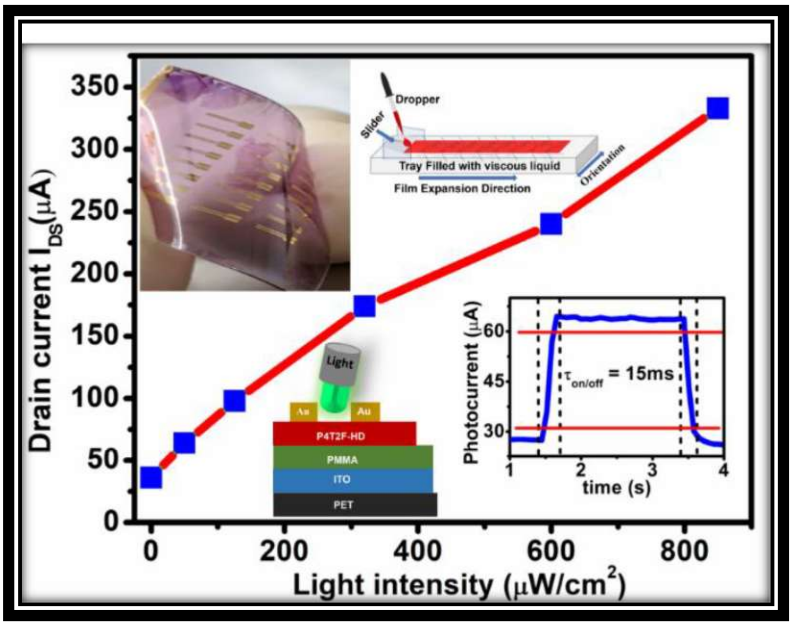
Chapter 4

Fabrication of Highly Sensitive Flexible Phototransistors through Unidirectional Floating Film Transfer Method Using P4T2F-HD Thin Film



This chapter discusses the fabrication of highly sensitive, flexible organic phototransistors (OPTs) using a unidirectional floating film transfer method. This technique helps preserve polymer-based dielectrics, overcoming degradation issues common in conventional methods.

4.1. Introduction

In the realm of optoelectronics, the quest for flexible, lightweight, and highly sensitive sensing devices has led to burgeoning interest in organic phototransistors (OPTs)[100-106]. These devices, pivotal in converting light into electrical signals, stand at the forefront of innovations aimed at revolutionizing applications ranging from digital imaging and optical communication to environmental monitoring and healthcare diagnostics[104, 107-109]. The escalating demand for OPTs stems from their inherent advantages over their inorganic counterparts, including mechanical flexibility, low-cost fabrication, and the potential for integration into wearable technology and flexible displays[76, 102, 110-112]. To develop flexible OPTs, extensive research is being conducted on polymer semiconductors and polymer dielectrics[113]. These materials are particularly valued for their ability to be processed in solution form and their inherent flexibility, making them ideal candidates for flexible and printable electronics. Nevertheless, there are a limited number of polymers that have yet to be fully investigated for potential applications. It is crucial to explore new materials for organic phototransistors and other electronic applications. For instance, P4T2F-HD is an emerging semiconducting polymer that has not yet been extensively investigated for organic field-effect transistor (OFET) and OPTs. This exhibits promising characteristics due to its fluorinated properties, making it a promising candidate for future research in these areas. However, the fabrication of OPTs using solution-processable polymer semiconductors and polymer dielectrics presents particular difficulties. Notably the requirement for orthogonal solvents, this issue has been highlighted in previous studies, indicating a significant barrier to efficient manufacturing processes[74, 85, 114]. Incorporating polymeric dielectrics into OPTs presents difficulties related to hydrophobic interfaces[111]. Interactions involving polymers and hydrophobic surfaces may result in compromised adhesion, varying surface energies, and incomplete coverage at the interface, thereby jeopardizing the efficiency and durability of the devices[115]. Additionally, identifying appropriate orthogonal solvents capable of dissolving and applying various organic materials without harming the pre-existing layers poses a considerable challenge[102]. Zhang and team have effectively engineered a fully polymeric organic phototransistor (AP-OPT) by employing solution-processable regio-regular poly(3-hexylthiophene) (rr-P3HT) and poly(methyl methacrylate) (PMMA), using a specialized orthogonal solvent during their fabrication process.[116]. Nonetheless, the AP-OPT demonstrates a limited photo response, with a photosensitivity rating of 1000 and a responsivity of 22 mA/W. The process of fabricating films from polymer solutions often leads to the degradation of organic gate dielectrics, an issue that continues to occur despite the use of orthogonal solvents[48, 117]. Park and their team introduced a novel dry transfer technique for producing P3HT-based polymer organic field-effect transistors (OFETs) that circumvents the issue of solvent compatibility[117]. This technique involves the use of a hydraulic press to transfer the polymer, effectively avoiding the solvent-related degradation of underlying layers. However, this method introduces its own set of challenges; specifically, the use of a hydraulic press can be complex and may risk damaging the bottom layers due to the exerted pressure. Consequently, there is a significant interest in developing an alternative semiconducting polymer deposition method that minimizes impact on the already deposited gate dielectric layer, thereby preserving the integrity and performance of the device.

In the quest to enhance organic phototransistors (OPTs), researchers have faced numerous obstacles, ranging from the orientation of thin films to the compatibility of solvents with underlying layers[88, 118, 119]. These challenges stem from the intrinsic properties of solution processable polymer semiconductors and dielectrics, which, while offering flexibility and ease of processing, introduce difficulties in achieving optimal device performance and stability[120, 121]. Techniques such as using orthogonal solvents and dry transfer methods have been explored to mitigate issues like polymer degradation and damage to bottom layers during fabrication[122, 123]. Despite these efforts, achieving a balance between high device performance and material compatibility has remained elusive. Addressing these challenges, my group has innovated the Unidirectional Floating Film Transfer Method (UFTM) as a pioneering solution in fabricating OPTs. This technique enables the fabrication of well-aligned thin films made from organic semiconductor polymers. One of the key advantages of UFTM is its ability to separate the process of forming oriented thin floating films from their transfer onto a chosen substrate. This segregation ensures that the solvent does not adversely affect the dielectric layer beneath. Furthermore, UFTM offers unparalleled precision in controlling the morphology, thickness, and interfacial characteristics of the film. Such meticulous management enhances charge transport and, by extension, the performance of the final device, presenting a substantial leap forward in the field of OPT fabrication.

