High-Mobility n-Channel Organic Field Effect Transistors based on Epitaxially Grown C_{60} Films

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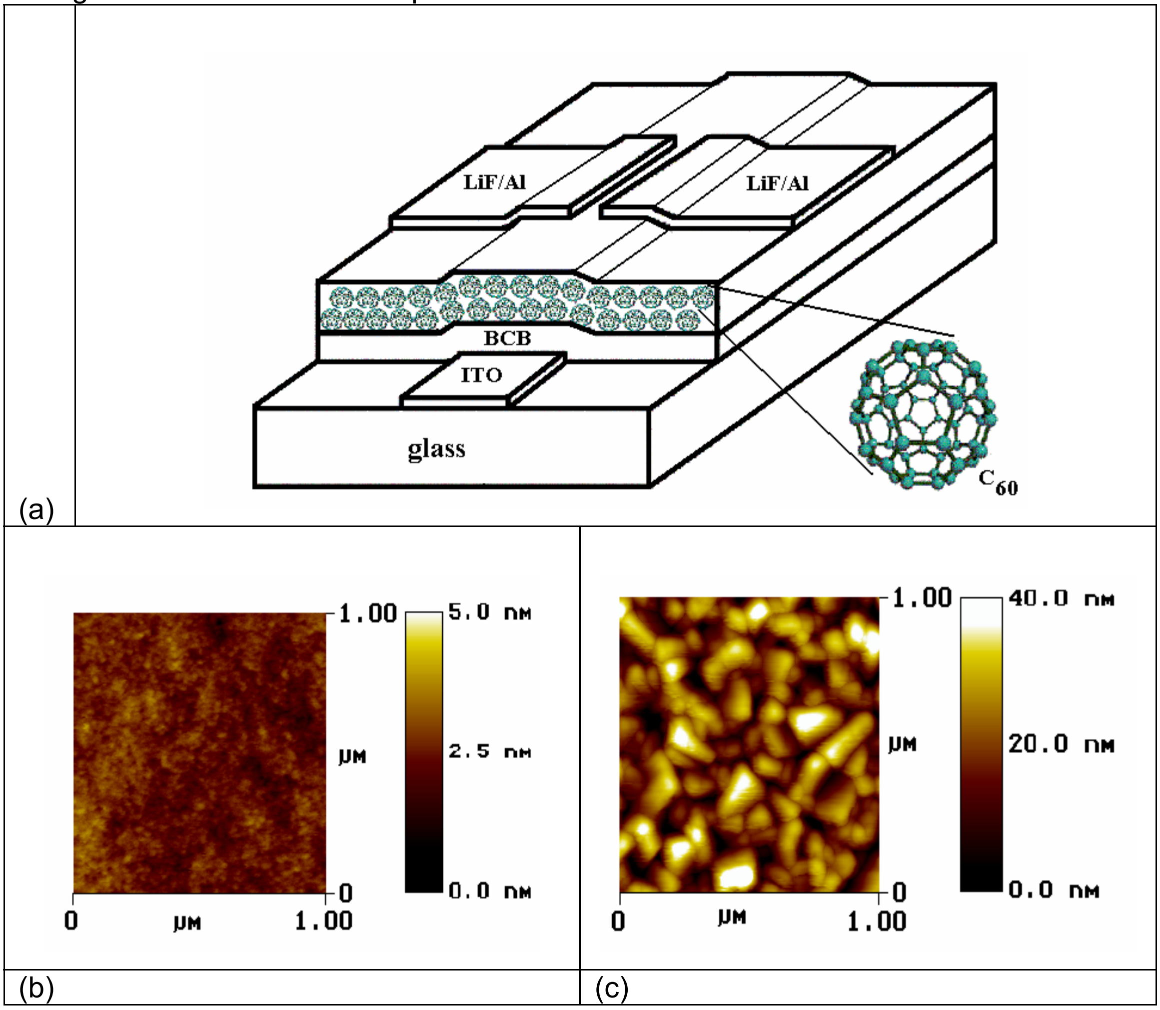
Introduction

