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Citation network analysis of plastic electronics: Tracing the evolution and emerging research fronts

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ABSTRACT

This paper aims at tracing the evolution and finding the emerging research fronts of organic electronics. The discovery of electrically conductive polymers has opened a pathway to a new dimension in technological evolution, which replaces the rigid electronics to organic electronics. Its tremendous potential of flexibility, strength and minimal weight inspired many physicists, chemists, material scientists, electrical and electronics engineers to focus their research in this area. Traces over the past forty years made by this field inspire futurists to investigate and forecast the trajectory of organic electronics technology. Hence, by tracing the evolution and identifying the emerging research fronts, this paper will be helpful for researchers and manufacturers to directly concentrate on the upcoming research areas of organic electronics. The evolving phase of the growth curve fitted to the number of research articles related to "plastic or organic electronics" published per year shows that the research activities are still in the ascendant phase and have not reached the maturity level. This ensures that organic electronics is a promising area of research. Further, we systematically analyse the corpus of research articles related to organic electronics to trace the trajectory of the global evolution and emerging research fronts as well as the prospects of organic electronics using tools of social network analysis. We visualize the main path of evolution in the citation network and investigate the patterns to trace the knowledge diffusion path, major milestones and the emerging research fronts. Thus, we obtain the origin of third-generation solar cells and found that the emerging research articles are from articles of organic solar cells. The cluster analysis of the citation network identifies the major topics of the emerging research domains of organic solar cells.

Selection and peer-review under responsibility of the scientific committee of the International Conference on Photochemistry and Sustainable Energy (ICPSE 2019).

1. Introduction

Since ancient times, predictions always stimulate human interest to know about the future. The futurists are the ones whose interest is futurology that attempts to systematically explore the emerging possibilities in the near future that evolved from the current scenarios. Organic electronics or Plastic electronics make use of organic polymers/oligomers for the fabrication of electronic devices [1]. In its initial stage, researches were focused on developing new conducting polymers/oligomers with high charge carrier mobility by various synthetic approaches [2]. Organic molecules are used to fabricate various electronic devices such as Organic Photovoltaics (OPVs), Organic Light Emitting Diodes (OLEDs) and Organic Field Effect Transistors (OFETs) [3]. Introduction of organic integrated circuits with 1888 transistors, which was developed by Bell Labs using vacuum evaporation techniques turn its path in achieving more compatible as well as reliable ICs [4]. In the last twenty years, advanced electronic devices like a model of radiofrequency tags using organic integrated circuits, matrix display arrays using TFT (thin-film transistor), OFETs, OLEDs and organic solar cells was introduced [4]. The steady growth in these areas introduced many innovative devices such as, organic thin-film electronics which left a promising impression in technology. From here, researches routes to develop electronic devices with higher switching speed, low cost, scaled-down geometry without compromising on stability and reliability. The wide range of applications of thin-film transistors includes biosensing, logic circuits, and neuromorphic engineering and organic solar cells [5]. The flexibility, affordability, wearable nature, and low toxicity of thermoelectric

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materials and devices seek attention in the energy market too [6]. The integration of electronic devices with fabrics, pushed science further into a new dimension which creates an unpredictable environment in research areas called smart textiles research. As they are flexible enough to wrap around a person, it takes a wide range of applications in the medical field [7]. Behind a current processor or computer occupied world, a better future surrounded by organic electronics is equally evolving undisturbed [8].

For the last ten years, the field of organic electronics entered the commercial market leading to the commercial phase. Even though it is promising, there are many challenges faced when it comes to commercialization [9]. The enormous diversification into many areas and challenges in implementation in a real-time scenario inspire the futurist to explore its trajectory so far traversed and to predict its future trend. The structure of the research domain is characterized by the diversified version of numerous multi-disciplinary sub-domains, which can be analysed with the help of a research review. A research review gives a glimpse of the knowledge structure of the concerned area which in turn helps researchers to extend the existing theories, to develop new theories and detect areas that need more attention. The evolution of research fronts can be traced by a citation network, where nodes of the network represent the articles and edges represents the citation. By using the principles of network theory, the major path of information flow on the evolution of research fronts can be identified through tracing its edges. Social Network analysis tools and Citation network analysis (CNA) deals with analysing research article in the concerned area to bring out the evolution and predict its future trends [10]. It is a good alternative to a conventional expert-based approach.

