

Plasmon-Electrical Effects on Organic Solar Cells by Incorporation of Metal Nanostructures

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(Invited Paper)

Abstract—Recently, plasmonic effects of metal nanostructures have been intensively exploited to enhance the performance of organic solar cells (OSCs). The plasmonic-optical effects of localized surface plasmon resonances, scattering effect and propagating surface plasmon resonances, etc., are well recognized in considerably enhancing the active layer absorption. Besides, the improved electrical properties of OSCs by plasmonic-electrical effects have recently been reported to be of equal importance in enhancing the performance of OSCs through the introduction of plasmonic metal nanostructures into different layers of OSCs. In this review, the plasmonic-electrical effects of metal nanostructures-induced space-charge limit elimination, transfer of plasmonically excited hot carriers, and charge-accumulation effects would be briefly discussed. The mechanisms of each plasmonic-electrical effect including tailored transport path of charge carriers (electron and hole), reduced extraction barrier of carrier transport layer, and redistributed exciton generation in active layer for enhancing the performance of OSCs would also be studied simultaneously with the experimental and theoretical results. The promoted electrical properties of OSCs by the plasmonic-electrical effects and the future combination of plasmonic-optical and electrical effects would promisingly offer an alternative way to further improve the performance of OSCs.

Index Terms—Organic solar cell, plasmonic-optical effects, plasmonic-electrical effects, nanostructure.

I. INTRODUCTION

THE efficiency of organic solar cells (OSCs) is still low for practical application due to the poor optical absorption of active layer, which is typical hundreds nanometer thickness, electrically restricted by the low exciton diffusion length [1] and charge carrier mobility [2], [3]. To improve the performance of OSCs, the tailored organic materials with large absorption coefficient are highly essential to achieve high active layer absorption [4], [5]. On the other way, the investigation of device physics [6]–[8] and incorporation of light trapping structures into OSCs also increase the efficiency of device [9]–[16].

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For instance, through tuning the thickness of the optical spacer layer, the internal electromagnetic field (near field) distribution in active layer could be maximized by constructively wave interference then lead to improve the active layer absorption [17]–[20]. In addition, adoption of the antireflection coating structures also reduce the light reflection loss and improve light incoupling by destructive interference of incident and reflected wave [9], [21], [22].

Plasmonic effects of metal are emerging as a promising tool in optoelectronics that allow the manipulation and confinement of light at the nanoscale [23], [24]. The plasmonic effects in optical aspects including localized surface plasmon resonances (LSRPs), scattering effect and propagating surface plasmon resonances (SPRs), etc., have been extensively used to efficiently improve the active layer absorption which was well known and here termed as the plasmonic-optical effects [25]–[27]. (a) Through embedding metal nanomaterials directly into active layer, both the highly concentrated near fields around metal nanomaterials (LSPR effect) and the elongated optical path in active layer (scattering effect) efficiently enhanced the active layer absorption [12], [28]–[35]. (b) In addition, the incorporation of plasmonic metal nanomaterials into carrier transport layer (CTL) has also been studied to enhance performance of OSCs [11], [36]–[43]. The mechanisms of morphology modification, hot carriers transfer [41], [42] and charge-accumulation effects [43] have been reported to improve the performance of OSCs. (c) The introduction of metal nanopatterned structure as electrode was also reported, the excitation of a bounded surface wave along the interface of metal nanopatterned electrode and the surrounding materials by SPR effect and confinement of near field in active layer by quasi-guide modes were attributed to the improvement of active layer absorption [44]–[52]. (d) The enhancement of active layer absorption has demonstrated to be further enhanced in the broadband spectrum through incorporating metal nanostructures with different shapes (nanospheres, nanoprisms, nanorods) [13], [29], [30], [53], different materials (silver, gold, copper, aluminum, etc.) [12], [54], [55], multiple structures into active layer and CTL [11], [12], [31], [32], [56], [57], and engineering of metal nanopatterned electrode into quasi-periodic structures [58]–[60] and wrinkle surface [48], [61]–[63]. In addition, the plasmonic-optical effects by the incorporated metal nanostructures (e.g., metallic nanocubes, patterned electrodes, etc.) have also been widely used to enhance the semiconductor absorption for colloidal quantum dot and silicon thin film solar cell [64]–[66]. There are enormous reports on this topic and will not be discussed here.

Besides, there are some critical issues need to be carefully handled such as the parasitic optical absorption of the metal nanostructures and the incurred quenching effect around the metal interface, etc. [30], [67]. The parasitic optical absorption of the incorporated metal nanostructures is coherently existed, while minimizing such dissipated metal loss gives the potential to further enhance active layer absorption. For instance, through tuning the thickness of the adjacent spacer layer of the metal nanopatterned electrode, the minimization of the metal absorption can be achieved. [67]. The introduction of dielectric-metal core-shell nanostructures is proposed to not only mitigate the quenching effect around the interface between the metal and semiconductor but also reduce the metal loss [30], [67]–[69]. With the careful consideration of these issues, the plasmonic-optical effects actually give considerable enhancement of active layer absorption.

