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Dependence of Photovoltaic Effects in Organic Semiconductors on the BCP Layer Thickness

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We fabricated solar-cell devices based on zinc-phthalocyanine (ZnPc) as a donor (D) and fullerene (C_{60}) as an electron acceptor (A) with doped charge transport layers and with bathocuproine (BCP) an exciton blocking layer (EBL). We measured the photovoltaic characteristics of the solar-cell devices by using a Xenon lamp as a light source. Several thicknesses of BCP were made between C_{60} and Al, and we obtained characteristic parameters such as the short-circuit current, the open-circuit voltage, and the power conversion efficiency of the device. With an EBL, the fill factor and the power conversion efficiency were 0.57 and 0.435 %, respectively, at 100 mW/cm^2.

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I. INTRODUCTION

In recent years, the power conversion efficiency of thin-film organic photovoltaic (PV) cells have increased steadily and rapidly. These improvements have come from the introduction of device concepts, such as the donor-acceptor (DA) heterojunction, the exciton-blocking layer (EBL), and highly doped crystalline materials. The photovoltaic effect is a way of converting solar radiation into electricity, which was first discovered by Becquerel [1]. These days, the solar power conversion efficiency of a monocrystalline silicon solar-cell can reach up to 24 % [2]. However, a production of this kind of inorganic device requires difficult manufacturing processes with high temperatures and numerous lithographic steps [3,4].

Most of the small molecules used in organic photovoltaic cells are deposited using thermal evaporation to obtain a desired film thickness [5, 6]. These photovoltaic cells have been intensively studied for the last ten years. In 1986, Tang developed a photovoltaic cell using CuPc/PV organic materials and obtained a solar power efficiency of about 1 % with corresponding external quantum efficiency of about 30 % [7]. Thus, we studied the dependence of the photovoltaic effects on the photoactive organic layer's thickness and the EBL. In this paper, we report the photovoltaic effects for an ITO/ZnPc/C_{60}/BCP/Al device structure.

II. EXPERIMENTS

Indium-tin-oxide (ITO) glass having a sheet resistance of 15 Ω/□ was received from Samsung Corning Co. The

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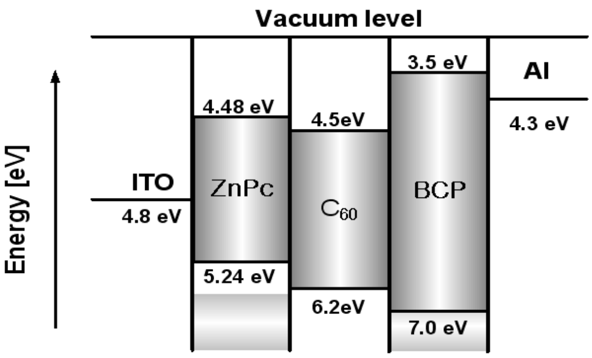

Fig. 1. Schematic of the energy band diagram in a PV cell.

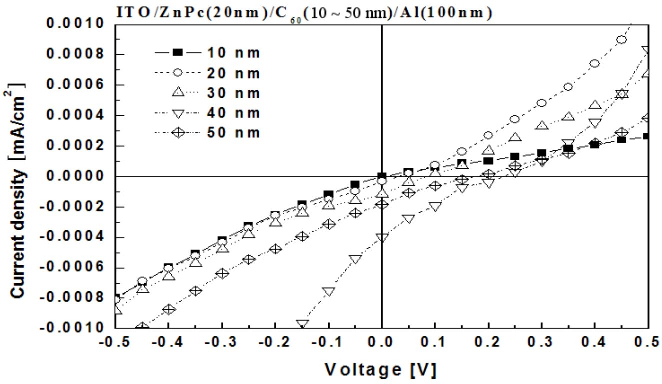

Fig. 2. Current density-voltage characteristics of an ITO/ ZnPc(20 nm)/C_{60}/Al device for various thicknesses of C_{60} at 100 mW/cm^2.

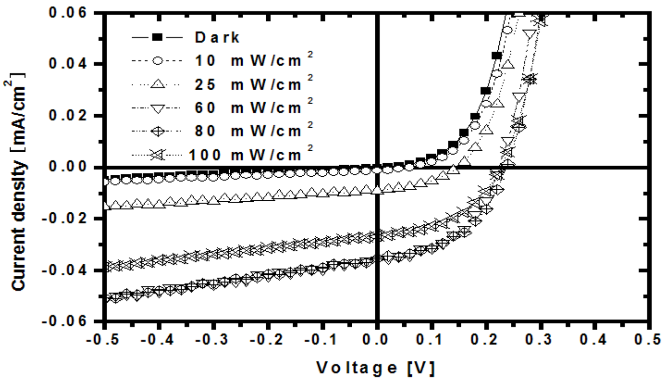

Fig. 3. Current density-voltage characteristics of an ITO/ ZnPc(20 nm)/C_{60}(40 nm)/BCP(10 nm)/Al device under illumination.

