Highly transparent singlet fission solar cell with multistacked thin metal contacts for tandem applications

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Abstract
Singlet fission solar cells combined with silicon photovoltaics allow the construction of parallel tandem solar cells, which benefit from better usage of high-energy photons. A key limiting factor for the performance of such a tandem configuration is the transparency of the singlet fission front cell. Here we show highly transparent singlet fission solar cells with a top contact of thin Ca:Ag blends. The optimized contact leads to 81% average solar cell transmittance in the near-infrared while maintaining more than half the short-circuit current density compared with an opaque device. We simulate the performance of the parallel tandem stack and assess the improvements needed to fully realize the potential of singlet fission in this device configuration.

KEYWORDS
singlet fission, small molecule semiconductor, solar cell, tandem solar cell, transparent electrode

Charge carrier multiplication in solar cells allows the extraction of more than one charge carrier per absorbed photon.1 This multiplication effect increases the theoretical power conversion efficiency (PCE) limit from 34% to 45%. One of the most promising carrier multiplication mechanisms is a process known as singlet fission, where a spin-singlet exciton, generated by the absorption of a high-energy photon, spontaneously converts into two triplet excitons with half of the original singlet exciton energy. Small molecule organic semiconductors, such as pentacene, facilitate very high singlet exciton to triplet exciton conversion yields, approaching 200%.4-6 Thus, in configurations where these triplet excitons can be extracted, the photocurrent of the device can be increased.7 One implementation of singlet fission-based solar cells is the use of parallel-connected tandem devices, where the singlet fission cell acts as the high-band gap front cell in conjunction with a narrow-band gap solar cell. Down-conversion via singlet fission facilitates voltage-matching between the high- and the low-band gap subcells. Recently, we demonstrated such a parallel connected tandem solar cell based on pentacene and crystalline silicon.8 Such voltage-matched parallel connected tandem solar cells show more stable performance under a change of solar spectrum compared with the most common current matched series-connected tandem devices. However, parallel tandem solar cells did not achieve a high PCE so far due to optical losses at the front solar cell. Ideally, the front cell would absorb all photons above the band gap of the singlet fission material and be perfectly transparent at energies below that band gap to maximize the number of harvested photons in the back cell. Therefore, the performance of the tandem stack is crucially determined by the transparency of the singlet fission front cell.

Here we investigate highly transparent, inverted pentacene solar cells with two transparent contacts, an ITO bottom contact and a thin metal layer stacked top contact. The semiconducting singlet fission layer acts as a filter that absorbs high-energy photons, while being perfectly transparent to below band gap radiation. Consequently, below band gap transparency is critically limited by the near-infrared (NIR) transparency of the electrodes in such devices. Therefore, we focus on the fabrication of a conductive and transparent top metal electrode. Indium tin oxide (ITO) is the most common material used for transparent contacts because of its remarkable optical transparency and electrical conductivity.9 However, ITO deposition demands high power sputtering, which would decompose any underlying organic layer during the deposition process. Metal nanowire networks,10-12 nanomeshes,13,14 and carbon nanostructures based on carbon nanotubes15,16 and graphene17 have shown sufficient optical transparency and electrical conductivity as a top electrode for semitransparent organic solar cells. However, those nanostructured layers are assembled by wet chemical processing and thermal annealing to form a uniform and electrically conductive layer. A predeposited organic layer can be dissolved or degraded by solvents during those processes. Recently, it was shown that multilayers of thin metals can lead to >90% of optical transparency with an electrical conductivity comparable with ITO.18-20 This multilayer structure is easily prepared by a mild thermal evaporation process, which avoids the degradation of the...
underlying organic layers during the deposition. Despite the advantages, multistacked metal electrodes are designed for hole-carrier collection, whereas conventional singlet fission-based solar cells require electron extraction at the top electrode.

