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Improved multicrystalline silicon ingot quality using single layer silicon beads coated with silicon nitride as seed layer

G. Anandha babu [a,b,*], Isao Takahashi [a], Satoru Matsushima [a], Noritaka Usami [a]

[a] Graduate School of Engineering, Nagoya University, Nagoya 464-8603, Japan
[b] Department of Physics, SSN College of Engineering, Kalavakkam, Tamil Nadu 603110, India

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A B S T R A C T

We propose to utilize single layer silicon beads (SLSB) coated with silicon nitride as cost-effective seed layer to grow high-quality multicrystalline silicon (mc-Si) ingot. The texture structure of silicon nitride provides a large number of nucleation sites for the fine grain formation at the bottom of the crucible. No special care is needed to prevent seed melting, which would lead to decrease of red zone owing to decrease of feedstock melting time. As we expected, mc-Si ingot seeded with SLSB was found to consist of small, different grain orientations, more uniform grain distribution, high percentage of random grain boundaries, less twin boundaries, and low density of dislocation clusters compared with conventional mc-Si ingot grown under identical growth conditions. These results show that the SLSB seeded mc-Si ingot has enhanced ingot quality. The correlation between grain boundary structure and defect structure as well as the reason responsible for dislocation clusters reduction in SLSB seeded mc-Si wafer are also discussed.

1. Introduction

Global needs for solar energy have been increasing rapidly. Crystalline silicon solar cells constitute ~90% of current global production capacity and are the most mature of all photovoltaic technologies. Silicon solar cells are classified as single crystalline silicon (sc-Si) or multicrystalline silicon (mc-Si), with respective market shares of ~35% and ~55% in 2014 [1]. The mc-Si offers advantages over sc-Si with respect to the lower manufacturing cost, higher throughput, simple processes and wider feedstock tolerance. However, during mc-Si ingot growth, crystal defects such as grain boundaries, dislocations, dislocation clusters and impurities precipitation are introduced from feedstock, crucibles, coating and due to the nature of the process. The interaction between impurities and crystal defects including grain boundaries causes severe recombination centers for the photogenerated electrons and holes. Recombination of the minority carriers at the dislocations and dislocation networks significantly reduces the energy conversion efficiency of the mc-Si solar cells [2]. Dislocation clusters are known to be detrimental for minority carrier lifetime. Sopori et al. claim an efficiency loss due to dislocation clusters in mc-Si solar cells of more than 3–4 absolute percentage points [3]. Dislocation clusters reduction is a significant technological challenge in order to obtain higher energy conversion efficiencies of mc-Si solar cells, as the region of dislocation clusters generally limits particularly the open circuit voltage of such solar cells. In order to diminish the influence of dislocations on the efficiency of mc-Si solar cells, a dislocation density below $10^4\ cm^{-2}$ is necessary [4]. On the other hand, controlling of dislocation density led to the development of new crystallization techniques for growing mc-Si ingot with reduced dislocation density, like the so-called dendritic casting [5], quasi-mono or mono-like casting [6–8], floating casting [9,10], noncontact crucible [11,12] and high performance (HP) mc-Si casting methods [13,14].

Among various methods, HP mc-Si casting methods become dominant during the last few years, and the most of the major suppliers of mc-Si have now tuned their production to produce HP mc-Si. HP mc-Si is an emerging material in photovoltaic industry, and consists of small grains, homogeneous distribution of the different grain orientation, high percentage of random grain boundaries and less twin boundaries. Due to its excellent performance, this material is expected to replace conventional mc-Si completely in the near future. HP mc-Si is possible to control proliferation of dislocation clusters during growth process. The reasons to limit dislocation density and less severe multiplication are: (1) stress may be released by the disordered structure of random angle grain boundaries so that random angle grain boundaries do not act as dislocation sources; (2) dislocation

* Corresponding author at: Department of Materials, Physics and Energy Engineering, Graduate School of Engineering, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8603, Japan. Tel.: +81 52 789 3246; fax: +81 52 789 4516.
E-mail address: anandcgc@gmail.com (G.A. babu).

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clusters may be terminated at random grain boundaries. To obtain small grains with homogeneous distribution of orientation, silicon beads or silicon chunks have been used as seed layer to grow HP mc-Si ingots [13,15–17]. However, very precise temperature controlling is necessary at the bottom of crucible to prevent complete melting of Si granular seed layer unless other materials for efficient heterogeneous nucleation are used. As a result, feedstock melting time is increased. The red zone width is increased at bottom of the ingot due to more impurities diffusion. If the seed layer completely melts, the grown ingot will have more dislocation density resulting in poor cell efficiency.

