Research Article

Plasmonic Circular Nanostructure for Enhanced Light Absorption in Organic Solar Cells

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This study attempts to enhance broadband absorption in advanced plasmonic circular nanostructures (PCN). Experimental results indicate that the concentric circular metallic gratings can enhance broadband optical absorption, due to the structure geometry and the excitation of surface plasmon mode. The interaction between plasmonic enhancement and the absorption characteristics of the organic materials (P3HT:PCBM and PEDOT:PSS) are also examined. According to those results, the organic material’s overall optical absorption can be significantly enhanced by up to ~51% over that of a planar device. Additionally, organic materials are enhanced to a maximum of 65% for PCN grating pitch = 800 nm. As a result of the PCN’s enhancement in optical absorption, incorporation of the PCN into P3HT:PCBM-based organic solar cells (OSCs) significantly improved the performance of the solar cells: short-circuit current increased from 10.125 to 12.249 and power conversion efficiency from 3.2% to 4.99%. Furthermore, optimizing the OSCs architectures further improves the performance of the absorption and PCE enhancement.

1. Introduction

Recent studies have demonstrated the feasibility of designing metallic nanostructures to increase optical absorption in solar cells by excitation of surface plasmon polaritons (SPPs) mode [1–5]. The absorption properties of plasmonic material have also been investigated, based on multiple resonances [6–8] and omnidirectional absorption [6, 9, 10] as well as frequency dispersion engineering [11, 12]. As electromagnetic waves at the interface between a dielectric material and a metal surface, SPPs propagate along a metal-dielectric interface with exponentially decaying into both media [13–16]. For the excitation of SPPs, a previous study used circular grating structures, which alter the light momentum to achieve phase matching condition [17]. This structure has received a significant amount of interest for several applications, including the enhancement of transmitted light [18], plasmonic lens [19, 20], distributed feedback (DFB) lasers [21], and plasmonic antennas [22, 23].

This study describes the enhancement of broadband absorption in advanced plasmonic circular nanostructures (PCN). Reflected intensity is measured at a white light source and three visible wavelengths (488 nm, 532 nm, and 632 nm) by using a charge-coupled device (CCD). Owing to the rotation symmetry in circular structures, the optical absorption is enhanced in both transverse-magnetic (TM) and transverse-electric (TE) polarizations. Additionally, absorption spectra for normally incident light are evaluated by UV-Vis spectrophotometer. The absorption spectrum reveals the enhancement broadband absorption in concentric circular metallic gratings due to the structure geometry and the excitation of SPPs mode. Furthermore, the organic solar cells (OSCs) performance properties are investigated with respect to interaction between periodic PCN structure with organic materials, revealing an enhancement of broadband absorption and power conversion efficiency.

2. Experiments

Periodic PCN structures were fabricated using standard electron beam lithography and lift-off procedures [24]. In our experiments, a 2 nm-thick Cr film and a 50 nm-thick gold
film were sequentially deposited on a glass substrate. Cr was used as an adhesion layer between the glass substrate and Au layer. The 50 nm-thick Au concentric circular gratings were then fabricated for various periods (ranging from 400 nm to 800 nm) and for a duty cycle of 50% on top of the first Au layer. The area of each circular grating was 1.2 × 1.2 mm². Figures 1(a) and 1(b) show a schematic representation and a scanning electron microscope (SEM) picture of the periodic PCN structure sample. The grating ring width and pitch size of the pattern are 250 nm and 500 nm, respectively.

For PCN measurement systems, angular interrogation mode of reflection angle measurement system (θ-2θ) was used for the SPPs resonance angular absorption. Figure 1(c) illustrates the optical measurement setup. The samples were illuminated by using a white light source (halogen lamp) with red, green, and blue (RGB) filters (488 nm, 532 nm, and 632 nm). The reflected light was then collected by using a CCD camera. Notably, the incident polarization was controlled by a linear polarizer. Moreover, absorption spectra for normally incident light by UV-Vis spectrophotometer (Hitachi U-2900) were determined.

The OSC device used for this study was fabricated as follows. Prepatterned ITO-coated glass (sheet resistance of 15 Ω/sq) substrates were ultrasonically cleaned for about 3 min in deionized water with 10% detergent, deionized water, acetone, and isopropanol alcohol, sequentially. A 50 nm-thick concentric Au metal PCN was fabricated on the ITO anode layer using standard electron beam lithography and lift-off procedures. A PEDOT:PSS (Baytron P) film of 40 nm thickness was spin-coated at 4000 r.p.m. for 60 s, and the resulting PEDOT:PSS layer was baked at 170°C for 15 min. A 20 mg/mL 1,2-dichlorobenzene (DCB) solution of P3HT:PCBM with a 1:1 weight ratio was stirred under nitrogen atmosphere at 40°C for 14 h. The active layer was obtained by spin coating the blend at 600 r.p.m. for 50 s, and the film thickness was ~250 nm. Before cathode deposition, the films were thermally annealed at 110°C for 10 min. Finally, the Ca/Al (20 nm/100 nm) were used in thermal evaporation to deposit as an electrode, as shown in Figure 1(d).

3. Results and Discussions

Figure 2 illustrates the reflected intensity images of a periodic PCN structure with a pitch size of 800 nm. Absorption of the sample appears dark and colorless in reflected intensity
The images. According to this figure, the images vary with incident angles and incident wavelengths. Experimental results indicate that the enhancement of optical absorption is associated with polarization of the incident light. Enhancement of the optical absorption in both TM and TE polarizations is attributed to rotation symmetry in a periodic PCN structure. When the incident light is TM polarized, the optical absorption is enhanced in a horizontal direction. When the incident light is TE polarized, the optical absorption is enhanced in a vertical direction.

