High performance Organic thin film transistor based on π–conjugated organic materials

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Abstract

Copper phthalocyanine (CuPc) and Pentacene are technologically important π–conjugated organic materials for organic thin film transistors (OTFTs) to be used for all organic display. CuPc and Pentacene have completely different surface morphologies, CuPc thin films show elongated grain structure whereas Pentacene thin films show pyramidal growth which is combination of diffusion limited aggregation (DLA) with vertical mound growth. The charge carrier transport in organic thin films predominantly depends on its structural and morphological properties. We have shown how to achieve high performance OTFTs by engineering the growth conditions of organic thin film. Pentacene based OTFTs have charge carrier mobility of 0.2cm^2/Vs in which organic thin film grown at substrate temperature 30^{o}C and at low evaporation rate whereas CuPc based OTFTs have best device performance at substrate temperature 100^{o}C. Pentacene grown at higher deposition rate based OTFTs shows high threshold voltage but there is not much change in mobility.

1. Introduction

Organic materials have π-orbitals which play primary role in the semiconducting properties and carrier transport. Organic thin film transistors (OTFTs), are of considerable interest because of their potential application in low cost integrated circuits for a variety of large area electronic applications and display backplanes[1]. Generally, organic thin films are polycrystalline with isotropic grainy morphology resulting large grain boundaries which act as barrier for charge transport. This problem can be circumvented by reducing the number of grain boundaries between source and drain in OTFT to maximize the π- π overlapping along the direction of current flow. Here, we show that this can be achieved through controlling the deposition rate and substrate temperature to make crystalline organic films. We have used Pentacene and CuPc organic molecules. Pentacene is one of the promising material with high mobility and CuPc is the most chemically and thermally stable organic molecule.

2. Experimental details

High purity Pentacene and CuPc were purchased from Sigma Aldrich and were used without any further purification. Organic layers were deposited on Si/SiO_2 substrate using oil free thermal evaporation unit at a various deposition rate and substrate temperature(T_G). Thickness of organic layers (50nm) was measured in-situ by quartz crystal thickness monitor. For OTFTs, a 35nm Au contacts were deposited to form S/D electrodes on the top of the organic layers through a shadow mask. The devices have channel length of 20µm and channel width of 3mm. All thin films have been grown at base pressure of 10^{-6} mbar. The thin film morphology was analyzed using Park Systems XE70 atomic force microscope (AFM). The transistor characteristics were measured at room temperature using Keithley picoammeter and Keithley/Agilent voltage sources.

3. Result and Discussions

The morphology of the organic thin film plays important role on the performance of the devices. Whenever a molecule comes close to the substrate it gets physisorbed or chemisorbed depending upon the interaction between substrate and deposit. For nucleation, the surface energy of the deposit should be high compared to that of the substrate while vice versa is true for monolayer. Fig. 1a shows the AFM image of CuPc film grown at 30^{o}C with low deposition rate of 0.1 Å/sec, surface morphology reveals uniform distribution of grains. The grains in film deposited at 105^{o}C with low evaporation rate 0.1 Å/sec (Fig. 1b) show elongation with larger dimensions. As the evaporation rate increases with fixed T_G 105^{o}C inspite of higher kinetic energy of molecules, nucleation rate increases due to higher flux of incoming molecules giving rise to polycrystalline isotropic grainy morphology at highest evaporation rate of 10Å/sec (Fig. 1d). In our previous work[2,3] we have shown that for CuPc based OTFTs the optimized deposition rate and T_G are 0.1 Å/sec and ~100^{o}C, respectively. At this optimized growth condition, the surface morphology consists less grain boundaries resulting high carrier mobility µ~0.01 cm^2/Vsec and low threshold voltage V_{th} ~-5V.

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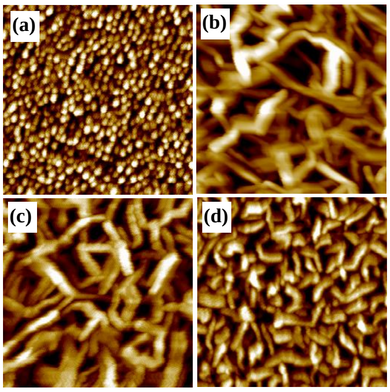

Figure 1. AFM topographic images (1μm X 1μm) of CuPc thin films deposited on SiO_2 substrates at substrate temperatures (a) 30°C and (b,c,d) 100°C with various deposition rate (a,b) 0.1 Å/sec, (c) 1 Å/sec, and (d) 10 Å/sec.

