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## Research Article

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# Electrospun Ferroelectric PVDF-TrFE-Based Nanofibrous Active Layers for Next-Generation Organic Solar Energy Conversion

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## Abstract

The morphology of the active layer plays a decisive role in governing charge generation, transport, and collection in organic solar cells (OSCs). In this work, electrospinning is introduced as an effective strategy to fabricate nanofibrous active layers based on PVDF-TrFE:PCDTBT:PCBM, aiming to improve the structural organization and photovoltaic performance of inverted OSCs. Three active-layer architectures were investigated: a conventional spin-coated PCDTBT: PCBM film, electrospun PCDTBT: PCBM nanofibers, and electrospun ferroelectric PVDF-TrFE:PCDTBT:PCBM composite nanofibers. The structural, optical, dielectric, and charge-transport properties were systematically examined using scanning electron microscopy (SEM), X-ray diffraction (XRD), Fourier transform infrared spectroscopy (FTIR), UV-Vis absorption spectroscopy, photoluminescence (PL), dielectric spectroscopy, AC conductivity ( $\sigma_{ac}$ ), dark charge extraction by linearly increasing voltage (dark-CELIV), external quantum efficiency (EQE), and current density-voltage (J-V) measurements. SEM observations confirmed the formation of a uniform interconnected nanofibrous network, while XRD and FTIR analyses demonstrated that electrospinning and PVDF-TrFE incorporation preserved the chemical structure of the active layer without inducing undesirable structural changes. The electrospun composite nanofibers exhibited enhanced optical absorption, pronounced PL quenching, an increased dielectric constant of 3.91, and improved carrier mobility of  $6.44 \times 10^{-4} \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ , indicating more efficient exciton dissociation and charge transport. Consequently, the photovoltaic performance was significantly enhanced, with the power conversion efficiency (PCE) increasing from 5.86% for the spin-coated PCDTBT: PCBM device to 7.12% for the electrospun PVDF-TrFE:PCDTBT:PCBM nanofiber device, accompanied by increases in both the short-circuit current density and open-circuit voltage. The improved device performance is attributed to the synergistic effect of the electrospun nanofibrous architecture and the ferroelectric characteristics of PVDF-TrFE, which collectively promote light harvesting, charge separation, and carrier

transport. These findings demonstrate that electrospun ferroelectric composite nanofibers represent a promising active-layer design strategy for developing high-efficiency organic solar energy conversion devices.

**Keywords:** Organic photovoltaics; Electrospun nanofibers; PVDF-TrFE; Carrier mobility; Dielectric properties; Dark-CELIV; Solar energy conversion.

## 1. Introduction

The increasing global demand for clean and sustainable energy has accelerated the development of renewable energy technologies capable of reducing dependence on fossil fuels and mitigating environmental challenges. Among the various renewable energy sources, solar energy has attracted considerable attention because of its abundance, environmental compatibility, and long-term sustainability. In this context, OSCs have emerged as promising photovoltaic devices owing to their lightweight nature, mechanical flexibility, semitransparency, and compatibility with low-cost solution-based fabrication techniques [1–6]. These advantages make OSCs attractive candidates for wearable electronics, portable power sources, and building-integrated photovoltaic applications.

Significant progress has been achieved in OSC technology over the past decade through the development of advanced donor and acceptor materials, optimized device architectures, and improved interfacial engineering. Nevertheless, the power conversion efficiency and long-term operational stability of polymer-based OSCs remain strongly dependent on the morphology of the bulk heterojunction active layer [7,8]. The nanoscale organization of donor and acceptor domains governs light absorption, exciton diffusion, charge separation, carrier transport, and charge collection. Consequently, controlling the active-layer morphology is considered one of the most effective approaches for improving photovoltaic performance[9–11].

Among the available donor polymers, poly[N-9'-heptadecanyl-2,7-carbazole-alt-5,5-(4',7'-di-2-thienyl-2',1',3'-benzothiadiazole)] (PCDTBT) has attracted widespread interest because of its broad absorption, deep highest occupied molecular orbital (HOMO) energy level, and excellent photochemical stability [12–15]. When blended with the fullerene derivative [6,6]-phenyl-C<sub>61</sub>-butyric acid methyl ester (PCBM), PCDTBT forms an efficient bulk heterojunction capable of delivering balanced charge generation and transport [16–21]. However, conventional spin-coated

active layers often exhibit relatively compact morphologies with randomly distributed donor/acceptor domains, which can limit exciton dissociation and increase charge recombination. Electrospinning has recently emerged as an attractive technique for producing continuous polymer nanofibers with high surface area, interconnected networks, and controllable morphology [22–24]. Compared with conventional solution casting or spin coating, electrospun nanofibers provide direct pathways for charge transport while increasing the donor/acceptor interfacial area available for exciton dissociation. Although electrospinning has been extensively explored for filtration, sensors, tissue engineering, and energy-storage applications, its application in the fabrication of photoactive layers for organic solar cells remains relatively limited. Developing electrospun nanofibrous active layers, therefore, represents an attractive strategy for improving the optoelectronic properties of polymer photovoltaic devices [25,26].

In addition to morphology engineering, incorporating functional polymers capable of modifying the internal electric field has attracted growing interest. Among these materials, poly(vinylidene fluoride-trifluoroethylene) [PVDF-TrFE] is a ferroelectric polymer characterized by high dielectric polarization, excellent chemical stability, and favorable solution processability [27,28]. The intrinsic polarization of PVDF-TrFE can facilitate exciton dissociation, reduce Coulombic attraction between photogenerated electron-hole pairs, suppress charge recombination, and promote carrier transport. Furthermore, its compatibility with electrospinning enables the fabrication of uniform ferroelectric nanofibrous architectures that combine structural and electrical advantages within a single active layer [29–33].

Although previous studies have separately investigated electrospun polymer nanofibers or ferroelectric polymers in organic photovoltaic devices, systematic studies combining electrospinning and ferroelectric PVDF-TrFE within a PCDTBT:PCBM active layer remain scarce. Establishing the relationship between nanofibrous morphology, dielectric properties, charge transport, and photovoltaic performance is therefore essential for understanding how electrospun ferroelectric composite active layers influence device operation [34,35].

In the present work, inverted organic solar cells employing ITO/ZnO/active layer/MoO<sub>3</sub>/Ag architecture were fabricated using three different active-layer configurations: a conventional spin-coated PCDTBT:PCBM film, electrospun PCDTBT:PCBM nanofibers, and electrospun PVDF-TrFE:PCDTBT:PCBM composite nanofibers. The influence of electrospinning and ferroelectric polymer incorporation on the structural, optical, dielectric, and electrical properties of the active

layer was systematically investigated using SEM, XRD, FTIR, UV-Vis spectroscopy, photoluminescence spectroscopy, dielectric analysis,  $\sigma_{ac}$ , dark-CELIV, EQE, and current density-voltage measurements. By correlating these complementary characterization techniques, this study demonstrates how ferroelectric nanofiber engineering enhances charge generation, transport, and collection, leading to significantly improved photovoltaic performance. The proposed strategy provides a practical route for designing high-performance nanostructured active layers for next-generation organic solar energy conversion.

## **2. Experiments**

### **2.1. Materials**

Indium tin oxide (ITO)-coated glass substrates with a sheet resistance of approximately  $15 \Omega \text{ sq}^{-1}$  were used as transparent conducting electrodes. PCDTBT, PCBM, PVDF-TrFE, and all analytical-grade solvents were purchased from Sigma Aldrich and used without further purification.

### **2.2. Preparation of the Active-Layer Solutions**

Three different active-layer formulations were prepared to investigate the effects of electrospinning and ferroelectric polymer incorporation. For the reference solution, 4 mg of PCDTBT and 6 mg of PCBM were dissolved in 1 mL of chlorobenzene and magnetically stirred at 60 °C for 12 h to obtain a homogeneous solution. For the electrospun PCDTBT: PCBM nanofibers, the same polymer-fullerene solution was used without changing the composition. For the ferroelectric composite solution, 3 mg PVDF-TrFE was added to the PCDTBT: PCBM solution, and stirring was continued until complete dissolution, producing a homogeneous electrospinning solution.

### **2.3. Device fabrication**

ITO-coated glass substrates were sequentially cleaned by ultrasonication in detergent solution, deionized water, acetone, and isopropyl alcohol for 15 min in each solvent, followed by drying under nitrogen flow and UV-ozone treatment before device fabrication. A compact ZnO electron transport layer was prepared through a sol-gel process and deposited onto the cleaned ITO substrates by spin coating and subsequently annealed to remove residual solvent [5,6].

Three inverted organic solar-cell architectures were fabricated:

**Device I:** ITO/ZnO/PCDTBT: PCBM/MoO<sub>3</sub>/Ag,

The PCDTBT:PCBM solution was deposited onto the ZnO-coated substrate by spin coating, followed by thermal annealing to form a compact active layer.

**Device II:** ITO/ZnO/PCDTBT:PCBM/MoO<sub>3</sub>/Ag,

The PCDTBT:PCBM solution was deposited by electrospinning for 3 min, producing a continuous nanofibrous active layer with an average thickness of approximately 200 nm.

**Device III:** ITO/ZnO/PVDF-TrFE:PCDTBT:PCBM/MoO<sub>3</sub>/Ag,

The composite PVDF-TrFE:PCDTBT:PCBM solution was electrospun onto the ZnO layer for 3 min, yielding a uniform ferroelectric nanofibrous active layer with an average thickness of approximately 200 nm. Finally, MoO<sub>3</sub> (10 nm) and Ag (100 nm) electrodes were sequentially deposited by thermal evaporation under high vacuum to complete the device fabrication.

