

## Research Article

# Flexible Polymer Solar Cells with High Efficiency and Good Mechanical Stability

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Single-junction polymer solar cells have demonstrated exceptional power conversion efficiency. Interlayer adhesion will be critical in building flexible polymer solar cells since inorganic conveyance layers would surely break. Aluminium-doped zinc oxide modified by polydopamine has emerged as a viable electron transportation layer in polymer solar cells, enhancing mechanical qualities by offering a high degree of flexibility and adhesion to the active layer. Power conversion efficiency of 12.7% is achieved in nonfullerene polymer solar cells built on PBDB-T2F:IT-4F with aluminium-doped zinc oxide 1.5% polydopamine electron transporting layer. Furthermore, the device based on Ag-mesh wire-wound electrodes has a power conversion efficiency of 11.5% and retains more than 90% of original power conversion efficiency afterward 1500 cycles of bending. For implantable and adaptable polymer solar cells for wide areas, roll-to-roll fabrication of inorganic electron transport layers is advantageous because of their mechanical resilience and thickness insensitivity.

## 1. Introduction

Polymer solar cells [1] have studied extensively as attractive substitute to development of the sustainable photovoltaic technology because of their ability to be manufactured by vast chemical functionalization whereas the sustaining capabilities such as low density, stretchability, and programmable visibility [2, 3]. Power conversion efficiency (PCE) of more than 14% has been obtained in laboratory size using polymer solar cells

(PSCs) [4] so far. Flexible, long-lasting, and low-cost electronic components are essential to making flexible and wearable over a vast area PSCs a reality in the manufacturing process [5]. Additionally, many papers have concentrated on the fabrication of superior photoelectric, substrate lack of sensitivity, and mechanical characteristics in actively and interface materials [6] in addition to those generating stretchy transparent conductive electrodes [7, 8]. Recently, the idea of a metal oxide transport layer has been floated around a replacement for the

hygroscopic and acidic PEDOT: PSS hole transporting layer (HTL), as well as the fullerene derivative electron transport layer that has an amalgamation problem [9–14]. There are numerous advantages of using ZnO as an electron transport layer material [15] including low cost, easy accessibility, environmental friendliness, excellent stability, and photochromic capabilities, and the applications of solar cells are shown in Figure 1 [16].

As a result, the commonly used sol-gel-derived ZnO exhibits surface flaws that can be linked to interstitial zinc or adsorbed oxygen. Due to ZnO's relatively poor conductivity, it would not be applicable to large wrap printing since it does not create thick layers [17–20]. There are numerous ways to passivate ZnO's surface imperfections and increase its conductivity, such as using aluminium-doped ZnO [21–23]. However, in a prior study, we developed AZO nanoparticles (NPs) that are highly conductive and surfactant-stable, allowing for outstanding a thick adhesive improves both storage stability and performance characteristics of more than 80 nm [24–26]. For flexible and wearable polymer solar cell applications, inorganic AZO's intrinsic brittleness and low stickiness limit its use. For this reason, in polymer solar cells, AZO electron transport layer shattering and operative layer interparticle deformation are inevitable [27–29]. This can have a significant impact on charge transit and extraction. As far as we are aware, there has been no official report on the subject matter. Polyvinylphenol (PVP), an insulating polymer, can be doped into an indium oxide ( $\text{In}_2\text{O}_3$ ) a preterminology approach and processed at 225°C to produce polycrystalline films [30–35]. These works shows that thermal annealing temperatures are too high for flexible PSCs made of PET, which has a lower glass transition temperature than other plastic substrates [36]. Thus, our aim is to produce polymer solar cells that can be bendable with consistent solar behavior and roll-to-roll printing for huge area production, inorganic electron transport layers with such width lack of compassion, mechanical durability, and interfacial adhesion qualities. PDA has been added to crucifix nanostructures with AZO to create electron transport layer with adhesiveness in situ in order to achieve a bendable electron transport layer.

