REVIEWS

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Flexible perovskite solar cells: Materials and devices

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Abstract: Flexible perovskite solar cells (FPSCs) are supposed to play an important role in the commercialization of perovskite solar cells due to their unique properties, such as high efficiency, thin thickness and being compatible with roll to roll (R2R) process for mass production. At present, deformable and lightweight FPSCs have been successfully prepared and applied as power supply by integrating with different wearable and portable electronics, which opens a niche market for photovoltaics. In this mini review, we will introduce the recent progress of FPSCs from the aspect of small-area flexible devices, R2R processed devices with large scale and emerging flexible cells with deformability and stretchability. Finally, conclusion and outlook are provided.

Key words: flexible perovskite solar cell; roll to roll process; stretchable and deformable solar cell; low temperature processing

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1. Introduction

Perovskite solar cells (PSCs) have attracted extensive attentions as the most promising candidate for the new generation photovoltaic technologies. The power conversion efficiency (PCE) has developed rapidly from 3.8% to a certified 25.5% within about ten years due to the superior optoelectronic properties of perovskites, such as high light absorption coefficient, long charge diffusion length, desirable/tunable bandgap and high defect tolerance[1–11]. Besides, relative good mechanical flexibility of perovskite materials enables the realization of flexible perovskite solar cells (FPSCs) on various flexible substrates[12]. FPSCs are supposed to be a breakthrough for photovoltaics with high commercial value due to the compatibility with roll to roll (R2R) mass production, which could significantly decrease the production cost and increase the productivity[13, 14]. Furthermore, FPSCs with intriguing properties, such as lightweight, conformality, deformability and stretchability could fulfill various interesting applications on smart integrated buildings, wearable and portable electronics and unmanned systems[15–17]. Thus, the development of FPSCs plays a critical role in the practical applications of PSCs.

Since the first report of FPSC with an efficiency of 2.62% in 2013 by Kumar *et al.* intensive efforts on investigating flexible substrates, transparent electrodes, charge transport materials, perovskite films and interfacial layers have been made to achieve the current record efficiency over 21% with small device area (<1 cm^2)[18–20]. The mechanical flexibility has also been improved significantly[21]. These methods specifically developed for FPSCs and the obtained results have provided valuable insight on device and material design, facilitating the fabrication of large-scale FPSCs with high performance. In the meantime, the fabrication of large-scale FPSCs or flexible modules by R2R or R2R compatible processes has developed rapidly thanks to many innovative coating methods and compositional engineering of perovskite precursors recently developed, making it possible to prepare high-quality perovskite films with large scale[22, 23]. So far, fully R2R processed FPSCs with small area (except for top metal electrodes) demonstrated a record efficiency of 13.8% by Kim *et al.*, which is much lower than the record for a normal FPSC[24]. Therefore, there is a considerable room for improvement in the R2R-process FPSCs. For practical applications, deformable and stretchable FPSCs with light weight have been realized and applied as a power supply for different devices, such as rechargeable batteries, sensors and aircrafts[25, 26].

In this mini review, we will focus on the recent progress of FPSCs including efficiency improvement of small-scale FPSCs, R2R processed large-area devices and emerging flexible photovoltaic technologies. We will summarize the criteria/requirements for different component of a FPSC, such as flexible substrate, transparent electrode, charge transport layer and perovskite film. The innovative techniques on coating methods and perovskite precursors for R2R process are discussed. The emerging photovoltaics based on deformable and stretchable FPSCs are demonstrated. Finally, we will conclude and address the remaining challenges and potential future directions of this research field.

2. Device components of high-performance FPSCs.

A FPSC contains several essential components, including a substrate, two electrodes with at least one being transparent, a perovskite layer and two charge transport layers (CTLs) for electrons or holes respectively. The major thickness of the whole device comes from the substrate since the perovskite layer and electrodes are always very thin (< 1 μm) and thus the mechanical flexibility of the device is mainly influenced by the substrate. On the other hand, flexible substrate plays a key role on the photovoltaic performance of the flexible device because the following layers deposited on it could be

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influenced by its chemical and mechanical properties. Therefore, the selection of flexible substrate is important for the whole fabrication process. Unlike traditional glass substrates, flexible substrates usually have high roughness and low-temperature processing requirement. Hence, it is necessary to precisely optimize the deposition conditions of electrodes, CTLs and perovskite layers to ensure both high efficiency and mechanical robustness of resultant flexible devices.

2.1. Flexible substrates

A desirable flexible substrate for FPSCs should have high optical transmittance, high thermal tolerance, low roughness, high resistance to chemical solvents, robust mechanical flexibility and good oxygen and water barrier properties. However, it is hard to integrate all these properties in one kind of substrate. Currently, there are mainly three types of flexible substrates applied in FPSCs, such as plastic polymer substrates, metal foils, and glass substrates.

