Chapter 7

Summary and Future Scope

summary of the key findings presented throughout this thesis and discusses the potential future directions for my research.

7.1 Conclusion:

This thesis explores the great challenges and limitations linked with the fabrication of highly oriented thin films in electronics and optoelectronics, looking towards the critical relationship between film orientation, charge transport, and device performance. Classical fabrication methods for thin films can hardly attain the exact molecular alignment critical for optimal charge mobility, especially in organic semiconductors where directionality plays a pivotal role. Other issues include achieving dielectric stability in these films and scalability for producing them, which often turn out to be dependent on expensive or complex methodologies. To address such issues, this research work presents a low-cost technique for preparing highly oriented edge-on thin films. Utilizing the UFTM, this dissertation has successfully shown an avenue towards the achievement of desired alignments at the molecular level which would lead to improved charge transport yet stay consistent with good dielectric stability. Both, the use of the different polymers DPP-TTT, and P4T2F-HD at the liquid-air interface, help out the development of thin films with improved alignment and charge carrier mobility. Furthermore, I further investigate polymer nanocomposite thin films as a promising pathway for fine-tuning charge mobility, especially through anisotropic charge transport mechanisms, making use of both standard I-V characterization and electric-field-induced TRM-SHG analysis in order to gain more detailed information regarding carrier dynamics. Ultimately, this thesis provides a practical and scalable route for making thin films that overcome the current issues with the making of organic electronic devices, paving the way for the implementation of more efficient and flexible organic electronic devices.

At the initial stage of my PhD work, I used the UFTM to prepare highly oriented thin films in a specified direction that can allow better charge transport properties. During that study I chose P4T2F-HD as an organic polymer to fabricate thin films at the liquid-air interface.

This study clearly indicates that the charge carrier mobility along the major polymer chain orientation as against the transverse one. Then I looked into the anisotropic charge transport properties of such highly oriented P4T2F-HD thin films. For that purpose, I have used an electric-field-induced TRM-SHG for gaining insight into anisotropy of charge transport. The TRM-SHG proved to be useful in revealing more details about dynamics of charge transport in oriented P4T2F-HD thin films, giving time-resolved information about how molecular orientation influences charge mobility under an electric field. My results show a significant directional disparity: mobility was 6×10^{-2} $cm^2/V\cdot s$ parallel to the film orientation but much less, 4.01×10^{-3} $cm^2/V\cdot s$, perpendicular to it. Further, TRM-SHG showed maximum mobility of the film is ~ 0.045 $cm^2/V\cdot s$ in the preferred direction whereas the minimum mobility is recorded to be ~ 2.1×10^{-3} $cm^2/V\cdot s$. These findings promote how molecular orientation within thin film directly affects the device performance which is very crucial information to fabricate high performance organic thin film devices.

In addition, it is observed from the research that an FTM performs a transmutative function in the formation of OPT based on polymers and, above all, through the P4T2F-HD polymer. This polymer is known for its unique optoelectronic characteristics and especially supports its application with UFTM, as this preserves dielectric purity and enables the polymer's semiconducting chains to become highly aligned. Whereas the other non-conventional fabrication techniques sacrifice the stability and the orientation of the P4T2F-HD, UFTM shows stable devices, which are really excellent for photoresponsive materials properties-sensitivity to 167%, responsivity to 292 A/W, and detectivity of 8.5×10^{13} Jones, and these are particularly improved at very low illumination levels, 125 $\mu W/cm^2$. Another very interesting property of OPTs was their mechanical properties, which were remarkable as they exhibited excellent mechanical robustness during repeated bending tests with the functionalities of the devices being uniformly intact even after the tests. The following

results underline the unique capabilities of UFTM in making mechanically flexible high-sensitivity optoelectronic devices with exceptional quality P4T2F-HD.