In this paper, the dynamics of research activities in organic electronics are studied by the corpus of research articles using social network analysis tools. The corpus of research articles is a collection of a number of words in an electronic form that occurs in academic journal articles published by Elsevier that become a reliable source of an early indicator of innovations [11]. In this paper, the analysis of organic electronics research papers is done in three different ways, fitting growth curve, main path analysis and cluster analysis.

2. Methodology

2.1. Main path analysis

We collected citation data related to organic electronics and the giant component was extracted to carry out the main path and cluster analysis. Primary inter-related articles and the trajectory of the development of the new ideas in a particular research domain were identified using main path analysis. The main paths are the sequence of edges that connects the most significant nodes in the acyclic directed networks. Initially, a weight is assigned to each directed edge connecting two nodes in a citation network. The major measures suggested by Hummon and Dereian for finding the weights of the edges of the network are Node Pair Projection Count (NPPC), Search Path Node Pair (SPNP) and Search Path Link Count (SPLC) [12]. From the tail node to its ancestral nodes of the acyclic directed network, all possible paths were counted by SPLC [13]. From a source node, the main path is formed by adding edges with the highest weight one after another until a leaf node is reached. Each main path edges denotes the diffusion of knowledge from the previous article to the subsequent publications at a later period and thus it is widely used to trace the trajectories of the evolution of the research domain where each node represents a major milestone [14,15]. The first step in tracing the global main path is finding the edge with the highest traversal count starting from all sources. Its next edge is obtained starting from the previous or end node by the same procedure and continued until a leaf node arrives. If a tie occurs, all edges with the tie are considered. In this work, the global main path with the emergence and divergence field of organic electronics was constructed using software package, PAJEK [16].

2.2. Cluster analysis

To identify the giant component of a diversified research stream, the topological clustering approach was suggested by Newman [17]. Articles in a particular cluster are related to one another, and there will be a leading article possessing a high score and centrally located in the cluster. The clustering algorithm is based on modularity Q that is given as the difference between the fraction of links that fall within the cluster and the expected value of the same quantity, without considering cluster structures:

$$Q = \sum_{1}^{Nm}\left[\frac{ls}{l} - \left(\frac{ds}{2l}\right)^{2}\right]$$

where Nm is the number of clusters, ls is the number of edges between the nodes in cluster S and ds is the total sum of degrees of the nodes in the cluster [18,19]. If Q value is high, it indicates good cohesion within the cluster. For research topic detection of each cluster; Shibata suggested a procedure for the automatic content analysis of abstracts of the articles in a cluster [20].

3. Results

Optimal keywords are used to retrieve the bibliographic information of around 200,000 articles from Web of Science (WoS) from 1990 to 2019. A research article alone is considered for analysis without any restriction on language. The growth curve is predicted with the logistic equation,

$$F(t) = \frac{\alpha}{1 + e^{(-(t-\beta)/\gamma)}}$$

that shows whether the research domain is currently in the innovation phase, ascendant phase or maturity stage [10]. The growth curve fitted to the number of year-wise extracted cited articles using the equation given above gives the current scenario of organic electronics, which shows that the research area is still in the ascendant phase, as shown in Fig. 1. It enters the maturity stage beyond 2025.

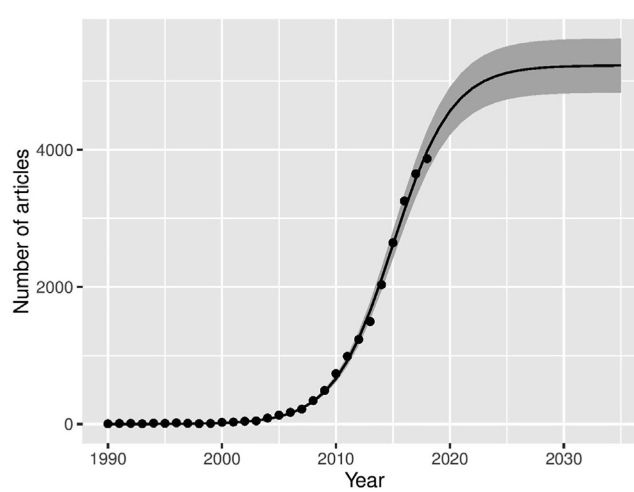

Fig. 1. The plot of the growth curve given in Eq. (3) fitted to the year-wise published articles.

