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An effective light trapping configuration for thin-film solar cells

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Many thin-film solar cells make a compromise between achieving complete optical absorption using films that are thicker than the optical absorption length and achieving efficient conversion of the absorbed photons into photocurrent which is favored in thinner structures. We evaluate the performance of a V-shaped light trapping configuration that substantially increases the photocurrent generation efficiency for all angles of incidence and that is applicable to a broad class of low-cost thin-film solar cells. We experimentally demonstrate its effectiveness for small molecular weight and polymer organic solar cells. A 52% efficiency enhancement is obtained for a 170-nm-thick polymer cell. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2789677]

In crystalline silicon solar cells, surface texturing is used to trap light, leading to an enhancement in optical path length by up to $4n^2$, where n is the refractive index of the active layer.[1,2] The increase in effective absorption allows one to reduce the volume of the active layer, leading to lower recombination currents, a higher operating voltage, and higher conversion efficiencies. However, this approach becomes increasingly challenging as the film thicknesses become comparable or smaller than the wavelength of light[3] and alternative light trapping schemes are needed for thin-film solar cells.

In many thin-film solar cells, the probability that an absorbed photon contributes to photocurrent, known as the internal quantum efficiency (IQE), decreases as a function of film thickness over distances shorter than the optical absorption length.[4] This is especially the case for organic photovoltaic (OPV) cells where either exciton diffusion[5] or carrier collection in a donor-acceptor blend[6] limits the IQE for active layers thick enough to absorb most photons. In this case, it is important to achieve complete optical absorption for active layers much thinner than an optical absorption length to maximize the photocurrent and minimizing the active layer volume is less important than minimizing its thickness. Light trapping schemes that use metal gratings,[7] buried nanoelectrodes[8] and scattering elements[9] have been used to enhance light absorption in OPV cells. However, the feature sizes of the scattering structures need to be comparable to the film thickness of the OPV cells, i.e., 50–300 nm, making low-cost fabrication challenging. Furthermore, the device performance was found to degrade using these approaches.[9]

Here, we analyze a simple light trapping scheme that structures thin-film solar cells on a length scale much larger than the active layer thickness and requires no modification of the device structure. The scheme increases the efficiency of thin-film solar cells significantly for all angles of incidence. Structuring on such a large length scale has been used with success in thin-film silicon solar cells.[10]

The geometry of the proposed light trapping scheme is shown in Fig. 1(a). The active layer and reflective metal electrode are deposited on a V-shaped transparent substrate coated with a transparent electrode such as indium tin oxide (ITO). Incident optical rays bounce off the solar cell structure multiple times. The maximum number of bounces a ray undergoes as a function of the V-fold opening angle 2α is $N_{\max}=[(\pi-\theta_i+\alpha)/2\alpha]$, where θ_i is the angle of incidence with respect to the substrate normal [Fig. 1(a)]. Using geometric ray tracing, the enhancement in number of ray bounces per unit cell area over that in a planar structure at each point in the V-fold structure was calculated as a function of 2α, as shown in Fig. 1(b). The V-fold acts as an

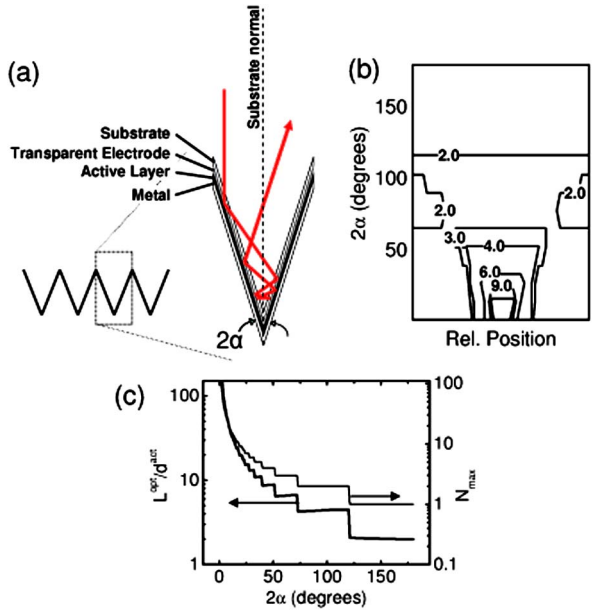

FIG. 1. (Color online) (a) The geometry of the V-shaped light trapping structure. The active layer is very thin compared to the thickness of the transparent substrate. (b) The density of ray bounces at each location of the V-shaped substrate compared to that in a planar configuration. (c) Optical path length normalized to the active layer thickness and the maximum number of bounces as a function of the opening angle 2α of the V shape.

