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Current voltage perspective of an organic electronic device

Ayash K. Mukherjee *, Nikita Kumari

Department of Physics, Indian Institute of Technology Patna, Bihta Campus, P.O. Bihta, Patna, Bihar, 801118, India

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ABSTRACT

Nonlinearity in current (I) – voltage (V) measurement is a well-known attribute of two-terminal organic device, irrespective of the geometrical or structural arrangement of the device. Most of the existing theories that are developed for interpretation of I–V data, either focus current-voltage relationship of charge injection mechanism across the electrode-organic material interface or charge transport mechanism through the organic active material. On the contrary, both the mechanisms work in tandem charge conduction through the device. The transport mechanism is further complicated by incoherent scattering from scattering centres/charge traps that are located at the electrode-organic material interface and in the bulk of organic material. In the present communication, a collective expression has been formulated that comprises of all the transport mechanisms that are occurring at various locations of a planar organic device. The model has been fitted to experimental I–V data of Au/P3HT/Au device with excellent degree of agreement. Certain physical parameters such as the effective area of cross-section and resistance due to charge traps have been extracted from the fit.

1. Introduction

Charge dynamics across organic electronic devices (OED) has remained a contentious issue. This could be affirmed through the non-existence of a concrete and universal theory on charge transport mechanism across these devices. Such a non-discreetness is primarily because of the superposition of charge dynamics at interface and carrier movement through bulk or thin-organic-film. A quick look at the available literature reveals that there are dedicated article either belonging to transport mechanisms through electronic organic material [1–5] or charge injection mechanism across electrode-organic film interface [7–13]. On the other hand, the overall current flow through these devices is governed by the superposition of these two mechanisms. In addition, the current flow through OEDs is also affected by the presence of interface traps [14–16] and charged scattering centres. Therefore, it is interesting to explore how these scattering mechanisms come into play and affect the response (current) of a device upon a given excitation (voltage). In this communication, two terminal OED is investigated from this very standpoint.

Two terminal OED are studied in two architectures, namely sandwich and planar. The sandwich architecture is commonly reported. Various aspects of sandwich device with electronic organic active material have been widely investigated [5,16–23]. This is because sandwich cells allow measurement in capacitive geometry, which further facilitates accurate I–V, C–V measurements. The data is interpreted in various ways. For example, Horowitz and coworkers have stressed upon the existence of depletion theory in pentacene based sandwich devices [24]. According to the report, the depletion region extends throughout the whole thickness of Au/Pentacene/Al sandwich cell. However, the existence of depletion region in organic devices is difficult to define as there are quite a few fundamental differences between an inorganic and organic semiconductor. Particularly, a complete account of nature and distribution of undesired impurities in organic electronic materials is yet not understood. Furthermore, in the same report, in depth analysis of I–V characteristics is hardly explored. Similarly, I–V measurement in various organic devices in staggered configuration has been analyzed to reveal the charge injection mechanism at the interface [7–12]. However, in a two-terminal electrode-organic device, the charge transport process is a three step mechanism, the first step being the charge injection in the bulk or thin film, the second being the charge transport through the bulk or thin film, and the last step is the charge extraction from the bulk. Therefore, focussing the investigation only on the injection mechanism may not be the right method of data analysis. For a complete analysis, all the three mechanisms should be looked upon, and integrated into one equation.

Organic devices in planar geometry are mostly studied in the form of thin film transistor (TFT). There is an overwhelming count of reports on organic TFTs [25–29,39–46,57,58]. In these devices,

* Corresponding author.
E-mail addresses: akm@iitp.ac.in (A.K. Mukherjee), nikita.iitp@gmail.com (N. Kumari).

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the charge injecting/extracting electrodes could be in the configuration of bottom contact (BC) or top contact (TC). Since it is a TFT, a gate electrode along with gate dielectric is also placed parallel to the direction of charge flow. Charge dynamics in an organic TFT is not similar to that of MOSFET. Primarily because of the absence of depletion region. Although, work by Horowitz indicates otherwise [24]. In the first generation organic TFTs, the physical concepts of MOSFET were bluntly used [30]. However, on a conceptual platform, the actual physics of such organic devices was worked out by Biaggio and co-workers [31]. This theoretical investigation has yielded well-defined expressions for drain current as a function of source-drain voltage and drain current as a function of contact voltage. Subtle experimental studies on organic TFTs on different forefront could also be traced out in published literature [1–4,6,25–29,39–46]. For example, dependence of threshold voltage and channel saturation current on thickness of active layer of pentacene TFT has been reported by Schroeder et al. [2]. Bias stress induced degradation of channel has been studied in depth by Sirringhaus and co-workers [3]. Here, it is concluded by the authors that de-trapping of charge carriers by exposure to band-gap illumination is the root cause of bias-stress degradation. Bias stress related instability in pentacene based TFT is also reported by Wang et al. [4]. One of most important paradigms of organic TFT is contact resistance, as it plays a *foul sport* in upgrading the performance of any organic device. Jackson and coworkers [7], investigated contact resistance (CR) in the configuration of TC and BC. They found that the CR for BC TFT depends on gate bias and drain bias, while CR for TC TFT is comparable to or even exceeds channel resistance. The same group of authors also investigated the dependence of CR and gate bias for a pentacene based TFT in another report [8]. In all above-mentioned reports, the charge transport is investigated in FET configuration where there are two crossed electric fields, one due to drain-source bias and other due to gate. The charge conduction takes place under the influence of these two fields and it is rather complicated. According to inorganic semiconductor theory, the gate field is responsible for creating the conduction-channel while the drain field is responsible for charge injection to and rejection from the channel at the two interfaces with electrodes [32]. Further, the situation becomes more complicated because of the presence of charged species at the dielectric-semiconductor interface. It is possible to simplify the situation if only two electrodes are employed, one for carrier injection and other for extraction, and then focus the investigation on three step process of charge transport as highlighted earlier.

