Numerical Study of Plasmonic Nanoparticles Enhanced Light Emission in Silicon Light-Emitting Diodes

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***Abstract*—We theoretically investigate the influence of metallic nanoparticles on light emission in silicon light-emitting diodes (LEDs) by an improved effective mode volume model proposed in this paper. We show that an enhancement of the radiative efficiency of silicon LEDs can be achieved by localized surface plasmons on silver (Ag) nanoparticles. The calculated result of optimal Ag nanoparticle size to enhance light emission of silicon LEDs at 900 nm wavelength is in very good agreement with those obtained from the experimental results.**

Keywords-component; enhanced light emission; metallic nano-particles; silicon LEDs

I. Introduction

Silicon-on-insulator (SOI) light-emitting diodes (LEDs) are very promising light sources for optical communication technologies. However, the development of these components is hampered by their low efficiencies. Efforts to improve the limitations of the efficiency have amongst others made use of plasmonic nanostructures [1]. Large efficiency enhancement of luminescence was achieved by placing metal nanoparticles close to light emitters. This has attracted intense research interests devoted to demonstrating such an enhancement in various media [2-3]. Since the surface plasmon resonance frequency is determined by various parameters such as shape, size and distribution of nanoparticles, an accurate theoretical model is very important in the design of nanoparticle enhanced light emitters.

There exist various methods developed to investigate the efficiency enhancement of electroluminescence. Among these, the recently introduced method based on the effective mode volume theory is known as a systematic and rigorous model to predict emission enhancement of quantum well LEDs in the vicinity of metal nanoparticles [4]. However, the method failed to explain the experimental results of an enhanced light emission of SOI-LEDs due to silver (Ag) nanoparticles. While the experiment demonstrated that a significant enhancement in electroluminescence from SOI-LEDs at 900 nm via excitation of surface plasmons in silver nanoparticles was obtained at the average particle size of a radius of 50-70 nm, those obtained by the theory of [4] (referred to as the conventional approach thereafter in this work) for the particle radius is only around 20-30 nm. This is attributed to the use of the Drude approximation in determining the enhanced Purcell factor. To overcome this problem, the Lorentz-Drude model for metal dispersion, which is well-known as a more accurate model [5], combined with a calculation without approximations of the enhanced Purcell factor due to nanoparticles are proposed in this paper. The calculated results by the improved approach are shown to be in very good agreement with the experiment.

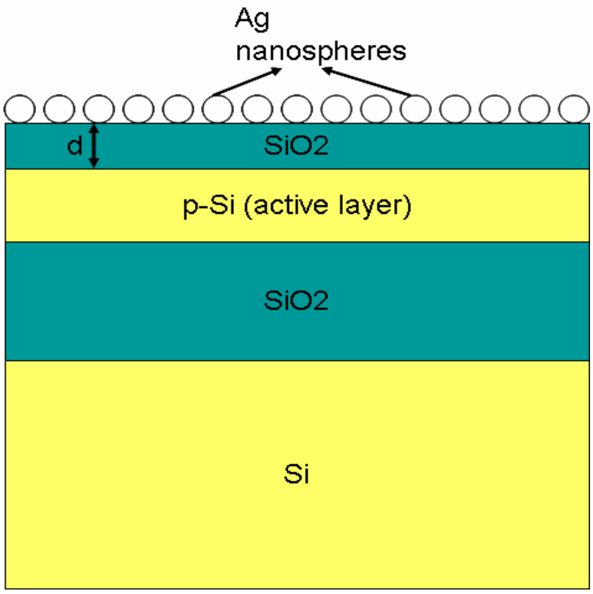

Fig. 1. Geometry of silicon-on-insulator LEDs with Ag nanospheres embedded on top

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II. An Improved Model of Plasmonic Nanoparticles Enhanced Light Emitters

The theoretical model employed to evaluate the radiation enhancement of SOI-LEDs is usually described as a two-step process. The first step describes an energy transfer from matter to a surface plasmon-polariton (SPP) mode at the metal-dielectric interface. Owing to the high mode density in the SPP, the Purcell factor $\boldsymbol{F}_p$ [6] is significantly enhanced. The second step is a conversion of the energy from the confined SPP modes to actual propagation modes with a certain coupling rate, and this process competes with nonradiative loss due to absorption in metal nanoparticles. Typically, tightly-confined large wavevector SPPs are more difficult to couple to the outside world. Hence, the overall radiative efficiency from the excited matter to free-propagating waves has a complicated dependence on the SPP characteristics. It was shown that for a given original radiative efficiency η_{rad} there exists an exact value of SPP enhancement [4].

The geometry of isolated metal nanospheres being placed on top of a SOI-LED is shown in Fig. 1. The effective volume of the SP mode supported by the metal sphere is given as follows [4]:

$$V_{eff} = \frac{4}{3}\pi a^3\left(1+\frac{1}{2\varepsilon_D}\right) \tag{1}$$

with a being the radius of the nanoparticle and ε_D being the dielectric constant of the surrounding media.

