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COMMUNICATION

Optically enhanced semi-transparent organic solar cells through hybrid metal/nanoparticle/dielectric nanostructure

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Abstract
Semi-transparent organic solar cells (st-OSCs) that hold high recovery of efficiency with sunlight illumination from both electrodes are of great interest in different applications. While the issues for improving the recovery of efficiency from top-illumination are very limited studied, we propose a hybrid optical nanostructure metal/nanoparticle/dielectric (M/NP/D) to achieve high recovery of efficiency. The M/NP/D nanostructure consists of high index and low-loss nanoparticles (NPs) (here we use Si NPs scatter instead of metal NPs) and index matching material (here we use Tris(8-hydroxyquinolinato) aluminum-Alq_3) on ultra-thin Ag film, i.e. Ag/Si NPs/Alq_3 as the top hybrid electrode of st-OSCs. Our results show that the transmission of the electrode is improved complementarily in long (due to Si NPs) as well as short wavelength regions (due to Alq_3 layer) with additional synergetic improvement (due to hybrid M/NP/D nanostructure). Subsequently, the enhanced average visible transmittance (AVT) up to 32% is achieved for the proposed st-OSCs. Simultaneously, compared to the optimized control st-OSC with the bare ultra-thin Ag electrode, the power conversion efficiency (PCE) for top-illumination case is improved by about 34%, with a recovery of efficiency up to 68%. Moreover, angular dependence of short circuit current (J_{sc}) of st-OSCs with the hybrid electrode can be also alleviated. Consequently, the proposed transparent hybrid electrode can contribute to the emerging semi-transparent optoelectronics.

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Introduction

Semi-transparent organic solar cells (st-OSCs) not only inherit the unique properties of organic solar cells (OSCs), but also bring innovation to both anode and cathode to preserve high transparency [1-9]. The commercialization of the st-OSCs can extend the potential application of OSCs such as the solar power-generating window, foldable solar curtains [4,6,10]. Nevertheless, the performance of st-OSCs is still low compared to opaque OSCs (o-OSCs) due to single pass of the light through devices and thus reduction of light absorption [8,9,11].

The recovery of efficiency here is defined as the ratio between the efficiency of the semi-transparent solar cell from top/bottom-illumination to that of its opaque one. An ideal st-OSC is expected to achieve high recovery of efficiency with sunlight illumination from both electrodes. However, the severe imbalance of device efficiency can exist between top- and bottom-illumination cases [4,12-14]. Studies in addressing these issues are limited especially the relative low recovery of efficiency from top-illumination [9]. Thus it's desirable to improve the device efficiency when sunlight illuminates from top transparent electrode and thus simultaneously achieves high recovered efficiency for both sides illumination for emerging applications.

Transparent ultra-thin metal film has been reported as a good candidate being top transparent electrode due to its easy processing, high conductivity and long skin depth [4,10,15-17]. However, the trade-off between conductivity and transparency is a critical issue for highly efficient st-OSCs [17,18]. For instance, the transmission of 10 nm Ag film is less than 70% in near ultraviolet region, especially, the transmission will decrease to below 50% after the wavelength of 660 nm [18,19]. Meanwhile, studies of the issue in reducing the reflectivity of transparent metal electrode of st-OSCs are limited [20,21]. Developing a low surface reflectivity of the transparent electrode is essential to achieve high efficiency st-OSCs.

The issue of the low transmittance of ultra-thin metal electrode can degrade the light incoupling into the active layer of st-OSCs, the antireflective coating (ARC) layer is widely used to reduce the interfacial reflection thus increase the transmittance of metal electrode by light wave interference through finely tuning the thickness of the ARC layer [22-25]. Nevertheless, the use of ARC layer on ultra-thin metal film that functions as top electrode is not well studied in st-OSCs. In addition, the improvement from mere adoption of planar ARC layer would be weakened under sunlight with an oblique incident angle, due to the deviation of wave destructive interference condition.

Another potential solution is the plasmonic effect of metal nanomaterials and nanostructures, which is emerging as an excellent tool to enhance light harvesting by its highly confined near field distribution [26-34]. For st-OSCs, the incorporation of metal nanomaterials into device would increase some degree of surface roughness, it would bring difficulties to form high quality and uniform ultra-thin metal film, leading to poor electrical properties and thus hindering to achieve high efficiency of st-OSCs [15,20,35]. Therefore, the incorporation of metal nanomaterials into st-OSCs can only be expected to be located out of the device, where the light incoupling improvement mainly come from the scattering effect of metal nanomaterials other than the highly localized near field [36]. However, the use of metal nanomaterials at top electrode side will introduce the intrinsic loss as light impinging and be detrimental to achieve high transparency of ultra-thin metal electrode [36,37].

Compared to metal nanomaterials, the dielectric nanomaterials conversely have no such metal loss, and are an excellent candidate to improve light incoupling by the scattering effect [38-40]. Previous literatures report the utilization of whispering-gallery mode from the highly close-packed silica (SiO_2) sphere for improving light incoupling in amorphous silicon (Si) solar cells [41,42], while the size of the sphere should be on the magnitude of several hundred nanometers because of the relatively low refractive index. Besides, through employing the two-dimensional (2D) photonic pattern that was made by interference lithography and soft-imprint lithography, an ultra-low reflectance of Si wafer from the top electrode can also be achieved for Si solar cells [43,44]. However, the direct integration of photonic patterns on thin top electrode for st-OSCs through the lithography process may damage the ultra-thin metal electrode and the organic active layer. Consequently, it is of great importance to offer a simple and efficient structure by using dielectric materials to realize low reflectivity for ultra-thin metal electrode and enhance the light incoupling of the active layer for highly efficient st-OSCs.

Moreover, performances of the planar st-OSCs will degrade as the incident light tilt away from the normal following the Lambert's cosine law, which indicates the incident light intensity would vary as the cosine of incident angle of light [40,45,46]. Therefore, an alleviated angular dependence of device performance on polarization and incident angle of light is highly desirable for the commercialization of st-OSCs.

Here, we proposed the metal/nanoparticle/dielectric (M/NP/D) nanostructure as transparent electrode, which consists of high index scatter of Si nanoparticles (Si NPs) together with index matching material (here we use Tris(8-hydroxyquinolinato) aluminum, Alq_3) as a hybrid optical structure on top of ultra-thin Ag film for enhancing the light incoupling. The hybrid electrode (Ag/Si NPs/Alq_3) can improve average visible transmittance (AVT, defined as an average of transmission in wavelength region 380–740 nm) to about 72% with an enhancement ratio of 24% compared to that of the bare Ag thin film electrode (AVT=58%). After utilizing the proposed M/NP/D nanostructure as top electrode, the AVT of 32% is achieved for the proposed st-OSCs. Simultaneously, the power conversion efficiency (PCE) of st-OSCs can be improved by about 34% compared to the optimized control device without any optical incoupling structures. Moreover, by simultaneously utilizing Si NPs hybridized with Alq_3 layer, the transmission is improved complementarily in long (due to Si NPs) and short wavelength regions (due to Alq_3 layer) with additional synergetic improvement (due to hybrid M/NP/D nanostructure), resulting in a broadband absorption enhancement that almost cover the whole visible spectrum. Compared to the opaque counterpart, a recovery of efficiency up to 68% and 87% can be attained in our proposed st-OSCs in top and bottom