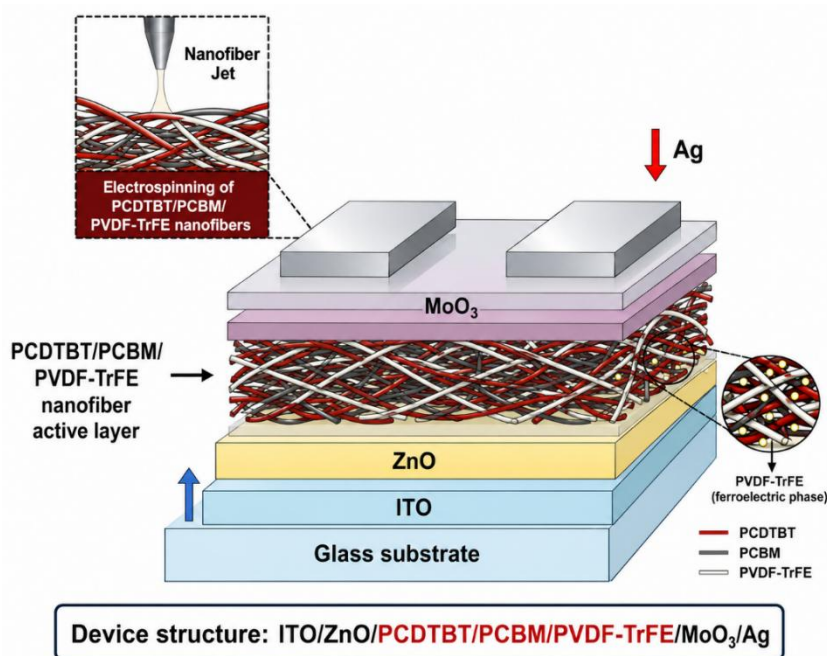


**Figure 1.** Schematic illustration of the inverted organic solar cell architecture (ITO/ZnO/PVDF-TrFE:PCDTBT:PCBM/MoO<sub>3</sub>/Ag) fabricated in this work.

## 2.4.Characterization techniques

The surface morphology of the prepared samples was examined using SEM. Structural characteristics were analyzed by XRD, while the chemical interactions between the constituent materials were investigated using FTIR spectroscopy. Optical absorption measurements were

carried out using a UV-vis spectrophotometer. J-V characteristics were recorded under simulated AM 1.5G solar illumination ( $100 \text{ mW cm}^{-2}$ ). The EQE spectra were measured over the spectral response range of the devices. Space-charge-limited current (SCLC) measurements were performed under dark conditions to estimate the hole mobility. Dielectric properties were evaluated using impedance spectroscopy, and Dark-CELIV measurements was employed to investigate carrier extraction dynamics and charge transport behavior.

### **3. Results and Discussion**

#### **3.1. Morphological Characterization of Electrospun Active Layers**

The surface morphology of the electrospun active layers was examined by SEM to evaluate the influence of the electrospinning process and the incorporation of the ferroelectric polymer on the nanofibrous architecture. Representative SEM micrographs of the electrospun PCDTBT:PCBM and PVDF-TrFE:PCDTBT:PCBM active layers are presented in Fig. 2. The electrospun PCDTBT:PCBM layer exhibited a continuous three-dimensional fibrous network composed of randomly distributed nanofibers with smooth surfaces and good structural integrity. The absence of bead-like defects indicates that the electrospinning parameters were appropriately optimized, resulting in a stable jet and uniform fiber formation. Such an interconnected fibrous architecture is expected to provide continuous pathways for charge transport while maintaining intimate contact between neighboring fibers, which is advantageous for carrier collection.

Following the incorporation of PVDF-TrFE, the nanofibrous morphology was preserved without noticeable structural collapse or fiber discontinuity. The composite fibers remained homogeneous and well interconnected, demonstrating that the addition of the ferroelectric polymer did not adversely affect the electrospinning process. Instead, the PVDF-TrFE:PCDTBT:PCBM sample exhibited a more compact and densely packed fibrous network, suggesting improved structural cohesion within the active layer. The successful integration of PVDF-TrFE into the electrospun fibers indicates good compatibility between the constituent polymers and the fullerene acceptor, leading to the formation of a stable composite morphology. The interconnected nanofibrous framework is expected to increase the effective donor/acceptor interfacial area while simultaneously providing continuous transport pathways for photogenerated charge carriers. In addition, the incorporation of ferroelectric PVDF-TrFE is anticipated to introduce localized polarization fields throughout the active layer. These internal electric fields can facilitate exciton dissociation and suppress charge recombination, provided that the fibrous morphology remains

uniform. The well-preserved fiber network observed in the composite sample, therefore, provides a favorable structural foundation for the enhanced electrical properties and photovoltaic performance discussed in the subsequent sections. The SEM observations confirm the successful fabrication of uniform electrospun nanofibrous active layers and demonstrate that the incorporation of PVDF-TrFE maintains the structural integrity of the fibers while producing a compact interconnected morphology that is expected to promote efficient charge generation, transport, and collection in the fabricated organic solar cells.

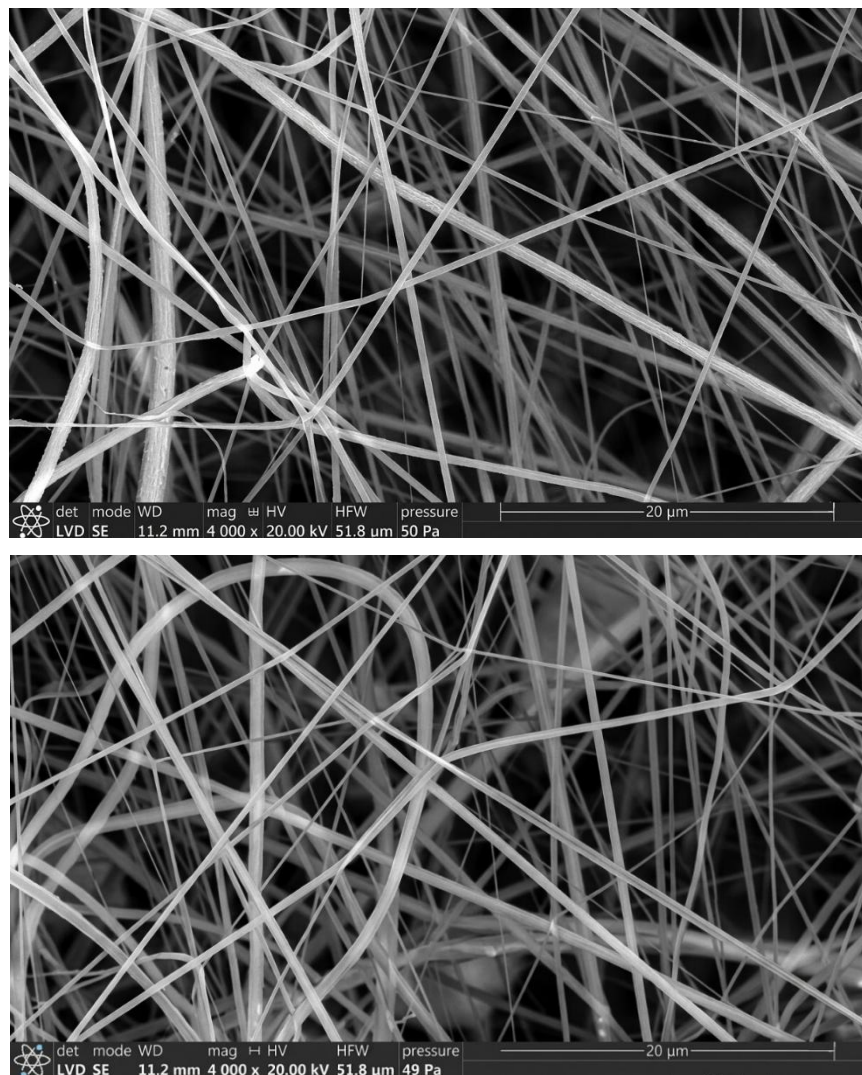


**Figure 2.** SEM images of electrospun nanofibers (a) PCDTBT:PCBM and (b) PCDTBT:PCBM:PVDF-TrFE.

### 3.2. Structural Analysis of the Active Layers

The structural characteristics of the prepared active layers were investigated by XRD, and the corresponding diffraction patterns are presented in Fig. 3. The principal diffraction parameters extracted from the XRD profiles, including the peak position ( $2\theta$ ), interplanar spacing (d-spacing), and full width at half maximum (FWHM), are summarized in Table 1.

As shown in Fig. 2, all samples exhibit broad diffraction profiles without distinct sharp reflections, confirming the predominantly semi-amorphous nature of the PCDTBT: PCBM active layer. This structural characteristic is typical of conjugated polymer/fullerene bulk heterojunctions, where short-range molecular ordering is favored over highly crystalline domains. Such a morphology is advantageous because it maintains a finely intermixed donor/acceptor network that facilitates exciton dissociation while preventing excessive phase segregation. The spin-coated PCDTBT: PCBM film exhibits a broad diffraction maximum centered at  $2\theta = 20.45^\circ$ , corresponding to an interplanar spacing of 4.34 Å (Table 1). The broad diffraction peak, with an FWHM of  $4.78^\circ$ , reflects the limited long-range ordering of the polymer blend and confirms that the active layer consists primarily of a disordered molecular network. This structural arrangement is consistent with the amorphous nature generally reported for PCDTBT-based photovoltaic blends.

Replacing spin coating with electrospinning produces a slight shift of the diffraction maximum toward a lower diffraction angle ( $20.27^\circ$ ) together with an increase in the calculated d-spacing to 4.38 Å. In addition, the diffraction peak becomes slightly broader (FWHM =  $5.46^\circ$ , Table 1). The small increase in intermolecular spacing suggests that the electrospinning process relaxes the molecular packing while the applied electric field promotes local chain orientation during fiber formation. As a result, the electrospun fibers preserve the semi-amorphous framework of the active layer while generating a nanofibrous morphology that is expected to provide more continuous pathways for charge transport.

Following the incorporation of PVDF-TrFE, the principal diffraction maximum shifts further to  $20.07^\circ$ , corresponding to a d-spacing of 4.42 Å, while the FWHM remains nearly unchanged ( $5.43^\circ$ ). The gradual increase in d-spacing indicates a slight expansion of the average intermolecular distance after introducing the ferroelectric polymer. At the same time, the absence of additional diffraction peaks demonstrates that PVDF-TrFE is incorporated into the active layer without inducing undesirable crystallization or phase separation. The nearly constant FWHM

between the electrospun samples further suggests that the ferroelectric polymer modifies the local molecular environment without significantly altering the overall structural disorder of the blend. Overall, the XRD results demonstrate that electrospinning and the incorporation of PVDF-TrFE induce subtle changes in molecular packing while preserving the semi-amorphous structure of the PCDTBT:PCBM active layer. The gradual increase in d-spacing, together with the maintained broad diffraction profile, indicates that the structural modifications occur at the local molecular level rather than through the formation of new crystalline phases. These structural characteristics are expected to facilitate carrier transport while maintaining the nanoscale donor/acceptor morphology required for efficient photovoltaic operation, consistent with the electrical and photovoltaic results discussed in the following sections.

