

# Advanced plasmonic interfaces for optimized light trapping in photovoltaics

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**Abstract.** Plasmonic interfaces are integrated to photovoltaic devices to enhance light trapping and improve efficiency. The optimum thickness of the spacer layer used to passivate the absorber layer and adjust its distance from the metal nanoparticles remains unclear. We integrate plasmonic interfaces consisting of Ag nanoparticles and silicon nitride spacers of different thicknesses to the back of a-Si:H absorber to investigate the optimum thickness of the spacer layer and use the photocurrent in a-Si:H to indicate the enhancement in light-trapping. For integration to the back or front of the device, the localized surface plasmon resonance (LSPR) is shifted and broadened into the red with increased spacer layer thickness and the effect is more pronounced for integration to the back. An appreciable enhancement of photocurrent in a-Si:H is consistent with this broadening of LSPR and has a critical dependence on spacer layer thickness.

**Keywords**— plasmonic interfaces, photocurrent, light trapping, spacer layer.

## 1. Introduction

The performance of photovoltaic devices depends on efficient light absorption and photocarrier collection mechanisms. Even if the most efficient carrier collection is achieved, significant portion of the solar spectrum remains unused. Advanced light management schemes to optimize light absorption include surface texturing, up and down conversion, plasmonics and other surface nanostructures [1,2]. Plasmonic interfaces consisting of metal nanoparticles integrated to PV devices with a spacer layer have shown a promising potential for enhancing light-trapping and improving solar cell efficiency [2 – 4]. Extinction of light as characterized by a minimum in transmittance occurs at the localized surface plasmon resonance (LSPR) when the frequency of incident photons matches the collective frequency of oscillating electrons at the surfaces of metal nanoparticles [5,6].

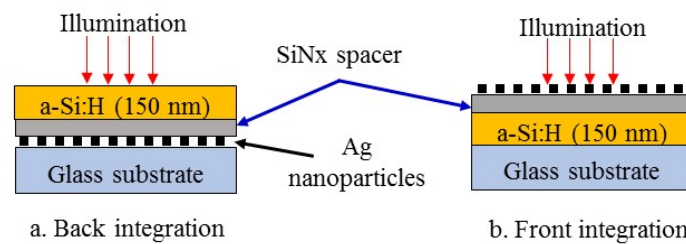
Optical extinction is red-shifted and broadened into the 500 – 700 nm region with increasing nanoparticle size and also with spacer layer thickness [2]. Theoretical calculations predict that the scattering cross-section increases while preferential scattering decreases with increasing spacer layer thickness, suggesting that the optimum photocurrent is a compromise between the increased scattering cross-section and decreased preferential scattering at a given spacer layer thickness [3]. Scattering can be preferentially directed towards the a-Si:H absorber by the appropriate selection of refractive indices.

In this study, we integrate silver nanoparticles to the back surface of a-Si:H serving as the absorber layer (figure 1a) using SiN<sub>x</sub> spacer layers of 0.30 and 60 nm in thickness and use the enhancement in the spectral dependence of photocurrent normalized to incident photon power as a means of measuring enhanced light trapping dependence on spacer layer thickness.



## 2. Samples and experiment

The self-assembled Ag nanoparticles were fabricated by dewetting 15-nm-thick sputtered Ag films on glass substrates in  $N_2$  at 420 °C for one hour as was explained previously [7]. The SiNx spacer layers of 0, 30, and 60 nm thicknesses followed by a 150-nm-thick a-Si:H layer were deposited using plasma-enhanced chemical vapor deposition (PE-CVD). Another sample with the plasmonic interface on top of the a-Si:H layer using a 30-nm thick spacer was fabricated for comparison.

