Direct comparison of the electrical properties of multicrystalline silicon materials for solar cells: conventional p-type, n-type and high performance p-type

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Abstract

We compare the recombination properties of three important types of multicrystalline silicon wafers for solar cells, namely conventionally-solidified p-type and n-type multicrystalline wafers, and also the recently developed ‘high performance’ p-type multicrystalline wafers. Three distinct regions of the wafers are examined in detail. These are the intra-grain regions, the grain boundaries, and the dislocation networks. The response of these regions to phosphorous gettering and hydrogenation are also characterised and compared. The electrical properties of intra-grain regions are assessed based on both the minority carrier lifetime and diffusion length. The recombination activity of dislocations is evaluated qualitatively based on photoluminescence images. Our results show that the main performance limiting factors are likely to be recombination at crystal defects. Overall, grain boundaries in conventional p-type samples are more recombination active than those in high performance p-type and conventional n-type samples. The benefits of hydrogenation are most visible on n-type samples, leading to significant deactivation of most of the grain boundaries. As-grown grain boundaries and dislocations in high performance multicrystalline silicon tend not to be recombination active, and only become active after either gettering or hydrogenation.

Keywords: Dislocation, Grain boundary, Multicrystalline silicon, Photoluminescence imaging, Recombination

1. Introduction

Multicrystalline silicon (mc-Si) material is the most commonly used material in solar cell production, giving an effective compromise between high efficiency and low material cost. As a result of the ingot growth process, mc-Si material inherently contains crystal defects such as grain boundaries (GBs) and dislocations, and also relatively high metal impurity concentrations, originating from the less pure crucibles and coatings. These act as recombination centres for photo-generated carriers, and hence reduce the minority carrier lifetime, resulting in less efficient cells in comparison to monocrystalline silicon material.

Since the final cell performance strongly depends on the material quality, there are continuing efforts to develop new ingot growth methods for higher quality mc-Si materials. The conventional approach has been to grow mc-Si ingots with larger grains in order to minimise the density of GBs in the material [1,2]. However, it was recently shown that the solar cell efficiency can also benefit from the opposite approach, with small grain size and significantly more GBs [3,4]. It has been suggested that the propagation of dislocation networks can be suppressed by the increased presence of GBs of certain types, which act as alternative sites for stress release [4,5]. Material developed based on this concept contains smaller grains, larger amounts of GBs, and lower numbers of dislocation clusters. It is commonly referred to as ‘high performance’ multicrystalline silicon, and is now being deployed in mc-Si solar cell production, with its market share expected to increase dramatically in the future.

On the other hand, while most solar cells today are based on boron doped p-type silicon, phosphorous doped n-type silicon has attracted increasing attention in the solar industry recently. N-type monocrystalline silicon solar cells with efficiencies at or above 25% have been reported by SunPower [6,7] and Panasonic [8]. A major advantage of n-type silicon is that it does not suffer from the well-known boron-oxygen-related defect, as opposed to widely used boron doped Czochralski-grown (Cz) silicon [9,10]. N-type silicon also has higher tolerance to metal impurity contamination than p-type silicon [11], making it very suitable for mc-Si material which tends to inherently contain higher metal...
contents. N-type mc-Si material therefore has the potential for low cost high efficiency solar cells, although it has not been implemented in industry.

Despite its obvious importance, direct comparisons of conventional p-type and n-type mc-Si are rare in the literature. Schindler et al. [12] compared the potential cell efficiency of p-type and n-type mc-Si materials crystallised under the same conditions, through simulations with PC1D [13] and Sentaurus [14], based on lifetime images captured using photoluminescence (PL) after different solar cell process steps. The analysis suggests a higher material related efficiency for n-type mc-Si in comparison with p-type mc-Si. In contrast, Geerligs et al. [15] evaluated the effects of phosphorous gettering and hydrogenation on crystal defects in conventional directionally solidified p-type and n-type mc-Si, and observed no fundamental difference between the p-type and n-type materials in terms of the recombination activity of crystal defects. Detailed studies on the electrical properties of high performance mc-Si are even scarcer, despite their commercial significance. Lan et al. [3] suggested that the improvement in their cell efficiency compared to conventionally-solidified mc-Si solar cells, is due to the reduction of dislocation density in the material, achieved by growing mc-Si ingot with smaller grains through nucleation and grain control.