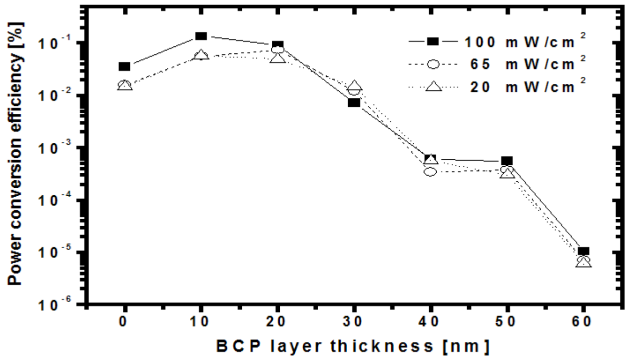

Fig. 4. Power conversion efficiency-thickness characteristics of an ITO/ ZnPc(20 nm)/C_{60}(40 nm)/BCP/Al under illumination.

line-patterned ITO glass was cleaned by sonicating it in chloroform for 20 minutes at 50 °C. Then the ITO glass was heated at 80 °C for 1h in a solution made with twice distilled deionized water, ammonia water, and hydrogen peroxide with a volume ratio of 5 : 1 : 1. We sonicated the substrate again with chloroform for 20 minutes at 50 °C and in deionized water for 20 minutes at 50 °C. After sonicating the substrate, we dried it with N_2 gas stream and stored it under vacuum.

Figure 1 shows a schematic structure of a photovoltaic cell and an energy band diagram of the materials used in our experiment. Double-layered organic photovoltaic cells of ITO/ZnPc/C_{60}/Al were fabricated to see the correlation between the photovoltaic performance and the layer thickness of ZnPc (or C_{60}). The thickness was varied from 10 nm to 50 nm, and the layer was deposited using thermal-vapor deposition at 7×10^{-6} Torr. To compare the performance with that of a photovoltaic cell with an exciton blocking layer, we fabricated a device structure of ITO/ZnPc/C_{60}/BCP/Al. The layer thickness of BCP was varied from 0 nm to 60 nm, and the Al cathode (100 nm) was deposited at 7.0×10^{-6} Torr by using thermal evaporation. The active cell area of the device was made by using a shadow mask and was 3 mm × 5 mm.

The current density-voltage characteristics of the organic photovoltaic cells were measured by using a Keithley 236 source-measure unit and a 500W xenon lamp (ORIEL 66021). The light intensity on the device was measured by using a radiometer/photometer from International Light Inc. (IL14004). All measurements were carried out at room temperature.

III. RESULTS AND DISCUSSION

Figure 2 shows the current density-voltage characteristics of the ITO/ZnPc(20 nm)/C_{60}/Al device for various thicknesses of C_{60} under a light intensity of 100 mW/cm^2. Figure 2 shows that the short-circuit current density for a thickness ratio of 1 : 2 is higher than it is for other ratios.

Figure 3 shows the current density-voltage characteristics of the ITO/ZnPc(20 nm)/C_{60}(40 nm)/BCP(10 nm)/Al device, and Figure 4 shows the power conversion efficiency-illumination intensity characteristics of

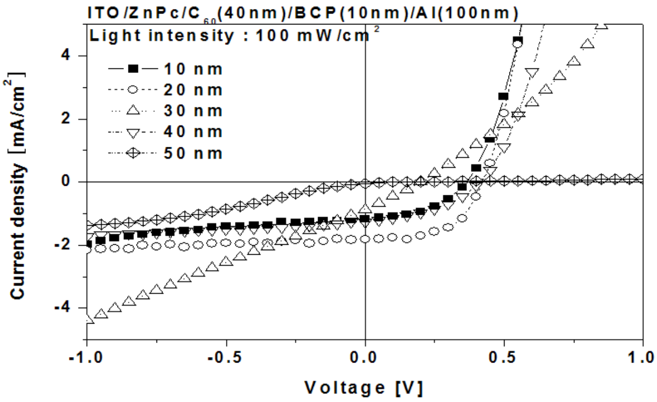

Fig. 5. Current density-voltage characteristics of an ITO/ZnPc/C_{60}(40 nm)/Al device for various thicknesses of ZnPc at 100 mW/cm^2.

