Advanced Nonvolatile Organic Optical Memory Using Self-Assembled Monolayers of Porphyrin– Fullerene Dyads

Lyubov A. Frolova, Yulia Furmansky, Alexander F. Shestakov, Nikita A. Emelianov, Paul A. Liddell, Devens Gust, Iris Visoly-Fisher, and Pavel A. Troshin*

Cite This: ACS Appl. Mater. Interfaces 2022, 14, 15461−15467

ABSTRACT: Photo-switchable organic field-effect transistors (OFETs) represent an important platform for designing memory devices for a diverse array of products including security (brand-protection, copy-protection, keyless entry, etc.), credit cards, tickets, and multiple wearable organic electronics applications. Herein, we present a new concept by introducing self-assembled monolayers of donor−acceptor porphyrin−fullerene dyads as light-responsive triggers modulating the electrical characteristics of OFETs and thus pave the way to the development of advanced nonvolatile optical memory. The devices demonstrated wide memory windows, high programming speeds, and long retention times. Furthermore, we show a remarkable effect of the orientation of the fullerene−polymer dyads at the dielectric/semiconductor interface on the device behavior. In particular, the dyads anchored to the dielectric by the porphyrin part induced a reversible photoelectrical switching of OFETs, which is characteristic of flash memory elements. On the contrary, the devices utilizing the dyad anchored by the fullerene moiety demonstrated irreversible switching, thus operating as read-only memory (ROM). A mechanism explaining this behavior is proposed using theoretical DFT calculations. The results suggest the possibility of revisiting hundreds of known donor−acceptor dyads designed previously for artificial photosynthesis or other purposes as versatile optical triggers in advanced OFET-based multibit memory devices for emerging electronic applications.

KEYWORDS: porphyrin−fullerene dyad, self-assembled monolayer, organic field-effect transistors, OFETs, optical memory, photoswitching

INTRODUCTION

The photoactive dyads, formed by linking electron-donor organic molecules such as porphyrins with electron-acceptor fullerene derivatives, have been attracting much attention for the last two decades as promising functional materials for organic optoelectronic devices.1−3 The donor−acceptor dyads can undergo efficient intramolecular photoinduced charge separation, which has inspired intense research on the application of these materials in artificial photosynthesis4−6 and photoelectrochemical cells for solar energy conversion.7−19 Hundreds of exciting molecular assemblies have been designed and investigated, and extraordinarily long lifetimes of charge-separated states have been reported.20−22 These fundamentally important findings have not as yet resulted in any commercialized technologies, and the focus of the research has gradually shifted to more conventional photovoltaic concepts such as organic and more recently also perovskite solar cells.23,24

Since donor−acceptor dyads represent molecular light-triggered switches, there is a huge and largely unexplored potential for their application in optoelectronics, particularly in the design of memory devices. Among the many possible architectures of organic memories, organic field-effect transistors (OFETs) represent one of the most promising platforms for the design of affordable, flexible, and lightweight
data storage devices. Currently, nonvolatile organic memory devices are actively being developed using floating‐gate OFET architectures,25–27 transistors with charge‐trapping layers of polymeric electrets,28–31 or ferroelectric components.32–36 However, despite the tremendous progress achieved in this field, most of the demonstrated organic memories operate at relatively high voltages (tens of volts), require long programming times (seconds to minutes), and rarely demonstrate retention times exceeding 105 s.

Given the fact that the highest density of the charge carriers in an operating OFET is carried in a few molecular layers of the semiconductor adjacent to the interface with the dielectric,37 changing the properties of this interface can induce significant modulation of the device electrical characteristics. Recently, we have explored this approach and introduced photochromic molecules at the semiconductor/dielectric interface. The organic photochromic compounds served as molecular triggers, which could be modulated using different optoelectrical programming regimes to enable advanced organic memory elements operating with high switching optoelectrical programming regimes to enable advanced polymeric electrets,28 (Figure S1). Using the dyads, we have shown that the adsorption of the dyads on an AlOx surface results in complete distinction and stable electrical states as required for memory applications. Furthermore, it was found that the molecular structure of the fullerene-porphyrin dyad governs the device programming behavior, thus enabling the design of both flash and ROM types of memory with advanced electrical characteristics.