In this work, we directly compare the recombination properties of conventionally-solidified p-type and n-type multicrystalline silicon wafers, and also recently developed high performance p-type multicrystalline wafers. Fig. 1 shows PL images of the three types of mc-Si wafers studied here. Recombination active GBs appear as dark lines, whereas dislocation networks appear as dark clusters in the PL images. As illustrated in Fig. 1, the recombination behaviour in a mc-Si wafer can be divided into three distinct regions, namely the intra-grain regions, GBs and the dislocation networks. These three distinct regions of the wafers are examined in detail in this work, along with their response to phosphorous gettering and hydrogenation. It is important to consider the influence of phosphorous gettering and hydrogenation when evaluating mc-Si materials, given that gettering and hydrogenation are incorporated in common solar cell fabrication steps during the formation of pn junctions and firing of metal contacts, and it has been shown that the electrical properties of mc-Si can change significantly after these processes [12,16–18].

The electrical properties of intra-grain regions are assessed based on their minority carrier lifetimes and diffusion lengths, which are experimentally determined as a function of injection level from PL calibrated carrier lifetime images, after applying a recently proposed carrier de-smearing technique [19] to correct for the influence of lateral carrier diffusion. The recombination activities of grain boundaries are compared quantitatively in terms of their effective surface recombination velocities ($S_{GB}$), extracted from PL imaging and 2D modelling of the emitted PL signal [20].

![Fig. 1. PL images of as-grown non-passivated mc-Si wafers from the (a) conventional p-type, (b) n-type and (c) high performance p-type mc-Si ingot studied in this work. Note that different scales were applied to the images to allow a better visual inspection of grain size, spatial distribution of GBs and dislocation networks. Examples of an intra-grain region, GB and dislocation network are highlighted in blue, magenta and red. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).](image-url)
Lastly, the recombination behaviour of dislocations is evaluated qualitatively based on PL images.

2. Experimental methods

2.1. Sample preparation

Wafers used in this work were cut from three commercially grown directionally-solidified mc-Si ingots, that is, a conventional p-type boron doped ingot, a conventional n-type phosphorous doped ingot, and a high performance p-type boron doped ingot. The conventional n-type and high performance p-type mc-Si wafers were around 180 μm and 200 μm thick respectively and have a similar background doping of around 1.2 × 10^{16} cm^{-3}. The conventional p-type mc-Si wafers were around 330 μm thick with a background doping of 1.5 × 10^{16} cm^{-3}. The resistivity of the conventional p-type, n-type and high performance p-type mc-Si wafers is around 1 Ω cm, 0.45 Ω cm and 1.25 Ω cm respectively. Wafers with similar background doping were selected in this work to avoid its impact on carrier lifetime, and therefore allow direct comparisons of lifetimes and diffusion lengths between the samples. We note that, in principle, the variation in wafer thickness could impact their response to gettering or hydrogenation to some extent. However, we expect such effects to be small given the long annealing time used for the phosphorous gettering and the high diffusivity of hydrogen at the firing temperature (700 °C) [21].

After a short chemical polishing etch using HF and HNO₃ acid to remove saw damage, sister wafers from each ingot were divided into two groups (A, B). Wafers from group A were phosphorous gettered. Phosphorous gettering was performed by subjecting the wafers to a 30 min POCl₃ diffusion at 880 °C, followed by an extended annealing in an N₂ ambient for more than 12 h at 600 °C in the same diffusion furnace, resulting in sheet resistance values of around 20 Ω/square measured using a 4-point probe. Instead of a standard industrial diffusion process, we chose to use a higher deposition temperature followed by an extended anneal in order to improve the gettering effectiveness, and maximise the global lifetime after gettering, as suggested in previous studies [22–24]. The wafers were then chemically etched to remove the phosphorous diffused layers. Afterwards, half of the sister wafers from both group A and B received silicon nitride films on both surfaces for passivation, while the other half of the wafers received silicon nitride films on the front surfaces and thin metallic aluminium films (approximately 10 nm) on the rear surfaces using thermal evaporation, to achieve instantaneous rear surface recombination conditions. The double-side passivated wafers were used to evaluate the bulk lifetime of the intra-grain regions, while the single-side passivated wafers were used to investigate dislocations and GB behaviour, using techniques described in more detail in Ref. [20].