## 2. Methodology and Materials

Inorganic material long-term stability would be substantially harmed by the high PVP doping concentration. It is still possible to use an inorganic carrying layer in flexible polymer solar cells with good mechanical properties, though, thanks to this approach. A unique bendable AZO derivative was used as an electron transport layer in flexible PSCs that were produced in situ by adding low-content PDA to AZO. Intense hydrogen-bonding connections between molecular constituents are established. Because of the PDA modification, the AZO exhibits outstanding mechanical properties, including strong electron mobility at low temperatures and good adhesiveness between organic active layer and the interfacial area. When using PBDBT-2F:IT-4F with aluminium-doped zinc oxide:1.5% polydopamine (PDA) electron transport layer, nonfullerene PSCs can achieve power conversion efficiency of 12.7%. The fully flexible polymer solar cells have also achieved a significant power conversion efficiency of around 11.5%. According to

our knowledge, this is the most efficient flexible PSC on the market. After 1500 bending cycles, the flexible gadget retains more than 90% of its initial power conversion efficiency. After peeling 3M tape ten times, the AZO active layer is perfectly formed. Just a slit of PDA is visible, demonstrating excellent interlayer adhesion. Fully flexible polymer solar cells can now take use of the improved mechanical qualities of modified AZO electron transport layers. For mass manufacture of solar modules, it is even more favorable because of its protracted durability and depth insensitivity (up to 80 nm).

## 3. Result and Discussion

The optical characteristics of AZO and the PDA-modified AZO have been studied using transmittance and photoluminescence (PL) measurements inserting insulated PDAs in order to study it. PDA-modified AZO films showed improved flexibility more than 90% in the range of specific wavelength of 450–850 nm, making them suitable for use as electron transport layers in inverted photovoltaic cells (PCs).

As shown in Figures 2(a)–2(d), the oxygen deficiency and the ZnO bond  $\text{O}_2$  ions show up in the O 1s XPS spectra at 530.1 and 531.15 eV, respectively. A drop in the strength of the second peak at 531.5 eV indicates that the PDA has effectively movement that occurs and traps in the PDA-modified AZO. Because of the N-Zn bond interaction between AZO and PDA, the X-ray photoelectron spectroscopy spectra of aluminium-doped zinc oxide and the polydopamine-changed AZO exhibit a modest change in the peak location of N 1s toward a low specific term. AZO and polydopamine-modified aluminium-doped zinc oxide 2p X-ray photoelectron spectroscopy spectra are also shown. Aluminium-doped zinc oxide and polydopamine interact via the N-Zn link, as seen by the shifting at the top of zinc 2p 3/2 for the polydopamine-modified compound.

Using this method of AZO and AZO changed by PDA, the signal intensity of UV photoelectron spectroscopy has been examined (UPS). Figure 2 shows that the equivalent zones of conductivity for aluminium-doped zinc oxide, AZO:1.0% polydopamine, AZO:1.5% PDA, and AZO:2.0 percent PDA are -4.30, -4.24, -4.11, and -4.17 eV, respectively; for AZO, better frequency syncing with lowest unoccupied molecular orbital is seen for AZO:1.5 percent PDA when used as electron transporting layer in polymer solar cells, which is commensurate with the higher photocurrent. The XRD pattern measurement of aluminium-doped zinc oxide and the polydopamine-modified aluminium-doped zinc oxide demonstrates showing that the crystalline nature of AZO is unaffected by the insertion of PDA, while revealing a typical wurtzite crystal structure [30]. In light of the data presented herein, we can say with confidence that using AZO in PDA improves ohm contact with the active layer while simultaneously reducing flaws, making it a perfect electron transport layer to increase performance of the component. As far as we can determine, the majority of electron transport layers are used in high-performance PSCs that are less than 2–10 nanometers thick because of their low conductivity.

