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Co-planar bi-metallic interdigitated electrode substrate for spin-coated organic solar cells

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ABSTRACT

A bulk heterojunction organic solar cell with co-planar interdigitated electrodes was fabricated and tested. The co-planar electrodes had a separation distance of 1–3 μm and were fabricated from aluminum and nickel on a heavily oxidized silicon wafer using photolithography. The device was prepared by spin-coating MEH-PPV:PCBB in a 1:3 wt ratio with a total donor:acceptor solution concentration of 2.44%. The device demonstrated a strong photovoltaic response under AM1.5 illumination of 80 mW/cm^2 with an open circuit voltage of 0.704 V. The co-planar electrode design offers advantages in terms of electrode material selection and reliability as well as simplified device fabrication.

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1. Introduction

While the efficiencies of inorganic photovoltaics continue to improve, market penetration is still limited due to their high cost in comparison to non-renewable energy sources. Due to the high energy processing required for silicon, the cost per kilowatt-hour for electricity from Si-based solar cells is as high as $0.25–0.65 /kW h [1]. This is roughly 5 times more than the price of electricity produced using fossil fuels. Adding to the high cost of inorganic solar cells, the potential increase in demand for Si crystals can lead to even higher costs for the devices. One estimate on the amount of silicon needed to supply electricity for a family consuming 20 kW h/day using 15% efficient solar cells is approximately 10,000 times more than the amount of silicon in a computer[2]. Clearly, a low cost alternative to inorganic solar cells is needed.

Polymer-based solar cells are being widely investigated as a potential low cost alternative to silicon because, in principle, they can be produced on a large scale using inexpensive solution-based processes such as spraying, painting, and roll-to-roll printing [3–5]. For example, it has been shown that the manufacturing cost of polymer solar cells can be reduced very quickly (from 35 to 8 Euros/W in one year) [3]. On the other hand, the lifetime of polymer solar cells is still too short to allow comparisons with crystalline silicon [3]. In addition to their lower cost, polymeric materials are lighter, have much greater mechanical flexibility, and are capable of being directly fabricated onto most surfaces including plastics [6].

Bulk heterojunction polymer solar cells convert light into electricity using a straight forward process. Photons are absorbed by an organic semiconductor (the polymer) resulting in the creation of mobile electron–hole bound pairs known as Frenkel excitons [7]. The electron–hole pairs are then separated at a polymer/electron-acceptor interface. Typical acceptors include titanium dioxide, and carbon fullerenes. The holes travel through the polymer to the anode, and the electrons travel through the electron-acceptor toward the cathode resulting in an externally measurable current. The device efficiency depends on a number of important design parameters. For example, electron–hole separation requires a symmetry breaking condition such as using electrode materials with different work functions to provide a preferred direction to the internal electric fields [8].

Polymer solar cells typically take the form of a sandwich structure with the active layer placed in between the anode and cathode electrodes. There are several challenges with this design. For example, at least one of the electrodes must be an optically transparent material such as Indium Tin Oxide (ITO) or Fluorinated Tin Oxide (FTO) [9]. These materials typically have lower conductivity than metal electrodes and are often deposited using high temperatures, which can be harmful to the polymer. In addition, the device fabrication requires a two-layer coating (at a

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minimum) with fabrication of the active layer, and the counter electrode.

In this paper, we report on the development and testing of organic solar cells using co-planar interdigitated electrodes of dissimilar materials. This device structure offers some potential advantages in comparison to the conventional multilayered sandwich configuration. For example, because transparency is not required, co-planar interdigitated electrodes in organic solar cells allow the use of a wider variety of electrode materials. In addition, the interdigitated structure has an inherent reliability due to the incorporation of multiple junctions for charge collection. Interdigitated electrodes of a single metal have been used in sensors [10], transistors [11], and even in a photovoltaic devices [12]. There are limited reports of the use of vertically oriented two-metal interdigitated electrodes in polymer solar cells [13]. However, to the authors' knowledge, there are no published reports of polymer photovoltaics using co-planar horizontally oriented two-metal interdigitated electrodes.

2. Experiment

The co-planar two-metal electrode substrates were fabricated on the oxidized surface of silicon wafers using photolithography. Two photomasks were prepared and the masks were used to pattern photoresist using UV light and standard photolithographic techniques. Aluminum and nickel electrodes with a separation distance of between 1 and 3 μm were deposited at a thickness of approximately 100 nm. Fig. 1 is a schematic and microscope image of a completed interdigitated two-metal electrode substrate. The total device area was 0.11 cm^2.

The minimum electrode separation in these devices was limited by our photolithographic capabilities (about 1 μm) and we estimate, based on the short diffusion length of the donor material, that the separation between the two-metal electrodes should be closer to 100–200 nm for efficient charge collection. Therefore, we expect a relatively poor device efficiency due to incomplete charge collection. However, the primary goal of this work was to introduce and demonstrate the feasibility of a new co-planar electrode geometry and at this time we have made no effort to optimize the device efficiency.

