2 NPs can block the injected electric current from flowing through the Ag NPs. To make metal NPs close to the QW, an effective approach is to embed the metal NPs in the p-GaN or n-GaN layer. SP coupling can also be applied to a vertical LED.

V. Surface Plasmon Coupling in a Deep UV LED

Currently, the major problems of deep UV LED include the low crystal quality of AlGaN and hence low internal quantum efficiency of Al_xGaN/Al_yGaN QW, the low hole concentration in p-AlGaN and hence low current injection efficiency into the QWs, the lack of a good transparent conductor in the UV range and hence poor current spreading and poor electrical property in such an LED, the low light extraction efficiency (LEE) of such a device due to the lack of a proper light extraction technique, the dominating c-axis-polarized (TM-polarized in a c-plane LED) emission when wavelength is shorter than ~300 nm and hence even lower LEE due to lateral propagation of such TM-polarized light, and the UV absorption of the p-GaN and p^+-GaN layers, which are needed for forming a p-i-n junction because of the poor p-AlGaN quality, and hence further reduction of the LEE of such a device. Here, we report the simulation study results of using embedded Al NPs in the p-AlGaN layer to induce SP resonance for coupling with the radiating dipoles in an AlGaN QW such that the emission efficiency of the QW can be enhanced, the p-GaN absorption can be reduced, and the TM-polarized emission can be suppressed. The reduction of p-GaN absorption is due to the major SP resonance energy distribution in the non-absorbing p-AlGaN layer. In this situation, the UV emission from the SP-QW coupled system mainly propagates downward for avoiding the absorption in the over-grown p-GaN layer. Also, we can design the geometry and position of the Al NP for enhancing the emission of a TE-oriented dipole (x-dipole) and simultaneously reducing the emission of a TM-oriented dipole (z-dipole) such that the TM-polarized emission can be suppressed. We use an Al nanosphere embedded in an AlGaN layer close to a radiating dipole oriented in either x or z direction to demonstrate the results of numerical simulation on the SP coupling effects, including the emission enhancement at a chosen wavelength (270 nm), the reduction of GaN absorption at this wavelength, and the suppression of TM-polarized emission at the same wavelength.

VI. Conclusions

We have first reviewed the theoretical model and numerical algorithm for the simulation study of the SP coupling with a radiating dipole in an InGaN/GaN QW to demonstrate the advantages of SP-coupled LED in the visible range, including internal quantum efficiency enhancement, droop effect reduction, and modulation bandwidth increase. Then, we applied the similar method for investigating the SP coupling behavior in a UV LED for showing its functions of reducing p-GaN absorption and suppressing TM-polarized emission.