For hydrogenation studies, all wafers had their dielectric or metallic films etched off. All samples were then re-coated with fresh silicon nitride films and were fired in a rapid thermal processing (RTP) furnace (Unitek UTP-1100) for 3 min at 700 °C in N₂ ambient to produce bulk hydrogenation. After firing, all annealed silicon nitride films were removed via HF dip and the samples were re-passivated with fresh films for lifetime measurements. All samples were chemically etched to remove around 3 μm of silicon using HF and HNO₃ acid after each removal of the surface films, to remove any surface defects which may have occurred during the firing or film deposition. The deposited silicon nitride films in this work were around 85 nm thick and were deposited with a Roth & Rau plasma enhanced chemical vapour deposition (PECVD) system with deposition temperatures between 250 °C and 300 °C.

2.2. Characterisation methods

PL images in this work were captured using a BT Imaging LIS-R1 tool with high magnification lens, giving a lateral spatial resolution of 22 μm per pixel. An 808 nm laser was used for carrier excitation. A short pass filter with a cut off wavelength of 1050 nm is fitted in the imaging lens to reduce the impact of lateral light scattering both within the sample itself and within the camera’s CCD chip. Image deconvolution using an experimentally determined point-spread function (PSF) was applied to the PL images to further reduce the impact of image blurring caused by cross-talk in the CCD chip [25].

In this work, we choose to compare both the minority carrier lifetime and diffusion length of the intra-grain regions, to allow a more meaningful comparison between the p-type and n-type wafers. The lifetimes of intra-grain regions and their injection dependence were extracted from a series of calibrated PL lifetime images captured at different laser intensities, on the double-side passivated samples, in areas far away from crystal defects. The PL images were calibrated into absolute lifetime images based on an optically corrected calibration constant extracted from monocrystalline calibration wafers, described in detail in Ref. [26]. Moreover, a recently proposed carrier de-smearing technique [19] was applied to the calibrated lifetime images to correct for the influence of lateral carrier smearing within the sample and thus to allow more accurate extraction of the intra-grain lifetime. This is important because during the conversion of PL images into lifetime images, it is typically assumed that the lateral diffusion of the minority carriers is negligible. However, such an assumption is not necessarily valid for well passivated samples with high lifetimes, when the minority carrier diffusion length is much larger than the pixel size of the images, leading to a significant underestimation of the extracted lifetime values near grain boundaries and other defects.

The recombination activity of a GB is evaluated in terms of its surface recombination velocity (S_GB), determined by fitting the simulated PL profile across the GB, modelled using a finite difference method based on the continuity equation, to an experimental PL profile extracted from a PL image. The details of the method are described in Ref. [20]. The surface recombination velocity (S_GB) represents the intrinsic recombination properties of a GB in absolute terms, and does not depend on other parameters such as the lifetime of the intra-grain regions. This allows a direct comparison of GB properties in different materials, before and after various processes.

One of the challenges of applying the PL imaging technique to study dislocations in mc-Si is carrier smearing. Dislocations tend to form closely packed loops or networks in mc-Si wafers. As illustrated in Fig. 2(a), the influence of multiple dislocation overlaps with each other and they appear as dark clusters in the PL image, making it difficult to isolate their influence and study their properties. In this work, instead of using the typical double-side passivated wafers, we investigate dislocations in single-side passivated mc-Si wafers, with an infinite surface recombination velocity at the rear surfaces, achieved by evaporating a thin layer of aluminium. As shown in Fig. 2(b), the PL image of such a single-side passivated sample is much sharper compared to the one in the double-side passivated case shown in Fig. 2(a), due to a large reduction in the carrier smearing as a result of significantly shorter effective minority carrier diffusion lengths. This allows closely packed dislocation networks to be studied more accurately. Single-side passivated samples are also used for evaluating GB behaviour for similar reasons. The infinite surface recombination at the rear surfaces is properly accounted for in the modelling and does not affect the extracted S_GB, as we have shown previously [20].
3. Results

3.1. Intra-grain regions

Fig. 3 compares the minority carrier lifetime and diffusion length of intra-grain regions in conventional p-type (p mc-Si), n-type (n mc-Si) and high performance p-type (HP p mc-Si) mc-Si wafers at an injection level equivalent to approximately 0.1 suns. The error bars denote one standard deviation of the data. The total numbers of sampled intra-grain regions are shown above the y-axis.