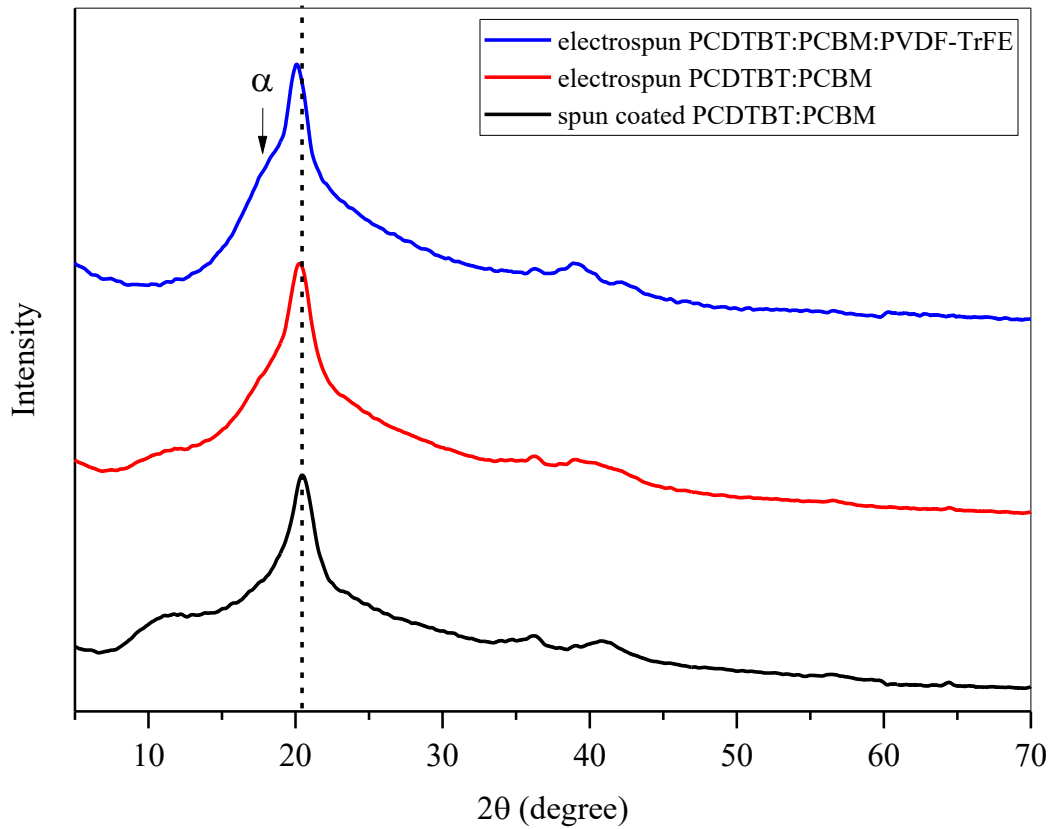


**Figure 3.** XRD patterns of the spin-coated PCDTBT:PCBM film, electrospun PCDTBT:PCBM nanofibers, and electrospun PVDF-TrFE:PCDTBT:PCBM composite nanofibers.

**Table 1.** Structural parameters obtained from the XRD patterns of the prepared active layers.

| Sample                      | 2 $\theta$ (°) | d-spacing (Å) | FWHM (°) |
|-----------------------------|----------------|---------------|----------|
| PCDTBT: PCBM film           | 20.45          | 4.34          | 4.78     |
| PCDTBT: PCBM fiber          | 20.27          | 4.38          | 5.46     |
| PVDF-TrFE:PCDTBT:PCBM fiber | 20.07          | 4.42          | 5.43     |

### 3.3. Chemical Structure and Molecular Interactions

The chemical structure of the prepared active layers was investigated by FTIR spectroscopy, and the corresponding spectra are presented in Fig. 4. The principal absorption bands and their assignments are summarized in Table 2. FTIR analysis was performed to verify the chemical integrity of the polymer blend after electrospinning and to examine the interaction between PCDTBT, PCBM, and the ferroelectric PVDF-TrFE.

The spin-coated PCDTBT: PCBM film exhibits the characteristic absorption bands of the conjugated polymer blend. The weak band located near 3047  $\text{cm}^{-1}$  is assigned to the aromatic C-H stretching vibration of the PCDTBT backbone, whereas the absorption around 2902  $\text{cm}^{-1}$  originates from aliphatic C-H stretching vibrations. A distinct band observed at approximately 1581  $\text{cm}^{-1}$  corresponds to the stretching vibration of the aromatic C=C bonds within the conjugated polymer backbone. Additional absorption bands at 1439 and 1202  $\text{cm}^{-1}$  are associated with  $\text{CH}_2$  deformation and C-C/C-F stretching vibrations, respectively, while the band near 789  $\text{cm}^{-1}$  arises from out-of-plane deformation of the aromatic framework.

The FTIR spectrum of the electrospun PCDTBT: PCBM fibers preserves all characteristic absorption bands of the spin-coated film without the appearance of new vibration modes. This observation confirms that the electrospinning process does not alter the chemical structure of either PCDTBT or PCBM. Minor variations in the relative intensity of several absorption bands are observed after electrospinning, which are attributed to changes in molecular orientation and local chain packing induced by the high electric field during fiber formation rather than to chemical modification of the polymer blend.

Following the incorporation of PVDF-TrFE, the composite nanofibers exhibit the characteristic absorption bands of both the conjugated polymer blend and the fluorinated ferroelectric polymer. In particular, the absorptions centered at approximately 1332, 1172, and 795  $\text{cm}^{-1}$  become more pronounced, reflecting the contribution of  $\text{CF}_2$  vibrational modes originating from PVDF-TrFE. The enhanced intensity of the absorption near 795  $\text{cm}^{-1}$ , commonly associated with the

electroactive  $\beta$ -phase of PVDF-TrFE, confirms the successful incorporation of the ferroelectric component within the electrospun active layer. Importantly, no additional absorption bands or significant spectral shifts are observed, indicating that PVDF-TrFE is physically incorporated into the polymer matrix without inducing chemical reactions or degradation of the conjugated backbone.

Overall, the FTIR results demonstrate that both electrospinning and the incorporation of PVDF-TrFE preserve the chemical integrity of the PCDTBT:PCBM active layer while introducing the characteristic fluoropolymer vibrations associated with the ferroelectric component. The coexistence of the characteristic absorption bands of all constituents, together with the absence of new chemical species, confirms the successful fabrication of the composite nanofibrous active layer. These molecular-level observations are consistent with the XRD results, which indicate that the structural evolution arises primarily from changes in molecular organization rather than from chemical transformation.

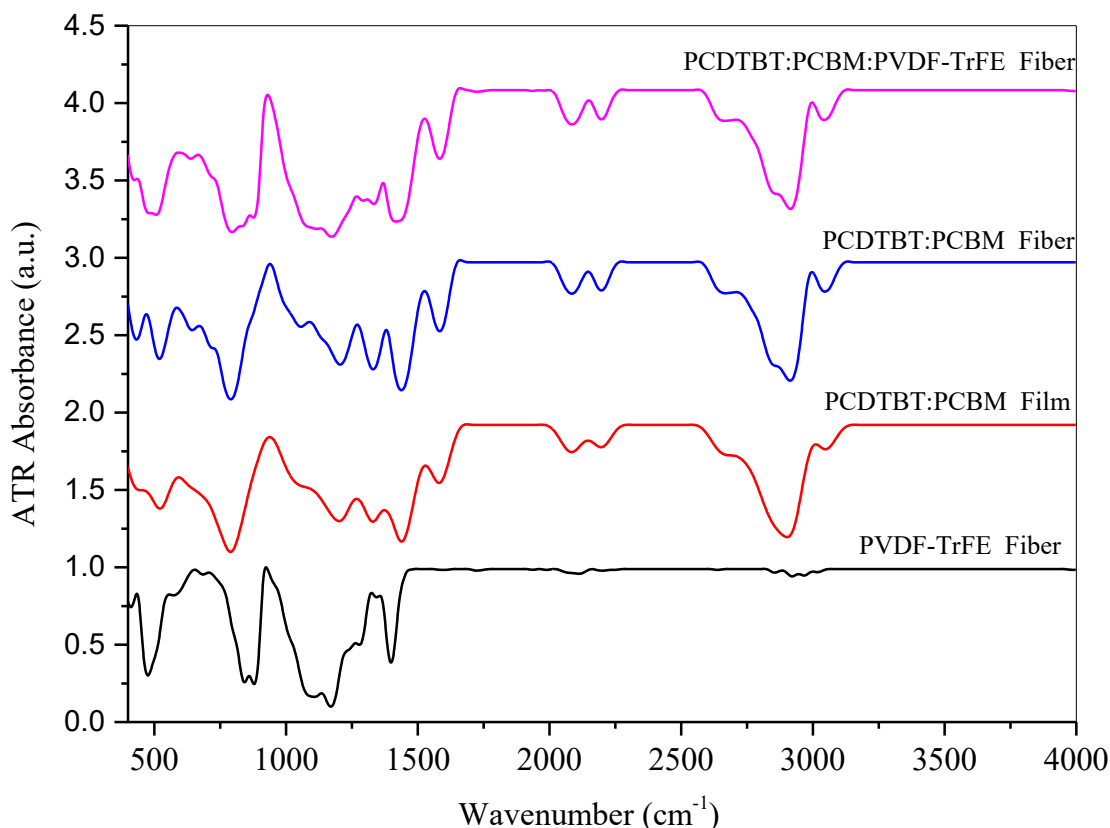


**Figure 4.** FTIR spectra of electrospun PVDF-TrFE, PCDTBT/PCBM, and PCDTBT/PCBM/PVDF-TrFE nanofibers.

**Table 2.** Principal FTIR absorption bands of the prepared active layers and their assignments.

| Wavenumber<br>(cm <sup>-1</sup> ) | Assignment                                               | Main component   |            |
|-----------------------------------|----------------------------------------------------------|------------------|------------|
| ~3040-3050                        | Aromatic C-H stretching                                  | PCDTBT           | [36,37]    |
| ~2902-2922                        | Aliphatic C-H stretching                                 | PCDTBT:PCBM      | [36,37]    |
| ~1581-1584                        | Aromatic C=C stretching                                  | PCDTBT           | [38,39]    |
| ~1416-1440                        | CH <sub>2</sub> deformation / CF <sub>2</sub><br>bending | PVDF-TrFE        | [33,40–42] |
| ~1330-1332                        | C-F stretching                                           | PVDF-TrFE        | [33,40–42] |
| ~1170-1206                        | Symmetric CF <sub>2</sub> stretching                     | PVDF-TrFE        | [33,40–42] |
| ~1056-1108                        | C-F/C-C skeletal vibration                               | PVDF-TrFE:PCDTBT | [43,44]    |
| ~789-795                          | β-phase CF <sub>2</sub> vibration                        | PVDF-TrFE        | [33,40–44] |
| ~506-520                          | CF <sub>2</sub> skeletal deformation                     | PVDF-TrFE        | [33,40–44] |