3.1. Tracing the evolution trajectory

The information obtained from WoS is then converted to a citation network that contains around one lakh nodes. The evolution of the research activities is traced using the main path analysis as given by Hummon, Dereian, and Batagelj. Based on SPLC, we have obtained the global main path in the citation network using the algorithm described in the methodology. Fig. 2 shows the global main path extracted from the citation network and the corresponding articles representing nodes of the main path are listed in Table 1. The analysis of the topics related to each core node in the main path gives insight into the evolution of research activities in the divergent areas [21]. The main path consists of a single base path and traversing further towards four branches representing the emerging trends.

The main path analysis starts at node 77 with the article "Doping effect on the two-layer organic solar cell" by "Hiramoto and others" as mentioned in the tabular column [22]. This paper is about the investigation of organic solar cells formed by two thin–layer metal-free film of H2Pc and Me-PTC, which results in a drastic increase of photocurrent density and thus power conversion efficiency (PCE) of about 1% was achieved. The author extended his studies by fabricating two combined unit organic cells (Tandem type organic solar cells) where each unit cell had two-layer metal-free organic solar cells with an ultra-thin Au layer in between them [23]. The above paper was represented as node 81 in the main path. These studies were the core of motivation behind subsequent research on organic solar cells by Wohrle (1991), and Yanagi (1993), etc.

The research evolved by investigating photoelectrochemical properties of thin-film naphthalocyanines derivatives that are used as layers of solar cells which are evident at nodes 104, 49 [24,25]. From here, (node 73, 95, 38, 54, 28) research focussed in developing organic solar cells with substantial increase in power conversion efficiency from 0.43% to 3% [26,27]. Traces continues by introducing heterojunction hybrid organic photovoltaic cells having a maximum current density (node 28 and 78) [28] and then by designing air-stable polymer photovoltaic cells (node 82 to 98) [29,30]. As discussed in the introduction, the main advantage of organic electronics is its flexibility. This happens with the fabrication of flexible polymer solar cells module using the roll to roll method (traces from node 34 to 75) [31,32]. In this way, the research trend continued until Ball (2013) investigated on low-temperature processed meso-superstructure thin-film perovskite solar cells. From here, mainstream perovskite solar cells became a new era of organic electronics. Subsequently, the research by Ball (2013) was at the major point of divergence of research that further converged on the studies on the slow dynamic processes in lead halide perovskite solar cells made by Sanchez (2014) [33,34]. The emphasis on the research theme of the evolution of organic electronics continued sequentially until Juarez (2014)

Fig. 2. The global main path of research on organic electronics.

Table 1
The list of articles in the main path shown in Fig. 2.

