Numerical Study on Quantum Efficiency Enhancement of a Light-Emitting Diode Based on Surface Plasmon Coupling With a Quantum Well

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Abstract—We demonstrate the numerical study results of the enhancements of internal quantum efficiency (IQE) and external quantum efficiency (EQE) of a semiconductor quantum well when it is coupled with surface plasmons (SPs) induced on a grating interface between Ag and semiconductor. The IQE and EQE enhancements depend on the emission dipole position and the assigned intrinsic IQE. The SP dissipation in metal and the grazing-angle SP radiation lead to a significant difference between IQE and EQE. The enhancement of EQE is less significant when the intrinsic IQE becomes larger. In applying the SP coupling phenomenon to an InGaN–GaN quantum-well light-emitting diode, the efficiency enhancement is more significant in the green–red range, in which the intrinsic IQE is normally quite low.

Index Terms—Light-emitting diodes, quantum wells (QWs), surface waves.

SURFACE PLASMON (SP) coupling with a light emitter/absorber has been widely implemented for enhancing emission/absorption efficiency. In particular, by coupling a light emitter with a bright SP mode, which can effectively radiate, the emission efficiency can be enhanced for practical device application [1]–[7]. In such a coupling process, the light emitter first transfers its energy into the SP mode through the coverage of the light emitter by the evanescent field of an SP mode. If the SP mode can radiate effectively, the coupling process can enhance not only the internal quantum efficiency (IQE), but also the light extraction efficiency of a light-emitting device. However, an SP mode may suffer from the high loss of metal dissipation. Also, the grazing-angle SP radiation is practically not useful that further degrades the external quantum efficiency (EQE) [7]. Therefore, it is important to evaluate the IQE and EQE of a light emitter, which couples with SP modes in a metal/dielectric interface geometry, before the coupling process can be applied to a practical device. In particular, the net contributions to IQE and EQE of a light emitter array, for simulating an excited quantum well (QW), in coupling with SP modes are interesting for the application to an InGaN–GaN QW light-emitting diode.

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Fig. 1. Enhancement factor spectra of dipole radiation rate (RR) and detectable downward-propagating emission (DE) in the cases of dipoles p1 (–p1) and p2 (–p2) when the grating period is 80 nm. The structure geometry under study is shown in the inset.

In this letter, we report the numerical study results of IQE and EQE enhancements of a radiation dipole when it is coupled with SP modes generated on a grating interface between a half-space of Ag and a half-space of GaN. Because this research means to reveal the fundamental characteristics of SP coupling, the detailed device structure is not considered such that the device EQE cannot be evaluated. Instead, a quasi-EQE (QE_Q) is defined to represent the emission efficiency after the factors of SP loss and SP grazing-angle radiation are taken into account. The dependencies of IQE and QE_Q on the dipole position relative to the grating phase are illustrated. Based on the assumption of incoherent superposition, the average IQE and QE_Q, including the contributions of multiple dipoles at different positions, are evaluated. The numerical calculations are performed using the plane-wave-assisted boundary integral-equation method [8]. For computation, we discretize the unknown equivalent surface currents on all boundaries and interfaces by expanding them with the local linear bases. Then the Galerkin testing procedure is used to transfer the whole integral equation into a matrix equation.

Fig. 1 shows the enhancement factors of the dipole radiation rate and the downward-propagating emission [7] in a problem geometry shown in the inset. Here, a one-dimensional grating interface of 80 nm in period (denoted by $a/80$) divides the space into a half-space of Ag and a half-space of GaN (with a fixed refractive index at 2.5). The shape of grooves is described by a super-Gaussian function. The permittivity of Ag is assumed to follow the Drude model [9] with the angular plasma frequency set at $\omega_p = 1.19 \times 10^{16}$ (rad · s^{−1}) and damping constant set at $\gamma = 1.33 \times 10^{14}$ (rad · s^{−1}), leading to the surface plasmon polariton (SPP) resonance energy of 2.92 eV (425 nm

