Anti-Glare Coatings Based on Porous Silicon Structures

I. A. Iwe, E. A. Gosteva, V. V. Starkov, D. M. Sedlovets and O. Mong

Modern photovoltaic cells use conductive oxides or dielectric materials as antireflection coatings. Today, solar systems are the fastest growing energy generation systems due to the environmental concerns and increasing demand for a clean and renewable energy source. Silicon solar cells have dominated the current market of photovoltaic solar cells (PVs), accounting for over 95% in the market. This is due to the abundance of raw materials (silicon), low cost, simple and cheap manufacturing technology. Despite its dominance, fabrication of silicon solar cells with a high conversion efficiency has been challenging due to high sunlight reflectance (over 35%). Traditional techniques such as antireflection coating (ARC) and texturing have failed to provide a solution as they leave a large potential energy unused due to inefficient light harvesting in the near infrared spectrum. In this work, we varied the shape, height and width of the silicon surface structure to control the optical resonance and guide more light to the PV surface by bouncing the light around inside the PV cell, keeping the light in the cell longer and consequently increasing the chances of colliding with electrons. The surface reflection has been drastically reduced to almost zero using gradient porous silicon technique.

Keywords: Porous silicon; Photovoltaics; Antireflection coating; Silicon; Etching; Optical resonance

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1. Introduction

Porous silicon is a high-tech material with exclusive physical and chemical properties. This material can be used to produce light-emitting diodes, photodetectors and optical fibers, which can be combined into a single unit as a transmitter, optical information transmission medium and receiver. The relative simplicity of formation of structures with controlled morphology of the porous material, compatibility with silicon-based microelectronics technological operations serves as a ground to expect the development of other electronic and optical devices on the basis of layers with low, medium, high porosity and macroporous regular structures. Maruska et al first developed an electrochemical processing technique for preparing silicon samples with nanostructural carrier confinement properties. Quantum size effects in the material apparently lead to an increase in the optical gap energy, corresponding to the energy of carrier confinement. The acidic etching of the surface of silicon wafer usually results in a homogeneous porous silicon (PS) surface layer having a reflectance as low as 9% or less. Therefore, surface texturing is a vital tool incorporated to improve the conversion efficiency of silicon solar cells by varying the bandgap and absorption properties of the silicon materials. In addition to reducing reflection of the incoming light, light-trapping of long wavelength is also desirable, which becomes even more important for thinner wafers or ribbon materials. Etching of silicon wafers in a diluted nitric and hydrofluoric acid (NHO/HF) at room temperature leads to an appropriate porous surface layer, which gives the wafer a blue-to-purple look in order to minimize reflectance effect. The common objective is to form an antireflection (AR) "coating" and simultaneously etch back the emitter by forming Porous Silicon on finished cells. At present, the main approaches to producing highly efficient solar cells rely solely on silicon, which is the workhorse of the photovoltaics industry, although GaAs is also given much consideration. Efficiencies exceeding 20% have been achieved with the two materials, but costs still remain above competitive levels. GaAs has a direct bandgap that gives strong optical absorption and hence a short absorption length requirement of only a few microns; however, GaAs is a very costly material, and a non-absorbing GaAs substrate must be provided for mechanical support. In other words, Silicon is abundant in the earth's crust and therefore less expensive than GaAs, but its poor optical absorption properties (basically an indirect bandgap) lead to the requirement of very thick solar cells. Consequently, high efficiency silicon solar cells require complicated and costly processing procedures. However, since porous silicon material exhibits such intense photoluminescence, it appears as if this form of silicon has acquired a direct bandgap. The possibility, therefore, exists that by a relatively simple, quick, low-cost etching process, a thin film of highly absorbing silicon can be formed, with a band edge and absorption length comparable to that of expensive GaAs. Development of solar cell structures in this new form of silicon could lead to enhanced single

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Electrochemical etching system. (a) Cross-sectional view of lateral anodization cell. (b) Setup electrochemical cell for deep anodic etching of silicon. (c) Silicon wafer showing the polished surface and the etched area.
chiefly in the near-surface layer and do not diffuse deep into pores. Therefore, it was proposed to cut off the pump periodically during the synthesis in order to raise the vapor pressure in the reactor up to the level of 500 mmHg. The reactor was then evacuated quickly. Sharp pressure changes were thus, created in the reaction zone. The experiments revealed that synthesis in the SPC mode, firstly, facilitates deeper alcohol vapor penetration into the pores and secondly, provides removal of by-products of ethanol pyrolysis from porous membrane nanostructures.

3. Results And Discussion

Reflectance Measurement: The experiment was performed in the Single Crystals Based Laboratory of NUST, MISIS, Russia using the UV-Vis-NIR Spectrophotometer to investigate the reflectance spectra of various structures of silicon wafers for [100] and [111] orientations, respectively, extending from macro- to nanostructures, and then to gradient structures.

