Scattering and plasmonic phenomena of nanoparticle self-assembled arrays in the thin-film organic lighting devices and photovoltaics

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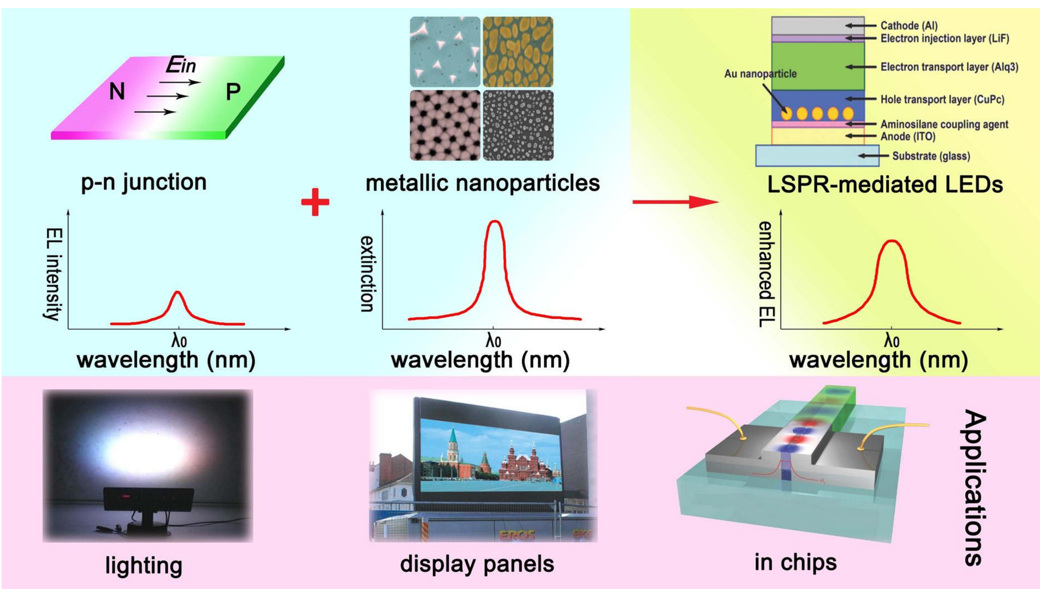
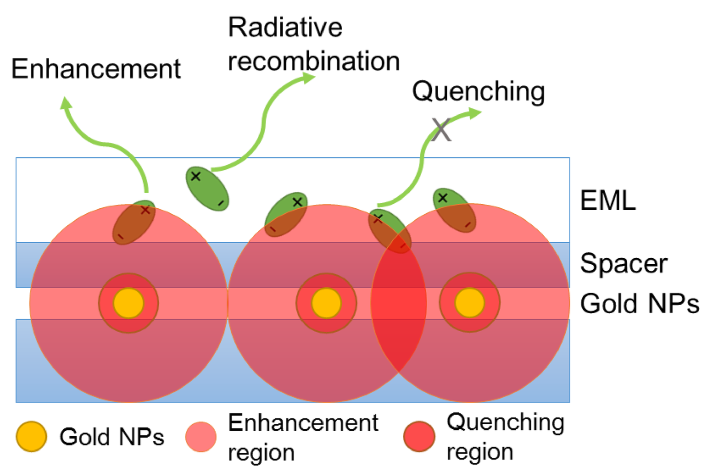
Introduction

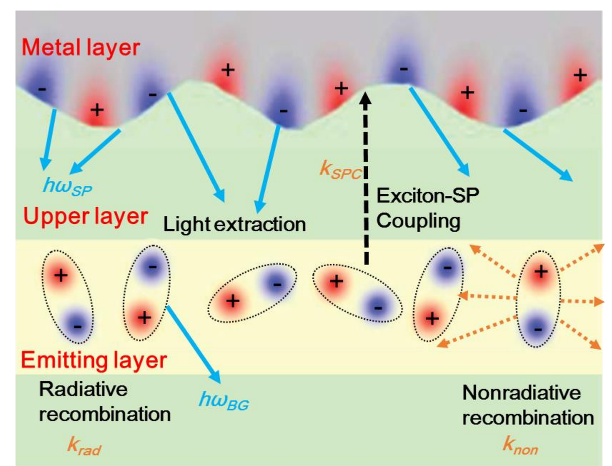
Application of nanoparticle-based plasmonics



Gu et al. Nanoscale Research Letters (2011)

