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A Thin Silicon Solar Cell on Glass: Cell Design and Process Physics

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ABSTRACT

We describe a new design for a low-cost thin-film solar cell on a glass substrate. The structure of the cell is discussed in detail. Several verified steps in the fabrication of this cell are also presented.

INTRODUCTION

A solar cell based on a thin film of Si (TF-Si) on a low-cost substrate offers a promise of significantly lowering photovoltaic energy costs. This potential comes from several features of a thin Si cell, including: (i) relaxed material quality of the Si film needed to make a high-efficiency device comparable to a wafer-based cell, (ii) reduced amount of Si in the cell, and (iii) thin-film processing, which is conducive to lower cost technologies. The main advantage of the TF-Si solar cell emerges from its reduced volume recombination of the minority carriers. However, such a cell also poses many challenges involving both device design and fabrication. The challenge in the device design is to devise a cell structure that can enhance the optical absorption within a thin (an indirect-bandgap semiconductor) Si film, while maintaining a low-cost fabrication potential. The challenge in the cell fabrication is to deposit a thin Si film of a reasonable material quality on a low-cost substrate, and carry out cell fabrication in a manner compatible with the film-substrate combination. Typical problems arise from thermal mismatch between Si and substrate, impurity in-diffusion from the substrate to the Si film, and minimizing the process costs. Finally, because it is important to ensure that the cell design and fabrication are intimately connected, a TF Si cell requires many new features and fabrication processes.

This paper is a review of our design and processing approaches to a thin film Si solar cell proposed earlier (1). We first describe this new cell structure for a single-junction thin film Si cell, and show a rigorous theoretical design that can attain an efficiency, as high as 18%.

DESIGN OF THIN-FILM SOLAR CELL

Optical considerations

Because Si is an indirect-bandgap semiconductor, its optical absorption near the band edge is quite weak. Thus, in order to absorb a major portion of the solar spectrum (useable by the bandgap of Si), the semiconductor thickness must be quite large—leading to a conventional wafer-based cell approach. As expected, a decrease in the cell thickness is accompanied by a reduced photon-absorption loss. However, there are other somewhat unknown losses that can occur in a thin cell structure. One of these is the photon absorption caused by metal contacts. To illustrate this, Figure 1 shows the dependence of the maximum achievable current density (MACD) of a planar, single-junction solar cell with a reflecting-Al back contact on the cell thickness. The structure of the cell is illustrated in the inset in Figure 1. Also shown in Figure 1 is the calculated Metal Loss (in mA/cm^2) as a function of thickness. It should be pointed out that the cell does not have an antireflection (AR) coating.

Several conclusions can be drawn from this figure:

1. The MACD decreases with a decrease in the cell thickness; however, there is a sharp drop when the thickness of the cell is below 20 µm. This thickness can be used as a dividing point between thick and thin cells. For thin cells, light-trapping features must be included in the design to get satisfactory MACD.
2. The metal loss increases with a decrease in the cell thickness, particularly for thin cells. As seen from the figure, the metal loss for thick, wafer-based cells is typically less than 0.5 mA/cm^2. This is why this loss is often ignored and is not well known. However, as the cell thickness decreases below 10 µm, this loss can exceed 15% of the MACD, and must be taken into account. Thus, minimization of the metal loss is an important issue in the design of a thin-film solar cell.

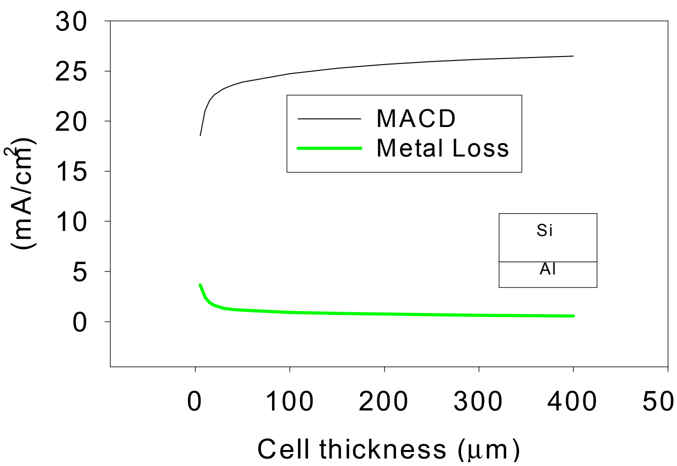


Figure 1. The calculated MACD and Metal Loss as the functions of cell thickness for a planar cell without AR coating. Calculations are done with *PV Optics* (2).

