

# Amorphous Si:H solar cells plasmonic enhancement by nano particle in short circuit current density

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**Abstract**—p-i-n junction amorphous silicon (a-Si:H) plasmonic solar cells front side coated with silver nano particles (NP) embedded in aluminium doped zinc oxide (AZO) for plasmonic enhancement have been prepared. The solar cell structure is glass/AZO/Ag NP/AZO/p-i-n a-Si:H/Al. More than 18% enhancement in short circuit current density ( $J_{sc}$ ) has been achieved with respect to a non-embedded solar cell. Over the wavelength range of 400 nm to 740 nm a broadband photocurrent enhancement was observed. The device performance was improved due to the strong local field enhancement effect from plasmonic Ag NPs which plays the major role.

**Index Terms**—Nanoparticles, plasmons, silver, photovoltaic cells, amorphous materials, silicon.

## 1. INTRODUCTION

The fundamental requirement of photovoltaic (PV) technology is to enhance the conversion efficiency at reduced cost. The material cost can be reduced by using a thin absorber layer. For achieving an optically thick film out of a physically thin layer, several light trapping mechanisms such as anti-reflection (AR) coating, back reflectors, photonic crystal structures, plasmonic patterning have been studied extensively. Indeed, for wide scale commercial application of thin film PV, a potentially cheap and large area compatible light trapping scheme is also desirable. Plasmonic effect is capable of exhibiting improved AR property, coupling of light to waveguide modes, local field enhancement etc. [1-3] which are expected to be realized in thin film solar cells by relatively inexpensive experimental techniques like thermal evaporation [4] or nano imprinting methods [5, 6]. However, for broadband photocurrent enhancement, proper designing and integration of the plasmonic nano structures into existing device layout is still a challenge in this area. Front patterned plasmonic solar cells offer relatively easy-to-implement integration

method and therefore are increasingly explored concept to date. In this paper, we investigate front side plasmonic Ag nano particles embedded in aluminium doped Zinc Oxide (AZO) which serves as a transparent conducting window layer for the amorphous silicon solar cells (SCs). Numerical simulations using Finite Difference Time Domain (FDTD) method of the optical response of the SCs is performed. We demonstrate that for the front side Ag NPs when separated from the a-Si:H absorber layer by a thin TCO layer, near field enhancement effect play an important role in enhancing the electrical performance of the device.

## 2. METHOD

**Solar Cell Preparation:** The step-by-step fabrication sequence of the various layers of the hydrogenated amorphous silicon (a-Si:H) solar cells is described below:

I) Deposition of first Al:ZnO (AZO) layer (Z1) of thickness 400 nm over glass substrate by RF Magnetron Sputtering. II) Vacuum thermal evaporation of ultra-thin Ag film of thickness 0.5 nm over Z1 at a pressure  $10^{-6}$  Pa. The film was annealed at 300°C for 1 hr. under high vacuum to form agglomerated Ag NPs of average size of 20 nm. III) A very thin (20 nm) AZO buffer layer (Z2) is then sputter coated to avoid the diffusion of the metal in the a-Si:H layer. IV) Deposition of the a-Si:H film with the intrinsic layer thickness of 280 nm in p-i-n configuration by plasma enhanced chemical vapor deposition (PECVD) method. V) Al layer as back contact was then deposited by thermal evaporation method. A schematic representation of the different layers of the plasmonic SC is shown in Fig. 1(a). A reference device is also fabricated in the same manner by skipping step II) and III). Therefore, the reference

SC differs from the plasmonic SC only in the absence of Ag NPs. SEM image in Fig.1 (b) shows a typical image of agglomerated Ag NPs over AZO as obtained by step II) for Ag mass thickness of 0.9 nm. The effective area for both the plasmonic and reference SC is 1 cm<sup>2</sup>. The conversion efficiency ( $\eta$ ) of the SCs has been measured by a solar simulator with AM1.5G insolation using a calibrated reference cell. The external quantum efficiency of the SCs was measured over the range 340 nm - 800 nm using a xenon lamp and a monochromator with respect to a calibrated Si photo diode in the presence of red (620 nm) bias light.

