Optical Design of Organic/Polymer Solar Cells and Light Emitting Devices

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***Abstract*—In this talk, we will study the effects of the microcavity structures and plasmonic resonances on the quantum efficiencies and photon lifetime. Theoretical and experimental results will be discussed on organic LEDs and solar cells (SCs).**

I. Introduction

The optical properties of organic optoelectronic devices depend strongly on device structures such as the microcavity effect of multilayered structure and plasmonic resonances (PRs) of metallic nanostructures. For organic LEDs (OLEDs), the optical properties include the change of emission wavelength, internal, out-coupling and external quantum efficiencies as well as the photon lifetime. For organic thin-film solar cells (OSCs), the optical properties include light trapping, concentration and absorption for improving the carrier generation. In this talk, we will discuss the contributions of the microcavity structures and surface plasmon resonances on the optical properties. Theoretical and experimental results will be discussed on OLEDs and OSCs.

For SCs, a systematic study of the plasmonic thin-film SCs with various metallic nanostructures has been investigated through our comprehensive electromagnetic models. For the numerical results, the physics of the absorption of thin-film SCs is explained by electromagnetic theory and correspond to waveguide modes, Floquet modes, and PRs. Meanwhile, we have also conducted experimental work in OSCs incorporated with Au nanoparticles. Our theoretical and experimental results show that both optical and electrical properties have to been investigated in detail in order to understand the device physics and optimize performances.

For organic/polymer LEDs, we will discuss our experimentally and theoretically work on some important issues including the optical design of multi-layered device structures for optimizing the external quantum efficiency, the extraction of internal quantum efficiency, and the determination of recombination region.

II. Results and Discussions

(a) Organic Solar Cells

Amongst various emerging technologies in the field of photovoltaics, the bulk-heterojunction OSCs have proved to be a highly promising candidate, due to its simple fabrication procedure, physical flexibility and low material cost [1]. However, there are still some challenges in organic photovoltaics. In particular, the low exciton diffusion length and low carrier mobility of organic semiconductors [2] limits the light absorption efficiency hence the power conversion efficiency (PCE) in such cells.

Efforts have been made to cater for this problem. One method of particular interest is the incorporation of metallic nanoparticles (NPs), commonly Au or Ag NPs, as a buffer layer or into the active layer. By utilizing PR effect, the local electromagnetic field of NPs can theoretically be enhanced, thus improving the optical absorption in OSCs [3-5]. Optical scattering induced by PR effects may also result in a longer optical propagation path within a SC [6,7], which subsequently increases absorption within the active layer.

Although efficiency enhancements in PSCs by incorporating NPs have been demonstrated experimentally [8-10], these enhancements are commonly attributed to PR through improvements in Incident Photon-to-Electron Conversion Efficiency (IPCE) enhancement. However, IPCE is also highly affected by the electrical characteristics of OSCs and can only provide indirect support to claims of PR effects. On the contrary, direct evidence of significant enhancements in active layer absorption has been relatively rare [9, 10]. On the whole, the degree of contribution of PR effects on OSCs incorporating NPs is still inconclusive. Meanwhile, some reports have stated that the variation of SC performance may be due to the introduction of ‘dopant states’ in the active layer or modified electrode interfaces [11]. Furthermore, it is also possible that doping the active layer with nanoparticles will alter the internal networking and phase separation of the layer. The study of both electrical and optical effects is highly important to fully understand the actual physics within a ‘plasmonic’ OSC.

The effects of the incorporation of Au NPs into the active layer of OSCs with newly synthesized donor polymer are investigated in detail. The low concentration of Au NPs (0.5 wt%) improves the efficiency by ~ 32% from 1.64% to 2.17%, while the further increase of Au NP concentration degrades device performances. The experimental absorption of the active layer and the theoretical results from our rigorous model on the photovoltaic structure suggest that the plasmonic enhancement alone cannot completely interpret device performances. The impact of Au NPs on the carrier mobility and exciton dissociation should also be considered to explain our results and optimize OSCs with Au NPs. The results and analysis contribute to the practical uses of the metallic NPs in OSCs.

(b) Organic light emitting devices

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Top-emitting OLEDs (TOLEDs), that allow the fabrication of OLEDs on silicon wafers with active-matrix backplanes, have been the subjects of intensive research recently [12-14]. The strong microcavity formed between the two metal electrodes not only influences the photon out-coupling efficiency but also significantly modifies the molecule's spontaneous emission rate [15]. The latter effect is so-called the Purcell effect [16], which can alter the lifetime of the excitons and the ratio of radiative and non-radiative decay rate, resulting in the change of internal quantum efficiency (IQE), external quantum efficiency and thus plays an important role in device performances. However, in the analysis of TOLED, the Purcell effect has not been treated properly. For example, a widely used approach on the analysis of electroluminescence (EL) efficiency of TOLED considers only the photo out-coupling efficiency [13], which usually results in underestimating the EL efficiency. Some other theoretical analysis [14, 17] overlooks the modification of the exciton lifetime in the microcavity, overestimating the efficiency enhancement. This error can be noticeably large when the emitting material has an IQE of 1.0 such as some phosphorescent materials. Another important issue of the microcavity based OLEDs is the relatively strong directionality of the emission [17, 18]. Highly angle dependent color or intensity of the emission in most cases is a problem for flat panel display applications. Optimization of TOLEDs for simultaneously achieving wide viewing angle and high EL efficiency is challenging but desirable for display applications.

We present an accurate analysis of light emission in TOLEDs by explicitly considering the Purcell effect. TOLEDs are optimized separately for maximum zero-degree luminance, maximum electroluminescence (EL) efficiency and wide viewing-angle with high EL efficiency. For fluorescent material with material IQE of 0.25, the maximum zero-degree luminance and EL efficiency can be achieved by locating the emitters around the first antinode of the microcavity while for phosphorescent material with material IQE =1.0, the maximum zero-degree luminance and EL efficiency are around the second antinode. Through relaxing the efficiency by 10-20%, the angular intensity distribution can be even better than the Lambertian distribution, meanwhile, the color shows only a small variation over an angle range of 150°. Our results which are in good agreement with experiments show that the Purcell effect on TOLED performances is significant and should be carefully examined in studying TOLEDs.

In addition, it is difficult to determine some device parameters which are important for optimizing device performance such as device IQE and exciton recombination location. A comprehensive analysis is given on the modifications of the exciton lifetime and device IQE for OLEDs. A linear relation is derived between the exciton lifetime and IQE, which is difficult to measure directly. IQE can thus be estimated easily through the measurement of the exciton lifetime. Besides, the exciton recombination location can be extracted through experimental and theoretical studies of OLEDs. By optimizing the recombination location, the polymer LEDs with power efficiency of 40lm/W has been achieved experimentally.

III. CONCLUSIONS

In conclusion, the electrical and optical properties of organic optoelectronic devices have been investigated theoretically and experimentally with plasmonic effects and microcavity effects. With the physical understanding and optimization of the device structures, we have experimentally demonstrated improvement in the device performances of OSCs and OLEDs.

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