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Stability of bilayer trimethine cyanine dye / fullerene organic solar cells

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Abstract

The long-term (up to 100 days) stabilities of thin films of a trimethine cyanine dye (Cy3-P) and of Cy3-P/C₆₀ bilayer solar cells with initial power conversion efficiencies of up to 3.6% in the regular and inverted device architecture were studied. For storage conditions under nitrogen at room temperature in the dark, Cy3-P films were stable and no decrease in performance was measured for inverted ITO/TiO₂/C₆₀/Cy3-P/MoO₃/Ag solar cells. ITO/PEDOT:PSS and aluminum were found to be responsible for a slight inherent degradation of regular solar cells under inert storage conditions. Solar cells stressed at accelerated (80 °C) full sun simulation showed a burn-in period of ~ 5 days with a performance loss of 75%. This initial performance decrease might be linked to the photopolymerization reaction of C₆₀. For longer times, performances stabilized and arrived at 15% of the initial values after a test period of 17 days.

1. Introduction

Small semiconducting molecules are attracting interest for efficient solar energy conversion in low-cost, flexible and lightweight photovoltaic devices [1-3]. Equally important from an application point of view is the lifetime of small-molecular solar cells. Durability analysis and studies on degradation mechanisms in small-molecular solar cells, especially carried out under recommended standard testing conditions [4], are relatively rare, however, as compared to their polymeric counterparts [5-8].

For pentacene/fullerene C₆₀ heterojunction solar cells that were stored at a relative humidity of 33% in the dark, an operation time of about 850 h was found until 50% of the initial power conversion efficiency was lost (T₅₀) [9]. Inverted, non-encapsulated copper

phthalocyanine (CuPc)/C₆₀ cells with a shelf lifetime of over 1500 h in air were reported [10]. Pentacene/PCBM (a soluble fullerene derivative) and CuPc/PCBM cells were studied for different atmospheric storage conditions under continuous illumination. For cells encapsulated with polydimethylsiloxane or stored under vacuum and using UV-filtered light illumination, T₅₀ of ~2000 and 2500 min (for pentacene) and of ~1450 and 1900 min (for CuPc) were measured [11]. The degradation behavior under illumination of zinc phthalocyanine (ZnPc):C₆₀ cells encapsulated with different barrier films was studied. It was found that water was critical for the long-term stability compared to oxygen. Lifetimes T₅₀ of 4000 h were obtained for glass-encapsulated devices [12]. No sign of degradation of glass-encapsulated ZnPc:C₆₀ cells was observed after accelerated full sun simulation (100 mW cm⁻², 85 °C) for 1800 h [13].

Here, we report on the durability of bilayer cyanine dye/C₆₀ solar cells. Cyanine dyes are charged polymethine colorants where a usually positive charge is delocalized over an odd number of sp² carbons forming the π -conjugated bridge. Cyanines are notable for their exceptionally high light extinction coefficients, tunable absorption throughout the visible and into the NIR region such as the presence of specific and relatively mobile counter anions [14,15]. Cyanine/fullerene bilayer solar cells in the regular and inverted architecture with power conversion efficiencies (η) of 2.9-3.7% were demonstrated so far [16-18]. Numerous cyanine dyes are commercially available. At present, these dyes are at least a factor of ten cheaper than the most popular semiconducting polymers in the fields, which make them interesting candidates for cost-effective organic solar cell applications.

Solar cells with different charge extraction layers and top metal electrodes in the regular and inverted geometry were fabricated using a trimethine cyanine dye with the counter anion PF₆⁻ (Cy3-P) and C₆₀ as active materials. In a first step, the performance of these devices was optimized. The low photo- and thermal stability of cyanines has repeatedly been reported [19-21], especially with increasing number of methine groups. Therefore, in a second

step thin cyanine films, individual layer stacks and completed solar cells were tested for their inherent stability under different atmospheric storage conditions in the dark. Finally, the durability of solar cells was measured under accelerated full sun simulation.

