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Conclusions and Future Scope

Though many aspects of OFETs were explored for this dissertation and various outlined goals were achieved; a lot of research and development needs to be done before this technology matures with high performance flexible OFETs used in future commercial products. In this chapter, the scope of extension of the research work is discussed. A brief summary of the dissertation work and concluding remarks are discussed followed by discussion on future scope.

8.1 SUMMARY

With the aim of fabricating OFETs with superior performance using solution processed organic semiconductors, a high mobility and highly air stable organic semiconductor; TIPS-pentacene was selected to carry out research work. The desired improvement in the device performance was sought by means of enhancing the crystallinity of the active organic semiconducting layer and improving the quality of dielectric-semiconductor interface. Realization of improved device performance and stability on flexible substrates and their utilization in sensing applications were among the main goals of the research work in this thesis. With above aims, following experimental executions were performed and inferences were drawn;

I. Process of solvation of TIPS-pentacene, role of various intermolecular and intra-molecular forces in the process of solvation and overall effect on the final crystallinity of the TIPS-pentacene crystallites due to the presence and absence of additive solvents was comprehensively studied.

II. An analysis based on Hansen's solubility theory suggested that a binary mixture having higher dissimilarity between component solvents is a weaker solvent of TIPS-pentacene. A weaker solvent system is unable to overcome the binding forces in TIPS-pentacene and hence supports better molecular aggregation imparting higher degree of crystallinity in the resulting crystals. Due to the improvement in crystallinity, OFETs fabricated from toluene/hexane solvent demonstrated a more than two-fold improvement in the field-effect mobility as compared to that for toluene solvent.

III. To achieve high carrier mobility and electrical stability in TIPS-pentacene based OFETs, two types of devices were fabricated on Si/SiO_2 substrates; neat TIPS pentacene, and TIPS-pentacene:PS blends. TIPS-pentacene:PS blend devices outperformed the neat TIPS-pentacene devices with an average mobility of 1.5 $cm^2 V^{-1} s^{-1}$ (maximum of 2.6 $cm^2 V^{-1} s^{-1}$), which was much higher than neat TIPS-pentacene devices with average mobility values of 0.1 $cm^2 V^{-1} s^{-1}$. The high performance in the blend devices can be attributed to vertical phase separation which causes formation of a high quality dielectric-semiconductor interface and improves crystalline order in the active layer. In addition, TIPS-pentacene:polymer blend devices exhibited much lesser drain current decay (~30%) under the effect of bias stress compared to neat TIPS-pentacene devices (drain current decay of ~80%). TIPS-pentacene:PS blend devices experienced lesser charge trapping due to a fine quality of dielectric-semiconductor interface and hence devices were fully recoverable. However, the electrical characteristics of neat TIPS-pentacene devices could not be recovered completely even after rest duration of 24 hours due to extensive charge trapping in deep trap states. Repeatability studies also proved a high electrical stability in TIPS-pentacene:PS blend devices as compared neat TIPS-pentacene devices.

IV. The two types of OFET device strategies (neat TIPS-pentacene on HfO_2/PVP and TIPS-pentacene:PS blend HfO_2) were implemented on flexible substrates and were examined for their electrical performance and stability. Blend devices exhibited maximum field-effect mobility up to 0.93 $cm^2 V^{-1} s^{-1}$ with average of 0.44(±0.25) $cm^2 V^{-1} s^{-1}$ compared to 0.11(±0.08) $cm^2 V^{-1} s^{-1}$ for neat devices for -10 V operation. High I_{ON}/I_{OFF} of the order 10^5 and near zero V_{TH} were obtained for both type of devices. Blend devices outperformed their neat counterparts due to virtue of a high quality of dielectric-semiconductor interface and higher crystallinity of the active layer. In addition, under effects of bias stress, blend devices demonstrated lesser levels of current decay than neat devices.

V. High performance TIPS-pentacene:PS blend flexible OFETs were further explored for operating voltages reduction and performance stability under combined effect of mechanical and electrical stress. These devices exhibited a high mobility up to 1.1 $cm^2 V^{-1} s^{-1}$, low threshold voltages, and high current on-off ratios ~10^5 at low operating voltage of -5 V. Their performance remained largely unaffected under the effect of continuous mechanical strain for 2 days and 100 consecutive tensile-compressive strain cycles. Low I_{DS} decay (~10%), very large trapping time of ~10^8 s, and corresponding threshold voltage shift of 0.3 V were observed under the effect of bias-stress. Similar bias-stress induced changes were maintained even after 2 days of mechanical strain. However, after 100 cycles of mechanical strain, I_{DS} decay was increased to ~20% with a still small threshold voltage shift (0.5 V), which signified a high overall electro-mechanical stability in these devices.