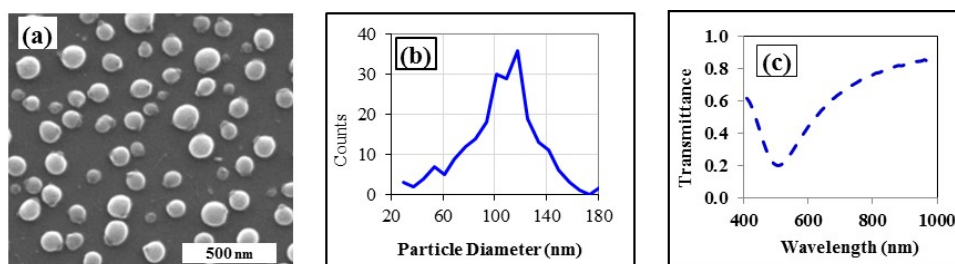


**Figure 1.** Schematic diagrams for the back (a), and front (b), integrations of plasmonic interfaces dewetted at 420 °C (front interface).

Scanning electron microscope (SEM) images and optical transmittance and reflectance over the spectral range of 400 – 1100 nm were performed using an optical system as described previously [7]. Aluminum electrodes of standard coplanar geometry were evaporated on the a-Si:H side using a shadow mask. The photocurrent in a-Si:H was measured versus wavelength under illumination from a halogen lamp through a monochromator with 10 nm wavelength increments over the spectral range of 400 – 1100 nm.

## 3. Results

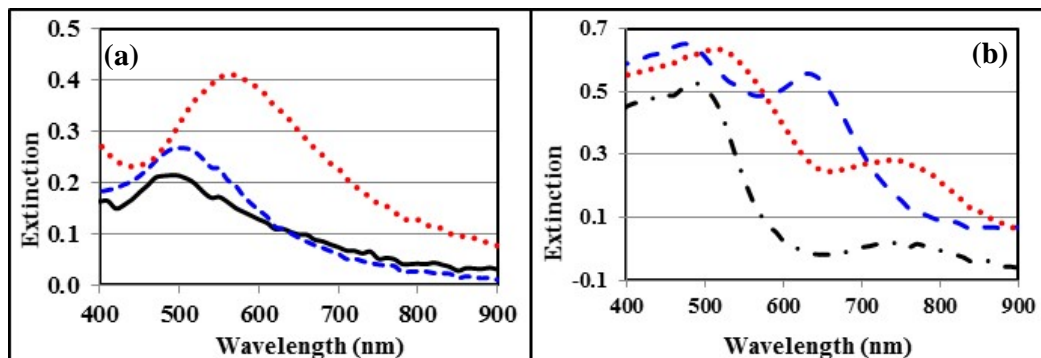
In figure 2, we show an SEM image of Ag nanoparticles dewetted at 420 °C on a glass substrate, the Ag nanoparticle size distribution and the transmittance versus wave length. The SEM image shows round and completely separated particles while the particle size distribution shows a normal distribution with a mean particle size of about 110 nm. Round particles in the range of this size are essential in promoting scattering and minimizing losses. Previous studies show that smaller size particles exhibit large parasitic losses and high absorption [9]. The transmittance curve shows a pronounced plasmonic resonance at about 520 nm wavelength. These measurements were repeated for the two other interfaces to make sure that all interfaces were identical before the subsequent steps are added.



**Figure 2.** (a) SEM micrograph of Ag nanoparticles dewetted on glass substrate at 420 C, (b) the corresponding particle size distribution, and (c) the transmittance showing a minimum at 520 nm.

Figure 3a shows the extinction spectra calculated as  $E = 1 - T - R$ , where T is transmittance and R is reflectance, for the three interfaces with 0 (no spacer), 30-nm and 60-nm thick SiNx spacers. The extinction maxima are clearly shifted and broadened into the red with increased spacer layer thickness. The effect of these plasmonic interfaces on the extinction spectrum of a-Si:H are plotted in figure 3b