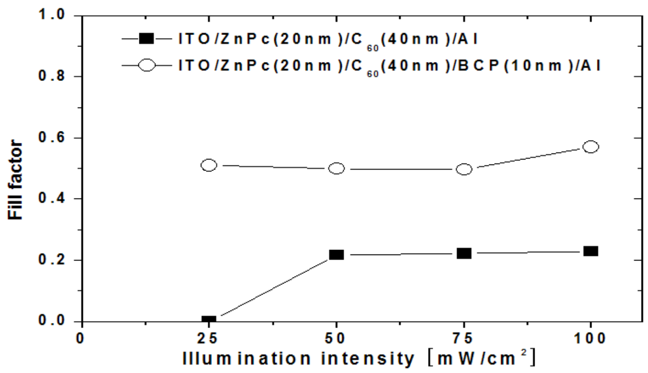

Fig. 6. Power conversion efficiency of an ITO/ZnPc/C_{60}(40 nm)/Al device for various thicknesses of ZnPc at 100 mW/cm^2.

ITO/ZnPc(20 nm)/C_{60} (40 nm)/BCP/Al. The BCP transports electrons to the cathode from the adjoining acceptor layer while effectively blocking excitons in the lower-energy-gap acceptor layer from recombining at the cathode. From the current density-voltage characteristics under light illumination, we can obtain two important parameters, the x- and the y-intercept of the curve. One is the open-circuit voltage V_{OC} (x-intercept), and the other is the short-circuit current density J_{SC} (y-intercept). When the BCP layer thickness is increased by 20 nm, there is a big improvement in the conversion efficiency of the device by using a BCP layer, as is seen in Figure 4.

Figure 5 shows the current density-voltage characteristics of an ITO/ZnPc/C_{60}(40 nm)/BCP(10 nm)/Al device for various thicknesses of ZnPc under a light intensity of 100 mW/cm^2. Figure 6 shows the fill factor, and Figure 7 shows that the power conversion efficiency in the device for a thickness ratio of 1 : 2 is much higher than it is for other thickness ratios. Thus we observed that the optimum thickness ratio of the ZnPc : C_{60} layer was 20 nm : 40 nm. We obtained some important parameters.

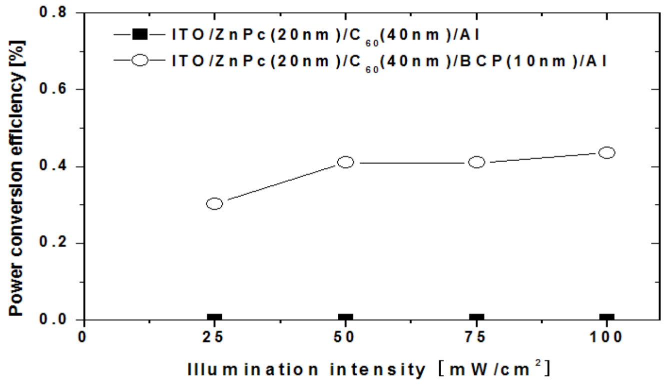

Fig. 7. Power conversion efficiency of an ITO/ZnPc/C_{60}(40 nm)/Al device for various thicknesses of ZnPc at 100 mW/cm^2.

The short-circuit current density was 1.82 mA/cm^2, the open-circuit voltage was 0.42 V, the fill factor was 0.57, and the power conversion efficiency was 0.435 %.

IV. CONCLUSIONS

We studied the dependence of the photovoltaic effects in the device structure of ITO/ZnPc/C_{60}/Al and ITO/ZnPc/C_{60}/BCP/Al on the ZnPc and the C_{60} layer thickness. The ZnPc/C_{60} heterojunction device with a ZnPc/C_{60} thickness ratio of 1 : 2 gives a higher conversion efficiency than the other devices. We confirmed the optimum thickness ratio of the DA heterojunction with a ZnPc : C_{60} layer to be about 1 : 2.

We determined the electrical properties and the photovoltaic properties of organic solar cells employing an EBL layer. We found that the use of a BCP exciton blocking layer improved the conversion efficiency of photovoltaic cells and that the proper layer thickness of BCP was 10 nm. We obtained some important parameters, the short-circuit current density was 1.82 mA/cm^2, the open-circuit voltage was 0.42 V, the fill factor was 0.57, and the power conversion efficiency was 0.435 %.

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