ABSTRACT

There is a growing demand to improve solar-cell efficiency. Among several methods under investigation, surface texturization is an important alternative. This paper presents an alternative texturization of crystalline silicon to improve solar-cell efficiency. The method is based on anisotropic etching of bulk silicon and requires only a single exposure mask and two etching steps with a KOH aqueous solution. The surface texture consists of smooth hemispherical cavities that have their parameters accurately controlled. There is no need for a lithographic mask or intricate technology processes to obtain the hemispherical cavities. By this method, it is possible to increase both the frontal surface exposed to light and the depletion region. That implies in a higher probability of photon collection, contributing to the improvement of the conversion efficiency of the device. The textured silicon solar-cell transmittance under small incident angles during the day is improved compared to a flat surface, increasing the generated photocurrent.

INTRODUCTION

Texturization is usually employed in order to increase the solar-cell surface area (1, 2). A particular method, based on inverted pyramids, is meant to reduce reflection losses at a solar cell surface by promoting light trapping upon multiple reflections. The overall efficiency of a solar cell also depends on: composition of the semiconductor, metallic contacts, presence and properties of anti-reflection coatings, and type and architecture of the cell layers. Silicon is predominantly used for the manufacture of solar cells because it is abundant in nature, processing technologies are mature and its energy bandgap and sensitivity are compatible with the solar spectrum. Despite the abundance of silicon, current statistics point at a 5.6M-ton deficit in 2010 (3). Nowadays, the world production of solar cells is concentrated in polycrystalline (c-Si poly) and monocrystalline silicon (c-Si mono). The production of amorphous silicon (a-Si) solar cell is increasing moderately. In 2004, 54.7% of the world production represents polycrystalline, 36.2% represents monocrystalline silicon and 4.4% represents the production of amorphous silicon (a-Si) solar cell (4).

In this paper we use a rather straightforward and inexpensive method to texturize the silicon surface in order to improve the optical transmittance, especially at low sun-elevation angles. The method gradually transforms an inverted pyramid into a...
hemispherical cavity by means of a single-step anisotropic etching with a KOH aqueous solution (5). Starting from an array of inverted pyramids we are able to texture the cell with a contiguous arrays of truncated hemispherical cavities, yielding a 100% fill factor. Doping the textured surface, either by diffusion or by ion implantation, results in a ‘wavy’ emitter-substrate junction profile and that consequently enhances the depletion volume. It is possible to increase both the frontal surface exposed to light and the depletion region. That implies in a higher probability of photon collection. This can be alternatively accomplished by depositing a doped emitter thin film on the processed surface. The textured surface also serves as perfect molding for microlens concentrators (6). We report on the influence of the proposed texturization on the transmittance at the air-silicon interface, representing the portion of the solar radiation effectively penetrating the cell bulk.

TECHNOLOGY FOR HEMISPHERICAL TEXTURIZATION

The method used to develop the array of smooth hemispherical depressions on the silicon surface is based on bulk micromachining with an anisotropic etchant. The process only requires a single exposure mask and two etching steps in a KOH:H₂O solution. The use of a lithographic mask as the exposure mask is not strictly necessary. Instead, high-quality laser-printed transparencies can be used in order to reduce costs. The texturization method is based on a modestly known subtlety of bulk etching: a <111> pyramidal pit formed by a KOH anisotropic attack through an oxide mask eventually evolves into a smooth hemispherical cavity under subsequent etching. A short intermediate stage exists when a 19.47° <411>-faced pyramid replaces the initial 54.74° inverted pyramid. The distance from base to vertex of the <411>-faced pyramid determines the depth of the spherical cavity. The complete replacement of the <111> walls occurs at a frontal wafer thinning  \( h_{\text{off}} \) of approximately 1/3 of the <111> initial pit base (\( d_0/3 \)). Figure 1 shows the evolution of the etching process, whereas Figure 2 indicates some useful parameters.

![Figure 1](image.png)

Figure 1 – Evolution of an inverted pyramid into a hemispherical depression

The diameter \( D \) of the hemispherical depression is determined by the initial opening on the oxide mask \( d_0 \) and by the etch depth \( h \), whereas its depth \( s \) is determined by \( d_0 \) and the etching conditions. The empirical expression for the cavity diameter is \( D = 7.8 \ d_0^{0.42} \ h^{0.58} \), and it is valid for etch depths in excess of 2.5\( d_0 \) (6). The cavity
depth, also called sagitta, is \( s = \alpha d_s \), where \( \alpha \) is a process parameter that depends on the KOH concentration in the solution and on the temperature. The minimum initial opening is limited by the resolution of the exposure mask. Lithographic masks or e-beam direct writing can define sub-micrometric openings, whereas transparencies patterned with a high-definition printer define openings that are several microns large.

![Diagram](image)

**Figure 2 – Parameters related to the etching process**

TRANSMITTANCE ANALYSIS

Solar radiation that strikes a ground-level surface can be composed of three components: direct, diffuse and albedo radiation (7). Only the first is taken into account in our analysis, which aims at the comparison between a surface textured with hemispherical cavities and a flat surface. Albedo radiation is mostly considered in tilted panels; diffuse radiation can be as high as 15% of the impinging radiation, but due to its spatially random nature, it has been assumed to have equal contributions to transmittance on both surfaces considered here.