Polyethylene terephthalate (PET) and polyethylene naphthalate (PEN) films are the most used flexible polymer substrates for FPSCs due to their high optical transmittance, mechanical robustness, good chemical resistance and R2R processability. The current FPSCs with record efficiency are prepared on these polymer substrates[19]. Although these polymer substrates could enable FPSCs with high efficiency and mechanical flexibility, some drawbacks cannot be ignored. First, the thermal resistances of these plastic substrates are relatively poor. The glass phase transition temperatures for PET and PEN are 78 and 120 °C, respectively[27]. Higher temperature could deform the substrates and degrade the efficiency and flexibility of devices. Therefore, the whole fabrication processes and working conditions must be conducted at a low temperature. Second, the polymer substrates have high water and oxygen transmission rates, which seriously degrade the long-term stability of FPSCs[28]. Encapsulation technologies or new materials are desired to solve these drawbacks[29, 30].

Metal foils have better thermal resistance, lower water and oxygen transmission rate and higher mechanical durability. They can be used as substrates, electrodes and even CTLs in one cell simultaneously, which significantly simplifies the fabrication process. Ti and Cu foils are the most used materials for flexible substrate[31–34]. Since the metal foils are opaque, transparent top electrodes are needed. Lee *et al.* introduced Ti metal substrate to prepare FPSC with a structure of Ti/TiO_2/mesoporous TiO_2/perovskite/Spiro-MeTAD/Ag and a PCE of over 6% for the first time[35]. The large resistance of ultrathin Ag film as the top electrode seriously suppressed the performance. Heo *et al.* reported a Ti based FPSC with a record efficiency over 15% by employing graphene as top transparent electrode[36]. For the FPCs based on metal foils, the exploration of top electrode with high optical transmittance and low resistance is the critical issue.

A glass substrate with thickness lower than several hundred micrometers could become mechanically flexible[37]. The flexible glass substrate owns the similar properties with rigid glass counterparts. Tavakoli *et al.* first employed willow glasses with thickness of 50 μm as flexible substrates to fabricate FPSCs with a champion efficiency of 12.06%[38]. The flexible device could maintain original performance after 200 bending cycles with a radius of 4 cm. Dai *et al.* used blade-coating method to fabricated flexible perovskite module on flexible glass substrate with a high PCE of 15.86% and an area of 42.9 cm^2. The small-area (8 mm^2) device could achieve a best efficiency of 19.72%[39]. Although flexible glass substrates have several advantages, the fragility nature and high cost prevent the practical applications.

2.2. Transparent electrode

ITO is the most used transparent electrode due to high optical transmittance and low resistance. While the high production cost is a drawback for the mass production due to the presence of noble metal. Therefore, other transparent conductive oxides electrodes have been explored as alternatives to prepare FPSCs, such as aluminum-doped zinc oxide (AZO)[37]. These conductive oxide electrodes usually are fragile, which limits their applications in extreme conditions, such as deformable and stretchable devices.

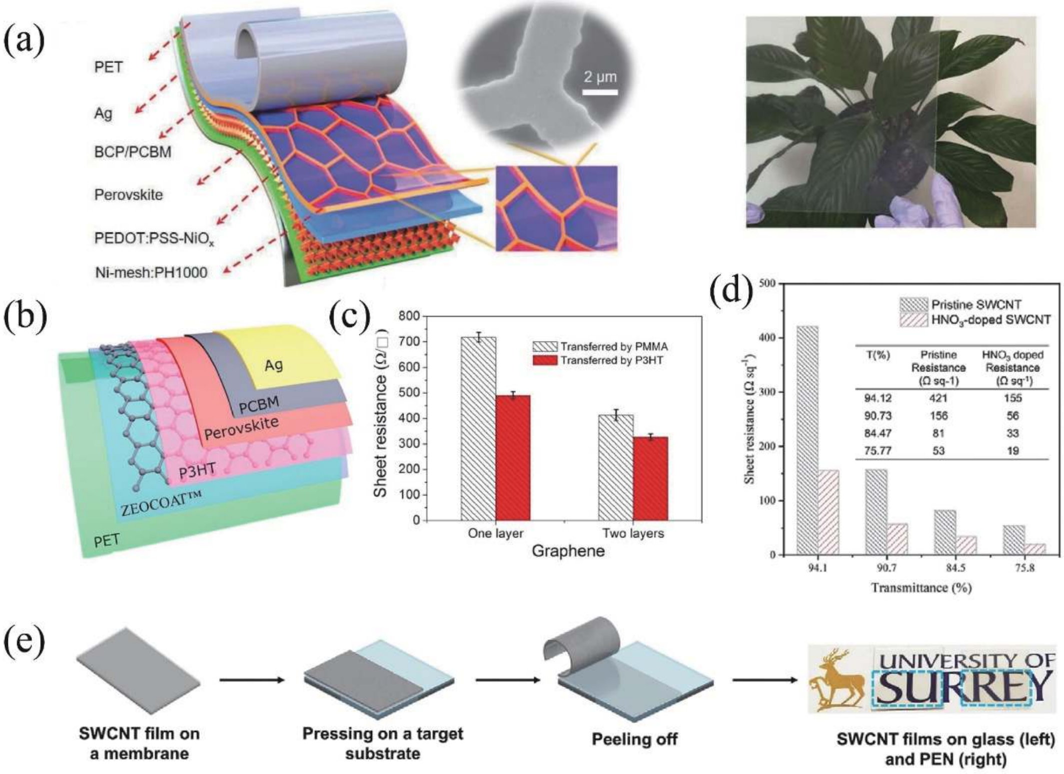
Solution-processable metal nanowire/mesh are promising materials for transparent electrodes due to high conductivity, transparency and flexibility[40]. Moreover, the solution processability for metal nanowires could enable R2R mass production. Ag/Cu/Ni nanowires/mesh have been widely used in FPSCs as electrodes[41–44]. Recently, Li *et al.* reported a FPSC with an efficiency of 17.3% based on nickel mesh as electrode with low sheet resistance and high transmittance[45] (Fig. 1(a)). The resultant flexible device could retain 76% of the initial efficiency after 2000 bending cycles. For these metal nanowire/mesh applied in FPSCs, surface modification is usually needed due to the high roughness and chemical reaction with perovskite materials. ITO, AZO, graphene oxide (GO), Graphene and PEDOT:PSS have been coated on surface to solve these issues[48–50].

