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Fabrication of honeycomb texture on poly-Si by laser interference and chemical etching

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ABSTRACT

In this paper, we present a laser-interference method to fabricate honeycomb textures on poly-Si wafer for reflection reduction. When exposed to three interfering pulsed laser beams at 532 nm, the Si surface was periodically melted in accordance with the interference pattern. As a result, concave holes were generated on the surface because the melted material overflowed and condensed at the periphery. Subsequent acid etching revealed uniform and clean honeycomb textures. The texture depth could be controlled by varying the irradiation condition and a minimum reflectance of 10% was obtained. Transmission electron microscopy analysis showed that no irradiation-induced damage remained after etching. This approach can be a cost-effective alternative to lithographic processes for fabricating high-efficiency poly-Si solar cells.

1. Introduction

Si exhibits high reflectivity over the whole optical spectrum. Surface structuring, typically called texturing, is thus necessary for Si to be used for solar cells. It is well known that (1 0 0)-oriented single-crystalline Si wafer can be textured into randomly distributed pyramids by alkali etchants such as KOH or NaOH [1–6]. The pyramid structure induced by anisotropic etching reflects the incident light twice before escaping from the textured surface, reducing the total reflectivity to less than 20%. Since poly-Si has multi-orientations, it is impossible to uniformly control its surface structure by anisotropic alkali etching. Acid etching is generally used to reduce the surface reflectance of poly-Si solar cells. A HF/HNO_3 solution, which tends to isotropically etch, can result in features owing to the inhomogeneity of etching speed. As opposed to flat-sided features obtained by anisotropic etching, the acid-etched wafer exhibits rounded surfaces.

Although acid etching helps suppress the surface reflectivity to some degree, the obtained irregular structures are less effective than the pyramid structures. Therefore, a great deal of research effort has been carried out to reduce the surface reflectivity of poly-Si. The so-called “black silicons” with very low reflectances have already been developed by many different methods [7–10]. Nevertheless, they are still not utilized for solar cells because of high recombination rates resulting from the significantly increased surface area. Low surface reflectivity is required for high-efficiency solar cells but it does not guarantee high performance. While it needs to trap more light, the increase in total surface area should be minimized at the same time. Non-chemical methods like mechanical grooving [11] and reactive-ion etching [12,13] have also been investigated for texturing poly-Si. However, they are complicated processes requiring expensive systems and may cause degradation in the electrical characteristics [13]. In the meanwhile, honeycomb textures are known to give very high efficiencies when applied to poly-Si solar cells [14,15]. While the honeycomb structures have been generally fabricated by photolithography, interference lithography can be used to produce a variety of one, two, and three-dimensional periodic structures [16,17]. Three-beam lithography has been employed to create the desired photoresist pattern in order to etch the Si substrate [18]. A similar laser-based technique [19,20] has also been suggested, where a laser-patterned layer is used as the etching mask for the underlying Si wafer. Although the hard mask film is directly patterned by laser ablation, this technique also needs multiple steps including thin film deposition and etching. In this paper, we show that regular honeycomb structures can be fabricated on poly-Si wafer by irradiation with interfering laser beams and subsequent acid etching. Unlike the previous approaches, this method does not require any mask, which greatly simplifies the fabrication process.

2. Experimental procedure

Poly-Si wafers (p-type, resistivity = 1–30 Ω cm, thickness = 200 μm) were supplied from LG SILTRON. The saw damage was removed by dipping the wafer into a 20% KOH solution at 80 °C for 10 min. Then, the wafer was cleaned by acetone,

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ethanol, deionized (DI) water and dried using N_2 gas. A pulsed Nd:YAG laser (Model: Brilliant b, Quantel, wavelength = 532 nm, pulse width = 5 ns, repetition rate = 10 Hz, maximum pulse energy = 350 mJ, beam diameter = 0.9 cm) was employed as the laser source. The output laser beam had already a hat-top profile and thus a beam homogenizer was not used. An output beam was transmitted through a trigonal pyramid-shaped prism made of quartz (n = 1.52) and the three refracted beams were made to interfere on the wafer. The used pulse energy was 70–100 mJ and the irradiation time was less than 1 s. Acid etching was performed at 35 °C using a HF/HNO_3 solution ($HF:HNO_3$:DI water = 1:2:2 in volume). Alkali etching was carried out using a 20% KOH aqueous solution at 80 °C. The surface morphology was investigated by a field-emission scanning electron microscope (JEOL JSM-7001F, 15 kV). The crystalline quality of Si was analyzed by a high-resolution transmission electron microscope (JEOL JEM-2100F) and a focused ion beam apparatus (FEI NOVA600) was used for the sample preparation. The surface reflectance was measured using a spectrophotometer with an integration sphere (Agilent Cary 670) in the range of 200–1100 nm.

3. Results and discussion

Our approach is fundamentally based on the laser-driven melting of material. We have found that Si can be melted by irradiation with a nanosecond-pulsed laser at 532 nm. When the wafer was exposed to three interfering laser beams, the surface was locally melted in accordance with the interference pattern of two-dimensional hexagonal symmetry. As a result, concave holes were periodically generated on the surface because the melted material overflowed and condensed at the periphery. This phenomenon was employed to make a regular texture structure on the surface of Si wafer. Fig. 1 shows a schematic illustration of the fabrication process. The Si wafer is first irradiated by three interfering laser beams which are generated by transmitting an output laser beam through a refracting prism. A surface pattern consisting of concave holes is then formed on the surface. The melt-condensed material could be quickly dissolved by an acid solution (within 10 s by a HF/HNO_3 solution). Since the surface orientations within the hole are position-dependent, the inner wall will be etched at different rates by an alkali solution, resulting in polyhedron-shaped morphology. In contrast, isotropic acid etching will make the original holes deeper and wider and ultimately give rise to a honeycomb structure.