2. Experimental

Solar cells were fabricated on cleaned glass/ITO substrates (Thin Film Devices, resistivity $20 \text{ Ohms square}^{-1}$, 150 nm thickness). For cells in the regular geometry, hole extraction layers consisted of thermally evaporated MoO_3 (20 - 40 nm, Sigma Aldrich, 99.99%) or spin-coated PEDOT:PSS films (PEDOT, 90 nm, Clevios P VP Al 4083) that were heated at 120°C for 15 min. Between C_{60} (SES Research, 99.5%) and the metal electrodes, a 2.5 nm thick Alq_3 layer (Sigma Aldrich, 99.995%) was thermally evaporated. For inverted cells, thermally evaporated MoO_3 (30 nm) and TiO_2 (40 nm, anatase phase) thin films deposited by magnetron sputtering were used as buffer layers. Active electron donor 1-Ethyl-2-[3-(1-ethyl-3,3-dimethyl-1,3-dihydro-indol-2-ylidene)-propenyl]-3,3-dimethyl-3H-indolium hexafluorophosphate (Cy3-P, FEW Chemicals) films were spin coated inside a nitrogen-filled glove box ($<5 \text{ ppm H}_2\text{O}$, $<6 \text{ ppm O}_2$) from filtered 2,2,3,3-tetrafluoropropanol (TFP, Sigma Aldrich) or chlorobenzene (CB, Sigma Aldrich) solutions, and thermally evaporated C_{60} was used as electron acceptor. Cells were completed by evaporating Al (Lesker, 99.999%) or Ag (Cerac, 99.99%) electrodes through a shadow mask defining eight cells per ITO substrate with areas of 0.031 cm^2 and 0.071 cm^2 , respectively. All thermal evaporations were carried out in the same vacuum chamber ($4 \cdot 10^{-6} \text{ mbar}$) with deposition rates of $0.2 \text{ \AA s}^{-1}$ for C_{60} , Alq_3 and MoO_3 , and of $0.5 \text{ \AA s}^{-1}$ for Al and Ag.

To study the intrinsic lifetime, cells were stored in the glove box in the dark. A homemade air-tight transfer box was used to measure cell J-V characteristics outside the glove box on a calibrated solar simulator (Spectra Nova) using a Xe lamp with 100 mW cm^{-2} simulated AM 1.5G solar irradiation. Accelerated cell testing over a period of 17 days was

carried out in a homemade environmental chamber. Stressing took place in an N_2 atmosphere. Light was supplied by water-cooled white LEDs (Citizen Electronics, CL-L340-MC41W1-C) with a calibrated illumination intensity of 1 sun. The LED spectrum is characterized by a broad light distribution over the visible wavelength range with a maximum at ~ 580 nm and an additional sharp peak at 450 nm. Samples were mounted on a copper sample holder lying on a heating plate at a temperature of 80 °C. Cells were held in short-circuit conditions and cell parameters were measured periodically without breaking the test conditions. To avoid any contact with oxygen and humidity during transfer from the glove box to the environmental chamber and during experimental setting, these cells were encapsulated using epoxy and a cover glass. To study the initial stress-induced degradation, non-encapsulated cells and individual films were treated in the glove box at 80 °C on a hot plate and with light (1 sun) from a Xe-lamp for 24 h. Scanning probe microscopy scans were performed with a Nanosurf Mobile S in tapping mode at a resonance frequency of 170 kHz with silicon cantilevers from Mikromasch, Nanosensors.

3. Results and discussion

3.1. Initial solar cell performance

Cy3-P/ C_{60} bilayer solar cell architectures with five different layer sequences were fabricated (Table 1). Devices (1) – (4) from Table 1 were regular geometries with varying electrode materials to test their influence on cell lifetime, device (5) was fabricated in the inverted structure (Fig. 1a, right). For device optimization and lifetime studies, more than 1200 solar cells on over 150 glass/ITO substrates were fabricated in this study. For all architectures best performances were measured experimentally for thicknesses of ~ 20 nm for Cy3-P and ~ 40 nm for C_{60} . Optical modeling confirmed that these layer thicknesses maximize the electric field amplitude at the donor-acceptor interface, thus maximizing the generated photocurrent [22].

Table 1 summarizes cell performances directly after fabrication, and J-V curves of the best-performing devices are shown in Fig. 1b. For regular device structures (1) – (3), no systematic trends for $J_{sc} \sim (6.5 \pm 1 \text{ mA cm}^{-2})$ were observed. J_{sc} ($4.5 \pm 0.9 \text{ mA cm}^{-2}$) of inverted cells were lower. This is due to the non-optimized TiO_x layer that was deposited via sputtering. In the meantime, TiO_x layers prepared via a sol-gel process resulted in solar cells with increased values for the short-circuit current and good performance ($J_{sc} = 6.2 \text{ mA cm}^{-2}$, $V_{oc} = 0.88 \text{ V}$, $\text{FF} = 67.8\%$, $\eta = 3.7\%$ [18]). Device (4) was fabricated to study the durability of cells in the absence of ITO. This control structure was not systematically optimized.