Carbon-based materials, such as graphene and carbon nanotubes, are investigated as transparent electrodes for FPSCs due to their high transmittance and conductivity[51–54]. Graphene was first used by Liu *et al.* as electrode to fabricate FPSCs with a champion efficiency of 11.5%[46] (Figs. 1(b) and 1(c)). Jeon *et al.* have compared the performance of FPSCs based on graphene and single-walled carbon nanotubes (SWNTs)[55]. The better morphology and transparency of graphene enabled higher efficiency. While the SWNTs based FPSCs exhibited better mechanical flexibility due to the randomly oriented SWNTs. Recently, Zhang *et al.* used SWNTs as electrode by simple dry transfer technology to fabricate a FPSC with a high efficiency of 18.1%[47] (Figs. 1(d) and 1(e)).

PEDOT:PSS is a widely used conductive polymer material in flexible and stretchable electronics[56]. As-cast PEDOT:PSS films could have high conductivity up to about 4000 S/cm by various doping and coating strategies[57]. Therefore, it is a promising alternative for ITO electrodes in solar cells. Hu *et al.* used high conductive PEDOT:PSS to prepare FPSCs with a best efficiency up to 19%[58]. Although the high efficiency can be achieved based on PEDOT:PSS electrode, its acidic property could corrode the perovskite materials and seriously degrade the long-term stability of devices.

2.3. Charge transport layers

In a working PSC, a charge transport layer would extract charge carriers from perovskite absorber and transport to corresponding electrode. Therefore, the band structure, film morphology and mobility are key factors for the selection and preparation of CTLs for high performance and stable PSCs[59].



T(%)	Pristine Resistance (Ω sq-1)	HNO_3 doped Resistance (Ω sq^{-1})
94.12	421	155
90.73	156	56
84.47	81	33
75.77	53	19

Fig. 1. (Color online) (a) Schematic illustration of the PET/Ni-mesh substrate, Ni-mesh:PH1000 hybrid electrode, and perovskite device; the top right image shows the SEM image of Ni-mesh. The right is the optical image of PET/Ni-mesh substrate. Reprinted with permission from Ref. [45]. Copyright 2020, John Wiley & Sons, Inc. (b) Schematic diagram of a flexible PSC with the structure of PET/graphene/P3HT/perovskite/phenyl-C70-butyric acid methylester (PCBM)/Ag. (c) The sheet resistances of one and two layers of CVD graphene transferred by using poly(methyl methacrylate) (PMMA) or P3HT. Reprinted with permission from Ref. [46]. Copyright 2016, Elsevier Ltd. (d) The sheet resistances of SWCNT films with different optical transmittance values before and after HNO_3 treatment. (e) Dry transfer procedure of a SWCNT film and transferred SWCNT on glass and PEN substrates. Reprinted with permission from Ref. [47]. Copyright 2021, John Wiley & Sons, Inc.

Due to the temperature limitation of flexible substrates, low temperature process is an additional requirement for CTLs.