A conventional approach for incorporating light trapping is to include texturing at one or more interfaces of the cell. This procedure is used both in wafer-based, crystalline-Si and in thin a-Si cells, and can also be pertinent to TF-Si. The major remaining issues are identifying which interface(s) should be textured and what shape is optimum for the texture. Here we will only illustrate the effect of texturing different interfaces of a single-junction cell on the light-trapping ability. We have used *PV Optics* to calculate the MACD of a single-junction cell structure with an Al back contact under different surface/interface conditions. Figure 2 shows the calculated spectra of a cell for four different interface configurations: planar, front texture/back planar (FTBP), front planar/back textured (FPBT), and both front and back interfaces textured (FTBT). These figures show reflectance, absorbance in Si and metal absorbance for the four different cases. The MACD and Metal Loss under different configuration are also marked in these figures. The thickness of the cell, considered in the calculation, is 10 microns, and the back contact metal is Al. An optimized AR coating consisting of 710 Å of material with refractive index n=1.95 on 100 Å of SiO_2, is used. The texture height is 1 µm. From this figure it can be seen that a texture either on the front, the back, or both sides of the cell,

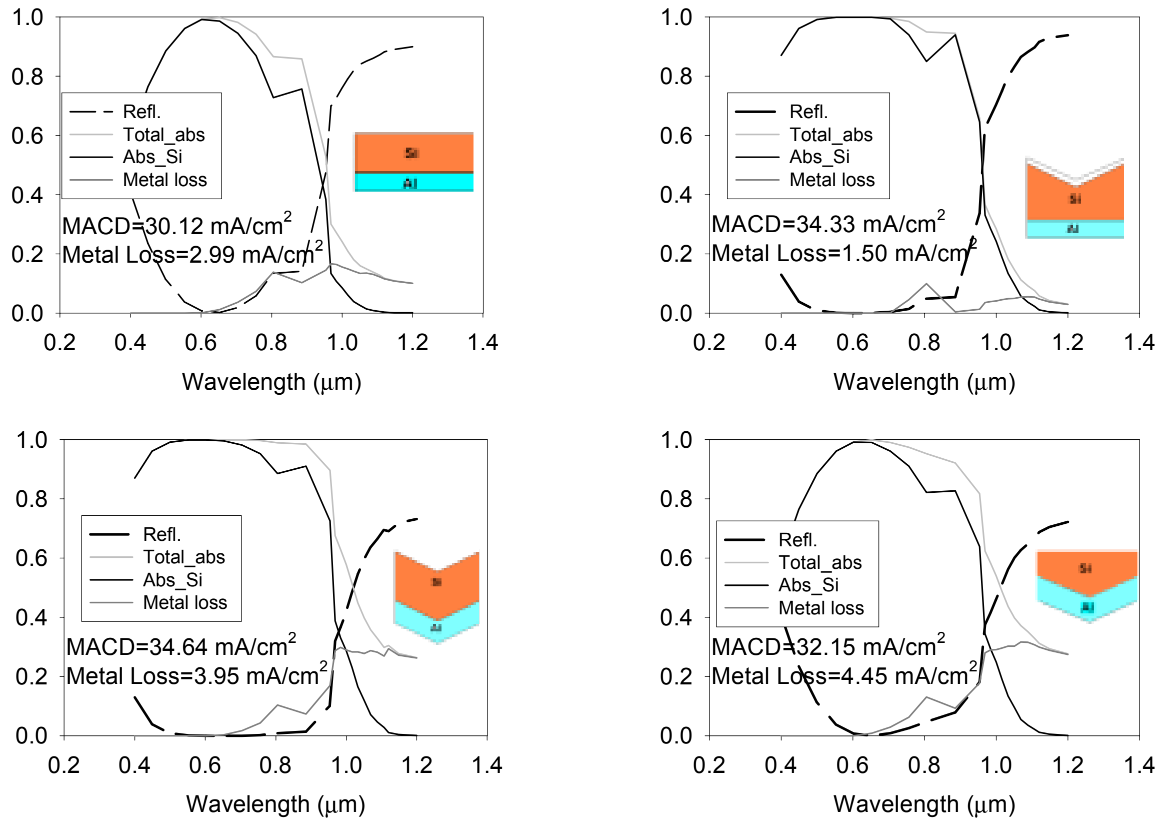


Figure 2. Calculated optical properties, MACD, and Metal Loss of an AR coated, 10-µm-thick single junction cell at different surface configurations. Calculations are done with *PV Optics* (2).

will give higher MACD than a planar cell, in spite of the fact that in some cases the metal loss may be higher.