In the present study, I have utilized UFTM to fabricate organic thin films at the air-liquid interface, employing PMMA as the dielectric material. By integrating these approaches, we are pioneering the development of flexible OPTs. This innovative application of UFTM enables the fabrication of exceptionally uniform and well-oriented thin films, essential for the high performance of OPTs. The use of PMMA as a dielectric layer further enhances device flexibility and stability, marking a significant advancement in the fabrication of flexible electronic devices. Through this study, my aim is to demonstrate the effectiveness of UFTM in overcoming challenges in OPT production, which may pave the way for the next generation of flexible electronics.

4.2. Materials and Methods:

4.2.1. Materials:

The semiconducting polymer known as P4T2F-HD is a distinguished material procured from Ossilla Co. It is chemically designated as $(C_{48}H_{70}F_2S_4)n$, and has been identified with an average molecular mass around the order of 43 kDa, and its chemical structure of polymer is shown in ***Figure 2.1(b).*** Its CAS registry number is 1260685-66-2. The polymer is lauded for its notable ease of processing and robustness against environmental factors, making it an exemplary material for a plethora of technological applications. Key reagents, including PMMA, ethylene glycol, and chloroform, were supplied by Sigma Aldrich. The PMMA obtained from Sigma Aldrich possesses a molecular weight of roughly 125 kDa. Additionally, the ITO-coated PET films, which serve as substrates in the fabrication of electronic devices, were procured from Global Nanotech Ltd. Toluene, essential for the surface treatment processes, was sourced from TCI, ensuring that all materials used meet the high standards required for the development of advanced optoelectronic devices.

4.2.2. Device Fabrication:

P4T2F-HD thin film OPTs were fabricated on ITO-coated PET substrates. The integration of P4T2F-HD thin films into flexible OPTs necessitated a meticulous fabrication process as shown in ***Figure 4.1.*** To eliminate any residual impurities, the substrate was ultrasonicated in acetone and isopropyl alcohol (IPA) for 10 minutes each, then dried and annealed at 80°C for 30 minutes. Prior to the P4T2F-HD deposition, the surface was coated with a 6 wt.% PMMA solution, which was spin-coated at 2000 rpm to achieve a smooth, insulating layer[124]. Subsequently, the P4T2F-HD thin film, optimized through the UFTM technique, was carefully aligned and transferred onto the PMMA surface[125]. An additional annealing at 80°C was performed to perfect the film's conformation to the substrate. The OPT fabrication was completed by thermally evaporating a 60 nm thick gold layer through a nickel shadow mask to form precise source and drain electrodes, with channel lengths 60 µm and a width of 2.8 mm.

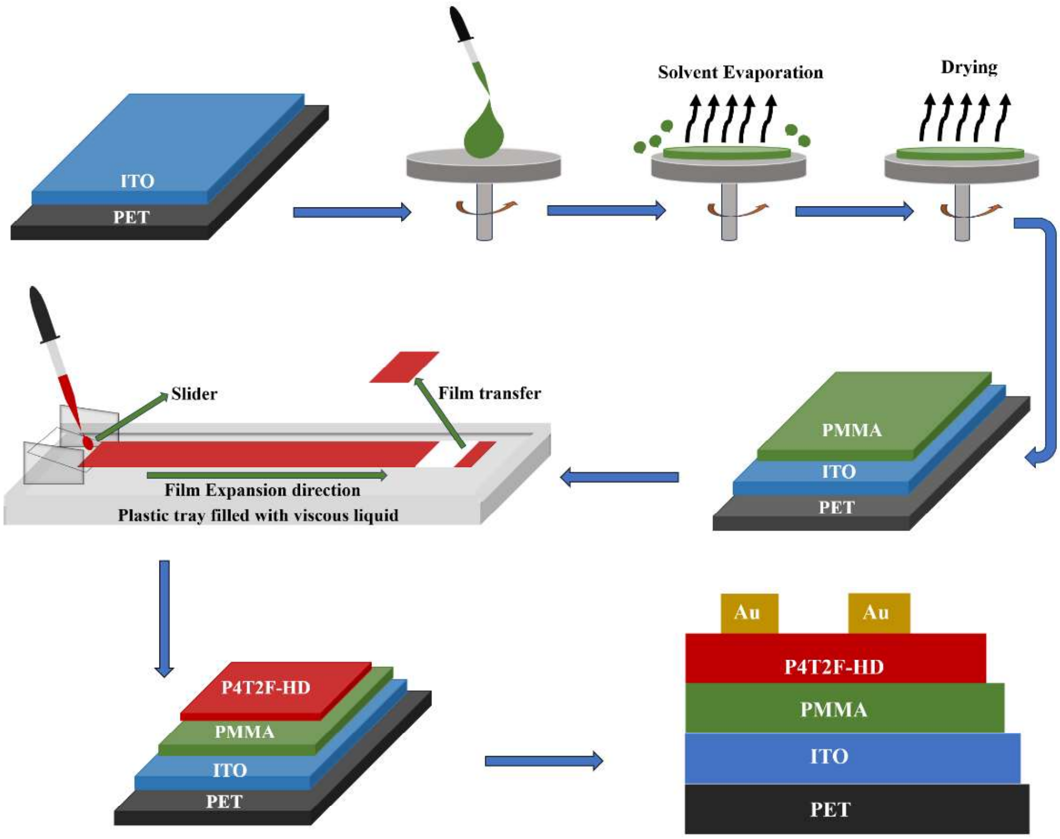


Figure 4. 1 *Schematic represents the fabrication of OPTs.*

4.3 Results and Discussion:

4.3.1. Dielectric Characterizations:

4.3.1.1. Surface Characterization:

PMMA thin film was characterized using AFM, as illustrated in ***Figure 4.2 (a),*** and its three-dimensional view in ***Figure 4.2 (b)***. These images reveal that the PMMA thin film has a smooth surface, with a root mean square roughness (R_q) of 147.23 pm, indicating a high degree of smoothness. ***Figure 4.2 (c)***, high-resolution SEM (HR-SEM) imaging has been used to observe the surface morphology of the PMMA thin film. The resulting micrographs exhibit a uniform and smooth surface texture, reflective of an optimal film formation technique. Such smoothness is critical for facilitating uniform layering and the formation of interfaces within multilayered device structures. ***Figure 4.2 (d)*** provides a cross-sectional SEM of PMMA dielectric thin film thickness about 851 nanometers. The utilisation of PMMA with a film thickness exceeding 800 nm in this paper has resulted in a notable reduction in pinholes and other defects, thereby enhancing the dielectric strength of the material.