In FPSCs with n–i–p structure, low temperature processed ZnO, SnO_2, TiO_2 are usually used inorganic electron transport layers (ETLs)[61–65]. Among the various preparation methods, deposition of ETLs with pre-synthesized nanoparticles (NPs) or nanocrystals with high crystallinity is a successful and R2R compatible strategy to prepare high-quality CTLs on flexible substrates at low temperature[66, 67]. Besides the inorganic materials, other low temperature processed materials, such as C60, metal-organic framework, and ionic liquid, are also explored as ETLs for FPSCs[68–70]. PEDOT:PSS, poly[bis(4-phenyl)(2,4,6-trimethylphenyl)amine] (PTAA) and NiO_x are the most used hole transport layer (HTL) materials for FPSCs with p–i–n structure. PEDOT:PSS and PTAA could be processed at low temperature[71, 72]. For NiO_x, pre-synthesized nanoparticles/nanocrystals can be successfully deposited on flexible substrates[73]. Due to the deformation of flexible substrates during fabrication process, the deposited CTLs usually have holes and defects. Further modifications are usually needed[74, 75]. Chung *et al.* presented a new porous planar ETL based on SnO_2 NPs and Zn_2SnO_4 NPs as a compact layer and porous layer to successfully fabricate a FPSC with a PCE of 20.7%[60] (Fig. 2). This porous planar structure may be an efficient way to overcome the drawbacks of high roughness and deformation of flexible substrates.

2.4. High-quality perovskite layer

The processing approaches and compositions of perovskite films on flexible substrates are different from counterparts on rigid ones due to the different properties of substrates. The preparation methods at low temperature and compatible with R2R mass production are highly desirable for practical applications.

Laser annealing is an efficient method crystalizing perovskite films at room temperature at a fast rate. Jeon *et al.* first used a laser with wavelength of 1064 nm to anneal the perovskite film via photo-thermal heating induced by the light absorption of ITO and PEDOT:PSS layers[76] (Fig. 3(a)). The prepared FPSC demonstrated an efficiency of 8.0%. You *et al.* used a laser with visible light to directly induce photo-thermal heating in perovskite films, which lead to large grain size and low defect density[79]. Vacuum deposition methods have also been used to prepare perovskite films on flexible substrates. Recently, Feng *et al.* reported FA based rigid PSCs with a record efficiency of 21.32% prepared by a vacuum deposition approach assisted by 60 °C thermal annealing[77] (Figs. 3(b) and 3(c)). For vacuum deposition, high cost and energy consumption are main drawbacks.

Composition tailoring for perovskite precursor is necessary since the direct transfer of perovskite deposition from rigid to flexible substrates usually leads to poor morphology and low performance[80]. Dimensional composition engineer-