Organic thin-film electronics has developed to a promising technology in the last two decades with demonstrated prototypes of organic thin film transistors, organic integrated circuits for radio frequency identification tags (RFID-tags) [1], [2] and active matrix displays [3]. Organic field effect transistors (OFETs) have also been fabricated in arrays to drive electrophoretic display pixels [4]. The performance of the individual transistor limits the switching speed in an integrated circuit, which can be roughly estimated by the ratio of mobility and channel length of the transistor [3]. To obtain higher switching speed, the search for higher mobility materials is therefore important along with the effort to downscale the transistor geometry.

In this paper, we present results on OFETs fabricated using hot wall epitaxy (HWE) grown C_{60} films on top of an organic insulator. HWE, working close to thermodynamical equilibrium, is well known as appropriate technique to grow highly ordered organic thin films, including C_{60} films. The relatively smooth surface of the organic insulating film interfaced with a highly ordered HWE grown C_{60} film resulted in mobilities of 0.4 – 1 cm^2/Vs and an on/off ratio $>10^4$. The obtained mobility is found to be nearly gate voltage independent with a normalized sub-threshold slope of 8 $V{\cdot}nF/decade{\cdot}cm^2$. Furthermore, the field effect mobility has been found to be thermally activated with an activation energy of ~100 meV within the temperature range of 90 – 300 K.

Experimental

A scheme of the device geometry is shown in Fig. 1 (a). The device fabrication starts with the etching of the indium tin oxide (ITO) on the glass substrate. After patterning the ITO and cleaning in an ultrasonic bath, a BCB layer is spin coated at 1500 rpm resulting in a 2 µm thick film. BCB was used as received from Dow Chemicals and curing was done according to the standard procedure. BCB is an excellent dielectric material with a rather low dielectric constant ε_{BCB}= 2.6 and a small, nearly temperature independent thermal expansion coefficient [5]. A 300 nm thick C_{60} film was grown by HWE on top of the dielectric at a substrate temperature of 130 °C. The top source and drain electrodes (LiF/Al 0.6 / 60 nm) were evaporated under vacuum ($2x10^{-6}$ mbar) through a shadow mask. LiF / Al is expected to form ohmic contacts on fullerenes [6]. The channel length L of the device is 35 µm and channel width W = 1.4 mm, which results in a W/L ratio of ≈40. From the measurement of the BCB film thickness, d = 2 µm and the dielectric constant of BCB, ε_{BCB} = 2.6, a dielectric capacitance C_{BCB} = 1.2 nF/cm^2 was calculated. In our devices we have a d/L ratio ≈0.05 acceptable not to screen the gate field by the source drain contacts. Device transportation from the HWE chamber to the glove box and further electrical characterization (using Keithley 236 and Keithley 2400 instruments) were carried out under argon environment. The surface morphology and thickness of the dielectric was determined with a Digital Instrument 3100 atomic force microscope (AFM) and a Dektak surface profilometer respectively. Device characterization at various temperatures was performed in a He flow cryostat (Cryo Industries) using a Lakeshore 331 as temperature controller.



(a)

(b)

(c)

Fig. 1: (a) Scheme of the staggered n-channel OFET device structure; (b) AFM image of the BCB dielectric surface; (c) AFM image of the C_{60} surface in the channel region of the fabricated OFET.

Results

As shown in Fig. 1 (b), the dielectric layer showed a very smooth surface with a roughness <5 nm. This enables us to grow the next layer (C_{60}) with a very good control of the film morphology (Fig. 1 (c)). A recent study shows that the first couple of monolayers next to the dielectric dominate the charge transport in an organic semiconductor layer.