We introduce an inverted singlet fission-based organic solar cell to incorporate the highly transparent multilayer electrode. The device architecture and energy band diagram of conventional and inverted singlet fission-based organic solar cells are illustrated in Figure 1(a) and (b). For the conventional singlet fission cell, we follow Congreve et al., using a heterojunction between pentacene and C₆₀ fullerene with poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS)/poly(3-hexylthiophene-2,5-diyl) (P3HT) as the hole extraction layers and bathocuproine (BCP) as the electron extraction layer. For the inverted cell, we use molybdenum oxide (MoOₓ) as the hole extraction (top) layer and zinc oxide (ZnO) as the bottom electron extraction layer. The current density-voltage (J-V) performance of opaque conventional and inverted solar cells are shown in Figure 1(c) and summarized in the inset. The conventional cell shows a short-circuit current density (J_SC) of 6.7 ± 0.3 mA/cm², which is higher than the J_SC of 5.1 ± 0.2 mA/cm² from the inverted cell. However, the inverted solar cell shows superior open-circuit voltage (V_OC) of 0.40 ± 0.01 V and fill factor (FF) of 56% ± 2% in comparison with

![Figure 1 Illustration of the solar cell architecture and energy band diagram of (a) the conventional pentacene solar cell based on reference and (b) the inverted solar cell with different top contact structures such as the opaque silver (100 nm thick), transparent thin silver and transparent calcium:silver blended layer. (c) Current density-voltage (J-V) characteristics of conventional and inverted solar cells. (d) J-V characteristics and short-circuit current density (J_SC, inset) of inverted solar cells with 20 to 100 nm of pentacene layer thickness. (Color figure can be viewed at wileyonlinelibrary.com)
thickness of the Ag layer down to 10 nm. To achieve uniform Ag deposition, we deposited 1 nm of aluminum (Al) underneath of Ag as a seed layer. The transmittance of the semitransparent inverted pentacene solar cell with the thin Al/Ag contact is shown in Figure 2(a). Upon reducing the thickness of Ag from 70 to 10 nm, the transmittance in the visible to NIR region (400–1100 nm) increases from 5% to 40%. To reduce the reflection from the top electrode, we introduced 94 nm of molybdenum oxide (MoO$_3$) on top of the Al/Ag electrode as an antireflection (AR, $\lambda/4 = 225$ nm) coating considerably enhancing the transmittance of the device in the near-IR region (dashed lines in Figure 2(a)). Figure 2(b) shows the average transmittance of the full device in the visible region (400 to 800 nm, $T_{\text{vis}}$) and the region below the pentacene band gap, which we call NIR region (700 to 1100 nm, $T_{\text{NIR}}$) as a function of Ag layer thickness. The transmittance continuously decreases with top contact thickness. With the AR coating, both $T_{\text{NIR}}$ and $T_{\text{vis}}$ are enhanced by 5%–15%. The sheet resistance ($R_S$) of the contact has to be considered for efficient charge collection in a solar cell. Ag contacts of all thicknesses without AR coating present $R_S$ below 6 $\Omega/\square$ except for the 10 nm Ag contact with much larger $R_S$ of 127 $\Omega/\square$ (see Figure 2(c)), presumably because of the formation of unconnected Ag domains.

The second semitransparent multilayer metal contact we apply is a blend of calcium and silver (Ca:Ag). Schubert et al. showed that this combination of materials exhibits an unusually high optical transmittance, while maintaining good conductivity. We sequentially deposited 1 nm of Al and Ag seed layers on top of the solar cell structure to form a blend that self-assembles as a Ag network surrounded by a Ca shell. Figure 2(d) shows the transmittance of semitransparent solar cells with varying Ca:Ag thicknesses. All devices with Ca:Ag electrodes show superior transmittance, almost 30% higher over the entire wavelength range in comparison with devices with the same thickness of thin Ag electrode. As an AR coating, we used 90 nm of tris(8-hydroxyquinolinato)aluminium (Alq$_3$) on top of the Ca:Ag electrode, following Schubert et al. (dashed line in Figure 2(d)). The AR coating is designed to maximize $T_{\text{NIR}}$ ($\lambda/4 = 200$ nm) and thus decreases the $T_{\text{vis}}$, whereas $T_{\text{NIR}}$ is enhanced by around 10% for all Ca:Ag thicknesses. The AR layer enhanced the transparence of the solar cell in the 700 to 1100 nm region even more significantly compared with the thin Ag electrode. The device with 10 nm of Ca:Ag electrode with AR coating achieved the maximum transmittance of 92% at 820 nm. $T_{\text{vis}}$ and $T_{\text{NIR}}$ are decreasing with increasing Ca:Ag layer thickness, but with a much weaker thickness dependence compared with the thin Ag electrode (Figure 2(b) and (e)). The thickness of the Ca:Ag layer also determines the electrical performance, and in the following, we optimize the solar cell for best overall performance. The MoO$_3$/Al/Ag/Ca:Ag structure shows higher $R_S$ than the MoO$_3$/Al/thin Ag for all layer thickness (see Figure 2(f)). The 40 nm of Ca:Ag contact allows 29 $\Omega/\square$ of $R_S$ with 60% of $T_{\text{NIR}}$, which is comparable with the 22 $\Omega/\square$ of our commercial ITO (125 nm), whereas it sharply increases to 140 $\Omega/\square$ at 10 nm of Ca:Ag electrode, unfavorable for solar cell operation. We note that the resistance of our Ca:Ag contact is higher than reported previously for this electrode, presumably because the surface roughness of the underlying active layer is larger (see Supplementary Information S2).

