Fabrication of Textured Silicon Solar Cell using Microlens as Anti-Reflection Layer

Hye Jin Nam[†], Soon Cheol Jeong[†], Duk-Young Jung[†*],
Young Kuk Kim[‡], Kyu Min Han[‡], JunSin Yi[‡]
[†]Department of Chemistry, [‡]Department of Electronic and Electrical Engineering,
Sungkyunkwan University, 300 Cheoncheon-Dong, Jangan-Gu, Suwon, Korea 440-746
Email: dyjung@skku.edu
Telephone: +(82)-31-290-7074, Fax: +(82)-31-290-7075

Abstract—**This paper presents facile, reproducible soft-lithographic technique for fabricating textured crystalline silicon solar cell with hexagonally close-packed hemispherical arrays using ordered polymeric microspheres. Close-packed monolayers of polymer microspheres were deposited on flat cleaned glass substrate using spin-casting technique. The relief structure of highly ordered microspheres successfully generated their negative replica of elastomers. Hemispherical microlens arrays were molded by dispensing and curing liquid ultraviolet-curable photopolymers into the negative replica on crystalline silicon solar cell module. Sub-micrometer scaled microlens with uniform, cleaned surface morphology were easily reproduced by using the prepared molds, without multi-step engineering processes. The microlens-coated crystalline silicon solar cell showed additional increment of 1% in solar cell efficiency, compared to that of SiN_x anti-reflection coated one, as well as remarkable decrease of reflectance in SiNx-uncoated solar cell.**

Keywords-Textured Silicon Solar Cell, Microlens, UV-curable Photopolymer,Soft-Lithography, Solar Cell Efficiency

I. INTRODUCTION

Surface texturization of mono-crystalline silicon to minimize a loss by light reflection in solar cell fabrication as anti-reflection coating (ARC) has become a well-established and important technique in photovoltaic industry [1]. In large area commercial mono-crystalline silicon solar cells, the fabrication of textured surface using PECVD and etching processes has been performed in batch process but it is a very costlier one and requires complicated multi-step processing. Thus, many technical efforts to minimize the optical loss in solar cell have been achieved through several manufacturing methods using metallic thin films.

Recently, attentions for fabricating highly ordered microlens arrays with fine surface feature have been increased together with development in areas of optical systems and display devices. Microlenses are small lenses with diameters less than a millimeter and consisted of spherical convex surface to refract the light. Microlens on substrates allows us to collect light in micro-optical systems such as optical switches, fiber bundles and charge-coupled device cameras, and improves out-coupling efficiency in OLED [2-3]. Microlens arrays can be fabricated by several technical methods such as ink-jet process using microdrops of hybrid sol, self-assembly and melting of polymer microspheres, photo-induced polymerization and replica molding by UV-curable epoxy. Among those, the most facile and inexpensive method for microlens may be the replica molding using UV-curable epoxy by soft-lithography using poly(dimethylsiloxane) (PDMS) as a patterned stamp, which is the most efficient techniques applicable to surface patterning of wide range of materials containing metals, polymers and biological materials, even non-planar surface patterning.

In micro-optics system, the lens effect on collecting a light generally can be identified by detecting the white light illuminated through the microlens arrays under the objective lens. The hemispherical microlens shows brighter and clearer spot than the spherical one showing a blurred optical image due to the spherical aberration in spherical lens. A microlens with spherical surface has difficulty in focusing incoming rays to a point on the optic axis. That is the reason why we fabricated the hemispherical microlens, not spherical one. We prepared close-packed hemispherical microlens arrays with plano-convex shape by two-step replica molding using PDMS and UV-curable photopolymer from the monolayer of polystyrene (PS) microspheres as the pristine template. The PDMS mold and photopolymer have optical transparency, fitted for optical materials. Here we report a new and efficient technique for fabricating textured mono-crystalline silicon solar cell using highly ordered hemispherical microlens arrays as anti-reflection coating layer by twice replica molding over large area and the ARC effect of the microlens arrays on solar cell efficiency. We believe that this technique provides an efficient anti-reflection coating method to minimize light loss by reflection in solar cell system.