# EXPERIMENTAL SECTION

## Characterization of the Porphyrin–Fullerene PF and FP Dyads Molecular Layers. Adsorption of the dyads on an AlOx gate electrode surface was confirmed by contact angle and absorption spectroscopy measurements. The water contact angle increased from ca. 1° to ca. 90° ± 2° indicating the formation of dyad layers, with only a minor reduction (<5°) after thorough sonication in mesitylene. Quantitative characterization of the dyad layer density was performed by desorption of the dyads from electrodes of a known area in mesitylene solution containing 3% (v/v) of trimethylamine and 10% (v/v) of ethanol. The shape of the UV–vis spectrum of the desorbed dyad matched the spectrum of the pristine material in solution (Figure S1). Using the dyads’ extinction coefficients in mesitylene solutions (487 807 M−1 cm−1 for PF-dyad and 568 948 M−1 cm−1 for PF-dyad at 420 nm, according to our calibration) and the measured absorbance, the molecular density of the dyads adsorbed on AlOx was estimated to be about 7.4 × 1013 molecules per cm2, which is comparable with the literature values reported for carboxylic acid induced monolayers adsorbed on TiO2 and AlOx surfaces.40,41 We therefore conclude that the adsorbed layer is likely to have a density in the order of a monolayer.

To evaluate the uniformity of the adsorbed on AlOx molecular layers of PF- and FP-dyads, scattering-type scanning infrared near-field optical microscopy (IR s-SNOM, Neaspec, Germany) has been applied. This technique provides the local infrared spectroscopy analysis with the lateral resolution of ca. 25–35 nm. In the context of our study, IR s-SNOM could directly visualize the distribution of the dyad layer on the AlOx surface. The IR s-SNOM images obtained by scanning at the IR absorption frequencies of PF and FP dyads (1608 and 1691 cm−1, respectively) revealed that both of them form uniform coatings over the AlOx films without any voids or pinholes as indicated by homogeneous red color distribution on the corresponding images in Figure S3. At the same time, the reference blank aluminum oxide films showed virtually now s-SNOM signal on these frequencies.

### Fabrication and Characterization of the Memory Device. The glass substrates were first sonicated in piranha solution (a mixture of H2O2 and H2SO4) for 5 min, then are thoroughly rinsed in deionized water and dried in an oven at 60 °C for 20 min with subsequent RF plasma treatment (150 W) for 5 min. Aluminum gate electrodes with a thickness of 200 nm were deposited by thermal evaporation from a target of Al in an Ar atmosphere at a growth rate of 10 Å s−1 at 30 °C. These devices demonstrated good write−read−erase cycling endurance as well as data retention times exceeding 1 month.40,41 Unfortunately, the writing speeds were still relatively slow (10–30 ms), which leaves substantial room for further improvements.

Herein, we present a new concept for designing advanced organic memories using monolayers of porphyrin–fullerene dyads placed at the semiconductor/dielectric interface in OFETs. We demonstrate for the first time that donor−acceptor dyads can be used as molecular triggers enabling strong photoswitching of OFETs which leads to the formation of multiple distinct and stable electrical states as required for memory applications. Furthermore, it was found that the molecular structure of the fullerene-porphyrin dyad governs the device programming behavior, thus enabling the design of both flash and ROM types of memory with advanced electrical characteristics.

## RESULTS AND DISCUSSION

We have investigated two structurally similar fullerene-porphyrin dyads FP and PF, which have the surface-anchoring carboxylic groups attached to either the porphyrin or the fullerene moieties, respectively (Figure 1). The synthesis and characterization of the porphyrin–fullerene dyads were reported previously.46,47 The molecular formulas of PF and FP enable their different orientations within the self-assembled monolayers as shown in Figure 1. The porphyrin moieties of the FP dyad are linked to the oxide surface, whereas the fullerene part is bonded to AlOx in the case of the FP dyad. These different arrangements of the donor−acceptor dyads on the oxide surface result in completely different electrical behavior of the devices as will be discussed below. Both PF and FP dyads were investigated as light-sensitive components integrated into the structure of OFETs at the semiconductor/dielectric interface (Figure 1).

The performance of the fabricated OFETs as memory elements was evaluated by using a hybrid optoelectrical programming regime based on the simultaneous application of an electrical bias between the source and gate electrodes.
In combination with light is applied, both types of devices dyads upon such programming. When a positive transfer characteristics of the OFETs comprising FP or PF, respectively. Programming with the negative $V_P$ bias ($-10$ V) and light enables a reverse transition of the device transfer characteristics accompanied by a decrease in $V_{TH}$ value for the OFETs incorporating the FP dyad (Figure 2b).