As a result, new electron transport layer materials with great charge mobility have been developed recently in order

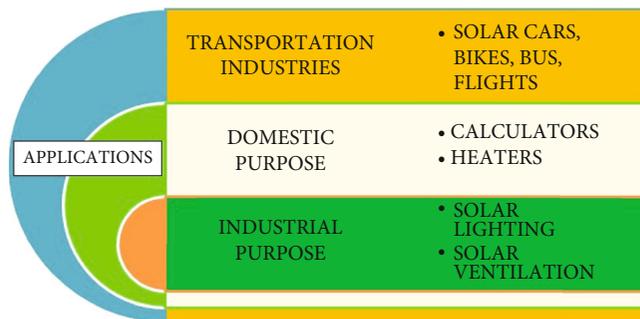


FIGURE 1: Applications of solar cell.

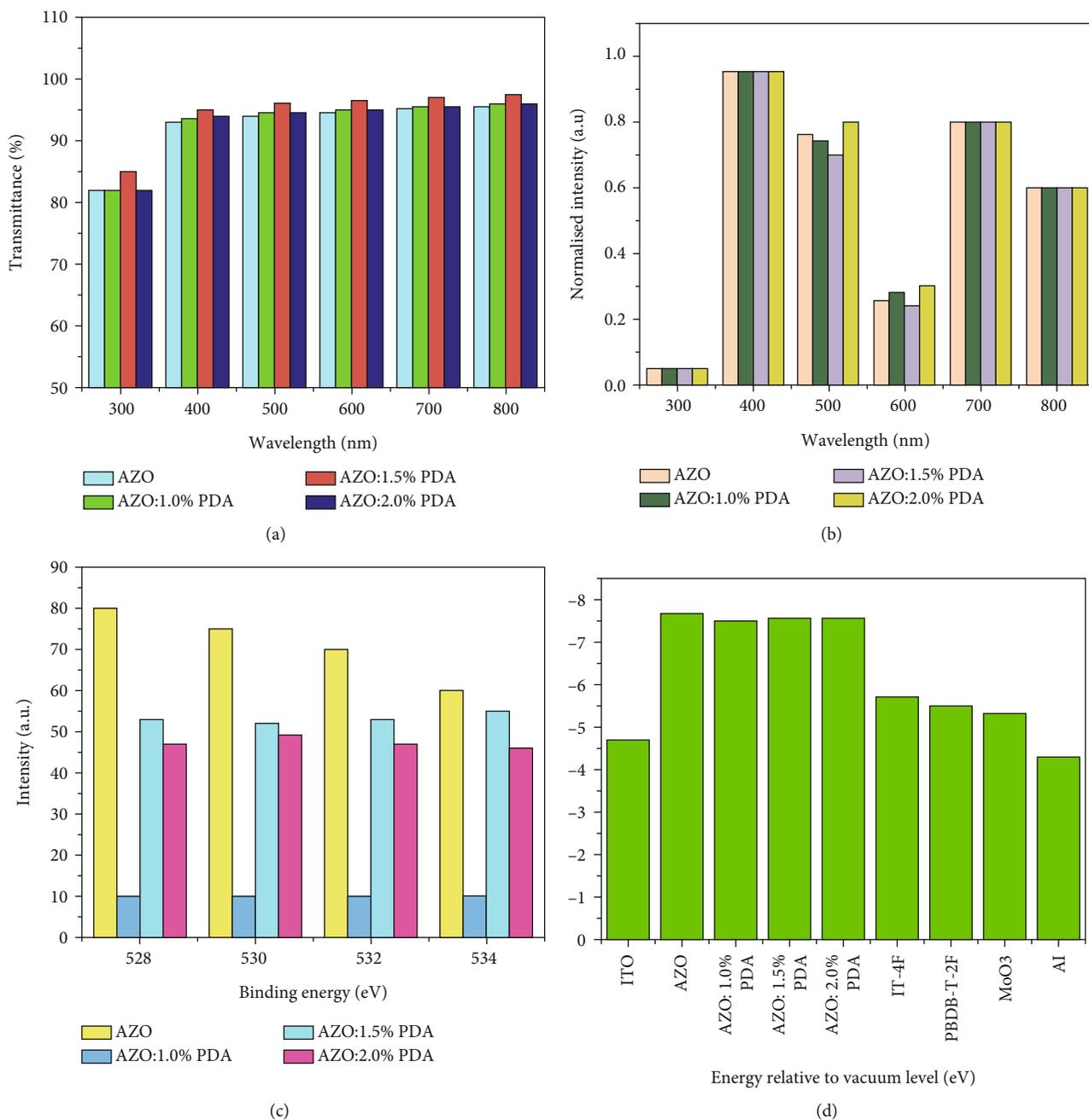


FIGURE 2: AZO performance in terms of (a) transmission spectra, (b) room temperature excitation of 315 nm excitation PL, (c) X-ray photoelectron spectroscopy, and (d) energy levels in existence of additive PDA.