Another point seen from Figure 2 is that the MACD will be higher for a front side textured cell than the back textured/front planar cell, while the double-side-textured cell will give the highest MACD. This conclusion suggests that double side textured or front side textured structure should be used in the design of a TF-Si solar cell.

Using the above results as a guide, we can now briefly describe our cell design. Figure 3 shows the structure of our proposed cell. It consists of a p-type Si film, about 10 µm thick, deposited on a metal-coated glass substrate. An n-type junction can be made by any conventional method, followed by an AR coating and front metallization. As illustrated in the figure, the cell has texture on both the back (Si-metal) interface and the front surface. Some other important features of the cell are:

1. The thickness of the Si film is about 10 µm, with a preferred grain size in the range of 10–50 µm.

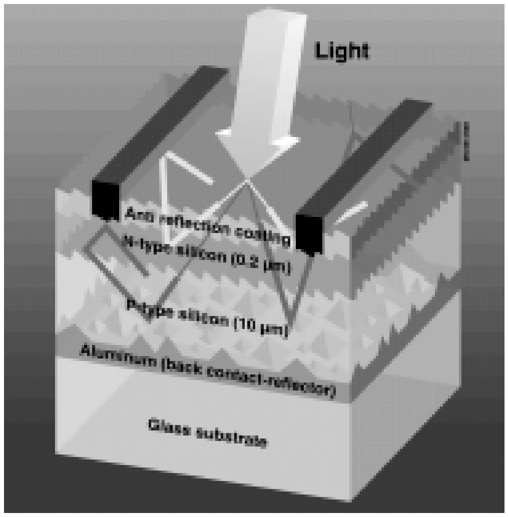


Figure 3. The design of NREL Si thin film cell.

2. Double side textured with AR coating on the front side. The texture height is around 1 µm.

3. The substrate material is low-cost glass, which is isolated by a metal layer from the Si layer. The back metal (at the Si-glass interface) has multiple functions—it serves as an optically reflecting back electrode, a gettering medium, and an interface layer to relieve the stress resulting from thermal mismatch between glass and Si.

As identified earlier in the paper, it is necessary to ensure that the effect of metal absorption is minimized. To accomplish this, we have done a series of calculations to determine MACD of a single-junction cell, for different interface configurations. Figures 4 and 5 show the calculated MACD and Metal Loss as a function of the cell thickness for the following interface configurations—FTBP, FTBT, and FPBT. We have assumed a texture height of 1 µm and an optimized AR coating. Several data points from Keneka's experimental result (3) are also shown in the figure. The calculated results match the experimental data very well, indicating the accuracy of our calculations.

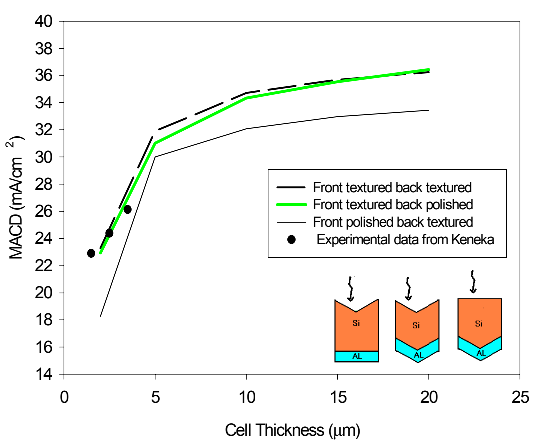


Figure 4. Calculated MACD as functions of the cell thickness under different surface configurations. Calculations are done by using *PV Optics* (2).

