Improvement of Short-Circuit Current in Plasmonic Organic Solar Cells Based on Grating Structures

Akira Baba*, Dai Murashima, Nobutaka Aoki, Kazunari Shinbo, Keizo Kato, Futao Kaneko

Center for Transdisciplinary Research and Graduate School of Science and Technology, Niigata University
8050 Ikarashi 2-nocho, Nishi-ku, Niigata, Japan
*Phone: +81-25-262-7369 E-mail: ababa@eng.niigata-u.ac.jp

1. Introduction
Organic thin-film photovoltaic cells are one of the most promising candidates for inexpensive and flexible photovoltaic cells based on organic materials. An important challenge in the advancement of the organic thin-film photovoltaic cells is reducing their film thickness while maintaining their high efficiency. Hence, it is essential to develop a way to strongly absorb light in the thin-film layer. Because surface plasmon resonance (SPR) offers an enhanced optical field, i.e., increased absorption in the cell, there has been considerable interest in fabricating plasmonic-structured photovoltaic cells. The use of surface plasmons (SPs) in organic photovoltaic cells utilizing metal nanoparticles has been investigated as improved light absorption systems that provide high-efficiency cells. The prism-coupling method has also been used for the improvement of the organic photovoltaic cell. Although several SP-enhanced organic thin-film photovoltaic cells have been investigated to some extent with promising results, there have been a few reports on grating-coupled SP-enhanced organic thin-film photovoltaic cells. In particular, few working organic photovoltaic devices with plasmonic grating structures have been reported, whereas several important studies using finite-difference time-domain (FDTD) simulations have been reported recently. The grating-coupled technique is a prismsless, convenient, propagating SPR excitation method. There have been reports that light scattering and light trapping can be obtained on the grating surface (without SP excitation), resulting in the improvement of the obtained photocurrent. Hence, in addition to the light scattering improvement effect, a remarkable improvement in the photocurrent of the cells might be obtained if the SP-enhanced field can be obtained on grating substrates. Recently, we demonstrated multimode SP excitations and enhanced photoluminescence properties of a metallic grating by using compact disc-recordable substrates.

In this study, we demonstrate the fabrication of organic thin-film bulk-heterojunction photovoltaic cells on Blu-ray Disc recordable (BD-R) substrates for the excitation of grating-coupled SPs, which efficiently improve the photocurrent conversion. We also studied the distance dependence of the plasmon-enhanced photocurrent property by controlling the thickness of the P3HT:PCBM layer because the SP is an evanescent wave that exponentially decays as it moves away from the metal surface. Furthermore, in order to understand the experimental results, finite-difference time-domain simulations were performed by assuming that the organic thin-film photovoltaic cells had a grating structure. FDTD calculations indicated an increased electric field distribution in the cell, which corresponded well with the experimental results.

2. Experimental
Figure 1 depicts a schematic diagram of the fabricated bulk-heterojunction photovoltaic cell. The BD-R polycarbonate grating substrates were deposited with an ~150-nm-thick silver layer by vacuum evaporation. A procedure similar to the preparation technique reported in (17) was used to prepare the BD-R substrates. P3HT and PCBM were dissolved in trichloromethane with a P3HT:PCBM mass ratio of 1:1. The P3HT:PCBM thin film was deposited on silver/grating substrates by spin-coating the mixed solution at 2000 rpm for 1 min. The sample was then annealed at 100 °C for 1 h. Then, a multilayered film of low conductive PEDOT:PSS (conductivity = 1 × 10−5 S/cm) and poly(diallyldimethyl-ammonium chloride) (PDADMAC), which acted as a hole transport layer, was fabricated by the layer-by-layer (LbL) deposition technique. The P3HT:PCBM surface samples were then alternately immersed in aqueous solutions of PEDOT:PSS and PDADMAC for 15 min each until a10 bilayers were obtained. Between consecutive immersions, the samples were rinsed twice using deionized water for a duration of 2 min. Finally, high conductivity PEDOT:PSS (conductivity = 150 S/cm) was deposited on the PEDOT:PSS/PSS LbL film by spin-coating at 3000 rpm for 1 min; this acted as the anode. The sample was then annealed at 100 °C for 30 min.

Figure 1. Schematic drawing of the fabricated SPR-enhanced organic thin-film photovoltaic cell.
3. Results and Discussions

To study the effect of SP excitation, we investigated the short-circuit photocurrent properties both with and without SP excitation. We performed photocurrent measurements by irradiating collimated visible light from a 350-mW xenon lamp. Figure 2 shows the short-circuit photocurrent properties of the fabricated organic photovoltaic cells in which the thickness of the P3HT:PCBM layer is approximately 40 nm. For SP excitation measurements, the sample was irradiated with p-polarized light, whereas for non-SP excitation measurements, the sample was irradiated with s-polarized light. As shown in Fig. 2, for all cases, the short-circuit current with SP excitation increased more compared with that without SP excitation. This result clearly indicates that the grating-coupled SP excitation can enhance the photocurrent conversion in the cell. The current for the grating-coupled SP excitation increased up to two-fold more than that with no SP excitation. We plotted the enhanced factor p/s, i.e., the ratio of the current with SP excitation (p-polarization) to the current without SP excitation (s-polarization), as a function of the incident angle (Fig. 4) for each thickness of the P3HT:PCBM layer. It should be noted that the enhanced factor p/s increased with decreasing film thickness. Because the SP-enhanced optical field exponentially decayed as the distance from the silver surface increased, the increased current with the thinner P3HT:PCBM layer was caused by the stronger optical field in the wide range of the film. Furthermore, it should be noted that the short-circuit current increased at all incident angles, as exhibited by this plot. In all cases, the p/s factor was higher at higher incident angles. It should be noted that the p/s factor obtained using BD-R grating substrates showed the highest enhancement among all the other grating pitches, which were measured using Compact Disc recordable (CD-R) (λ=1.6 μm) and Digital Versatile Disc recordable (DVD-R) (λ=740 nm) grating substrates.

3. Conclusions

In conclusion, we have demonstrated the fabrication of grating-coupled SPR-enhanced organic thin-film photovoltaic cells and their improved short-circuit current properties. Obvious increases in the short-circuit photocurrent can be obtained when the propagating-SP is excited on the silver gratings as compared to that without SP excitation. The FDTD simulation indicates that the electric field in the P3HT:PCBM layer can be effectively increased using the grating-coupled SP technique. The demonstrated method should provide new opportunities to remarkably increase the efficiency of organic thin-film photovoltaic cells.

References