Contrary to J_{sc} , significant V_{oc} variations for different anode materials were observed. For regular device structures with ITO/PEDOT, V_{oc} values were $\sim (0.65 \pm 0.15) \text{ V}$. Replacing PEDOT by MoO_3 increased V_{oc} to $> 0.9 \text{ V}$. This is in agreement with recent findings on cyanine dye/ C_{60} bilayer cells [16], and was explained by the high effective work function of MoO_3 . A high V_{oc} (0.84 V) was also observed for the inverted device structure.

The solvent used for spin coating the Cy3-P layer was essential to the FF. For the inverted device structure in Table 1 only TFP could be used, since CB would dissolve the subjacent C_{60} layer. For regular devices higher FF were measured for CB. The origin of this discrepancy is not yet understood and requires further investigation. A fundamental difference between the two solvents is that in the polar TFP the cationic Cy3 chromophore and the PF_6^- anion are fully dissociated, whereas in CB they are mainly present as ion pairs [23]. We suspect that the different degree of ion pairing in the two solutions transforms into substrate-specific differences in solid-state packing with associated varying hole mobilities upon rapid spin coating Cy3-P into a thin film [24]. Also note that PEDOT is not inert when in contact with TFP. TFP swells PEDOT during spin coating and cyanine dyes infiltrate over several nm into the polymer layer (data not shown). In addition, it has been shown that cyanine counter anions are relatively mobile and are displaced within the cyanine layer and into adjacent layers, either by diffusion or by internal or applied external electric fields [14,15]. This build-

up of ionic space charge creates electric fields and induces potential energy shifts at junctions. This can facilitate or impede hole extraction by inducing an energy shift between the Cy3-P HOMO level and the anode work function.

Highest initial power conversion efficiencies ($\eta = 3.6\%$) were measured for the regular device structure (3) when using CB as coating solvent. This presents a considerably improvement compared to reported efficiencies of regular Cy3-P/C₆₀ cells so far ($\eta = 2.9\%$ [16], $\eta = 3.0\%$ [17]).

Table 1.

Initial device performance / parameters from Cy3-P(20 nm)/C₆₀(40 nm) solar cells. V_{oc} is the open-circuit voltage, J_{sc} the short-circuit current, FF the fill factor, and η the external power conversion efficiency. Ranges of values originate from # different devices with eight cells per device. The illumination intensity was 100 mW cm⁻². Solvents used for dye coating were 2,2,3,3-tetrafluoropropanol (TFP) and chlorobenzene (CB).

	Device structure	Cy3-P coating solvent	V_{oc} (V)	J_{sc} (mA cm ⁻²)	FF (%)	η best (%)
(1)	ITO/PEDOT/Cy3-P/C ₆₀ /Alq ₃ /Al	TFP (#5)	0.58 – 0.79	6.4 – 6.6	34.8 – 43.5	2.3
		CB (#1)	0.48 – 0.6	5.5 – 6.7	48.8 – 54.8	2.0
(2)	ITO/PEDOT/Cy3-P/C ₆₀ /Alq ₃ /Ag	TFP (#1)	0.54 – 0.67	6.7 – 7.7	29.7 – 35.6	1.6
		CB (#3)	0.64 – 0.68	6.3 – 7.7	48.5 – 52.1	2.7
(3)	ITO/MoO ₃ /Cy3-P/C ₆₀ /Alq ₃ /Ag	TFP (#4)	0.86 – 0.95	5.9 – 6.5	39.9 – 52.4	3.2
		CB (#5)	0.67 – 0.92	5.9 – 6.6	56.5 – 63.8	3.6
(4)	Ag(12 nm)/PEDOT/Cy3-P/C ₆₀ /Alq ₃ /Ag	TFP (#1)	0.35 – 0.51	3.5 – 5.0	30.4 – 32.4	0.8
(5)	ITO/TiO ₂ /C ₆₀ /Cy3-P/MoO ₃ /Ag	TFP (#4)	0.82 – 0.84	3.6 – 5.4	61.1 – 63.3	2.9