Fig. 2. Uncalibrated PL image (counts/s) of a (a) double-side passivated and (b) single-side passivated n-type mc-Si wafer.

although the average as-grown intra-grain lifetime of the conventional p-type samples is considerably lower than the high performance p-type samples, the difference is diminished after phosphorous gettering and hydrogenation. The results here imply that, among the intra-grain regions, the n-type material is more likely to yield a higher voltage at maximum power than the p-type materials, and both the conventional and high performance p-type materials would perform similarly, assuming other parameters affecting the device voltage remain the same. Interestingly, while hydrogenation alone is not very effective on p-type materials, it largely improves the intra-grain lifetime in the n-type samples.

In addition to minority carrier lifetime, we also compare the diffusion length. The current output of a solar cell is partly determined by the number of minority carriers that diffuse to the collecting junction before recombining, and hence is affected directly by the minority carrier diffusion length, rather than the carrier lifetime. Comparing Fig. 3(a) and (b), it can be seen that the lifetime advantage of n-type material is largely offset by its significantly lower minority carrier mobility, resulting in a similar minority carrier diffusion length. After phosphorous gettering and hydrogenation, the average diffusion length of the intra-grain regions in the n-type samples is only marginally higher than the other two p-type samples. Furthermore, we note that the diffusion lengths of all three samples are at least four times higher than a typical modern solar cell thickness (around 200 μm). In such cases its influence on the obtainable short circuit current saturates as the vast majority of the generated carriers in the base can diffuse to the junction. Under this condition, the current output of a solar cell is dominated by its optical properties and surface recombination. This suggests that the three different materials studied here are likely to have similar performance in terms of current output from the intra-grain regions (ignoring the influence of nearby GBs and dislocations).

Fig. 4 shows the injection dependant lifetime of one of the intra-grain regions in each type of mc-Si wafer after both gettering and hydrogenation. It can be seen that while there is no significant difference in terms of the intra-grain lifetime between the three mc-Si materials at 1 sun condition, a substantial variation is observed at 0.1 sun condition. The lifetimes of the p-type samples are subject to a strong injection dependence and have a considerably lower lifetime at low injection levels compared to the n-type samples. This is likely due to the fact that many of the dominant impurities in mc-Si, such as interstitial iron, act as donor levels [11] and have a higher electron capture cross-section than hole capture cross-section, hence such impurities have a more detrimental influence in p-type materials than n-type materials at low injection levels. The lifetime measurement performed at 1 sun condition reflects the solar cell performance at open circuit, whereas the measurement at 0.1 sun condition
corresponds to operating conditions close to the maximum power point, and is therefore more relevant for a working device. The injection dependence of the lifetime, particularly the reduction of lifetime between open circuit and maximum power conditions, leads to a reduction of the fill factor in a solar cell [28]. Our results indicate that the p-type materials are likely to suffer a lower fill factor than the n-type material. Note that although all samples have been passivated with silicon nitride, the extracted lifetimes could still be affected by surface recombination. Here, we also plotted the injection dependant lifetime of passivated monocrystalline control wafers which have a similar background doping to our mc-Si samples to demonstrate the quality of surface passivation and to verify that the extracted lifetime values at 0.1 sun are not surface limited.

3.2. Grain boundaries

Fig. 5 compares $S_{GB}$ of GBs from the three groups of samples before and after gettering and hydrogenation. Note that lower values of $S_{GB}$ indicate a lower recombination activity. It can be seen that the median $S_{GB}$ value of GBs from conventional p-type samples after gettering and hydrogenation is considerably higher than the n-type material. Note that although all samples have been passivated with silicon nitride, the extracted lifetimes could still be affected by surface recombination. Here, we also plotted the injection dependant lifetime of passivated monocrystalline control wafers which have a similar background doping to our mc-Si samples to demonstrate the quality of surface passivation and to verify that the extracted lifetime values at 0.1 sun are not surface limited.

and our quantification method is not sensitive to inactive GBs ($S_{GB} < 200 \text{ cm/s}$). This is confirmed by Electron Backscatter Diffraction (EBSD) measurements, which indicate that around 75% of the sampled GBs in the conventional p-type samples are RA GBs. The lower recombination activities of GBs in high performance mc-Si could contribute to the improvement in its cell performance in comparison with conventional p-type mc-Si solar cells, considering that there is little variation in their lifetime in the intra-grain region, as described above. Note that GBs in conventional p-type, high performance p-type and conventional n-type samples exhibit distinctive behaviour in response to the various process steps.

