6

Summary and Conclusions

This Chapter summarizes the work presented in this thesis. The main findings and future prospects of this thesis work are also discussed in this Chapter.

6.1 SUMMARY

Organic TFTs have shown high potential to be used in driving circuits for flexible and large-area electronic systems, due to advantages such as low temperature processing and compatibility with flexible plastic substrates. However, there are various issues which need to be addressed before these organic TFTs are employed in commercialized applications. Some of the important issues for organic TFTs addressed in this thesis are:

(a) Demonstration of high-performance and environmentally stable flexible TFTs.

(b) Bias-stress induced instability, which limits the 10%-current decay lifetime of these transistors. High 10%-lifetime of organic TFTs are desirable for long term stable and reliable operation of systems in which they are used. Most of the reported lifetimes are very low, and mainly on rigid silicon substrates. The conclusion made on the 10%-lifetime for organic TFT on rigid silicon substrates is not necessarily applicable for organic TFTs on flexible plastic substrates due to the impact of surface roughness and thermal budget, making it essential to study bias-stress effects on flexible plastic substrates.

(c) Understanding the trapping mechanism in TFT devices. The trapping of charge-carriers is believed to be one of the most crucial factors limiting the device performance.

The summary obtained from all the above mentioned work is given as follows:

(i) The high-performing and stable organic TFTs are demonstrated in this thesis. These TFTs were fabricated on flexible plastic substrates with maximum operating temperature in range of 60 °C to 90 °C. Six promising hole-transport (pentacene, DNTT, C_{10}-DNTT, and DPh-DNTT) and electron-transport (F_{16}CuPc and NTCDI) organic semiconductors are used for fabricating p-channel and n-channel organic TFTs, respectively. The p-channel organic TFTs exhibit field-effect mobility in range of 0.5 cm^2/Vs and 4.1 cm^2/Vs. The F_{16}CuPc and NTCDI TFTs exhibit field-effect mobility values of 0.03 cm^2/Vs and 0.16 cm^2/Vs, respectively.

(ii) The Repeatability of transfer characteristics upon multiple repeated scans (1985 scans) for duration of 10 hours reveals that DPh-DNTT based TFTs show high operational stability on providing these acute conditions. The threshold voltage and field-effect mobility value changes by less than 20% and 30% respectively. The current on/off ratio does not degrade by more than one order of magnitude, which changes from 10^7 to 10^6, which is still very high for switching and low power applications.

(iii) The shelf-life study was conducted on all fabricated p-channel and n-channel organic TFTs. DPh-DNTT and NTCDI based TFTs show good stability upon exposing these TFTs on ambient conditions with humidity of 40-50% for the duration of 40 and 10 days, respectively. The performance of DPh-DNTT and NTCDI devices varies by less than 15% and 20%, respectively; upon exposure of these TFTs to ambient conditions.

(iv) A comprehensive and detailed study of bias-stress induced instability in the performance of all the fabricated organic TFTs was performed. In particular, the extent to which the choice of the semiconductor; and applied voltages during bias-stress at gate-source and drain-source, affects the bias-stress-induced decay of the on-state drain current of the TFTs is studied. The results obtained from this measurement indicate that, depending on the choice of the semiconductor and on the voltages applied during bias stress, the 10%-current-decay lifetimes range from 15 seconds to about 1 week. These results also indicate that a larger applied gate-source voltage generally leads to a shorter 10%-lifetime and *vice versa*. For p-channel TFTs, DPh-DNTT and C_{10}-DNTT provide somewhat better stability than DNTT; which shows better stability than pentacene. For the n-channel TFTs, the results show that in addition, to substantially larger electron mobility, NTCDI also provides significantly better bias-stress stability over the entire range of gate-source and drain-source voltages compared with F_{16}CuPc. In general, the p-channel TFTs examined in this study all provide larger carrier mobilities and better bias-stress stability compared with the n-channel TFTs.

(v) The threshold voltage shift induced due to bias-stress can be calculated by measuring the transfer characteristics once before bias stress and again immediately after completion of the bias-stress experiment. For p-channel organic TFTs, the smallest threshold-voltage shifts (ΔV_{th} = -0.2 V) are seen for the DPh-DNTT TFTs after 138 hours of bias stress and for n-channel organic TFTs, the smallest threshold-voltage shifts are seen for the NTCDI TFTs (ΔV_{th} ~ 0 V) after 64 hours of bias stress.