Fig. 2. IQEs as functions of wavelength for the two cases of constant dipole intrinsic IQE at 10% (I-a) and 50% (I-b) with dipoles p1 (p1-a for the case of I-a and p1-b for the case of I-b) and p2 (p2-a for the case of I-a and p2-b for the case of I-b).

in wavelength) at the plane Ag–GaIn interface. Two dipoles denoted by p1 and p2 are located at 10 nm right below a grating valley, with the coordinate at (0, −20 nm), and at 20 nm right below a crest of the grating, with the coordinate at (40 nm, −20 nm), respectively. The dipoles are extended infinitely in the $+z$ - and $-z$ -directions to form a two-dimensional problem. Because Ag is infinitely thick, only the downward-propagating emission (denoted by DE in Fig. 1) is detectable. The definitions of IQE and QE are given by $\eta_{\text{int}} = P_{\text{rad}}/(P_{\text{rad}} + P_{\text{non}})$ and $\eta_{\text{qext}} = P_{\text{down}}/(P_{\text{rad}} + P_{\text{non}})$, respectively. Here P_{rad} denotes the total radiated power by the dipole source, P_{down} is the downward-propagating emission power, and P_{non} is the power corresponding to the nonradiative recombination, which can be calculated for a given intrinsic IQE value.

In Fig. 1, the curves of RR-p1 and DE-p1 (RR-p2 and DE-p2) represent the enhancement factors of the dipole radiation rate and the downward-propagating emission, respectively, when dipole p1 (p2) is coupled with the generated SP modes on the grating. The differences between the RR and DE curves are attributed to the SP dissipation loss and the SP grazing-angle radiation. The three peaks in the case of p1 originate from the SPP on the plane Ag–GaIn interface (around 430 nm), the localized surface plasmon (LSP) corresponding to the groove shape (around 470 nm), and the SPP corresponding to the grating of 80 nm in period (around 510 nm). In the case of p2, the aforementioned three peaks can still be seen even though their peak positions are slightly shifted and the relative intensities are changed. The lower LSP feature around 480 nm in the p2 case is due to the longer distance of p2 from the semiconductor groove of either side. The spectral shifts of the peaks show that the excited SP mode energy is dependent on the dipole position. In the p2 case, both radiation and emission enhancements show long tails on the long-wavelength side. There is a strong peak of radiation enhancement around 680 nm. This feature of insignificant downward-propagating emission is related to a mixture of SPP and LSP modes and will be elucidated elsewhere.

Fig. 2 shows the evaluated IQEs corresponding to the problem geometry in Fig. 1. The IQE is evaluated by first assigning an intrinsic IQE to determine the nonradiative recombination rate. Then, the intrinsic radiative recombination rate is replaced by the radiation rate shown in Fig. 1 to obtain the IQE under the SP coupling condition. In Fig. 2, we consider two intrinsic IQE values (constants over the whole concerned spectral range) at

Fig. 3. QE as functions of wavelength for the cases shown in Fig. 2.

10% (I-a) and 50% (I-b). The IQEs of dipole p1 (p2) are shown in the curves of p1-a and p1-b (p2-a and p2-b) when the intrinsic IQEs of I-a and I-b are considered, respectively. Here, one can see that the spectra of IQEs essentially follow the patterns of radiation rate enhancement in Fig. 1. Over 95% IQE of dipole p1 in the blue–green range can be achieved when the intrinsic IQE is 50%.

Fig. 3 shows the spectra of QE as corresponding to the cases in Fig. 2. The evaluation of a QE is similar to that of an IQE except that the enhanced radiation rate is replaced by the enhanced downward-propagating emission. Here, one can see that the SP coupling with dipole p1 can enhance the QE from 10% intrinsic IQE (the same as EQE if the light extraction is 100%) up to around 45% (up to 4.5 times) in the blue range (around 460 nm). Also, the SP coupling with dipole p2 can enhance the QE from 10% intrinsic IQE up to 35% (up to 3.5 times) in the green range (around 520 nm). However, when the intrinsic IQE is increased to 50%, only up to 1.5 times enhancement in QE can be achieved through the SP coupling. In other words, the SP-coupling-induced QE enhancement becomes less significant as the intrinsic IQE increases. This result is reasonable because a high intrinsic IQE or low nonradiative recombination rate implies that the photon emission channel through SP coupling does not necessarily help in emission because of the extra loss channels of SP dissipation and grazing-angle radiation.