3.2. Solar cell stability

3.2.1. Intrinsic stability

The intrinsic stability of cyanine solar cells was studied for devices that were stored in the glove box at room temperature in the dark. We first measured UV-vis spectra of individual solar cell layer combinations as function of storage time. Data in Fig. 2 suggest that Cy3-P thin films did chemically not degrade over a period of at least two months under inert conditions, as demonstrated by the unchanged absorption at $\lambda = 580$ nm, which corresponds to the cyanine absorption maximum. The situation was different when the cyanine dye was exposed to oxygen, humidity and light at the same time. The inset of Fig. 2 shows the absorbance change of a Cy3-P film kept in an environment with relative humidity of $\sim 66\%$ and exposed to light (40 mW cm^{-2}). Under these conditions, Cy3-P degraded within ~ 2 h. The reason for cyanine degradation is self-sensitized energy transfer from the triplet excited state of Cy3-P to triplet oxygen leading to reactive singlet oxygen [21]. Additionally, there is an energetically allowed electron transfer reaction from photoexcited cyanine to triplet oxygen. This creates reactive superoxide anions that induce further photobleaching [21,25]. These results show that the careful exclusion of oxygen and humidity is essential for any solar cell application using cyanines.

As a next step, completed cyanine solar cells with architectures from Table 1 were stored for 100 days in the glove box in the dark and performances were periodically monitored. Initial performance values after fabrication are shown in Table 1, and normalized values as function of storage time are summarized in Fig. 3. For ITO/PEDOT/Cy3-P/C₆₀/Alq₃/Ag cells with the spin coating solvent TFP, V_{oc} remained constant with time, but J_{sc} and FF decreased by about 20% after 100 days (Fig. 3a). A similar decrease was observed for all parameters when using CB. When the Ag top electrode was replaced by Al, trends for J_{sc} and FF did not change, but now also V_{oc} decreased (Fig. 3b). Comparing regular cells with anodes composed of ITO/PEDOT (Fig. 3a) or ITO/MoO₃ (Fig. 3c), similar performance

trends were observed, but the overall decrease for MoO_3 was smaller, $\sim 10\%$ after a storage time of 100 days. For regular cells with an Ag/PEDOT electrode (Fig. 3d), a slight performance increase was observed during the first 10 days of storage, for longer times V_{oc} remained constant and J_{sc} and FF decreased by about 10%. Most stable were finally cells in the inverted architecture (Fig. 3e), where V_{oc} was constant and J_{sc} and FF increased by $\sim 10\%$ over time.

Comparing parameter trends for the different cell configurations allows identifying several critical material layers that intrinsically lead to a performance decrease. Firstly, regular cells were more stable when Ag was used as top electrode instead of Al. This is a well-known observation. High work function metals are inherently less reactive than low work function metals and improve solar cell stability [6-8]. Except for storage conditions under high vacuum, contact with moisture and oxygen is indeed unavoidable, leading to slow oxidation of the low work function metal. The diffusion through pinholes of the top electrode was reduced by using smooth and homogeneous Ag films [26].

Secondly, we identify ITO/PEDOT as critical layers leading to device degradation, since ITO/ MoO_3 or Ag/PEDOT anodes resulted in more stable regular cells. This observation is in agreement with reported works on the stability of ITO/PEDOT-free cells. A degradation study of ITO and Ag anode organic solar cells showed that Ag is chemically more stable than ITO when used in conjunction with PEDOT. The rapid degradation of ITO-based devices was the result of continuous migration of indium into the PEDOT layer [27]. Due to the presence of PSS, the pH of the water-dispersed PEDOT:PSS solution is below 3 and corrosive to ITO [28]. The ITO etching triggers the desorption of indium atoms that may diffuse into adjacent layers [29,30]. This is different from the ITO substrate onto which MoO_3 was deposited by thermal evaporation. PEDOT:PSS is also a strongly hygroscopic material [28]. This promotes infiltration of humidity through device edges leading to degradation [31]. The stability of our

Ag/PEDOT cells suggest that this mechanism is of minor importance for storage conditions in the glove box.

