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Invited Paper

# Enhancement of light harvesting efficiency of silicon solar cell utilizing arrays of poly(methyl methacrylate-*co*-acrylic acid) nano-spheres and nano-spheres with embedded silver nano-particles

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ABSTRACT

An array of uniformly distributed monolayer of poly(methyl methacrylate-*co*-acrylic acid) nano-spheres were deposited onto an amorphous silicon photovoltaic cell utilizing dip coating technique. The electrical characteristics of the coated photovoltaic cell reveal that the nano-spheres with an average diameter size of 101 nm exhibits excellent light harvesting characteristics if compared to the nano-spheres of other sizes. The power conversion efficiency from such integration of the nano-structures (i.e. 3.14% per PV cell) indicates that at least 1.6 times of improvement (or relative enhancement of 57%) can be achieved comparatively to the uncoated photovoltaic cell (i.e. 2% per PV cell). Further increment of the power conversion efficiency of the solar cell has been attained with the incorporation of the silver nano-particles into the nano-spheres of similar average size. With the inclusion of the silver nano-particles into such nano-spheres, the power conversion efficiency of the solar cell has attained 5.57% per PV cell, which is about 2.8 times (or relative enhancement of 179%) if compared to the uncoated samples. Hence, this novel and controllable technique of fabricating omnidirectional light-harvesting nano-spheres with embedded silver nano-particles will indubitably be beneficial to various types of optoelectronic devices.

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## 1. Introduction

To date, photovoltaic (PV) which serves as a crucial source of renewable energy has received explosive attention due to its ability in producing clean energy. For this reason, a dramatic growth in the usage of PV as an alternative energy resource has been observed compared to the fossil fuels for the last few years [1]. Nevertheless, silicon has been identified as one of the most widely used materials due to its well-established processing techniques, vast availability and non-toxicity to the environment [2]. However, silicon PV has suffered low optical efficiency mainly due to the surface light reflection [3]. To overcome this problem, various light-trapping mechanisms have been adopted. These include integration of microstructures in addition to nanostructures onto the silicon substrates. For instance, microstructures such as microlenses [4] and anti-reflection coatings [5] were fabricated. In their work, a novel light trapping configuration based on an array of micro lenses with a self aligned array of micro apertures located in a highly reflecting mirror was demonstrated. An enhancement of the absorption rate of the solar cell with the increment of photocurrent by 25% has been realized. Besides, nanostructures such as nano-hole [6], nano-sphere [7], nano-bowl [8], nano-wire and nano-cone [9], nano-spike [10] nano-rod arrays [1], high index nano-structures [11] and colloidal crystals [12] were also rigorously studied. The integration of such microstructure or nanostructure has demonstrated a remarkable improvement in terms of the optical efficiency of the PV devices.

Nevertheless, most of the reported micro-structures or nanostructures were fabricated utilizing costly clean room processes such as photolithography and dry etching techniques. As a matter of fact, the involvement of such processes is not cost effective and thus inhibits a large-scale production of the PV panels. On the contrary, employment of low cost materials and methods to synthesize nanostructures for advanced light management are always more practical and favourable. Hence, we have reported the fabrication of poly(methyl methacrylate-*co*-acrylic acid) (P(MMA-*co*-AA)) nanospheres employing an emulsion polymerization technique. It has been reported that the size of the nano-spheres may play an important role in altering the performance of the PV device [2,13]. Two different ranges of size of nano-spheres, such as nano-spheres with smaller sizes (ranging from 0 to 50 nm) [13] as well as nano-spheres with larger sizes (ranging from 150 nm to 1000 nm) [2] have been

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studied. To fill the missing gap of the medium sizes of the nano-spheres, the size of the nano-particles in this work has been varied from 50 nm to 160 nm in order to verify the effect of the nano-spheres with such range of sizes in improving the performance of such device.

Moreover, much attention has also been drawn on the plasmonic materials to improve light-trapping efficiency [14,15]. As a matter of fact, incident light stimulates the oscillation of the conduction electrons of the metal nano-particles or nano-structures of subwavelength size. A localized surface plasmon resonance occurs if the natural frequency of the incident light matches the oscillation frequency of the conduction electron. Therefore, light will be preferentially scattered by the metal nano-particles deposited on the surface of the solar cell into the active layer of the solar cell. Subsequently, this process increase the generation of the free carriers [16–19]. For this reason, silver (Ag) nano-particles with the size of less than 10 nm (i.e. 3–7 nm) has been incorporated into the nano-spheres to substantiate the effectiveness of plasmonic nano-particles in enhancing the light-trapping capability and hence the photo-conversion efficiency. Ag nano-particles was employed due to its strong resonance and hence yielded large scattering cross-section but yet low absorption cross-section in the near infrared region of the solar spectrum [19].