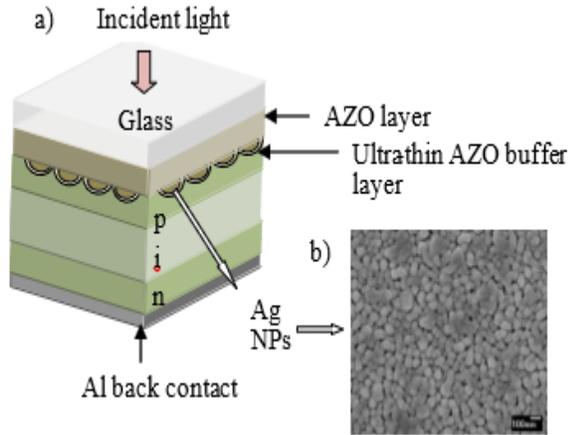


Fig. 1: (a) Schematic of the plasmonic solar cell. (b) A typical SEM image of Ag NPs over AZO for Ag mass thickness of 9 nm.

Optical Simulation: Numerical simulations were carried out using 3D Finite Difference Time Domain (FDTD) method [7] to estimate the optical absorption in the i-layer of the SCs while taking into account the whole device structure. Modeling random NPs is difficult due to huge requirement of both the time and computer memory space for simulation. So instead of randomly oriented particles we considered a regular Ag NP matrix with the size of the NPs same as the average size of the Ag NPs obtained experimentally to reflect the trend of the observed results. The modeling process for front patterned Ag NPs is described in details in our earlier publications [8].

### 3. RESULTS AND DISCUSSION

The comparison of the EQE spectra of the plasmonic solar cell and reference cell over the spectral range of 360 nm to 800 nm as shown in Fig. 2.

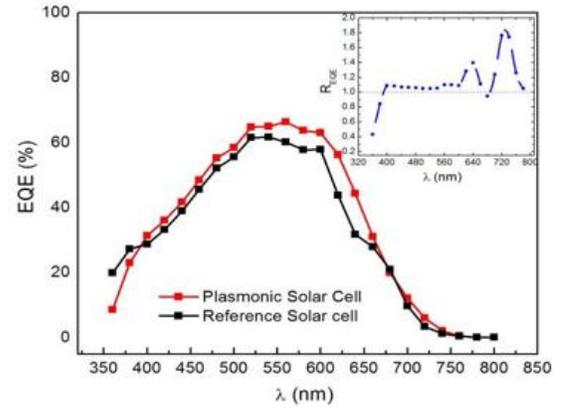


Fig. 2: External quantum efficiency (EQE) spectrum and EQE enhancement ratio ( $R_{EQE}$  shown in inset) of plasmonic solar cell and reference cell.

The inset shows the EQE enhancement ratio ( $R_{EQE}$ ) as a function of wavelength where

$$R_{EQE} = \frac{EQE \text{ of plasmonic cell}}{EQE \text{ of reference cell}}$$

Table 1 indicates the electrical parameters for both the plasmonic and reference solar cells. It is evident that the plasmonic cell exhibits more than 18% enhancement in the short circuit current density ( $J_{sc}$ ). Table 1: Electrical parameters of the plasmonic solar cell and the reference cell.

Sample	Voc (Volt)	J <sub>sc</sub> (mA cm <sup>-2</sup> )	FF (%)	$\eta$ (%)
Plasmonic cell	0.74	11.82	0.394	3.47
Reference cell	0.71	9.97	0.337	2.46

As evident from Fig. 2, the value of  $R_{EQE}$  becomes less than 1 in the UV range (wavelength below 400 nm). It indicates the reduction in the photocurrent for the plasmonic cell due to increased parasitic absorption loss within the NPs in the vicinity of plasmon resonance wavelength ( $\lambda_{SPR}$ ) [9, 10]. For 400 nm to 740 nm spectral range, value of  $R_{EQE}$  greater than 1 implies there is enhancement in the photocurrent of the plasmonic cell. The peaks and valleys observed in the EQE enhancement spectra for longer wavelengths are resulted from the Fabry Perot interference effect within the a-Si:H layer [9].