However, the overall device efficiency is not only limited by the optical absorption of active layer but also next constrained by the electrical properties of OSCs such as location of exciton generation, mobility of charge carriers, interfacial morphologies and extraction of charge carriers, etc., [33], [39], [70], [71]. Recently, the incorporation of metal structures has been reported to improve these electrical properties of OSCs [33], [39]. The mobility of the charge carrier in organic materials was enhanced with three folds by the embedded metal NPs and also the better interfacial morphology between organic and CTL has been demonstrated to favor the charge carrier extraction [33].

Besides, with the plasmonically excited hot carriers transferred from metal structures to metal oxide, the carrier extraction barrier was improved by incorporating the metal nanomaterials into CTL [41], [42]. In addition, the exciton generation has demonstrated that could be tailored by incorporation of the metal nanostructure in OSCs [71]. The concept of plasmonic-electrical effects was proposed to explain the plasmonically induced improvement of electrical characteristics in OSCs. In this review, the recently experimental results and theoretical simulations are summarized to understand the improvement of electrical properties in OSCs by the mechanism of plasmonic-electrical effects.

The manuscript is organized as following. Section I briefly reviews the enhanced performance of OSCs by plasmonic effects (optical and electrical effects). Section II discusses the plasmonic-electrical effects that induced by metal nanopatterned electrodes, Sections III and IV are the improvement of electrical properties in OSCs by incorporation of plasmonic metal nanomaterials into CTL and active layer, respectively. Section V concludes the review.

II. ELECTRICAL EFFECTS IN METAL NANOPATTERNED ELECTRODE

Through engineering the metal electrode into different nanopatterns such as periodic structure of 2-D, 3-D grating, quasi-periodic structures and random structures, the absorption of active layer was reported to be distinctly improved by the optical effects such as SPR, Bloch mode, Fabry–Perot mode and quasi-guide mode [44]–[52]. In addition, the promoted electri-

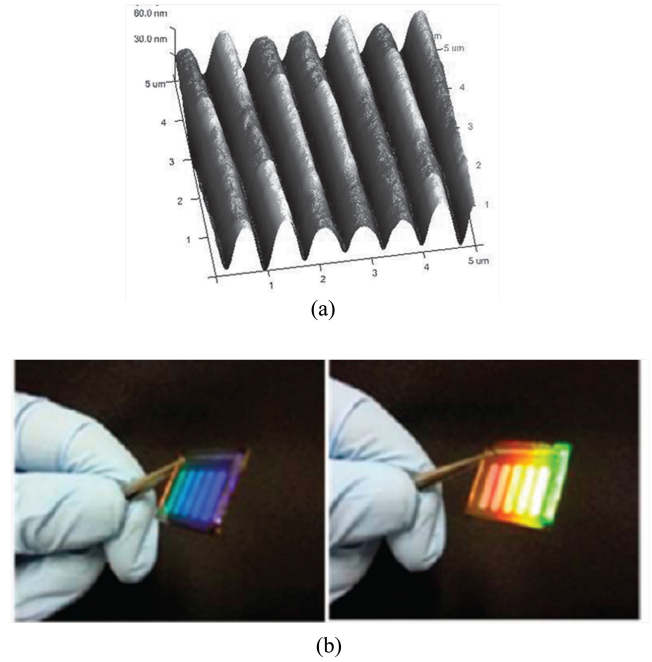


Fig. 1. (a) Atomic force microscopy (AFM) images of the PTB7:PC₇₁BM grating with the period of 700 nm and depth of 40 nm [44]. (b) Photographs of a patterned device irradiated under indoor daylight lamps at different tilted angles [45].

cal properties of OSCs were subsequently found by the introduction of such metal nanopatterns [44], [45], [71], [72]. The modification of the morphology and the distribution of exciton generation would be discussed in this section.

A. Morphology Modifications

For instance, with the PDMS nanoimprinted method in the inverted OSCs, the low bandgap polymer benzodithiophene polymers (PTB7):[6,6]-phenyl-C71-butyric acid methyl ester (PC₇₁BM) conspicuously revealed the nanopattern of grating with 700 nm period and 40 nm depth (see Fig. 1(a)) [44], [45]. Since the MoO₃ CTL was very thin about 10 nm, the thermally evaporated Ag anode would form a metal nanograting pattern on the active layer. The photograph of the patterned device irradiated under indoor light lamps at different tilted angles showed the diffraction feature of light that confirmed the formation of the grating structures in metal electrode as shown in Fig. 1(b) [45]. Aside from the observation of absorption enhancement of active layer, the high fill factor (FF) was attributed to the enlarged interfacial area and reduced series resistance (R_s) induced by the grating structure that favored the efficient collection of the charge carriers [45], [46]. Meanwhile, the theoretical work revealed the superior absorption of polymer was dependent on the coupling between chain morphology and surface plasmon wave [73]. The introduction of nanopatterns on organic materials can reorient the crystallization and chain morphology of thin film active layer to align with the field component of the surface wave [74] (see Fig. 2). The alignment of polymer chain and component of surface wave would strength the coupling and then lead to the enhancement of active layer absorption.

