Fabrication of a Nanoscale Plasmonic Fishnet Structure for the Enhancement of Absorption in Thin Film Solar Cells

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Abstract— Incorporating plasmonic structures in the back spacer layer of thin film solar cells (TFSC's) is an efficient way to increase the yield. The plasmonic fishnet structure is one such geometry using which this effect can be realized. Numerical simulations have shown the ability of these structures to bring about an enhancement in the short circuit current density of TFSCs at specific wavelengths. We show that light absorption in the a-Si absorber layer is enhanced by a factor of 10.6 at the design wavelength of 690 nm due to the presence of the fishnet structure. Furthermore, the total absorption over all wavelengths was increased by a factor of 3.2. The short circuit current density of the TFSC was increased by 30% as a result of including the fishnet.

This paper presents the fabrication process of the fishnet structure. A fishnet structure made of silver was fabricated using a combination of electron beam lithography and thermal evaporation. A complete TFSC was fabricated using PECVD to deposit a-Si on the fishnet structure. In effect, the fishnet was placed in the back spacer layer preventing shadowing effects. The final structure optically resembled a TFSC in all respects except that there were no doped layers. The fishnet structure is essentially a mesh of linewidth 100 nm, and a thickness of 20 nm.

1. INTRODUCTION

Solar cells are among the most widely researched form of renewables in the world today. What makes solar cells and renewables in general, attractive is the fact that it is a one-time investment. However, there is also good reason why solar cells are not preferred over fossil fuel based solutions despite their obvious advantages. The reason is that the efficiency of solar cells does not compare to conventional energy sources. Hence the cost per watt of solar cell technology is far from competitive as it stands today. One plausible option to reduce the cost per watt figure is to use less material for the active region of the solar cell. In fact, the cost of silicon (Si), the most prevalent material used in wafer solar cells today, constitutes a majority of the cost of production [1, 2].

However, reducing the amount of material in the active region would automatically reduce efficiency further — this is because the probability of absorption of an incoming photon reduces drastically as the volume of material decreases. If a suitable method can be devised to ensure that the absorption within a smaller volume of material is comparable to that within a comparatively thicker wafer, the overall production costs may be greatly reduced. Thin Film Solar Cells (TFSCs) offer such a solution. Instead of expensive crystalline Si wafers, these cells use cheap, vapor-deposited amorphous Si (a-Si) as the active material. The principle of making this thin layer of a-Si (usually only a fraction of the wafer thickness of wafer-based cells) appear optically comparable to a Si wafer is simple to understand. Multiple reflections are induced within the thin film, so that the effective path length of an incoming photon is increased within the active material. This is achieved by scattering the incoming light (photons) at the back surface of the active layer, giving rise to diffuse reflections and enhancing the optical path of the photon within the absorber layer.

Several solutions for achieving this back-surface scattering have been offered in the form of nanodomes [3, 4], blazedgratings [5], and incorporating plasmonic nanoparticles in the spacer layers [6–8]. Of the aforementioned solutions, the embedding of nanoparticles to achieve enhanced scattering has been the subject of greatest interest and debate. To begin with, they are easy to process, and offer significant increase on absorption with a minimal increase in volume.

However, plasmonic nanoparticles do offer advantages with one major drawback — they resonate only at specific frequencies dictated by the size and distribution of nanoparticles. A better solution would be one that has all the benefits offered by a plasmonic back-surface design, but without the frequency limitation. The plasmonic fishnet structure proposed by Ji and Varadan [9] offers precisely that. A metallic fishnet at the back spacer layer of a TFSC was predicted to cause an enhancement in the useful absorption within the active layer. It must be noted that the entire enhancement in absorption as a result of employing plasmonic structures does not necessarily translate to the generation of an EHP which will lead to subsequent increase in the current output from the cell. A large percentage of the absorbed energy is dissipated as loss in the nanoparticles.

It was demonstrated that for a plasmonic fishnet structure, the loss in the fishnet was negligible, and most of the scattered radiation was absorbed by the active region of the solar cell.

