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Topographic characterization of thin film field-effect transistors of 2,6-diphenyl anthracene (DPA) by fractal and AFM analysis

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ABSTRACT

Presented article is aimed at experimental investigation of the scalable nature of the 3-D surface micromorphology of 2,6-diphenyl anthracene (DPA). Films under study were evaporated in vacuum chamber on various substrates. The surfaces of the films were probed by means of atomic force microscopy (AFM) and obtained images were processed numerically to determine fractal characteristics. Performed analysis revealed that DPA samples followed allometric scale behavior at nanometer range, characterized with only one scaling exponent varying in the range from 2.53 to 2.92 depending on the deposition details.

1. Introduction

Organic field-effect transistors (OFETs) focus increasing attention due to their potential application in light-weight, cheap and mobile electronics, such as transparent circuits and flexible display panels [1–7]. Significant progress in this field gave rise to OFETs with high charge carrier mobility as a result of optimized microelectronic structure and the use of self-assembled monolayer-modified dielectrics [8].

Polyacenes are organic semiconductor compounds made up of linearly fused benzene rings, in which high carrier mobility can be obtained due to the enlargement of the π-conjugation followed by smaller reorganization energy and larger intermolecular transfer integrals [9]. Unfortunately, poor structural stability and low solubility of these compounds are main factors that limit their practical applications [10]. In order to overcome these problems, various solutions were proposed. For example, Wang et al. prevented chemical degradation of polyacenes by saturation their active sites with pentacene molecules [11], whereas Amin et al. proposed to replace benzene rings with other heteroaromatic molecules, such as thiophenes [12]. Outstanding examples of such derivatives were demonstrated, for example: TIPS-pentacene (6,13-bis (triisopropylsilylethynyl)pentacene) and BTBTs (benzothieno [3,2-*b*][1]benzothiophene) [13]. An alternative approach towards high-mobility, stable organic semiconductors was to use other acenes with smaller π-conjugation in comparison to parent compound, such as anthracene [14]. For example, diphenylvinyl-anthracene (DPVAnt) was found to have thin film mobility equal to 1.28 $cm^2\ V^{-1}\ s^{-1}$ and single crystal mobility 4.3 $cm^2\ V^{-1}\ s^{-1}$ [15,16]. Even higher carrier mobility (larger than 10 $cm^2\ V^{-1}\ s^{-1}$) was found in another derivative compound called 2,6-diphenyl anthracene (DPA) that became the most promising material in this respect [15].

Further progress in the field requires deeper understanding of charge carrier transport mechanisms. At the same time, the downsizing of electronic devices leads to thin film structures, in which the ratio between the surface area and bulk volume are largely increased. Although the surface itself manifests crystal lattice's discontinuity, the effect of this structural disorder might extend into several subsurface layers. As a result, the overall performance of the device turns out to be influenced by the surface phenomena rather than the bulk ones. On the other hand, recent progress in nanoscience has revealed significant dependence of the interfacial interactions on surface morphology [17–21], stimulating intensive research works.

Surface geometry can be investigated in many ways, but only Atomic Force Microscopy (AFM) is capable of sampling real surface heights making use of the forces that occur during direct contact (either persistent or temporary) between surface and the scanning tip. However, to extract any pattern in spatial complexities, obtained AFM images need to be further processed numerically. Depending on a method, a variety of measures can be considered, each of which describes specific aspect of recorded data: statistical distribution, scaling behavior etc. Basic analysis derives statistical parameters, such as: RMS