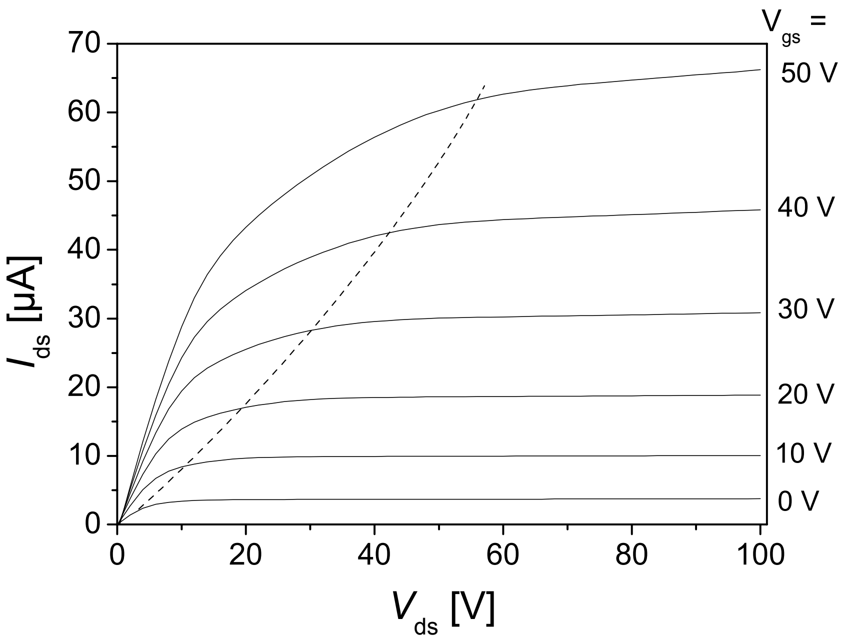


Fig. 2: $I_{ds}(V_{ds})$ curve of the OFET in the accumulation mode. The dotted line is a guide for the eye for saturated I_{ds}. The data shown here are taken in ascending V_{gs} mode with integration time of 1s

Figure 2 shows the transistor characteristics of a device with a well saturated curve occurring pinch off at drain source voltage $V_{ds} \geq V_{gs}$ (gate Voltage). From the slope at V_{ds}= 0 V of the curve V_{gs} = 0 V, we evaluated a conductivity of 5 x 10^{-6} Scm^{-1}. For the same device (see Fig. 3) we measured the transfer characteristics. The data presented in Fig. 3 hold for V_{ds} = 60 V. One can see that the transistor turns on at an onset voltage of V_t = -35 V without significant hysteresis and drain-source current I_{ds} increases quadratically. The device shows an on/off ratio >10^4 which is calculated as a ratio of I_{ds} at V_{gs} = 60 V and I_{ds} at V_{gs} = V_t. We have observed consistently the effect of having large drain-source current even when V_{gs} = 0 V. This effect is minimized when the dielectric layer is preheated at high temperature prior to the deposition of the active layer. This results in the shift of V_t. This effect is proposed to the presence of unintentional dopants at the interface of the untreated dielectric. Interfacial effects seem to play a major role in these devices. From $V_t = -(qn_0d_s/C_{BCB}) + V_{fb}$, where V_{fb} = 0.1 V is the flat band potential (which accounts for the work function difference between the semiconductor and the gate electrode without considering fixed charges at the dielectric and at the interface), d_s is the thickness of the semiconductor, q is the elementary charge and C_{BCB} is the capacitance of the gate dielectric, we were able to estimate the density of free carriers at equilibrium n_o. This yields a relatively high electron density of ~10^{17} cm^{-3}.