### 3.4. Optical Absorption Characteristics

The optical absorption properties of the prepared active layers were investigated by UV-vis spectroscopy, and the corresponding spectra are presented in Fig. 5. Optical absorption is one of the key factors governing the performance of organic solar cells because it determines the fraction of incident photons that can be converted into excitons. The characteristic absorption parameters extracted from the spectra are summarized in Table 3.

As shown in Fig. 5, all samples exhibit broad absorption extending from the ultraviolet region into the visible spectral range, confirming the effective light-harvesting capability of the PCDTBT:PCBM active layer. The absorption profile is characteristic of PCDTBT-based bulk

heterojunctions, where the high-energy absorption in the ultraviolet region is attributed to the  $\pi$ - $\pi^*$  transitions of the conjugated polymer backbone, while the broad absorption extending throughout the visible region originates from intramolecular charge-transfer transitions within the donor polymer. The preservation of the spectral profile for all samples indicates that neither electrospinning nor the incorporation of PVDF-TrFE alters the intrinsic electronic structure of the PCDTBT: PCBM blend.

The spin-coated PCDTBT: PCBM film exhibits the lowest absorption intensity over the investigated wavelength range, with a maximum absorbance of 1.364 at approximately 247.5 nm (Table 3). Replacing the conventional spin-coated film with electrospun PCDTBT: PCBM nanofibers increases the maximum absorbance to 1.458 while maintaining the same absorption maximum. The enhanced optical response can be attributed to the interconnected nanofibrous architecture produced by electrospinning, which increases the effective optical path length and promotes multiple light-scattering events within the active layer, thereby improving photon harvesting.

A further increase in optical absorption is observed after incorporating PVDF-TrFE into the electrospun fibers. The composite active layer exhibits the highest absorbance among all investigated samples, reaching 1.706 with an absorption maximum near 240.6 nm. Although a slight shift of the ultraviolet absorption maximum is observed, the overall absorption profile remains essentially unchanged, indicating that the ferroelectric polymer does not modify the fundamental electronic transitions of the PCDTBT: PCBM blend. Instead, the increased absorption is attributed to the improved morphology of the electrospun composite and the more homogeneous distribution of the photoactive material within the nanofibrous network. These structural characteristics increase the probability of photon absorption and consequently enhance exciton generation under solar illumination.

The gradual enhancement in optical absorption from the spin-coated film to the electrospun fibers and finally to the PVDF-TrFE-containing nanofibers is consistent with the morphological observations obtained from SEM analysis. The three-dimensional fibrous network provides a larger effective surface area and improved light-management capability compared with the compact spin-coated film. Consequently, the increased optical absorption is expected to contribute directly to the higher photocurrent density and improved photovoltaic performance discussed in the subsequent sections.

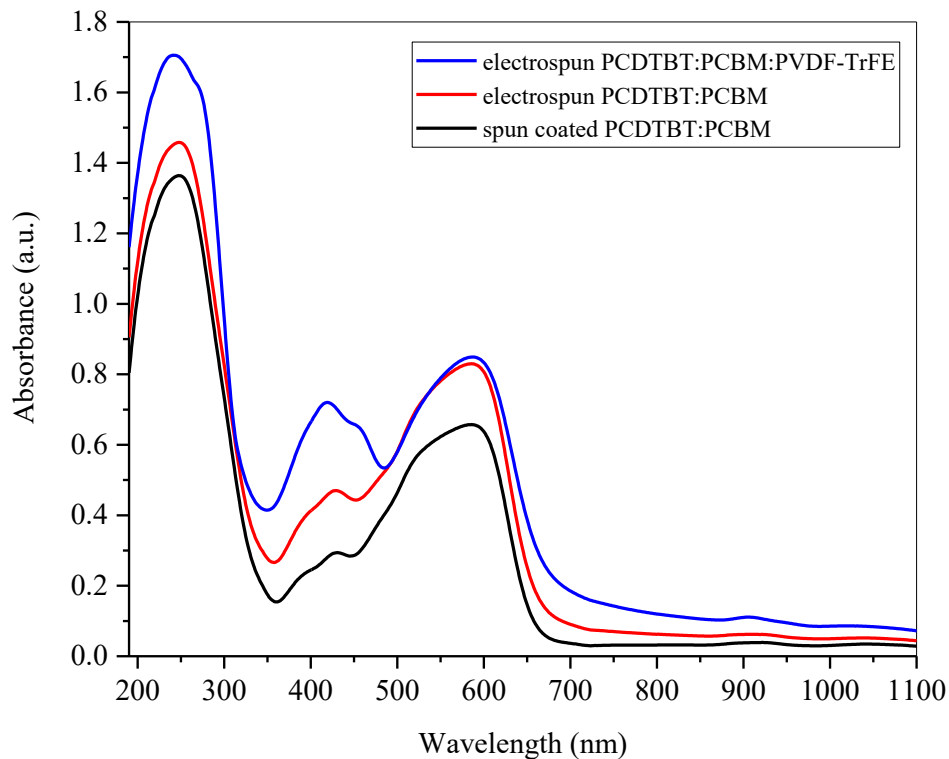


**Figure 5.** UV-vis absorption of the PCDTBT/PCBM, and PCDTBT/PCBM/ PVDF-TrFE nanofibers.

**Table 3.** Optical absorption characteristics of the prepared active layers obtained from the UV-visible spectra.

| Sample                      | Absorption maximum, $\lambda_{\max}$<br>(nm) | Maximum absorbance |
|-----------------------------|----------------------------------------------|--------------------|
| PCDTBT: PCBM film           | 247.5                                        | 1.364              |
| PCDTBT: PCBM fiber          | 247.5                                        | 1.458              |
| PVDF-TrFE:PCDTBT:PCBM fiber | 240.6                                        | 1.706              |

### 3.5. Photoluminescence Properties and Exciton Dissociation

The PL spectra of the prepared active layers are presented in Fig. 6. PL spectroscopy was employed to evaluate the exciton recombination behavior and to investigate the influence of electrospinning and ferroelectric PVDF-TrFE incorporation on charge-transfer processes within the active layer. As shown in Fig. 6, all samples exhibit a broad emission band extending over the near-infrared region with a maximum centered at approximately 700 nm, which is characteristic of radiative recombination in the PCDTBT: PCBM bulk heterojunction. The similarity in the emission profile indicates that the fundamental emissive states of the polymer blend are preserved after electrospinning and after incorporating PVDF-TrFE. No significant shift in the emission maximum is observed, suggesting that the electronic structure of the conjugated polymer remains essentially unchanged.

The spin-coated PCDTBT: PCBM film exhibits the highest PL intensity, indicating that a considerable fraction of the photo-generated excitons recombine radiatively before charge separation occurs. Upon replacing the conventional film with electrospun PCDTBT: PCBM nanofibers, the emission intensity decreases noticeably while maintaining nearly the same emission wavelength. This PL quenching demonstrates that the nanofibrous morphology facilitates exciton dissociation and suppresses radiative recombination, which can be attributed to the larger donor/acceptor interfacial area and the more continuous charge-transport pathways created by the interconnected fiber network.

A further reduction in PL intensity is observed after incorporating PVDF-TrFE into the electrospun active layer. The composite nanofibers exhibit the weakest emission among all investigated samples, indicating the most efficient suppression of exciton recombination. The pronounced PL quenching suggests that the ferroelectric polymer enhances charge separation by introducing localized polarization within the active layer, thereby assisting the dissociation of Coulombically bound electron-hole pairs and promoting more efficient charge extraction. Since no appreciable spectral shift accompanies the decrease in emission intensity, the observed quenching is primarily attributed to improved charge-transfer efficiency rather than to chemical modification of the PCDTBT: PCBM electronic structure.

The progressive decrease in PL intensity follows the same trend observed in the morphological and optical characterization. The electrospun nanofibrous architecture improves the donor/acceptor interface, while the incorporation of PVDF-TrFE further facilitates charge

separation and reduces radiative recombination losses. These findings are consistent with the enhanced dielectric response and charge-carrier mobility discussed in the subsequent sections and provide direct spectroscopic evidence for the improved photovoltaic performance of the electrospun ferroelectric composite devices.