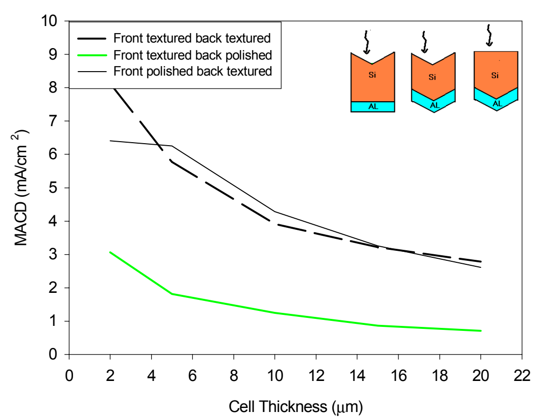


Figure 5. Calculated Metal Loss as functions of the cell thickness under different surface configurations. Calculations are done by using *PV Optics* (2).

As we have pointed out, the MACD of FTBP and FTBT cells are much higher than that of FPBT cells, although the metal loss of FTBT cells does not differ much from that of the FPBT cells. It can be seen in Figure 4 that when the cell thickness increases beyond 15 μm, the increase in MACD is quite small. So, from the view of optical design, the thickness of the thin-film solar cells should be around 10–20 μm to get the most benefit.

Materials considerations

To minimize the overall cell cost, the TF-Si solar cells are expected to be based on poly-crystalline Si deposited on low-cost substrates (for example, glass). Even though a TF-Si cell can perform better than wafer-based cells with similar materials quality, some challenges still need to be overcome to reach this goal. These challenges result from:

1. The low-cost glass is not thermally matched with Si. Hence, it is important to employ low-temperature processing, both in the deposition of Si film and in its subsequent cell processing. A low-temperature process can also reduce the release of impurities from the substrate during the Si deposition. However, in most cases, the low-temperature deposition does not yield desired properties of the Si film.

2. The deposition of Si at low temperatures results in a very small grain size that will significantly lower the effective lifetime of the minority carriers. In addition, they can lower the V_{oc} and the FF of the cell. To get cells with acceptable qualities, the grain size of the film cannot be too small, and the impurity density should be fairly low.

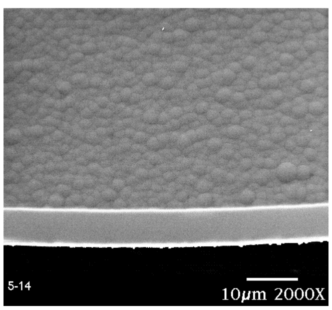
PROPOSED TECHNIQUES FOR CELL FABRICATION

We have developed some of the main process steps required by the design indicated above. The most critical aspect of the processing is to attain a large-grain thin Si film on a glass substrate. We have been able to obtain large-grain films using the following procedure: the glass substrate is coated with a thin layer of Al/Cr, followed by deposition of the Si film. The Si film can be deposited by a number of techniques that include plasma CVD, thermal CVD, and spraying methods. Our approach for producing such a film is to use an a-Si deposition and rely on conversion of a-Si into microcrystalline Si by the presence of the existing metal. It is important to recognize that in this approach the deposition rate of a-Si can be high. Unlike a-Si cells, where the electronic quality of a-Si deteriorates with an increase in the deposition rate, here the a-Si is only a precursor for poly Si. One of the considerations in the deposition is the substrate temperature. It is clear that the deposition temperature should be low – to prevent softening of glass and interaction of metal with Si. We have observed that as long as the substrate temperature is below 300 ºC, one can get excellent metal-induced crystallization (4) and confine metal to the Si-metal interface. Typically, the grain size of the Si film produced by this process is about 0.1 μm; this limitation is primarily because of the need to maintain a low deposition temperature. Our calculations show that this grain size is too small for a high efficiency cell; hence, a second process step is required to enhance the grain size.

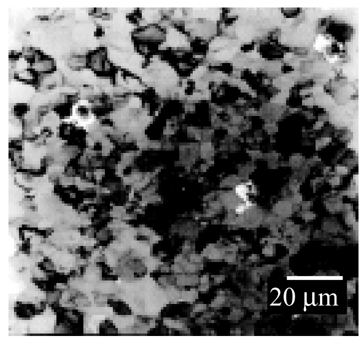
Al plays an important role in our cell design and processing. It is involved in several major reactions including the formation of the textured Si-Al interface, grain enhancement, and impurity gettering. The details of the processing have been described elsewhere (5). In this paper, some results after processing will be presented.

