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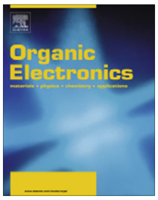

Origin of mechanical strain sensitivity of pentacene thin-film transistors

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ABSTRACT

We report on bending strain-induced changes of the charge carrier mobility in pentacene organic thin-film transistors employing a combined investigation of morphological, structural, and electrical properties. The observed drain current variations are reversible if the deformation is below 2%. The morphology and structure of the active pentacene layer is investigated by scanning force microscopy and specular synchrotron X-ray diffraction, which show that bending-stress causes morphological rather than structural changes, modifying essentially the lateral spacing between individual pentacene crystallites. In addition, for deformations >2% the rupture of source and drain gold electrodes is observed. In contrast to the metal electrodes, the modification of the organic layer remains reversible for deformations up to 10%, which suggests the use of soft and flexible electrodes such as graphene or conducting polymers to be beneficial for future strain sensing devices.

1. Introduction

Thin films of conjugated organic molecules are subject of intense research due to their applicability in novel (opto-)electronic devices, including organic thin-film transistors (OTFTs). Pentacene (PEN) is the prototypical hole-conducting material with notably high charge carrier mobilities of up to 5.5 cm^2/V s [1–3] in p-type OTFTs. One key advantage of organic electronic devices is the possibility to produce flexible all-organic OTFTs with the functional organic semiconductor films deposited on flexible plastic foils like Mylar® or polyethylenetherephthalate (PET) as substrate [4]. Through their intrinsic flexibility, OTFTs can be applied as mechanical strain-sensing devices [5,6] exhibiting significant advantages over conventional types of sensors: they can be processed under ambient conditions and are generally inexpensive to fabricate [4–11]. For sensing strain, reversible changes in the electrical characteristics of OTFTs were employed, including drain current, charge carrier mobility, threshold voltage, and contact resistance for deformations up to 1–2% [5,6,9,12,13]. In particular, the reported changes in mobility were proposed to be due to morphological changes of the PEN layers under mechanical strain and/or the activation of trap states in the PEN/electrode interface region [5,6,9,14,15]. However, up to now there has been no direct experimental evidence to support these suggestions. In order to enable targeted research for improving current OTFTs for future reliable sensing applications, further experimental work is needed to complete the microscopic picture of strain-impact on OTFT performance. Here we report a comprehensive electrical characterization of flexible OTFT devices under applied bending-stress, relating the device characteristics to morphological and structural

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properties of the active layer, as determined by a combination of scanning force microscopy (SFM) and specular X-ray diffraction (XRD). We identify the deterioration of the metal electrodes to be responsible for irreversibilities in the device characteristics, while the observed modifications of the active organic layer remain reversible for deformations up to 10%, which suggests using soft organic electrodes for future improved sensing applications.

2. Experimental

OTFTs were fabricated on 200 µm thin and flexible polyethylenetherephthalate (PET) substrates. A gold layer was vacuum-deposited on the substrates as gate electrode. Polyvinylalcohol (PVA) with ammonium dichromate (AD) salt (cross-linking agent) was deposited from water solution as gate dielectric by spin-coating and subsequent UV-curing for cross-linking. Gold source and drain electrodes (Fig. 1a) were patterned by thermal deposition through a shadow mask. Pentacene (PEN) was used as organic semiconductor. PEN films were evaporated at a base pressure $<10^{-7}$ mbar; the film thickness and the deposition rate (0.5 nm/min) were monitored by a quartz crystal microbalance placed next to the sample; the device is sketched in Fig. 1a. A special apparatus for defined bending of the OTFT (Fig. 1c) was developed to be suitable for use in both SFM and specular XRD experiments. XRD measurements were carried out at the beamline W1 at DESY–HASYLAB (Hamburg, Germany) with a primary beam energy of 10.5 keV, using the bending apparatus (Fig. 1c) as sample holder for *in situ* experiments, and a standard setup (PVA samples fixed planar on a Si wafer) for reference measurements. The electrical and morphological characterization of the PEN layers under deformation was carried out *in situ* under ambient conditions. For electrical characterization a Keithley 2636A sourcemeter was used. The surface topography was imaged with SFM (Nano Wizard, JPK instruments). The PEN film strain was calculated with the model of beam buckling (Fig. 1b), which allows to calculate the film strain, ε, directly from the bending radius [16], as demonstrated before [9,17]. The bending radius was calculated taking into account the homogeneous bending of the PET foil. This setup allowed to strain PEN films up to 10%, with the upper limit defined by the smallest accessible radius of curvature and the thickness of the PET substrate. All electrical device characterization, XRD and SFM measurements, were carried out under ambient conditions.

3. Results

Transfer curves (i.e., drain current (I_D) *versus* gate voltage (V_G) characteristics) of the devices were recorded for different degrees of strain. The bending-stress was released after acquiring transfer characteristic for a particular strain in order to verify the reversibility of the process (i.e., if the current recovers to the initial value). We find, as expected [9], a decrease in drain current as function of device deformation (Fig. 2a). For deformations of up to 1.7%, straining of the device causes reversible variations of the transfer curves. Starting from 1.7% I_D does not recover to the initial value of the pristine device upon bending-stress relief. Transfer characteristics exhibit a pronounced hysteresis with the hysteresis loop-area increasing with increasing

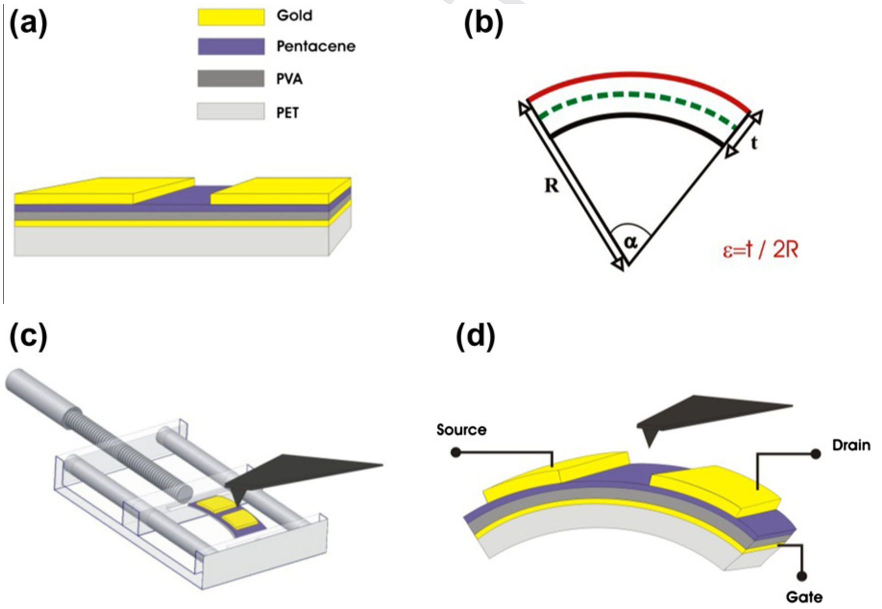

Fig. 1. (a) Schematic representation of the top-contact OTFT architecture. (b) Model used to calculate PEN film strain ε; R denotes the radius of curvature, t the device thickness. Red and dashed green lines indicate the upper and neutral plane, respectively. Strain of PEN film is assumed to be equal to the strain of the beam surface. (c) The bending apparatus with the OTFT device in place. (d) Scheme of the device under bending stress with the SFM-tip; electrical contacts are indicated for the drain-current sensitivity measurements in the deformed OTFT and for the *in situ* morphological investigations on both electrodes and active layer by SFM. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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