Surface Plasmon Coupling in a Deep-UV Light-emitting Diode with an Embedded Al Nanoparticle

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***Abstract*- The radiated power enhancement (suppression) of a c-plane (c-axis) oriented radiating dipole at a given emission wavelength in the quantum well of a c-plane, deep-UV light-emitting diode (LED) when it is coupled with a surface plasmon (SP) resonance mode induced on a nearby Al nanoparticle (NP) is demonstrated. Also, the enhanced radiated power mainly propagates in the direction from the Al NP toward the dipole. Such SP coupling behaviors can be used for suppressing the TM-polarized emission, enhancing the TE-polarized emission, and reducing the UV absorption of the p-GaN layer in such a deep-UV LED.**

I. INTRODUCTION

Although a few research groups have been trying to commercialize their deep-ultraviolet (UV) light-emitting diodes (LEDs). A few major problems still exist, including (1) the low crystal quality of AlGaN and hence low internal quantum efficiency (IQE) of an Al_xGaN/Al_yGaN quantum well (QW), (2) the poor conductivity of p-AlGaN and hence the use of a UV-absorbing p-GaN layer at the top for increasing the current injection efficiency into a QW, and (3) the dominating c-axis-polarized (transverse-magnetic- or TM-polarized) emission in a c-plane LED when the Al content of an AlGaN QW is higher than ~25 % or the QW emission wavelength is shorter than ~300 nm, and hence the even lower light extraction efficiency (LEE) due to the lateral propagation of such TM-polarized emission.

Surface plasmon (SP) coupling in an InGaN/GaN QW LED has been proved to be an effective approach for enhancing the IQE of a QW. The coupling process between an SP mode induced on an embedded Ag nanoparticle (NP) and a radiating dipole has been numerically studied. From the simulation results, a few points are worth noting for deep-UV LED application. First, in the SP-dipole coupling process, the enhanced radiated power mainly propagates in the direction from the Ag NP toward the radiating dipole. In a lateral LED with an Ag NP embedded in the p-type layer, the enhanced radiation mainly propagates toward the substrate side. Second, the emission enhancement or suppression at a wavelength relies on the orientation of the source dipole. In the case of an embedded metal nanosphere (NS), emission enhancement (suppression) is usually observed at the wavelength of a lower-order (higher-order) SP resonance mode for a radial-oriented source dipole and vice versa for an orbital-oriented source dipole. Hence, in a c-plane LED, by embedding a metal NS in the p-type layer, the emission of a transverse-electric- or TE- (TM-) oriented dipole can be enhanced (suppressed). In this paper, we report the simulation results of using an embedded Al NS in a p-AlGaN layer to induce localized surface plasmon (LSP) resonance for coupling with a radiating dipole in an AlGaN QW such that the TE-polarized emission can be enhanced, the absorption of the over-grown p-GaN layer can be reduced, and the TM-polarized emission can be suppressed.

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 be calculated numerically. We can then evaluate the total radiated power as well as the absorbed power in the metal region.

III. SIMULATION GEOMETRIES

In Figs. 1(a)-1(d), we schematically demonstrate the four simulation structures (A-D). Figure 1(a) shows the structure

(A) of an x- or z-oriented radiating dipole embedded in a transparent AlGaN layer at the depth of a. Structure B shown in Fig. 1(b) corresponds to a typical deep-UV LED structure, in which a GaN layer of b in thickness is placed on top of the AlGaN layer. To obtain the SP coupling effects, in structure D, an Al NS of d in diameter is embedded in the AlGaN layer with a distance t from the radiating dipole, as shown in Fig. 1(d). The coordinate of the Al NS center is set at (x, y, z) = (0, 0, t + d/2 –a). For understanding the effect of the GaN layer in the situation with SP coupling, structure C is designed by replacing the GaN layer with AlGaN, as shown in Fig. 1(c). Throughout the numerical study, we fix the geometry parameters as a = 125 nm, b = 30 nm, d = 50 nm, and t = 30 nm. The dielectric constants of GaN and Al based on experimental measurements are used for computations. The background AlGaN layer is assumed to be transparent in the spectral range of >220 nm with the refractive index at 2.1. The radiated and absorbed powers of either dipole orientation in structures B-D to be shown below are normalized with respect to the total radiated power of the same dipole orientation in structure A.

