The Promise and Challenges of Enhancing Solar Cell Efficiency Using Patterned Nanostructures

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Abstract—This study provides a brief review of the different methods of using patterned nanostructures to improve light-coupling efficiency in Photo-voltaic (PV) cells. The different kinds of patterned nanostructures reviewed include nanowire solar cells with nanopillars placed periodically on top of a Si substrate, quantum dot solar cells, mesoscopic solar cells, and plasmonic solar cells. For plasmonic solar cells, the relationship between energy conversion efficiency in thin-film Si solar cells and the type of metallic nanoparticle, the size of the metallic nanoparticles, and the distance between neighboring metallic nanoparticles in a periodic array of the metallic nanoparticles deposited on top of the Si substrate are explored. Of the different metallic nanoparticle systems studied, it is found that silver nanoparticles with diameter of 100 nm and spaced 220 nm from neighboring nanoparticles in a periodic array of the metallic nanoparticles deposited on top of the Si substrate provides a significant increase in the generated short circuit current density ($J_{sc}$) in the wavelength region of $\lambda = 400 – 1100$ nm. Aluminum nanoparticles with diameter of 100 nm and spaced 220 nm from neighboring nanoparticles provides a significant increase in the generated short circuit current density ($J_{sc}$) in the relatively bluer wavelength region of $\lambda = 200 – 600$ nm. This can be attributed to the plasmon resonance wavelength of Ag being more red-shifted than that of Al. The increase in $J_{sc}$ appears to be strongly correlated to the plasmon resonance wavelength of the metal nanoparticles. Additionally, this study also shows the near-field enhancement image for an Ag nanoparticle on top of a Si substrate. The near-field images suggest that enhancements in the near-fields can eventually lead to the increase in $J_{sc}$ as shown in this study.

Keywords—photovoltaics, plasmonics, thin-film solar cells, light trapping, nanoparticles, surface plasmons, silver nanoparticles, gold nanoparticles, aluminium nanoparticles.

I. INTRODUCTION

As we delve further into a future where our dependence on fossil fuels must be curtailed due to the non-renewable nature of fossil fuels, the interest in alternative and renewable sources of energy has been greatly peaked. Solar energy is the most promising of these alternatives. Photovoltaic (PV) cells are utilized to convert the energy from the Sun into electrical energy [1]–[3]. Theoretically, this should provide a potentially unlimited source of clean and sustainable electrical energy. However, two major complications prevent them from revolutionizing the generation of energy. Firstly, the conversion efficiency of commercially available PV cells leaves a lot to be desired – at their most optimum conditions, the efficiency is no more than 20%. Secondly, the cost of PV cells is an issue. Although costs have decreased greatly over the past few decades, they are yet to be at a financially viable level [4]. The record efficiencies for Si based PV cells is 25%, while overall it is 41% for GaAs PV cells – both have too large a cost-to-efficiency ratio [4], and thus are commercially unfeasible. The challenge, therefore, is to reduce this ratio to as low a value as possible, as the possible benefits are immense.

The energy conversion efficiency depends on certain factors [5], including

- Optical absorptivity
- the minority carrier lifetime, which is the average time a carrier can exist in its excited state.
- diffusion length, which is the average length a carrier can travel before recombination.

To keep these factors in check, significant amount of research, including ours, has been focusing on thin-film PV cells (less than 10µm thick), as they reduce the mismatch between the electronic and photonic length scales [6]. However, the reduced thickness results in lower number of electron-hole pairs produced, and hence adversely affects the overall efficiency of thin-film PV cells. If light absorption could be improved in thin-film cells of Si substrate, it could directly lead to higher energy conversion efficiencies.

II. THE EFFICACY OF NANOSTRUCTURES

To improve light-coupling efficiency, patterned nanostructures are designed and implemented in tandem with PV cells. These structures can be made of different materials depending on their optical properties, and are designed to enhance the light coupling efficiency. The nanoscale dimensions of these structures mean that they have a high surface-to-volume ratio, which complements their overall purpose. The usage of nanostructures provides a significantly cost-effective method to improve cell efficiency, and simultaneously improve efficiency beyond theoretical limits (Shockley-Queisser limit) [7].
Examples of nanostructured solar cells include:

a) Nanowire solar cells, with nanopillars placed periodically on top of the Si substrate
b) Quantum dot solar cells
c) Plasmonic solar cells
d) Mesoscopic solar cells

The advantages and challenges of these designs are discussed in Figure 1 [4].