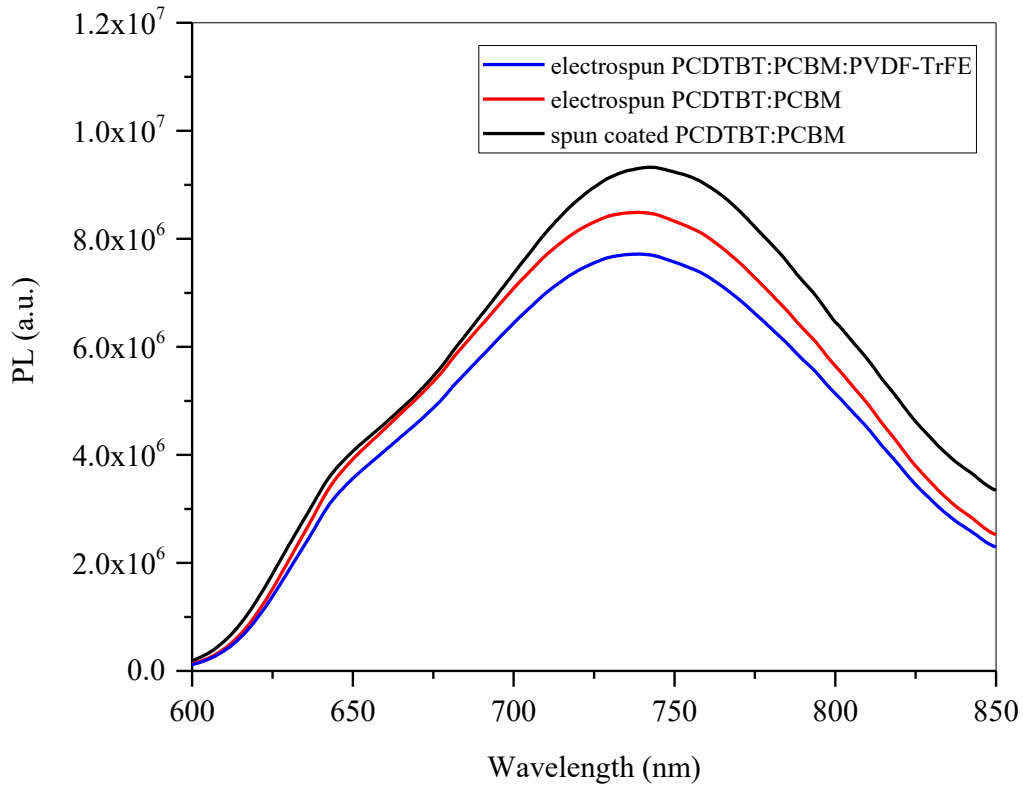


**Figure 6.** Room-temperature PL spectra of the spin-coated PCDTBT: PCBM film, electrospun PCDTBT: PCBM nanofibers, and electrospun PVDF-TrFE:PCDTBT:PCBM composite nanofibers.

### 3.6. Frequency-Dependent Electrical Conductivity

The frequency dependence of the  $\sigma_{ac}$  of the prepared active layers measured at 303 K is shown in Fig. 7. The electrical conductivity was calculated from the dielectric measurements using [45,46]:

$$\sigma_{ac} = 2\pi f \epsilon_0 \epsilon'', \quad (1)$$

where  $f$  is the applied frequency,  $\varepsilon_0$  is the permittivity of free space, and  $\varepsilon''$  is the dielectric loss. The extracted conductivity data were further analyzed using Jonscher's universal power law [47–49],

$$\sigma_{ac} = \sigma_{dc} + A\omega^s, \quad (2)$$

where  $\sigma_{dc}$  is the DC conductivity,  $A$  is a temperature-dependent constant,  $\omega$  is the angular frequency, and  $s$  is the frequency exponent that provides insight into the dominant conduction mechanism. As illustrated in Fig. 7, the  $\sigma_{ac}$  increases continuously with increasing frequency for all investigated samples. At lower frequencies, the conductivity remains relatively small because charge carriers are strongly influenced by localized trapping sites and interfacial polarization. As the frequency increases, charge carriers acquire sufficient energy to hop between neighboring localized states, leading to a gradual enhancement in conductivity. This frequency-dependent behavior is characteristic of disordered conjugated polymer systems and is consistent with Jonscher's universal dielectric response.

The conductivity values increase systematically from the spin-coated PCDTBT:PCBM film to the electrospun PCDTBT:PCBM nanofibers and reach the highest values for the electrospun PVDF-TrFE:PCDTBT:PCBM composite throughout the investigated frequency range. The improved electrical response of the electrospun fibers can be attributed to the interconnected nanofibrous architecture, which provides more continuous pathways for carrier transport than the compact spin-coated film. The additional enhancement observed after incorporating PVDF-TrFE is associated with the ferroelectric polarization of the polymer, which promotes charge separation and reduces carrier trapping, thereby increasing the concentration of mobile charge carriers available for electrical conduction.

To obtain further insight into the conduction process, the conductivity data were analyzed using Jonscher's power law, and the extracted fitting parameters are summarized in Table 4. The frequency exponent ( $s$ ) decreases slightly from 0.336 for the spin-coated film to 0.330 for the electrospun PCDTBT:PCBM nanofibers and 0.321 for the PVDF-TrFE-containing composite. Since all  $s$  values are lower than unity, the AC conduction is attributed predominantly to a hopping mechanism involving localized electronic states within the polymer matrix. The gradual reduction in  $s$  suggests that electrospinning and the incorporation of PVDF-TrFE facilitate carrier hopping by improving molecular connectivity and reducing the energy barriers associated with localized transport.

The  $\sigma_{ac}$  results are consistent with the structural and optical characterization presented in the previous sections. The enhanced molecular organization observed by XRD, the preserved chemical structure confirmed by FTIR, the increased optical absorption, and the pronounced PL quenching collectively indicate more efficient charge generation and transport in the electrospun composite nanofibers. Consequently, the improved  $\sigma_{ac}$  is expected to contribute directly to the enhanced carrier mobility and photovoltaic performance discussed in the following sections.

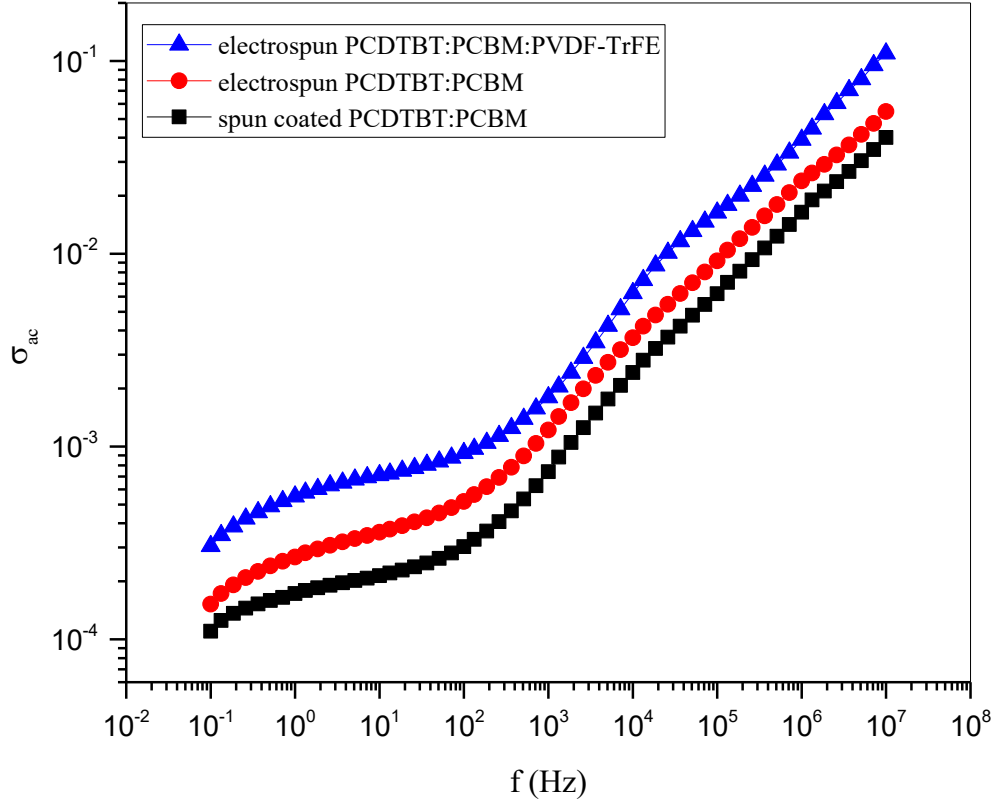


**Figure 7.** Frequency dependence of the  $\sigma_{ac}$  measured at 303 K for the spin-coated PCDTBT:PCBM film, electrospun PCDTBT:PCBM nanofibers, and electrospun PVDF-TrFE:PCDTBT:PCBM composite nanofibers.

**Table 4.** Jonscher's power-law fitting parameters for the prepared active layers at 303 K.

| Sample                      | Frequency exponent, (s) | Interpretation                        |
|-----------------------------|-------------------------|---------------------------------------|
| PCDTBT: PCBM film           | 0.336                   | Frequency-dependent hopping transport |
| PCDTBT: PCDTBT fiber        | 0.330                   | Frequency-dependent hopping transport |
| PVDF-TrFE:PCDTBT:PCBM fiber | 0.321                   | Frequency-dependent hopping transport |

### 3.7. Charge Transport Characteristics

The charge-transport properties of the prepared active layers were further investigated using the space-charge-limited current (SCLC) technique. The corresponding J-V characteristics are presented in Fig. 8, while the extracted carrier mobilities are summarized in Table 5. The SCLC method provides direct information on carrier transport under high injection conditions, where the current is dominated by injected charge carriers rather than thermally generated carriers.

The carrier mobility was determined using the Mott-Gurney equation [50]:

$$J = \frac{9}{8} \epsilon_r \epsilon_0 \mu \frac{V^2}{L^3}, \quad (3)$$

where  $J$  is the current density,  $\epsilon_r$  is the relative dielectric constant of the active layer,  $\epsilon_0$  is the permittivity of free space,  $\mu$  is the carrier mobility,  $V$  is the applied voltage, and  $L$  is the active-layer thickness (approximately 225 nm). As shown in Fig. 8, the current density increases nonlinearly with increasing applied voltage for all investigated samples, indicating the transition into the space-charge-limited conduction regime. The spin-coated PCDTBT: PCBM film exhibits the lowest current density throughout the investigated voltage range, reflecting relatively limited carrier transport within the compact active layer. In contrast, the electrospun PCDTBT: PCBM nanofibers display higher current densities, demonstrating that the interconnected fibrous morphology provides more effective pathways for carrier transport.