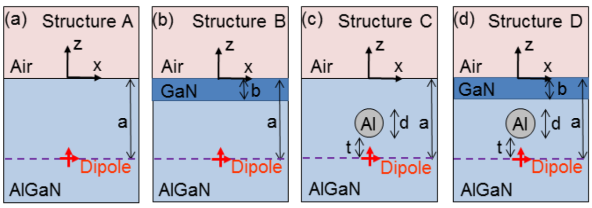

Fig. 1. (a)-(d): Schematic demonstration of the four simulation structures (A-D). The center of the Al NS in structure C or D is located at (x, y, z) = (0, 0, t + d/2 - a).

IV. Simulation Results

In Fig. 2, we show the spectra of the normalized radiated power in structures B-D when an x-oriented dipole (x-dipole) at (x, y, z) = (0, 0, -a) is used. The curves of X-total and X-downward (X = B-D) show the total and downward-propagating radiated powers, respectively. Here, one can see that the downward-propagating power is close to the total radiated power in either structure C or D, indicating that the enhanced radiation of the SP-coupling system mainly propagates downward. In either structure C or D, one can see two peaks of normalized radiated power with the stronger one around 270 nm (indicated by a vertical arrow) and the relatively weaker one around 315 nm, showing the enhancements of radiated power through dipole couplings with two LSP resonance modes. Below ~375 nm in wavelength, the normalized total radiated power of structure B is lower than unity, indicating the effect of GaN absorption above its band gap. Between structures C and D, the relatively larger difference in their total radiated powers around the shorter-wavelength peak shows that GaN absorption is more effectively suppressed around the longer-wavelength peak. To further understand the GaN absorption suppression in the SP coupling process, in Fig. 3, we show the spectra of the normalized absorbed power of the GaN layers in structures B and D when either an x- or z-dipole at (x, y, z) = (0, 0, -a) is used. In the case of x-dipole, the GaN absorption power in structure D is always lower than that in structure B, indicating that GaN absorption is significantly suppressed through SP coupling. The stronger suppression of GaN absorption around the longer-wavelength peak (~315 nm) explains the smaller difference between curves C-total and D-total around this peak in Fig. 2. In Fig. 4, we show the results similar to those in Fig. 2 when a z-dipole is placed at (x, y, z) = (0, 0, -a). Here, only one above-unity peak in either structure C or D is observed. The minor peak around 245 nm corresponds to a higher-order LSP resonance mode, which leads to radiated power suppression for forming a minimum near 270 nm. By comparing the levels at 270 nm between curves D-total and B-total in Figs. 2 and 4, one can see that with SP coupling, the radiated power of an x-dipole (z-dipole) at (x, y, z) = (0, 0, -a) is enhanced (reduced) by 103 (67 %). In Fig. 3, we can also see that with a z-dipole, below (above) ~280 nm, GaN absorption is significantly reduced (increased) due to the emission suppression (enhancement).

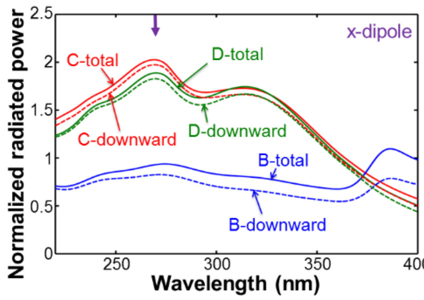

Fig. 2. Spectra of the normalized radiated power in structures B-D when an x-dipole at (x, y, z) = (0, 0, -a) is used. The vertical arrow marks 270 nm.

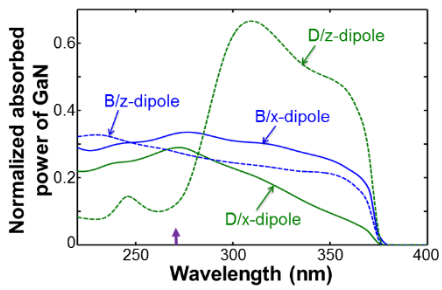

Fig. 3. Spectra of the normalized absorbed power of the GaN layers in structures B and D when either an x- or z-dipole at (x, y, z) = (0, 0, -a) is used.

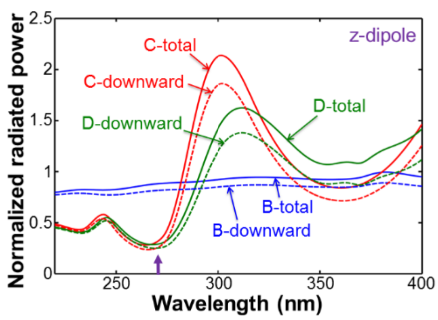

Fig. 4. Similar to Fig. 2 except when a z-dipole at (x, y, z) = (0, 0, -a) is used.