Nanstructures, in many cases, implement principles that are adhered to in other fields to enhance optical and electrical efficiency of solar cells. For example, moth-eye anti-reflective coatings (ARC) are inspired by the structure of the cornea of nocturnal moths which they utilize to have better vision in the dark [8] – [9]. Mesoscopic solar cells couple photo-sensitive pigment within the PV cell itself to provide a cheap thin-film solar cell that in recent studies have proved to be flexible in nature, allowing them to be coated on other machineries and equipment [10]. Organic solar cells utilize materials synthesized from organic substances or polymers that are optically and electronically active, facilitating them to be used as an environmentally friendly source of electrical energy [11].

![Advantages and Challenges: (a) Nanowire solar cells, (b) Quantum dot solar cells, (c) Plasmonic solar cell](image)

**Advantages**
- Anti-reflective coat
- Reduced amount of material used

**Challenges**
- Reflection at top contact
- Efficacy of dopants

![Advantages and Challenges: Plasmonic solar cell](image)

**Advantages**
- Several possible band-gap energies
- Multiple electron-hole pairs

**Challenges**
- Long-term stability

![Advantages and Challenges: Mesoscopic solar cell](image)

**Advantages**
- Large spectral efficiency
- Useful for thin-film

**Challenges**
- Effective cost
- Loss due to resonant scattering in different direction

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**III. PLASMONIC SOLAR CELLS**

The use of plasmonics in a variety of applications have led to significant research and development in this field over the past three decades. Surface plasmon polaritons (SPP) are generated by electromagnetic fields due to the oscillation of electrons on a metal-dielectric interface [12]. The use of these SPPs in improving PV efficiency has garnered great interest and research [13]. Studies conducted recently demonstrated the optical absorption and photocurrent generation in semiconductor photodiodes induced by scattering from SPP resonances in metallic nanoparticles deposited on the photodiode surface. Furthermore, they have been coupled with amorphous thin-film Si cells as well [14]. In order to properly optimize the usage of SPPs, detailed analysis of the dependence of the improvement of PV efficiency on the physical parameters of plasmonic nanostructures must be performed. This study will provide a brief analysis of this optimization as an example of how plasmonic nanostructures can improve the optical and electrical efficiencies of solar cells in general, and that this can be achieved by modifying physical parameters of the nanostructures used.

Plasmonic solar cells allow the thickness of the PV cell to be less than 2µm. Surface plasmon polaritons undergo resonance at certain frequencies, depending on the metal with which the nanostructure is made and the size and shape of the nanostructure [13]. At this state, SPPs demonstrate maximum resonance (e.g., scattering) with the incident electromagnetic waves (e.g., sunlight), which results in greater absorption within the cell substrate. This phenomenon can be manipulated to improve light coupling efficiency within thin-film solar cells. The metal with which the plasmonic nanoparticles are made is important, as different metals exhibit distinguishable surface plasmon resonances, and thus have varying impacts on the overall absorption enhancement. Below are examples of three possible configurations to incorporate plasmonic nanoparticles/nanostructures in thin-film Si solar cells:

- a) Nanoparticles on the surface the substrate
- b) Nanoparticles within the substrate
- c) Nanostructures as/on back contacts

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**A. Optimization of Parameters**

As part of this study, we wished to observe the overall influence that the physical parameters of plasmonic nanoparticles distributed periodically over a Si substrate had on the substrate’s light coupling efficiency. In order to do so, we defined a quantity that would be an appropriate indicator for any form of enhancement or otherwise. Hence, we defined the parameter of absorption enhancement, $g$, which is the ratio of the power absorption within the Si substrate with the nanoparticles to that without the nanoparticles ($g = \text{power absorbed with the Si substrate with nanoparticles/power absorbed within the Si substrate with no nanoparticles}$). We then chose to calculate the short circuit current density, $J_{SC}$, to analyze how the absorption enhancement translates to the electrical energy conversion efficiency. Furthermore, to visually analyze the flow of the electric fields within the
substrate as a result of the interaction of the plasmonic nanoparticles on the Si substrate, we generated and analyzed the near-field enhancement images.