The electrospun PVDF-TrFE:PCDTBT:PCBM composite nanofibers exhibit the highest current density over the entire voltage range, indicating the most efficient charge transport among the prepared active layers. The enhanced electrical response is attributed to the synergistic effect of the electrospun nanofibrous architecture and the incorporation of the ferroelectric polymer, which promotes more efficient charge separation and facilitates carrier transport through the active layer.

The carrier mobilities extracted from the SCLC analysis are listed in Table 5. The mobility increases from  $6.97 \times 10^{-3} \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$  for the spin-coated PCDTBT: PCBM film to  $3.30 \times 10^{-2} \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$  for the electrospun PCDTBT: PCBM nanofibers, representing an increase of nearly one order of magnitude. A further enhancement is achieved after incorporating PVDF-TrFE, where the mobility reaches  $9.85 \times 10^{-2} \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ , corresponding to approximately a three-fold increase compared with the electrospun PCDTBT: PCBM fibers and more than one order of magnitude compared with the spin-coated film.

The progressive enhancement in carrier mobility agrees well with the structural and optoelectronic characterization presented in the previous sections. SEM observations demonstrated the formation of a continuous nanofibrous network after electrospinning, while XRD revealed subtle improvements in molecular organization without altering the semi-amorphous nature of the active layer. Moreover, the increased optical absorption together with the pronounced PL quenching confirms more efficient exciton dissociation and reduced radiative recombination. The higher dielectric constant of the PVDF-TrFE-containing composite further facilitates charge separation by reducing Coulombic attraction between photogenerated charge carriers. Consequently, the combined influence of improved morphology, enhanced dielectric properties, and reduced recombination contributes to the substantial increase in carrier mobility, which is expected to play a key role in the improved photovoltaic performance of the fabricated organic solar cells.

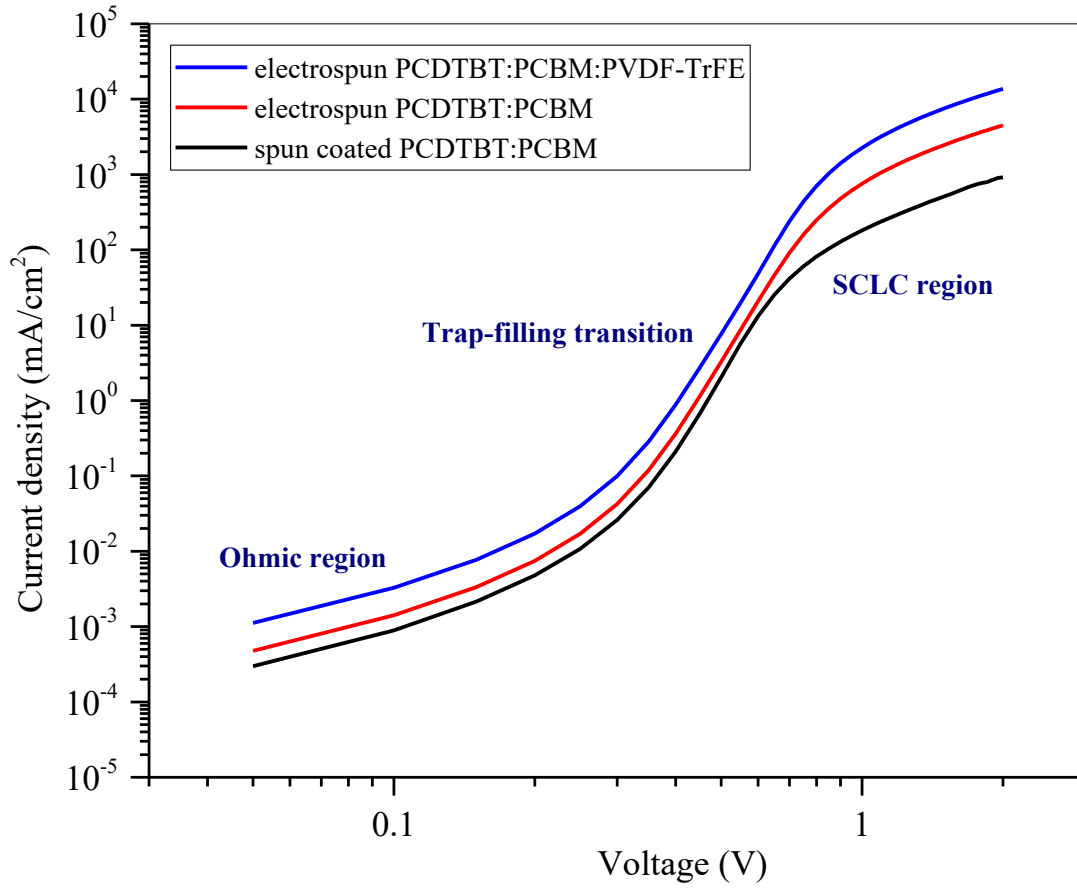


**Figure 8.** SCLC characteristics of the spin-coated PCDTBT: PCBM film, electrospun PCDTBT: PCBM nanofibers, and electrospun PVDF-TrFE:PCDTBT:PCBM composite nanofibers.

**Table 5.** The dielectric constant of the active layer from CELIV measurements and  $\mu_{\text{SCLC}}$ .

| Device                      | $\epsilon_r$ | $\mu_{\text{SCLC}}$<br>(cm <sup>2</sup> V <sup>-1</sup> s <sup>-1</sup> ) |
|-----------------------------|--------------|---------------------------------------------------------------------------|
| PCDTBT: PCBM film           | 3.79         | $5.75 \times 10^{-3}$                                                     |
| PCDTBT: PCBM fiber          | 3.83         | $2.95 \times 10^{-2}$                                                     |
| PCDTBT:PCBM:PVDF-TrFE fiber | 3.91         | $8.88 \times 10^{-2}$                                                     |

### 3.8. Photovoltaic Performance of OSCs

The photovoltaic performance of the fabricated organic solar cells was evaluated under simulated AM 1.5G solar illumination ( $100 \text{ mW cm}^{-2}$ ). The corresponding J-V characteristics are presented in Fig. 9, and the extracted photovoltaic parameters are summarized in Table 6. As shown in Fig. 9, all fabricated devices exhibit typical photovoltaic behavior with well-defined diode characteristics under illumination. The reference device employing the conventional spin-coated PCDTBT:PCBM active layer delivers an open-circuit voltage ( $V_{OC}$ ) of  $0.86 \pm 0.01 \text{ V}$ , a short-circuit current density ( $J_{SC}$ ) of  $10.58 \pm 0.04 \text{ mA cm}^{-2}$ , a fill factor (FF) of  $64.48 \pm 0.12\%$ , and a power conversion efficiency (PCE) of  $5.86 \pm 0.04\%$ . These values are consistent with the expected performance of PCDTBT:PCBM bulk heterojunction solar cells fabricated by conventional solution processing.

Replacing the spin-coated active layer with electrospun PCDTBT:PCBM nanofibers results in a noticeable enhancement in device performance. Although the  $V_{OC}$  remains unchanged at  $0.86 \pm 0.01 \text{ V}$ , the  $J_{SC}$  increases to  $11.55 \pm 0.01 \text{ mA cm}^{-2}$ , accompanied by a slight improvement in the fill factor to  $65.48 \pm 0.08\%$ . Consequently, the PCE increases from 5.86% to 6.50%, corresponding to an improvement of approximately 10.9% relative to the spin-coated device. The enhanced performance is primarily attributed to the electrospun nanofibrous morphology, which provides a larger donor/acceptor interfacial area and more continuous pathways for charge transport, thereby facilitating exciton dissociation and reducing carrier recombination.

A further improvement is achieved by incorporating PVDF-TrFE into the electrospun active layer. The PVDF-TrFE:PCDTBT:PCBM nanofiber device exhibits the highest photovoltaic performance, with a  $V_{OC}$  of  $0.91 \pm 0.00 \text{ V}$ , a  $J_{SC}$  of  $12.13 \pm 0.12 \text{ mA cm}^{-2}$ , an FF of  $64.55 \pm 0.10\%$ , and a maximum PCE of  $7.12 \pm 0.01\%$ . Compared with the spin-coated reference device, the efficiency increases by approximately 21.5%, while the  $J_{SC}$  increases by approximately 14.7%. The improvement in  $V_{OC}$  further suggests a reduction in non-radiative recombination losses and more efficient charge extraction at the electrode interfaces.

The evolution of the series ( $R_s$ ) and shunt ( $R_{SH}$ ) resistances provides additional insight into the improved device operation. As summarized in Table 6, the  $R_s$  decreases progressively from  $0.0069 \text{ k}\Omega \text{ cm}^2$  for the spin-coated film to  $0.0061 \text{ k}\Omega \text{ cm}^2$  for the electrospun PCDTBT:PCBM nanofibers and further to  $0.0055 \text{ k}\Omega \text{ cm}^2$  for the PVDF-TrFE:PCDTBT:PCBM device. The lower  $R_s$  indicates reduced internal electrical losses and more efficient carrier transport through the active layer.

Simultaneously, the  $R_{SH}$  increases from  $1.03 \text{ k}\Omega \text{ cm}^2$  to  $1.42 \text{ k}\Omega \text{ cm}^2$  and finally  $1.97 \text{ k}\Omega \text{ cm}^2$ , reflecting suppressed leakage current and improved junction quality. These changes contribute directly to the enhanced charge collection efficiency and overall photovoltaic performance.

The observed improvement in photovoltaic characteristics is in excellent agreement with the structural, optical, and electrical analyses presented in the previous sections. SEM observations confirmed the formation of a uniform interconnected nanofibrous network after electrospinning, while XRD analysis indicated improved molecular organization without altering the fundamental structure of the active layer. The enhanced optical absorption and significant PL quenching demonstrated more efficient light harvesting and exciton dissociation. Furthermore, dielectric spectroscopy revealed an increase in the dielectric constant after incorporating PVDF-TrFE, which reduces the Coulombic attraction between photogenerated electron-hole pairs and facilitates charge separation. This behavior is further supported by the higher  $\sigma_{ac}$  and enhanced carrier mobility obtained from the SCLC measurements. The excellent correlation among these characterization techniques demonstrates that the electrospun ferroelectric nanofibrous architecture simultaneously improves photon absorption, charge generation, charge transport, and charge collection, ultimately leading to superior photovoltaic performance.