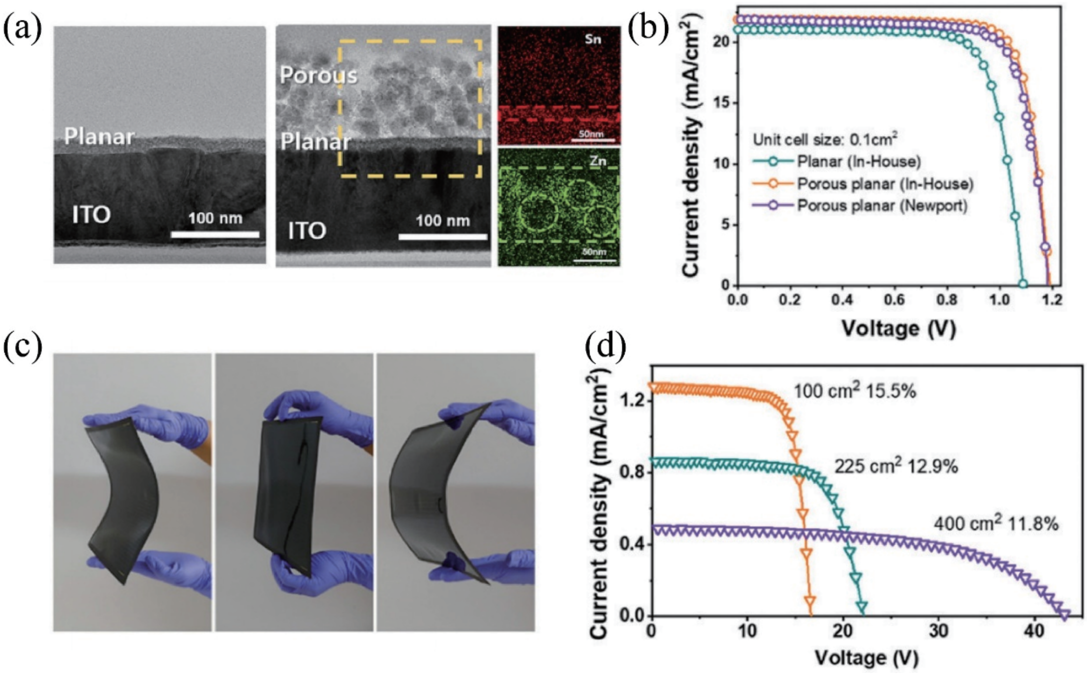


Fig. 2. (Color online) (a) TEM image of planar layer and porous planar layer coated on ITO/glass substrate and EDS mapping. (b) *J*–*V* curves of planar (green) and porous planar (orange) flexible unit cell (active area: 0.094 cm^2) measured in the lab and that of Newport certification data (purple). The device based on porous planar layer exhibits a lab PCE of 20.75% and a certified PCE of 19.9%. The planar device demonstrates a PCE of 17.5%. (c) Photograph of flexible module based on porous planar CTL with an area of 400 cm^2. (d) *J*–*V* curves of best-performing flexible sub-module at an aperture area of 100, 225 and 400 cm^2. Reprinted with permission from Ref. [60]. Copyright 2020, Royal Society of Chemistry.

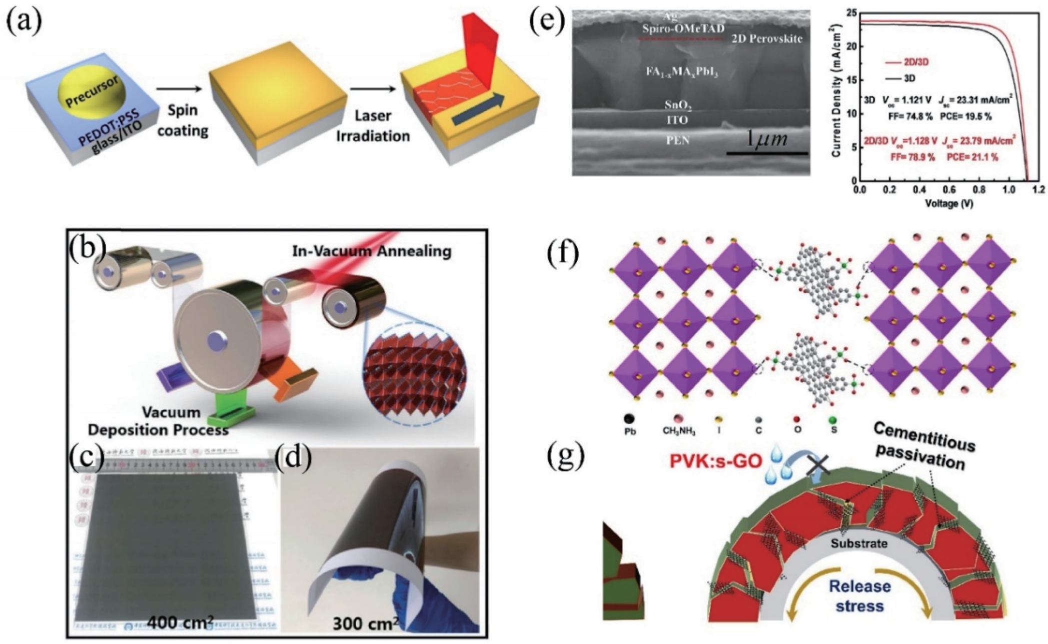


Fig. 3. (Color online) (a) Schematic description of perovskite film formation process by laser annealing method. Reprinted with permission from Ref. [76]. Copyright 2016, American Chemical Society. (b) Schematic illustration of multisource vacuum deposition with an in-vacuum annealing process for large-area perovskite films. Photographs of FA-based perovskite films deposited on (c) glass and (d) PET substrates. Reprinted with permission from Ref. [77]. Copyright 2021, Royal Society of Chemistry. (e) Cross-section SEM images of an FPSC with a structure of PEN/ITO/SnO$_2$/3D/2D perovskite/ Spiro-OMeTAD/Ag and *J*–*V* curves of 3D and 2D/3D FPSCs. Reprinted with permission from Ref. [20]. Copyright 2021, John Wiley & Sons, Inc. (f) Schematic illustrate of the interaction between s-GO with perovskite. (g) Schematic diagram of the enhanced water resistance with flexural endurance due to cementation and passivation of grain boundaries. Reprinted with permission from Ref. [78]. Copyright 2020, Elsevier Ltd.