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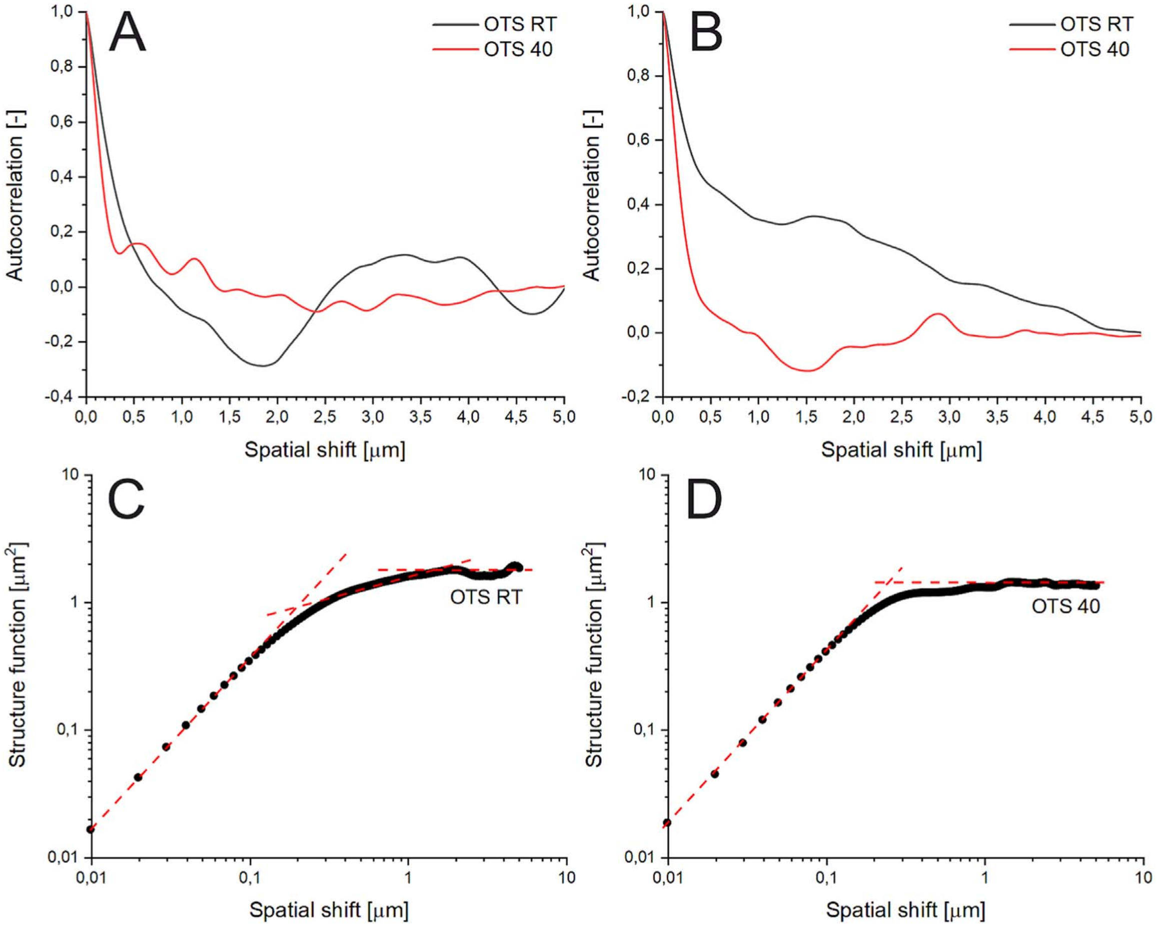

Fig. 1. Example plots of autocorrelation and structure functions of two selected OTS samples (50 nm thick) deposited at room temperature and 40 °C, derived from their AFM images: (A) Fast-decay profile autocorrelation plots, (B) Slow-decay profile autocorrelation plots, (C) Log-log plot of the structure function of a bifractal structure, (D) Log-log plot of the structure function of a monofractal structure.

roughness, mean height, higher statistical moments (skewness, kurtosis) etc. Despite their simplicity, though, statistical measures usually suffer from sensitivity to the measurement conditions (scan size, sampling interval etc.), as well as distortions introduced by pre-processing procedures used to get rid of long wavelength components, image artifacts, signal noise and others. Hence, alternative characterization methods are necessary.

It is well known that many surfaces of natural solids appear irregular and disordered, because surface morphology is a nonstationary process [22] and any fragment of the surface remains rough upon magnification. However, the morphology could be conceived as a roughness modulated at many scale lengths by roughness, which is called self-affinity. It is a specific fingerprint of fractal objects whose properties and complexity characterization can be represented by fractal geometry [23–27]. In general, fractal approach reveals spatial regularities between height samples over a wide range of wavelengths (roughness, waviness) using a minimal set of parameters: fractal dimension D and corner frequency τ_c.

Previous AFM studies on fractal properties of films of polycyclic aromatic hydrocarbons (PAH) such as tetracene [28] demonstrated that the submonolayer PAH structures formed 100 μm fractal islands. Dominating formation mechanism was diffusion-limited aggregation, i.e. hit-and-stick process. However, the islands were found more anisotropic with increasing deposition time exhibiting two perpendicular growth directions. Published results indicated significant change in the surface morphology that occurred when the film was around three monolayers thick. In this study we investigate the fractal nature of the DPA thin films in connection with their surface morphology as a key factor to faster electronic devices.

2. Methods

2.1. Materials and synthesis

All reagents used throughout this study were used without prior purification. 2,6-Diphenylanthracene, DPA: to a 100 mL flask, 474 mg (1 mmol) 2, 268 mg (2.2 mmol) phenylo boric acid and $Pd(PPh_3)_4$ 63 mg (0.05 mmol) were added under argon atmosphere. Afterwards, 2 mL ethanol, 8 mL toluene and 2 mL 2 M K_2CO_3 aqueous solutions were added. The whole system was heated to 90 °C, kept for 24 h and finally filtered. The filtrate was washed with triethylamine, dichloromethane, water, and ethanol, and purified by sublimation. DPA was obtained as a 85% (280 mg) yellow solid [1]. Within the $P2(1)/c$ space group, monocrystalline DPA exhibits a typical herringbone structure characterized by three-dimensional lattice geometry with the following lattice constants: a = 17.973(8) Å, b = 7.352(3) Å, c = 6.245(3) Å and β = 90.646(9)°, respectively [1,15]. Organic thin film transistors were produced making use of 5 nm and 50 nm thick