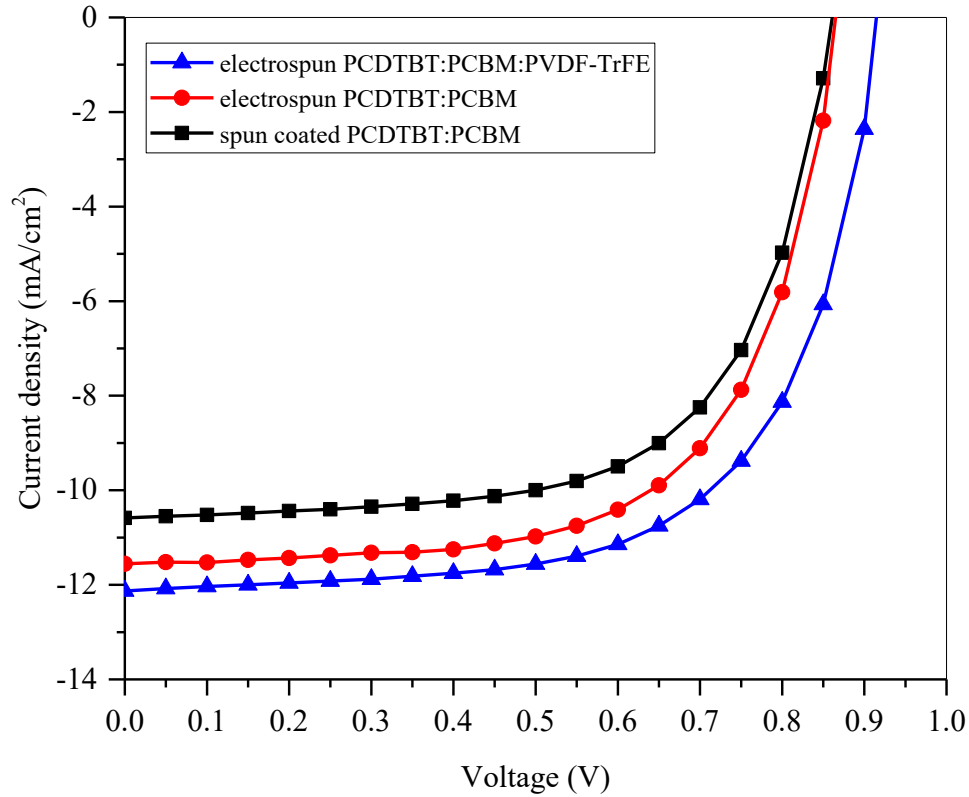


**Figure 9.** J-V characteristics of organic solar cells based on spin-coated PCDTBT: PCBM films, electrospun PCDTBT: PCBM nanofibers, and electrospun PVDF-TrFE:PCDTBT:PCBM composite nanofibers measured under simulated AM 1.5G solar illumination ( $100 \text{ mW cm}^{-2}$ ).

**Table 6.** Photovoltaic parameters of the fabricated organic solar cells measured under simulated AM 1.5G illumination ( $100 \text{ mW cm}^{-2}$ ).

| Device                              | $V_{OC}$<br>(V) | $J_{SC}$<br>( $\text{mA/cm}^2$ ) | FF<br>(%)        | $R_S$<br>( $\text{K}\Omega \text{ cm}^2$ ) | $R_{SH}$<br>( $\text{K}\Omega \text{ cm}^2$ ) | PCE<br>(%)      |
|-------------------------------------|-----------------|----------------------------------|------------------|--------------------------------------------|-----------------------------------------------|-----------------|
| PCDTBT:<br>PCBM film                | $0.86 \pm 0.01$ | $10.58 \pm 0.04$                 | $64.48 \pm 0.12$ | 0.0069                                     | 1.03                                          | $5.86 \pm 0.04$ |
| PCDTBT:<br>PCBM fiber               | $0.86 \pm 0.01$ | $11.55 \pm 0.01$                 | $65.48 \pm 0.08$ | 0.0061                                     | 1.42                                          | $6.50 \pm 0.03$ |
| PCDTBT:PC<br>BM:PVDF-<br>TrFE fiber | $0.91 \pm 0.00$ | $12.13 \pm 0.12$                 | $64.55 \pm 0.10$ | 0.0055                                     | 1.97                                          | $7.12 \pm 0.01$ |

### 3.9. External Quantum Efficiency Analysis

The EQE spectra of the fabricated organic solar cells are presented in Fig. 10. EQE measurements provide direct evidence of the wavelength-dependent photoelectric conversion capability by determining the fraction of incident photons that are successfully converted into collected charge carriers. As shown in Fig. 10, all fabricated devices exhibit a broad photoresponse covering the ultraviolet and visible regions, extending from approximately 320 to 700 nm, which corresponds well with the optical absorption characteristics of the PCDTBT: PCBM active layer. The similar spectral profiles indicate that electrospinning and the incorporation of PVDF-TrFE do not alter the fundamental photoactive characteristics of the donor/acceptor system, while the magnitude of the EQE is significantly enhanced.

The spin-coated PCDTBT: PCBM device exhibits the lowest quantum efficiency over the entire spectral range. Replacing the compact active layer with electrospun PCDTBT: PCBM nanofibers results in a noticeable increase in EQE, particularly within the principal absorption region of the active layer. This improvement demonstrates that the electrospun morphology enhances photon utilization and facilitates more efficient generation and collection of photogenerated charge

carriers. The highest EQE values are obtained for the electrospun PVDF-TrFE:PCDTBT:PCBM composite nanofibers. The enhancement is observed across almost the entire photoactive spectral region without introducing additional spectral features or shifting the response to different wavelengths. The preservation of the spectral shape confirms that PVDF-TrFE functions primarily as a morphology- and transport-modifying component rather than contributing directly to optical absorption. Instead, the higher quantum efficiency originates from improved charge separation and more efficient carrier collection within the active layer.

The enhancement in EQE is in excellent agreement with the results obtained from the previous characterization techniques. The increased optical absorption observed by UV-Vis spectroscopy provides a larger population of photogenerated excitons, while the significant PL quenching confirms the suppression of radiative recombination. Furthermore, the higher dielectric constant of the PVDF-TrFE-containing nanofibers facilitates exciton dissociation by reducing the Coulombic attraction between electron-hole pairs. The enhanced  $\sigma_{ac}$  and higher carrier mobility determined from SCLC measurements further promotes efficient carrier transport toward the electrodes. Consequently, these synergistic effects lead to more effective charge collection, which is directly reflected in the increased EQE and the corresponding enhancement in short-circuit current density observed in the photovoltaic measurements.

The progressive increase in EQE closely follows the trend of the measured  $J_{SC}$  values, confirming that the improvement in device performance primarily originates from enhanced photogenerated carrier collection rather than from changes in the intrinsic absorption characteristics of the active material. This strong correlation between the optical and electrical measurements provides additional evidence for the effectiveness of the electrospun ferroelectric nanofibrous active layer in improving the overall photovoltaic performance.

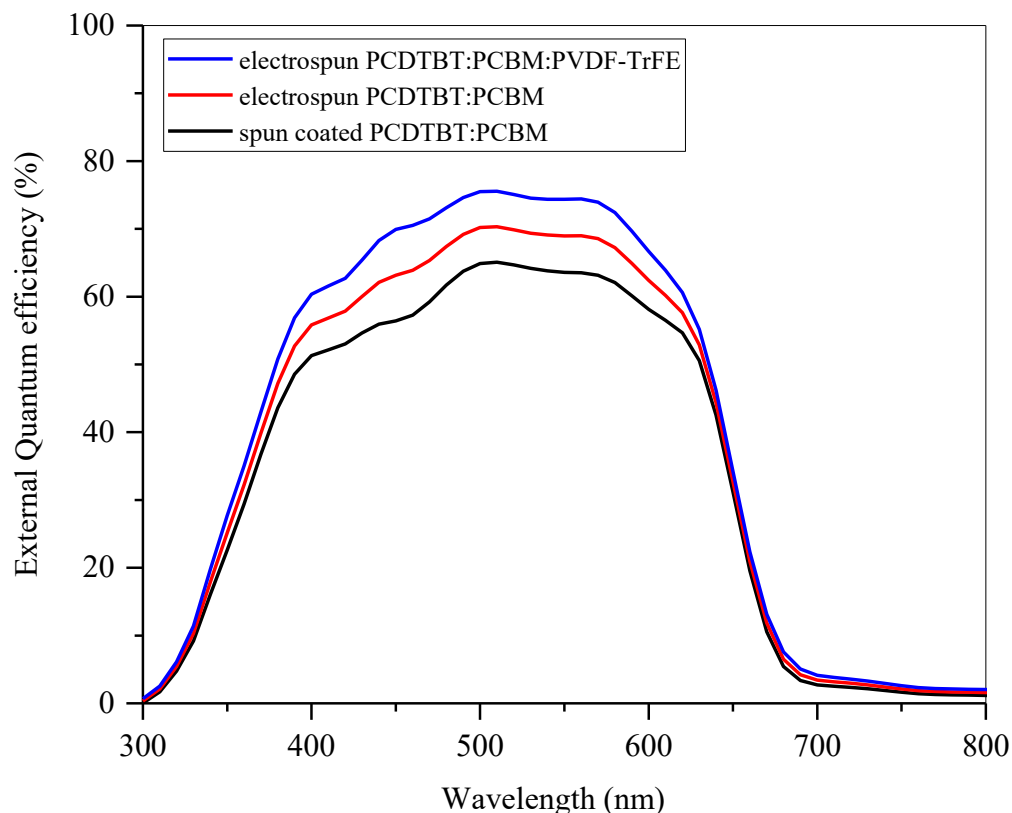


**Figure 10.** EQE spectra of organic solar cells based on spin-coated PCDTBT: PCBM films, electrospun PCDTBT: PCBM nanofibers, and electrospun PVDF-TrFE:PCDTBT:PCBM composite nanofibers.