For the dipole positioned at the distance d from the particle surface and oriented in z direction normal to the surface, the effective density of the SP modes is

$$\rho_{SP} = \frac{L(\omega)}{V_{eff}}\left(\frac{a}{a+d}\right)^6, \tag{2}$$

where the normalized line shape of the dipole oscillation is

$$L(\omega) = \frac{\mathrm{Im}[(\varepsilon_M(\omega)+2\omega_D)^{-1}]}{\int \mathrm{Im}[(\varepsilon_M(\omega)+2\omega_D)^{-1}]d\omega}, \tag{3}$$

with ε_M being the metal dispersion. In [4], Eq. (3) was calculated by a Drude approximation. This is the main reason the method failed to explain the enhancement of the light emission from SOI-LEDs due to large nanoparticles. However, this can be remedied by considering the more accurate Lorentz-Drude model [5] combined with no approximation of the line shape of the dipole oscillation, as performed in this work.

For Ag nanoparticles embedded in a silica (SiO2) medium, the enhanced fields that occur near metal particles as a result of SP resonance give rise to an enhanced absorption. According to a generalized form of Kirchoff's law which is valid for luminescent emission, enhanced absorption corresponds to an enhanced emission [1]. Figure 2 shows the scattering and absorption cross-sections for 100 nm diameter of Ag sphere embedded in air and SiO2 calculated by Mie theory [7]. Cross sections are normalized to the geometry particle cross section. For each embedded medium, a dipole resonance is observed. At resonance frequency ω_0, the Purcell factor $F_p(\omega_0)$ can be estimated as a ratio of the effective density of the SP modes to that of the radiation components as follows:

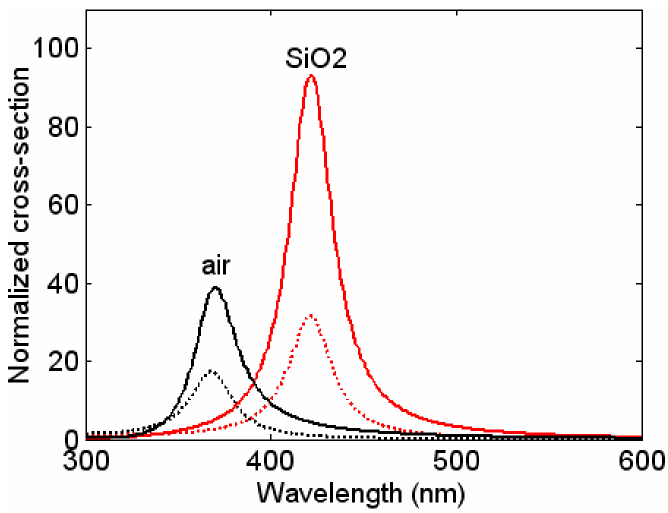

Fig. 2. Scattering (solid lines) and absorption (dotted lines) cross-sections for a 100 nm diameter Ag sphere embedded in air (black) and SiO2 (red) normalized by the projected area of the sphere.

$$F_p(\omega_0) = \frac{\rho_{SP}}{\rho_{rad}} = \frac{L(\omega_0)}{V_{eff}}\left(\frac{a}{a+d}\right)^6\left[\frac{1}{3\pi^2}\left(\frac{2\pi}{\lambda_D}\right)^3\frac{1}{\omega_0}\right]^{-1}, \tag{4}$$

with $\lambda_D = \lambda / n$ being the emission wavelength in the dielectric.

Now, given an original radiative efficiency, the expression for the enhancement factor due to a single metal nanoparticle is described as [4]:

$$F_{single} = \frac{\eta_{SP}}{\eta_{rad}} = \frac{1+F_p\eta_{pr}}{1+F_p\eta_{rad}}, \tag{5}$$

where η_{pr} is the radiative coupling efficiency of the SP mode.

For the example of InGaN quantum well LEDs, with isolated silver nanoparticles placed in close proximity to the active region, it was shown that the output enhancement due to isolated silver nanoparticles is significant while only modest enhancement can be achieved with an ordered array of nanoparticles. Furthermore, a random assembly of isolated particles may hold an advantage over the ordered arrays for light emitter devices of finite area.