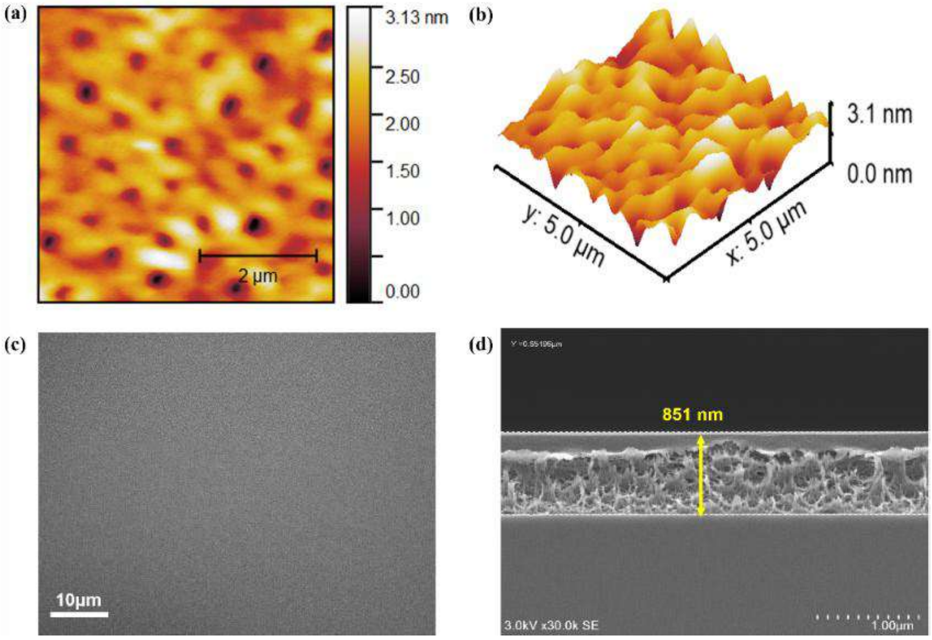


Figure 4. 2 *(**(a)** 2D AFM image of PMMA thin film, **(b)** 3D-AFM imager of PMMA, **(c)** SEM image of PMMA thin film **(d)** cross-sectional SEM image of PMMA dielectric.*

4.3.1.2. Leakage Current Characterization:

I measured the leakage current characteristics of the PMMA dielectric by fabricating a metal-insulator-metal (MIM) structure. This MIM structure, with an active area of 0.15 cm^2, was designed to simulate the electrical behavior of the dielectric under the applied voltage. Leakage current was measured to assess the insulating quality of PMMA, as excessive leakage would lead to energy dissipation and reduced device reliability. The results of these measurements, including the current density vs. voltage (J-V) characteristics, are shown in ***Figure 4.3.*** The areal capacitance of the gate insulator was 6 nf/cm^2 [124].

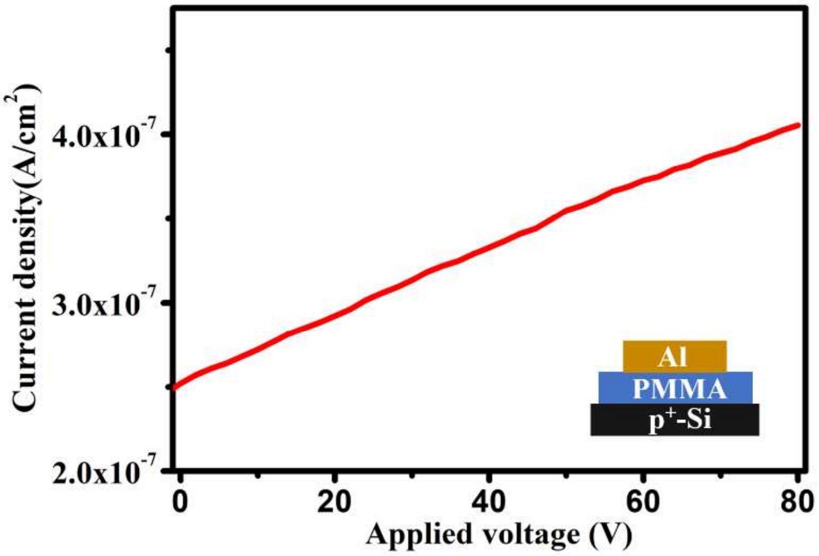


Figure 4. 3 *Leakage current vs applied voltage for PMMA dielectric.*

4.3.2. P4T2F-HD Thin Film Characterization:

4.3.2.1. XRD Analysis:

Out-of-plane XRD and in-plane GIXD measurements were performed to investigate the thin-film crystallinity and observe the macromolecular orientation of the P4T2F-HD thin film. Out-of-plane XRD for the P4T2F-HD films is shown in ***Figure 4.4(a)***, which exhibit sharp diffraction peaks (*h*00) associated with the lamellar stacking of the side chains up to the 3rd order at 4.67, 9.29, and 13.99°. These observations indicate that the prepared film is crystalline. The presence of well-defined peaks, particularly at the (100), (200), and (300) lattice planes, indicates that the polymer chains are preferentially oriented parallel to the substrate surface, thereby confirming the effectiveness of the UFTM in achieving high orientation. In-plane GIXD of P4T2F-HD films is shown in ***Figure 4.4 (b)***. No diffraction peaks associated with alkyl side chains were observed, and only (0*k*0) diffraction peak related to the π–π stacking was observed at 22.6°, reflecting that all the crystallites are edge-on oriented. Further, the lamellar spacing was calculated from the lattice plane of (100) based on the out of plane XRD data, yielding a value of 19.18 Å. The characterization of the P4T2F-HD thin films via XRD not only validates the structural integrity and orientation induced by the UFTM but also predicts the promising electronic properties of the resulting flexible phototransistor[91]. The highly ordered structure is a precursor to superior optoelectronic performance, potentially translating to enhanced sensitivity and stability in the final device applications.

