

# Light Enhancement of Solar Module

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## Abstract

This paper presents sputtered-deposited Ag nanoparticles (NPs) on the encapsulant material (ethylene vinyl acetate, EVA) with the variation of annealing condition on crystalline silicon solar cell to enhance the light intensity, and a conventional solar cell is also performed for comparison. It was found that an increase in the transmittance at the wavelength of 500 - 800 nm was detected in the Ag nanoparticle solar cells. And red-light enhancement of around 2% was measured in the Ag-sputtered solar module under annealing condition of 700°C for 3 min from incident photon to converted electron (IPCE) profile. The photovoltaic performance of solar modules was characterized by a flasher system in AAA class (temporal instability, spectral match, and irradiance non-uniformity). The IV curve showed a current enhancement with Ag-EVA sample, and thus a high power output around 0.250 W was observed. A high fill factor of 73.63% also implied a high performance in series and shunt resistance. Surface plasmonic resonance effects of Ag nanoparticles deposited on the surface of solar cell were examined and discussed. This paper not only illustrated the performance of the surface plasmonic resonance of a solar device but also verified the application in the industrial production.

## Keywords

Light Enhancement, Solar Module, Ag Nanoparticles

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## 1. Introduction

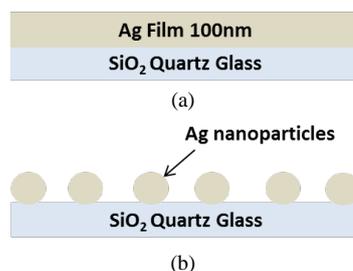
Renewable energy has become a blooming trend on both academic research and industrial production due to the limited natural energy resources. Photovoltaic technology is especially focused on its environmental-friendliness and long-term application. According to the reports of concerning the estimates the solar technology and installation capacity [1] [2], crystalline solar technology is still the main stream at a percentage of 86% in year 2012, and keeps growing >90% till year 2020. However, high conversion efficiency is the most important issue that researchers and industry are working on for a significant improvement. Aside from n-type wafer technology

which increases the minority carrier lifetime [3] [4], the enhancement of optics is an efficient solution for improving the solar cell efficiency. According to the previous literature [5] [6], optical enhancement can be approached by producing light trapping effect on the cell surface and depositing anti-reflection coating on the surface. These technologies are applied to increase the reflectance path in the solar device; furthermore, an even efficient way to enhance the absorption is to produce surface plasmonic resonance effect [7] on the cell surface. Theoretically, surface surface plasmonic resonance effect is an optical phenomena generated by light when it interacts with conductive NPs that are smaller than the incident wavelength. As in surface plasmon resonance, the electric field of incident light can be deposited to collectively excite electrons of a conduction band, with the result being coherent localized plasmon oscillations with a resonant frequency that strongly depends on the composition, size, geometry, dielectric environment and separation distance of NPs. It is reported that Ag-nanoparticles deposited on ZnO layer can improve the surface absorption at the wavelength of 550 - 800 nm, thus an increase of 14% in current density is approved for thin film solar cell [7] [8]. However, the application of surface plasmonic effect on crystalline solar cell is quite limited, and the availability on solar module process has not been studied. This study is to realize the surface plasmonic resonance of Ag nanoparticles on crystalline solar cell and the module performance is also proved.

## 2. Experimental

Ag films are prepared by a sputtering system and deposited on SiO<sub>2</sub> quartz substrate (5 cm × 5 cm). The sputtering mechanism of Ag films is shown in **Figure 1** and detailed sputtering parameters are shown in **Table 1**. The sputtered Ag film was around 100 nm in thickness and then processed with rapid annealing to form granular silver nanoparticles. The rapid annealing conditions were set to 700°C and 800°C for 2 min and 3 min. After annealing, surface morphology of Ag NPs in various annealing condition are analyzed by scanning electron microscope (JEOL, JSM 6701F).