Node no	Node	Publication details
77	(Hiramoto et al., 1990a)	Doping effect on the two-layer organic solar cell. Chemistry Letters
81	(Hiramoto et al., 1990b)	Hiramoto and others, 1990b. Effect of thin gold interstitial layer on the photovoltaic properties of tandem organic solar cell. Chemistry Letters
69	(Wohrle and Meissner, 1991)	Organic solar cells. Advanced Materials
105	(Yanagi et al., 1993)	Epitaxial growth of naphthalocyanine thin films vacuum deposited on alkali halides.
18	(Ball et al., 2013)	Low-temperature processed meso-super structured to thin-film perovskite solar cells. Energy and Environmental Science
27	(Sanchez et al., 2014)	Slow dynamic processes in lead halide perovskite solar cells. Characteristic times and hysteresis. The journal of physical chemistry letters
40	(Juarez-Perez et al., 2014)	Photoinduced giant dielectric constant in lead halide perovskite solar cells. The journal of physical chemistry letters
4	(Kim and Park, 2014)	Parameters affecting iv hysteresis of $ch_3nh_3pbi_3$ perovskite solar cells. The journal of physical chemistry letters
44	(Gottesman et al., 2014)	Extremely slow photoconductivity response of $ch_3nh_3pbi_3$ perovskites. The journal of physical chemistry letters
71	(Wang et al., 2015)	Flexible thermoelectric materials and generators: Challenges and innovations. Advanced Materials
50	(Zhou et al., 2016)	Dithieno [3, 2-b: 2′, 3′-d] pyrrole cored p-type semiconductors enabling 20percent efficiency. Angewandte Chemie.
57	(Yu et al., 2017)	Synergistic effects of lead thiocyanate additive. ACS Energy Letters
61	(Liu et al., 2018)	All-inorganic cspbi2br perovskite solar cells with high efficiency exceeding 13 percent. Journal of the American chemical society 140
101	(Liu et al., 2019)	Poly (3-hexylthiophene)/zinc phthalocyanine composites for advanced interface engineering of 10.03 percent-efficiency. Journal of Materials Chemistry
107	(Tang et al., 2019)	Toward efficient and air-stable carbon-based all-inorganic perovskite solar cells. Chemical Engineering Journal
93	(Yin et al., 2019)	Dithieno [3, 2-b: 2′, 3′-d] pyrrole-cored hole transport material enabling over 21percent efficiency. Advanced Functional Materials
108	(Zhou et al., 2019)	Dithieno [3, 2-b: 2′, 3′-d] pyrrole cored p-type semiconductors enabling 20percent efficiency. Angewandte Chemie.
109	(Wang et al., 2019)	Indeno [1, 2-b] carbazole as methoxy-free donor group to construct efficient and stable hole-transporting materials. ACI Edition.
110	(Dong et al., 2019)	A dithieno [3, 2-b: 2′, 3′-d] pyrrole-cored four-arm hole transporting material for over 19 percent efficiency. Journal of Materials Chemistry C
92	(Moia et al., 2019)	Ionic-to-electronic current amplification in hybrid perovskite solar cells. Energy and Environmental Science
83	(Gelmetti et al., 2019)	Energy alignment and recombination in perovskite solar cells. Energy and Environmental Science
90	(Stolterfoht et al., 2019)	The impact of energy alignment and interfacial recombination on the internal and external open-circuit voltage of PVS. EES.
91	(Caprioglio et al., 2019)	On the relation between the open-circuit voltage and quasi-fermi level splitting in efficient perovskite solar cells. AEM

made a study on the key aspects of the photovoltaic operation of high-efficiency perovskite solar cells [35]. Again divergence of the mainstream of research was split into two different paths where first one by Gottesman (2014) who investigated the slow photoconductivity response of $CH_3NH_3PbI_3$ perovskites and the second one was researched by Kim (2014) who made research on parameters affecting I–V hysteresis of $CH_3NH_3PbI_3$ perovskite solar cells [36,37].

The convergence on research streams was at the research by Wang (2015), on additive-modulated evolution of HC (NH_2) $2PbI_3$ black polymorph for mesoscopic perovskite solar cells [38]. The subsequent main path research was on the synergistic effects of lead thiocyanate additive and solvent annealing on the performance of wide-bandgap perovskite solar cells. This study prompted the mainstream research to diverge to three emerging research streams, as shown in the truncated main path shown in Fig. 3. The first stream is on the construction of dopant free perovskite solar cells using different efficient heterojunction materials for achieving a high-power conversion efficiency together with high hole mobility [39–41]. The second stream is on the investigation of key factors like Quasi-fermi level splitting (QFLS), change in energy level position and non-radiative recombination losses in perovskite cells that are influencing open-circuit voltage(V_{OC}) [42–44] and the third stream is on the fabrication of all inorganic perovskite solar cells (PSCs) [45,46,48]. This helps researchers to focus their ideas on the above emerging research domains. With reference to Fig. 3, the three different colour bubbles (green, yellow, brown) represent emerging research trends in organic electronics.

3.2. Different generations of solar cell

First-generation solar cells include single crystal, multi-crystal solar cells that are produced on wafers. Second-generation solar cells are silicon (Si) thin-film solar cells, mc-Si solar cells, CdTe solar cells, CIGS solar cells. Third-generation organic solar cells generally are focussed on multi-layer(tandem) cells that include dye-sensitized solar cells, hybrid organic–inorganic (perovskite) solar cells, quantum dot solar cells, CZTS(copper zinc tin sulphide) solar cells, Polymer-based solar cells, Nano crystal-based solar cells (Table 2).

