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Effects of substrate topography on current injection and light emission properties of organic light emitting devices

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ABSTRACT

Substrate topography plays a critical role in the function of nano-scale materials and devices. We study small molecular organic light emitting devices (OLEDs) deposited onto non-planar substrates, where the substrate's radius of curvature in some regions approaches the thickness of the active device layers. As a result, the electric field profile inside the organic charge transport layers is modified, influencing carrier injection, transport, and light emission properties. Experiments and numerical modeling suggest that charge balance and electroluminescence efficiency potentially can be improved in electron injection-limited OLED architectures *via* substrate geometry. These findings elucidate the optoelectronic behavior (and degradation) of OLEDs on imperfect substrates, and suggest a strategy based on substrate topography for controlling device behavior.

1. Introduction

Micro- and nano-scale substrate topography can exert a strong influence on the properties of a surface (e.g. altering the surface energy [1], changing the electric or magnetic field distribution, affecting light scattering), and thereby influence the properties of functional coatings deposited onto substrates textured at very small scales. While the overwhelming majority of optoelectronic devices are deposited on flat substrates, rough or non-planar substrates are inevitably encountered, which have the potential to dramatically affect optoelectronic device performance [1–18]. In some instances, substrate roughness can lead to defect incorporation and reduce manufacturing yield [3], while in others it can be advantageous, depending on the length scale and shape of surface features. For example, thin-film solar cells deposited onto textured surfaces exhibit enhanced optical absorption due to light trapping [4–6]. Organic light emitting devices (OLEDs) have been deposited on pre-patterned substrates to improve light out-coupling efficiency [7]. Organic photovoltaic cells and OLEDs deposited onto cylindrical substrates exhibit optical characteristics independent of the azimuth of incident or emitted light [8,9]. Moreover, when the feature size of a non-planar substrate becomes comparable to the thickness of the active device, device operation is further affected. Previous work [10–12] has shown that the device active area becomes localized due to active layer thickness variation, caused by the manner in which the substrate geometry affects thin-film deposition in vacuum. When the feature size of the non-planar substrate is in the nano-scale regime, surface electronic structure is modified, changing the charge injection behavior [13]. For example, lowering of the tunneling barrier at the sharp end of nanostructures, such as sharp silicon tips, $TaSi_2$ nanowires, and carbon nanotubes, has been used in realizing

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field-emission devices [14–16]. In gas sensors based on Schottky junctions to MoO_3, the reverse bias response to H_2 concentration has been improved [17]. The lowering of the Schottky barrier at the vertex of diamond nano-crystals improves thermionic energy conversion [18]. In the present work we show that the typically problematic electron injection from a pre-deposited metal electrode of an OLED [19] can be improved by substrate texturing alone, rebalancing electron and hole populations and thereby increasing electroluminescence efficiency. These findings also suggest a mechanism by which localized charge injection and subsequent filamentary charge conduction can occur in disordered semiconductors [20].

This paper is organized as follows. First, we briefly review the basic OLED configuration and the limitations with respect to electron injection. We discuss how substrate curvature can facilitate electron injection in the absence of doping and can improve charge balance in an OLED, introducing a highly simplified single-layer model that decouples effects of charge mobility and deposition sequence from the influence of OLED curvature. We examine unipolar devices, followed by heterojunction OLEDs on planar, pyramidal, and truncated pyramidal substrates, which allow us to deduce the contribution to net current and light emission from the highly curved, vertex regions. We then examine the light output from OLEDs on textured substrates, which indeed modify the charge balance. We then summarize and conclude by a brief discussion of the broader implications of the findings.