However, the fishnet TFSC was a theoretical concept. Despite its advantages, the major barrier standing in the way of this theory becoming a commercial solar cell was the fabrication process for the super fine metallic fishnet. The subject of this paper is the design of a reliable and repeatable process for the fabrication of a metallic fishnet, designed to resonate around a wavelength of 700 nm.

2. MATERIALS AND METHODS

Figure 1 shows a schematic that outlines the various steps required to fabricate a fishnet solar cell. The inset figure shows a schematic of the complete TFSC structure. The design of the fishnet corresponded to a plasmonic resonance at 700 nm, since the goal was to optimize the absorption in this wavelength range. This is because the absorption of a-Si, the material of choice for the active region of the cell, has very low absorption near this wavelength. The line width of the optimized fishnet was 100 nm, spaced 600 nm apart, and 20 nm thick.

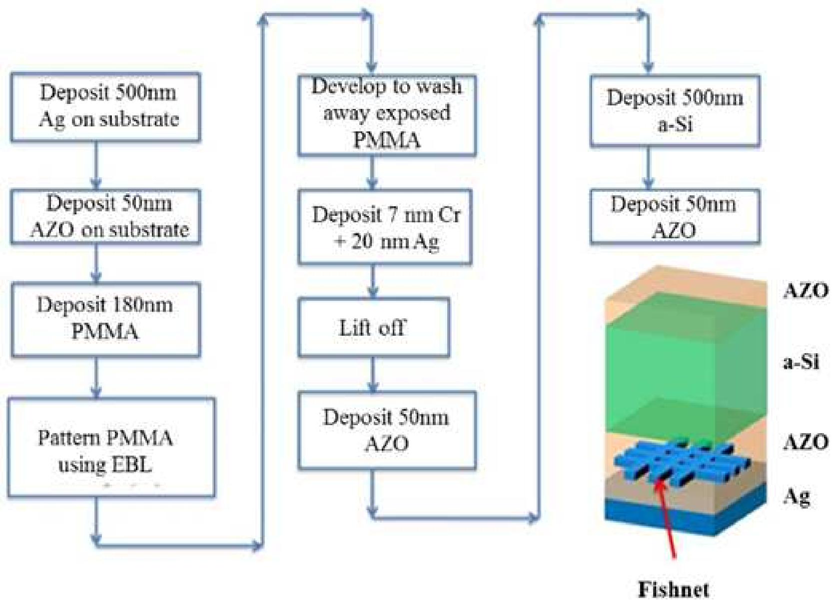


Figure 1: Schematic showing the fabrication process for the fishnet thin film solar cell.

The most involved step in the fabrication process is Electron Beam Lithography — the process that allows us to literally draw the fishnet pattern onto a substrate. The JBX 550ZD system from JEOL was used for this purpose.Obtaining a successful pattern is a combination of the resist thickness, electron dose and development time. Prior to lithography, the substrate was coated with an electron beam sensitive resist, Poly-Methyl-Methacrylate (PMMA). Ideally the resist layer should be made as thin as possible. This would allow us to use a smaller electron dose and enable us to write patterns with very small line widths, but thick enough so that the lift-off process would not be inhibited. After this step, the sample has to be dipped in acetone to dissolve the remaining PMMA, thus getting rid of the metal layer above the PMMA, as if we "lift off" the metal. The resist thickness was chosen to be around 180 nm for this design. The spin speed was chosen as 4000 rpm from the spin speed curves for 4% PMMA provided by MicroChem.

The thickness of the resist layer was measured to be around 180 nm averaged over ten measurements across randomly chosen points on the sample surface. Once the proper resist thickness was determined, the Electron Beam Lithography (EBL) process followed. The principle of EBL is in similar to photolithography in many respects. The surface of the substrate was spin coated with an electron sensitive resist. A controlled electron beam then engraved the pattern onto this resist. No mask was required like in photolithography.