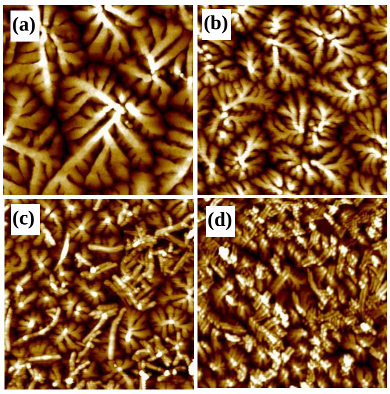

Figure 2. AFM (5μm X 5μm) images of Pentacene film of thickness 50nm deposited on SiO2/Si substrate at fixed substrate temperature of 40°C and various deposition rate of (a) 0.2Å/sec, (b) 1Å/sec, (c) 2Å/sec, and (d) 10Å/sec.

Pentacene is a linear molecule which show pyramidal growth, combination of diffusion limited aggregation (DLA) with vertical mound growth[4,5]. Pentacene thin film grown at higher substrate temperature show poor device performance, because at higher substrate temperature desorption of molecule occurred resulting low surface coverage. Fig. 2 shows the AFM images of Pentacene film grown at different evaporation rate with fixed T_G at 30°C. The thin films shows the characteristics DLA growth with pyramidal structures, however with increasing the deposition rate the average grain size gets reduced as the molecules do not get enough time to diffuse across the surface meeting already existing nuclei. Thus the deposition rate has been found to increase the nucleation density. The large nucleation density and structural disorder at organic/gate insulator interface form deep trap states which increases as deposition rate increases. We have fabricated OTFTs based on Pentacene film which is grown at different deposition rate with fixed T_G .

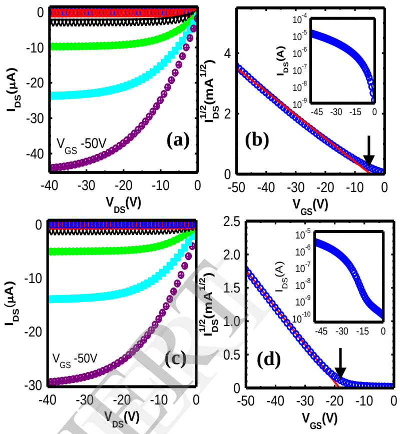

Figure 3. Output and transfer characteristics of Pentacene based OTFTs in which organic film were deposited at (a,b) 0.1 Å/sec and (c,d) 10 Å/sec. V_{GS} is varied at the step of 10V in output characteristics and transfer characteristic is observed at V_{DS}=-1V. Arrow indicates the threshold voltage (V_{th}). At higher deposition rate V_{th} is increased from -4.7V to -18.4V.

Fig. 3 shows the OTFTs characteristic of Pentacene transistors which grown at different deposition rate. The performance of transistors is determined by mobility μ, which is "figure of merit" of thin film and thin film based transport devices, threshold voltage V_{th}, which is required to induce charge for complete filling of traps in thin film and/or organic/dielectric interface, subthreshold swing S, and on-off ratio. Fig. 3d shows the transfer characteristic of transistor in which Pentacene film was grown at high deposition rate (10 Å/sec), has high threshold voltage i.e. the density of trap state is large in organic film and at organic/gate insulator interface. At high deposition rate Pentacene molecules have not enough time to acquire their stable position and structural disorder is created which forms trap states.

Table 1. Device parameters of Pentacene based OTFTs in which active layers were grown at different deposition rate.

Deposition rate	μ(cm^2/Vs)	V_{th}(V)	S (V/decade)
0.1 Å/sec	0.25	-4.7	2.4
1 Å/sec	0.23	-11.3	2.6
2 Å/sec	0.21	-15.2	3.2
10 Å/sec	0.08	-18.4	5.7

The device parameters of Pentacene OTFTs in which thin films were deposited at different deposition rate are shown in table 1. Table 1 shows that the carrier mobility is almost same for devices in which deposition rate is <10 Å/sec. At higher deposition rate(10 Å/sec), island growth is more preferential which gives large grain boundaries and mobility is decreased by one order. As the deposition rate increases, a large shift has been observed in V_{th} which is related to the required voltage to induce charge for complete filling of deep traps. Subthreshold swing(S) of OTFTs measure how easy or difficult to switch a transistor from off-state to on-state and is related to concentration of deep traps. Hence the value of S is less in OTFTs where organic films were grown at low deposition rate.

4. Conclusions

In conclusion, we have studied that by engineering the growth conditions, a particular surface morphology has been ocurred which gives the best device performance. For CuPc the optimized conditions are T_G 100°C and low deposition rate 0.1 Å/sec. For Pentacene, T_G should be 30°C and deposition rate is less than 1 Å/sec. The Pentacene film grown at 30^0C revealed less trap states and grain boundaries with improved crystallinity, shows highest mobility 0.25 cm^2/Vs and V_{th} -4.7V.

5. Acknowledgement

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6. References

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