B. Simulation Setup

All of the simulations were performed with cells placed under a plane wave source at a solar spectral irradiance of AM1.5G, with the average intensity taken to be 1000 W/m² at 25°C. The analysis was done using the solvers FDTD Solutions (for optical absorption enhancement) and DEVICE (for the calculation of J_SC), developed by Lumerical Solutions, Inc. For each simulation, boundary conditions of anti-symmetric in the x-axis, and symmetric in the y-axis, were chosen to reduce simulation time. The simulation setup is illustrated in Figure 2.

C. Results and Discussion

Initially, we analyzed the absorption, scattering and extinction spectra for three metals (e.g., silver – Ag, gold – Au and aluminum – Al) with diameters of 50nm, 100nm and 200nm respectively to determine the exact range of wavelengths over which their resonances occur. The particles were then placed periodically over a 2µm thick Si substrate at a pitch (center-center) of 300nm. The absorption enhancement graph for the Si substrate coupled to each type of metal with the diameters of interest were then generated. The pitch was kept constant in order to observe the variation in optical absorption with respect to the diameter of the nanoparticles. The source wavelength range was chosen to be 400nm to 1100nm for Ag and Au, and 200nm to 1100nm for Al as Al exhibited resonance on the bluer region of the spectrum. The results obtained are illustrated in Figure 3.

It can be seen that there is almost no absorption enhancement for Si substrate with nanoparticles of diameter of 50nm on the surface for all three metals. The absorption enhancement factor is observed to have a peak for 100 nm Ag at approximately λ ~ 420nm and for 200 nm Ag at approximately λ ~ 470nm, while the same for Au is around 560nm (diameter = 100nm) and no clear peaks for the D = 200nm nanoparticle, respectively. For Al, the peaks lie closer to the λ ~ 350 nm. This is in agreement with our scattering spectra analysis (data not shown), as the plasmon resonance for each of these particles are around the same wavelengths.

The analysis was then repeated for a pitch of 220nm (center-center). Absorption enhancement graphs were once again generated for all three metals with the three different diameters, and the results are shown in Figure 4. The absorption enhancement for particles of diameter 50nm is the same as before.
For particles of diameter 100nm, however, a greater enhancement is seen, as the peak absorption enhancement factors for all three particles are now greater than it was with a pitch of 300nm. Furthermore, it is observed that for particles with diameter 200nm, the absorption enhancement factor is less than 1 for a greater part of the spectrum. One possible explanation for this could be that for this diameter of metallic nanoparticles, the scattering is occurring towards a direction away from the Si substrate.

The short circuit current density $J_{SC}$ was calculated for all of the possible physical parameter combinations with the three different types of metals (Ag, Au and Al), three diameters (50nm, 100nm and 200nm) and two separate pitches (300nm and 220nm). $J_{SC}$ was also calculated for the nanostructures at an incident wavelength range of 400nm to 700nm for Ag and Au, and 200nm to 600nm for Al, as it is within these ranges that the solar cell exhibited the highest respective absorption enhancements. The resultant $J_{SC}$ are given in the following tables.

### TABLE I. $J_{SC}$ FOR THE LARGER INCIDENT SPECTRUM

<table>
<thead>
<tr>
<th>Structure</th>
<th>Ag ($\lambda=400$nm to 700nm)</th>
<th>Au ($\lambda=400$nm to 700nm)</th>
<th>Al ($\lambda=200$nm to 600nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$J_{SC}$</td>
<td>% Change</td>
<td>$J_{SC}$</td>
</tr>
<tr>
<td>No Particles</td>
<td>76.2793</td>
<td>0%</td>
<td>76.2793</td>
</tr>
<tr>
<td>$D = 50$nm</td>
<td>78.2283</td>
<td>2.55%</td>
<td>76.5712</td>
</tr>
<tr>
<td>$D = 100$nm</td>
<td>95.5242</td>
<td>25.20%</td>
<td>76.6562</td>
</tr>
<tr>
<td>$D = 200$nm</td>
<td>41.1047</td>
<td>-46.11%</td>
<td>19.2681</td>
</tr>
</tbody>
</table>