$J-V$ characteristics of semitransparent solar cells with thin Ag and Ca:Ag electrodes of varying thickness are shown in Figure 3(a) and (b), respectively. A semitransparent solar cell with a thin Ag (40 nm) electrode 0.90% of PCE shows a performance of only slightly less than the opaque solar cell (Figure 3(a), full solar cell details in Supplementary Information Table S3). The solar cell performance is almost identical with and without the AR coating (Supplementary Information S4). When the Ag thickness is reduced to 20 nm to yield higher transmission ($T_{\text{NIR}}$ of 40%), the solar cell performance is considerably reduced (PCE, 0.45%), mostly due to a lower $J_{SC}$ of 2.5 mA/cm$^2$. The Ca:Ag
electrode allows for much higher $T_{\text{NIR}}$ values for comparable solar cell efficiencies. The AR-coated semitransparent solar cell with a 50 nm thick Ca:Ag electrode presents 3.0 mA/cm$^2$ of $J_{\text{SC}}$, and a PCE to 0.64% at 54% of $T_{\text{NIR}}$ (see Figure 3(b)). An extremely transparent solar cell with only 20 nm Ca:Ag layer shows 81% of $T_{\text{NIR}}$ while maintaining 2.3 mA/cm$^2$ of $J_{\text{SC}}$, yielding 0.50% of PCE. We note that the reduction in $J_{\text{SC}}$ in the transparent solar cell is mostly because of the absence of a reflective silver contact. The reflection off the silver contact allows designing the organic solar cell as a Fabry-Perot cavity, leading to much stronger absorption in the pentacene layer.24 Transparent solar cells thus require materials with large triplet exciton diffusion length or selective reflectivity of the contact. Figure 3(c) summarizes the $J_{\text{SC}}$ as a function of $T_{\text{NIR}}$ with the 2 types of electrodes. The Ca:Ag layer yields nearly 20% higher $T_{\text{NIR}}$ for the same $J_{\text{SC}}$ value than solar cells based on the Al/Ag contact. $J_{\text{SC}}$ continuously decreases to half the value of the opaque device at 70% of $T_{\text{NIR}}$ owing to lower conductivity and reduced reflection off the back contact. $V_{\text{OC}}$ and FF are almost identical for all contact thicknesses >10 nm.