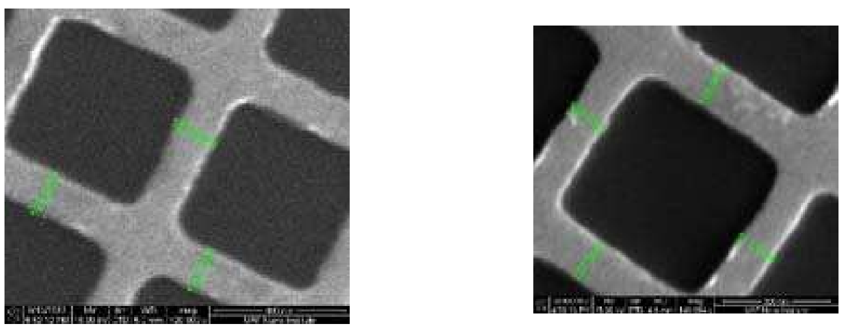
The number of electrons incident on the resist per square cm is defined as the dose. It is measured in $\mu C/cm^2$. This dose was optimized for this particular design. For the fishnet structure was varied from 500 $\mu C/cm^2$ to 800 $\mu C/cm^2$. The best results were obtained for a dose of 800 $\mu C/cm^2$. After the writing process was completed, the sample was developed using a solution of MIBK : IPA (1 : 3).

The final development time for a 1 mm × 1 mm fishnet pattern was 25 seconds. After development there was a fishnet shaped groove in the PMMA layer. The sample was washed using IPA for 30 seconds to remove any residual developer within the grooves and the sample was blown dry using nitrogen. Following this, the resist was baked at 100°C on a hot plate for 60 seconds. This rid the sample surface of moisture or organic residues, and made the PMMA columns structurally more rigid.

The next step was to evaporate metal onto the grooves to obtain a metallic fishnet structure on the substrate. The sample was loaded onto a thermal evaporator. According to design specifications, the thickness of the fishnet should be 20 nm, but it was found that thin films of silver had issues adhering to the AZO surface. So a 7 nm layer of chromium was used below the silver layer to promote adhesion. Once evaporation was completed a lift off had to be performed, followed by the deposition of the final layers of a-Si and AZO.

3. RESULTS AND DISCUSSIONS

The theoretically optimized design for the silver fishnet structure had a linewidth of 100 nm. Fig. 2 shows the result obtained in the first trial. A dose of 1000 μC/cm^2 was used initially and the fishnet was patterned on a 180 nm thick layer of resist. The development time was varied between 35 seconds and 30 seconds.



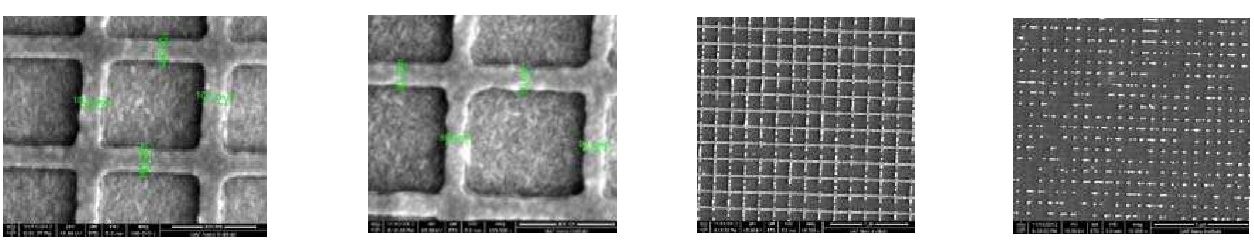
(a) (b)

Figure 2: Optimization of development time. (a) Development time = 35 seconds. (b) Development time = 30 seconds.

A development time of 35 seconds worked best giving a linewidth of 115 nm. However the linewidth was not uniform over the entire pattern and varied between 108 nm to 123 nm. 30 seconds gave narrower linewidths overall, but regions around the corners showed signs of underdevelopment. The linewidth obtained was still around 115 nm, but there was much more consistency in the linewidth than before.