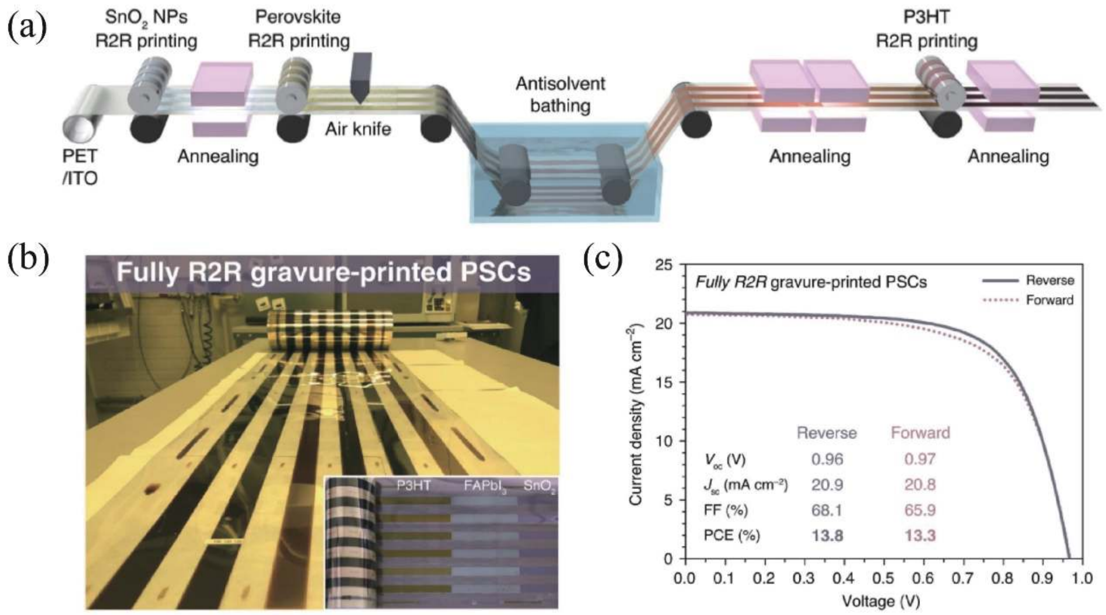


Fig. 4. (Color online) (a) Diagram showing R2R processing for the fabrication of FPSCs. (b) Photograph of fully R2R processed PSCs. (c) The *J*–*V* curves of fully R2R gravure-printed PSCs. Reprinted with permission from Ref. [24]. Copyright 2020, Nature Publishing Group.

ing might be a promising method for high performance FPSCs[20, 81] (Fig. 3(e)). Besides, various additives have been introduced into perovskite films to manipulate the crystallization process and passivate the defects. Recently, Yang *et al.* used artemisinin to passivate the perovskite grains to boost the efficiency of FPSCs to a record value of 21.1%[19]. Moreover, special additives have been introduced into grain boundaries of perovskite films to improve the mechanical flexibility of flexible devices[82, 83]. Hu *et al.* introduced sulfonated graphene oxide to construct a cementitious grain boundary in perovskite films[78] (Figs. 3(f) and 3(g)). The flexible devices demonstrated better photovoltaic performance and mechanical flexibility due to the tough grain boundaries.

3. R2R fabrication

Low cost and high efficiency are two advantages promising the commercialization of PSCs in the near future. R2R fabrication might be a breakthrough to realize commercialization due to the cost-effective high throughout mass production. In order to realize R2R production of FPSCs, uniform and large-area deposition of sequential layers should be achieved. The R2R deposition of CTLs have already been established in other photovoltaic technologies, such as organic solar cells[84]. Thus, the investigation of FPSCs by R2R process mainly focuses on the deposition of high quality perovskite films. It is key to depositing uniform precursor wet films with following complete conversion to perovskite phase[22]. Several R2R compatible coating technologies, such as blade coating, slot-die coating, spray coating and gravure-printing, have been applied[39, 85–88]. In addition, the perovskite precursor composition needs to be tailored to obtain stable perovskite intermediate phase during the deposition process which is critical for the final quality of perovskite films. Therefore, solvent tuning and additives have been investigated.

Galagan *et al.* used dimethyl sulfoxide (DMSO) and 2-butoxyethanol as solvents for perovskite precursor to prepare FPSCs with a best PCE of 13.5% by R2R slot-die coating method[86]. It was found that the addition of 2-butoxyethanol could reduce the surface tension of precursor leading to better wettability and formation of uniform layer and accelerate the perovskite crystallization process resulting in the formation of large crystals. Kim *et al.* employed a hot slot-die coating method to prepare perovskite films by heating the substrate to 130 °C during the deposition process[89]. Poly(ethylene oxide) PEO was introduced into perovskite films to significantly improve the stability. The flexible devices exhibited a best PCE of 11.7%.

Dai *et al.* reported that the addition of ammonium chloride (NH_4Cl) into the perovskite precursor solution could form high quality perovskite film with good contact with substrates by retarding the crystallization process[39]. The blade-coated FPSCs with areas of 8 and 42.9 cm^2 could reach efficiencies of 19.72% and 15.86%, respectively. Wang *et al.* used thiourea as an additive to modulate the crystal growth of perovskite films by blade-coating deposition. An efficiency of 19.41% and a fill factor of 81% have been achieved[90].