Cells in the inverted architecture were stable under N_2 storage conditions in the dark. In addition, no sign of performance degradation was observed for inverted cells that were stored at ambient air in the dark for 28 days. In the inverted structure, the critical ITO/PEDOT layer of regular cells was replaced by ITO/ TiO_x . Recently, improved stabilities of cells in the inverted geometry were demonstrated [32-34]. Several reasons contribute to the merits of the inverted cell architecture. Al is often replaced by high work function metals Ag or Au which improves cell stability. In addition, the hole-collecting buffer layer (MoO_3 in our case) inserted between the active organic layers and the top electrode seems to play an essential role. This layer protects the organic materials and prevents physical and chemical damage during deposition of the metal electrode. It provides also an effective barrier for the ingress of moisture and oxygen into the device [32,34]. Solar cells were fabricated with vanadium oxide/Al or titanium oxide/Al top electrodes [35,36]. In both examples, good stability was observed despite the use of the low work function Al top electrode, demonstrating the beneficial role of the buffer layer. For bilayer cells as studied here, it must also be considered that the sequence of active organic layers in the regular and inverted geometry is reversed. For similar bilayer cells with CuPc as electron donor and C_{60} as acceptor, the shelf lifetime of non-encapsulated devices in the inverted geometry was 25 times longer than for regular devices [10]. This was attributed to the well-documented sensitivity of C_{60} against oxygen. In the inverted geometry, C_{60} was better protected by the additional overlying CuPc, and oxygen penetration into the fullerene layer was delayed.

3.2.2. Stress-induced performance response

Regular and inverted solar cells (device structures (3, TFP) and (5) from Table 1) were exposed to light and heat for a period of 17 days in an environmental chamber and J_{sc} , FF and

V_{oc} were periodically measured (Fig. 4). To prevent exposure to oxygen and water during experimental setup, cells were glass-encapsulated before transferring them from the glove box to the chamber. For both devices, stability trends were similar and characterized by a pronounced performance decrease of 75% during the first ~5 days. After that, performances stabilized and during the period from 5 to 17 days FF, J_{sc} and V_{oc} decreased linearly by $(15 \pm 10)\%$.

The scattering of data between 6 and 7 days (Fig. 4a) was due to the periodic switching off of the LEDs due to interruption of the cooling water circuit. The ISOS protocols [4,13] define the times T_0 , T_{80} , T_S and T_{S80} to accurately describe the decay characteristics of an organic solar cell. T_{80} is the time when the performance has decayed to 80% of the initial value at T_0 immediately after fabrication (Table 1). For both device data shown in Fig. 4, T_{80} was ~10 hours. To account for the burn-in period, we arbitrarily define the time $T_S = 5$ days when a stabilized performance was recorded. T_{S80} is the time when the performance has decayed to 80% of the value at T_S , and this time was ~3 days for both the regular and inverted solar cell. After a test period of 17 days, performances have decayed to 15% of the initial values.

In a series of further experiments we investigated degradation during the first days of stressing. From the curve progressions in Fig. 4 continuous ingress of oxygen and moisture with time through the encapsulant into the device can probably be excluded. This implies that the fast initial decay must be intrinsic to the material components or be caused by the encapsulant itself.

Non-encapsulated cells were exposed in the glove box for 1 day separately to heat or light, and to both components at the same time (Fig. 5a). Performance values did not change when devices were heated in the dark. J_{sc} and V_{oc} values dropped by 10-20%, however, when cells were exposed to light only, or to light and heat. Results were the same for cells that were held in short-circuit conditions or that were electrically not contacted during the experiment.

From this we conclude that the initial fast degradation (Fig. 4) was triggered by light, in agreement with the findings that cells were stable for several months when kept under N_2 in the dark (Fig. 3). FF increased by $\sim 10\text{-}20\%$ during initial stressing in the glove box (Fig. 5a), in contrast to the environmental chamber where FF decreased. This observation remains unexplained at this moment. One difference was the light sources (LEDs vs. Xe lamp) used in the two experimental setups. Although unlikely, we can not exclude that the encapsulation material/procedure introduced some impurity in the sealed device that induced a lowering in FF.

We further checked the stability of Cy3-P films during 1 day of light stressing. The unchanged absorption spectra of Cy3-P films before and after irradiation (Fig. 5b) indicate that the cyanine film was chemically stable. This does not necessarily mean, however, that this layer does not degrade in terms of its function in a solar cell. It has been reported that J_{sc} can degrade without observable change in the absorption characteristics, due to morphological changes or electronic defects [6]. The stability of Cy3-P/ C_{60} films was also tested under light irradiation (Fig. 5c). Before and after irradiation, absorption spectra were measured of films and of solutions after dissolving with CB. At $t = 0$, film and solution spectra were the composition of the two components [37]. After irradiation, the film absorption changed considerably in the wavelength region below ~ 450 nm where C_{60} absorbs. In addition, the film was partly insoluble in CB and absorption characteristics of the soluble fraction did not match with the solution spectrum of pristine C_{60} . This points to a chemical transformation of C_{60} during illumination. Similar changes in the absorption spectra were observed for illuminated pure C_{60} films in the absence of Cy3-P. Also these C_{60} films were partly insoluble in contrast to pristine films, which dissolved completely in seconds in CB at room temperature.