II. EXPERIMENTS

A. Fabrication of PDMS Negative Replica Mold

Two-dimensional colloidal monolayer of 688 nm PS beads was prepared by spin-casting of 10 wt% PS colloidal solution at 600 rpm for 80 s onto the plasma-treated silicon substrates, followed by the same method as our previous report [4]. Then, the PDMS prepolymer solution was poured in the container involving the PS monolayer templates on silicon substrate. The PDMS molds were treated under vacuum for 30 min to remove the entrained gas bubbles, and then cured in a conventional drying oven at 70 °C for 40 min. The cured PDMS molds were peeled off from the PS template, cleaned with acetone and dried under a stream of nitrogen. The prepared PDMS replica molds were used as secondary templates for forming a microlens array on silicon solar cell.

B. Fabrication of Textured Silocon Solar Cell

The viscous UV-curable photopolymer, Norland optical adhesive (NOA 60), was cast onto the embossed PDMS substrate by spin-casting at 1000 rpm for 30 s, which gave a thick layer onto PDMS replica. The p-type, (100)-oriented mono-crystalline silicon substrates with resistivity of 0.5-3 Ωcm and 125 mm × 125 mm dimension were used. To examine an ARC effect of the microlens on solar cell efficiency, two types of silicon solar cells prepared by different etching process were used, of which one is mono-crystalline silicon solar cell with textured surface prepared by 2 % NaOH solution after saw damage removal using 8 % NaOH solution, and the other is one with 80 nm of SiN layer as anti-reflection coating layer prepared by plasma enhanced chemical vapor deposition (PECVD) after acid-etching using HF and HNO_3, respectively. The front and back metallization of the silicon substrates were carried out using standard Ag paste and Al paste [5]. The NOA 60 is adhesive to the substrates, optically transparent, colorless photopolymer, which was cured by UV light of a high-pressure Hg lamp producing 600 W/cm^2 for 10 minutes. The PDMS molds were easily separated from the patterned photopolymer layer with about 50 µm in thickness, resulting in hemispherical photopolymer microlens arrays onto silicon solar cell substrates. The LIV (illuminated Current-Voltage) characteristics of the solar cells fabricated on different textured-etched substrates have been measured on 100 mW/cm^2 illumination intensity and AM 1.5 G spectrum.

III. Results and Discussion

We optimized experimental conditions for PS monolayer over large area by controlling three major factors; spinning speed, spinning time and concentration of colloidal solution. The best result for a monolayer assembly of 688 nm PS microspheres was obtained in 10 wt% PS solution at 600 rpm for 80 seconds on the plasma treated silicon surface. By AFM measurement, the diameter along the direction to nearest neighbors is 686 nm and that along the void space among three microspheres is 665 nm, respectively. The PDMS molds were obtained by casting of prepolymer against PS arrays, which gave patterned hemispherical holes in hexagonal closed-packed lattice. The PDMS mold has a protruded surface formed by the PDMS prepolymer solution infiltrated into the empty space among the assembled microspheres. Herein, we prepared the PDMS prepolymer solution containing 20 % curing agent larger than the conventional ratio of 10 %. The 20 % prepolymer gives less viscous characteristics to improve effective penetration into the voids of PS arrays by capillary action during replica molding. The resulting cured PDMS molds showed harder and less adhesive to the embedded PS microspheres for easy peel-off. The PDMS mold showed the width of 678 nm and the height of 335 nm. One hexagon on the honeycomb patterns had approximately 720 nm in lateral width, corner-to-corner and 640 nm in edge-to-edge distance, respectively. The change in diameter of the hexagons may result mainly from additional thermal deformation of PS microspheres during the PDMS curing steps.

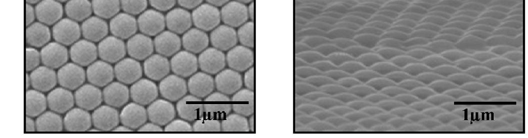


Figure 1. SEM images of microlens arrays formed on mono-crystalline silicon solar cell (a) and the side view image (b).

