Plasma texturing and porous Si mirrors boost thin-film Si solar efficiency

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ABSTRACT

Thin-film silicon solar cells are a potentially low-cost alternative to solar cells based on bulk silicon that are commonly used in the industry at the present time. However, a major drawback of the current epitaxial semi-industrial screen-printed cells is that they only achieve an efficiency of about 11-12%. By upgrading their efficiency, this kind of solar cell would become more attractive to the photovoltaic industry. The optimization of the front surface texture by dry texturing based on a fluorine plasma and the introduction of an intermediate porous silicon reflector at the epi/substrate interface (multiple Bragg reflector) has proven to result in an efficiency boost up to about 14%.

Introduction

Epitaxial thin-film silicon solar cells are cheaper compared to solar cells based on bulk silicon. However, the main drawback of the current epitaxial thin-film solar cells is their relatively low efficiency. Two techniques have been proven to upgrade the efficiency of this type of solar cell: the optimization of the front surface texture by plasma texturing based on halogen atoms, and the introduction of an intermediate reflector at the epi/substrate interface. The optimized front surface texture combines the requirements of uniform light diffusion (Lambertian refraction) and reduced reflection with very limited removal of silicon (since the epitaxial silicon layer is already quite thin). The introduction of the intermediate reflector (multiple Bragg reflector) prolongs the path length of the low energy photons by a factor of at least 7, ultimately boosting the efficiency of the solar cells.

Epitaxial thin-film solar cells

Silicon solar cells based on mono- or multicrystalline bulk silicon substrates dominate the photovoltaic market. However, being made entirely of high purity silicon, the production of this type of solar cell is very energy consuming and relatively expensive. To further promote the photovoltaic industry, the production cost of solar cells should drastically decrease by reducing the material cost.

Epitaxial thin-film silicon solar cells have the potential to be a low-cost alternative to bulk silicon solar cells. These screen-printed solar cells use a cheaper substrate and a thinner active silicon layer (20µm) compared to the current bulk silicon solar cells (200µm). The low-cost substrate consists of highly doped crystalline silicon wafers (impure silicon from metallurgical grade silicon or from scrap material) [1]. On this substrate, a thin epitaxial active silicon layer is deposited using the CVD process.

The production process of epitaxial thin-film silicon solar cells is very similar to that of conventional bulk silicon solar cells. Therefore, compared to any other thin-film technology, it will be relatively easy to implement it in the existing production lines. However, a major drawback for the industrial competitiveness of epitaxial thin-film silicon solar cells is their moderate efficiency compared to conventional bulk silicon solar cells. The open-circuit voltage and fill factor of these cells can reach similar values as bulk silicon solar cells but, due to the optically thin active layer (20µm compared to 200µm), light is lost in the low-quality substrate from the moment it is transmitted from the epi layer into the substrate, resulting in a loss of short-circuit current, which can amount to as much as 7mA/cm^2.

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This paper describes two developments that increase the optical path length and consequently positively influence the efficiency of epitaxial thin-film silicon solar cells: plasma texturing and the insertion of a porous silicon mirror at the interface between the low-cost silicon substrate and the active layer. It has been shown that these adaptations raise the efficiency of the epitaxial thin-film silicon solar cell to almost 14%.

Efficiency improvement by plasma texturing

By texturing the front surface of the active layer of a solar cell, surface light scattering changes, thereby influencing the performance of the solar cell. The purpose is to make an optimal front surface that is 100% diffusive (Lambertian Refraction, exhibiting complete scattering). In such a case, photons would move through the active layer at an average angle of 60˚, resulting in an increase in pathlength by a factor of 2. In other words, an active layer of only 20µm would then optically behave as if it were 40µm thick.

Using plasma texturing based on fluorine, the optimal surface front end, exhibiting Lambertian Refraction, can be reached with only a very limited removal of silicon (only 1.75µm). This is very important in epitaxial thin-film silicon solar cells, as the active layer in this type of solar cells is already quite thin (20µm). Apart from the efficiency improvement due to optimized scattering, plasma texturing also lowers the reflection, achieves oblique light coupling and lowers contact resistance. This results in an additional improvement of the short-circuit current with 1.0 to 1.5 mA/cm^2 and an extra efficiency improvement of 0.5 to 1.0%.