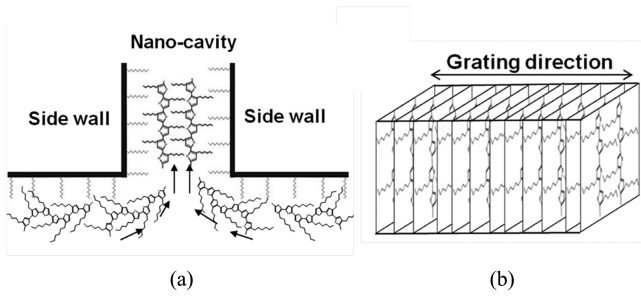


Fig. 2. (a) The schematic mechanism of the chain of P3HT thin film modified by the grating structure. (b) Ideal structures of P3HT chain aligned by grating [74].

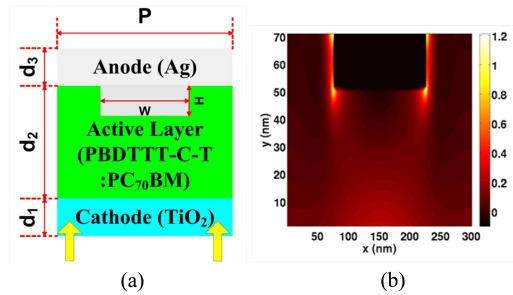


Fig. 3. (a) The schematic patterns for the unit cells of the plasmonic OSCs with nanopatterned anode. (b) The generation rate map (logarithmic scale) of the plasmonic cell divided by that of the standard cell (in the active layer) [70].

B. Redistribution of Exciton Generation and the Elimination of Space Charge Limit (SCL)

The incorporation of metal nanopatterned electrode can induce a large enhancement of active layer absorption. The theoretical work demonstrated that the photogenerated excitons are highly localized around the grating structures in the inverted OSCs with rectangular grating anode [70] (see Fig. 3). Therefore, the specifically enhanced absorption regions in active layer are mainly around the nanopatterned electrode.

In the subsequent work, the plasmonic-electrical effects of the metal nanopatterned electrode on the SCL was investigated [71]. SCL is a universal phenomenon that can be observed in OSCs if existence of unbalanced carriers mobility in relative thick active layer and especially with dense carriers generation [71], [75], [76]. The elimination of SCL has been observed by the incorporation of the nanopatterned electrode into the inverted OSCs [71]. The plasmonic-electrical effects of the metallic grating anode have been attributed to the redistribution of the exciton generation regions that move from region near cathode to near grating anode and then shorten the transport paths of low-mobility holes. The schematic illustration of transport paths for the electrons and holes in inverted OSCs with metallic planar and grating anode was shown in Fig. 4. It reported that the better balanced transport paths for charge carriers (electron and hole) would reduce the bulk recombination and hole accumulation result in the elimination of SCL. The inverted OSC device with structures of ITO/TiO₂ (20 nm)/active layer (220 nm poly(3-hexylthiophene): phenyl-C61-butyric acid methyl ester, P3HT:PCBM)/MoO₃ (10 nm)/Ag (with or without

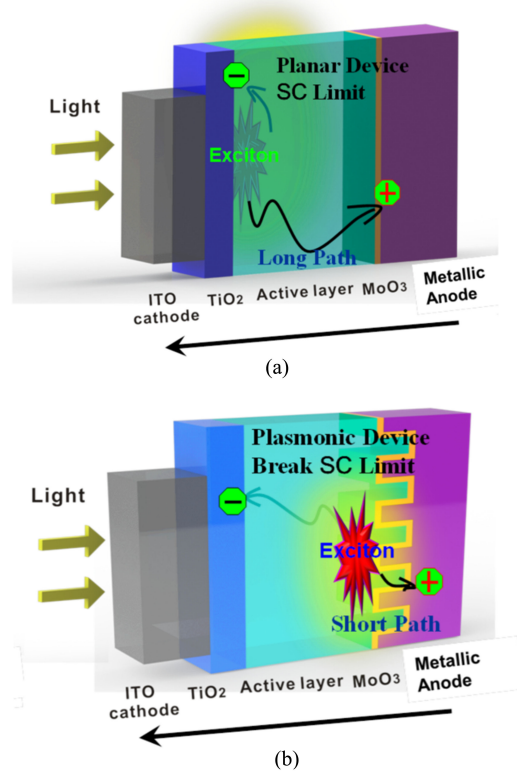


Fig. 4. A schematic mechanisms of transport paths of charge carriers in inverted OSC devices. (a) inverted OSCs with a planar metallic anode; (b) inverted OSCs with a grating metallic anode [71].

grating) (100 nm) were experimentally fabricated. The experimentally measured photocurrents (J_{ph}) versus effective applied voltage ($V_0 - V$, V_0 is built-in potential) at different incident light intensities were shown in Fig. 5. When $V_0 - V$ is less than 0.2 V (i.e., a low internal field), the approximately linear relationship between J_{ph} and $V_0 - V$ is mainly governed by the diffusion and drift current effects. As internal field starts to increase, a square-root dependence of J_{ph} and $V_0 - V$ emerges for the Ag-planar inverted OSCs as shown in Fig. 5(a) (black line denoted by SCL region, i.e., existence of charge accumulation). When the internal field further increases (i.e., under a sufficiently large reverse bias), J_{ph} become saturated and recombination does not occur (the critical effective voltage is denoted as V_{sat}). As shown in Fig. 5(b), the elimination of SCL region was conspicuously observed in inverted OSCs with Ag grating anode. Differently, regarding to the normal OSCs device with structure ITO/ poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate) (PEDOT:PSS, 30 nm)/active layer (220 nm)/Ca (10 nm)/Ag (with or without grating) (100 nm), the elimination of SCL region cannot be observed even with Ag grating electrode because of the existence of charge accumulation. The coupled optical and electrical simulations with redistribution of exciton generation were simultaneously carried out to clarify the underlying physics [71]. The existence of SCL phenomenon in the normal OSCs device even with the Ag grating cathode (for collecting the electron not holes) was explained by severely unbalanced transport paths of the high-mobility electrons and low-mobility