The preparation of the solar module is illustrated in **Figure 2**. A pre-cure EVA film as initial cross-linked reaction is laminated at temperature of 150°C for 15 minutes. And the pre-cured EVA is covered on the annealed silver nanoparticles which are deposited on quartz, and then laminated at 150°C for 20 minutes. The EVA is peeled from the quartz, thus the Ag NPs were transferred from the quartz and adhere on the EVA surface. The Ag-contained EVA was measured by UV spectrometer (HITACHI, U-4100) to obtain the optical properties. The photovoltaic performance of solar modules was characterized by a flasher system in AAA class (temporal instability, spectral match, and irradiance non-uniformity), and electroluminescent instrument (EL, Hong-Ming Technology, SWIR-320DE3) was also performed to realize the electrical distribution image of solar module [9].



**Figure 1.** Schematic of sputtering Ag (a) before and (b) after annealing.

**Table 1.** Parameters of sputtering Ag nanoparticles.

Parameters	Value
Ag pwer	40 W
Background pressure	$4.8 \times 10^{-6}$ torr
Working pressure	$7.0 \times 10^{-6}$ torr
Target-substrate distance	10 cm
Substrate temperature	Room temperature
Thickness	100 nm
Ar flow rate	35 sccm

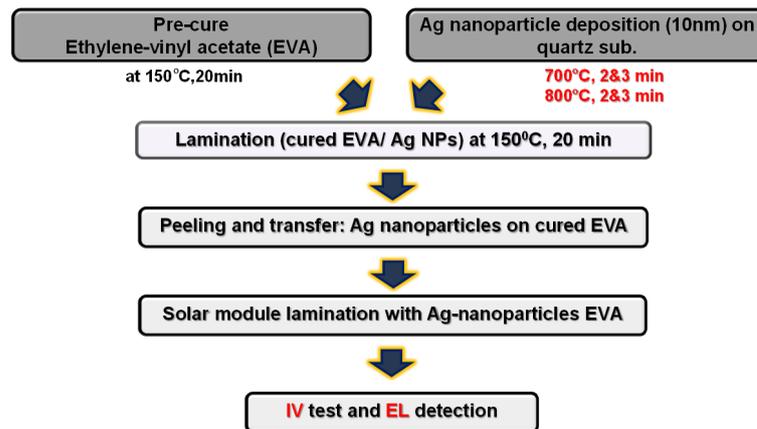
### 3. Characterization and Analyses

#### 3.1. Optical Analyses

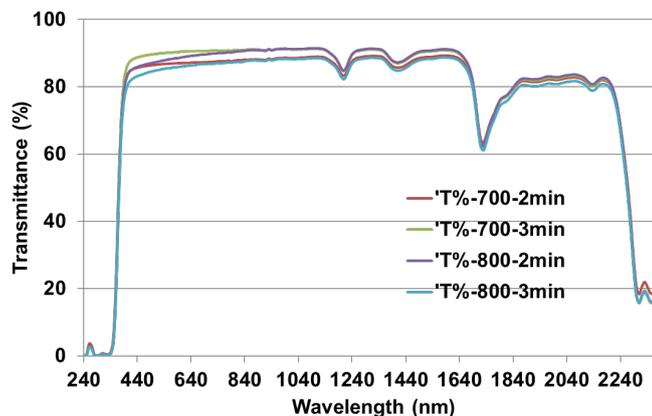
EVA containing nano silver particles through the transfer printing process after (Ag-EVA) light transmittance shown in **Figure 3**. In general, the Ag-EVA sample annealed at 700°C for 3 min shows a highest transmittance, it is worth to note that at a wavelength of >450 nm and higher than reference curves showing a sample of this Ag-EVA annealing conditions have the effect of improving the degree of penetration, the 800°C annealing Ag-EVA sample of 2 minutes of penetration is mainly to enhance the long-wavelength (>780 nm), compared to 700°C annealing 2 minutes and low penetration of analysis results 800°C annealing 3 minutes of Ag-EVA, we can see 700°C annealing 3 minutes of the Ag-EVA with better light transmission.