Fig. 2 displays the responses of porous silicon structure to photons under varying wavelength conditions. The results show a great deal of improvement in porous silicon technology seeing the enormous reduction of reflectance below 0.01 % compared to most antireflection coated structures with extremely high reflectance up to 12.6 % at about 650 nm. Strehlke et al. detailed the performance evaluation of silicon wafers with/without porous silicon, showing over 9 % reflection of the incoming radiation with ordinary wafers, while their porous counterparts exhibit a lower reflection. A comparative analysis of previous studies based on porous silicon for antireflection coatings is presented in Table 1.

As illustrated in Fig. 2, it is noticeable that the porous silicon solar cells have better photo absorption potential compared to the technologies with antireflection coatings. Our work (Fig. 2, Table 2) illustrates the performance and solar reflection of the various structures at 650 nm. By default, the polished structure reflects more than 30 % of the incident radiation. Therefore, porosifying the structural surface enhances photo-absorption and consequently improves the overall performance. Altogether, the gradient porous silicon (Fig. 2d) performs better than all other structures because it has the tendency of absorbing a wider spectrum of light and generate a corresponding photo-current in photovoltaic applications. Other structures also demonstrate good performance as well.

Material Characterization: The microscopic images illustrate the surface makeups and structures of different silicon surface morphologies considering the different porous layout. Fig. 3 demonstrates the SEM and optical images of gradient-porous GPSi–var structure [100] and [111], indicating from the bottom to the top the macro-, meso-, to nano-layers respectively. The macro layer is about 122 μm, meso 200 μm and nano ~2 μm, giving a total of 324 μm (Fig. 3a). The topmost thinnest (distal) layer in Fig. 3a B&C represent a nanoporous film. The presence of this nanoporous layer practically doubles the reflection coefficient in comparison with the lower-lying macroporous layer.

In conclusion, the result shows that the porous structures cannot only reach the low value of the reflection in the visible and IR regions of the spectrum but also can expand to the short-wavelength (UV) region of the solar spectrum. Our findings have proven that porous
### Table 1 Effective reflectance from different silicon surfaces.

<table>
<thead>
<tr>
<th>Silicon Surface</th>
<th>Reflectance (%)</th>
<th>Reference</th>
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<th>Reflectance (%)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>PS (60 %), 105 nm, (n⁺ - p), Si (100)</td>
<td>7.3</td>
<td>[15]</td>
<td>PS (78 %)/PS (38 %)/(n⁺ - p) Si</td>
<td>2.4</td>
<td>[16]</td>
</tr>
<tr>
<td>Mc – Si (acid textured)</td>
<td>11.4</td>
<td>[17]</td>
<td>SiNₓ/mc-Si (alkaline textured)</td>
<td>5.3</td>
<td>[17]</td>
</tr>
<tr>
<td>CZ – Si (alkaline textured)</td>
<td>12.6</td>
<td>[13]</td>
<td>PS (strain etching)/CZ -Si (alkaline textured)</td>
<td>3.4</td>
<td>[13]</td>
</tr>
<tr>
<td>PS (stain etching)/CZ -Si (alkaline textured)</td>
<td>3.1</td>
<td>[13]</td>
<td>PS/Si (100)</td>
<td>9.0</td>
<td>[18]</td>
</tr>
<tr>
<td>PS/(n⁺ - p) Si</td>
<td>4.0</td>
<td>[19]</td>
<td>PS NW/Si</td>
<td>0.1</td>
<td>[20]</td>
</tr>
</tbody>
</table>

### Table 2 Reflectance of various silicon structural surfaces at 650 nm (this work).

<table>
<thead>
<tr>
<th>Sample</th>
<th>Description</th>
<th>% Reflectance</th>
<th>Figure Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polished Silicon</td>
<td>[100] substrate</td>
<td>33.2300</td>
<td>2a</td>
</tr>
<tr>
<td>Mesoporous Silicon</td>
<td>[100] substrate</td>
<td>1.6130</td>
<td>2a</td>
</tr>
<tr>
<td></td>
<td>[111] substrate</td>
<td>1.6143</td>
<td></td>
</tr>
<tr>
<td>Nanoporous Si(100)</td>
<td>With graphene</td>
<td>0.1463</td>
<td>2b</td>
</tr>
<tr>
<td></td>
<td>Without graphene</td>
<td>0.1561</td>
<td></td>
</tr>
<tr>
<td>Nanoporous Structure</td>
<td>[111] orientation</td>
<td>0.0437</td>
<td>2c</td>
</tr>
<tr>
<td>Gradient Structure</td>
<td>[100] orientation</td>
<td>0.0043</td>
<td>2d</td>
</tr>
<tr>
<td></td>
<td>[111] orientation</td>
<td>0.0010</td>
<td></td>
</tr>
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</table>
structures can comfortably replace the conventional cells with antireflection coating at extremely low technology cost, which will, in turn, make it affordable to all categories of users as possible. The method does not require any expensive engineering technique to implement as compared to the traditional systems. The technology is not only promising in photovoltaics, but it can also be applied in lithium batteries (to store lithium ions), water splitting (to generate hydrogen/oxygen), LED fabrication, gas sensing, and piezoelectric technology.

References