Coupling between excitons and plasmons





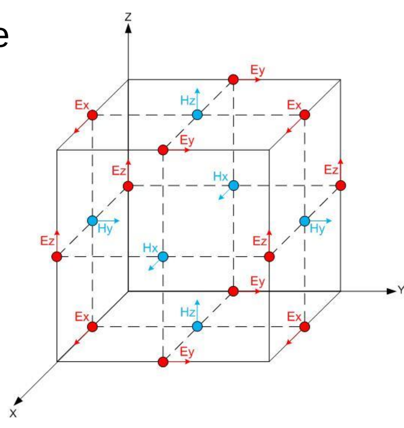
When a metal layer is grown within the nearfield of the active layer and when the bandgap energy (ω_{BG}) of emitting layer is close to the electron oscillation energy (ω_{SP}) of SP at the metal/ semiconductor surface, the exciton energy can transfer to the SP.

Finite-Difference Time-Domain (FDTD)

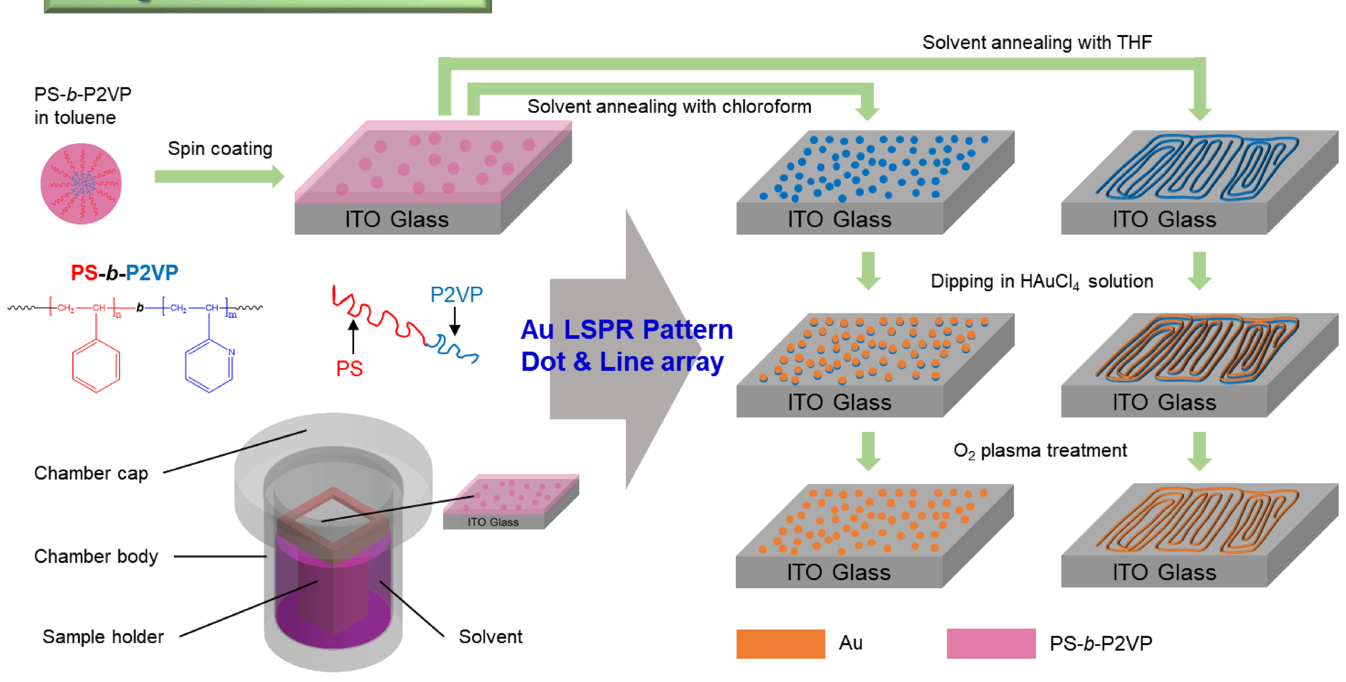
- FDTD directly solves Maxwell's curl equations in the time domain.

$$\frac{\partial H_x}{\partial t} = -\frac{1}{\mu}\left(\frac{\partial E_y}{\partial z} - \frac{\partial E_z}{\partial y}\right) \qquad \frac{\partial E_y}{\partial t} = -\frac{1}{\varepsilon}\left(\frac{\partial H_x}{\partial z} - \frac{\partial H_z}{\partial x}\right)$$

- The most common method to solve these equations is based on Yee's mesh and computes the E and H field components at points on a grid with grid points spaced Δx, Δy, and Δz apart.
- The E and the H field components are interlaced in all three spatial dimensions.