#### 3.2. Surface Morphology

**Figure 4** illustrates surface topography analysis of the Ag nanoparticles on quartz before and after transferring. From the figure can be found, turn preprocess 700°C annealing process which forms the shape of the Ag NPs irregular granular, annealing 3 minutes of the silver particles are dispersed more evenly and the diameter is about 150 nm. Ag NPs annealed at 800°C for 2 minutes are nearly circular shape, and distribution is denser. 800°C annealing 3 minutes of the silver particles exhibit irregular and uneven distribution. In fact, according to the previous literature [9] [10], the shape of the Ag NPs can be found in light trapping effect is closer to a circle to achieve the effect of the optical gain. Comparison of the observed SEM images, of four annealing conditions for Ag nanoparticles, 700°C-3 minutes annealing treatment exhibits uniform particle size and well distribution, thereby the higher optical enhancement.



**Figure 2.** Preparation of device with Ag NPs.



**Figure 3.** Transmittance of EVA sputtered Ag nanoparticles in various annealing conditions.

### 3.3. Performance of Device

Figure 5 depicts the performance of Ag-EVA on crystalline solar cell, and the electrical characters are shown in Table 2. It is observed that variation in  $I_{sc}$  is more significant than that in  $V_{oc}$ , suggesting that surface plas-