Apart from the emerging research areas, main path analysis also gives the origin of third-generation organic electronics that starts in the year 2000 with reference to node 95 shown in Fig. 2, the node is "an article about the construction of a new three-layer organic cell, ITO/MPCI/C 60-doped TiOPc/TiOPc/Au, that exhibited a higher quantum yield for charge-carrier photogeneration than a two-layer cell [47], where articles on the third-generation organic solar cell are denoted in red arrows in the truncated main path (Fig. 2).

3.3. Cluster analysis

We carried out the cluster analysis of the large component as per the procedure mentioned in methodology based on the following steps.

Step 1. The main topological clusters of the giant component of the citation network are found.
Step 2. The research topics of the main clusters are found by analysing the title and abstracts of articles in the cluster.
Step 3. The evolution of clusters is traced by constructing the main path within each cluster. All nodes of the main path represent critical papers in a cluster. It gives the following observations as shown in Fig. 4.

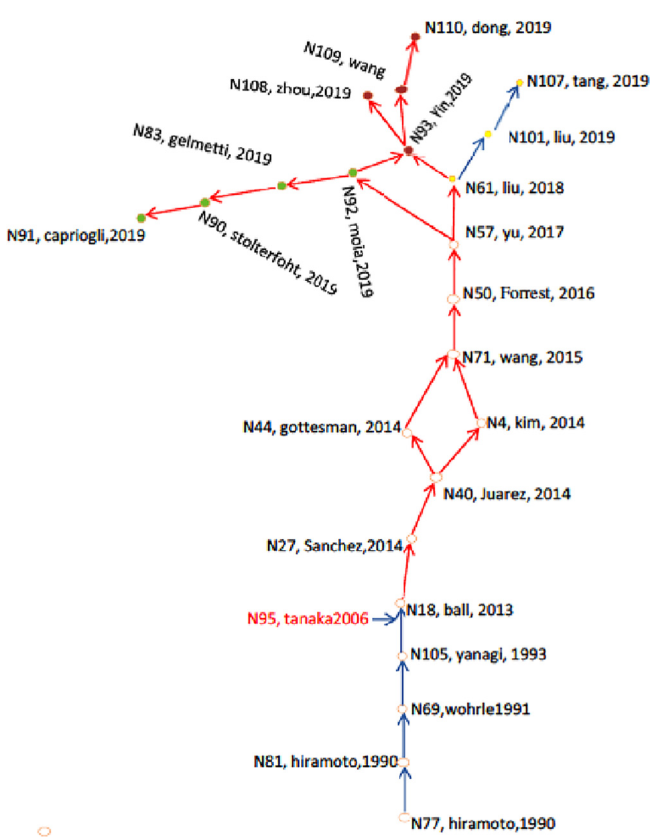

Fig 3. The truncated main path of evolution of organic electronics.

Table 2
The list of different types of organic solar cells in each generation.

S. no	Solar cell Generation	Solar cell types
1	First Gen	Single crystal, multi-crystal solar cells (SC).
2	Second Gen	Si thin-film solar cells, mc-Si solar cells, CdTe solar cells, CIGS solar cells.
3	Third Gen	Dye-sensitized SC, hybrid perovskite SC, quantum dot SC, CZTS SC, Polymer-based SC, Nano crystal-based SC.

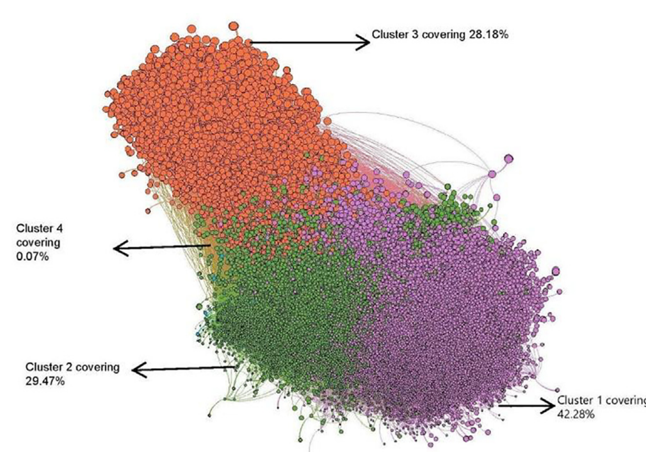

Fig 4. The clusters: Cluster #1 - Violet colour (42.28%) Cluster #2 - green colour (29.47%) cluster #3 - Orange colour (28.18%) Cluster #4 - yellow colour (0.07%). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 3
The keywords related to clusters.