Further, I have successfully fabricated a near-infrared (NIR) sensitive organic phototransistor (OPT) with low operating voltage, using the UFTM to improve charge transport in the active layer. In this work I integrated sol-gel derived Li-Al_2O_3 gate dielectric into an organic semiconductor device. This ion-conducting oxide thin film shows areal capacitance of 410 nF/cm² that enables me to achieve a stable, low-voltage operation voltage (~2.0 V) OPT. The UFTM approach enabled the formation of a highly oriented organic semiconductor layer with a notable dichroic ratio of 1.76, facilitating enhanced charge mobility (0.21 cm²/V·s) through the channel. This precise alignment of polymer chains contributed to the OPT's impressive photosensitivity (97%) at low NIR power (120 μW/cm²) and high photoresponsivity (~77 A/W), along with a specific detectivity of 1.4×10^{10} Jones under accumulation mode. The study highlights the potential of integrating ion-conducting dielectrics with unidirectionally oriented organic films to fabricate high-performance, low-voltage optoelectronic devices. This unique approach not only advances the functionality of organic semiconductor devices but also paves the way for scalable, cost-effective, and energy-efficient solutions in flexible electronics.

Finally, OFETs have been fabricated through the integration of an organic/inorganic composite material. This development and analysis of OFETs has been made through the integration of a composite material comprising DPP-TTT and C_3N_5. The strategic incorporation of C_3N_5 nanoflakes within the DPP-TTT matrix significantly improved carrier mobility of the transistor, as indicated by a fivefold increase in average saturation mobility to 0.41 cm²/Vs. This enhancement was extensively evaluated using EFI-SHG measurements, which offered a clear visualization and quantification of the enhancement of mobility. The improvements in mobility are attributed to the structural role of C_3N_5,

which promotes a more orderly lamellar packing, facilitating efficient charge transport while reducing trap densities within the OFETs. This work highlights the importance of composite material design in optimizing the performance of organic electronic devices. By demonstrating how C_3N_5 nanoflakes act as templates to enhance charge transport and stability, our findings contribute valuable insights to material science and organic electronics, setting a foundation for future developments in high-performance, efficient organic devices.

7.2 Future Prospects:

This thesis works successfully demonstrated that without relying solely on traditional electrical measurements, we can gain a direct, non-invasive view of charge transport dynamics at the nanoscale by incorporating methods such as time-resolved second harmonic generation (TRM-SHG). Real-time probing of molecular orientation and the associated anisotropic charge carrier mobility by TRM-SHG provides critical information on the underlying connection between polymer ordering and device performance. This method makes it possible to precisely adjust molecular alignment, which directs the creation of flexible electronics and optoelectronics with great performance. The prospects for the future of the current work include:

- A more thorough study of orientation behavior will make it possible to logically design polymer thin films with controlled anisotropy. Techniques like TRM-SHG may help in identifying the critical factors that determine chain alignment in order to guide efforts to induce orientation in polymers that are not intrinsically liquid crystalline.
- Technique of molecular alignment can be explored for n-type conjugated materials, since high increases in electron mobility are possible through high molecular align

thin film as of p-type polymers, so that complementary logic circuits fabrication would be possible by using UFTM deposition method.

- Orthogonally stacked materials that exhibit orientation-dependent optical properties may make changeable-colour LEDs based on polarization of incident light feasible. Such devices would provide polarization-tunable or "colour-changing" LEDs for sophisticated applications in sensing, signalling, and information display and will open up new possibilities for interactive lighting systems and display technologies.
- Such orientation and visualization approaches applied to ultrathin, flexible substrates will make it easier to create conformable sensors that may be incorporated into the human body. With controlled anisotropy and enhanced charge carrier transit, one would develop extremely sensitive, stretchy, and low-power sensors for soft robotics, skin-interfaced electronics, and human health monitoring.
- Neuromorphic computing components can also benefit from the improved charge dynamics and accurate molecular alignment made possible by UFTM. Strong, energy-efficient charge transfer is necessary for these devices, and the controlled anisotropy may help create artificial synapses and neurons that more closely resemble organic neural networks.