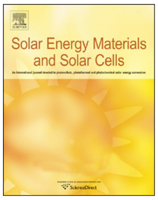
Solar Energy Materials & Solar Cells 155 (2016) 88–100

Contents lists available at ScienceDirect

Solar Energy Materials & Solar Cells

journal homepage: www.elsevier.com/locate/solmat



Review

# An insight into dislocation density reduction in multicrystalline silicon

Soobin Woo [a], Mariana Bertoni [b,c], Kwangmin Choi [a], Seungjin Nam [a], Sergio Castellanos [b], Douglas Michael Powell [b], Tonio Buonassisi [b], Hyunjoo Choi [a,b,*]

[a] *School of Advanced Materials Engineering, Kookmin University, 77 Jeongneung-ro, Seongbuk-gu Seoul, 136-702, Republic of Korea*
[b] *Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*
[c] *School of Electrical Computer and Energy Engineering, Arizona State University, Phoenix, AZ 85004, USA*

## ARTICLE INFO

*Article history:*
Received 27 January 2016
Received in revised form
29 March 2016
Accepted 31 March 2016
Available online 16 May 2016

*Keywords:*
Multicrystalline silicon
Solar cells
Dislocation density
Pair-wise annihilation
Dislocation engineering

## ABSTRACT

Dislocations can severely limit the conversion efficiency of multicrystalline silicon (mc-Si) solar cells by reducing minority carrier lifetime. As cell performance becomes increasingly bulk lifetime–limited, the importance of dislocation engineering increases too. This study reviews the literature on mc-Si solar cells; it focuses on the (i) impact of dislocations on cell performance, (ii) dislocation diagnostic skills, and (iii) dislocation engineering techniques during and after crystal growth. The driving forces in dislocation density reduction are further discussed by examining the dependence of dislocation motion on temperature, intrinsic and applied stresses, and on other defects, such as vacancies and impurities.

**Contents**

## 1. Introduction

Despite the benefits of solar cells as a next-generation energy source, their high cost per wattage has kept them from achieving widespread use [1,2]. Although multicrystalline silicon (mc-Si) solar cells currently account for ~50% of worldwide photovoltaic

---

* Corresponding author at: School of Advanced Materials Engineering, Kookmin University, 77 Jeongneung-ro, Seongbuk-gu, Seoul 136-702, Republic of Korea.
*E-mail address:* Hyunjoo@kookmin.ac.kr (H. Choi).

http://dx.doi.org/10.1016/j.solmat.2016.03.040
0927-0248/

production owing to their low cost and scalability [3], conventional processes introduce many deleterious defects within the material, which deteriorate cell performance and hence offset the cheaper production costs [4,5]. For example, at a given cost target of electricity (~6 cents per kWh), an increase in the module efficiency from 10% to 20% allows an increase (from \$10/m$^2$ to \$75/m$^2$) in the module price [6].

Dislocations are well known as one of the most serious defects limiting the performance of mc-Si solar cells [7]. In principle, the reduction of dislocation densities from $10^6$–$10^8$ cm$^{-2}$ to as low as $10^3$–$10^4$ cm$^{-2}$ may lead to an improvement in the cell performance (from 13–14% to $>20\%$). Hence, efforts have been made to suppress the harmful impact of dislocations on cell performance, to avoid the formation of dislocations during crystal growth [8,9] and to remove dislocations after ingot growth [10–13]. Despite numerous studies on the passivation of dislocations and the gettering of fast-diffusing metal impurities from dislocations, the improvement of cell performance after these processes is still very limited in regions with high dislocation densities ($>10^6$ cm$^{-2}$) [14]. One possible reason for this is that metal impurities and precipitates trapped in dislocation cores cannot be readily removed during gettering [15]. These impurities form deep-level recombination centers, which deteriorate cell performance [16]. Hence, alternative approaches for dislocation removal are required, in addition to gettering or passivation methods. Although technical reports on engineering dislocations during/after ingot growth have been published elsewhere; each work is concerned only with certain types of materials under certain conditions.

The present work departs from previous approaches in several respects. First, it reviews previous literature to provide a comprehensive understanding of (i) when dislocations are harmful, (ii) how they can be detected, and (iii) how they can be controlled in mc-Si. Second, it examines the underlying physics to clarify the thermal-mechanical conditions necessary to annihilate dislocations effectively. The effects of each key parameter, namely thermal input, activation energy for dislocation motion, and stress, on dislocation density reduction are investigated.