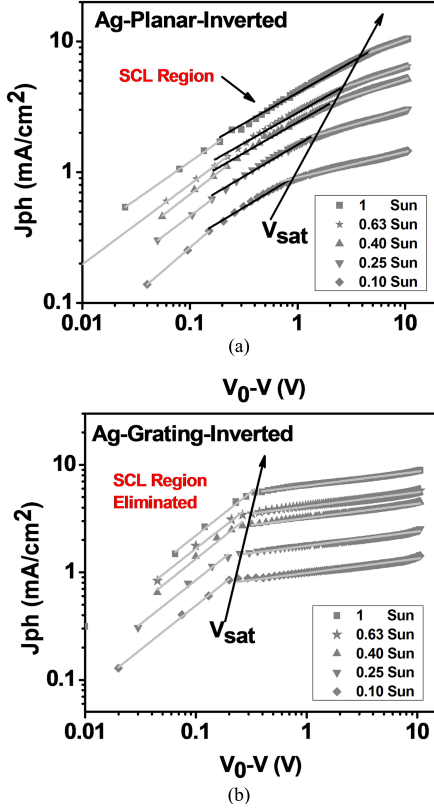


Fig. 5. SCL characteristics for Ag-inverted OSCs measured at room temperature ($T = 300$ K) with photocurrents (J_{ph}) versus effective applied voltage ($V_0 - V$, V_0 is the built-in potential) at different incident light intensities. Here, V_{sat} is the voltage that photocurrent J_{ph} is saturated. (a) Ag-planar-inverted OSCs, and (b) Ag-grating-inverted OSCs. The black solid lines in (a) represent the square-root dependence of photocurrent on effective applied voltage (SCL region) [71].

holes because of inversely moving the exciton generation regions from near anode (ITO) to near cathode (Ag grating) [71]. Both the results of normal and inverted OSCs with metallic planar and grating electrode confirmed the resultant SCL elimination was due to the redistribution of photogenerated excitons by the plasmonic-electrical effects. An appropriate manipulation of the exciton generation region and better balanced transport paths of charge carriers would be beneficial to improve the performance of OSCs.

III. ELECTRICAL EFFECTS BY INCORPORATION OF METAL NANOMATERIALS INTO CTL

The performance of OSCs was reported to be improved by incorporation of the plasmonic metal nanomaterials into CTL such as hole transport layer of PEDOT:PSS [36]–[39] and MoOx [40], electron transport layer of ZnO and TiO_x [41]–[43]. The mechanisms of such improvement by metal nanostructures are considered to be of different origins, such as plasmonic resonance, scattering effect [38], interfacial morphology [39], hot carrier transfer [41], [42] and charge-accumulation effects [43]. Aside from the enhancement of active layer absorption by plasmonic-optical effects of metal nanostructures, the observation of the improved electrical properties of OSCs was recently reported

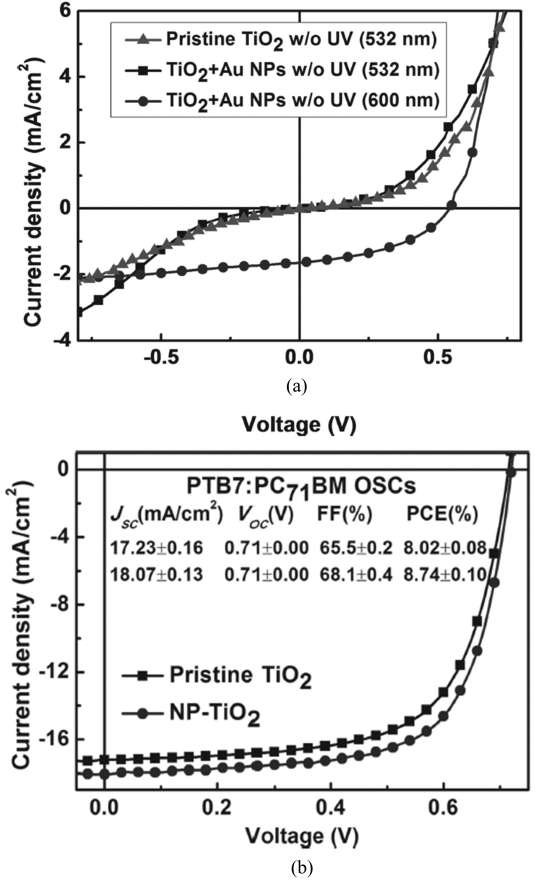


Fig. 6. (a) J - V characteristics of P3HT:PC₆₁BM OSCs measured under monochromatic light of 532 and 600 nm with pristine TiO₂ and NP-TiO₂ composite (TiO₂+Au NPs) as the electron transport layers. (b) PTB7:PC₇₁BM OSCs with TiO₂ and NP-TiO₂ composite with the optimized NP concentration (2 wt%) as the electron transport layers [41].

