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Laser interference-driven fabrication of regular inverted-pyramid texture on mono-crystalline Si

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ABSTRACT

We show that inverted-pyramid (IP) textures can be fabricated on mono-crystalline Si wafer by laser interference combined with alkali etching. When exposed to three interfering nanosecond-laser beams at 532 nm, the surface was periodically melted in accordance with the interference pattern, generating concave holes. Subsequent etching with a KOH solution revealed IP structures as a result of the anisotropic etching. It was found that not only the etching condition but also the in-plane orientation relationship of interfering beams is an important factor to fabricate low-reflectance, uniform IP textures. An average reflectance less than 20% was obtained over the spectral range of 400 nm to 1 μm. This mask-free process may be effectively utilized for the production of low-cost, high-efficiency crystalline Si solar cells.

1. Introduction

Laser texturing provides a unique opportunity to modify the surface properties of materials. For example, the surface reflectivity of metals and semiconductors can be greatly reduced by laser-induced self-organized texturing processes [1–4]. The formation of nano- and micro-scale textures have been widely investigated in many different materials using femtosecond and nanosecond lasers [5–9]. A fundamental problem with the self-organized processes is that it is very difficult to obtain highly ordered uniform textures. This can limit the device applicability. Si has a high surface reflectance due to the large refractive index. For photovoltaic applications, its surface should be textured to reduce reflection loss and thus enhance light trapping. The standard texturing process for mono-crystalline silicon (c-Si) solar cells is alkaline texturing. It is well known that (001)-oriented c-Si wafer can be textured into randomly distributed pyramids by alkali etchants such as KOH or NaOH [10–13]. The pyramid structure, revealed by etching anisotropy, enables the incident light multi-bounced from the textured surface, thus reducing the total reflectivity.

Since poly-Si (p-Si) has multiple orientations, it is impossible to uniformly control its surface structure by anisotropic alkali etching. Therefore, acid etching is generally employed to reduce the surface reflectivity of p-Si. A HF/HNO_3 solution tends to etch Si isotropically but can generate surface features as a result of the etching speed inhomogeneity. Although acid etching suppresses the surface reflectivity to some degree, the obtained irregular structures are less effective than the pyramid textures. In the meanwhile, honeycomb patterns have proved highly efficient for the light trapping of solar cells [14,15]. Various techniques have been reported to fabricate honeycomb textures in p-Si, including conventional lithography [14,16], masked reactive ion etching [17,18], nanoimprint lithography [19,20], masked laser texturing [15,21], and direct laser texturing [22–24]. We have recently shown that regular honeycomb structures can be fabricated on p-Si wafer by irradiation with three interfering laser beams and subsequent acid etching [25]. Transmission electron microscopy analysis showed that no irradiation-induced damage remained after etching. Unlike conventional lithography, this method does not require the deposition and removal of a masking layer on the wafer. In addition, it is much fast and scalable than the direct laser texturing technique which is a focused beam-utilized serial process.

In this study, we demonstrate that inverted-pyramid (IP) textures can be fabricated on c-Si wafer via pulsed laser interference combined with alkali etching. Compared to the random pyramid structure with a wide distribution in size and shape, the IP structure offers a more efficient light-trapping geometry [26,27]. In fact,

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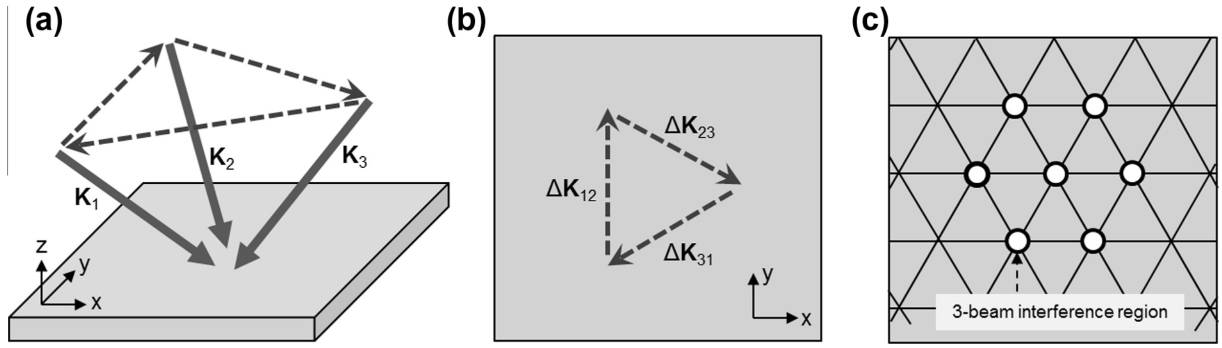

Fig. 1. Schematic illustration of the three-beam interference. (a) Three refracted beams generated by a trigonal pyramid-shaped prism are made to overlap on the wafer in a symmetric fashion, i.e., at the same angle of θ from the normal z axis. (b) The difference vectors of $\Delta\mathbf{K}_{12}$, $\Delta\mathbf{K}_{23}$, $\Delta\mathbf{K}_{31}$ forms a regular triangle on the surface. (c) An interference pattern of hexagonal symmetry is obtained with the interference fringes perpendicular to these difference vectors.