## 2. Experimental

### *2.1. Materials for polymerization*

Methyl methacrylate (MMA) from Daejung (Korea) was freed from inhibitors prior to usage. On the other hand, acrylic acid (AA) from Merck (Germany), potassium persulphate (KPS) from Sigma-Aldrich and sodium dodecyl sulphate (SDS) from Systerm (Malaysia) were consumed without further purification.

### *2.2. Preparation of poly(methyl methacrylate-co-acrylic acid) nono-spheres*

P(MMA-*co*-AA) nano-spheres were synthesized by copolymerizing 95 wt% MMA and 5 wt% AA using an emulsion polymerization technique. KPS was utilized as a thermal initiator while SDS was used as a stabilizer. The polymerization was carried out in a five-necked reactor flask with the stirrer speed controlled at about 600 rpm. The mode of polymerization was a semi-batch process which was performed at about 75 °C for a duration of 3 h. Nano-spheres with different particle sizes were prepared by adjusting the concentration of surfactant in the mother liquor to $0.53 \times 10^{-5}$ mol cm$^{-3}$, $1.05 \times 10^{-5}$ mol cm$^{-3}$, $1.58 \times 10^{-5}$ mol cm$^{-3}$ and $2.10 \times 10^{-5}$ mol cm$^{-3}$, respectively, during the synthesis process.

### *2.3. Synthesis of poly(methyl methacrylate-co-acrylic acid) nano-spheres embedded with silver nano-particles*

The polymer nano-spheres with an average diameter of 101 nm were prepared using the method as described in the previous section. Ag nano-particles with sizes of 3–7 nm (Sigma-Aldrich) were embedded in the polymer nano-spheres during the emulsion polymerization process. The concentration of surfactant was fixed at $1.58 \times 10^{-5}$ mol cm$^{-3}$ but the amount of Ag nano-particles being added during the polymerization process was varied from 1.25 mg to 5.0 mg, with a common difference of 1.25 mg, per 100 g of polymer.

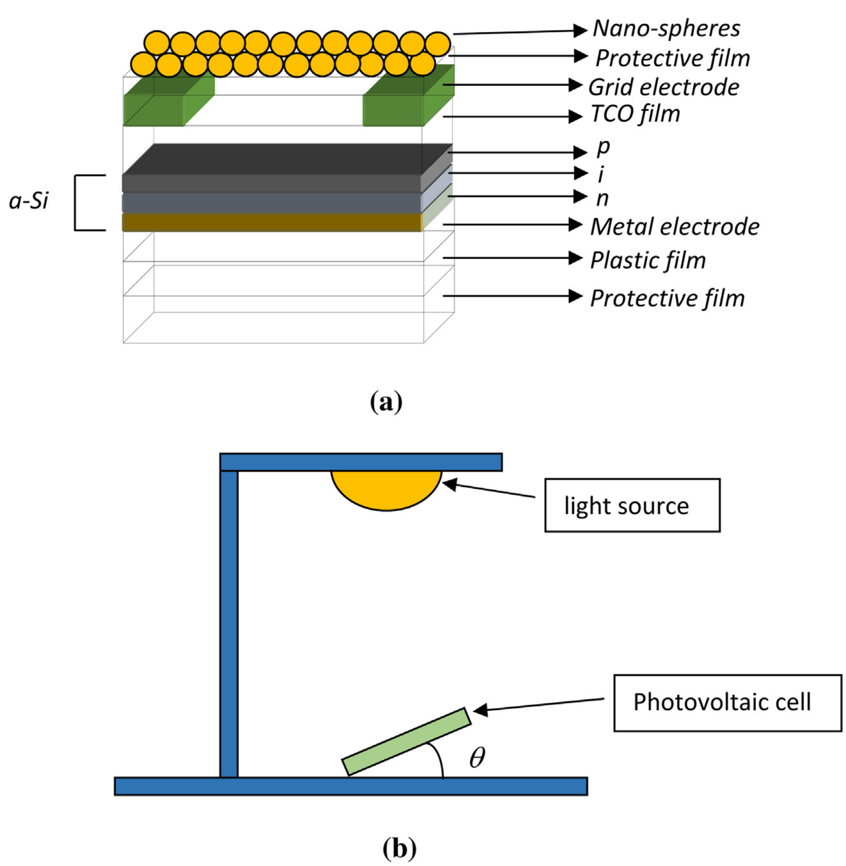


**Fig. 1.** (a) A schematic diagram of the solar cell employed in this experiment and (b) A schematic diagram of the experimental setup for the indoor measurement of the output power of PV cells tilted at various angles, $\theta$.

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