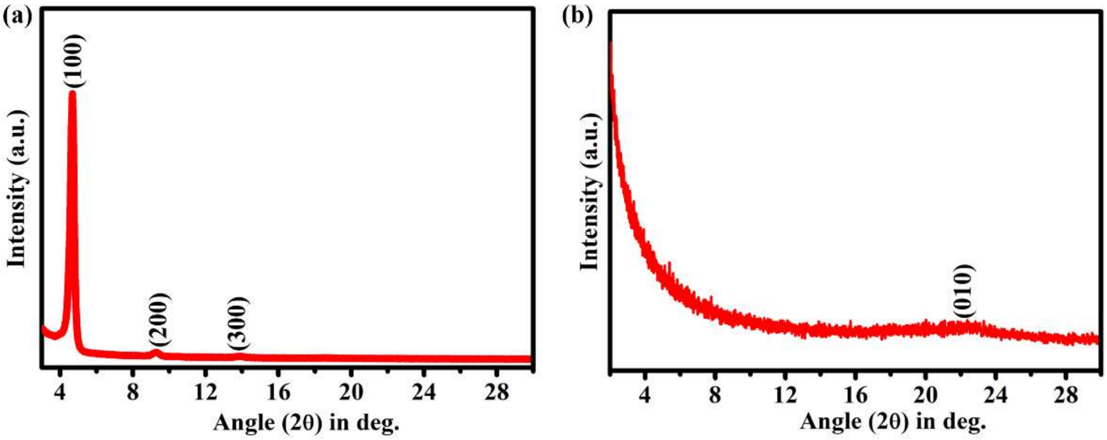


Figure 4. 4 ***(a)*** *Out of plane XRD pattern of thin film* ***(b)*** *represents the in plane XRD pattern of thin film.*

4.3.2.2. Optical Analysis:

The thin film of P4T2F-HD, fabricated using the UFTM, underwent comprehensive optical characterization to determine its electronic absorption profile in the solid state. ***Figure 4.5(a)*** shows the thin film fabricated by UFTM. The thin film of P4T2F-HD is shown being transferred onto a target substrate. The transfer process is critical as it determines the orientation and the uniformity of the film, which are crucial parameters for the film's optoelectronic properties. As depicted in ***Figure 4.5 (b)***, the absorption spectrum revealed a prominent peak absorption (λ_{max}) at 553 nm, indicating the principal electronic transition of the polymer. Additionally, the spectrum exhibited notable vibronic shoulders at 600 nm, which are characteristic of the molecular structure of P4T2F-HD and its electronic conjugation. To assess the molecular orientation of the P4T2F-HD film, the optical dichroic ratio (DR) was calculated. The DR is a quantitative measure obtained from polarized UV-visible absorption spectroscopy, where $A\|$ and $A\perp$ are the absorbances parallel and perpendicular to the polymer chain alignment, respectively, at the peak wavelength (λ_{max})[126]. The images in ***Figure 4.5(c) and 4.5 (d)*** demonstrates a significant dichroism, indicating a higher absorbance when the polarization of light is aligned parallel to the flow direction of the film ($A_{\|}$) compared to the perpendicular orientation ($A_{\perp}$)[127], and DR was calculated as about 3.5. This phenomenon is indicative of a high degree of molecular alignment within the film. The anisotropy in the optical properties, as evidenced by the polarized UV-Vis absorption, suggests that the UFTM process has effectively induced a high degree of molecular orientation in the P4T2F-HD thin films. This orientation is likely to have a pronounced effect on the charge transport properties of the film, which is pivotal for the performance of phototransistors made from these materials.

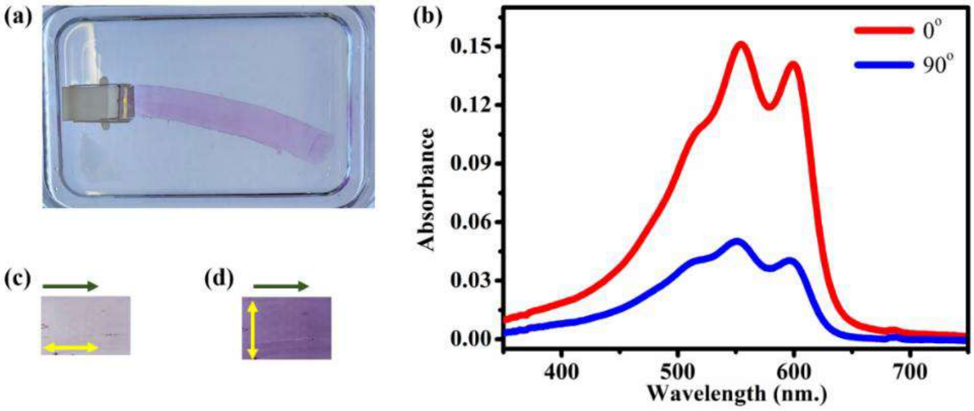


Figure 4. 5 ***(a)*** *Represents the image of UFTM thin film on air-liquid interface* ***(b)*** *represents the polarized UV-Spectrum of P4T2F* ***(c) & (d)*** *represents the polarized image of thin film in which green arrow represents the flow direction while yellow double-sided arrow presents the polarizer direction.*

4.3.2.3. Surface Characterizations:

Our research delves into the detailed examination of thin film surface morphology and the surface characteristics of a conducting polymer, P4T2F-HD. I employ both AFM and SEM for detailing the film orientation at a nanometre scale, and morphological insights. ***Figure 4.6 (a)*** represents the topographical nuances of the P4T2F thin film captured via AFM. A highlighted blue arrow indicates the direction of the polymer chains' predominant orientation, a factor that is integral to the assessment of the material's anisotropic electrical and optical properties. Additionally, the root mean square roughness (R_q) of the P4T2F-HD thin film was 1.5 nm. As demonstrated in ***Figure 4.6 (b),*** HR-SEM imaging has been used to observe the surface morphology of the PMMA thin film. The resulting micrographs exhibit a uniform and smooth surface texture, reflective of an optimal film formation technique. Such smoothness is critical for facilitating uniform layering and the formation of interfaces within multilayered device structures.

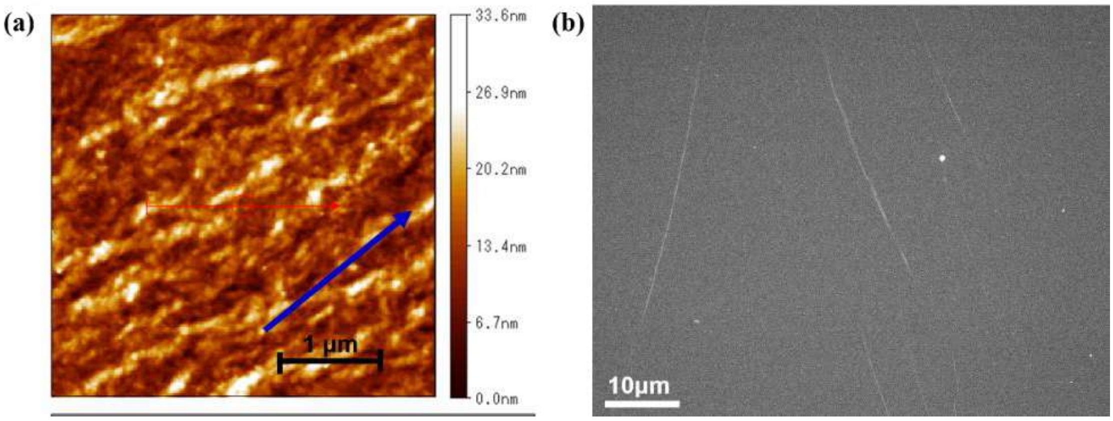


Figure 4. 6 *(a) Represents AFM image of P4T2F thin film,* ***(b)*** *SEM image of P4T2F-HD, thin film.*

