



Humidity, light and temperature dependent characteristics of Au/N-BuHHPDI/Au surface type multifunctional sensor

Muhammad Tahir^{a,b}, Muhammad Hassan Sayyad^a, Jenny Clark^b, Fazal Wahab^a, Fakhra Aziz^{c,*}, Muhammad Shahid^d, Munawar Ali Munawar^d, Jamil Ahmad Chaudry^d

^a Faculty of Engineering Sciences, GIK Institute of Engineering Sciences and Technology, Topi 23640, KPK, Pakistan

^b Cavendish Laboratory, University of Cambridge, JJ. Thomson Avenue, Cambridge CB3 0HE, United Kingdom

^c Department of Electronics, Jinnah College for Women, University of Peshawar, Peshawar 25120, Pakistan

^d Institute of Chemistry, University of the Punjab, Lahore 54000, Pakistan

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ABSTRACT

This paper reports the sensing properties of organic semiconducting material N-butyl-N'-(6-hydroxyhexyl) perylene-3,4,9,10-tetracarboxylic acid diimide (N-BuHHPDI). A multifunctional surface type Au/N-BuHHPDI/Au sensor has been fabricated by depositing 140 nm thin layer of N-BuHHPDI on pre-patterned gold (Au) electrodes, using vacuum thermal deposition. The effect of humidity, light and temperature on the electrical capacitance and resistance of the device has been investigated. The sensor responded exponentially toward the variation in humidity, light and temperature. An equivalent circuit of the multifunctional sensor has also been developed. By using the Tauc's law, optical band gaps (2 eV, 2.18 eV and 3.78 eV) of N-BuHHPDI have been obtained from its UV–vis spectrum. Atomic force microscopy (AFM) has been employed to study the morphology of N-BuHHPDI thin film. The environmental-conditions-dependent properties make the device useful for its applications in measurement of humidity, temperature and light.

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1. Introduction

Assessment of environmental conditions in our daily life and various fields can be accomplished by monitoring temperature, humidity, light and toxic gases, etc. present in the air [1,2]. Small molecular organic semiconductors based sensors are of great significance due to their low cost, ease of fabrication and greater stability. These materials have high sensing capability for the parameters such as temperature, radiations and humidity [3–5]. Due to strong π -conjugation system and low molecular weight, organic semiconductors like perylene and its derivatives belong to one of the important class of organic materials which bear promising optoelectronic properties and thus may be used as functional semiconducting materials [6,7]. They have strong absorption in the visible range [8] and have good chemical and thermal stabilities [9]. The n-type behavior of perylene [10] makes it a useful candidate for its potential application in different electronic and optoelectronic devices which include solar cells [11], field effect transistors and light emitting diodes [12,13]. Most of the perylene derivatives are

insoluble in water and possess excellent hydrophobic properties [14]. This hydrophobic property makes these materials more distinctive candidates for humidity sensing applications as compared to other water soluble organic materials. The high sublimation temperature (700 K) is another convincing characteristic of perylenes for their potential application as a temperature sensor to monitor temperature at elevated levels. At the same time, the broad UV–vis spectrum and good absorption of light recommend perylenes equally useful for light sensing applications. Thus, taking advantages of these motivating properties, the potential of perylene has been explored for humidity, temperature and light sensing applications due to the possession of such interesting properties all together.

Mainly, sensors are fabricated in two types of geometry; sandwich type and surface type. Though the sandwich type sensors are very reliable but expensive, complex and prone to shortening of the device while, on the other hand, surface type organic thin film structures are simple, low-cost, easy to fabricate and versatile alternatives to their counterparts [15,16]. Keeping these notable properties in view, surface type configurations are being extensively studied for the fabrication of various capacitive and resistive type sensors employing low molecular organic semiconductors. Humidity sensors, photocapacitive sensors and

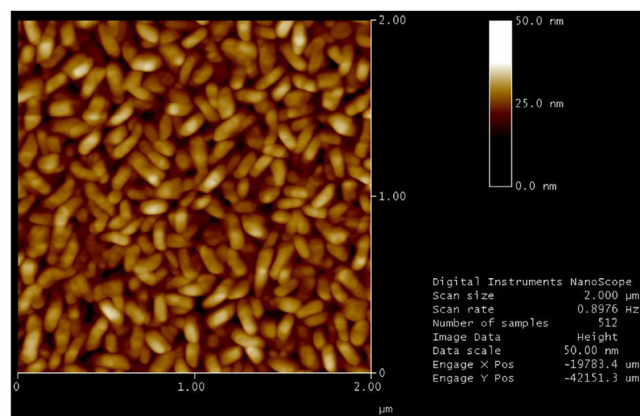
* Corresponding author. Tel.: +92 91 9216758; mobile: +92 300 5904028.
E-mail address: fakhra69@yahoo.com (F. Aziz).

temperature sensors based on organic semiconducting materials such as phthalocyanines, porphyrins, their derivatives and methyl red have been reported in the literature [2,16–20].