(vi) The transfer characteristics (before and after bias-stress) further reveal that for some of the semiconductors, the carrier mobility decreases during bias stress. To test whether the bias-stress induced shift in the threshold voltage and decay in the carrier mobility is permanent or temporary; transfer characteristics after relaxation (for 1 or 2 days) were also measured. The relaxation results reveal that the bias-stress-induced changes are usually not permanent; *i.e.* completely recoverable for air-stable semiconductors and partially recoverable for air-degradable semiconductors.

(vii) The lifetime of fabricated organic TFTs are benchmarked with other materials and different technologies for TFTs. One of the conclusion made while benchmarking the TFTs of same organic material is that, the 10%-lifetime is shorter when the channel sheet resistance is smaller, *i.e.*, when the gate-source voltage applied during bias stress is larger. This is likely related to the fact that the gate-induced carrier density and hence the trapping rate increase with increasing gate-source voltage. The second trend is that 10%-lifetimes obtained for some of the fabricated TFTs is as high as a-Si:H TFTs, considering the fact that organic TFTs are processed at much lower temperature and on flexible plastic substrates.

(viii) The displacement current measurements show that the number of injected, extracted, and trapped charge-carriers is uniformly distributed over the entire semiconductor area. The shift in threshold voltage with each successive sweep is observed, due to the filling of deep trap states. The density of trapped charges is very similar in all devices, despite the significant differences between the charge-carrier mobilities in the four semiconductors. Much like the choice of the semiconductor, the choice of the contact metal also does not appear to have a significant effect on the trapping behavior, except for a slightly larger density of trapped charges in devices with Cu contacts compared with devices fabricated using Au, Ag or Pd as the contact metal. The field-effect mobility and threshold voltage extracted from the DCM measurements are comparable to the values of field-effect mobility and threshold voltage obtained from device characteristics of TFTs.

6.2 CONCLUSION

This thesis work has shown that high-performing, stable, and flexible organic TFTs can be demonstrated, if suitable organic semiconductor, dielectric, and interface engineering is employed in device designing. DPh-DNTT based TFTs have shown high electrical stability under bias-stress, and upon continuous scans of transfer characteristics. The bias-stress measurement results show the dependence of 10%-lifetime of organic TFTs on the choice of the semiconductor and on the voltages applied during bias stress. These lifetimes are larger for smaller applied gate-source voltage and *vice versa*. The bias-stress induced degradation in device characteristics are usually not permanent; *i.e.* completely recoverable for air-stable semiconductors and partially recoverable for air-degradable semiconductors, making it essential to use an air-stable active layer in organic TFTs. The lifetime of fabricated organic TFTs are also benchmarked with other materials and different technologies for TFTs, showing that 10%-lifetimes obtained for some of the fabricated TFTs is as high as a-Si:H TFTs, considering the fact that organic TFTs are processed at much lower temperature and on flexible plastic substrates. Finally, the phenomenon of injection, extraction, and trapping of charge-carriers is understood using displacement current measurements. These findings emphasize that there is an immense potential of organic TFTs to be used in flexible circuitry and systems.

6.3 FUTURE WORK

This thesis makes way for the following work that can be undertaken in future:

(i) Though the study in this thesis primarily showed that DPh-DNTT is a very promising candidate for producing high-performance, air-stable, and electrically stable organic TFTs. However, being a relatively new organic semiconductor material, DPh-DNTT needs to be further studied before it claims to be used in commercialized circuitry and systems.

(ii) The bias-stress induced decay trends can be different for devices with different materials. Hence, understanding the phenomenon behind it is very essential for any successful commercialized used of organic TFTs.

(iii) Unlike in inorganic semiconductors, where the same device models are applied for various device designs, organic TFTs require different device models due to the changes in device structures and materials. Hence, it is essential to develop specific models to predict the behaviour of organic TFTs with any new promising material. These models will enable circuit and device engineers to design reliable systems.