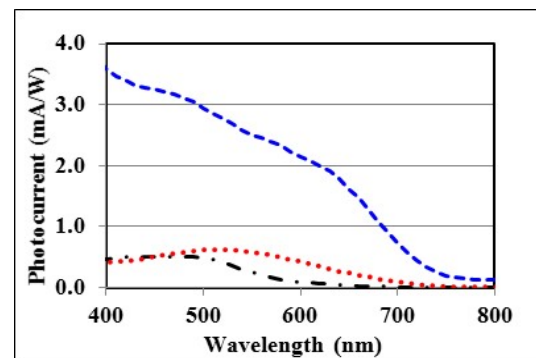
which shows the extinction spectra for the flat a-Si:H reference (no interface) and two others with interfaces integrated to the back using spacer layer thicknesses of 30 and 60 nm. The clean spectra in figure 3a, are complicated by the addition of the a-Si:H due to interference with reflections from the various interfaces in the stack. Despite the wiggles in the extinction spectra, the shift and broadening are still clear in figure 3b when compared with the flat a-Si:H reference although the effect of the spacer thickness is obscured.



**Figure 3.** (a) Extinction spectra for three plasmonic interfaces with identical Ag-nanoparticles size distributions using spacer layer thicknesses of zero (solid line), 30 nm (dashed) and 60 nm (dotted). (b) the extinction spectra of a flat 150 nm thick a-Si:H reference with no interface (dashed-dotted) and with two plasmonic interfaces with spacer layer thicknesses of 30 nm (dashed line) and 60 nm (dotted line).

Figure 4 shows the photocurrent versus wavelength for the two samples with plasmonic interfaces compared to the flat a-Si:H reference. The photocurrent shows appreciable enhancement in the region of 500 – 700 nm for both samples and the effect is more pronounced for the sample with the thinner spacer layer, which is consistent with their extinction spectra. The difference in their photocurrent enhancements below 500 nm will be discussed below.

The sample with zero spacer (not shown here) exhibits anomalous and non-repeatable results which we attribute to the direct contact of the a-Si:H with the conductive Ag nanoparticles acting as defects limiting the current [8,9].



**Figure 4.** Photocurrent versus wavelength in a-Si:H with plasmonic interfaces using: 30-nm (dashed line) and 60-nm (dotted line) spacer layers and flat a-Si:H reference (dashed-dotted line: multiplied by 50).

#### 4. Discussion

Extinction represents light that is either absorbed or scattered by the interface. Scattering can be made preferentially into the a-Si:H due to its high refractive index. To determine whether scattering is taking place, we measured the photocurrent in a-Si:H versus wavelength and used the enhancement in photocurrent as an indication of enhanced light trapping and preferential scattering into the absorber layer. The broadened Extinctions observed in figure 3 for samples with plasmonic interfaces compared to the flat a-Si:H reference represent either enhanced absorption by the interface (which decreases photocurrent) or enhanced preferential scattering into a-Si:H (which increases photocurrent). The clear enhancement in photocurrent in the spectral range of 500 – 700 correlate well with the shift and broadening into the red of the extinction spectra. This correlation strongly suggests that preferential scattering is taking place.

The lower photocurrent enhancement for the region below 500 nm may be attributed to the higher absorption in the thicker SiNx layer although rough calculations suggest that this alone may not account for the large difference between 30 nm and 60 nm spacer layer thickness. For front integration, light is already travelling towards the absorber layer and the plasmonic interface may improve photocurrent by preferential (forward) scattering the otherwise reflected light but may at the same time block or absorb part of the incident light which offsets the enhancement effect. We therefore see no clear enhancement for integration to the front [9]. For the back integration, on the other hand, the interface can only backscatter the otherwise transmitted light with no possibility of blocking it. These results suggest that the proper position for the plasmonic interface is the back of the absorber layer in agreement with previous results [10].

To achieve optimum light trapping and thus maximum device efficiency, it is therefore recommended that plasmonic interfaces are integrated to the back of the device (opposite side of light exposure). Nanoparticle shape should be round and the size should be approximately 100 nm in diameter to minimize parasitic loss and maximize preferential scattering. The remaining critical parameter of spacer layer thickness is not as straightforward. The spacer layer should be thin enough to promote preferential scattering but sufficiently thick to keep the absorber passivated. As the above results indicate, increasing the thickness to higher than 30 nm reduces the photocurrent because preferential scattering decreases. Our internal measurements (not shown here) show that SiNx spacers less than 20 nm in thickness may not be continuous which exposes the Ag to the absorber.

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