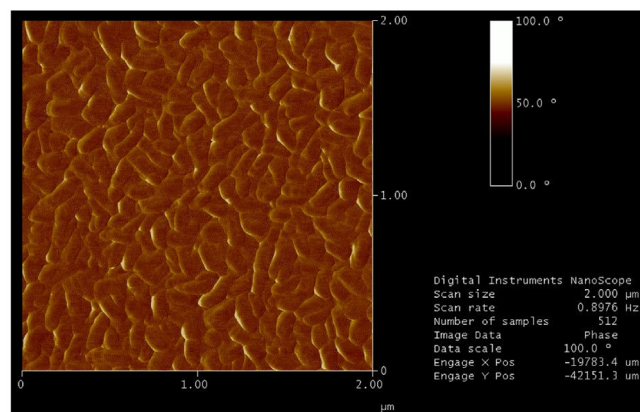
Since, very little is known about the sensing properties of perylene and its derivatives in the available literature. Thus the purpose of the present work is to use N-BuHHPDI as an active material for its potential applications in the fabrication of a surface type Au/N-BuHHPDI/Au multifunctional sensor. The capacitive and resistive responses of the sensor are investigated as a function of relative humidity (%RH), temperature and amount of illumination. The sensor has been characterized at normal pressure in the presence of air to realize its potential use in normal environmental conditions. The humidity sensing properties of the device are correlated to the morphology of N-BuHHPDI thin film.

2. Experimental work

The organic semiconductor N-BuHHPDI is used as an active layer in the fabrication of Au/N-BuHHPDI/Au multifunctional sensor. The molecular structure of N-BuHHPDI is shown in Fig. 1. Glass slide has been used as a substrate and cleaned in acetone for 10 min followed by cleaning in isopropanol for another 10 min using ultrasonic bath. The substrate is further cleaned for 5 min by producing plasma inside the vacuum thermal evaporator at pressure 10^{-3} mbar. Then 100 nm thick Au electrodes were deposited on the substrate such that the inter-electrode gap was kept 40 μm . Afterwards, 140 nm thick film of N-BuHHPDI was thermally deposited over the Au inter-electrode gap at 2.3×10^{-5} mbar. Fig. 2 shows the schematic diagram of the fabricated Au/N-BuHHPDI/Au surface type sensor. For vacuum thermal evaporation of Au and N-BuHHPDI thin films, Edward Auto 306 Vacuum Coater has been used with in situ FTM5 quartz crystal thickness monitor. The self-made humidity chamber, fitted with a commercial humidity meter is used for humidity dependent measurements in which humidity is controlled through dry nitrogen and wet air. The humidity-resistance and capacitance of the sensor were measured by using “ESCORT ELC-133 A” dual display LCR meter. For temperature-dependent capacitive and resistive measurements of the sensor, Karl Suss PM5 probe station with a thermo chuck ‘Alpha’ series system, model TP 0315A-TS-2 of Temptronic Corporation, USA, is used. The temperature-capacitance measurements were carried out in air at normal atmospheric pressure at 0%RH in dark conditions. To check the light sensitivity, the fabricated sensor is illuminated with a 25 W movable incandescent lamp. By varying distance between the lamp and sensor, light dependent characteristics have been



(a)



(b)

Fig. 3. (a) The AFM image on $2 \mu\text{m} \times 2 \mu\text{m}$ scale measured as height from image data (b) phases of the film.

measured using CEM DT-1300 light meter. The morphology of N-BuHHPDI film has been investigated by AFM NanoScope-IIIa SPM from Dimension™ 3100, Digital Instruments Veeco Metrology Group at Cavendish Lab, University of Cambridge, UK. The AFM was operated in the noncontact imaging mode to prevent damage to the film. The UV-vis spectrum was recorded with Hewlett Packard 8453, UV-vis spectrophotometer using unpolarized light in the wavelength range of 280–1100 nm, at a temperature of 300 K.

3. Results and discussions

The surface morphology of N-BuHHPDI thin film has been studied using AFM. Fig. 3 shows two dimensional AFM images on a scale size of $2 \mu\text{m}$. To see the fine features in the topography of the film, the scanning rate was kept at lower frequency of 0.8976 Hz while the tip height was maintained at 50 nm. A quite uniform distribution of grains with random orientations can be seen in Fig. 3. However, shapes and sizes of the grains are slightly different from each other. The surface profile also shows some pores and interstitial sites among the grains. Since the shape of the grain is nearly elliptical with an average length and width of 180 nm and 85 nm, respectively, so the average grain size is found to be $15,300 \text{ nm}^2$. These pores may be due to the random orientations of grains residing on one another. The film also contains voids, which produce discontinuity in the film and are responsible for absorbing water vapors causing the capacitance of sensor to increase. Moreover, the surface of the film has some non-uniform roughness with average roughness (R_a) value of 217 nm. The roughness of the film is possibly due to the non-uniform growth of some grains during the

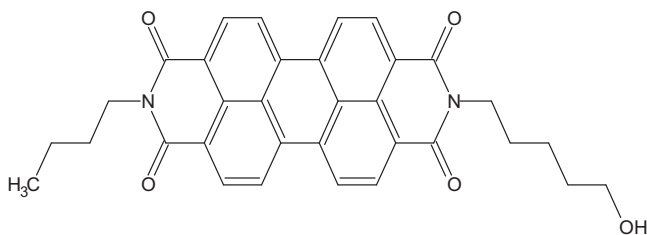


Fig. 1. Molecular structure of N-BuHHPDI.

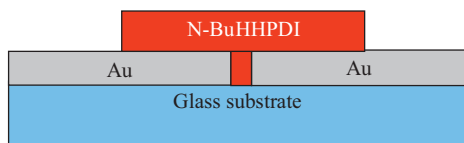


Fig. 2. Cross-sectional view of the fabricated Au/N-BuHHPDI/Au surface-type sensor.

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