Experiment



External Efficiency

Conventional OLED

$$\eta_{ext} = C'_{ext} \times \eta_{int} = C'_{ext} \times \frac{k_{rad}}{k_{rad} + k_{non}}$$

η_{ext} - external quantum efficiency C'_{ext} - light extraction efficiency
η_{int} - internal quantum efficiency

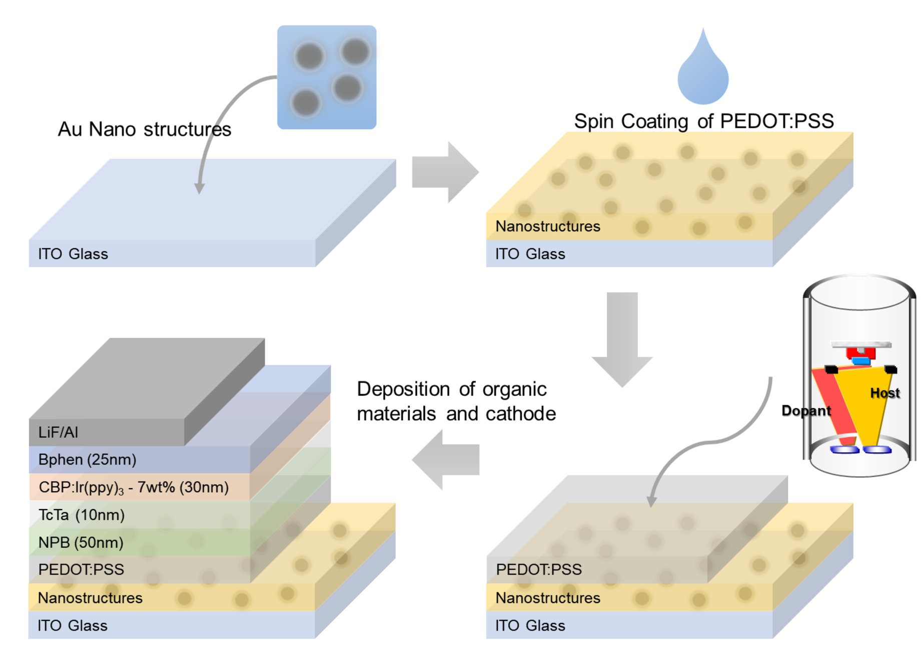
IQE is determined by the ratio of the radiative (k_{rad}) and nonradiative (k_{non}) recombination rates of carriers.

SP OLED

$$\eta^*_{int}(\omega) = \frac{k_{rad}(\omega) + C'_{ext}(\omega)k_{SPC}(\omega)}{k_{rad}(\omega) + k_{non}(\omega) + k_{SPC}(\omega)}$$

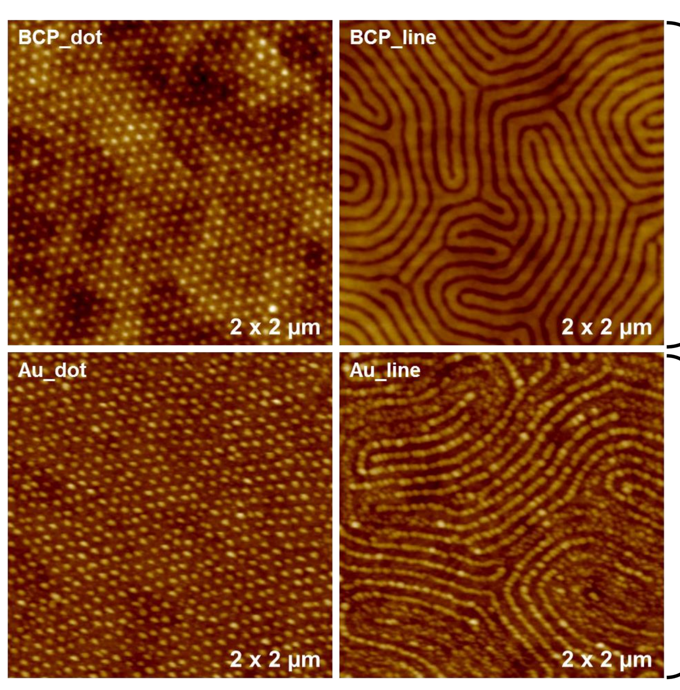
$k_{SPC}(\omega)$ - SP coupling rate $C'_{ext}(\omega)$ - probability of photon extraction from the SPs energy

$C'_{ext}(\omega)$ is decided by the ratio of light scattering and dumping of the SPP mode through nonradiative loss. $C'_{ext}(\omega)$ should depend on the roughness and nanostructure of the metal surface. If the SP coupling rate k_{SPC} is much faster than k_{rad} and k_{non}, the IQE should be dramatically increased.



