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High yield fabrication of vertical interdigital electrodes with sub micrometer distance and their application in an organic photovoltaic device

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ABSTRACT

This work reports on a new method to fabricate vertical, interdigital electrodes of different materials with sub micrometer distance. The electrodes are deposited by thermal evaporation on a micro replicated surface relief grating structure with high aspect ratio utilizing the shadowing effect of the structures. The optimized process presented here leads to a high yield in separated electrodes on micro replicated samples and tolerates topographical defects in them. As one of many potential applications, we demonstrate the functionality in organic solar cells (OSCs) composed of poly (3-hexylthiophene) (P3HT) blended with C_{61}-butyric acid methyl ester (PCBM). Using approx. 2500 electrode pairs connected in parallel a solar power conversion efficiency of 0.5% was achieved. This is a tenfold increase compared to previously reported values of OSCs on this setup, which is attributed to the improved processing scheme of the nanoelectrodes. Optical simulations were performed to evaluate the 2D-absorption profile and calculate the theoretical limit for the short circuit current density in these devices. The results indicate that the majority of the nanoelectrodes are intact.

1. Introduction

Interdigital electrodes are used in many organic electronic devices, for example in thin film transistors, light emitting diodes, solar cells and sensor applications [1–7]. The distance between the electrodes is one of the key parameters and the optimum distance depends strongly on the desired application and the production method. While lithographic methods can yield feature sizes on the length scale of some tens of nanometers, hetero electrode systems in those dimensions consisting of different metals require extreme precise alignment and are nearly impossible to generate on large area plastic substrates. Electroplating might be used to solve this problem, but limits the choice of materials. State of the art electrode configurations for organic electronic applications are therefore predominantly co-planar. We report on a fabrication method to obtain vertical electrodes, i.e., perpendicular to the substrate surface, which are separated by only some hundred nanometers (here: 300 nm), hence referred to as nanoelectrodes. The electrodes are deposited by a series of evaporation steps followed by a lift-off procedure. They can be composed of various evaporable materials. One approach to fabricate vertical electrodes on structured substrates was previously reported [8,9]. The method introduced at that time uses surface relief profiles on acrylic substrates, which are created by interference lithography and subsequent micro replication. A severe problem is that almost flawless substrates are required in order to obtain perfectly separated interdigital electrodes. Any defect in the struc-

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ture such as a (partially) missing lamella or a scratch in the structure will lead to the formation of a shunt between otherwise opposing electrodes. As it is almost impossible to obtain perfectly structured substrates on areas >1 mm^2, we altered the preparation technique. This way we managed to increase the yield of well separated electrodes, which can be measured quantitatively by the electric resistance between the interdigitating electrodes.

To demonstrate the performance of the nanoelectrodes we fabricated organic solar cells (OSCs) with the nanoelectrode system, as it was this application these electrodes were developed for initially [8,9]. In contrast to the commonly used planar electrode geometry, interdigital electrodes with comparable electrode distances allowed to study the effect of contact formation [10]. The results are compared with optical simulations to assess the obtained current density in this nanoelectrode setup.

OSCs possess many promising properties and might be cheaply producible, compared to their inorganic counterparts [11–13]. The highest reported efficiency to date is already above 10% [14]. Among the vast number of different materials for the photoactive layer of polymeric OSCs poly (3-hexylthiophene) (P3HT) is well known to work as a good (electron) donor material and C_{61}-butyric acid methyl ester (PCBM) as a good (electron) acceptor material. These two components are usually dissolved in an organic solvent (blend) and subsequently deposited on a suitable substrate with different methods such as spin-coating, doctor blading or gravure printing. Once the organic solvent has evaporated, the two components are closely intermixed and form a so-called bulk hetero-junction (BHJ). This junction must facilitate exciton dissociation and at the same time charge carrier transport towards the respective electrode [15]. For the performance of the OSC the morphology of the blend layer is therefore very important but at the same time also hard to control. It depends on many parameters, one of such being the materials used for the active layer. Furthermore the organic solvent and the materials used for the electrodes, as well as possible pretreatments and other factors influence the morphology significantly [16–18].

Finding the appropriate composition of the two materials as well as identifying the necessary post-treatment steps such as annealing usually requires a large number of experiments [19–23]. The nanoelectrode setup offers new possibilities for OSCs, as the electrodes are already in place before the photoactive layer is applied. Therefore this configuration provides an efficient tool to observe and manipulate the blend morphology as it allows for the application of an electric field by applying a voltage during the formation of the photoactive layer. We used substrate sizes which are in the order of 100 cm^2. Several hundreds of individual solar cells (in this work each composed of approx. 2500 electrode pairs connected in parallel) can be fabricated at a time on a single substrate, offering an efficient method for parameter screening of the blend composition (material, solvent, concentration, donor to acceptor ratio, etc.). A schematic overview of the layout is shown in Fig. 1. The structured substrates are flexible and transparent, the illumination can therefore be from bottom or top. Please note that other layouts and circuitries can be designed as well, e.g. connecting the electrodes in series in order to achieve high voltages [24]. With the new fabrication routine the efficiency of an OSC composed of P3HT:PCBM was ten-fold increased (from 0.05% to 0.5%).

2. Experimental details

Using interference lithography a surface relief profile was created in a photo resist layer [25,26]. The period of the profile can be adjusted to match the desired application, in this case it is 720 nm, with the trenches having a width and height of approx. 400 nm. This profile was afterwards transferred into a nickel stamp by the use of electroforming. With this stamp a replication into an acrylic UV curable photopolymer was conducted, yielding multiple nanostructured substrates. They were cleaned in deionized water with ultrasonic treatment and dried in an oven at 50 °C in a nitrogen atmosphere for several hours. The evaporation of the electrodes is separated in two steps that both involve a lift off procedure in deionized water (Fig. 2). The first step is to evaporate 100 nm lithium fluoride (LiF) at a

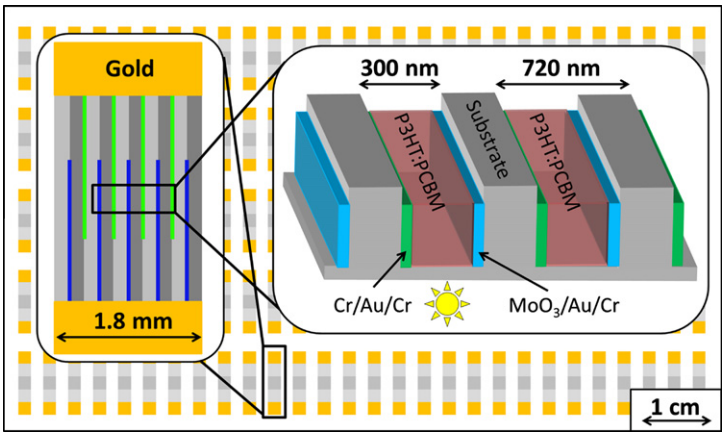

Fig. 1. Scheme of the layout of vertical electrodes. The electrode pairs in the top view of a single cell (left) are not drawn to scale. The schematic cross-section shows the interdigital area, where both electrodes face each other.