Figure 3 shows the normalized reflectance intensity spectra. The incident light is unpolarized. Although enhancement of the absorption depends slightly on incident angles, the absorption can be more significantly improved than that of a planar Au film without grating at a white light source and three visible wavelengths (488 nm, 532 nm, and 632 nm).

This study also attempts to more thoroughly understand how absorption enhancement and incident wavelengths are related by determining absorption spectra for normally incident light by UV-Vis spectrophotometer. In contrast to a planar Au film without grating, the absorption spectrum shows improved broadband absorption in Au concentric circular gratings, as shown in Figure 4(a). Additionally, several peaks of enhanced absorption in a spectrum are observed, due to the excitation of SPPs mode at the Au/air layer interface. As is well known, the periodic PCN structure can provide the in-plane momentum required for the incident light to excite SPPs. The SPPs excitation causes a strong electromagnetic field near the metal surface, which is expected to enhance optical absorption [13, 16, 25]. This enhancement occurs when the momentum matching condition is satisfied. The condition can be written as [16]:

\[
k_{//} = m \frac{2\pi}{\Lambda} = k_o \sqrt{\frac{\varepsilon_m \varepsilon_d}{\varepsilon_m + \varepsilon_d}} = k_{sp},
\]

where \(k_o = \omega/c\) is a free-space wave vector; \(k_{//}\) is an in-plane wave vector; \(m\) is to the resonant order; \(\Lambda\) is the grating pitch; \(\varepsilon_m\) and \(\varepsilon_d\) are the permittivities of the metal (Au) and dielectric (air), respectively. The position of the SP resonance
Figure 3: Normalized reflectance intensity as a function of incident angles for grating pitches = 400, 500, 600, 700, 800 nm and a planar reference sample (Au film without grating). The samples illuminated by a white light source (a) and three visible wavelengths 488 nm (b), 532 nm (c), and 632 nm (d), respectively. The incident light is unpolarized.

\[ \lambda_{sp} = \frac{2\pi}{k_0} \] for normally incident light can be expressed by the following relation [16]:

\[ \lambda_{sp} = \frac{\Lambda}{m} \sqrt{\frac{\varepsilon_m + \varepsilon_d}{\varepsilon_m \varepsilon_d}}. \] (2)

The peaks in the spectrum are near the positions calculated by (2). The observed resonant wavelengths for each grating are 409 nm (pitch = 400 nm), 544 nm (pitch = 500 nm), 610 nm (pitch = 600 nm), 681 nm (pitch = 700 nm), and 494 nm (pitch = 800 nm). Obviously, the experimental periodic PCN resonant wavelengths are close to the theoretical SPPs resonant wavelengths [26–28], as shown in Figure 4(b).

Figure 5 shows the absorption enhancement for organic materials (PEDOT:PSS/P3HT:PCBM) on a periodic PCN structure. Figure 5(a) reveals similar broadband absorption enhancement (ranging from 300 to 1100 nm) in the ITO/glass substrate (dashed lines). As mentioned earlier, the periodic PCN structure can enhance broadband absorption. Therefore, the overall optical absorption in organic materials can be significantly enhanced by up to ~51% over that of a planar device without grating. The absorption spectrum of the periodic PCN structure shows a greater broadband enhancement than that of the ITO glass without grating. Therefore, overall absorption of an organic layer can be significantly enhanced owing to the concentric Au metal grating. An absorption peak is also observed around 745 nm, due to the excitation of SPPs mode at the Au/organic layer interface. Excitation of the SPPs enhances the highly localized field around the nanostructures and absorption of specific wavelengths of light. To understand this phenomenon, this study determined the absorption spectra of ITO/Au circular-grating/PEDOT:PSS/P3HT:PCBM films with various pitch Au circular gratings. According to Figure 5(b), the absorption
increases for extended periods, owing to that the grating decreases the reflection and permits of more light to couple into the organic layer. The maximum enhancement of ~65% is obtained for a grating pitch of 800 nm. Optimization of OSC architectures further improves absorption enhancement.

Light current density-voltage (J-V) characteristics curves were taken under simulated AM1.5 illumination from a solar simulator of Oriel-Sol3A 94023A equipped with a 450 W Xe lamp and an AM1.5 filter (Newport Inc.) and a Keithley 2400 source meter. The light intensity was calibrated using a reference Si solar cell of Oriel-91150 (Newport Inc.). All photocurrent measurements were taken in ambient air at room temperature. Figure 6 shows the J-V characteristics of the OSCs devices with different structures, and Table 1 summarizes their parameters. Additionally, the periodic PCN structure (ITO/Au circular grating/PEDOT:PSS/P3HT:PCBM/Ca/Al)
structure, due to the relationship between the pitch size of a structure and the excitation of SPP modes. Furthermore, in the organic materials (P3HT:PCBM), optical absorption in PCN nanostructures is a highly promising means of increasing absorption by 51% over that of a planar device. In terms of the J-V characteristics of the devices, the power conversion efficiencies (PCE) are 3.2% and 4.99% for a planar device and a circular nanostructure, respectively. This novel approach for plasmonic circular nanostructure improves the performance of OSCs.

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