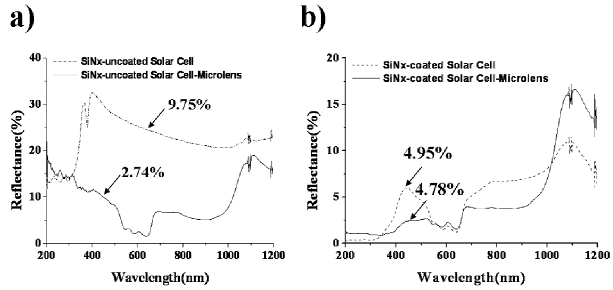
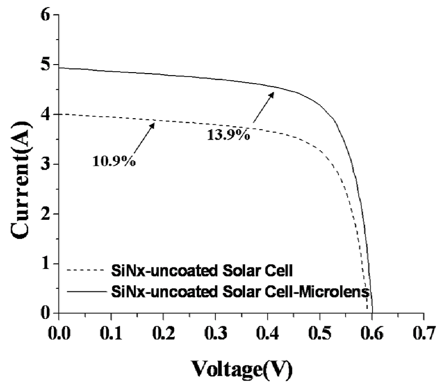


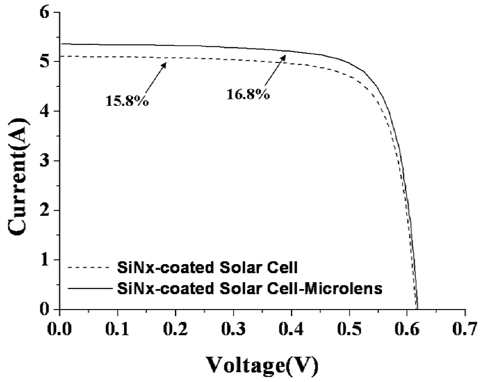
Figure 2. The normal incidence spectral reflectance of the SiNx-uncoated (a) and SiNx-coated (b) solar cells showing decreased reflectance ratios by microlens coating.

The photopolymer microlens patterns on mono-crystalline silicon solar cells were fabricated by replica molding of PDMS replica molds, and their SEM images were shown in Fig. 1. The high-magnification images showed that the microlens arrays consisted of hemispherical convex lenses with hexagon-like shape. By AFM measurement, the microlens showed the width of 670 nm and the lens-height of 342 nm. Considering the entire transformation of PS-PDMS-photopolymer, The PDMS replica molding against PS crystal produced the negatively patterned PDMS mold with hexagonal holes and the sequential photopolymer coating on PDMS mold produced uniform hemispherical microlens arrays on silicon solar cell where the diameters changed from 686 nm to 678 nm, and finally to 672 nm. The contraction is less than 4 % even after twice replica molding process, indicating a feasibility to control of structural parameters.

To demonstrate the microlens coating effect on solar cell efficiency, the total reflections ratios before and after microlens coating for the SiNx-uncoated and SiNx-coated solar cells were measured by using UV/vis spectrophotometer and the resulting data are shown in Fig. 2. The special ability of our microlens array for focusing and collecting a light previously had been demonstrated by a diffraction pattern obtained by amplifying the He-Ne laser beam transmitted through the microlens coating layer on glass substrate [4]. We also observed the microlens effect on collecting a light by applying it onto silicon solar cell instead of a glass substrate, where the microlens-coated samples showed the decrease in reflectance compared to those before microlens coating, demonstrating the decrease of a)



b)



c)

Type of solar cell	Area of solar cell (cm^2)	V_{oc} (V)	I_{sc} (A)	FF	Efficiency (%)
SiNx-uncoated Cell	148.58	0.593	4.010	68.4	10.9
SiNx-uncoated Cell-Microlens	148.58	0.602	4.941	69.6	13.9
SiNx-coated Cell	148.58	0.615	5.114	74.7	15.8
SiNx-coated Cell-Microlens	148.58	0.618	5.363	75.2	16.8

Figure 3. Illuminated current-voltage chanacteristics for SiNx-uncoated mc solar cells (a) and SiNx-coated mc solar cells (b) showing the change in solar cell efficiency for before and after microlens coating. The electrical parameters of each solar cell are also shown below (c).

light loss by microlens. In case of SiNx-uncoated silicon solar cell, the total reflectance remarkably decreased from 9.75 % to 2.74 % by microlens coating on solar cell, while the SiNx-ARC solar cell showed small change from 4.95 % to 4.78 % by microlens coating.