[39], [77]. By introduction of the Au NPs into hole transport layer of PEDOT:PSS, the interfacial area and surface roughness between active layer and PEDOT:PSS was increased and the route for holes to travel to the anode was shortened [39], [77]. Moreover, by incorporation metal nanomaterials into electron transport layer such as ZnO and TiO_x, the plasmonically induced electrical effects of hot carriers transfer and charge accumulation were also observed and will be discussed in the following context.

A. Transfer of Hot Carriers

Utilization of commonly used metal oxide such as ZnO and TiO_x as electron transport layer generally required UV illumination to improve the device performance [78]–[83]. Under the exposure of UV light with photon energy larger than the metal oxide bandgap ($h\nu > E_g$), the trap states in ZnO and TiO_x can be filled by electrons from carrier excitation of metal oxide [79]–[81], thereby improving the performance of OSCs. However, illumination of UV light may induce degradation of organic materials, employment of UV blocking filters, i.e., mere adoption of visible light illumination is typically essential for achieving reasonable device lifetime [84]. Recently, in virtue of the plasmonic-electrical effects of metal

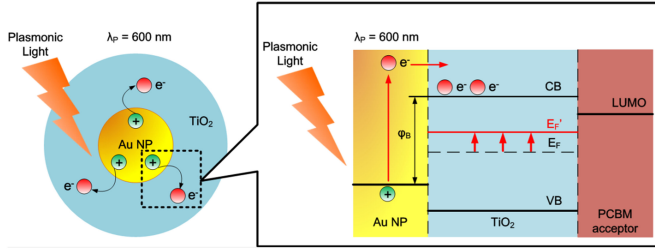


Fig. 7. Schematic plasmonic-induced charge injection process. CB and VB denote the conduction band and valence band respectively. ϕ_B is the Schottky barrier height between Au and TiO_2 . LUMO denotes LUMO of the PCBM acceptor in OSCs. Electrons are extracted from PCBM to TiO_2 in OSCs [41].

nanomaterials, the improved s-shape J - V characteristic and enhanced charge carriers extraction of the device without UV illumination has been demonstrated by introducing Au NPs in TiO_2 -based electron transport layer [41]. The J - V characteristic of the OSCs device with structure ITO/ TiO_2 (20 nm, with or without Au NPs)/P3HT:PC₆₁BM (220 nm)/MoO₃ (14 nm)/Ag (100 nm) was shown in Fig. 6(a). Without the UV exposure but under illumination with monochromatic light of 532 nm, the low FF in s-shape J - V characteristic was observed in the OSCs with electron transport layer of pristine TiO_2 or Au NPs- TiO_2 composite layer. Differently, the utilization of monochromatic light of 600 nm that falls into the resonant wavelength of Au NPs, the plasmonically induced hot carriers in Au NPs would transfer and fill the trap states in TiO_2 and then lower the effective extraction barrier of Au NPs- TiO_2 composite layer. The integrated optical and electrical model was also conducted with consideration of the hot carrier tunneling probability and extraction barrier between TiO_2 and the active layer. Experimental and theoretical results that confirmed the work principle of trap states in TiO_2 film filled by hot carrier transfer as depicted in Fig. 7. The power conversion efficiency of inverted OSC with low bandgap polymer thieno[3,4-b]thiophene/benzodithiophene (PTB7):PC₇₁BM summarized in the inset of Fig. 6(b) was enhanced to 8.74% due to the better carrier extraction favored by the plasmonic-electrical effects of metal nanoparticles. Therefore, the highly efficient OSCs can operate by optical activation only around the plasmonic excitation wavelength (560–600 nm) far longer than the originally necessary UV light (<400 nm).

In some other studies, it has been reported that the trap states in the electron transport layer of ZnO and TiO_x were attributed to the existence of oxygen vacancies that lead to the extraction barrier in the metal oxide [82], [83]. The work function (WF) of structure $\text{TiO}_x/\text{Ag NPs}/\text{TiO}_x$ (3 nm) was experimentally measured with visible illumination in vacuum and oxygen atmosphere, respectively. The lowered WF (WF = 3.9 eV) was remained in vacuum after the visible illumination but returned to the same value as before illumination (WF = 4.3 eV) once exposed in the oxygen atmosphere as shown in Fig. 8. Therefore, the decreased WF of TiO_x film embedded with Ag NPs under visible light was attributed to desorption of previously ionosorbed oxygen ($\text{O}_2^-(\text{ads.})$) [42], [82]. Moreover the photo-induced desorption of oxygen requires photogenerated

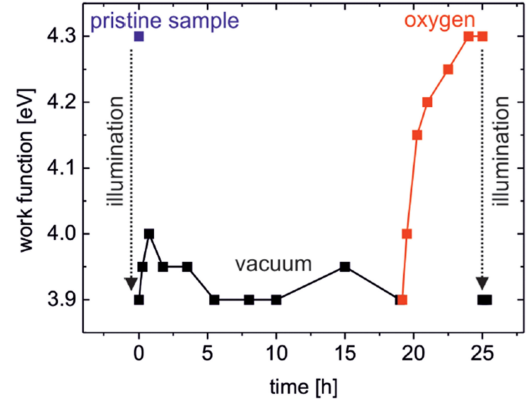


Fig. 8. WF of a $\text{TiO}_x/\text{Ag NP}/\text{TiO}_x$ (3 nm) layer after illumination with AM1.5 (with filter: $\lambda > 550$ nm) for 1 h upon storage in vacuum for several hours, subsequent exposure to oxygen atmosphere and repeated illumination with AM1.5 (with filter: $\lambda > 550$ nm) for 1 h [42].