As shown in Fig. 3, from the fit to the data using equation (1) [7]:

$$I_{ds} = \frac{\mu W C_{BCB}}{2L}\left(V_{gs} - V_t\right)^2 \qquad (1)$$

we extract a field effect mobility of 0.63 $cm^2V^{-1}s^{-1}$ in the saturation regime for V_{ds} = 60 V (note the fitting line used for the mobility extraction fits the data over a wide range of V_{gs}). However, while we calculated field effect mobility, contact resistance of LiF/Al and C_{60} is not taken into account assuming contact resistance is fairly low. Our studies of the dependence of field effect mobility on metal work functions on soluble methanofullerene based OFETs have shown a highest μ of 0.2 $cm^2V^{-1}s^{-1}$ with LiF/Al as drain-source electrode. Use of higher work function metal electrodes viz. Cr, Au etc. in these

OFETs leads to slightly reduced mobilities. Similarly we have also observed the slight decrease in field effect mobility in C_{60} OFETs with higher work function electrode (not shown here). To our best understanding of OFETs, the device performance and mobility strongly depend on the choice of the dielectric layer mainly due to a different surface energy of the dielectric layer. The sharp turn on of I_{ds} is a measure of the quality of the dielectric/semiconductor interface which is defined by the normalized subthreshold slope, $S = C_{BCB} dV_{gs}/d(\log I_{ds})$ [7]. As usually observed in organic FETs, subthreshold slope of 8 V·nF/decade·cm^2 obtained by us is very high which can be reduced by reducing the thickness of the dielectric layer. We presume, the most important factor in achieving this high mobility OFET is the combination of a smooth organic dielectric surface and a highly ordered C_{60} film grown by HWE.

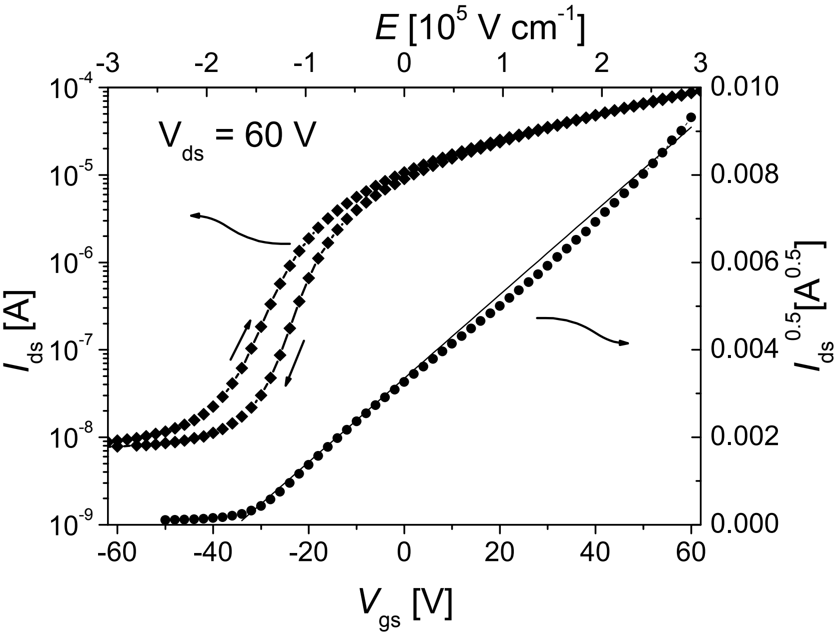


Fig. 3: Semilogarithmic plot of Ids vs. Vgs (left scale) and plot of Ids0.5 vs Vgs (right scale) for the same C60 OFET as in Fig. 2. The full line shows a fit to the data (return curve) using equation (1) from which a field-effect mobility μ = 0.63 cm2/Vs is obtained. Each measurement was carried out with an integration time of 1 s.

Conclusion

In conclusion, we have demonstrated an n-channel OFET with an electron mobility of 0.4 – 1 cm^{2}V^{-1}s^{-1} along with an on/off ratio >10^4 using a solution based organic dielectric BCB film in combination with HWE grown C_{60} films. The obtained mobility is nearly gate voltage independent. Very few studies have been done so far on growing highly ordered organic thin films on top of organic dielectrics partly due to low glass transition temperature and unwanted hysteresis. Use of BCB among other organic dielectrics is based on the fact that its low hysteresis and high glass transition temperature which is an additional advantage for optimizing the film growth condition at high substrate temperatures.

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