4.3.3. Electrical Characterization of OPTs:

The alignment of polymer chains significantly improves the efficiency of organic photovoltaics. To leverage this, devices with channels that are aligned parallel to the orientation of polymer chains have been fabricated. Furthermore, ***Figures 4.7 (a)*** and ***4.7 (b)*** display the output and transfer characteristics of the OPTs, respectively. The transfer characteristics are crucial for understanding the behavior of the devices under various conditions and were specifically recorded at V_D of -80 V. The device's output characteristics affirm the attributes of P-type transistors. Further field-effect mobility (μ), a key indicator of device performance, was calculated from the saturation region of the transfer characteristics using a specific formula, referred to as ***Equation 4.1.***

$$I_{DS} = \frac{\mu C_i W}{2L}(V_{GS} - V_{DS})^2 \tag{4.1}$$

Field-effect mobility (μ) was determined by evaluating the slope of the curve that represents the square root of the source-drain current $I_D^{1/2}$plotted against the gate voltage V_G within the saturation region of the device[66]. The calculated average mobility of the devices is 0.21 cm²/V.s.

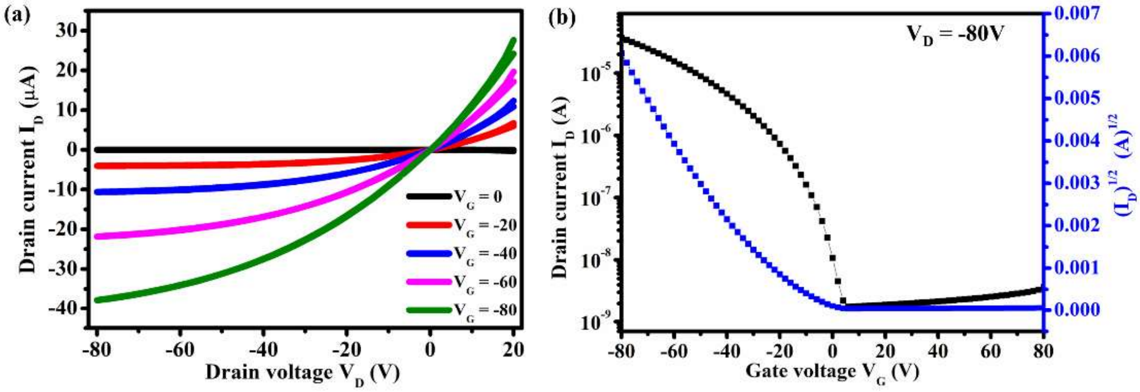


Figure 4. 7 *(**a**) Represents the output characteristics of the device (**b**) represents the transfer characteristics of device.*

4.3.3.1. OPTs Sensing Measurement

Electrical properties of OPTs devices were assessed in ambient environments, in dark room and upon exposure to green light at a wavelength of 540 nm, with intensity levels spanning from 50 to 850 μW/cm^2, as illustrated in ***Figure 4.8 (a)***. This experimental setup allowed for the observation of distinct behaviors in the device's operation, particularly in terms of the accumulation and depletion mode currents, which exhibit a marked increase in response to escalating light intensities, as depicted in ***Figure 4.8 (a).*** Notably, the increase in depletion mode current surpasses that of the accumulation mode, underscoring a differential sensitivity to light within these operational modes. Further results reveal a positive shift in the threshold voltage (V_{th}) of the device correlating with the intensity of the incident light. This phenomenon, along with the observed enhancement of the drain current (I_D), is attributed to the generation of charge carriers, electrons and holes prompted by the light exposure. Such effects are discernible even at the lower end of the light intensity spectrum, specifically at 50 $\mu W/cm^2$, highlighting the device's pronounced sensitivity to green light. The underlying mechanism involves the absorption of green light by the channel semiconductor within the OPT, which facilitates the separation of photo-generated excitons into free charge carriers, namely electrons and holes. The integration of these photogenerated holes into the channel's carrier concentration serves to augment the accumulation mode drain current (I_D). Conversely, the photogenerated carriers exhibit a relatively static behavior under these operational conditions, contributing to the positive shift in the threshold voltage (V_{th})[128, 129]. As the device transitions to depletion mode, the conductive role of these photogenerated electrons becomes prominent, leading to a reduction in the sheet resistance of the organic semiconductor channel. This reduction, in turn, enhances the 'off current' of the device, indicative of a significant modulation in device performance attributed to the dynamic interaction between the organic semiconductor material and incident light. Further to evaluate the performance of OPTs, key parameters such as responsivity (R), sensitivity (S), and detectivity (D) are calculated using ***(equations 1.11, 1.12,1.13)*** to understand its effectiveness in light detection[130, 131].