The influence of gettering and hydrogenation on GBs is evaluated through inspecting the response of individual GBs to each process. The results are summarised in Fig. 6. Our results show that phosphorous gettering increases the recombination strength
of all the GBs in the p-type wafers and most of the GBs in the n-type wafers. We suggest that it is due to the high temperature applied during the process or the rapid quenching afterward that causes a redistribution of impurities near the GBs [30–32].

In contrast, hydrogenation reduces the recombination strength of all the gettered GBs. Although the benefits of hydrogenation are clear, it appears that the effectiveness of hydrogen passivation strongly varies among different materials, as demonstrated in Fig. 5(c), which shows that the net influence of phosphorous gettering and hydrogenation varies largely for the three sets of samples. As-grown GBs in high performance p-type samples tend not to be recombination active and become more recombination active after both gettering and hydrogenation. On the other hand, GBs in n-type samples show a completely opposite response. They are recombination active in the as-grown state, but show a dramatic reduction in their recombination strength after gettering and hydrogenation, with their $S_{GB}$ values dropping below the detection limit of our method. We speculate that this could be related to the charge state of hydrogen. Most of the monatomic hydrogen is positively charged during the high temperature process [33], and hence they may be more likely to bond with detrimental negatively charged impurities in n-type materials due to coulombic attraction, improving the effectiveness of hydrogenation. GBs from the conventional p-type samples have a more varied response. Some of the GBs become more recombination active, whereas others become less active. This varied response could be attributed to variation in the GB geometry or type, which can have an impact on the ability to aggregate metal impurities [34,35].

It should be mentioned that our finding, however, is contrary to the results of Geerligs et al. [15], who observed little difference in the recombination activity of crystal defects between n-type and p-type mc-Si. We note that in general the electrical properties of crystal defects can be strongly affected by the impurity content and the thermal history of the ingot, which can vary to a large extent depending on the casting conditions. The process conditions, such as the temperature used for the gettering or hydrogenation, can also affect the results.

3.3. Dislocations

As mentioned above, dislocations tend to form small and closely pack loops in mc-Si. Limited by the spatial resolution of our PL images, we could not apply our method used in investigating GBs to evaluate the $S_{eff}$ of dislocations. Here, we assess the recombination properties of dislocations qualitatively based on PL images of single-side passivated wafers. Although only qualitative, this gives a picture of the recombination behaviour of dislocations before and after gettering and hydrogenation. The results are summarised in Fig. 7. The recombination behaviour of dislocations in conventional p-type and n-type samples is qualitatively similar. Most of them are already recombination active in the as-grown state before any processing. Gettering further increases their recombination strength. Hydrogenation neutralises part of the changes induced by gettering, and in some cases can even reduce the recombination activity to levels lower than those present in the as-grown state.

![Fig. 7. PL images of dislocation clusters in conventional p-type (p mc-Si), high performance p-type (HP p mc-Si) and conventional n-type (n mc-Si) wafers. The PL images are normalised against the PL intensity of an intra-grain region far away from the dislocations. The same scale is applied in all the images.](image-url)
Comparing dislocations in conventional p-type and n-type samples, it can be seen that the advantage of the high immunity to metal impurities in n-type material, as evident in the high intra-grain lifetimes shown above, does not apply at dislocations, indicating the possibility that crystal defects such as dislocations might have different origins of their recombination activities in comparison to intra-grain regions. This is supported by the study of Buonassisi et al. [30], who observed that nanoprecipitates containing elements with higher atomic flux such as copper and nickel are mainly found at structural defects, whereby particles of low-flux species such as titanium often appear within the intra-grain regions.

Surprisingly, dislocations in high performance mc-Si exhibit a distinct behaviour. Similar to GBs in high performance mc-Si, as-grown dislocations are not recombination active and only become active after either gettering or hydrogenation. Note also that, as illustrated from Fig. 1, the high performance mc-Si sample contains a much lower density of dislocation clusters compared to the two conventionally grown wafers.