The forward scattering from the front located NPs due to plasmonic effect can efficiently enhance the

absorption within the absorber layer of a solar cell if the NPs are sufficiently large for effective scattering [10]. The scattering ( $\sigma_{\text{scat}}$ ) and absorption cross section ( $\sigma_{\text{abs}}$ ) of a spherical NP can be expressed in terms of polarizability ( $\alpha$ ) as indicated in Eq. 1(a) and 1(b)

$$\sigma_{\text{scat}} = \frac{1}{6\pi} \left(\frac{2\pi}{\lambda}\right)^4 \alpha^2 \quad 1(a)$$

$$\sigma_{\text{abs}} = \frac{2\pi}{\lambda} \text{Im}(\alpha) \quad 1(b)$$

Where,  $\lambda$  is the wavelength. The value of  $\alpha$  is proportional to the volume of the NP. Therefore, the size of the NPs should be large for scattering to be effective over absorption. It has been found that spherical Ag NPs of diameter exceeding 100 nm can meet such requirement [10, 11]. In the present case, the average size of the Ag NPs is around 20 nm and thus possess inadequate scattering for absorption enhancement. Therefore, we propose that the broadband EQE enhancement may have resulted from the local field enhancement effect associated with localized surface plasmon resonance of the Ag NPs. To validate this fact, numerical simulations were performed using 3D FDTD method [7]. Fig. 4(a) and 4(b) shows the electric field distribution ( $|E^2|$ ) at wavelength of 600 nm and 730 nm respectively around a 20 nm Ag NP situated between the AZO/a-Si:H interface. The layout is analogous to the experiment. The incident light direction is along the positive Z axis. Clearly, a strong localization of the electric field takes place at the a-Si:H layer in proximity to the NPs. It allows more light to be absorbed by the a-Si:H layer which manifests in improved electrical response of the device by enhancing the  $J_{\text{sc}}$  value as well as the EQE spectra of the plasmonic cell.

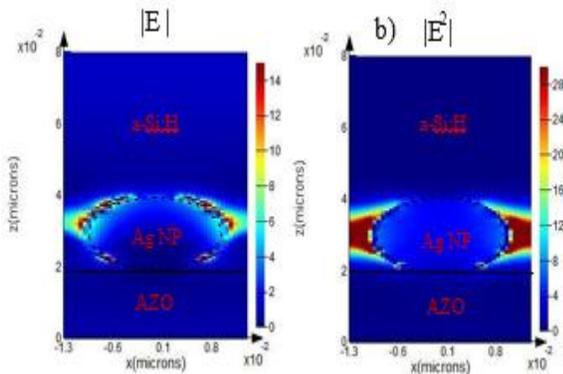


Fig. 4: Electric field distribution ( $|E^2|$ ) around a 20 nm Ag NP situated at the AZO/a-Si:H interface at wavelength (a) 600 nm and (b) 730 nm. Light is incident along the positive Z direction.

#### 4. SUMMARY

We fabricated plasmonic a-Si:H based solar cells front coated with ultra-small silver nano particles (average size 20 nm) exhibiting broadband enhancement in the EQE spectrum with respect to a reference solar cell without any Ag NP. Incorporation of Ag NPs also resulted in a 18.5% enhancement in short circuit current density. Through numerical simulations we identified the near field light concentration to be responsible for the improved performance of the device. Due to small size, plasmonic scattering from the NPs is negligible in this case. These findings indicate new approach for front patterned Ag NPs to improve the device performance by near field light concentration instead of enhanced forward scattering effect.

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