However, the speed of the backward transition was found to be considerably lower: Programming for about 1 ms was required to return the FP-based devices to the initial state, whereas 150 ms is sufficient for device switching with $k_{SW}$ exceeding $10^5$ (Figure S4). Thus, the OFETs loaded with the monolayer of the FP dyad can operate as flash memory devices supporting the recording (writing) of information at positive $V_P$ and the erasing at negative $V_P$. Surprisingly, the devices incorporating the PF dyad were completely insensitive to applying negative programming bias and light (Figure 2d).

Thus, the programming of PF-based devices with a positive $V_P$ bias was essentially irreversible. In other words, the information recorded in the memory cells by their exposure to the positive $V_P$ and light cannot be erased, so using the PF dyad enables the fabrication of so-called read-only memory (ROM) devices. Thus, the differences in the molecular geometry of the FP and PF dyads and the ways of their attachment to the oxide dielectric result in large effects on the electrical behavior of the devices and enable the fabrication of both flash and ROM memory devices.

Variation of the programming conditions can be used to induce multiple discrete electrical states in the OFETs comprising FP or PF dyads. Figure 3a,c shows the shifts of the transfer curves of the devices upon exposure to different programming voltages ranging from 0 to 10 V combined with the fixed laser pulse duration (10 ms). The device threshold voltage increases from $~0$ to $~7$ V in the case of FP-based OFETs and from $~1$ to $~7$ V for OFETs with PF.

The returning of the devices loaded with the FP dyad ($V_{TH}$ shifts from $~7$ to $~0.5$ V) to the initial state can be accomplished by applying negative $V_P$ biases (from 0 V down to $-10$ V) and light in a stepwise mode with a 1 s exposure time at each step. It is worth noting that the forward (positive $V_P$) and backward (negative $V_P$) transitions of the devices incorporating the FP dyad occur with some hysteresis as shown in Figure 3b. This behavior was found to be highly reproducible for multiple cycles (see below); therefore, it does not complicate the operation of the devices as reliable memory elements. The observed hysteresis appeared simply because the backward device transition requires a higher negative voltage amplitude (and usually longer time) as compared to the forward transition. The devices comprising the PF dyad showed no signs of the backward transition under the applied negative bias voltages and light (Figure 3d), which confirms that the induced electrical states cannot be erased as is typical of ROMs.

It should be emphasized that the simultaneous action of light and electric bias is crucial for switching the OFETs loaded with either PF or FP dyads. Indeed, applying electrical bias $V_P$ without light causes only negligible $V_{TH}$ shifts of the transistors, as illustrated by black lines in Figures 3b,d and sets of current–voltage characteristics presented in Figure S5. Similarly, the exposure of the OFETs to light without electric bias does not lead to any significant changes in their transfer characteristics (Figure S6).
The retention and endurance characteristics are among the most important parameters of memory devices. The endurance, i.e., the ability to withstand multiple writing and erasing cycles, was investigated only for the devices assembled using the FP dyad as the PF-based OFETs showed irreversible switching behavior (Figure 4c).

In our experiments, we switched the device many times between two arbitrary selected electrical states by simulating the “writing” ($V_P = 10$ V + light applied for 1 ms; red lines in Figures 4a and S7) and “erasing” ($V_P = -10$ V + light applied for 1 s, green lines) processes. Figure S8 shows 20 manually recorded “write—read—erase” cycles. It is seen from both Figures 4a and S8 that the FP-based devices demonstrate good reproducibility and endurance without any significant degradation in the performance from one cycle to another, which is important for flash memory applications.

To further assess the retention characteristics of the devices incorporating FP or PF dyads, we followed the evolution of the transfer characteristics of the OFETs with time (Figures 4b,d). For both types of devices, we monitored the change of the drain current and low-current) plotted as a function of time illustrate multiple switching of the devices assembled using the FP dyad (c). OFET drain currents for two distinct electrical states (high-current and low-current) plotted as a function of time illustrate retention characteristics of the memory devices comprising FP (b) or PF (d) dyads.

Figure 3. Evolution of the transfer characteristics of the OFETs comprising FP (a) or PF (c) induced by applying gradually increasing $V_P$ (from 0 to 10 V) and violet light ($\lambda = 405$ nm) for 10 ms. Evolution of the OFET threshold voltage as a function of the programming voltage $V_D$ for OFETs assembled using monolayers of FP (b) and PF (d) dyads. The backward programming was done by applying gradually decreasing $V_P$ (from +10 to −10 V) under simultaneous exposure to violet light ($\lambda = 405$ nm) for 1 s at each step.