III. Enhanced Light Emission by Isolated Nanoparticles

We now apply the developed model to evaluate the enhancement of the electroluminescence efficiency of silicon LEDs in which the active layer is placed in the vicinity of isolated Ag nanoparticles. The distance d from the active layer to a Ag particle is 35 nm as in the LED devices used in the experiments described in [8]. The calculated enhancement factor of the electroluminescence efficiency for a range of the original radiative efficiency of the emitter with respect to the sphere radius is shown in Fig. 3. We can see that the enhancement factor exhibits a strong dependence upon the nanosphere dimensions with the peak occurring when the radius is small enough to yield smaller effective mode volume

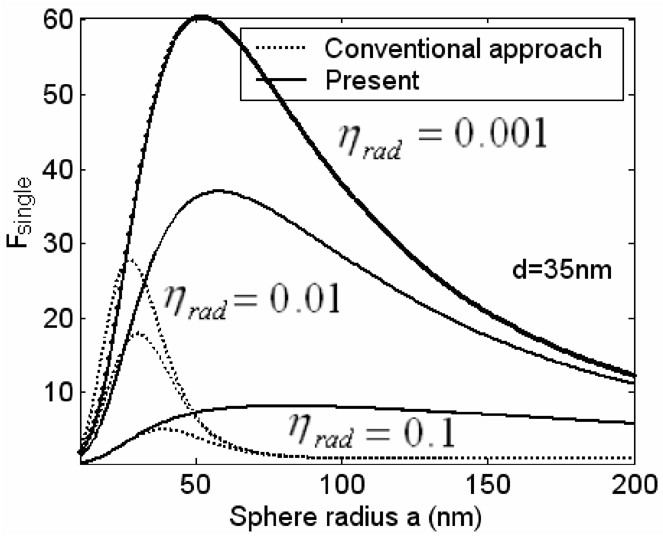

Fig. 3. Enhancement due to a single Ag sphere on SOI-LEDs with a distance of 35 nm from active layer to metal layer as a function of sphere radius for various original radiative efficiencies calculated by the conventional approach (dotted lines) and the present approach (solid lines).

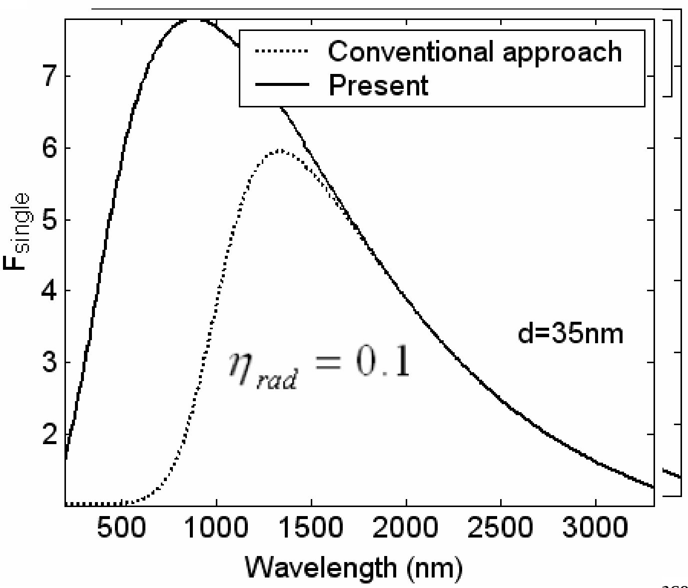

Fig. 4. Enhancement due to a single Ag sphere on SOI-LEDs with a distance of 35 nm from active layer to metal layer as a function of emission wavelengths calculated by the conventional approach (dotted line) and the present approach (solid line).

for an enhanced Purcell factor, yet is still sufficiently large to assure strong radiative coupling of the SP mode. Furthermore, the figure suggests that the higher the original radiative efficiency, the more important the concern for the efficient energy transfer from the SP mode into free-space radiation modes. This situation favors larger nanoparticles that can emit the SP energy photons into the free space prior to get lost in the metal. At the emission wavelength of 900 nm the enhancement of electroluminescence efficiency calculated by the present method can be found in the range of the particle radius to be around 50-60 nm which is very good agreement with the experimental results reported in [8], whereas those obtained from the conventional approach is only 20-30 nm.

In addition, Figure 4 shows the calculated enhancement factor of the electroluminescence efficiency as a function of emission wavelengths. It is seen that for a given original radiative efficiency of 0.1, the maximum enhancement factor is observed at the emission wavelength of around 890 nm. It is in good agreement with those obtained by the experimental result of the emission wavelength at around 900 nm while those obtained by the conventional method is around 1330 nm.

For a single nanosphere, although it may enhance light emission of only a very small emitter, an enhancement of light emission can be observed at certain optimal sizes. Therefore, with found optimal particle sizes one can consider disordered arrays of these isolated nanospheres to achieve practical enhancement of such devices as SOI-LEDs.

IV. Conclusions

The systematic and rigorous model based on the effective volume mode theory has been improved to evaluate the enhancement of the electroluminescence efficiency of SOI-LEDs due to isolated Ag nanoparticles. The improved model has well explained the plasmonic enhanced light emission of SOI-LEDs as reported in the experiment. Hence, it is very useful for the design of metal nanoparticles enhanced light emitters.

Acknowledgment

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