### 3.10. Charge Extraction and Carrier Mobility

To further investigate the charge transport characteristics of the fabricated active layers, dark charge extraction by linearly increasing voltage (dark-CELIV) measurements were performed. The transient current responses are presented in Fig. 11(a), while the carrier mobilities extracted at different ramp voltages are summarized in Fig. 11(b). Dark-CELIV provides direct information on charge extraction dynamics and carrier mobility under operating conditions, making it a valuable technique for evaluating transport processes in organic photovoltaic devices [51–53].

As shown in Fig. 11(a), all devices exhibit well-defined extraction current transients with a pronounced extraction peak following the application of the linearly increasing voltage pulse. The

transient response of the electrospun PVDF-TrFE:PCDTBT:PCBM nanofibers displays the highest extraction current, whereas the spin-coated PCDTBT: PCBM film exhibits the lowest response. The electrospun PCDTBT: PCBM nanofibers show intermediate behavior. The increase in extraction current demonstrates that electrospinning and the incorporation of the ferroelectric polymer facilitate more efficient extraction of photogenerated charge carriers.

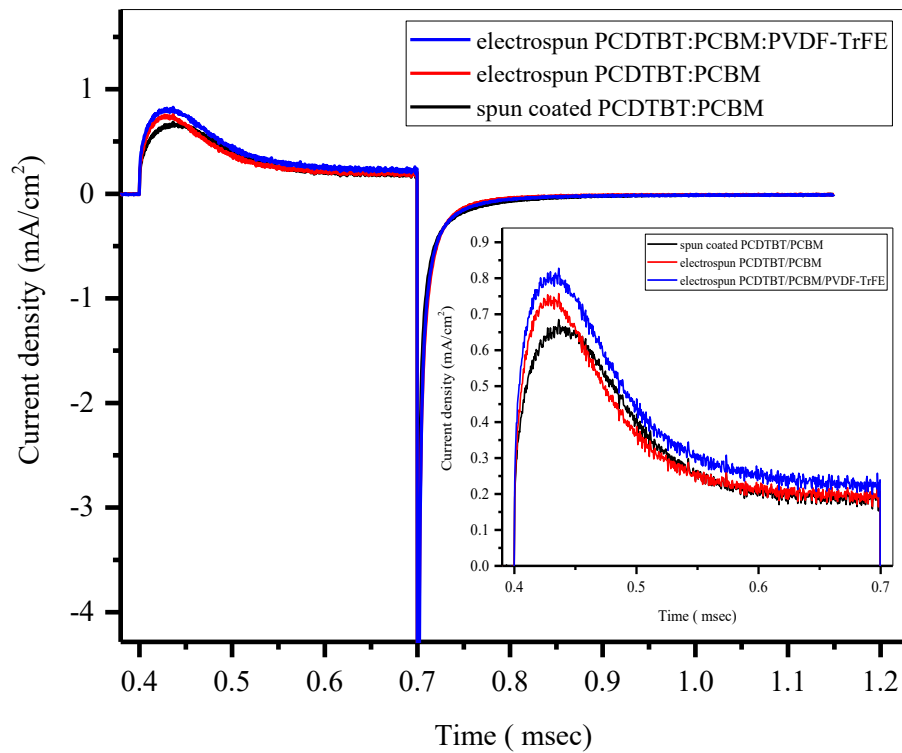
The carrier mobility extracted from the dark-CELIV measurements is plotted as a function of ramp voltage in Fig. 11(b). For all investigated devices, the mobility decreases gradually with increasing ramp voltage, indicating that carrier transport is influenced by energetic disorder and trap-assisted transport within the active layer. Nevertheless, the relative trend among the investigated samples remains unchanged throughout the entire voltage range.

The spin-coated PCDTBT: PCBM film exhibits the lowest carrier mobility, varying from approximately  $3.61 \times 10^{-4}$  to  $8.50 \times 10^{-5} \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$  over the investigated voltage range. Electrospinning the active layer increases the mobility to approximately  $4.26 \times 10^{-4} \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$  at low ramp voltage, confirming that the interconnected nanofibrous morphology provides more continuous pathways for charge transport. The highest mobility is obtained for the electrospun PVDF-TrFE:PCDTBT:PCBM composite nanofibers, reaching  $6.44 \times 10^{-4} \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$  at zero ramp voltage. Even at higher voltages, this device consistently maintains the highest mobility among all investigated samples, demonstrating the beneficial influence of the ferroelectric polymer on carrier transport.

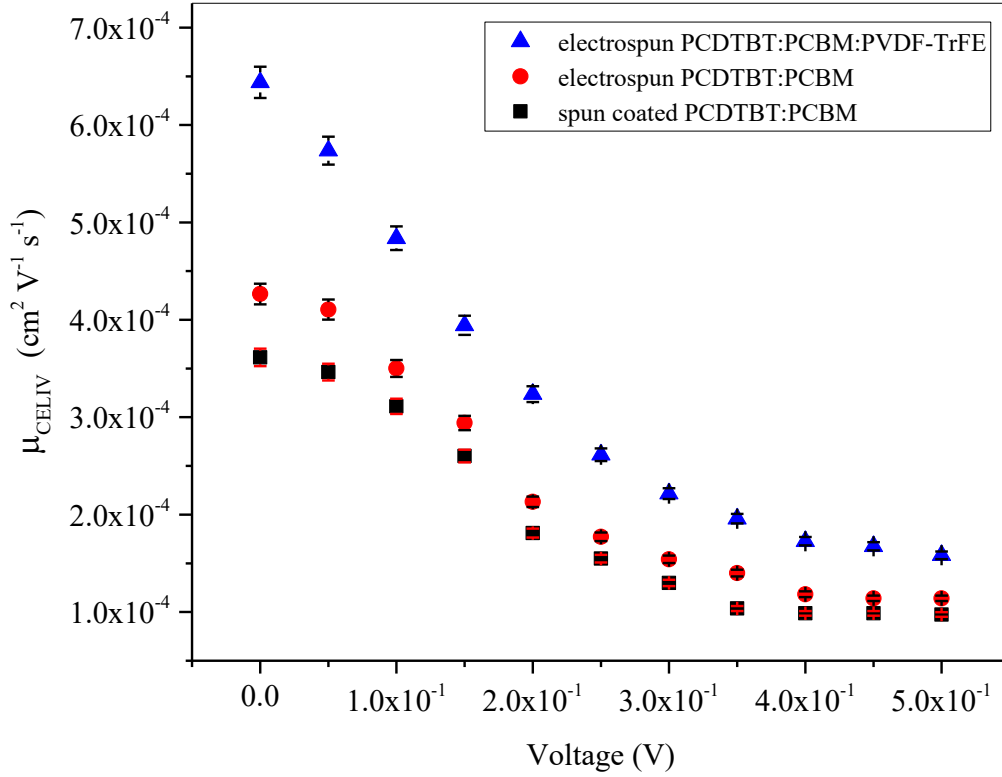
The enhanced carrier mobility is attributed to the synergistic effect of the electrospun nanofibrous architecture and the incorporation of PVDF-TrFE. The interconnected fiber network shortens carrier transport pathways and improves donor/acceptor connectivity, while the ferroelectric polarization of PVDF-TrFE promotes exciton dissociation and suppresses carrier trapping. These effects facilitate faster carrier extraction, resulting in higher extraction currents and improved charge transport.

The dark-CELIV results are fully consistent with the structural, optical, and electrical characterization discussed in the previous sections. The improved molecular organization observed by XRD, the enhanced optical absorption, the pronounced PL quenching, the increased dielectric constant, and the higher  $\sigma_{ac}$  collectively indicate more efficient charge generation and transport in the electrospun composite nanofibers. Consequently, the superior carrier mobility

determined from dark-CELIV provides direct electrical evidence for the enhanced photovoltaic performance of the PVDF-TrFE:PCDTBT:PCBM devices.



(a)



(b)

**Figure 11.** (a) Dark-CELIV transient current responses of the spin-coated PCDTBT: PCBM film, electrospun PCDTBT: PCBM nanofibers, and electrospun PVDF-TrFE:PCDTBT:PCBM composite nanofibers. (b) Carrier mobility extracted from the dark-CELIV measurements as a function of ramp voltage for the corresponding devices.

**Table 7.** Representative carrier mobility extracted from dark-CELIV measurements at zero ramp voltage.

| Device                           | Carrier mobility ( $\text{cm}^2 \text{V}^{-1} \text{s}^{-1}$ ) |
|----------------------------------|----------------------------------------------------------------|
| PCDTBT: PCBM film                | $3.61 \times 10^{-4} \pm 9.04 \times 10^{-6}$                  |
| PCDTBT: PCBM nanofibers          | $4.26 \times 10^{-4} \pm 1.07 \times 10^{-5}$                  |
| PVDF-TrFE:PCDTBT:PCBM nanofibers | $6.44 \times 10^{-4} \pm 1.61 \times 10^{-5}$                  |

#### **4. Concolusion**

In this work, electrospun PVDF-TrFE:PCDTBT:PCBM nanofibrous active layers were successfully developed for inverted organic solar cells, and their structural, optical, electrical, and photovoltaic properties were systematically investigated. Compared with the conventional spin-coated PCDTBT:PCBM film, the electrospun nanofibrous architecture enhanced molecular organization while preserving the chemical structure of the active layer. The incorporation of the ferroelectric polymer PVDF-TrFE further improved light absorption, increased the dielectric constant, suppressed radiative recombination, and promoted charge transport, as confirmed by PL,  $\sigma_{ac}$ , dark-CELIV, and EQE measurements. These improvements resulted in a progressive enhancement of the photovoltaic performance, with the power conversion efficiency increasing from 5.86% for the spin-coated device to 7.12% for the electrospun PVDF-TrFE:PCDTBT:PCBM device. The enhanced performance is attributed to the synergistic effect of the interconnected nanofibrous morphology and the ferroelectric polarization of PVDF-TrFE, which facilitate efficient charge separation and carrier extraction. Overall, this study demonstrates that electrospun ferroelectric composite nanofibers provide an effective active-layer engineering strategy for improving the efficiency of solution-processed organic solar cells and offer a promising platform for future high-performance and flexible photovoltaic devices.

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#### **Declaration of Competing Interest**

The authors declare no conflicts of interest.

#### **Data availability**

Data will be made available on request.

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