Results & Discussion

Precise control of plasmonic nanostructures



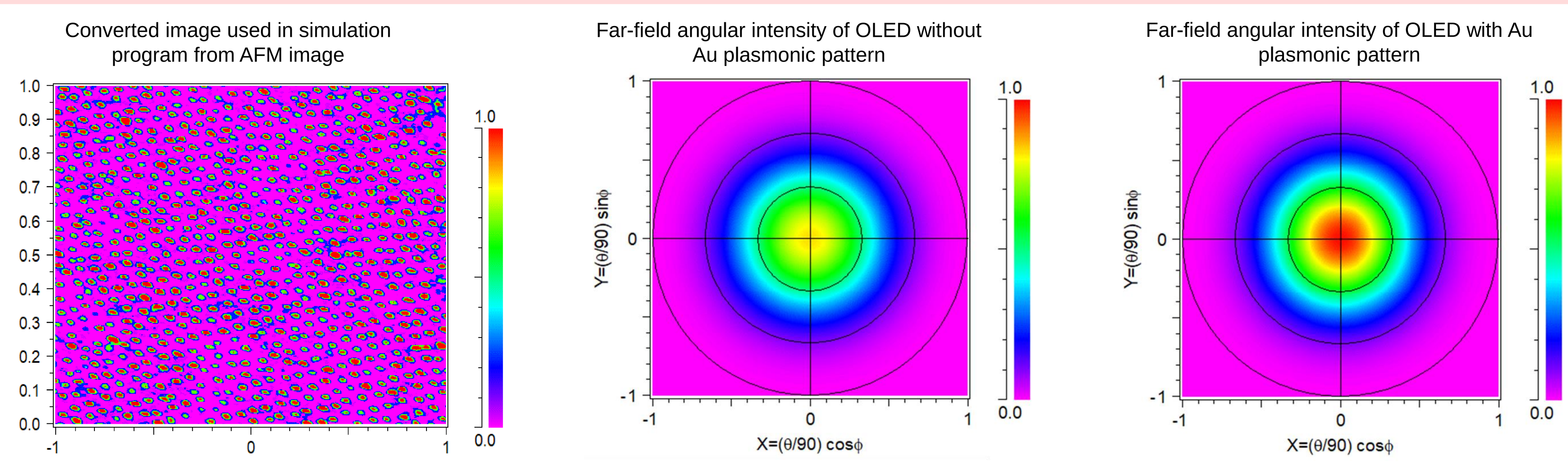
Block copolymer phase-separated patterns

Gold Pattern Dimension

	Height (nm)	Width (nm)
Dot	18 ~ 25	38 ~ 45
Line	10 ~ 15	38 ~ 45

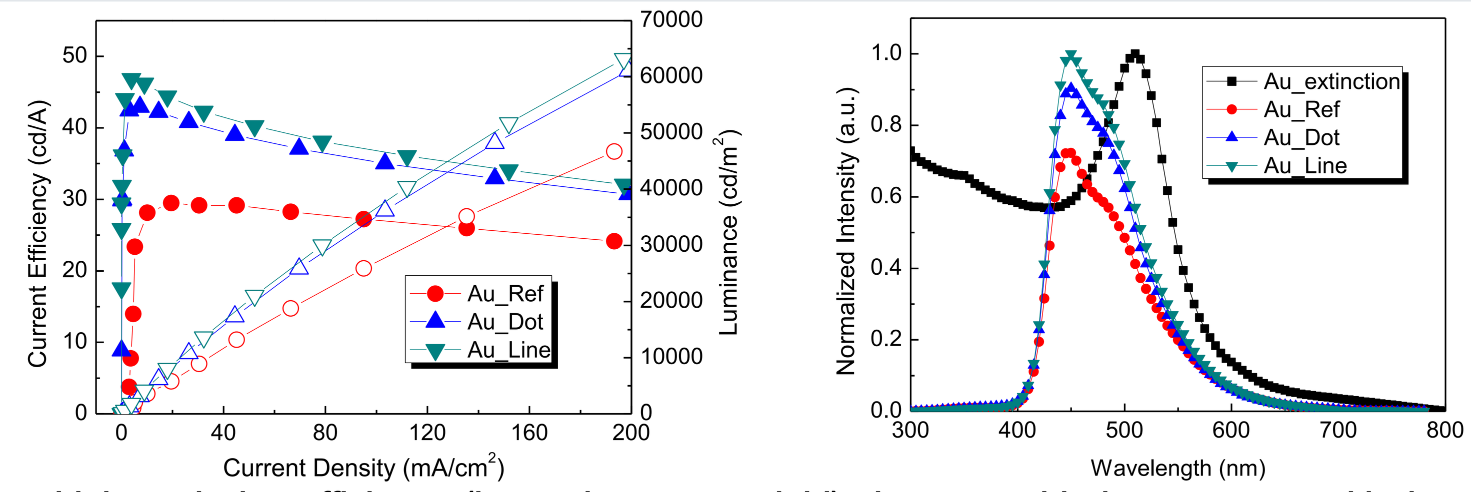
Au pattern treatment with $HAuCl_4$ and etching.