Fig. 2(a) shows the surface of as-irradiated poly-Si wafer. When the wafer was subsequently etched by a KOH solution, the inner morphology of the holes was changed into a polyhedron shape, which varied depending on the crystal orientation (Fig. 2(b)). An inverted-pyramid texture was obtained on the (1 0 0)-oriented grain (inset of Fig. 2(b)). When the sample was acid-etched, a

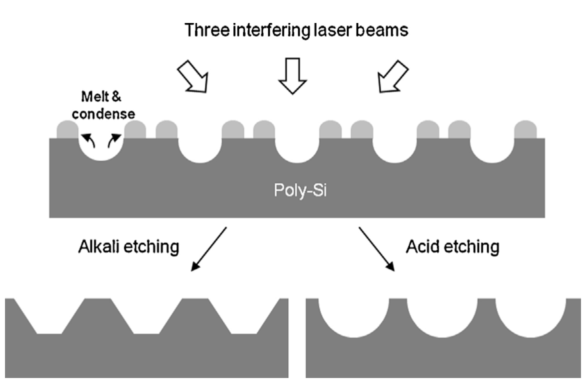

Fig. 1. Schematic illustration of the fabrication process of surface structures.

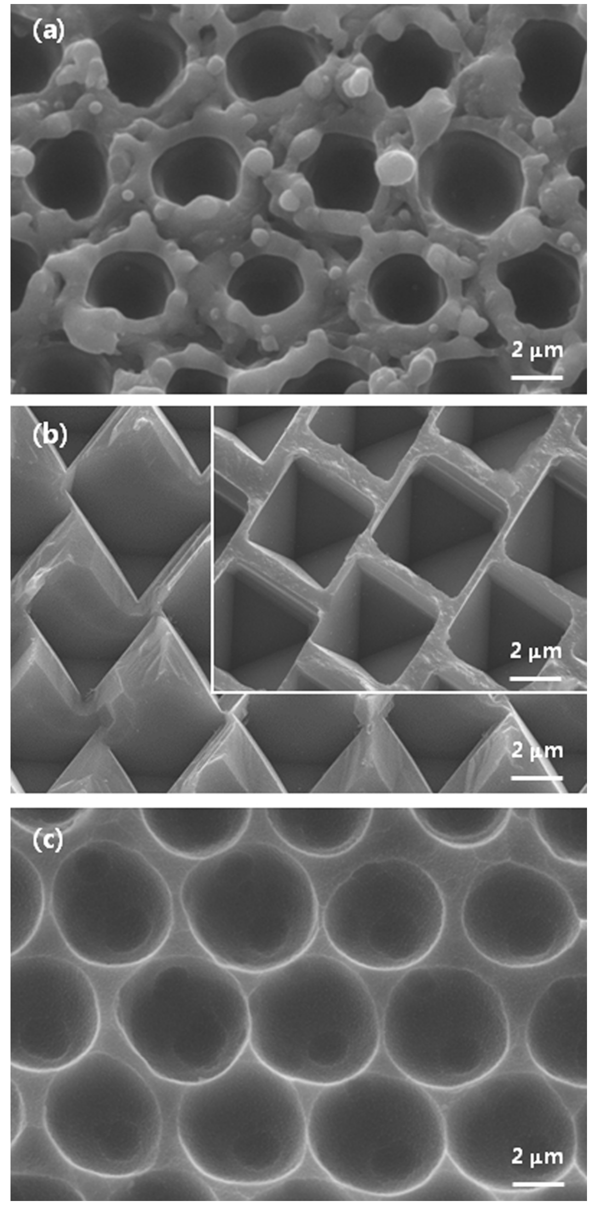

Fig. 2. Texturing of poly-Si. (a) Image of the surface irradiated for 0.5 s at 80 mJ. (b) Images observed after subsequent KOH etching for 4 min. (c) Honeycomb structure obtained by etching with a HF/HNO_3 solution for 45 s.

honeycomb texture was formed all over the irradiated area, regardless of the grain orientation (Fig. 2(c)). Transmission electron microscopy analysis showed that no irradiation-induced defects remained after etching (Fig. 3). The inset of Fig. 3(b) is an electron diffraction pattern taken near the top surface, which confirms high crystalline-quality.

Apart from the fabrication cost and time, this method has an additional advantage over lithographic processes. The reflectivity of honeycomb structure can be much affected by the hole depth-to-width ratio. In conventional lithography, the independent control of depth and width is a challenge because etching starts from the flat surface and even the masked areas will be undercut due to the isotropic nature of acid etching. On the contrary, the depth of holes could be controlled by varying the laser pulse energy and irradiation time in this method.

Fig. 4 shows the reflection spectra. As the minimum area required for reflectance measurement was 1.5 cm × 1.5 cm, the wafer was patterned over large area (2.0 cm × 2.0 cm) using a