A solution was prepared from a mixture of poly[2-methoxy-5-(2-ethylhexyloxy)-1,4-phenylenevinylene] (MEH-PPV) as the electron donor, and [6,6]-phenyl-C_{61} butyric acid butyl ester (PCBB) as the electron acceptor. MEH-PPV was diluted to 0.72% concentration in chlorobenzene, and stirred for a minimum of 2 weeks. PCBB was then added to the MEH-PPV solution with an additional amount of chlorobenzene to adjust the solution concentration. MEH-PPV:PCBB in a 1:3 wt ratio at 2.44% total concentration of donor:acceptor solution was prepared, and stirred overnight. The solution was spin-coated over the interdigitated two-metal electrode at 2000 rpm for 40 s. The thickness of the spin-coated polymer layer was approximately 2.4 μm as measured with a profilometer. This is sufficiently thick to absorb a large percentage of the incident light [14].

Devices were tested in dark and under AM1.5 illumination of 80 mW/cm^2 intensity. The current density–voltage (J–V) curve was measured using a Keithley 236 source generator by varying the applied voltage from −2 to 2 V in 0.04 V steps across nickel and aluminum electrodes. In addition, the resistance of the silicon dioxide substrate film was tested by measuring the illuminated J–V characteristics of the electrodes prior to depositing the polymer film in order to make sure the current response was due to that of the donor:acceptor film and not the silicon substrate.

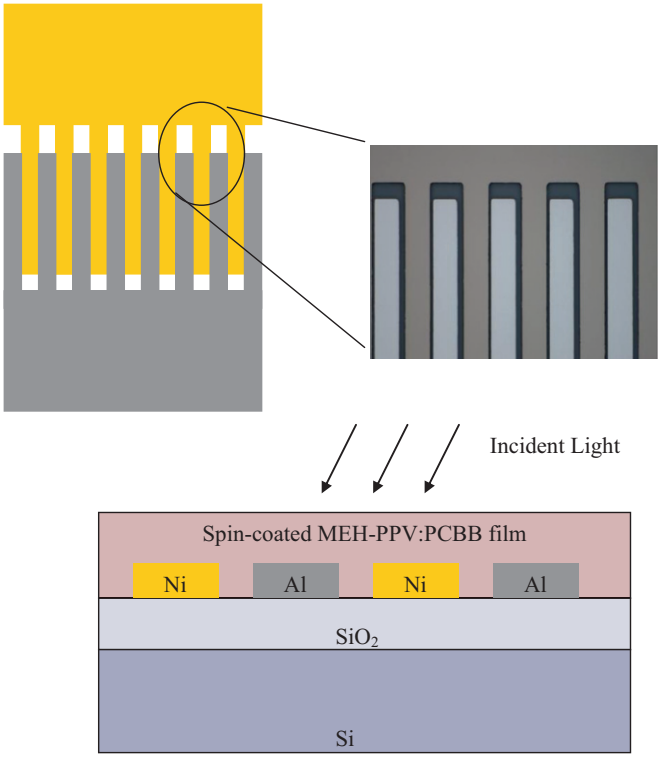

Fig. 1. (a) Interdigitated two-metal substrate wafer patterns after two-step photolithography. (b) Side view of interdigitated electrodes showing that electrodes do not block the incident light.

3. Results

The actual electrode separations of the co-planar interdigitated bi-metallic substrate used for the experiment were 1.21 μm on one side and 2.42 μm on the other. The electrode fingers were roughly 10 μm wide. Fig. 2 shows a 100× magnified image of the co-planar interdigitated bi-metallic electrode used for this experiment.

Fig. 3 is a plot of the J–V curves with cubic interpolation, obtained from the device after spin coating of MEH-PPV:PCBB donor:acceptor solution. The best-fit line through the experimental data is also included.

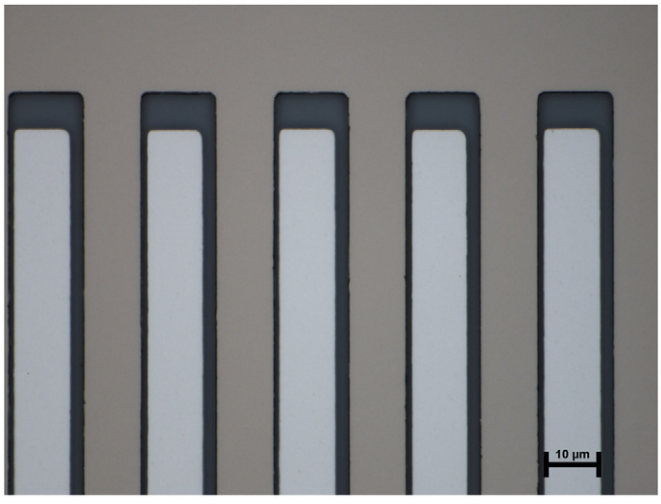

Fig. 2. 100× magnified image of the interdigitated 2 metal electrode substrate.

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