Efficiency improvement by introducing porous silicon mirrors

A further adaptation that improves the efficiency of epitaxial thin-film silicon solar cells is the incorporation of a porous silicon mirror at the interface between the active layer and the low-cost substrate. This mirror decreases the transmittance of long wavelength light into the substrate.

In practice, the reflector is made by electrochemical growth of a porous silicon stack of alternating high- and low-porosity layers (a multiple Bragg reflector), defined by the quarter

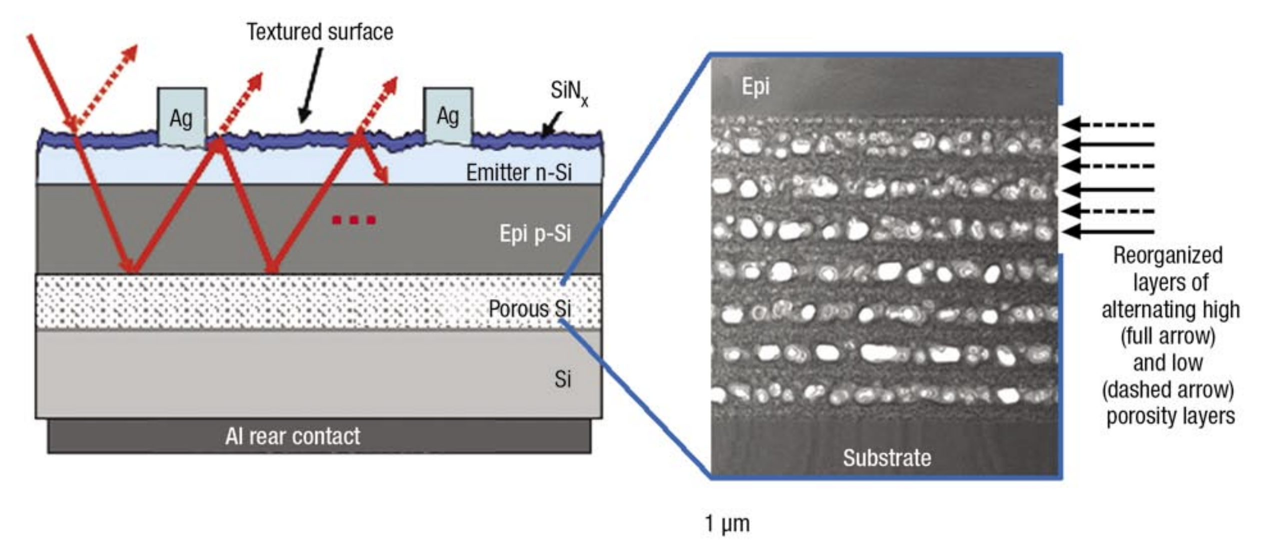

Figure 1. Porous silicon reflector – shows (left) an advanced epitaxial cell layout illustrating the concept of an intermediate reflector; (right) Transmission Electron Microscopy (TEM) picture of a reorganized porous silicon stack.

wavelength rule. During epitaxial growth of the active layer, the porous Si in the stack reorganizes into layers with small and large voids, but retains its original layout. This structure is a proven effective reflector. The mirror reflects the photons that reach the interface, either by the Bragg effect (for normal incidence on the mirror) or by total internal reflection (for light impinging obliquely onto the mirror at angles above the critical angle). As a result, they can pass a second time through the active layer. The reflected photons that reach the front surface of the active layer outside the escape angle – a large part of them, due to the diffusion of the light – will again be reflected. The introduction of the porous mirror will therefore cause multiple photon reflection. Consequently, the optical path length is enhanced, resulting in an increased efficiency of the solar cell. It was shown that, with a perfect Lambertian surface at the front end, a 15-layer porous silicon mirror resulted in a path-length enhancement of 14, meaning that an epitaxial thin-film silicon solar cell with a 15µm active layer would behave like a 210µm-thick bulk silicon solar cell [2].

