The Effect of Silver Nano-Particles on Surface Plasmon-enhanced OLEDs.

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Keywords : Surface plasmon, OLED, Silver nano-particle, Spontaneous emission rate.

Abstract

The effect of silver (Ag) nano-particles on OLEDs was investigated by using a finite difference time domain (FDTD) tool. The proposed OLEDs employed Ag nano-particles thermally deposited in a high vacuum on a cathode. The emission rate of the exciton was improved by 1.8 fold compared to the conventional OLEDs without Ag nano-particles. Less spacing between the dipole source and the Ag nano-particles resulted in a larger emission rate of the exciton in the OLED with nano-particles. The size of the Ag nano-particles was proportional to the emission rate of the exciton in a range of nano-meter scale of nano-particles. The enhancement of the emission rate of the exciton due to Ag nano-particles caused the improvement in the efficiency of the proposed OLED.

1. Introduction

In organic light-emitting diodes (OLEDs), spontaneous emission (SE) rate, which is expressed by Fermi's golden rule, depends on the transition frequency, transition dipole moment, and electromagnetic density of state [1-3]. In order to increase SE rate, we used surface plasmon (SP) excitation, which can increase electromagnetic density of state by concentrating light in a sub-wavelength structure. There are two ways to increase SP excitation-exciton emission: coupling [4] and fluorescence molecule excitation [5]. Previously designed OLED structures, in which Ag nano-particles are thermally deposited in a high vacuum on a cathode that had a 1-nm-thick LIF spacer, improved SP excitation using exciton emission SP coupling [6, 7]. In the experiment, the SP enhanced SE rate of OLED with Ag nano-particles is increased 1.75 fold compared with OLED without Ag nano-particles [6, 7]. In this study, the emission rate of the exciton resulted from SP due to Ag nano-particles was investigated in accordance with the size of Ag nano-particles and the distance between the bottom of the cathode and the dipole source.

2. Theoretical Analysis

A previously designed OLED structure is shown in Fig 1. Samples are fabricated by thermal vacuum evaporation at a base pressure of 1×10^{-7} Torr on 120 nm indium tin oxide (ITO) pre-coated glass substrates. A 40 nm N, N´- di(naphtha-2-yl)-N, N´-diphenyl-benzidine (NPB) layer is deposited to make the hole transport layer, and a 30 nm tris-(8-hydroxyquinolinato) aluminum (Alq_3) layer is deposited to make the emissive and electron transport layer. A 2-nm-thick LiF/150-nm-thick Al cathode is deposited in the same way as with a usual conventional OLED, and a 1-nm-thick LiF/Ag cluster/1-nm-thick LiF/150-nm-thick Al cathode is deposited especially for the designed OLED structure.

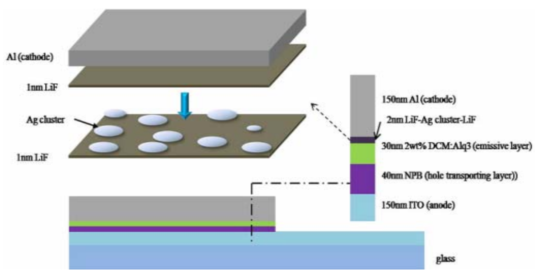

FIG. 1. Proposed OLED structure

In the previous study, continuous wave photoluminescence measurement results of a designed sample that has Ag nano-particles clearly show PL intensity enhancement in contrast with a sample without Ag nano-particles. We found the SP enhanced SE rate of OLED with Ag nano-particles is enlarged 1.75 fold compared with OLED without Ag nano-particles [6, 7].

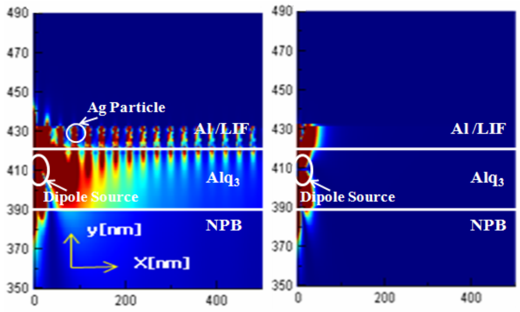

FIG. 2. Electric field distribution in Alq_3 layer (y axis: 390~420 nm) in OLED structure with Ag nano-particles (left) and without Ag nano-particles (right)

Starting from this study, we monitored E-field intensity in the Alq_3 layer because enhanced E-field enlarges exciton emission coupling, which is proportional to the SE rate that is also proportional to OLED efficiency. Fig 2 shows E-field distribution of previously designed OLED 2D structures. The range of the y axis from 350 to 390 nm is the NPB layer, from 390 to 420 nm is the Alq_3 layer, from 420 to 432 nm is the LiF layer of the cathode, upon which Ag nano-particles are inserted left of Fig 2, and from 432 to 582 nm is the Al layer of the cathode. Inserted Ag nano-particles are placed with 30 nm center-to-center spacing between neighboring particles. The dipole source is placed 411 nm on the y-axis for 2D simulation (471 nm on the z-axis for 3D simulation). Fig 2 shows the E-field in the Alq_3 layer (y-axis range from 390 to 420 nm). We can clearly observe that the OLED with Ag nano-particles generates an E-field, but the OLED without Ag nano-particles does not generate an E-field. Also, because of the SP effect by the Ag nano-particles, not only the LiF layer but also the Alq_3 layer E-field intensity is increased at the place around which the Ag nano-particles are inserted.