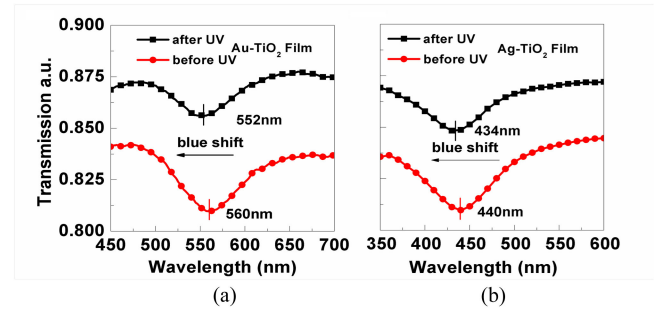


Fig. 9. (a) Transmission spectrum of the glass/ITO/Au- TiO_2 sample before and after UV illumination. (b) Transmission spectrum of the glass/ITO/Ag- TiO_2 sample before and after UV illumination [43].

holes to neutralize the negatively charged oxygen, i.e., $\text{O}_2^-(\text{ads.}) + h^+ \rightarrow \text{O}_2^{\uparrow}$. The plasmonically induced holes were considered as the hot carriers that transferred from Ag NPs to semiconductor TiO_x and accounted for the reduced WF of metal oxide. With incorporation of Ag NPs into TiO_x and ZnO, the altered WF with decrease up to 0.4 eV compared to the pristine one has demonstrated under illumination of visible light ($h\nu < E_g$).

B. Charge-Accumulation Effects

The charge-accumulation effects were also reported to contribute to the reduced extraction barrier through lowering the WF of metal-semiconductor composite that consisted of the TiO_2 film embedded with Ag or Au NPs [43]. Under UV light soaking, the UV-excited electrons of TiO_2 were transferred to metal NPs and enhanced the accumulation of electrons in metal NPs- TiO_2 composite next to reduce the WF of the electron transport composite layer. The charge-accumulation effects were verified by the blue shift of plasmonic resonance in Ag and Au NPs-incorporated TiO_2 film after UV light soaking (see Fig. 9). Moreover, the temporal WF changes were measured for the TiO_2 film, Au NPs- TiO_2 film and Ag NPs- TiO_2 film (see Fig. 10(a)) to demonstrate the charge accumulation effects. Under UV illumination, the WF of TiO_2 film with and without metal NPs revealed a relative low WF around 4.35 eV. After cutting off

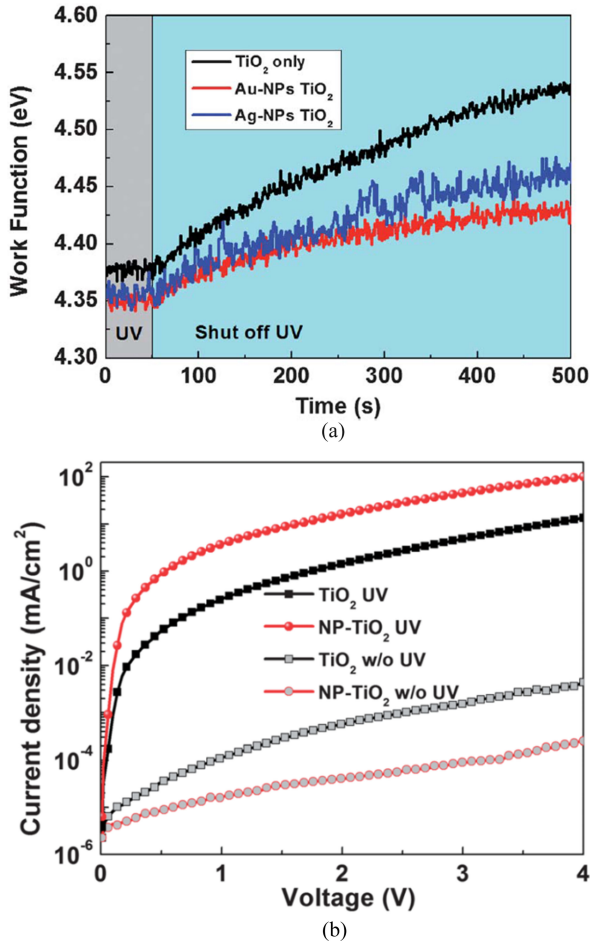


Fig. 10. (a) Temporal WF changes of the TiO₂ film, Au NPs-TiO₂ film and Ag NPs-TiO₂ film measured, after UV illumination for 15 min and the UV light is then turned off. (b) J - V characteristics of electron-only devices using TiO₂ and optimized NPs-TiO₂ as electron transport layer measured with and without (w/o) UV excitation [43].