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optical funnel, resulting in a high density of ray reflections near the tip of the V-fold structure, also seen in Fig. 1(a). Moreover, the density of reflections increases rapidly as the V-fold opening angle 2α decreases. The optical path length normalized to the active layer thickness as a function of the V-shape opening angle 2α is shown in Fig. 1(c). For organic semiconductors ($n=1.8$), an optical path length enhancement equal to the theoretical limit of Lambertian light trapping of $4n^2=13$ is reached for $2\alpha=30°$ and longer optical path lengths are possible for $2\alpha<30°$. Note that since the optical path length is normalized to the active layer thickness and not active layer volume, the thermodynamic limit of light trapping[1] is not violated. When normalized to active layer volume, a maximum optical path length enhancement of $2n^2$ is obtained, in agreement with Ref. 1 for structures with one specular surface.

To analyze the achievable performance gains using a V-shaped light trap, we modeled the spectral response of three thin-film organic solar cells, a thin-film amorphous silicon (*a*-Si) solar cell, and a microcrystalline silicon (μc-Si) solar cell. Optical modeling using the transfer matrix method is used to include optical interference effects in the thin-film solar cells.[11] Reflections in the transparent substrate are treated incoherently. Photocurrent generation in the organic solar cells is modeled by solving the exciton diffusion equation for planar organic solar cells[12] and using the drift-diffusion model[13] for the bulk-heterojunction polymer cell. Complete carrier collection is assumed for the *a*-Si and μc-Si cells[14] since we are interested in evaluating the increase in optical absorption for a typical film thickness. The cosine law is used to calculate the angular response of these cells.[15] All layers are assumed to have flat and smooth interfaces. The small molecular weight cell structures are 1500 Å ITO/100 Å copper phthalocyanine (CuPc)/30 Å 3,4,9,10-perylene tetracarboxylic bisbenzimidazole (PTCBI)/150 Å bathocuproine (BCP)/1000 Å Ag (Ref. 16) and 1500 Å ITO/80 Å CuPc/330 Å C_{60}/150 Å BCP/1000 Å Ag (Ref. 17). The structure of the modeled polymer blend cell is 1500 Å ITO/400 Å polyethylenedioxythiophene:polystyrenesulphonate (PEDOT:PSS)/1000 Å poly-(3-hexylthiophene) (P3HT):[6, 6]-phenyl C_{60} butyric acid methyl ester (PCBM) (1:1 blend by weight)/ 1000 Å Al. For the *a*-Si and μc-Si cells, a *p-i-n* structure was assumed, with 10-nm-thick *p* and *n* layers and active layer thicknesses for the *a*-Si and μc-Si cell of 300 nm and 1.2 μm, respectively.[18] A 1000-Å-thick Ag top electrode was assumed for these cells.

The modeled external quantum efficiency (η_{EQE}) of the CuPc/PTCBI cell is shown in Fig. 2(a) for the planar configuration ($2\alpha=180°$) and a V-fold light trap with $2\alpha=30°$. The η_{EQE} of an optimized planar cell whose layer structure is 150 Å CuPc/100 Å PTCBI is shown for comparison. The model predicts an increase and broadening of the η_{EQE} spectrum for the cell in the V-shaped light trap due to multiple reflections. The largest relative gains are made in regions where absorption is weak.

The modeled short circuit current density (J_{SC}) under 100 mW/cm^2 AM1.5 illumination at normal incidence as a function of 2α is shown in Fig. 2(b) for all five modeled cells (filled symbols) and is compared to cells optimized for the planar configuration (open symbols). The CuPc/PTCBI cell (squares) shows a 3.6-fold increase compared to the planar