In the present communication, a symmetric planar organic device in TC geometry is investigated. The active material used in this study is poly(3-hexylthiophene-2,5-diyl) (P3HT) and material for electrodes is gold. This choice of material is particularly suitable for working in open laboratory atmosphere. Since there is no presence of induced channel due to gate-field, measurement of miniscule quantity of current has proved quite of a challenge. I–V data of this planar device is thus obtained under extreme care and the data is analysed in view of physical mechanisms involved in three step process, namely, charge injection, transport through bulk and charge extraction.

2. Materials and methods

P3HT film is spin coated on cleaned and surface-functionalized glass substrate at around 1500 rpm. The concentration used is 0.01 g/ml in chloroform. The glass substrates are cleaned through treatment by Piranha solution. The functionalization of the substrate is achieved by exposure to Hexamethyldisilazane (HMDS). Usage of HMDS is a common practice for surface functionalization of substrates as it helps in lowering the surface energy which further results in better adhesion of the organic species [33,34].

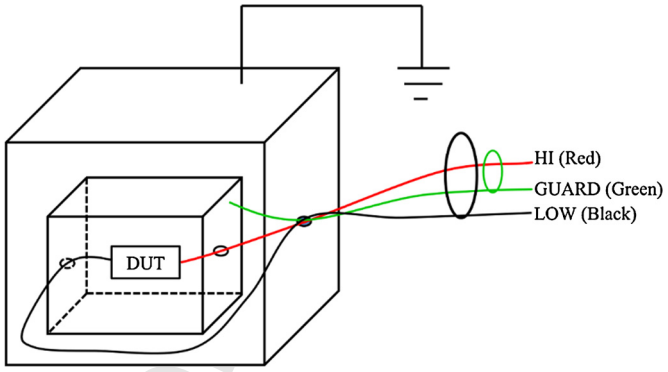

Fig. 1. Electromagnetically shielded box.

The films thus formed are further annealed for 10 hours at 100 °C at around 0.1 mbar. It could be found in various scientific reports that the annealing is typically done at a pressure of 10^{-3} mbar or lower so that the thermal agitation could drive out residual oxygen and moisture from film [35–37]. In this study, planar devices of Au/P3HT/Au are investigated with the absence of channel forming gate electrode. As a result, a very low degree of charge flow is expected. However, as reported in many scientific literature [38], oxygen could act as a doping agent for P3HT, thereby increasing its conductivity. Therefore, in the beginning of this study, it was presumed that scarce doping by oxygen could aid in charge conduction through the Au/P3HT/Au planar device. Inadvertently, it made us choose a pressure of 0.1 mbar for vacuum annealing. Later on, Gold electrodes are sputtered on the films.

In the upcoming sections, it is witnessed that the idea of oxygen doping did not work out as planned since the values of current through the planar device is recorded to be very low. To enhance the charge flow, a Lewis acid based *p*-type dopant is utilized. A 10% w/w aqueous solution of dodecylbenzenesulfonic acid (DBSA) is spin coated over P3HT films in order to surface dope the film. The rotational speed for spin-coating is kept at 7000 rpm.

For electrical characterization, the sample is kept inside custom fabricated electromagnetically shielded cascaded and electrically conducting boxes. The boxes are, however, electrically insulated from one another. A schematic of the arrangement is shown in Fig. 1. The cascaded arrangement of boxes contains two boxes. The outer box is connected to the ground terminal of Keithley 6487 pico-ammeter and the inner box is connected to the *Guard* terminal of pico-ammeter. Fig. 1 also shows electrical connections to the sample as well as the cascaded boxes. All the measurements are performed in dark and in presence of air.

The choice of measuring instrument is critical in I–V measurement of highly resistive samples. The primary reason for such criticality is the diminutive magnitude of current threading through the two-terminal organic device. For this measurement, Keithley 6487 pico-ammeter is utilized as it is equipped with independent low noise voltage source which has no connection with the current measuring circuit of pico-ammeter. Besides, it helps to avoid any kind current loading effect. Fig. 2 shows the network that is used for I–V measurement. Voltage is varied in a stepwise manner and instantaneous sample current was measured with minimal time delay. Also, it is evident from the network of Fig. 2 that current loading of the voltmeter (in-built in 6487) has got nothing to do with the I–V measurement.

3. Results and discussion

I–V measurement of two-terminal planar P3HT device is performed in the manner described in previous section. The data is shown in Fig. 3. Usually, while plotting data, the *x*-axis signifies