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Self-heating effects in organic semiconductor crossbar structures with small active area

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ABSTRACT

We studied the influence of heating effects in an organic device containing a layer sequence of n-doped/intrinsic/n-doped C_{60} between crossbar metal electrodes. These devices give a perfect setting for studying the heat transport at high power densities because C_{60} can withstand temperatures above 200 °C. Infrared images of the device and detailed numerical simulations of the heat transport suggest that the electrical circuit produces a combination of homogeneous power dissipation in the active volume and strong heat sources localized at the contact edges. Hence, close to the contact edges, the current density is significantly enhanced with respect to the central region of the device, demonstrating that three-dimensional effects have a strong impact on a device with seemingly one-dimensional current transport.

1. Introduction

Over the last few years, organic devices showing rather high power consumption have received increasing attention. Fast organic rectifying diodes are particularly interesting for applications in radio frequency identification (RFID) tags [1–3]. The required switching speed of at least 13.56 MHz at low driving voltage can only be achieved with high mobility materials. Nevertheless, the rather large current densities induce a high power dissipation within the device, so that efficient heat flow through a highly thermal conductive substrate becomes a key ingredient to prevent breakdown [1]. The high cost of the respective substrates is in direct conflict with commercial requirements.

For organic light-emitting diodes (OLEDs) detailed research has been made to understand the distribution of temperature and luminescence for rather large active areas [4]. One crucial point is the use of indium tin oxide (ITO) as a transparent contact, introducing nevertheless a certain series resistance leading to a drop of voltage and power. In contrast to OLEDs, rectifying diodes have a much smaller active area with a lateral extension smaller than the thickness of the substrate. For this geometry, a detailed study of heat transport away from the electronic circuit is still missing.

In the present work, we investigate the heat conduction of a vertical layer sequence consisting of n-doped/intrinsic/n-doped (nin) C_{60}. Similar to rectifying diodes we will use electrodes in a crossbar architecture, evaporated across a shadow mask. Identical doped layers surrounding the intrinsic layer reduce the contact resistance [5] and avoid

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a built-in potential. Combined with the particularly high electron mobility and thermal stability of C_{60}, we are able to study the temperature dependence of this device up to about 200 °C before eventually reaching thermal breakdown. Furthermore, we clarify whether our device geometry is suitable for the extraction of transport parameters, usually requiring simplifying assumptions like purely one-dimensional (1D) current transport. Instead, although the aspect ratio between height and width of this device is of the order of 1000, it will turn out that power dissipation along the edges contributes substantially to the observed temperature distribution, corroborated by detailed three-dimensional (3D) simulations of heat transport. These edge singularities also play a major role for the thermal breakdown of the device.

2. Experimental results

Our nin devices contain an intrinsic layer sandwiched between two n-doped layers adjacent to the metal contacts, compare Fig. 1. The thickness of the central intrinsic layer is varied from 100 nm to 400 nm, with the thicknesses of the n-doped layers kept fixed at 20 nm. The resulting sequence of layers is embedded between two metal electrodes using a combination of Al (>200 nm) and Au (20 nm) [6].

The samples are produced on glass substrates (Borofloat 33, Schott AG[3]) using thermal vapor deposition. As n-type organic semiconductor, we employ C_{60} with a mobility above 0.1 cm^2/Vs, ensuring high current densities at moderate driving voltages [2,7]. Doping of C_{60} is realized by coevaporation with tungsten paddle wheel $W_2(hpp)_4$ at a doping concentration of 2 wt% [8,9], guaranteeing Ohmic injection [5]. Structuring of the device is done by shadow masks, leading to an active area of 0.06 mm^2 with electrodes of a typically trapezoidal shape [10] as schematically visualized in Fig. 1 (c. Supporting information). The angle between top and bottom of the contact edge is below 1°, but the thickness of the organic material is uniform across the active area.