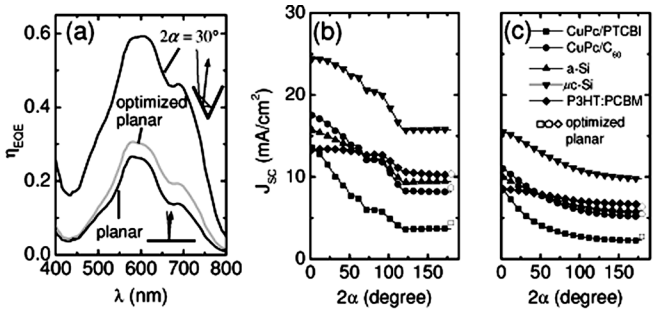

FIG. 2. (a) The modeled η_{EQE} of a ITO/100 Å CuPc/30 Å PTCBI/150 Å BCP/1000 Å Ag bilayer device for the planar configuration and in a V-shaped light trap with $2\alpha=30°$. The η_{EQE} of an optimized planar cell of structure ITO/150 Å CuPc/100 Å PTCBI/150 Å BCP/1000 Å Ag is also shown for comparison. (b) The calculated J_{SC} vs 2α for several thin-film solar cells (filled symbols) at normal incidence and (c) averaged on the whole day. The performance of optimized planar cells with layer structures 150 Å CuPc/100 Å PTCBI (open square), 150 Å CuPc/350 Å C_{60} (open circle), and 220 nm P3HT:PCBM (open diamond) is shown for comparison.

cell with the same structure, while the P3HT:PCBM cell (diamonds) exhibits a 30% increase. Our model indicates that the V-shaped light trap can achieve power conversion efficiencies of 3.6% for CuPc/PTCBI, 5.3% for CuPc/C_{60} (circles), and 5.4% for P3HT:PCBM, assuming no changes in open circuit voltage (V_{OC}) and fill factor. The very thin CuPc/PTCBI cell provides relatively weak absorption in the planar configuration and therefore improves strongly using light trapping. In the case of the P3HT:PCBM cell, on the other hand, the light trap mostly results in a broadening of the η_{EQE} spectrum. J_{SC} plateaus for small values of 2α because the metal electrodes absorb a nontrivial fraction of the incident light. Our models predict that the J_{SC} of the μc-Si (inverted triangles) and *a*-Si solar cells (triangles) increases by 60% and 67%, respectively, in a V-shaped light trap which is larger than the increase obtained using substrate texturing.[18,19] Figure 2(c) shows J_{SC} averaged over a 12 h daylight period. The V-shaped light trap is effective for all angles of incidence and similar increases in performance are predicted after averaging.

Whether the use of the V-shaped light trap is viable for a particular solar cell depends on the balance of the added cost of the shaped substrate and increase in active material use, with the reduction in installation cost for modules with higher efficiencies. For example, for the CuPc/PTCBI cell (100 Å CuPc/30 Å PTCBI) in the V-fold with $2\alpha=30°$, the amount of active material required is $(130\ \text{Å}/\sin\alpha)/250\ \text{Å}=2.0$ times that used in the corresponding optimized planar cell (150 Å CuPc/100 Å PTCBI), while J_{SC} increases 2.4-fold. Adopting the V-shaped light trap is in fact more attractive than what this analysis suggests since the active layers are responsible for only about 1/9th of the overall thin-film PV manufacturing cost.[20]

To verify our models, bilayer CuPc/PTCBI solar cell structures were fabricated on glass substrates coated with a 1300-Å-thick ITO anode. The organic materials were purified using thermal gradient sublimation.[21] The organic layers and metal cathode were deposited via thermal evaporation in high vacuum (base pressure of $\sim 1\times10^{-7}$ Torr). P3HT:PCBM solar cells were fabricated by spin coating a blend of P3HT/PCBM in 1:1 weight ratio in dichlorobenzene on glass substrates coated with a 1500-Å-thick ITO anode modified by a spin-coated 500-Å-thick PEDOT:PSS layer. A

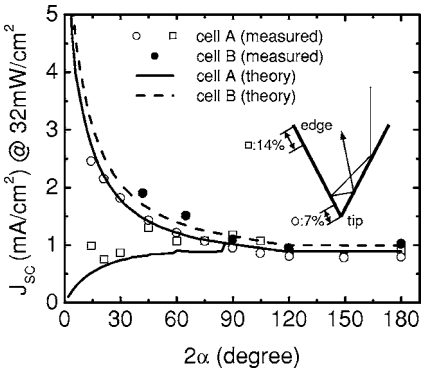

FIG. 3. The J_{SC} of the ITO/390 Å CuPc/420 Å PTCBI/150 Å BCP/1000 Å Ag bilayer device (cell A) measured in the V-shaped configuration near the tip (open circles) and near the edge (open squares). The solid lines are model calculations. The J_{SC} of a thinner cell with device structure ITO/300 Å CuPc/400 Å PTCBI/150 Å BCP/1000 Å Ag (cell B) near the tip of the V shape (filled circles) is also shown together with a model calculation (dashed line).