Grain enhancement

Although grain size of the deposited film can be enlarged by thermal annealing, it requires temperatures and times that are not compatible with the above cell structure. However, we have shown that point-defect injection can be used to lower the temperature at which copious grain growth can occur. In particular, optical processing can be used to inject vacancies from a Si-Al interface that can lead to grain enhancement at temperatures near 550ºC. Figure 6 shows the TEM/SEM pictures of several processed samples. The grain size grows to several microns after processing. The mechanisms involved in this grain-growth process are discussed in other paper (6).



(a)



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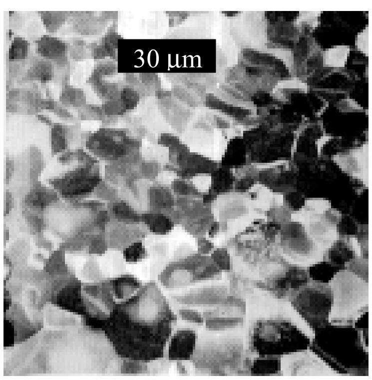

(c)

Figure 6. Photographs showing the grain size of thin Si films after the optical processing: (a) SEM photo showing the surface morphology, (b) and (c) TEM photos showing large grain sizes for longer process times.

Formation of the textured interface

It has been shown that the orientation dependence of the diffusion coefficient of Si in Al will lead to the formation of pyramid-shaped pits in Si, creating a textured Si-Al interface. Figure 7 shows a photograph of such a texture produced by optically processing a Si/Al interface. It can be seen that the density of the pits is fairly high, and the bottoms of these pits are very smooth, which results in a high reflectivity of this surface. In the case of a polycrystalline film, each grain orientation will have a different texture shape.

Figure 7. The morphology of the Si/Al interface after processing showing formation of texture

Al-related gettering

Al gettering is a very effective method for removing dissolved metal impurities that degrade the minority-carrier lifetime in Si. We have been able perform gettering at very low temperatures using optical processing. Figures 8a and 8b show the lifetime maps of a Si wafer before and after optical processing; the processing temperature was below 550ºC. The improvement in the lifetime is clearly observed. A similar gettering effect is expected to take place during the fabrication of our cell.

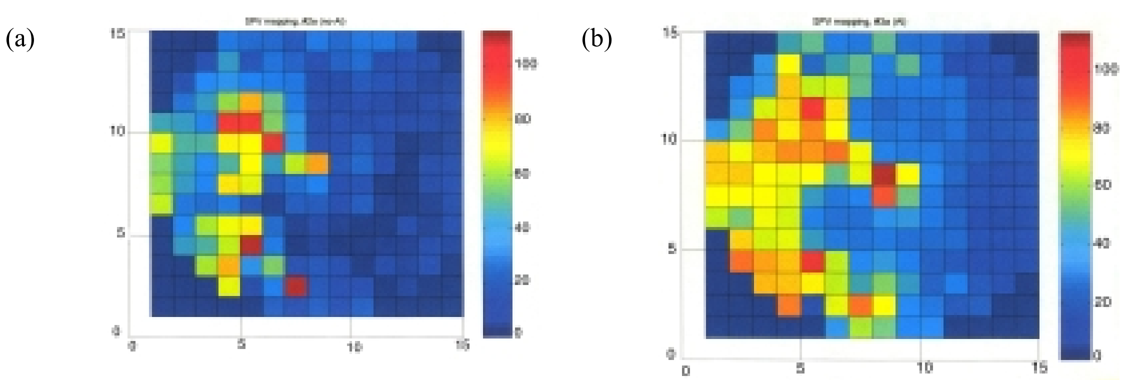

Figure 8. SPV lifetime map of a Si wafer before and after vacancy-injection gettering.

CONCLUSIONS

We discussed, in some detail, the requirements of a high efficiency, TF-Si cell. These criteria have been used to design a new cell structure, which was briefly described. Theoretical calculations were performed to arrive at the optimum parameters of the cell. Some unconventional processing techniques are needed to fabricate such a device. In particular, low temperature processing must be used to obtain Si films with grain size of about 20 µm. One possible process is presented.

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