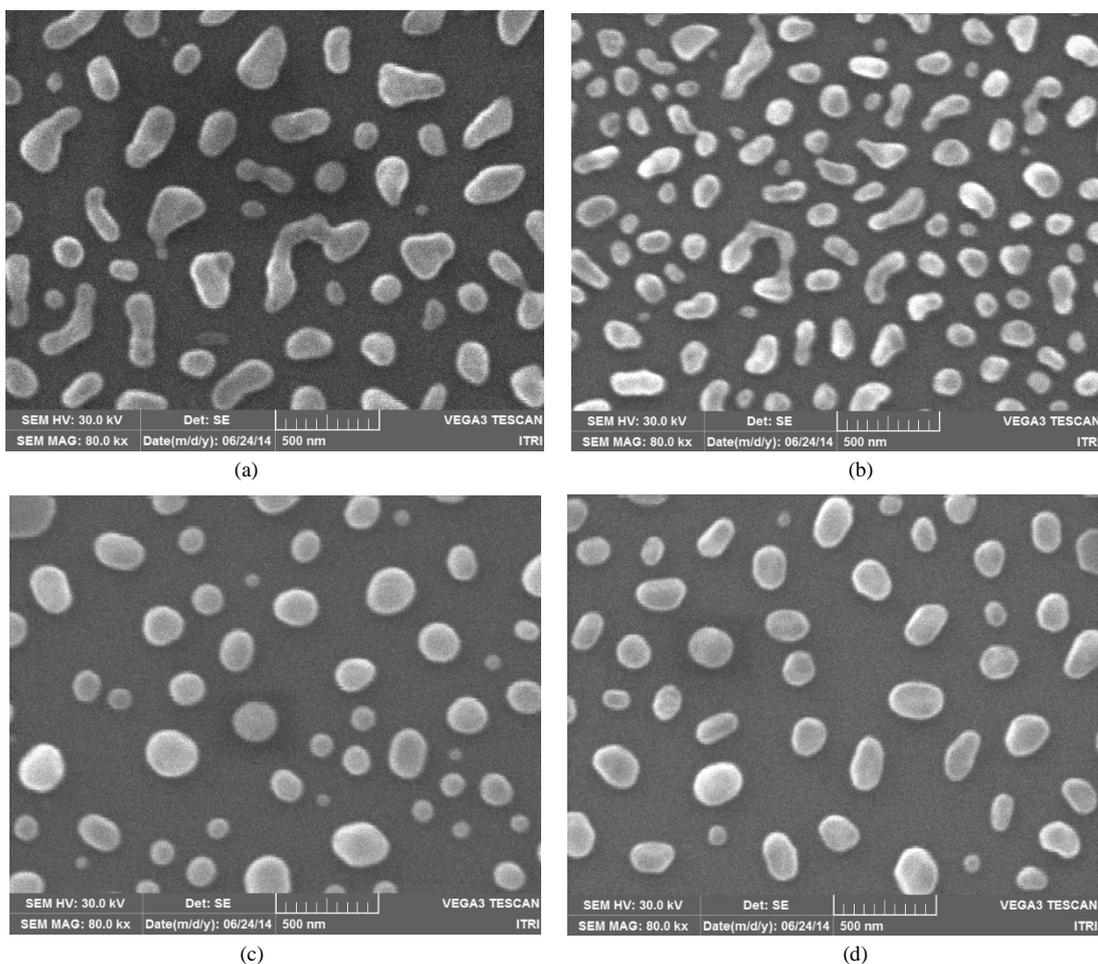


Figure 4. SEM images of Ag nanoparticles before transferring: (a) Annealing 700°C-2 min; (b) Annealing 700°C-3 min; (c) Annealing 800°C-2 min, and (d) Annealing 800°C-3 min.

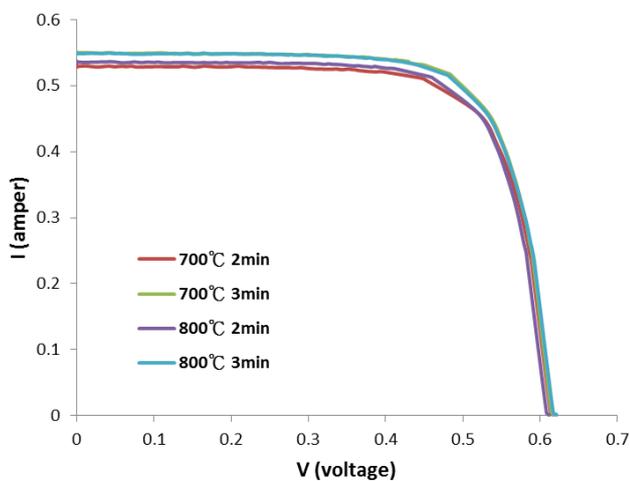


Figure 5. IV curve of EVA sputtered Ag nanoparticles in various annealing conditions.

**Table 2.** Electrical performance of Ag-EVA on crystalline solar cell.

Annealing	Rs (Ohm)	Rsh (Ohm)	Pmax (W)	Voc (V)	Isc (A)	FF (%)
700°C-2 min	0.385	0.026	0.238	0.618	0.530	72.85
700°C-3min	0.284	0.020	0.250	0.618	0.550	73.63
800°C-2 min	0.337	0.030	0.238	0.612	0.536	72.65
800°C-3 min	0.300	0.024	0.248	0.621	0.549	72.74

monic resonance enhances the light performance of solar module. 700°C-3 min sample shows a high Isc of 0.550 A; thus a high power output around 0.250 W was observed. And a high fill factor of 73.63% implies a high performance in series and shunt resistance was demonstrated. According to the IV measurement of solar module containing Ag-EVA, it is confirmed that the optical enhancement can be realized in solar module and the power output increased of 4.7%.

## 4. Conclusions

This study is to discuss the surface plasmonic resonance effect of Ag nanoparticles on the solar cell and module. Research results can be addressed as below:

- 1) With an annealing condition of 700°C for 3 min, surface plasmonic resonance effect of Ag nanoparticles is significantly observed with high transmittance of higher than 90% at wavelength 500 - 800 nm.
- 2) According to SEM morphology, the optimized surface plasmonic resonance effect is observed at particle size of 150 nm in diameter. The uniformity of and distribution of nanoparticles should also affect the light trapping effect of solar module, thus a high Isc is shown in the IV curve.
- 3) IV curve demonstrates that the Ag-EVA crystalline solar module has a lower series resistance, higher shunt resistance, and high fill factor. And the optical enhancement contributed by the Ag NPs is proven to increase the power output of 4.7% compared to traditional solar cell.

## Acknowledgements

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