the UV soaking, most of the photogenerated electrons of TiO₂ film without metal NPs will be lost to the electrode or relax that lead to an increase of WF. In contrast, the larger electron density accumulated in previous UV light soaking were retained by the metal NPs and resulted in a lower WF of the metal-semiconductor composite. In addition, such electron accumulation is distinctly different from the conventional doping effect in semiconductors which was affirmed by the dark current density of electron only device with structure (ITO/TiO₂ or Au NPs-TiO₂ (20 nm)/P3HT:PC₆₁BM (220 nm)/Ca (20 nm)/Al (100 nm)). The current density of electron only device with NP-TiO₂ composite film transport layer was lower than that of NP-free device suggesting that the mere presence of Au NPs without light excitation actually weakened the electron extraction in OSCs. However, after the identical UV illumination for both devices, the NPs-TiO₂ device disclosed a notable larger current density than that of NP-free device.

IV. ELECTRICAL EFFECTS BY INCORPORATION OF METAL NANOMATERIALS INTO ACTIVE LAYER

The distinctly improved performance of OSCs by the incorporation of metallic nanomaterials into active layer has been widely

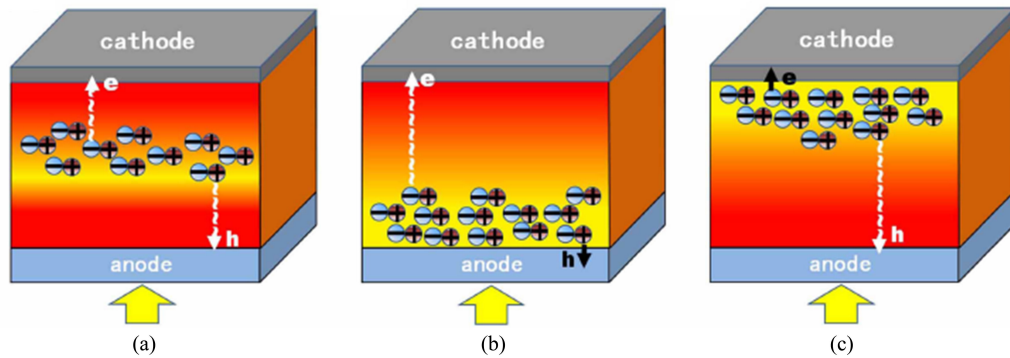
reported [12], [28]–[33], [35]. The highly concentrated near field from the LSPRs of nanomaterials that could enhance optical absorption of active layer was well recognized. Moreover, incorporation of multiple metal nanostructures with different shapes, sizes and materials into active layer were further reported to strength and broaden the active layer absorption spectrum [12], [13], [29]–[31], [53]–[55]. Meanwhile, the electrical properties of active layer embedded by such metal nanomaterials were simultaneously investigated [33], [34]. It has been reported that the incorporation of Au NPs into active layer poly[2,7-(9,9-dioctylfluorene)-alt-2-((4-(diphenylamino) phenyl)thiophen-2-yl)malononitrile] (PFSDCN):PC₆₁BM introduced dopant states within the bandgap of polymer materials which could provide hopping sites for the holes and thus enhance the carrier mobility. The hole mobility of active layer by the incorporation of 2 wt% Au NPs was enhanced to $4.25 \times 10^{-4} \text{ cm}^2 \cdot \text{V}^{-1} \cdot \text{s}^{-1}$ from $1.26 \times 10^{-4} \text{ cm}^2 \cdot \text{V}^{-1} \cdot \text{s}^{-1}$ with three folds increase [33]. However, the maximum performance of OSCs was achieved with 0.5 wt% Au NPs, mainly due to the reduction of exciton dissociation at high concentration of Au NPs and downward shift of the cathode WF by the modification of the interfacial charge states.

Aside from the nanopatterned electrode induced redistribution of carrier generation region in inverted OSCs [71], the incorporation of metal nanomaterials into different locations of active layer (near anode, middle, near cathode, see Fig. 11) has also demonstrated to have the capability to manipulate the locations of generated excitons and subsequently to achieve a better balanced transport paths of the charge carriers through shortening transport path for the low-mobility carriers [85], [86]. The device with structure ITO/MoO₃ (10 nm)/CuPc:C₆₀ ($d_1 = 20, 40, 60 \text{ nm}$)/Ag NPs/CuPc:C₆₀ ($d_2 = 60, 40, 20 \text{ nm}$)/BCP (10 nm)/Ag was fabricated, the nanomaterials of Ag NPs were embedded into different positions of the active layer by using thermal evaporation at different stages of film formation of the active layer (see Fig. 11(II)). The nonuniform exciton generation rate after incorporating Ag NPs into active layer was clearly seen in theoretically modeling results as shown in Fig. 12(a). Therefore, the plasmonic-electrical effects of the metal NPs can redistribute the optical absorption region of active layer. Regarding that the hole mobility ($3.4 \times 10^{-7} \text{ cm}^2 \cdot \text{V}^{-1} \cdot \text{s}^{-1}$) of CuPc:C₆₀ active layer is almost four order magnitude smaller than that of electron mobility ($1.0 \times 10^{-2} \text{ cm}^2 \cdot \text{V}^{-1} \cdot \text{s}^{-1}$), the better balanced transport paths for charge carrier was achieved by incorporating Ag NPs into CuPc:C₆₀ near the anode, which moved the generation exciton region to the near anode and shortened the transport path of low mobility hole to anode. Therefore, the maximum device performance was found to be the case of embedded NPs in active layer near anode (see Fig. 12(b)).