## 2. Impact of dislocations on the performance of Si solar cells

Extended crystal defects (e.g., dislocations, twins, stacking faults, and grain boundaries) interrupt crystal periodicity, inducing dangling bonds and deep states in the silicon band gap [17–20]. Stacking faults are relatively rare and twins are usually clean so they have negligible recombination activity in mc-Si [21,22]. Furthermore, Arafune et al. reported that the correlation between minority carrier lifetime and grain size is uncertain [17]. This is because the grain size of mc-Si is on the order of millimeters to centimeters, which is larger than the minority carrier diffusion length (generally less than 100 μm). Therefore, among crystal defects, dislocations are thought to be the most crucial defects limiting the photovoltaic performance of Si solar cells because they constitute the main source of recombination centers [23].

Dislocations act as recombination centers for electrons and holes by inducing deep trapping centers in the conduction and valence bands in Si. Dislocations primarily store carriers ejected from a band, and the extra carriers are promptly recombined when the source of excess carriers is removed. However, excess holes or electrons are ejected at a very low rate and the corresponding photocurrent decays very slowly, providing a slow and non-exponential recombination of holes and electrons, which deviates from the Shockley–Read theory. The space charge barrier surrounding the dislocation may have a dominant effect in determining the characteristics of recombination. Fig. 1 shows the correlation between dislocation density and effective bulk lifetime, which is calculated using Donolato's model [7]. A significant degradation of the effective bulk lifetime of mc-Si is predicted as the dislocation density increases.

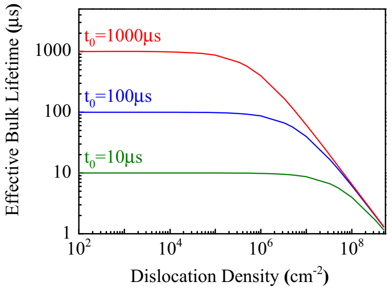


**Fig. 1.** Correlation between dislocation density and effective bulk lifetime, calculated using Donolato's model [7], for different dislocation-free lifetime ($\tau_0$) of the Si bulk.

Although dislocations themselves may influence the electrical properties and photovoltaic performances of an mc-Si solar cell, significant additional degradation of the cell performance also occurs when dislocations are decorated with impurities. Dislocations are usually positively charged by holes in p-type silicon, and interact with carbon-related impurities (e.g., $C_iO_i$) or metal impurities so as to form a space charge region around the dislocations [24]. Block-cast mc-Si wafers exhibit areas of reduced lifetime around the wafer edges owing to impurities diffusing from the crucible wall into the silicon melt during solidification. At the boundaries, different grains meet and strain fields attract contamination, leading to an increased recombination activity [25]. Dissolved iron, iron complexes, and precipitates are known to introduce deep levels in the band gap, thereby increasing the carrier recombination rate. Precipitated iron has a less detrimental effect on lifetime compared to interstitial iron [26]. The higher concentration of Fe-B pairs is also the main cause for the deterioration of carrier lifetime in the order layer of the wafer [27]. Carbon and oxygen precipitation are also known as the decisive factor for a grain boundary acting as a current collecting defect [28].

The cell performance depends not only on the number of defects in the substrates, but also on how the defects are distributed [4]. On mc-Si wafers, the defect density is spatially inhomogeneous. Areas of high dislocation densities show very low short circuit current, and their influence on the total current is much more important than that of the grain boundaries. When dislocations are decorated with impurities, their influence on cell performance greatly varies according to their distribution [29]. Areas with high dislocation density introduce excess currents under reverse bias conditions, revealing hot spots through localized Joule heating of the material [30]. This significantly limits the photocurrent, the photovoltage, and the minority carrier diffusion length.

The geometric characteristics of the dislocation also affect the recombination behavior at the dislocations. In particular, recombination at dislocation loops [31] gives rise to dislocation-related radiation, which is attributed to local gettering, and thereby causing a large increase in the minority carrier lifetime. Furthermore, dislocation loops generate a local strain field, thereby providing efficient room temperature electroluminescence at the Si band-edge. It is more efficient when the loops are smaller and their density is higher because the individual strain fields are more readily overlapped with the closer dislocation loops [32]. The dislocation loop edge distorts the silicon lattice by applying a negative hydrostatic pressure to the adjacent silicon lattice just outside the loop. It was found that dislocation conduction may