One reason for chemical reactions in C_{60} relates to its sensitivity towards the presence of oxygen [8-10]. Oxygen lowers the conductivity of fullerene films and favours exciton

quenching. The main chemical degradation mechanism is oxidation, leading to decomposition of the fullerene cage or to polymerization. Photoexcitation of fullerenes can result in the formation of reactive singlet oxygen [37]. Oxidized C_{60} and sub-products thereof have been found in aged encapsulated ZnPc/ C_{60} solar cells under illumination [38]. ITO was speculated to be the source of oxygen contamination.

In our experiments, C_{60} chemical transformations arising from the presence of oxygen impurities can probably be excluded. Films for the experiments shown in Fig. 5c were coated on glass substrates and samples were fabricated and exposed to light in a glove box with low contents of water and oxygen (<1 ppm). We rather think that the observed changes in the absorption spectra can be ascribed to the known photopolymerization reaction of C_{60} [39]. This reaction proceeds readily and completely in the absence of oxygen, probably via 2+2 cycloaddition between adjacent fullerene molecules [40].

Possible implications of the suggested C_{60} photopolymerization on the initial performance decay of stressed cells (Fig. 4) are the subject of ongoing work. It was found that the influence of polymerization on the charge transport properties of C_{60} was rather small [41]. The electron mobility at room temperature dropped by only ~10% upon complete polymerization. In our case, films were only partly photopolymerized and the situation might be different. Of relevance could also be the known bulk volume decrease associated with the polymerization reaction [41]. A volume decrease of the C_{60} film could potentially lead to the formation of voids, which will effectively decrease the contact area between C_{60} and the adjacent cyanine layer and electrodes. This assumption is supported by AFM phase images (Fig. 5d) of a 40 nm thick C_{60} film on glass after fabrication and after irradiation for 24 h. While the initial film was pinhole free, irradiation induced pronounced cracks in the C_{60} layer. At the same time, the surface flattened during illumination and root mean square roughnesses of 2.5 nm and 0.62 nm were measured for the untreated and illuminated film, respectively. C_{60} photoinduced degradation mechanisms would be consistent with the fact that performance

trends for the regular and inverted cells were rather similar (Fig. 4), although the inverted device geometry was found to be intrinsically much more stable.

4. Conclusions

Our results indicate that (at least trimethine) cyanine dyes are probably more photo stable than often assumed. Thin films of Cy3-P were found to be intrinsically stable in the dark and under illumination if water and oxygen were carefully excluded. The durability of Cy3-P/C₆₀ solar cells was mainly studied by following performance trends with time. From such measurements, little insight into specific chemical and physical degradation events are obtained; this is because several failure mechanisms can have a similar influence on the performance characteristics. However, by systematically varying electrode materials in the regular cell architecture, critical layers (ITO/PEDOT and Al) could be identified. Further studies on the photoinduced polymerization of C₆₀ are needed to possibly clarify the pronounced initial performance decrease of Cy3-P/C₆₀ cells stressed under accelerated full sun simulation.

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Figure captions

Fig. 1. (a) Schematic of regular and inverted cyanine dye/C₆₀ solar cells and the molecular structure of Cy3-P. (b) Initial J-V curves of best performing cells listed in Table 1.

Fig. 2. Absorption of thin films as function of storage time under N₂ at room temperature in the dark. Inset: Absorption change of a Cy3-P film when exposed to oxygen, humidity and light.

Fig. 3. Performance characteristics of solar cells stored under N₂ at room temperature in the dark.

Fig. 4. Performance characteristics of encapsulated solar cells stressed in an environmental chamber with light and heat (device structures (3, TFP) and (5) from Table 1).

Fig. 5. (a) Performance values for non-encapsulated regular and inverted solar cells (device structures (3, TFP) and (5) from Table 1) after stressing for 1 day in the glove box. (b) Absorption spectra of Cy3-P films before and after illumination in the glove box. (c) Absorption spectra of fresh and illuminated Cy3-P/C₆₀ films and after dissolution in CB. (d) AFM phase images of a C₆₀ film before and after illumination in the glove box.