Kim *et al.* employed tert-butyl alcohol (tBuOH) as an eco-friendly anti-solvent to prepare highly crystalline and uniform FA based perovskite film by gravure printing method on flexible substrates[24] (Fig. 4). It was found that the anti-solvent could extract the retardation mediator and excess processing solvent without dissolving the perovskite precursors from the wet film. The flexible devices based on gravure printed $FAPbI_3$ showed a best PCE of 19.1%. The fully R2R gravure printed FPSCs except for metal electrode exhibited a record efficiency of 13.8%.

Although significant improvements have been obtained on photovoltaic performance of R2R processed FPSCs, the current efficiency could not reach the commercialization level. More efforts are needed to study the deposition of high quality perovskite film by R2R compatible approaches. Higher efficiency (~20%) can been expected.

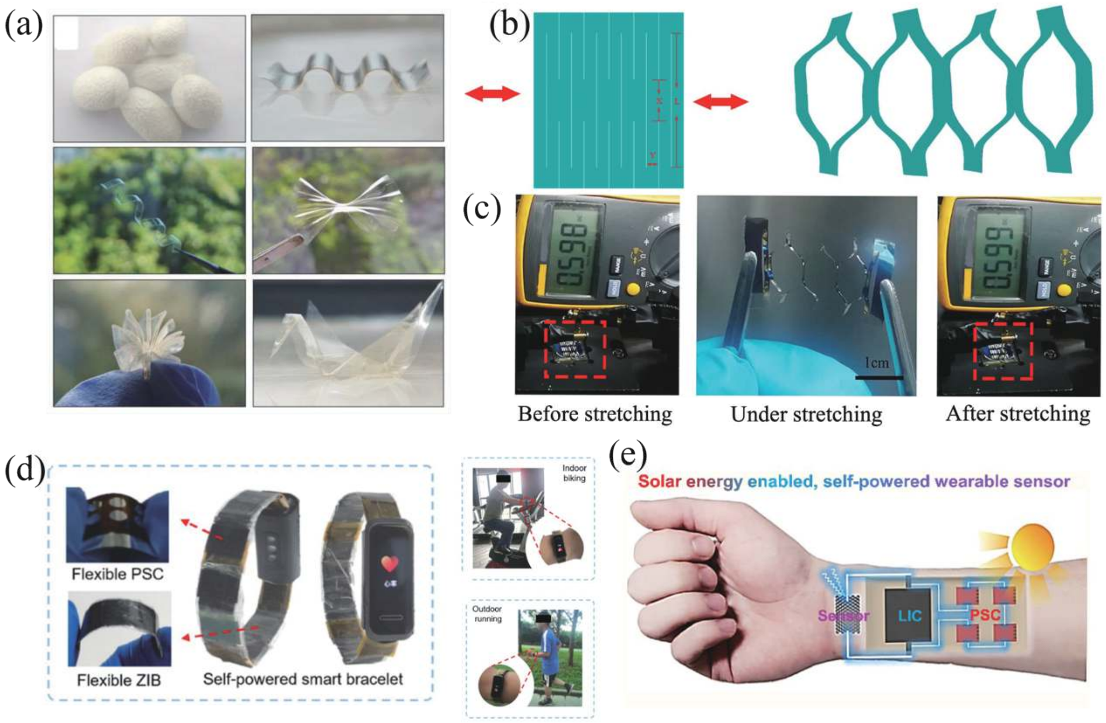


Fig. 5. (Color online) (a) Photographs of silk derived electrodes using natural silkworm cocoons as raw materials, which show high transmittance and various deformation including wave, spiral, bowknot, flower and paper crane. Reprinted with permission from Ref. [91]. Copyright 2020, John Wiley & Sons, Inc. (b) Schematic illustration of the stretching process of the kirigami structure at left) initial state and right) stretching state. (c) Voltage response of kirigami-based PSCs in a stretching cycle. Reprinted with permission from Ref. [92]. Copyright 2020, American Chemical Society. (d) Digital photographs demonstrating left) the integrating process of the self-powered smart bracelet and right) a subject wearing the self-powered smart bracelet on wrist during outdoor running and indoor biking. Reprinted with permission from Ref. [17]. Copyright 2021, American Chemical Society. (e) A photo of a solar powered wearable sensor. Reprinted with permission from Ref. [25]. Copyright 2019, Elsevier Ltd.

4. Emerging FPSCs

Due to the easy fabrication of perovskite films, different kinds of FPSCs have been successfully prepared on various flexible substrates extending the applicability and facilitating opening an emerging photovoltaic market. The deformable and lightweight FPSCs could be integrated with different functional devices to construct self-powdered smart systems.

The plastic substrates such as PET and PEN would cause environmental pollution due to the long decomposition periods[93]. This would hinder the wide use of FPSCs. Biodegradable and biocompatible materials could be a feasible strategy to solve this issue. Zhu *et al.* synthesized a biocompatible flexile cellulose nanofibril (CNF) substrate derived from the bamboos[94]. The corresponding flexible devices demonstrated a champion efficiency of 11.68% with a good bending stability. Gao *et al.* used a biodegradable nanocellulose paper as a flexible substrate to fabricate FPSCs[95]. Silk has also been used to prepare biocompatible flexible substrates for FPSCs[91] (Fig. 5(a)).