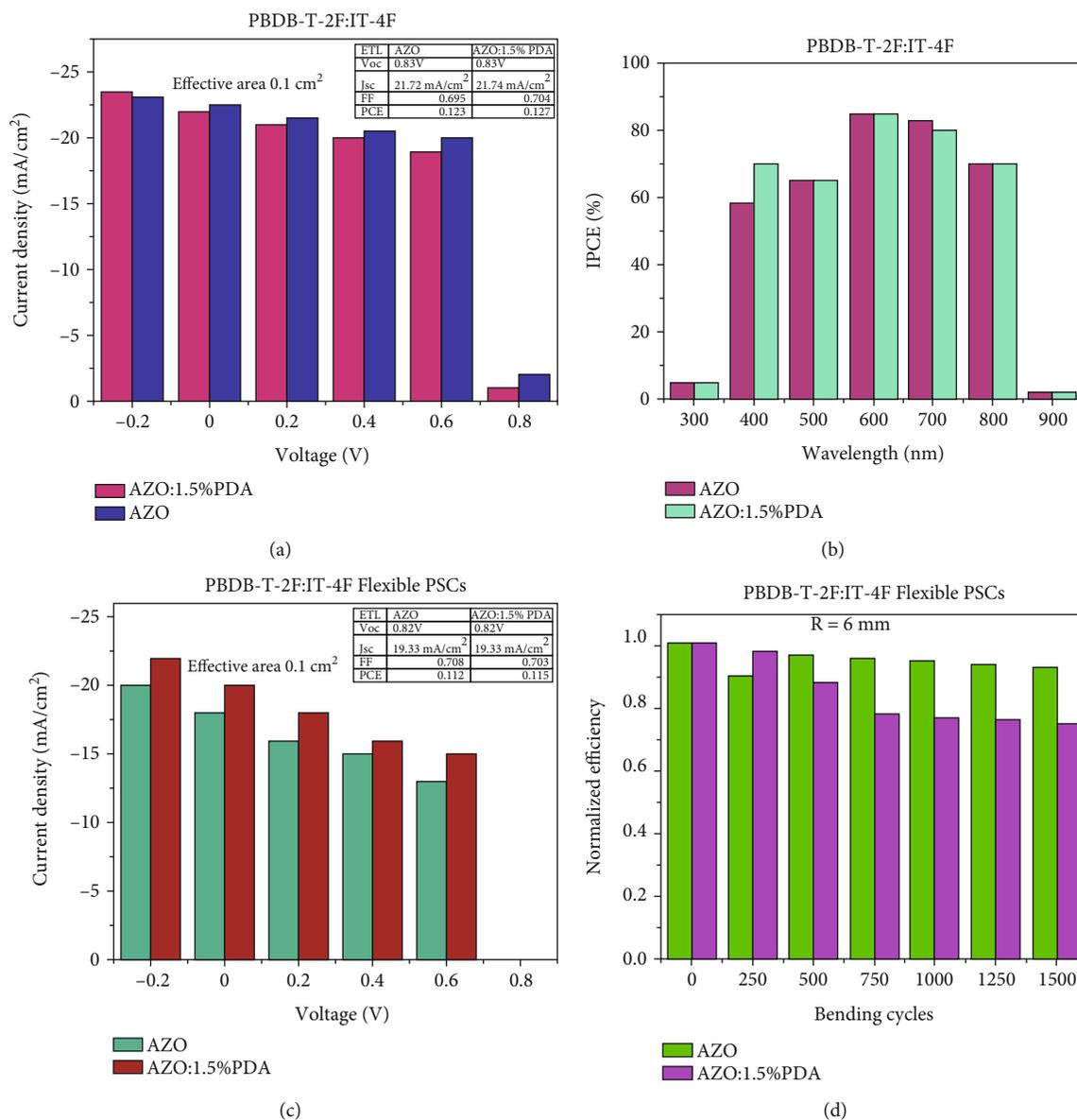


FIGURE 3: Device characteristics. (a) J-V curves. (b) IPCE spectra of inverted PSCs. (c) J-V curves of flexible devices. (d) Normalized average PCE of flexible PSCs.

to perform more effectively under thicker electron transport layers. Thick film (80 nm) electron mobility measurements show that AZO- and PDA-modified AZO are highly sensitive to the thickness of the plate electron transport layers in this study. Furthermore, it should be mentioned that both films were processed at 140°C for 20 minutes. Thick AZO films have a unique nanoripple pattern, which shows the atomic force microscopy images of the thicker films have a more textured surface. Because of this feature, the active layer has a greater area of contact, which facilitates charge transfer and collecting. PDA has been found to alter the electron transport properties of AZO electron transport layers, so in order to better understand this effect, two configurations of electron-only sensors have been introduced, one of which reveals the electron mobility of the whole device, while the other reveals the conductivities of the modified material, which is aluminium-doped zinc

oxide or aluminium-doped zinc oxide: polydopamine electron transporting layer/PBDB-T:ITIC/aluminium. There were three inverted PSCs tested for their photovoltaic performance, each with its own unique active layer material. The incident photon-to-current