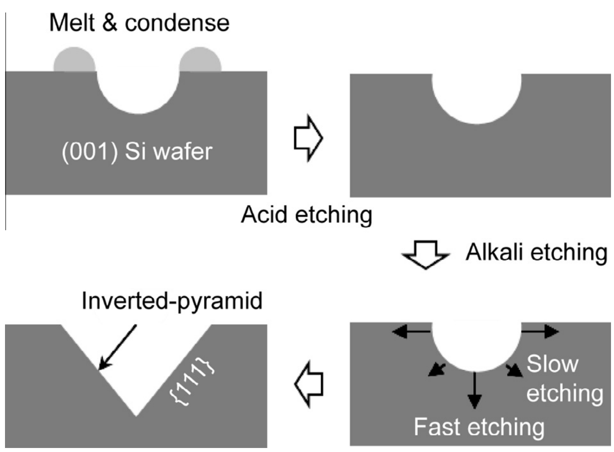

Fig. 2. Schematic for the fabrication process of IP texture.

the maximum efficiencies (~25%) of c-Si solar cells have always been achieved with IP surface structures [28,29]. Nevertheless, this structure has yet to be utilized for commercial solar cells due to the fabrication cost. Thus far, the IP textures have been fabricated through anisotropic etching of the masked Si surface. Therefore, a photoresist or dielectric layer should have been deposited and patterned. In this respect, the suggested mask-free approach may provide a breakthrough to the production of low-cost, high-efficiency c-Si solar cells. The laser interference method employed for this work has already been reported in our previous work [25], which discusses the fabrication of honeycomb texture on poly-Si. When exposed to three interfering pulsed laser beams, the surface of poly Si exhibited periodic concave holes in accordance with the interference pattern. Exposing it to an acid revealed a honeycomb structure on the surface, which might be a consequence of the isotropic etching. In the current work, we demonstrate that a regular IP texture can also be developed from the concave holes laser-generated on mono-crystalline Si wafer by alkaline etching with a KOH solution. Unlike the honeycomb texturing on poly-Si, the IP texturing on mono-Si required fine control of the etching concentration and time. Another crucial factor influencing the pattern uniformity and reflectance was the incident direction of interfering laser beams with respect to the in-plane orientation of the Si wafer. Since KOH etching is anisotropic and the wafer is single-crystalline, it was necessary to align a side of the interference pattern parallel to a specific in-plane orientation of the wafer in order to obtain highly ordered IP textures. All the relevant issues are here discussed.

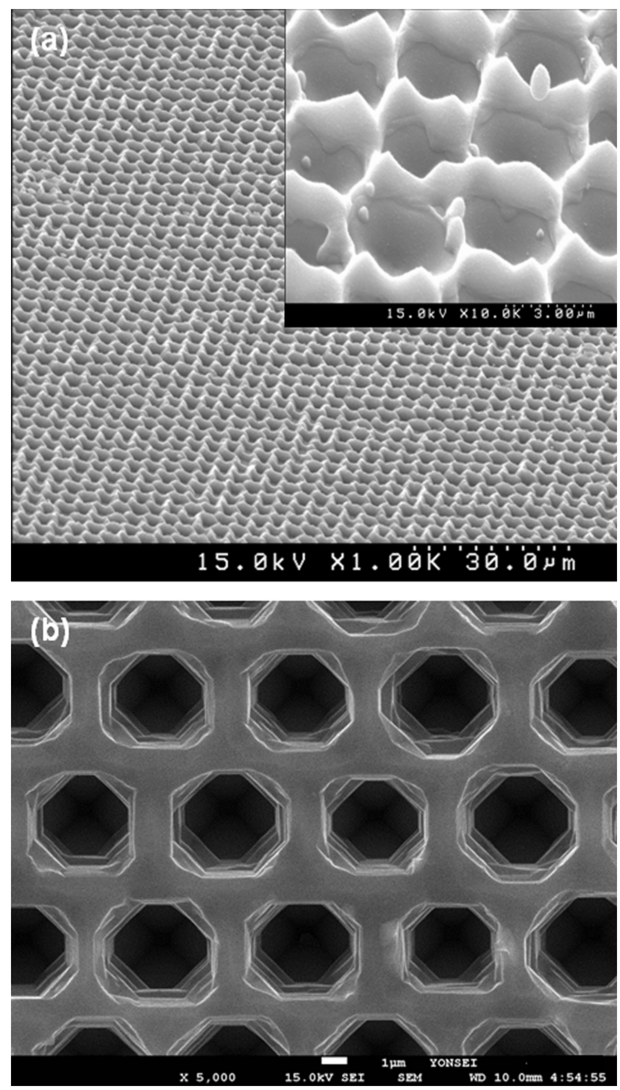

Fig. 3. (a) Surface morphology taken after irradiation with 355 nm-beams. (b) Surface image observed after 10 s acid etching and then 2 min alkali etching, where the wafer was irradiated by 532 nm-beams for 1 s.

2. Experimental procedure

The (001)-oriented c-Si wafers (p-type, resistivity = 1–30 Ω cm, thickness = 675–700 μm) were supplied from LG SILTRON. Before use, the single side-polished wafer was cleaned by acetone, etha-