The foldable and stretchable FPSCs are highly desirable for wearable electronics and vehicle- and building integrated photovoltaics. Kaltenbruner *et al.* fabricated FPSCs on PET substrates with a thickness of 1.4 μm[16]. This lightweight device could obtain a record power-per-weight as high as 23 W/g, which is much higher than other established photovoltaic technologies. Li *et al.* used a cellophane substrate with kirigami design to prepare FPSCs with a high stretchability (strain up to 200%), twistability (angle up to 450°) and bendability (radius down to 0.5 mm)[92] (Figs. 5(b) and 5(c)).

The application of flexible power supply by FPSCs has also been demonstrated. Zhao *et al.* reported a safe, flexible and self-powdered wristband system by integrating high performance zinc-ion batteries with FPSCs[17] (Fig. 5(d)). Li *et al.* demonstrated successful fabrication of a wearable strain sensors self-powdered by a lithium-ion capacitor recharged by a FPSC[25] (Fig. 5(e)). These works highly extend and enrich the application of FPSCs.

5. Conclusion and outlook

In summary, FPSCs are supposed to be a promising breakthrough for the next generation photovoltaic technology with a high possibility for commercialization. In addition, the successful fabrication of lightweight and deformable FPSCs applied in various self-powdered systems could open an emerging and pioneering market. Therefore, the development of FPSCs will play a critical role in the commercialization pathway of PSCs. Interestingly, the fabrication techniques of FPSCs have been developed very fast and the efficiency over 21% has been achieved. The integration with R2R process has been reported by several groups recently with promising performance achieved in large-area devices. In this review, we summarize the recent development of FPSCs, focusing on the key issues of flexible devices, R2R process and emerging applications of FPSCs, which provides a guideline for the future development of this field.

To further improve the device performance, we should carefully check and optimize each component of the devices.

In the efficiency evolution of FPSCs, many efforts have been made in optimizing flexible substrates, transparent electrodes, CTLs and perovskite absorbers for high performance FPSCs. For the three types of flexible substrates, including plastic polymer substrates, metal foils and flexible glasses, the polymer substrate-based devices demonstrate high efficiency and easy fabrication. Moreover, it is convenient to functionalize the polymer substrates (e.g. coating hydrophobic or antireflection layers), which will definitely enhance the performance of the FPSCs.

For transparent electrodes, ITO-based devices exhibit the highest efficiency while relatively poor mechanical flexibility. PEDOT:PSS could be a better electrode for stretchable and deformable devices. However, perovskites may degrade on the acidic PEDOT:PSS surfaces, leading to poor stability of the devices, so surface modification on PEDOT:PSS is needed, such as coating a suitable CTL on the surface.

The low-temperature processed materials with pre-synthesized nanoparticles/nanocrystals structure should be a useful strategy to prepare efficient CTLs for FPSCs. In addition, the CTLs with porous structure could successfully overcome the drawback of high roughness of flexible substrates. More efforts are needed to suppress the non-radiative recombination and facilitate the charge carrier transfer at the CTL/perovskite interfaces. Similarly, low-temperature crystallization technologies of perovskite films are needed. In view of mass production, laser annealing may be a promising method to crystalize the perovskite films at room temperature with fast rate. The fabrication of large-scale FPSCs by R2R procession along with laser annealing is expected to be a feasible strategy.

The development of R2R fabrication of FPSCs is still at early stage and the record efficiency for fully R2R processed devices is only 13.8%. There is a considerable room for further improvements. The key is to deposit uniform and pinhole-free wet perovskite precursor films by R2R compatible methods. Novel additives and precursor compositions need to be further probed. The deformable and stretchable FPSCs have been demonstrated as power supplies by integrating with sensors, batteries, and aircrafts. Potential future applications could be power sources for industrial monitoring and tactical security applications.

In the future studies on FPSCs, our focus should be on but not be limited to the following aspects: (1) Enhancement of long-term stability. The plastic polymer substrates have limited water and oxygen barrier abilities. Additional encapsulations on top and bottom of devices are necessary. (2) Large-area R2R fabrication. Although the record efficiency for FPSCs is over 21%, the corresponding device area is relatively small. Besides, the spin-coating method is not compatible with mass production. More efforts should be focused on the deposition of perovskite film with large scale by R2R compatible coating methods. (3) Extending the applicability of FPSCs. Due to high efficiency and mechanical flexibility, FPSCs have great potential to be integrated with different systems as power supply. The successful application in the field of wearable/flexible electronics maybe a preferential commercialization option. Overall, the rapid advancements along with the practical challenges in FPSCs suggest a bright future for this active field.

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