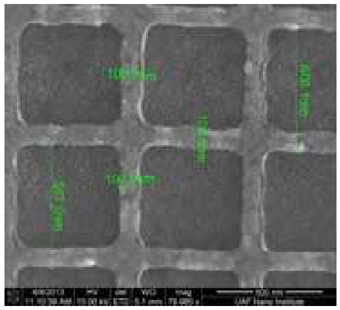
A dose optimization was performed next to get close toa 100 nm line width. Keeping the development time constant at 30 seconds, the dose was changed from 500 μC/cm^2 to 800 μC/cm^2 in steps of 100 μC/cm^2. From the results [Fig. 3], it can be observed that a dose of 800 μC/cm^2 gave an average linewidth of about 105 nm. Using a dose smaller than this resulted in underexposure.

It was expected that using a marginally shorter development time could give us a perfect 100 nm linewidth. The best results were obtained using a development time of 25 seconds [Fig. 4]. The

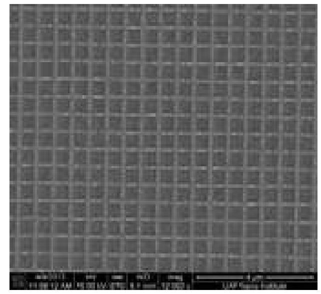


(a) (b) (c) (d)

Figure 3: Final dose optimization step at: (a) Dose = 800 μC/cm^2; (b) Dose = 700 μC/cm^2; (c) Dose = 600 μC/cm^2; (d) Dose = 500 μC/cm^2.



(a)



(b)

Figure 4: 100 nm linewidth pattern using a dose of 800 μC/cm^2, design linewidth of 85 nm, and develop time of 25 seconds. (a) Linewidth = 100 nm. (b) Pattern uniform over whole area.

linewidth was found to be uniformly 100 nm at the center of the pattern as well as the corners, with proper lift off across the entire patterned area. Also a consistent pitch size of 598 nm was obtained.

The above recipe was repeated on at least eight fishnets to make sure that a repeatable and reliable fabrication process was developed. The SEM showed the same 100 nm linewidth for all samples that were fabricated using the above recipe. Following the fabrication of the fishnet, the rest of the steps in Fig. 1 had to be completed to obtain a complete thin film solar cell structure. 50 nm of AZO was deposited using DC sputtering, followed by 500 nm a-Si using PECVD. The 50 nm AZO front spacer was deposited using DC sputtering as well. Thus the fabricated structure optically resembled a thin film solar cell in all respects. Fig. 5 shows that the absorption increased by a factor of 12.8× at the design wavelength of 700 nm as a result of including the fishnet.

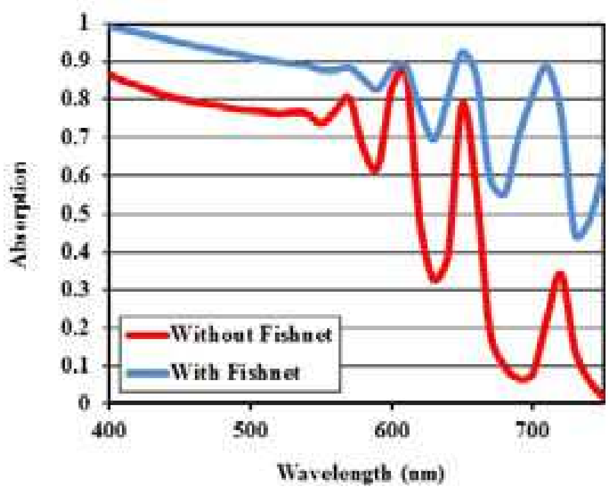


Figure 5: Experimental results showing a 12.8× enhancement in the absorption.

4. CONCLUSIONS

A reliable and repeatable process for the fabrication of a fishnet TFSC was established. The process allows for a clean pattern, tailored to meet the specifications of the solar cell. The key to the sucesful fabrication of this structure involved an appropriate combination of resist thickness, exposure dose, and development time. Measurements taken on the fabricated cell showed a 12.8× increase in the absorption of the solar cell, which predicted a 30% increase in the J_{SC}.

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