To solve these difficulties, we designed an effective seed layer, which provide a large number of nucleation sites for fine grain formation by using single layer silicon beads (SLSB) coated with silicon nitride. The SLSB seeded method offers advantages over other seeded methods with respect to shorter feedstock melting time, smaller red zone width at the bottom of the ingot, lower cost and no special care is needed to prevent seed melting. Silicon ingot with small grain size, homogeneous distribution of the different grain orientation, high percentage of random grain boundaries and less twin boundaries was obtained in comparison with conventional ingot, which is close to HP mc-Si ingot. Importantly, we could expect that wafers yield is enhanced due to decreased red zone region at the bottom of the ingot. A possible mechanism responsible for dislocation clusters reduction in SLSB seeded mc-Si

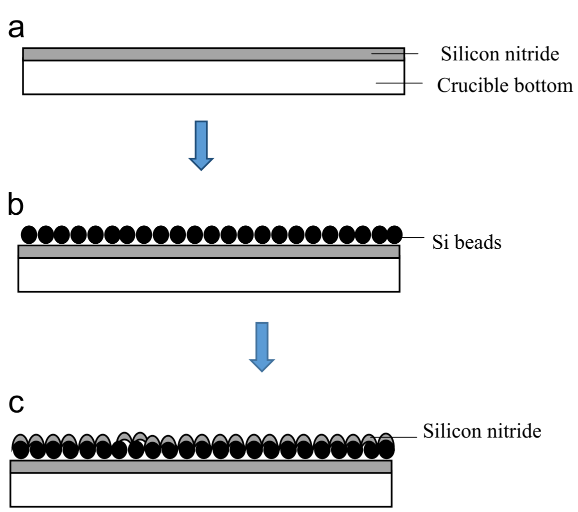

Fig. 1. Illustration of SLSB seed design with silicon nitride coating preparation (a) Bottom silicon nitride coating, (b) Si beads embedded on the silicon nitride coating, and (C) silicon nitride coating sprayed on Si beads.

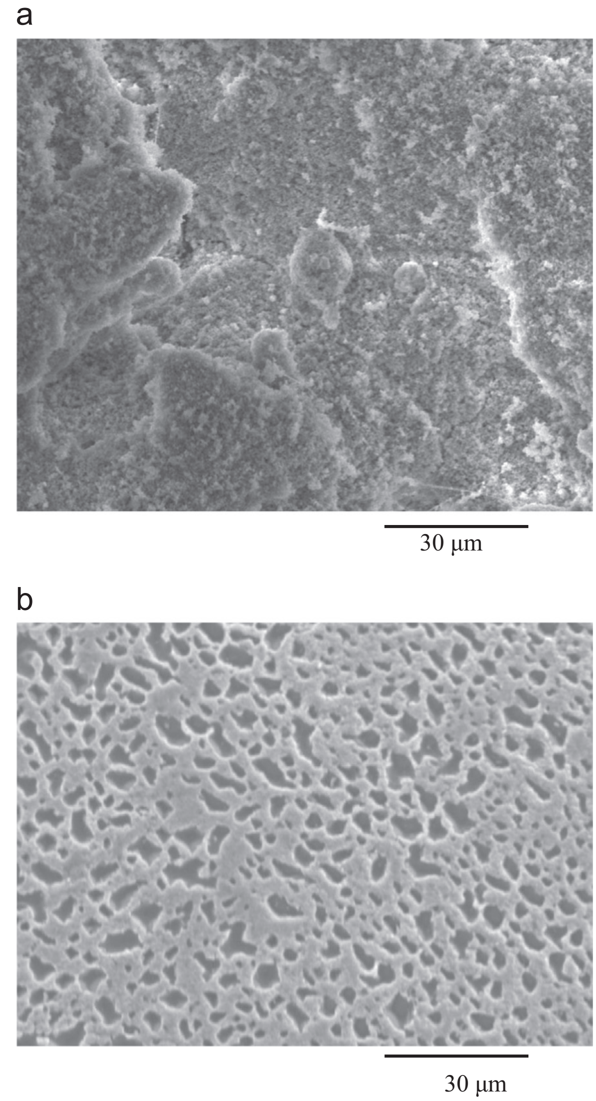

Fig. 3. SEM image of silicon nitride layer (a) conventional method and (b) on Si beads in SLSB seeded method after ingot growth.

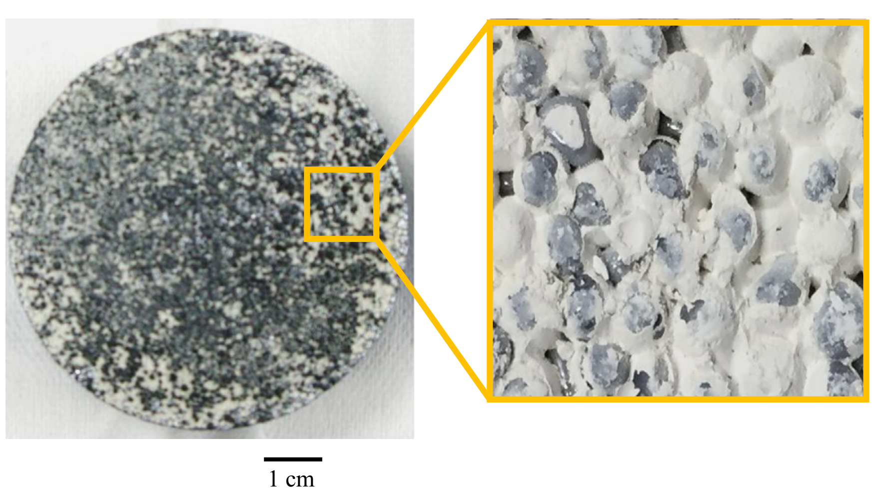

Fig. 2. Bottom of SLSB seeded mc Si ingot after growth. Marked in orange an exemplary enlarged image shows the shape of Si beads was kept after the process. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)