efficiency (IPCE) spectra and the current density-voltage (J-V) curves are in excellent agreement. PBDB-T:ITIC PSCs based on 1.5% PDA (80 nm) and a current density of 16.57 mA cm<sup>-2</sup>, a voltage of 0.886 V, and an overall fill factor of 67.4% obtained a power conversion efficiency of 10.3 percent.

For devices with electron transporting layers of aluminium-doped zinc oxide, AZO:1.0% PDA, AZO:1.5 percent PDA, and AZO:2.0 percent polydopamine, the integrated J<sub>sc</sub> values obtained from IPCE spectra and the J-V curves (4% misfit) are in excellent agreement. PSC inversions based on PBDB-T:ITIC and aluminium-doped zinc oxide or AZO/

TABLE 1: Device properties of inverted PSCs with PBDB-T-2F and IT-4F layers.

Device type	BH	$J_{sc}^a$ (mAcm <sup>-2</sup> )	$V_{oc}$ (V)	FF (%)	PCE (%)
AZO-PSCs	PBDB-T-2F:IT-4F	21.61 ± 0.11[20.75] <sup>b</sup>	0.830 ± 0.002	69.2 ± 0.3	12.1 ± 0.2[12.3] <sup>a</sup>
AZO:1.5% PDA-PSCs	PBDB-T-2F:IT-4F	21.62 ± 0.12[20.81] <sup>b</sup>	0.830 ± 0.004	70.1 ± 0.3	12.5 ± 0.2[12.7] <sup>a</sup>
AZO-flexible PSCs	PBDB-T-2F:IT-4F	19.15 ± 0.18	0.820 ± 0.003	70.6 ± 0.2	11.0 ± 0.2[11.2] <sup>a</sup>
AZO:1.5% PDA-flexible PSCs	PBDB-T-2F:IT-4F	19.82 ± 0.15	0.820 ± 0.003	70.0 ± 0.3	11.3 ± 0.2[11.5] <sup>a</sup>
AZO-flexible PSCs	PBDB-T:ITIC	14.89 ± 0.19	0.89 ± 0.002	67.9 ± 0.3	9.0 ± 0.2[9.2] <sup>a</sup>
AZO:1.5% PDA-flexible PSCs	PBDB-T:ITIC	16.09 ± 0.16	0.89 ± 0.002	66.9 ± 0.2	9.4 ± 0.2[9.6] <sup>a</sup>