Figure 4. Transfer characteristics illustrating multiple switching of the FP-based OFETs between two distinct electrical states (a) and the irreversible single switching of the devices assembled using the PF dyad (c). OFET drain currents for two distinct electrical states (high-current and low-current) plotted as a function of time illustrate retention characteristics of the memory devices comprising FP (b) or PF (d) dyads.

The electric field drives some of the negative charges from the fullerene moieties to the defect sites in the oxide dielectric. Switching off the light results in intramolecular recombination of positive and negative charges except for the dyads which lost their electrons. Therefore, these dyads keep positive charges on the porphyrin units since they cannot recombine with the electrons deeply trapped inside of AlOx layer. This electron trapping mechanism is supported by the experimental data since the observed increase in the OFET threshold voltage is fully consistent with the accumulation of positive charge carriers in the transistor channel.

At the erasing step (negative $V_P$), the light also generates long-living charge-separated states (Figure 5). However, the electric field is driving now-positive charge carriers from the dyads into the dielectric layer toward the negatively biased gate electrode. The injection of holes from the dyads to AlOx layers (through some defect sites capable of accommodating positive charge carriers) can readily occur in the case of the FP dyad since the positively charged porphyrin moiety is directly attached to the oxide surface. Therefore, the injected holes recombine with the electrons trapped in the AlOx at the recording step, which restores the electrical neutrality of the dielectric layer and converts the device to the initial state. This mechanism explains the flash memory behavior of the OFETs incorporating FP dyad molecules.
In the case of OFETs with PF dyads, on the contrary, injection of holes at the erasing step (negative V_p) is blocked since the porphyrin units bearing the positive charges are separated from the AlO_x layer by the fullerene moieties. DFT calculations revealed that the highest occupied molecular orbital (HOMO) of the fullerene part of the PF dyad has a much lower energy (−5.58 eV) as compared to the HOMO of the porphyrin unit (−4.74 eV), which makes hole transfer from the porphyrin to the fullerene energetically very unfavorable (Figure 5c). In other words, fullerene cages form a barrier for hole injection from the porphyrins to AlO_x in the case of OFETs with PF dyad, which does not allow quenching of the negative charges trapped in the dielectric and hence the erasing of the programmed electrical state. In a similar way, other self-assembled monolayers are commonly used in electronic devices to facilitate the injection of one type of charge carriers and block the other.\(^{50,51}\) Thus, the proposed mechanism explains why the OFETs incorporating the PF dyad show irreversible switching behavior and operate as read-only memory.

### CONCLUSION

To summarize, the self-assembled monolayers of donor–acceptor porphyrin–fullerene dyads were applied for the first time as light-sensitive triggers to modulate the optoelectrical switching of organic field-effect transistors and develop nonvolatile optical memory elements. These memory devices demonstrated superior performance characteristics such as low operational voltages, wide memory windows, high current modulation (switching) coefficients approaching \(10^5\), fast programming (recording time down to 1 ms), and good endurance and retention characteristics. We found that the position of the anchoring carboxylic group (on the fullerene (PF) or porphyrin (FP) moieties) in the dyads and, consequently, their orientation between the semiconductor and dielectric layers, drastically changes the electrical behavior of the devices. The OFETs comprising interlayers of the FP dyad (anchor group on the porphyrin) showed a reversible photoelectrical switching, which is characteristic for flash memory elements with good write–read–erase cycling stability. On the contrary, the devices based on the PF dyad (anchor group on the fullerene) demonstrated irreversible switching and operated as read-only memory (ROM). The operational mechanism explaining the observed electrical switching behavior of OFETs incorporating FP or PF dyads was proposed and supported by theoretical DFT calculations. Furthermore, both types of memory devices revealed the formation of multiple distinct electrical states and could eventually be used for the development of multibit memory elements capable of high-density information storage required for a variety of practical organic electronics applications. The new concept for the design of advanced organic memory elements demonstrated herein undoubtedly deserves further exploration, in particular by revisiting different donor–acceptor dyads, which were designed and investigated previously as artificial photosynthetic elements.

### ASSOCIATED CONTENT

* Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsami.1c24979.

Fabrication and characterization methods for porphyrin–fullerene dyads molecular layers and the memory devices, DFT calculations, UV–vis absorption spectra of PF- and FP-dyads, FTIR spectra, IR s-SNOM images, additional memory devices electrical characteristics (PDF).