1000-Å-thick Al cathode was deposited by thermal evaporation. The V-shaped light trap was configured using two planar cells held in place via optical mounts.

The CuPc/PTCBI cells were structured as an array of small devices (cell area=0.81mm^2) to verify the spatial dependence of the light intensity in the light trap. The J_{SC} of cells with structure ITO/390 Å CuPc/420 Å PTCBI/150 Å BCP/1000 Å Ag (cell A) under 32 mW/cm^2 AM1.5G illumination is shown in Fig. 3. J_{SC} was measured at two locations (see the inset of Fig. 3): 7% from the tip (open circles) and 14% from the edge (open squares). Modeling results are shown for comparison (solid lines). J_{SC} for a thinner structure ITO/300 Å CuPc/400 Å PTCBI/150 Å BCP (cell B) located 7% from the tip (filled circles) and the corresponding modeling results (dashed line) are also shown. As predicted by our models, J_{SC} for cell A near the tip increases threefold from 0.8 mA/cm^2 for the planar configuration to 2.5 mA/cm^2 for $2\alpha=14°$ since the V-shape funnels light toward the tip. Near the edge of the light trap, J_{SC} decreases from 0.9 mA/cm^2 for the planar configuration to 0.75 mA/cm^2 for $2\alpha=21°$, in agreement with our model. A 26% increase in overall J_{SC} would have been obtained for a cell that occupies the full substrate area. Larger increases in J_{SC} would be obtained with thinner cells as discussed above.

P3HT:PCBM cells of different thicknesses (70, 110, and 170 nm) were configured as large area devices (cell area =2.4–3.2 mm^2) that occupy the complete V-shaped area. J_{SC} vs 2α measured under 32 mW/cm^2 AM1.5G illumination is shown in Fig. 4(a). Compared to the planar configuration,

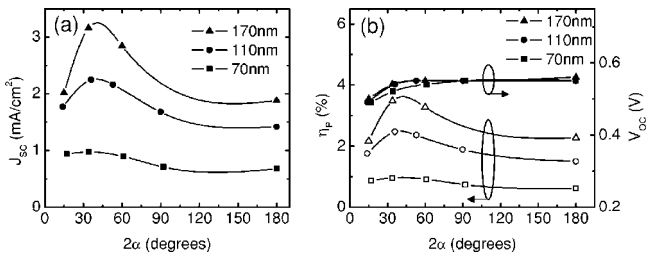

FIG. 4. (a) J_{SC} of ITO/500 Å PEDOT:PSS/P3HT:PCBM/1000 Å Al cells as a function of the V-shape opening angle 2α. The active layer thicknesses are 70 nm (square), 110 nm (circle), and 170 nm (square). (b) The V_{OC} (filled symbols) and η_P (open symbols) of the same cells. The lines are guides for the eye.

J_{SC} increases by 68%, 57%, and 43% for the 170-, 110-, and 70-nm-thick cells, respectively, for $2\alpha=35°$. The decrease in J_{SC} for $2\alpha<35°$ is attributed to anisotropy of the optical constants of the P3HT:PCBM films.[22] The polymer chain alignment is likely stronger for the thinner devices and may also explain the reduced benefit of the V-shaped light trap for the thinner P3HT:PCBM cells. The power conversion efficiency (η_P) and open circuit voltage (V_{OC}) are plotted in Fig 4(b). The 170-nm-thick cell achieves $\eta_P=3.5\%$ at $2\alpha=35°$ and a 52% increase over $\eta_P=2.2\%$ for the planar configuration. V_{oc} systematically decreases as 2α decreases due to an increase in dark current proportional with the area of the cell.

In summary, the V-shaped light trap is an alternative to surface texturing that can be used for solar cell structures with active layer thicknesses of the order of the wavelength of light or less. The scheme is particularly effective for solar cells whose IQE drops quickly as a function of film thickness. A 52% increase in power conversion efficiency was demonstrated using P3HT:PCBM polymer blend cells. We anticipate that applying the V-fold light trap to the most efficient organic solar cells[23–25] will lead to further improvements in their efficiency.

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