3.4. Impact on device parameters

We performed a simulation using QCell [36] to model the dependence of $V_{oc}$, $I_{sc}$ and $\eta$ on the material bulk lifetime. P-type silicon is chosen for the simulation. As shown in Fig. 8, the solar cell efficiency starts to saturate when the bulk lifetime reaches a certain value (around 200 – 300 $\mu$s). Simulations on n-type material reveals equivalent results. The solar cell efficiency in such cases is more limited by other factors such as the optical properties or surface recombination. As shown previously, the average lifetimes of the intra-grain regions for all three mc-Si samples after gettering and hydrogenation are at least above 200 $\mu$s, suggesting that the performance limiting factors in the three materials studied here are indeed recombination at GBs and dislocations.

Recombination active GBs and dislocations lead to a local reduction of lifetime and excess carrier concentration at the defects, resulting in a local reduction of both the open circuit voltage and the short circuit current, as demonstrated in Fig. 8. The local fill factor may also be lower as some crystal defects exhibit strong injection dependence, being more recombination active at lower injection levels [32,37,38]. Apart from the defects themselves, areas adjacent to the defects are also affected by the defects due to lateral carrier diffusion. The spatial extent of these effects depends not only on the intrinsic recombination properties of the defects, but also on other factors such as the surface conditions, the carrier diffusion length and the device operating conditions. Surface recombination reduces the overall impact of crystal defects as it acts as another competing recombination channel for carriers. By contrast, heavily doped layers at the surface provide additional paths for lateral carrier transport, hence further extending the region of influence of crystal defects [32]. Moreover, the range of influence of crystal defects tends to be larger under open circuit conditions in comparison to short circuit conditions. Under open circuit conditions, carriers can flow freely from the intra-grain regions to the crystal defects either via the heavily doped regions or via bulk diffusion [39,40]. Under short circuit conditions, most of the carriers that reach pn junction are more likely to be collected at metal contacts and extracted to external circuit rather than flowing into GBs or dislocations.

The behaviour of a complete mc-Si device is rather complex. In addition to the factors discussed above, other factors such as the density of crystal defects and their spatial distribution can all affect the performance of a large area mc-Si solar cell. Dislocation networks tend to be concentrated locally within several grains, whereas GBs are more equally distributed across the wafers. 2D or 3D modelling is required to properly simulate a mc-Si device [12,39–41], such modelling, however, is beyond the scope of this work. The emphasis of this work is to obtain a better understanding of the electrical behaviour in various types of mc-Si materials before and after gettering and hydrogenation. The work can be used as a reference to determine the key performance limiting factors in mc-Si solar cells and develop methods to improve their efficiency.

4. Conclusion

We have performed a direct comparison of the electrical properties of conventional p-type, n-type and high performance p-type mc-Si materials. It is found that the intra-grain lifetimes of the n-type samples can reach 1 ms or above and are considerably higher than the two p-type materials studied here. Nevertheless, among the intra-grain regions, all samples reveal high diffusion lengths after gettering and hydrogenation, indicating that the main performance limit factors in mc-Si are likely to be recombination at crystal defects. GBs in conventional p-type samples are more recombination active than those in high performance p-type and conventional n-type samples. Phosphorous gettering increases the recombination strength of most of the GBs. Hydrogenation is most effective on getterted n-type samples, being able to neutralise the influence of gettering and in fact deactivate most of the GBs. Hydrogenation, however, can only offset part of the increase in $S_{GB}$ induced by gettering in p-type samples. In terms of dislocations, the recombination behaviour of dislocations in conventional p-type and n-type samples is qualitatively similar, being already very recombination active in the as-grown state and becoming even worse after gettering. Their recombination strength reduces after hydrogenation, but does not disappear completely. Similar to GBs, as-grown dislocations in high performance mc-Si are not recombination active and they only become active after gettering or hydrogenation. Overall, among the three materials studied in this work, it is expected that both the conventional n-type and the high performance p-type mc-Si samples would outperform the conventional p-type mc-Si sample. The main advantage of the n-type mc-Si material is its superior electrical properties in the intra-grain regions and GBs, especially after both gettering and hydrogenation. The benefit of the high performance p-type mc-Si material is that it contains significantly fewer dislocation networks. Combining the advantages of both of these materials in a high performance n-type mc-Si ingot may prove to be the ideal multicrystalline silicon material for high efficiency low cost solar cells, due to its anticipated properties of high intra-grain lifetimes, relatively inactive GBs, and reduced frequency of dislocation networks.
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