PDA electron transport layers were tested for long-term stability. Power conversion efficiency deteriorates over time in a glove box filled with nitrogen. After 30 days of storage, the power conversion efficiency value of the AZO:1.5% PDA electron transport layer-based encapsulated PSCs is still >85 percent higher than the original power conversion efficiency value. AZO:PDA and active layer have strong interfacial contact, resulting in a high level of stability. On both plastic and glass substrates, the PBDB-T-2F:IT-4F dynamic material is utilised to illustrate the ubiquity of the polydopamine-modified AZO electron transport layer. Power conversion efficiency is 13.1 percent by a  $J_{sc}$  of 22.84 mA cm<sup>-2</sup>, and the FF is 70.4%.

This power conversion efficiency value is more than the aluminium-doped zinc oxide electron transport layer when compared to the PSC device (12.3%). A  $J_{sc}$  value of 20.75 cm<sup>-2</sup> for the AZO and the AZO:1.5% PDA is consistent with the J-V curves as shown in Figure 2(b). Power conversion efficiency of 11.5 percent can still be attained with the PET/Ag mesh-based flexible electrode, even with its lower  $J_{sc}$  of 19.97 mA cm<sup>2</sup> and higher  $V_{oc}$  of 0.79 V and FF of 69.3% for the aluminium-doped zinc oxide: 1.5% polydopamine-based device. Insensitive to thickness and bendable PSCs with AZO:1.5 percent polydopamine electron transporting layer have been claimed to have the greatest power conversion efficiency of any flexible polymer solar cells to date. The AZO:power PDA's conversion efficiency was normalized. As a function of six-millimeter bend cycles, the device was measured to verify the bendability of the device. Over the course of 1600 bending cycles, the AZO:1.5% fully flexible PDAs maintain more than 90% of their original power conversion efficiency. The PBDB-T:ITIC-based flexible polymer solar cells showed a similar outcome. Flexible devices' outstanding mechanical capabilities are mostly due to the addition of PDA to AZO, which promotes the interfacial interaction among the active layer and the AZO:PDA electron transport layer during the bending process and increases the bending durability and is shown in Figures 3(a)–3(d).

Because of its intrinsic brittleness, inorganic AZO cannot be used for flexible or wearable PSCs. The first time this difficulty has been addressed, AZO electron transport layers have been able to bend. In ITIC films AZO and AZO/PBDB-T, after 60 cycles of bending, there are evident cracks; however, the aluminium-doped zinc oxide:1.5% polydopamine and aluminium-doped zinc oxide:1.5% polydopamine/PBDB-T:ITIC films do not. Even after 250 bending cycles, ITIC retains its initial homogeneous shape. An increase in AZO nanocrystals'