### TABLE II. $J_{SC}$ FOR LIMITED INCIDENT SPECTRUM

(a) For Pitch = 300nm

<table>
<thead>
<tr>
<th>Structure</th>
<th>Ag ($\lambda=400$nm to 700nm)</th>
<th>Au ($\lambda=400$nm to 700nm)</th>
<th>Al ($\lambda=200$nm to 600nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$J_{SC}$</td>
<td>% Change</td>
<td>$J_{SC}$</td>
</tr>
<tr>
<td>No Particles</td>
<td>64.1602</td>
<td>0%</td>
<td>64.1602</td>
</tr>
<tr>
<td>$D = 50$nm</td>
<td>65.1141</td>
<td>1.48%</td>
<td>63.8908</td>
</tr>
<tr>
<td>$D = 100$nm</td>
<td>75.6064</td>
<td>17.84%</td>
<td>59.8337</td>
</tr>
<tr>
<td>$D = 200$nm</td>
<td>59.2331</td>
<td>-7.67%</td>
<td>26.0504</td>
</tr>
</tbody>
</table>

(b) For Pitch = 220nm

<table>
<thead>
<tr>
<th>Structure</th>
<th>Ag ($\lambda=400$nm to 700nm)</th>
<th>Au ($\lambda=400$nm to 700nm)</th>
<th>Al ($\lambda=200$nm to 600nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$J_{SC}$</td>
<td>% Change</td>
<td>$J_{SC}$</td>
</tr>
<tr>
<td>No Particles</td>
<td>64.1602</td>
<td>0%</td>
<td>64.1602</td>
</tr>
<tr>
<td>$D = 50$nm</td>
<td>65.8854</td>
<td>2.68%</td>
<td>63.6557</td>
</tr>
<tr>
<td>$D = 100$nm</td>
<td>79.7938</td>
<td>19.69%</td>
<td>56.1374</td>
</tr>
<tr>
<td>$D = 200$nm</td>
<td>32.9415</td>
<td>-48.65%</td>
<td>8.44858</td>
</tr>
</tbody>
</table>

This can be attributed to the fact that the absorption enhancement is occurring across all the wavelengths (frequencies) studied, and thus curtailing the frequency range also lowers the percentage increase in $J_{SC}$ for the case of Ag and Au. For Al, the opposite phenomenon occurs. This may be explained by the fact that the majority of the absorption enhancement for Al occurs in the limited incident spectrum range (i.e., $\lambda=200$nm to 600nm range).

### D. Near-Field Enhancement

Near-field plots would demonstrate the transmission of the electric field within the nanoparticle and the Si substrate at the resonant wavelength of the particle. To this end, we chose the physical parameters at which each Ag nanoparticle exhibited the highest absorption and $J_{SC}$ enhancement. This was found for Ag nanoparticles with a diameter of 100nm placed at a pitch of 220nm. We also had to first identify the approximate wavelength at which the nanoparticles of Ag displayed surface plasmon resonance $\sim \lambda = 460$nm. Three near-field images were generated – (a) the substrate without the particle at the given wavelength (b) the substrate with the Ag particle at the given wavelength and; (c) the enhancement image, which was calculated by dividing the raw data of the second image (Fig. 5b) with the raw data of the first image (Fig. 5a). All three images in that exact order are shown in Figure 5. The images were generated at a wavelength of $\lambda = 460$nm, which is approximately the wavelength at which the plasmon resonance phenomenon for Ag nanoparticle of diameter 100nm occurred. For the enhancement image, the color scale is in the log scale, and hence the areas which are dark red color have an
The near-field enhancement image (Fig. 5c) shows us the presence of the Ag nanoparticle on top of the Si substrate leads to significant increases in the electromagnetic field intensity around the Ag nanoparticle and within the Si substrate in the vicinity of the Ag nanoparticle. It is important to note that the near-fields calculated in Figure 5(b-c) can represent enhanced propagating radiation within the Si substrate. In Figure 5c, a significantly large portion of the image around the Ag nanoparticle is bright or dark red which depicts significant near-field enhancements in the region immediately surrounding the Ag nanoparticle which is induced by the incident radiation. These near-field enhancements which also carry into the Si substrate immediately surrounding the Ag nanoparticle can eventually lead to the absorption enhancements and increase in $J_{SC}$ as shown in Figures 3 and 4, and Tables I and II. Hence we see that nanoparticle systems displaying large absorption enhancements and increase in $J_{SC}$ also show very strong enhancements in the near-fields around the Ag nanoparticle.