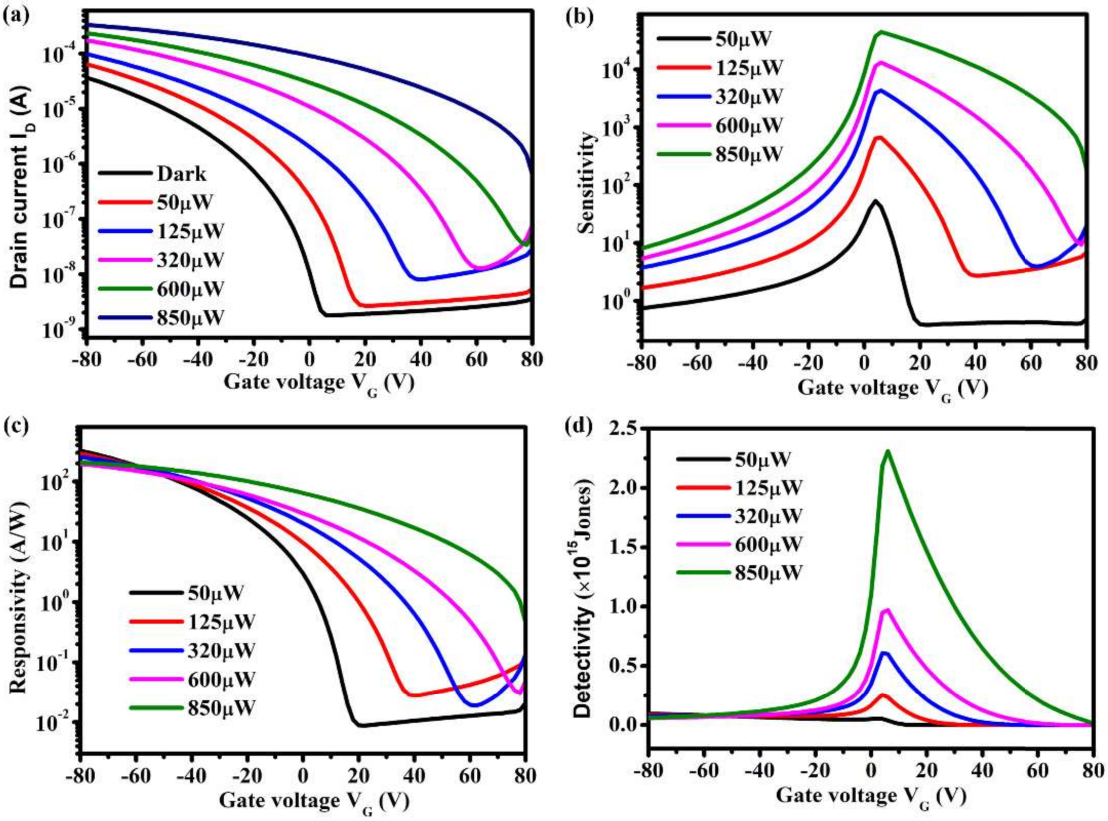


Figure 4. 8 ***(a)*** *Represents the drain current versus gate voltage with variable light intensity* ***(b)*** *represents the sensitivity of device at different gate voltage with varying in the intensity of light* ***(c)*** *represents the responsivity of device at different gate voltage with varying in the intensity of light* ***(d)*** *represents the detectivity of device at different gate voltage with varying in the intensity of light*

The sensitivity analysis, plotted in ***Figures 4.8 (b)***, reveals that the phototransistor exhibits more efficient sensitivity in the depletion mode compared to the accumulation mode, especially at higher light intensities. For instance, under a lower intensity of 125 µW/cm², sensitivity reaches approximately 169% at -80V and 689% at 80V in accumulation and depletion modes, respectively. At a higher intensity of 850 µW/cm², these values dramatically increase to 808% and 17,600% correspondingly. The responsivity of the OPT was thoroughly examined under various light intensity as shown in ***Figure 4.8 (c)***, emphasizing the device's behavior in both accumulation and depletion modes. At a relatively low light intensity of 125 µW/cm², the OPT demonstrated significant variations in responsivity, which is a critical parameter in evaluating the sensitivity of photodetectors.

In accumulation mode, the responsivity reached as high as 292 A/W, illustrating the device's exceptional sensitivity and efficiency in converting light into electrical current. Conversely, in depletion mode, the responsivity was markedly lower, recorded at only 0.1 A/W. This stark contrast in responsivity between the two modes underscores the OPT's potential for high-sensitivity applications, as it can be effectively tuned by altering the mode of operation depending on the required sensitivity and operational conditions. The detectivity of the OPTs under investigation demonstrates considerable variability based on the mode of operation and the intensity of incident light. Specifically, at a lower light intensity of 125 µW/cm², the device exhibits a detectivity of approximately 8.5×10^{13} Jones in accumulation mode and 3.5×10^{12} Jones in depletion mode, indicating robust sensitivity to light. This high level of detectivity, as shown in ***Figure 4.8 (d)*****,** underscores the device's effectiveness in weak light conditions. Conversely, when the light intensity is increased to 850 µW/cm², the detectivity in accumulation mode significantly decreases to around 1.3×10^{13} Jones. This decrease could be linked to several factors, including photocurrent saturation or thermal effects that influence the semiconductor properties of the device under elevated light conditions[132].

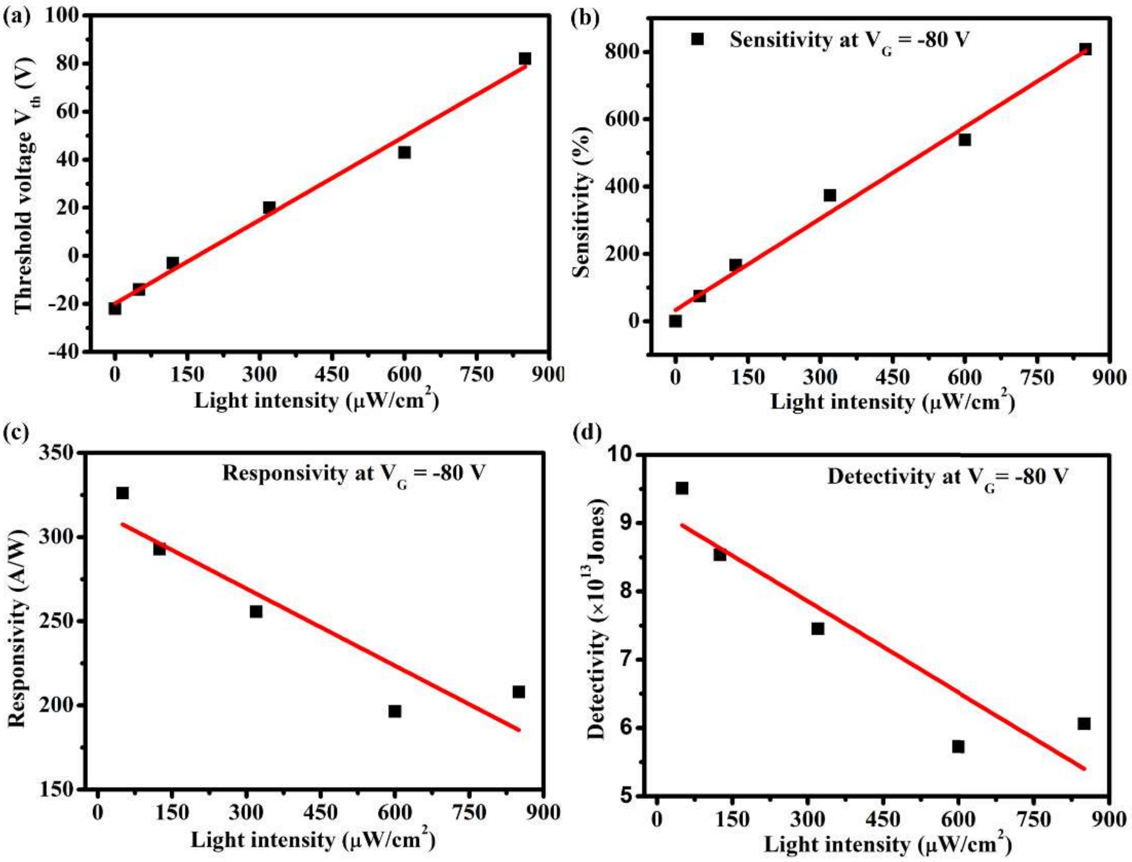


Figure 4. 9 ***(a)*** *Represents the shift in the threshold voltage with light intensity* ***(b)*** *represents the sensitivity with light intensity at V_{GS} = -80V* ***(c)*** *represents the responsivity with light intensity at V_{GS} = -80V* ***(d)*** *represents the detectivity with light intensity at V_{GS} = -80V*