2. Theory and calculation

2.1. Planar vs. highly curved substrates

In a conventional OLED fabrication process, the hole-injecting anode (e.g. indium tin oxide-ITO) is pre-deposited on the substrate, followed by the deposition (by spin-coating or vapor deposition) of the organic layers, and the vacuum deposition of an electron-injecting cathode (typically, a low work function metal). Historically, this fabrication sequence improved electron injection into the organic layer. In contrast, the reverse sequence (cathode pre-deposited onto the substrate) yields poor electron injection into the organic layer. It was hypothesized that interfacial damage occurs during cathode deposition onto the organic electron transporting/injection layer (ETL/EIL), facilitating electron injection [21]. Interfacial disorder (intrinsic or incurred during processing) can further enhance injection [22,23]. While Schottky junctions at the cathode in OLEDs have been reported [24], doping levels are typically too low for appreciable band bending to occur, particularly in the "inverted" OLED geometry, where the cathode is deposited first ("bottom-cathode" architecture). Consequently, "bottom-cathode" OLEDs typically exhibit higher turn-on voltages and lower emission efficiency, both due to the increase in operating voltage and due to charge imbalance [17,25–28].

Now consider an archetypal OLED deposited on a nanoscale surface feature, which has a radius of curvature on the order of the device thickness, as shown in Fig. 1a. Such a structure is representative of arrayed devices formed on nano-textured substrates in this work. Approximating the vertex as a hemisphere with a 50 nm radius of curvature and the OLED as a 100 nm thick organic semiconductor film sandwiched between two biased electrodes, we map the electrical potential of the device in cross-section in Fig. 1b, contrasted with that of a conventional planar OLED. In contrast to the planar configuration, for the non-planar device in Fig. 1b, the electric field established in the organic layers is spatially non-uniform, concentrated at the bottom electrode (BE) and diverging toward the top electrode (TE) [12], which can be clearly seen in Fig 1c. The effect of non-uniform electric field on device performance can be qualitatively explained by the energy level diagram shown in Fig 1d, where the BE is set as the cathode and the TE is set as the anode. The increased electric field near the BE, indicated by the higher curvature of the band edge, significantly increases the injection of electrons (and likely also the electron mobility) [26], resulting in a larger electron injection current density. On the other hand, the reduced electric field near the TE (anode), indicated by the lower curvature of the band edge, significantly decreases hole injection (and likely also the hole mobility) [26], resulting in a smaller hole injection current density. Together, these effects modify the ratio of electron and

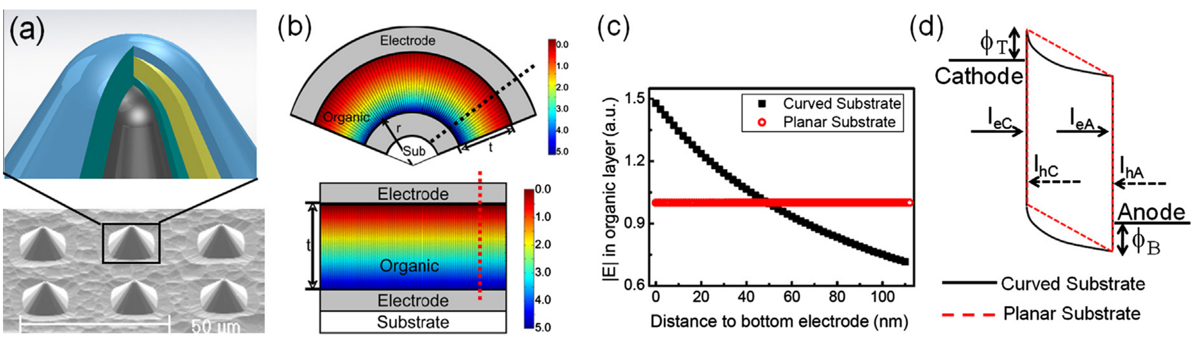

Fig. 1. (a) Scanning electron micrograph of a textured substrate and a digital rendering of the structure of an OLED formed on the vertices. (b) Cross-sectional schematic of the device structure in (a) and a color map of the potential contour inside device on hemi-spherical and planar substrates used in OLED modeling. (c) The electric field profile inside the organic layers of the OLEDs (on planar and curved substrates), as a scan along the dotted line in (b). (d) Energy band diagram and the parameters used in the simulation of devices on both curved and planar substrate. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)