The IV curves of the devices are shown in Fig. 2. In the voltage regime below 0.5 V, irrespective of thickness, the current–voltage dependence follows a linear potential law as expected for Ohmic injection. At voltages beyond 0.5 V, a strong increase of current can be measured, especially for samples with large thickness of the intrinsic layer. The highest current densities of up to 10^6 mA/cm^2 still remain far below the highest published values [11]. The shoot up of current is assigned to a thermal runaway due to Joule self-heating, leading to an increase in electrical conductivity and power dissipation [12]. This effect can occur for a positive temperature coefficient of the conductivity, $\partial\sigma/\partial T > 0$, which is realized for most organic semiconductors. In Fig. 2, additional lines of constant power density suggest a correlation between heating power and IV characteristic: more than the voltage, the power density gives a threshold between constant temperature and self-heating regime, starting at about 10 W/cm^2. The steeper IV characteristic for samples with larger

[3] product sheet: http://www.schott.com/borofloat.

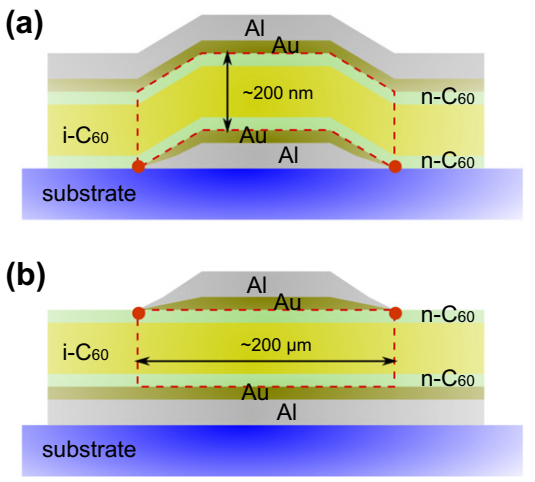

Fig. 1. Schematic structure of the device and cross sections along (a) top contact and (b) bottom contact. For simulating the heat conduction, we use a volume heat source (within red dashed line). Heat sources localized along lines oriented perpendicular to the picture are indicated by red dots. The arrows indicate the typical dimensions of length and height. For further geometric details compare the supporting information. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

thickness of the intrinsic layer can be related to the series resistance of the measuring circuit excluding the device. In the asymptotic region, the thinnest samples allow to assign a value of about 7 Ω to the series resistance. Since the thickest device with an intrinsic layer of 400 nm has the highest resistance, the current shoot up sets in at a somewhat higher voltage, but with a much steeper power law $j \propto U^{\alpha}$ with an exponent of $\alpha > 10$. For devices with lower thicknesses, smaller power laws can be obtained due to the stronger influence of the series resistor, e.g $\alpha \approx 4$ for $d = 200$ nm, compare Fig. 2.

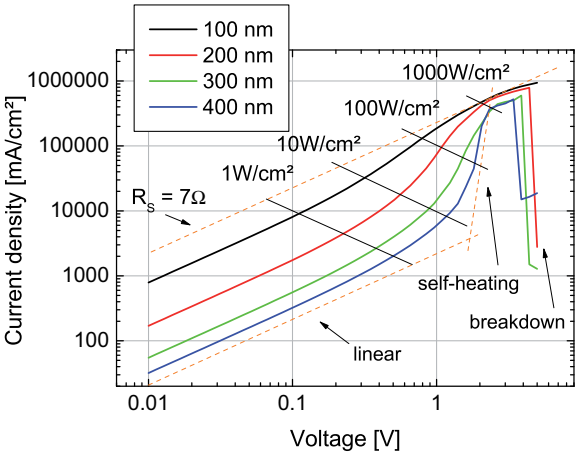

Fig. 2. IV characteristic of nin devices comprising different thicknesses of the intrinsic C_{60} layer, for grounded top electrode. Above power densities of 10 W/cm^2 the current densities increase rapidly due to Joule self-heating, only limited by a series resistance of about 7 Ω. Breakdown appears in the range 3 V–5 V.