VI. Neat TIPS-pentacene OFETs with HfO_2/PVP hybrid gate dielectric were explored as low voltage flexible photo-OFETs with a photo-sensitive active layer of TIPS-pentacene. Photo-response of the devices was measured under illumination with visible light (different minimum wavelengths, 620 nm, 520 nm and 460 nm, corresponding to red, green and blue colors respectively) and UV light (peak wavelength 365 nm). For blue, green and UV light illumination (intensity of 1.7 mW/cm^2, 0.4 mW/cm^2 and 1.8 mW/cm^2 respectively), a maximum current modulation of 4×10^4, 10^2 and 5×10^2 and photo-responsivity of 17 mA/W, 35 mA/W and 43 mA/W were achieved respectively. Photo-OFETs demonstrated a maximum detectivity of 6.9×10^8 cm $Hz^{0.5}$/W to UV light illumination. A fast dynamic response to visible and UV illumination switching pulses was also observed. Increasing illumination intensity, illumination time and applied gate bias during illumination were found to enhance the visible photo-response. For 500 s of blue light illumination and with a gate bias of 10 V, a maximum current modulation of 10^5 was demonstrated. However, an increased positive threshold voltage shift and reduction in mobility values were observed on increasing the UV irradiation time. The drain current at biasing conditions of V_{GS} = -10 V and V_{DS} = -5 V was found to rise slightly for smaller values of irradiation time, however decreased for higher values of illumination time due to slight deterioration in the crystallinity. Similar trend of positive shifting of V_{TH} and mobility roll-off was observed when gate bias during irradiation was increased.

8.2 CONCLUSIONS

After observing the results obtained from various studies of this thesis it can be concluded that TIPS-pentacene is a promising organic semiconductor, which has great potential to be viable in many future applications of organic electronics. Performance of solution processed OFETs depends on several factors such as molecular order in the active organic semiconducting layer and quality of dielectric-semiconductor interface. Variation in solvent composition could only bring some minor improvements. However, both of the above factors were simultaneously improved to a great extent for the case of TIPS-pentacene:PS blend devices. Due to amelioration in the above mentioned factors, superior electrical performance and stability could be achieved in corresponding devices (maximum mobility of 2.6 $cm^2 V^{-1} s^{-1}$ and 1.1 $cm^2 V^{-1} s^{-1}$ on rigid and flexible substrates respectively). TIPS-pentacene:PS flexible OFETs also demonstrated very high electro-mechanical stability of the device performance, which remained largely unaffected even after undergoing stress for large duration and multiple times. Neat TIPS-pentacene photo-OFETs exhibited a fair photo-response to visible and UV light illumination. All these outcomes indicate the vast potential of organic semiconductor TIPS-pentacene which can be used for variety of applications ranging from high electro-mechanical stability to optical sensing elements. In addition, the high performance OFETs developed under aegis of this study show that solution processing of organic semiconductors also has great capability to produce high performance devices similar to vacuum processing. With little more endeavors, solution processing may become the next technical trend in the global market of organic electronics in the form of a suitable alternative of vacuum processed conventional silicon based technology.

8.3 FUTURE SCOPE

The main objective of the research work undertaken in this thesis was to enhance the performance of solution processed OFETs by ameliorating the degree of crystallinity of the active organic semiconductor layer and quality of dielectric-semiconductor interface by various means. Achieving the superior performance further on the flexible substrates was the next main aim. Utilization of high performance solution processed flexible OFETs in sensing applications was the final goal of the work. Though the objectives of the research work undertaken are largely met, this accomplishment does not limit the future scopes of extension of this work. Numerous research facets emerging out of this work may provide worthwhile exploration directions to researchers for their endeavors. Some of the main directions can be as following;

I. Effect of ratio of poor solvent and good solvent in the semiconductor solution on the crystallinity of the active layer and corresponding device performance can be explored in detail. At an optimum ratio of bad and good solvent in the solution, a peak device performance can be achieved.

II. Various kind of insulating polymer binders can be used to make TIPS-pentacene:polymer blend solutions. This can be a vast study in itself where there are plethora of effects to explore like molecular weight of the polymers, crystallinity of the polymers, mixing ratios, incorporation of bad solvents in the blend solutions, solvent vapor annealing etc.

III. Flexible OFETs can be examined for their electro-mechanical stability while stress can be applied in different ways, which include stress type (tensile or compressive) and direction of stress (parallel or perpendicular to the channel).

IV. Digital logic circuitry can be designed using flexible high performance OFETs. TIPS-pentacene:PS blend OFETs which have been demonstrated with high electro-mechanical stability can be used for such purposes. Exploration of electro-mechanical stability of blend OFETs based logic circuitry can be a significant study which can be of great interest to organic electronics fraternity.

V. Several categories of OFET based sensing devices such as gas sensors, PH sensors, humidity sensors and bio-molecule sensors can be developed on flexible platforms. Electro-mechanical stability of their sensing response can be another noteworthy study, which can significantly contribute towards successful integration of such flexible and low cost sensing devices in several practical applications of flexible organic electronics.

VI. Environmental stability is another major concern for organic devices, when long term utilization of such devices is under consideration. Passivation techniques for high performance flexible OFETs and corresponding improvement obtained in degradation dynamics can be another significant study, which can put forward ways to enable long term usage of such devices in several practical applications.

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