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Estimation of built-in voltage from steady-state current–voltage characteristics of organic diodes

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ABSTRACT

A technique for extraction of built-in voltage from the steady-state current–voltage characteristics of a two terminal organic diode is described which does not require assumption of quadratic dependence of current on voltage. The technique relies instead on current voltage characteristics being exponential below built-in voltage and power-law above it to generate a sharply defined peak at a voltage proportional to built-in voltage. Simulation results are used to validate the proposed method and experimental results obtained with P3HT and P3HT:PCBM blends are presented.

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1. Introduction

Organic electronics holds the promise of low cost applications such as displays, solar cells, RFIDs, and sensors on flexible substrates such as plastic, paper and fiber using printing and roll-to-roll processing techniques [1–3]. Organic semiconductors are often large energy gap materials that are commonly undoped and have very few intrinsic carriers of their own. Thus, for their operation, organic semiconductor devices rely on carriers that are obtained through injection from the metal or conducting polymer electrodes. In bipolar devices such as light emitting diodes or solar cells, different metals in general are used at anode and cathode to facilitate charge injection/collection. As a result, there is an internal electric field even at zero bias and an associated built-in voltage (V_{bi}). In the case of light emitting diodes, this built-in voltage is a hindrance and has to be overcome by the applied voltage before significant current begins to flow. On the other hand, in the case of solar cells, the built-in field is beneficial for extraction of carriers to the electrodes before they recombine. In the case of thin film transistors as well, use of different source/drain and gate metals will result in built-in voltage which contributes to the flat band voltage and threshold voltages. As a result of its important role, an estimation of built-in voltage is thus essential for understanding almost all organic semiconductor devices.

Due to the existence of vacuum level discontinuity [4] in many metal/organic systems, the built-in voltage may not simply be the difference in work-functions of anode and cathodes and should be determined experimentally from the device itself. A widely reported method for measurement of V_{bi} is electroabsorption [5–7] which relies on changes in reflection coefficient with electric field inside the device. The method has the advantage of being non-invasive but assumes that the field inside the device is uniform, which may not always be true [8]. The method is also relatively complicated to be used on a routine basis. In this regard, estimation of V_{bi} from capacitance–voltage $C(V)$ [9] characteristics is attractive due to its simplicity. Due to contributions from diffusion current, a peak in $C(V)$ characteristics is observed and the voltage corresponding to the peak is proportional to the built-in voltage. The disadvantage of this method is that capacitance is very sensitive to traps and the peak capacitance voltage is seriously compromised when they are in significant number. Photovoltaic measurements [10,11] have also been reported for estimation of zero field voltage (also called onset voltage)

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from which V_{bi} is estimated. This method, however, may not be applicable to devices containing planar or bulk heterojunction where it has been reported that open circuit voltage is independent of electrode work-functions [12] or depends on factors other than electrode work-functions as well [13]. Estimation of V_{bi} from steady-state current voltage characteristics $J(V)$ [14] has also been reported where the onset voltage Vo is extracted by extrapolating the current to zero after the leakage component is subtracted from it. However, this method of extraction of Vo from $J(V)$ is considered to be arbitrary and imprecise because there is no strict onset of diffusion current [8]. In the present work, we report an improved method for extraction of onset voltage from the steady-state $I(V)$ characteristics from which the built-in voltage is estimated. The proposed method is explained in Section 2 along with simulation results. Section 3 illustrates the technique with experimental results obtained with two different material systems. The important conclusions from the work are summarized in Section 4.

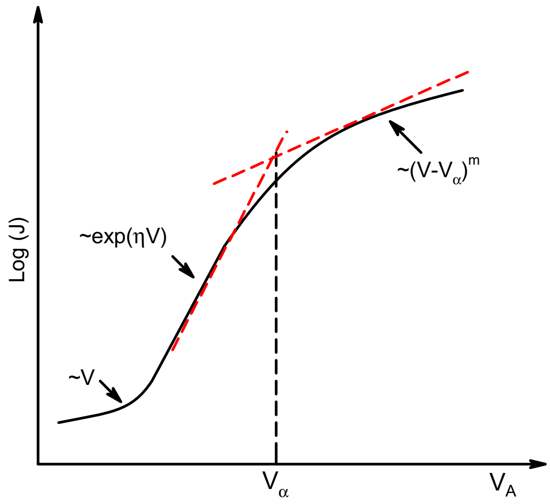

Fig. 2. Schematic variation of current density (log scale) with voltage for a single layer organic diode with built-in voltage.

2. Proposed method

2.1. Basic concept

Fig. 1 shows the schematic and energy diagram of a single layer diode. It is assumed throughout the discussion that barrier height for holes at the anode is small allowing efficient injection into the organic material. On the cathode side, barrier height for both electrons and hole injection is assumed to be large. As a result, no electrons are injected into the device and operation is unipolar.

The current–voltage characteristics of such a single layer diode (Fig. 1a) with built-in voltage is characterized by several distinct regions as schematically illustrated in Fig. 2. For low voltages, the characteristics are approximately linear and are due to leakage current paths in the device. This part of the characteristics is not intrinsic to the device behavior and is often modeled through addition of a shunt resistance in parallel to the diode. The next region is the exponential region [15] which appears as a straight line on the log-linear plot. In this part of the characteristics, the applied voltage is less than built-in voltage and thus electric field inside the device opposes flow of holes towards the cathode and diffusion is the main driver of current. The current is exponential in nature because holes have to overcome a potential barrier in order to reach the opposite electrode. Once the voltage applied becomes larger than the built-in voltage, the electric field reverses sign and now aids flow of holes towards the cathode. The drift current now becomes dominant and since electric field is significantly affected by space charge within the device, the current is appropriately called space charge limited current (SCLC). The relationship of current with voltage is power law $J = K \times (V - V_\alpha)^m$ with the exponent m being close to two in the absence of traps and field independent mobility. The transition voltage V_α, marking the onset of SCLC region is expected to be close to the built-in voltage V_{bi}.

Fig. 2 illustrates a simple extrapolation based method for locating the transition voltage V_α which however, suffers from the problem that characteristics above V_α is not linear (on the log-linear plot) and thus different tangents can be drawn at different points yielding different values of transition voltage. The presence of traps can also distort this region resulting in further inaccuracies in this particular approach. An extrapolation of $\sqrt{J}$ vs. V plot can also be used to determine the transition voltage [8]. The problem with this approach again is that in many practical devices, the characteristic is not quadratic thereby making the technique error prone. In the present work, this ambiguity in determination of transition voltage is minimized by pro-

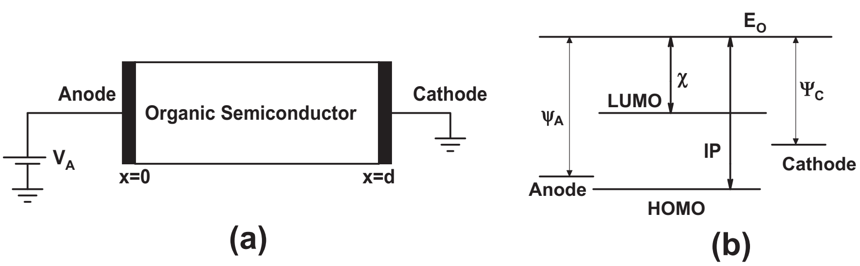

Fig. 1. (a) Schematic of a single layer diode (b) energy diagram illustrating the typical relationship between electrodes and organic material. χ is electron affinity, IP is ionization potential and Eo is vacuum level.

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