### AUTHOR INFORMATION

**Corresponding Author**

Pavel A. Troshin – Silesian University of Technology, 44-100 Gliwice, Poland; Institute for Problems of Chemical Physics of Russian Academy of Sciences, Chernogolovka, Moscow Region 142432, Russia; orcid.org/0000-0001-9957-4140; Phone: +7-496-522-1418; Email: troshin2003@inbox.ru

Figure 5. Schematic illustration of the proposed switching mechanisms of the OFETs comprising (a) FP or (b) PF dyads. (c) Energy level diagrams show the facile hole injection from the FP dyad to AlO_x (left) and the blocked hole injection in the case of the PF dyad (right), as deduced from DFT calculations.
Assembled Monolayers of Porphyrins and Porphyrin-Fullerene Dyads
Kim, S. K.; Kim, D.; Fukuzumi, S. Photovoltaic Properties of Self-Peroxide and Nitrite. Enzymatic Electrochemical Sensor for Sensitive Sensing of Hydrogen. Construction of a Zinc Porphyrin-Fullerene-Derivative Based Non-Photosynthetic Mimics. 9139. Porphyrin-Fullerene Dyads on TiO2. Tkachenko, N. V. Photophysical Study of a Self-Assembled Donor-Acceptor Two-Layer Film on TiO2.}

REFERENCES

This work was supported by the Ministry of Science and Higher Education of the Russian Federation (Grant No. 075-15-2020-779) and by the US–Israel binational science foundation (BSF) grant no. 2008340. Y.F. is grateful to the Mirage fellowship (BGU) for financial support. Y.F. and I.V.-F. are grateful for support from COST (European Cooperation in Science and Technology) Action MP 1307, “StableNextSol”.

ACKNOWLEDGMENTS

The authors declare no competing financial interest.