The introduction of the porous silicon mirror resulted in an internal reflectance of 80-84%, of which 25% could be attributed to the Bragg effect itself (see Figure 2) [3]. The effect could even be improved by using an optimized reflector design in which the thicknesses of the low- and high-porosity layers vary with the depth (chirped porous silicon stacks), resulting in a substantial bandwidth enlargement of the reflector. With this chirped specialized structure, the path length enhancement of low energy photons could be increased much above the current value of 7 (with the effect of the reflector alone. Combined with a perfectly light diffusing top surface, it increases to above 14). Solar cells prepared on low-cost Si substrate with this reflector and screen-printed contacts reached an excellent efficiency of 13.9% and a J_{sc} of 29.6mA/cm² [4].

Conclusions

Both plasma texturing and the introduction of a porous silicon mirror at the interface between the epitaxial layer and the substrate have been shown to improve the efficiency of epitaxial thin-film silicon solar cells and pave the way

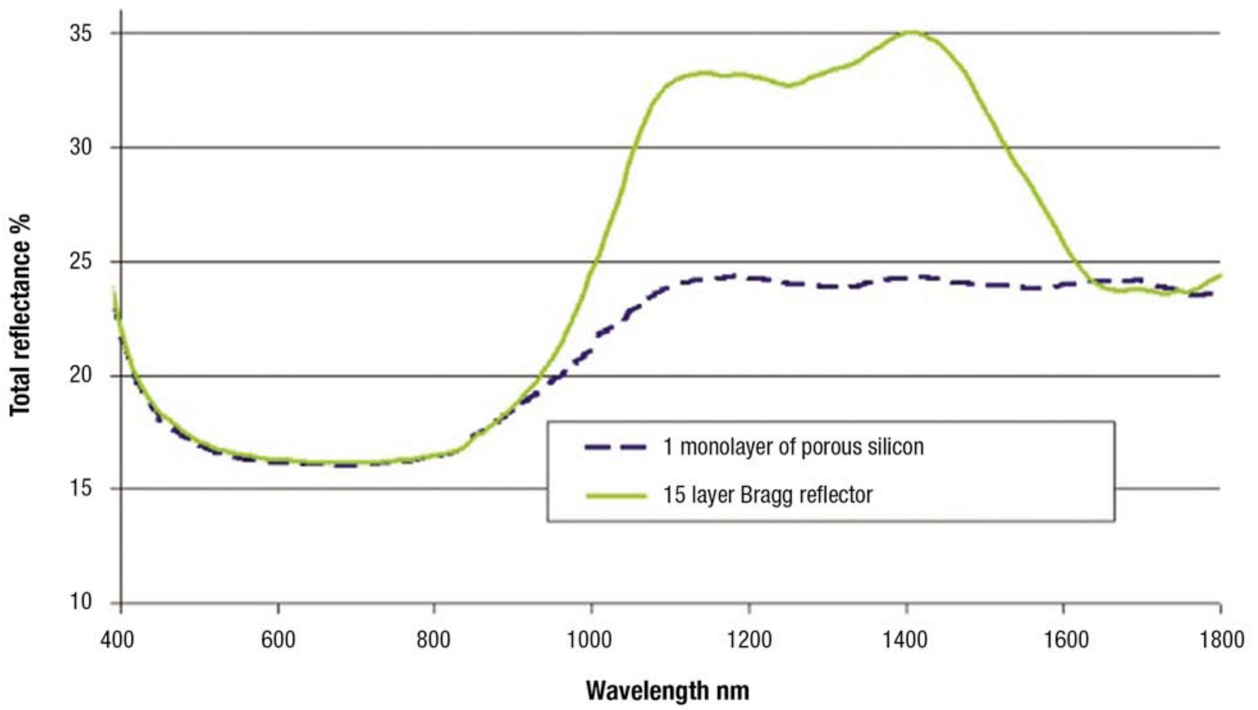

Figure 2. Reflectance comparison between 15-layer porous Bragg reflector and porous monolayer.

to low-cost industrial production of this type of solar cells as an alternative to bulk silicon solar cells.

Acknowledgements

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