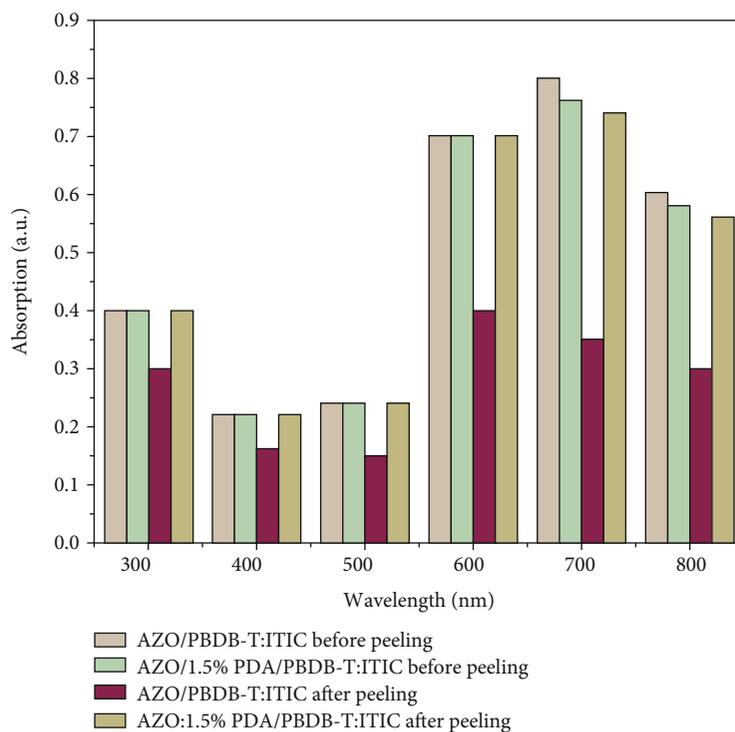
mechanical stability when bent can be achieved by using PDA as a flexible elastomer binder between the nanocrystals, according to this study. The AFM peak-force model shows that the AZO:PDA composite has a greater ductility than the pure AZO (255 MPa), indicating a better flexural endurance. For both AZO and the Young's modulus analysis, there is no noticeable difference in transmittance.

PDA 1.5% and AZO 1.5% are substantially stiffer than PDA:1.5 percent and AZO:1.5 percent after bending. We note that the PDA elasticized AZO exhibits superior transparency than the pure AZO, which may be explained by flaws being suppressed and heterogeneous nanocrystals being uniformly improved in uniformity. The bendable aluminium-doped zinc oxide:1.5, as shown in Table 1, percent PDA decreased the intensity of UV absorption of the PBDB-T:ITIC active layer more significantly than the bendable AZO:ITIC active layer, as shown in Figure 3.