The comprehensive performance analysis, including threshold voltage shifting, sensitivity, responsivity, and detectivity across different light intensities, is thoroughly shown in ***Figure 4.9(a-d)*** at a fixed gate voltage of -80 V. These measurements provide a detailed insight into how the device's performance metrics change under varying operational conditions. The performance of the OPT discussed in this work has been compared with existing literature and summarized in ***Table-4.1.*** The comparison reveals that our OPT exhibits notably improved performance metrics. This enhancement is largely attributed to the directional growth of the P4T2F-HD organic semiconductor within the device's channel. The unidirectional alignment of the semiconductor molecules likely promotes more streamlined charge transport, which is crucial for both the heightened responsivity and the swift switching behavior observed in our OPT. Such improvements in charge carrier dynamics are indicative of the potential advancements that can be achieved through careful material structuring in organic semiconductor channels, and they position our OPT as a competitive candidate for sophisticated optoelectronic applications[88].

Table 4.1: Comparative study of current work with previously reported.

S.No.	Semiconductor materials	Fabrication method	Mobility (cm²/V. s)	Intensity	Responsivity (A/W)	Remark
1	EHPDI	Spin Coating	0.08	91 mW/cm^2	0.024	Low mobility as well as low responsivity[133]
2.	PBIBDF-TT	PDMS	5×10^{-3}	47.1 mW/cm^2	0.44	Very low Responsivity[67]
3.	Perylene diimide	Spin coating	2.1×10^{-3}	5 mW/cm^2	120	Low mobility and low drain Current[134]
4.	BPE-PTCDI	Nonsolvent nucleation	0.018	36 mW/cm^2	0.033	Poor responsivity and mobility[135]
5.	**P4T2F-HD**	**UFTM**	**0.212**	**850 µW/cm^2**	**207**	**This Work**

This characteristic is further supported by the absorption properties of the P4T2F-HD material, as presented in ***Figure 4.5(b).*** The material's UV-Visible spectrum demonstrates a significant absorption peak coinciding with this wavelength, affirming the device's predisposition for selectivity. Such a wavelength-specific detection capability positions the device as a particularly useful asset in specialized optical sensing and imaging applications where the detection of specific wavelengths is imperative. Moreover, the transient response of the OPT characterized by the device's behaviour to shifts in light intensity was meticulously assessed. The phototransistor's transient response to different wavelength light pulse at an intensity of 125 μW/cm² is depicted in ***Figure 4.10 (b).*** This graph reveals that the device boasts a rapid rise time of approximately 125 milliseconds, followed by an impressive recovery time of about 100 milliseconds to return to its initial state as shown in ***Figure 4.10(a)***. These metrics underscore the phototransistor's capability for quick adaptation to changing light conditions, indicating its viability for applications that necessitate swift responses to dynamic optical signals.

4.3.3.2. Flexibility Measurement:

To assess the device's flexibility, the phototransistors underwent bending tests with a curvature radius of 1 cm. These tests were conducted in directions parallel and perpendicular to the channel, as depicted in the insets of ***Figure 4.10 (c)* and *4.10 (d)*** respectively. This mechanical stress test aimed to simulate the real-world conditions that flexible devices often endure and to observe the consequent effects on the transfer characteristics of the device. Throughout the bending cycles, the performance of the phototransistors was carefully monitored. The evaluation focused on key parameters such as the shift in threshold voltage, any changes in the subthreshold slope, and alterations in the on/off current ratio. The bending was performed for multiple cycles to rigorously assess the endurance of the device. The data revealed that the device demonstrated remarkable mechanical robustness. Despite being bent in both orientations relative to the channel, the device maintained consistent transfer characteristics. The threshold voltage remained stable, and no significant degradation was observed in the current modulation ability of the device. This consistency across numerous bending cycles underscores the device's suitability for applications that demand high mechanical flexibility without sacrificing electrical performance. This finding is particularly relevant for the emerging field of wearable electronics and soft robotics, where devices are not only expected to bend but also to withstand repeated mechanical deformation while maintaining optimal performance.