3D-FDTD simulation of intensity of OLED devices



Simulation result shows notable improvement with the contents of plasmonic nanoparticles, about 27.8% in terms of intensity for dot patterns of Au nanoparticles.

OLED devices with Au nanostructure

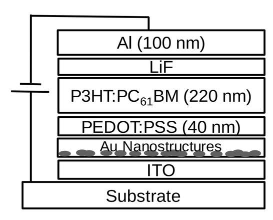


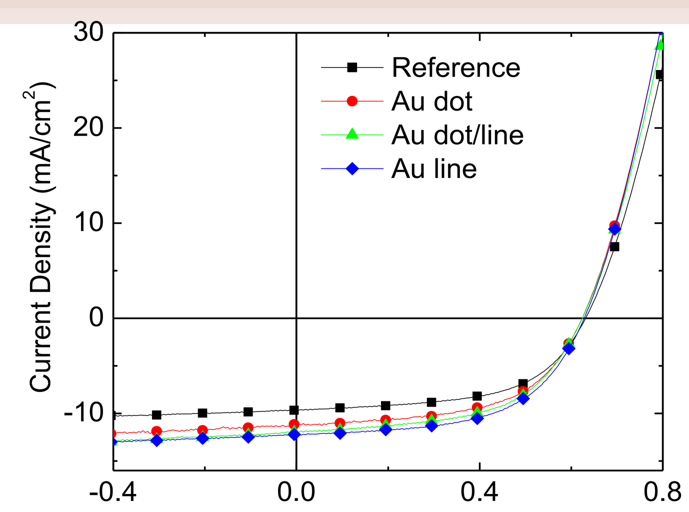
Light emission efficiency (internal quantum yield) shows notable improvement with the contents of plasmonic nanoparticles, about 33.1% and 43.8% in terms of current efficiency for dot and line patterns of Au nanoparticles, responsibility.

Organic Photovoltaics with Au nanostructure

	Reference	Au dot	Au dot/line	Au line (cylinder)
J_{sc} (mA/cm^2)	9.65	11.22	11.82	12.30
FF	0.56	0.56	0.56	0.56
V_{oc} (V)	0.63	0.62	0.62	0.63
PCE (%)	3.45	3.93	4.16	4.35

Short−circuit current (Jsc), fill factor, open−circuit voltage (Voc), and power conversion efficiency (PCE) of OSCs with reference and Au plasmonic nanostructures.





Current density vs. bias voltage for OSC devices with ITO/Au nano structrures/PEDOT:PSS coating/P3HT:PCBM/LiF/Al for different morphologies of Au patterns

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Conclusion

- We have successfully demonstrated the LSPR-enhanced OLEDs and OPVs by using a solvent annealing induced self-assembly process for BCPs : formation of patterns, such as simple Au dot and line patterns was controllable by the selection of the solvent at annealing process.
- The LRSP resulting from near-field enhancement can facilitate the radiative recombination of excitons, in favor of the decreasing the energy lost as non-radiative generation, and increasing the total number of excitons created in the emitting layer.
- Simulation result suggests that The SPP mode can be generated easily by direct energy transfer from electron-hole pairs without any special structures. Generated surface plasmon can be extracted from the interface as light and the emission efficiencies should be increased.
- The triggered LSPR resulted in a dramatic enhancement in the performance of the OPVs, showing a significant increase in the Jsc and the PCE by up to 126% of the reference value