As regards shading, an orthogonal hemispherical cavity array is prone to maximum shading at a critical angle \( \gamma_c \), which depends on the process parameters as follows:

\[
\gamma_c = \tan^{-1}\left( \frac{D}{2s} \right) \tag{1}
\]

Or

\[
\gamma_c = \tan^{-1}\left[ 3.9 \left( \frac{h}{\alpha \left( \frac{d_s}{\alpha} \right)^{0.58}} \right) \right] \tag{2}
\]

Figure 3 illustrates the relationship between these angles and a single cavity.
Figure 3 – (a) Elevation angle and cell parameters for a single cavity, (b) orthogonal array and a single truncated spherical cavity.

A conventional pyramidal pit configuration yields a critical angle $\gamma_c = 54.74^\circ$, whereas our approach results in critical angles from $2^\circ$ to $3^\circ$, as the ratio $h/d_0$ decreases from 5 to 2.5, as Figure 4 shows. Besides, maximum shading is only significant when the sun trajectory is at $45^\circ$ with the matrix orientation, for which each intersection peak casts a shadow towards the center of its respective cavity.

Figure 4 – Critical sun-elevation angle versus process ratio $h/d_0$.

The surface area of a truncated spherical cavity area is given by Equation [3].

$$S_{cav} = 2R \left[ -2R \cdot \arctg \left( \frac{P_{max}^2}{4R \sqrt{\frac{P_{max}^2}{2} + R^2}} \right) + 2P_{max} \cdot \arctg \left( \frac{P_{max}}{2 \sqrt{\frac{P_{max}^2}{2} + R^2}} \right) \right], \quad [3]$$
where $R = \frac{D^2}{8s}$ and $P_{\text{max}}$ is the maximum pitch between two cavity centers that still guarantees 100% structural fill-factor. For an orthogonal array this parameter assumes a value $P_{\text{max}} = \frac{D}{\sqrt{2}}$. Parameters $R$ and $P_{\text{max}}$, ruling the cavity area, are dependent on design and process parameters $d_0$ and $h$. We have found that the area increases as the ratio $h/d_0$ decreases, resulting in an area gain of 0.35% with respect to a plane surface when $h/d_0=2.5$.

Next we developed an algorithm to contrast the transmittance at the air-silicon interface of a flat cell to that of a hemispherically textured cell. Sun rays sweep the cells from 0 to 180° and the program outputs the total normalized transmittance over the cell area. Figure 5 shows the graphs for the two cases, where the textured surface has been obtained with the ratio $h/d_0=2.5$ and $d_0=40\mu\text{m}$.

![Graph 1](image1.png)

Figure 5 – (a) Transmittance as a function of elevation angle $\gamma$ for flat and textured cells; (b) difference in transmittance.
These results show that a textured cell exhibits considerable transmittance gain for elevation angles up to 30°. Using a textured cell, the transmittance can be more than 30% higher for dawn and dusk hours. Additionally we found out that the smaller $h/d_0$ and the larger the initial opening in the exposure mask $d_0$, the larger the transmittance. Maximum $d_0$ is dictated chiefly by the wafer thickness and the thinning $h=2.5d_0$, which cares for the hemispherical shape. In practice this value will range from 30µm to 160µm depending also on the back-end mechanical stability of the substrate. This range discards the need for high-resolution lithographic masks and for 100cm$^2$ the cost of a custom mask could be reduced from US$300 to about US$10. (A custom mask can be used for multiple exposures on a larger surface).

To evaluate the usefulness of a textured cell compared to a flat cell, we calculated the total number of photons effectively penetrating each cell per day taking into account the previously calculated transmittance. We made a couple of simplifying assumptions with no detriment to our comparative analysis: characteristics of both cells are exactly the same, except for the frontal surface texturization; albedo and diffuse radiation are null; cells are at sea-level and not tilted; average wavelength $\lambda = 650\, \text{nm}$, taken as the center of gravity of the solar spectral distribution (ASTM–G173-03) from 280 to 1100nm (silicon cut-off wavelength); sun is up 10h per day.

Figure 6 presents the gain in number of photons as a function of $h/d_0$ for the previous conditions. We observe that the lower $h/d_0$, the larger the gain. For $h/d_0=2.5$, the gain is higher than 2%. Considering that a flat silicon surface absorbs an irradiation of $\sim 900\, \text{kWh/m}^2$ over a year (8), due to direct incidence at a location prone to medium irradiation, then a textured cell could offer additional $18\, \text{kWh/m}^2$ absorption. This figure can range from $12\, \text{kWh/m}^2$ to as high as $25\, \text{kWh/m}^2$ for regions subjected to low and high irradiation levels, respectively.

![Figure 6](image_url)

Figure 6 – Gain in the number of absorbed photons for a textured solar cell compared to a flat one.
The process parameter $h/d_0$ plays an important role in the design of an optimal hemispherical texture for the frontal surface of a solar cell. Although the critical shading angle increases for the $h/d_0$ as small as possible, the area gain and transmittance gain are the largest for $h/d_0=2.5$. Also, the larger the mask opening feature is, the largest the transmittance for low elevation angles. This favors the employment of low-cost printing of exposure masks for the texturization patterning, as opposed to high-definition lithographic mask used in conventional texturization with inverted pyramidal pits.

CONCLUSIONS

We presented a method for the texturization of the frontal surface of silicon solar-cell with contiguous hemispherical cavities. The openings on the exposure mask and the extent to which the wafer is thinned define the area gain and transmittance gain in comparison to a flat cell surface. For optimal design with the process proposed, no lithographic mask is necessary. A textured surface improves the total number of absorbed photons per day in 2%. A detailed study to evaluate the energy balance between energy generation and fabrication is yet to be done. Our preliminary calculations indicate we might gain up to 25kWh/m$^2$ per year when we replace a flat surface with a textured surface featuring optimal hemispherical-cavity design.

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