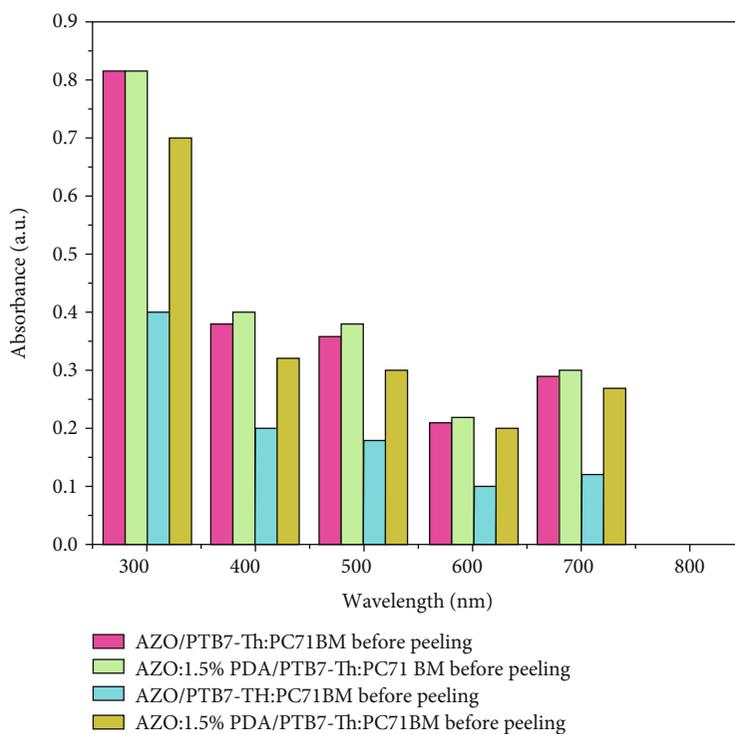
#### 4. Mechanical Stability

The adhesion between functional layers in a polymer solar cells is another important component in determining the mechanical properties of the device. Peeling perovskite layers from ZnO with scotch tape is a comparable method employed in this study to examine the interfacial adhesion of the 3M tape. Tablet machines were used to apply 0.5 MPa of force on 3 M tape with a layer of current collector, and the results were excellent. Next, a universal testing machine is used to perform a peeling test on the sample. The layer that is currently being used was easily pulled off after peeling five times due to low attachment of the absorber region to the AZO layer. Because of the attractive force contacts among polydopamine functional groups and natural at present layer, some well central to the effective on aluminium-doped zinc oxide:1.5% polydopamine is scarcely shed off until the 10 reapplications. After peeling procedure, a UV-vis absorption measurement was conducted to establish that the active layer's absorption intensity changed. Because the PDA-modified AZO is so sticky, the active layer maintains its uniformity and integrity under peeling, indicating that the active layer's absorption intensity is not diminished.

Due to PDA and organic active layer intermolecular interactions, devices' adhesion and mechanical properties have been improved. It was necessary to conduct a Fourier transform infrared spectroscopy (FTIR) measurement in order to verify the mechanism of contact. Notably, PTB7-Th:PC71BM was used to enhance visualization of intermolecular interactions



(a)



(b)

FIGURE 4: (a) UV-absorption spectra of AZO/PBDB-T:ITIC. (b) AZO:1.5% PDA/PTB7.

in the large-content PDA. Intricately symmetric tremors of NH and OH ( $\nu(\text{NH})$  and  $(\text{OH})$ ) and CO ( $\nu(\text{CO})$ ) in PDA were ascribed to the  $3000\text{--}3500\text{ cm}^{-1}$  and  $1750\text{ cm}^{-1}$  peaks, respectively. To demonstrate the establishment of a hydrogen bond, the PTB7-Th:PC71BM:PDA mix film had a broader and more

powerful NH and OH than the pure PDA film. Stretching vibrations of CO ( $\nu(\text{CO})$ ) have been found to shift toward a short wavenumber in agreement with this behavior. This can be attributed to the newly created hydrogen bond as well as shown in Figures 4(a) and 4(b).

The active layer systems PBDB-T:ITIC:PDA and PBDB-T-2F:IT-4F: polydopamine both used a similar method. AZO:PDA interfacial layer's NH and OH groups can establish hydrogen bonds with PTB7-Th:O PC71BM's and CO, which could improve the enhancing mechanical adhesion and durability by enhancing among the activated layer and the substrate and the interfacial layer. Since the PDA-elasticized AZO electron transport layers have such good properties, like bendability and interfacial adhesion, they provide a new way to make PSCs that are accessible and versatile and that perform reliably.

## 5. Conclusion

The PDA-integrated AZO has a number of advantages including the following:

- (i) Ultrahigh optical and electrical conductivities and the ability to be used as an electron transport layer without regard to thickness
- (ii) Optimizing inorganic electron transport layer flexural endurance, which improves the flexibility of polymer solar cell devices. Natural absorber layer adherence to the artificial electron transport layer, which contributes to the device's long-term performance
- (iii) With an interlayer thickness of 80 nm, the best power conversion efficiency of 12.7% has been attained using the AZO:1.5% PDA electron transport layer and even in that case to the power conversion efficiency of component-like dense interlayers that have been reported
- (iv) Furthermore, a power conversion efficiency of 11.5% has been achieved for totally versatile polymer solar cells focused on PET mesh electrodes, and the equipment is capable of storing greater than 92% of starting power conversion efficiency next bending for 1500 cycles

## Data Availability

The data used to support the findings of this study are included within the article. Further data or information is available from the corresponding author upon request.

## Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

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