IV. CONCLUSION

This study provides a brief review of the different methods of using patterned nanostructures to improve light-coupling efficiency in PV cells (e.g., thin film Si solar cells). The patterned nanostructures described can be designed and implemented in tandem with PV cells. These structures can be made of different materials depending on their optical properties, and are designed to enhance the light coupling efficiency of the PV cell. The different kinds of patterned nanostructures discussed include nanowire solar cells with nanopillars placed periodically on top of the Si substrate, quantum dot solar cells, mesoscopic solar cells, and plasmonic solar cells. The review discussed the advantages and disadvantages of using the different kinds of patterned nanostructures for enhancing PV cell efficiency.

In particular, this study expands upon the use of plasmonic metal nanoparticles for increasing the efficiency of thin-film Si solar cells [15]. This study explores the relationship between energy conversion efficiency in amorphous thin-film Si solar cells and the type of metallic nanoparticle, the size of the metallic nanoparticles, and the distance between neighboring metallic nanoparticles in a periodic array of the metallic nanoparticles deposited on top of the Si substrate.

The different configurations of metallic nanoparticle systems studied were as follows: $D = 50$ nm, $D = 100$ nm, and $D = 200$ nm Ag nanoparticles spaced with a pitch of 300 nm (center-center) and a pitch of 220 nm (center-center); $D = 50$ nm, $D = 100$ nm, and $D = 200$ nm Au nanoparticles spaced with a pitch of 300 nm (center-center) and a pitch of 220 nm (center-center) and; $D = 50$ nm, $D = 100$ nm, and $D = 200$ nm Al nanoparticles spaced with a pitch of 300 nm (center-center) and a pitch of 220 nm (center-center), respectively. Of the different metallic nanoparticle systems studied, it was found that Ag nanoparticles of $D = 100$ nm and spaced 220 nm (center-center) from neighboring nanoparticles in a periodic array of the metallic nanoparticles deposited on top of the Si substrate provides the maximum increase (i.e., 25%) in the generated short circuit current density ($J_{SC}$) in a specific wavelength region of the electromagnetic spectrum ($\lambda = 400$–1100 nm). It was also shown that Al nanoparticles of $D = 100$ nm and spaced 220 nm (center-center) from neighboring nanoparticles in a periodic array of the metallic nanoparticles deposited on top of the Si substrate provides the maximum increase (i.e., 35%) in the generated short circuit current density ($J_{SC}$) for the bluer wavelengths of the electromagnetic spectrum (i.e., of $\lambda = 200$–600 nm). This can be attributed to the plasmon resonance wavelength of Ag ($\lambda \sim 430$ nm) being more red-shifted than that of Al ($\lambda \sim 320$ nm). So the increase in $J_{SC}$ appears to be strongly correlated to the plasmon resonance wavelength of the metal nanoparticles.

Additionally, this study also shows the near-field enhancement image for a $D = 100$ nm Ag nanoparticle on top of a Si substrate (Figure 5a-5c). The near-field enhancement image (Figure 5c) shows the presence of the Ag nanoparticle on top of the Si substrate leads to significant increases in the electromagnetic field intensity around the Ag nanoparticle and within the Si substrate in the vicinity of the Ag nanoparticle when the system is illuminated by incident electromagnetic radiation. This observation suggests that such near-field enhancements can eventually lead to the absorption enhancements and increase in $J_{SC}$ as shown in this study.

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