In agreement with the results in reflectances, the increase of the solar cell efficiencies for the microlens-coated samples resulted in and the illuminated current-voltage characteristics including electrical parameters are shown in Fig. 3. It was observed that the efficiencies of the microlens-coated samples were much higher than those of the microlens-uncoated ones and that all electrical parameters of the microlens-coated ones were much more favorable for achieving better efficiency compared to those of the microlens-uncoated solar cells. The SiNx-uncoated solar cells showed greatly increased rate in solar cell efficiency, in which the microlens-coated one yielded the 13.9 % efficiency compared to the value of 10.9 % for the uncoated one. Despite of a small change in the reflectance, the solar cell efficiency of the SiNx-ARC silicon solar cell certainly demonstrated the sufficient evidence for microlens effect, representing 1 % more increased value from 15.8 % to 16.8 %, compared with that before microlens coating. In addition, we confirmed that the solar cell with flat surface of the same microlens materials revealed no additional increase of cell efficiency. The high efficiency of the solar cell may be due to the increases in the open circuit voltage (V_{oc}), short circuit current (I_{sc}) and fill factor (FF) values by microlens effect on light trapping. The decrease of reflectances and increase of solar cell efficiencies indicate the effectiveness of microlens as ARC layer for high efficient solar cell in the present study.

IV. CONCLUSION

Highly ordered 2D monolayer of PS microspheres over large area was obtained by spin-casting and two step replica molding, which successively developed hemispherical photopolymer microlens arrays with conformal surface on substrate, without using complicated photolithographic technique. Utilization of PDMS molding and PS arrays demonstrates high throughput and low-cost process, generating regular microlens array as effective layer for anti-reflection coating in solar cell, as well as use in optical components such as fiber, grating, filter and waveguides. This technique opens the way to provide reliable route to fabricate embossed thin layers from nanometer to micrometer diameters by controlling particle sizes of polymer microspheres on the substrates up to centimeter-scale, which may improve the efficiency to receive a light irradiated on the solar cell module.

ACKNOWLEDGMENT

This research was supported from the Brain Korea (BK) 21 program, the National Research Laboratory Program of Korea Science and Engineering Foundation (Program No. ROA-2007-000-10020-0), KISTEP (Program No. M1-0214-00-0228) and the Korea Research Foundation Grant funded by Korean government (MOEHRD) (KRF-2005-005-J11902).

REFERENCES

[1] M. A. Green, “Solar Cells: Operating Principles, Technology, and System Applications”, (Prentice-Hall, Englewood Cliffs, NJ, 1982, pp. 163).

[2] C. Ke, X. Yi, J. Lai and S. Chen, “Research on hybrid integration technology between charge-coupled devices and diffractive microlens arrays”, J. Micromech. Microeng., vol 14, pp. 125-128 , January 2004.

[3] C. F. Madigan, M. –H. Lu and J. C. Sturm, “Improvement of output coupling efficiency of organic light-emitting diodes by backside substrate modification”, Appl. Phys. Lett., vol 76, pp. 1650-1652, March 2000.

[4] H. J. Nam, D.-Y. Jung, G.-R. Yi and H. Choi, “ Close-packed hemispherical microlens array from two-dimensional ordered polymeric microspheres”, Langmuir, vol 22, pp. 7358-7363, July 2006.

[5] U. Gangopadhyay, K.H. Kim, S.K. Dhungel, U. Manna, P.K. Basu, M. Banerjee, H. Saha and Junsin Yi, “A novel low cost texturization method for large area commercial mono-crystalline silicon solar cells”. Sol. Energy Mater. Solar Cells, vol 90, pp.3557-3567, July 2006.