This generated E-field improves the emission rate in the Alq_3 layer, and finally it increases OLED efficiency. Using E-field intensity data getting from FDTD tool, we can calculate the emission rate of the exciton through Equation 1 [8].

$$\gamma_\gamma \propto \gamma_{exc} \propto |\, p \cdot [E_o(r_0, \omega_1) + E_s(r_0, \omega_1)]|^2 \quad \text{[Eq.1]}$$

In this equation, γ_γ is the emission rate of the excited molecule (in this study, a molecule is an exciton). γ_{exc} is the excitation rate, p is dipole source momentum, E_o is incident laser field, E_s is the secondary field, r_0 is free space radius, and ω_1 is the excitation frequency. The FDTD tool calculates E_o and E_s intensity, which locates in Alq_3 layer, and we set p as the z -axis direction in the simulation setting.

Figure 3 shows the emission rate of the exciton improvement of the designed OLED structure through further Ag nano-particle size increases while we fix distance between the bottom of the cathode and the Ag nano-particles as 10 nm.

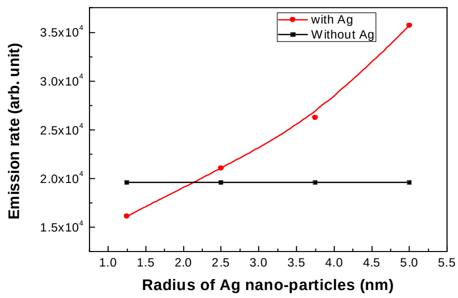

FIG 3. The emission rate of the exciton changes under the influence of Ag nano-particle size

In the previous study, Ag nano-particles were deposited on an LIF surface with 3-10 nm diameter spherical shapes and with 12.5% randomly distributed surface coverage [6, 7]. In this study, we put Ag nano-particles on an LIF surface with roughly 10% distribution and changed the Ag nano-particle diameter from 1 nm to 5 nm. When the Ag nano-particle radius increased, the SP peak wavelength (λ_{sp}) was redshifted [6, 7]. Also, the redshifted SP peak wavelength became close to the peak wavelength of Alq_3 (λ_{Alq_3}).This caused the emission rate of the exciton to increase. Consequently, the SE rate increased.

Simulation results show that as Ag nano-particle radius became bigger, the emission rate of the exciton increased proportionally.

From Fig 3, we see that if we put Ag nano-particles that are too small on the OLED, we cannot see an improvement from the SP effect through the Ag nano-particles. Also, we monitored the emission rate of the exciton changes while we changed the distance between the dipole source and the bottom of the cathode, which was the same place as the Ag nano-particle's bottom, through the FDTD tool. In the other thesis, the distance between one Ag nano-particle and the dipole source was set to 15 nm and changed from -*dx* to +*dx*, which is 5 nm [8]. The simulation result shows that the normalized emission rate is maximized when the distance between the dipole source and the Ag nano-particles is 10 nm. Therefore, we set the distance starting from 10 nm and ending at 18 nm. The result of this experiment is shown in Fig 4.

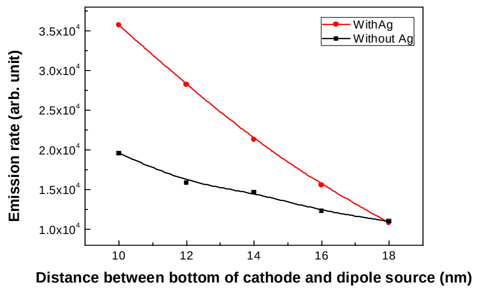

FIG. 4. Emission rate of the exciton changes under the influence of distance change between the bottom of the cathode and the dipole source

When the distance was 10 nm, the emission rate of the exciton of the designed OLED structure increased by 1.8-fold compared with a conventional structure that does not have Ag nano-particles. Distance changes in the conventional OLED structure influenced a little of the emission rate of the exciton, increasing about 1.7-fold.

From further work from the previous study using the FDTD tool, we discovered the SP effective distance, which is the limited distance that we can improve the emission rate by SP effect, was 18 nm in our structure. Consequently, if we set distance between the bottom of the cathode and the dipole source over 18 nm, we cannot get an improvement in the emission rate through the SP effect.

In summary, shortening the distance between the bottom of the cathode and the Ag nano-particles, as well as bigger Ag nano-particle size, can enhance the emission rate of the exciton and improve the OLED efficiency.

3. Conclusion

The SP mediated OLEDs were already reported in our previous work [6, 7]. The emission rate of the exciton resulted from SP due to Ag nano-particles plays a very important role in the enhancement of OLEDs' characteristics. In this work, the emission rate of the exciton was analyzed by using an FDTD tool. Through FDTD simulation results, we found that an OLED with Ag nano-particles improves the emission rate of the exciton 1.8 fold compared with a conventional OLED without Ag nano-particles when distance between the bottom of the cathode and the dipoles source is 10 nm. We found out when we change the distance from 10 nm to 18 nm the emission rate of the exciton decrease remarkably. There is an effective distance related to the SP effect by Ag nano-particles. In our structure, that was 18 nm. Therefore, if we increase the distance to further than 18 nm, we will not be able to improve the SP effect using Ag nano-particles. Also the emission rate of the exciton increased when we enlarged the radius of the Ag nano-particles from 1nm to 5 nm. However, when the Ag nano-particles were too small, such as under 2.5 nm in our structure, it was not able to enhance the emission rate of the exciton compared with the OLED without Ag nano-particles. Using FDTD tools we found that a bigger radius of Ag nano-particles and a shorter distance between the bottom of the cathode and the dipole source increased the emission rate of the exciton. So in order to optimize the previous work, we should make the Ag nano-particle radius size from 2.5 nm to 5 nm and make the distance between the bottom of the cathode and the dipole source as close as possible underthe effective distance, which was 18 nm in the previous structure.

Acknowledgements

This work was supported by a Korea Science and Engineering Foundation (KOSEF) grant funded by the Korean government (MEST) (Grant No. R11-2007-045-02001-0).

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