From Figs. 2 and 3, one can see the different contributions of dipoles p1 and p2 to IQE and QE. Dipoles at different lateral positions are supposed to result in different levels of IQE and QE. Fig. 4 shows the IQE and QE at 460 nm with the intrinsic IQE at 50% when the dipole is located at different x -coordinates. Two grating periods of 80 (a80) and 108 (a108) nm are considered. Here, one can see that although the IQEs can always be enhanced up to >70%, only those dipoles located around the grating valleys can make the QE slightly higher than the intrinsic IQE. Fig. 5 shows the IQE and QE at 520 nm with the intrinsic IQE at 10% when the dipole is located at different x -coordinates. In this situation, except those dipoles located around the grating valleys, QEs can always be higher than the intrinsic IQE in either case of grating period.

An array of dipoles in the plane of $y = -20$ nm can be used for simulating a QW, which couples with the induced SP modes on the metallic grating. In such a coupling process, we may expect certain coherency when more than one dipole is coupled with the same SP mode. Coherent coupling of multiple dipoles is supposed to lead to stronger emission when compared with the

Fig. 4. IQEs and QEQEs at 460 nm as functions of dipole position x when the intrinsic IQE is 50% (the horizontal dotted line) for the two cases of different grating periods at 80 (a_{80}) and 108 (a_{108}) nm.

Fig. 5. IQEs and QEQEs at 520 nm as functions of dipole position x when the intrinsic IQE is 10% (the horizontal dotted line) for the two cases of different grating periods at 80 (a_{80}) and 108 (a_{108}) nm.

TABLE I
AVERAGE IQE AND QEQE VALUES AT DIFFERENT GRATING PERIODS AND DIFFERENT INTRINSIC IQEs

Wavelength	460 nm	520 nm	620 nm
Intrinsic IQE (%)	50	10	2
<i>a80</i> grating			
IQE/QEQE (%)	79.03/21.61	46/21.99	3.89/2.91
<i>a108</i> grating			
IQE/QEQE (%)	87.93/19.10	26.19/16.08	9.12/4.34

completely incoherent emission of different dipoles in a QW. To simplify the discussion, we assume the completely incoherent emission among the dipoles to evaluate the lower bounds of IQE and QEQE. For numerical simulation, we use multiple incoherent dipoles equally spaced by 2 nm in the x -axis to simulate a QW for evaluating the average IQE and QEQE. Table I lists the average IQE and QEQE values at different grating periods and different intrinsic IQEs. The intrinsic IQEs for different wavelengths are chosen to be consistent with the realistic situations of crystal growth. In this table, one can see that with the assumed grating conditions, the SP coupling does not help in emission enhancement in the blue range [10], [11]. However,

because of the low intrinsic IQE in the green and red ranges, SP coupling can significantly enhance emission efficiency. It is noted that the assumed grating structure may not be optimized yet for the practical application because the LSP mode pattern, which determines whether it is a bright or dark mode, is sensitive to the metal shape. Compared with a grating structure, a nano-scale rough metal surface may be a better choice because it can provide various groove geometries for supporting various LSP and SPP modes [12]. Some of those SP modes may lead to a significant enhancement of emission efficiency.

In summary, we have demonstrated the numerical study results of IQE and QEQE of a dipole when it was coupled with the SP modes induced on a grating interface between Ag and GaN. The IQE and QEQE enhancements depended on the dipole position and the assigned intrinsic IQE. The SP dissipation in metal and SP grazing-angle radiation led to a significant difference between IQE and QEQE. The enhancement of QEQE became weaker as the intrinsic IQE was increased. It is noted that in photoluminescence (PL) measurement of SP-QW coupling, PL intensity could be significantly enhanced in an InGaN–GaN QW sample of high intrinsic IQE. Such a result can be due to the Fabry–Pérot effect of the PL excitation laser.

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