Semitransparent singlet fission solar cells can be used as the front cell of a tandem device configuration in combination with a Si back cell. Singlet fission allows the connection of devices in a 2-terminal parallel cell (Figure 4(a)), ensuring higher spectral stability compared with conventional, series connected tandem cells, while maintaining the 2-terminal advantage compared with 4-terminal cells (Figure 4(b)). In the following, we calculate the potential singlet fission/Si tandem solar cell efficiency based on the transmittance spectrum and the performance of the semitransparent singlet fission front cells with different Ca:Ag thicknesses (see Supplementary Information S6 for details of the simulation).25 Figure 4(c) shows the calculated $J_{\text{SC}}$ of parallel tandems made from the singlet fission cells together with the record performing silicon solar cell. A thick Ca:Ag contact enhances the $J_{\text{SC}}$ of a semitransparent front cell by lowering the $R_s$. However, more serious photon absorption and reflection at the thick electrode reduces the $J_{\text{SC}}$ of the Si back cell. The $J_{\text{SC}}$ of the parallel tandem solar cell is maximized at 32.6 mA/cm$^2$ for 15 nm of Ca:Ag contact thickness (Figure 4(d)). However, the tandem solar cells do not yield performances higher than the Si bottom cell alone, even with the highly transparent front cell obtaining >80% of $T_{\text{NIR}}$. To achieve a tandem cell performance higher than the 2 individual subcells, the current of the front cell needs to be higher than the current loss from placing it in front of the silicon cell. In the final device configuration, the silicon and the singlet fission cell might share a common ITO contact. Some silicon cells already feature ITO contacts, and the singlet fission cell could simply be placed on top. The AR coating of the Si cell would then need to be placed on top of the singlet fission cell. Thus, the absorption at the active layer of the singlet fission front cell needs to be maximized to benefit from carrier multiplication, while maintaining above unity quantum efficiency. In addition, the parallel tandem solar cell shows lower PCE in comparison with the 4-terminal tandem because of the large voltage difference between the maximum power point ($V_{\text{mp}}$) of the semitransparent pentacene device and the Si solar cell (see Supplementary Information Figure S6). $V_{\text{mp}}$ matching is required in order to maximize the performance of parallel connected tandem solar cells. For this reason, singlet fission cells based on materials with a higher triplet energy (such as tetracene), and thus larger voltage, would greatly benefit the tandem solar cell performance. However, in our hands, as well as in the literature, tetracene-based singlet fission solar cells have shown lower quantum efficiency than pentacene cells, despite the quantitative singlet fission in tetracene under optimized conditions.29-31 This illustrates the requirement for optimizing device architecture, interfaces, and tetracene growth. Furthermore, the series resistance of the singlet fission solar cell is high in comparison with the Si solar cell, which degrades the FF of the parallel tandem (see Supplementary Information S2).

In summary, we have demonstrated semitransparent pentacene solar cells introducing a highly transparent top contact, which could
be used to sensitize a silicon solar cell or other low-band gap cells in a parallel tandem configuration. We introduce an inverted singlet fission solar cell architecture, designed to allow for the transparent electrode, which achieves 1.21% of PCE, higher than 1.03% of conventional, non-inverted singlet fission solar cells. We characterize the inverted solar cells with thin Al/Ag and Al/Ag/Ca:Ag multistacked metals as a transparent electrode with various electrode thicknesses. Thin Ag shows low sheet resistance (below 6 Ω/□), whereas the Ca:Ag blend layer leads to a high optical transparency of the solar cell (e.g., 61% of T\textsubscript{NIR} with 29 Ω/□ sheet resistance at 40nm thickness). Furthermore, deposition of an antireflection layer on Ca:Ag enhanced the T\textsubscript{NIR} of the solar cell. The J-V characteristics of semitransparent solar cells were mainly determined by the thickness of the transparent top contact. In particular, the cell with a 20-nm Ca:Ag contact showed more than half the J\textsc{sc} of the opaque solar cell, with 81% T\textsubscript{NIR}. Finally, we calculate the efficiency of a parallel tandem configuration consisting of our semitransparent singlet fission front cells together with a Si back cell, absorbing high- and low-energy photons, respectively. The compromise between transmittance and performance of the front cell determined the J\textsc{sc} of the tandem configuration, resulting in a maximum J\textsc{sc} of 32.6 mA/cm\textsuperscript{2}. However, reaching a higher tandem performance than the Si cell alone is still challenging using the current semitransparent singlet fission front cells. Enhancing the absorption in the active layer is critical to maximize carrier multiplication, especially for singlet fission materials with high triplet energy to improve the V\textsc{oc} of the singlet fission cell and the overall tandem performance.

FIGURE 4  Illustration of tandem configuration based on semitransparent singlet fission front and silicon back cells. Subcells are electrically connected in (a) parallel and (b) 4-terminal. (c) Calculated J\textsc{sc} (d) PCE of singlet fission/Si tandem solar cells from our transparent pentacene cells with different Ca:Ag layer thicknesses [Colour figure can be viewed at wileyonlinelibrary.com]

Supporting information available: We provide details about fabrication and characterization of the semitransparent singlet fission solar cells and the model used to simulate the performance of singlet fission/Si tandem solar cells.

REFERENCES

ACKNOWLEDGEMENT
The authors acknowledge Marc Duursma for his technical support and Eric Johlin for his comments on the manuscript. This work is part of the research program of The Netherlands Organization for Scientific Research (NWO).


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