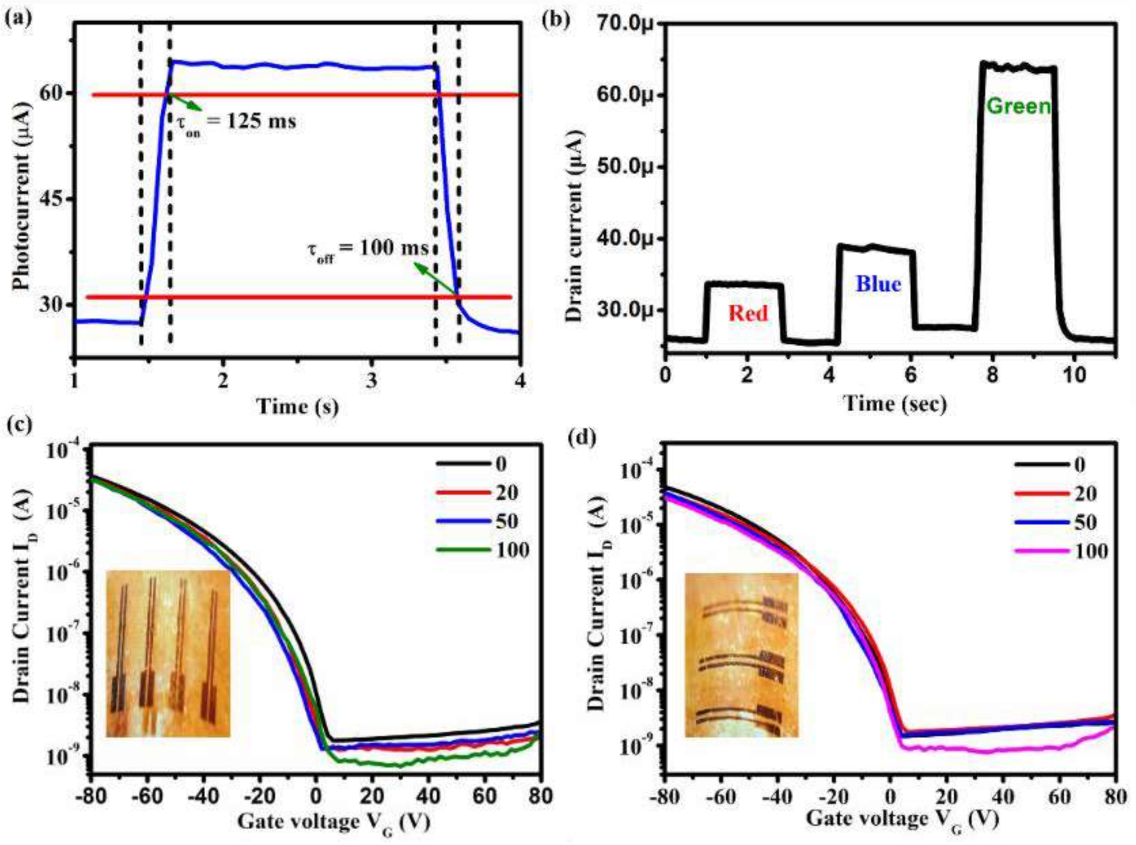


Figure 4. 10 ***(a)*** *Represents the transient response with time* ***(b)*** *represents the photo response under different wavelength* ***(c)*** *represents the* I_D-V_G *with different bending cycle parallel to channel width* ***(d)*** *represents the* I_D-V_G *with different bending cycle, bending is parallel to channel length*

4.3.3.3. Stability Measurement:

The long-term stability of OPTs is a pivotal aspect of their practical application in flexible electronics and optoelectronic devices. To assess the robustness and operational longevity of these OPTs, I initiated a comprehensive stability test under varying environmental conditions. Our approach involved a methodical evaluation of the electrical properties of the OPTs, such as the drain current behavior under dark and illuminated scenarios, charge carrier mobility, and the on/off current ratio over an extended period of 120 days. The stability test commenced with meticulously recorded baseline measurements to establish the initial performance benchmarks for the OPTs. This initial evaluation involved a comprehensive examination of the output and transfer characteristics, including measurements of threshold voltage, mobility, and the on/off ratio under both dark and illuminated conditions. Ensuing measurements were taken at regular intervals, and the results were meticulously compared to the initial data to ascertain any shifts or degradation in performance, which could indicate potential stability issues.

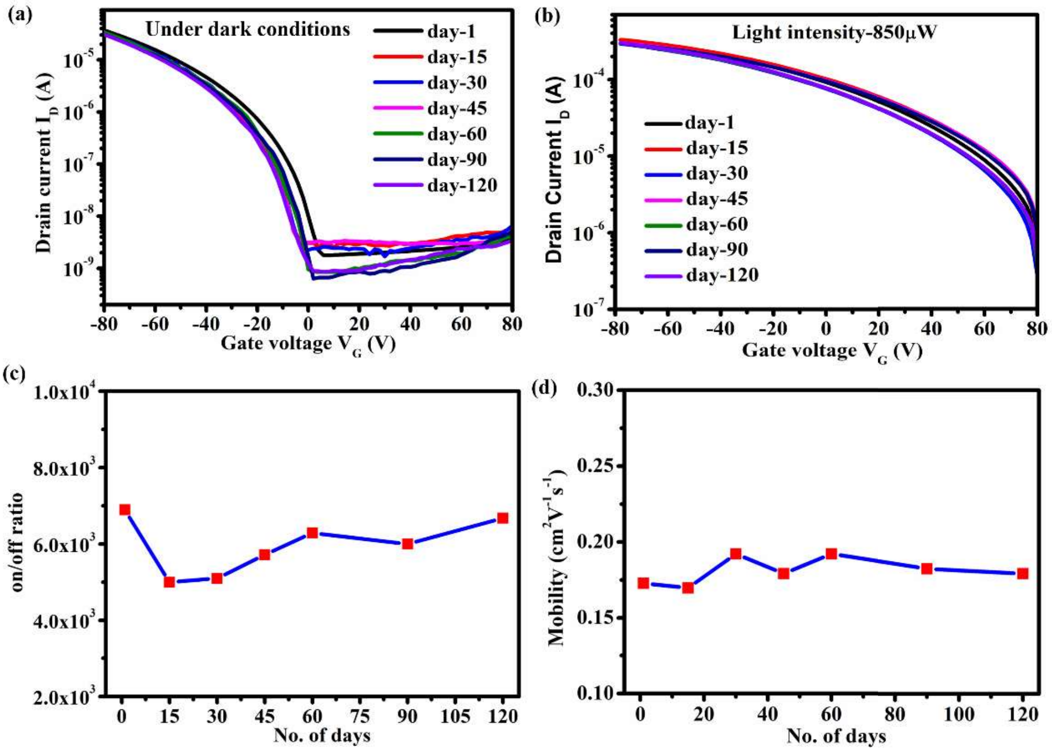


***Figure 4. 11 (a)** Represents the transfer characteristics of device with different no. of days **(b)** represents the transfer characteristics under illumination with different no. of days **(c)** represents the mobility v/s days **(d)** represents the on/off ratio v/s days*

Figure 4.11 (a) illustrates the device's stability under dark conditions, where transfer characteristics are measured for a span of 120 days. The data show how the electrical characteristics of the device evolve over time, reflecting the inherent stability of the device without the influence of light. ***Figure 4.11 (b)*** shows the device's performance under an illumination of light intensity of 850 μW/cm^2, measuring the photo response stability over the same period. The comparative analysis of the device's sensitivity to light, an essential aspect for optoelectronic applications where light is a significant operating factor. The device exhibits consistent mobility over the duration of the test, as shown in ***Figure 4.11 (c),*** which underscores the device's reliable charge transport characteristics. Similarly, ***Figure 4.11 (d)*** demonstrates a stable on/off ratio, effectively preserving the device's capability to differentiate between active and inactive states throughout the testing period. These findings are crucial as they demonstrate the device's potential for long-term operational stability.

4.4. Conclusion:

In conclusion, this study demonstrates the effective application of the unidirectional floating film transfer method to fabricate flexible phototransistors using P4T2F-HD thin films. This method has proven critical in minimizing the impact on underlying organic dielectric layers, leading to devices with remarkable photoresponsive characteristics such as a sensitivity of 167%, a responsivity of 292 A/W, and a detectivity of 8.5×10^{13} Jones at a light intensity of 125 μW/cm^2. Moreover, the fabricated devices showcased exceptional durability and maintained consistent performance despite undergoing multiple bending tests in various directions relative to the channel. This robustness, coupled with high sensitivity, underscores the potential of our approach for advancing flexible electronic applications where reliable and efficient optical sensing is crucial