V. CONCLUSION

In conclusion, we have reviewed the recent progress of plasmonic-electrical effects by the introduction of metal nanostructures in OSCs. The effects of redistribution of charge carrier and the shortened transport path of low-mobility holes on elimination of SCL are described in the inverted OSCs with the nanopatterned metallic anode. By incorporation of metal

(I)



(II)

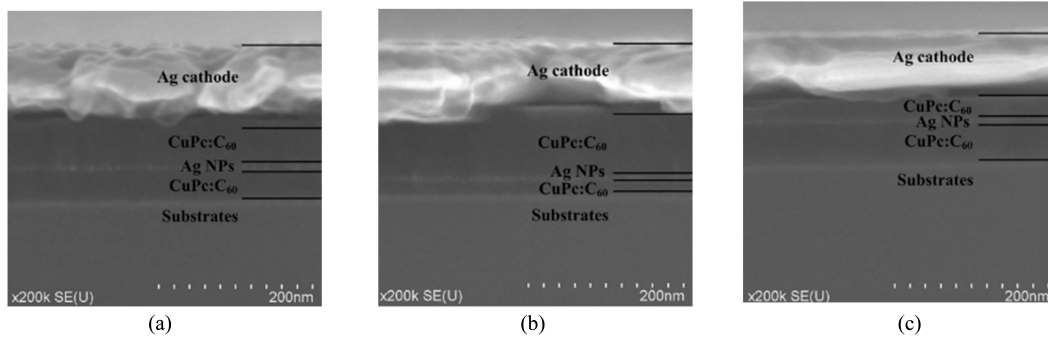


Fig. 11. Schematic (I) and cross sectional SEM images (II) of solar cell devices. Ag NPs are embedded (a) at the middle of CuPc:C₆₀ active layer, (b) near the anode, and (c) near the cathode in (I) and (II), respectively, [86].

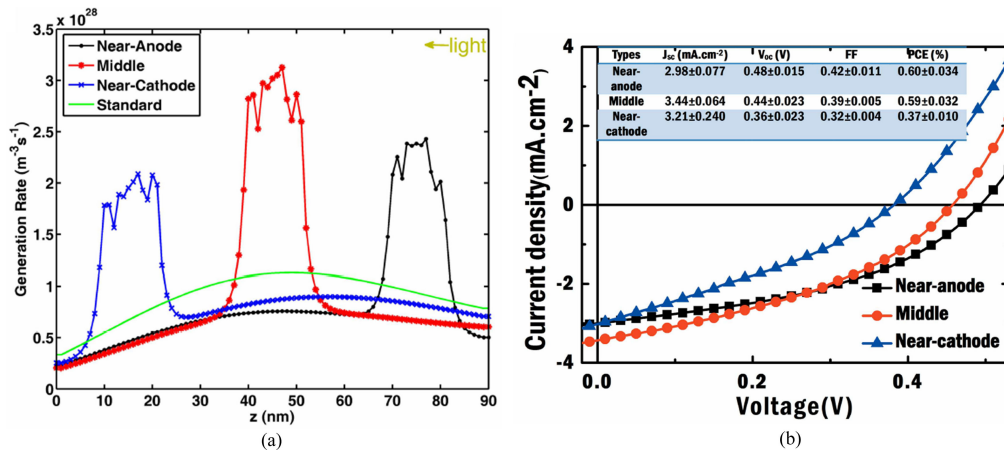


Fig. 12. (a) Laterally-averaged exciton generation at the active layer of a small-molecule bulk heterojunction solar cell. Silver NPs with a size of 10 nm and a spacing distance of 10 nm are embedded into different locations of the active layer corresponding to Fig. 11(a)–(c). (b) Experimental $J-V$ characteristics. Ag NPs are embedded at the active layer with different spatial locations corresponding to Fig. 11(a)–(c). The hole mobility is four orders of magnitude smaller than the electron mobility. The statistical parameters of three different plasmonic solar cells are summarized in the inset [86].

nanomaterials into CTL, the carrier extraction is improved by plasmonically induced hot carrier transfer from metal to semiconductor and the trap states filled in the metal oxide of ZnO and TiO₂. Moreover, the charge-accumulations effects are also reported to favor achieving a lower WF of metal NP-TiO₂ composite film and thereby reducing the carrier extraction barrier. In addition, the transport paths of the charge carriers (electron and holes) are also demonstrated that can be artificially manipulated

by engineering the location of the metal NPs in active layer. The coupled optical and electrical simulation is carried out to understanding the underlying physics of the plasmonic-electrical effects. With the careful engineering of the incorporated metal nanostructures, the performance of OSCs can be further improved with plasmonic-electrical effects by the easier charge carrier extraction and better balanced transport paths between the fast and low mobility charge carriers. Consequently, the

plasmonic-electrical effects of the metal nanostructures would be of great promising candidate for further enhancing the performance of OSCs.

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