Clusters	Size%	Keywords
#1.	42.28	Organometal halide perovskites, mesoscopic heterojunction solar cells.
#2.	29.47	Polymer heterojunction solar cells, bulk-heterojunction photovoltaic cells.
#3.	28.18	Efficiency-enhancement, High-throughput, machine-learning, crystal structures.
#4.	0.07	Transparent electrodes, nanowire, nanotube electrodes, flexible.

Table 4
The list of top articles in each cluster are listed in Table 4.

Article No	Clusters	Publication details
1	1	Organometal halide perovskites as visible-light sensitizers for photovoltaic cells, 2009, Kojima and others, Journal of the American Chemical Society.
2	1	Sequential deposition as a route to high-performance perovskite-sensitized solar cells, 2013, Burschka and others, Nature.
3	1	Efficient hybrid solar cells based on meso-superstructured organometal halide perovskites, 2012, Lee and others, American Association for the Advancement of Science.
1	2	High-performance polymer heterojunction solar cells of a polysilafluorene derivative, wang and others, 2008, Applied Physics Letters.
2	2	Thermally stable, efficient polymer solar cells with nanoscale control of the interpenetrating network morphology, ma, and others, 2005, Advanced Functional Materials.
3	2	Bulk heterojunction solar cells with internal quantum efficiency approaching 100%, park and others, 2009, Nature photonics
1	3	Efficiency enhancement in low-bandgap polymer solar cells by processing with alkane dithiols, peet and others, 2007, Nature materials
2	3	How to represent crystal structures for machine learning: Towards fast prediction of electronic properties, Schutt, 2014, Physical Review B
3	3	High-throughput electronic band structurecalculations: Challenges and tools, setyawan, 2010, Computational materials science
1	4	Solution-processed metal nanowire mesh transparent electrodes, lee and others, 2008, Nano Letters
2	4	Highly conductive PEDOT: PSS electrode with optimized solvent and thermal post-treatment for ITO-free organic solar cells, Kim, 2011, Advanced Functional Materials
3	4	Emerging transparent electrodes based on thin films of carbon nanotubes, graphene, and metallic nanostructures, Hecht, 2011, Advanced materials

Cluster 1, covers 42.28% of overall research areas that include articles related to the fabrication of organic–inorganic hybrid perovskite heterojunction organic solar cells. Cluster 2, Covers 29.47% of overall research articles; this cluster includes articles that describe achieving maximum power conversion efficiency from as low as 5.4% to 7.1%, which is evident from the top 10 articles. Cluster 3 are articles related to the prediction of band structure, electronic and molecular properties using machine learning techniques covering 28.18%. Cluster 4 covers articles related to the fabrication of flexible, transparent, conductive thin film electrodes in organic solar cells together with low fabrication cost and maximum power conversion efficiency occupying a minimal value of 0.07 overall percentage. The size, keywords of corresponding clusters are clearly tabulated in Table 3. The top articles in each cluster are listed in Table 4.

4. Conclusion

The fitted growth curve indicates the research is advancing in the growing phase. The main path traces the evolution of research topics and identifies three emerging research trends. The first stream is on the construction of dopant free perovskite solar cells using different efficient hole-transporting materials for achieving a high-power conversion efficiency with high hole mobility. The second stream is on the investigation of key factors like Quasi-fermi level splitting (QFLS), change in energy level position and non-radiative recombination losses in perovskite cells that are influencing open-circuit voltage (VOC). The third stream is on the fabrication of all inorganic perovskite solar cells (PSCs). It also gives the origin of third-generation organic electronics that starts in the year 2000. The cluster analysis identifies four clusters with major topics of research in organic electronics as 1. Perovskites, mesoscopic solar cells 2. Heterojunction solar cells 3. Computing methods to achieve high throughput, enhanced efficiency using machine learning technique. 4. The application of nanotubes, silver nanowires and microfilms as transparent, flexible organic solar cells.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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