REFERENCES

(1) Imahori, H.; Fukuzumi, S. Porphyrin- and Fullerene-Based Molecular Photovoltaic Devices. Adv. Funct. Mater. 2004, 14 (6), 525–536.
(2) Stranius, K.; George, L.; Efimov, A.; Ruoko, T.-P.; Pohjola, J.; Tkachenko, N. V. Photophysical Study of a Self-Assembled Donor-Acceptor Two-Layer Film on TiO2. Langmuir 2015, 31 (3), 944–952.
(3) Wu, H.; Fan, S.; Jin, X.; Zhang, H.; Chen, H.; Dai, Z.; Zou, X. Construction of a Zinc Porphyrin-Fullerene-Derivative Based Non-enzymatic Electrochemical Sensor for Sensitive Sensing of Hydrogen Peroxide and Nitrite. Anal. Chem. 2014, 86 (13), 6285–6290.
(4) Yamada, H.; Imahori, H.; Nishimura, Y.; Yamazaki, I.; Ahn, T. K.; Kim, S. K.; Kim, D.; Fukuzumi, S. Photoelectrochemical Properties of Self-Assembled Monolayers of Porphyrins and Porphyrin-Fullerene Dyads on ITO and Gold Surfaces. J. Am. Chem. Soc. 2003, 125 (30), 9129–9139.
(5) Imahori, H. Porphyrin-fullerene Linked Systems as Artificial Photosynthetic Mimics. Org. Biomol. Chem. 2004, 2 (10), 1425–1433.
(6) Umeyama, T.; Imahori, H. Self-Organization of Porphyrins and Fullerenes for Molecular Photoelectrochemical Devices. Photosynth. Res. 2006, 87 (1), 63–71.
(7) Garg, V.; Kojis, G.; Chachisvilis, M.; Hambourg, M.; Moore, A. L.; Moore, T. A.; Gust, D. Conformationally Constrained Macrocyclic Diporphyrin-Fullerene Artificial Photosynthetic Reaction Center. J. Am. Chem. Soc. 2011, 133 (9), 2944–2954.
(8) Toliki, A.; Kaunisto, K.; Efimov, A.; Kivistö, H.; Storbacka, L.; Savikoski, R.; Huttunen, K.; Lehtimäki, S.; Lemmetyinen, H. Directed Electron Transfer in Langmuir-Schäfer Layers of Porphyrin-fullerene and Pthalocyanine-fullerene Dyads in Inverted Organic Solar Cells. Phys. Chem. Chem. Phys. 2012, 14 (10), 3498.
(9) Fungo, F.; Otero, L.; Borsarelli, C. D.; Duranti, E. N.; Silber, J. J.; Sereno, L. Photocurrent Generation in Thin SnO2 Nanocrystalline Semiconductor Film Electrodes from Photoinduced Charge-Separation State in Porphyrin-C60 Dyad. J. Phys. Chem. B 2002, 106 (16), 4070.
(10) Gupta, N.; Naqvi, S.; Jewariya, M.; Chand, S.; Kumar, R. Comparative Charge Transfer Studies in Nonmetallated and Metallated Porphyrin Fullerenes Dyads. J. Phys. Org. Chem. 2017, 30 (11), No. e3685.
(11) Lee, M. H.; Kim, J. W.; Lee, C. Y. [60] Fulleropyrrophenofurocine Triad Self-Assembled Monolayers (SAMs) for Photovoltaic Applications. J. Organcem. Chem. 2014, 761, 20–27.
(12) Nikolaou, V.; Plass, F.; Planchat, A.; Charisiadis, A.; Charalambidis, G.; Angaridis, P. A.; Kaht, A.; Odobel, F.; Coutsolelos, A. G. Effect of the Triazole Ring in Zinc Porphyrin-Fullerene Dyads on the Charge Transfer Processes in NIO-Based Devices. Phys. Chem. Chem. Phys. 2018, 20 (37), 24477–24489.
(13) Strelnikov, A. A.; Androsov, D. V.; Konev, A. S.; Lukyanov, D. A.; Khlebnikov, A. F.; Povolotskiy, A. V.; Yamanouchi, K. Triaryl-Substituted Pyrrolo-P-Phenylene-Linked Porphyrin-Fullerene Dyads: Expanding the Structural Diversity of Photocative Materials. Tetrahedron 2018, 74 (24), 3007–3019.
(14) Hasobe, T.; Saito, K.; Kamat, P. V.; Troiani, V.; Qiu, H.; Solladié, N.; Kim, K. S.; Park, J. K.; Kim, D.; D’Souza, F.; Fukuzumi, S. Organic Solar Cells. Supramolecular Composites of Porphyrins and Fullerenes Organized by Polyamide Structures as Light Harvesters. J. Mater. Chem. 2007, 17 (39), 4160.
(15) Ichikawa, T.; Matsuura, Y.; Nakamura, E. Photostability of a Dyad of Magnesium Porphyrin and Fullerene and Its Application to Photocurrent Conversion. Chem. Commun. 2013, 49 (3), 279–281.
(16) Chukharev, V.; Vuorinen, T.; Efimov, A.; Tkachenko, N. V.; Kimura, H.; Fukuzumi, S.; Imahori, H.; Lemmetyinen, H. Photoinduced Electron Transfer in Self-Assembled Monolayers of Porphyrin-Fullerene Dyads on ITO. Langmuir 2005, 21 (14), 6385–6391.
(17) Gust, D.; Moore, T. A.; Moore, A. L. Solar Fuels via Artificial Photosynthesis. Acc. Chem. Res. 2009, 42 (12), 1890–1898.
(18) Gust, D.; Moore, T. A.; Moore, A. L. Realizing Artificial Photosynthesis. Faraday Discuss. 2012, 155, 9–26.
(19) Gust, D. Supramolecular Photochemistry Applied to Artificial Photosynthesis and Molecular Logic Devices. Faraday Discuss. 2015, 185, 9–35.
(20) Agnihotri, N. Computational Studies of Charge Transfer in Organic Solar Photovoltaic Cells: A Review. J. Photochem. Photobiol. C 2014, 18, 18–31.
(21) Hou, Y.; Zhang, X.; Chen, K.; Liu, D.; Wang, Z.; Liu, Q.; Zhao, J.; Barbou, A. Charge Separation, Charge Recombination, Long-Lived Charge Transfer State Formation and Intersystem Crossing in Organic Electron Donor/acceptor Dyads. Journal of Materials Chemistry C 2019, 7 (39), 12048–12074.
(22) Oikubo, K.; Fukuzumi, S. Long-Lived Charge-Separated States of Simple Electron Donor-Acceptor Dyads Using Porphyrins and Phalalocyanines. J. Porphyr. Phthalocyanines 2008, 12 (09), 993–1004.
(23) Duan, L.; Uddin, A. Progress in Stability of Organic Solar Cells. Adv. Sci. 2020, 7 (11), 1903259.
(24) Jena, A. K.; Kulkarni, A.; Miyasaka, T. Halide Perovskite Photovoltaics: Background, Status, and Future Prospects. Chem. Rev. 2019, 119 (5), 3036–3103.
