

Article

Effect of Heating Temperatures During Thermal Processes on the Electrical Properties of Cast Multi-Crystalline Silicon

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Abstract

Photoluminescence (PL) imaging techniques combined with a minority carrier lifetime measurement system were utilized to investigate the effects of heating temperature on the interstitial iron (Fe_i) concentration, the recombination activity of structural defects, and the minority carrier lifetime in cast multicrystalline silicon (mc-Si). The results indicate that heating mc-Si wafers to 800 °C followed by natural cooling led to a 21.4% increase in Fe_i concentration, a 121% increase in recombination-active dislocations, a 142% increase in recombination-active grain boundaries, a 158% rise in the “dark area percentage,” and a 46.6% decrease in minority carrier lifetime. When the heating temperature was increased to 1000 °C followed by natural cooling, the Fe_i concentration rose by a factor of 11.87, and the “dark area percentage” increased by 8668%, suggesting widespread metal impurity—particularly iron contamination across the entire wafer, which resulted in an extremely low minority carrier lifetime of only 0.224 μs.

Keywords: cast multicrystalline silicon; heating temperature; interstitial iron; structural defects; recombination-activity

1. Introduction

The cast multicrystalline silicon (mc-Si) was once regarded as one of the primary materials for fabricating solar cells due to its relatively low production cost. However, the presence of a large number of structural defects and higher concentrations of metallic impurities in mc-Si lead to reduced cell efficiency [1–3], thereby limiting its application in solar cells. In recent years, with the continuous decrease in the production cost of monocrystalline silicon (mono-Si), the dominant position of cast mc-Si in photovoltaic cell materials has been gradually replaced by mono-Si, leading to a decline in its market share within the photovoltaic industry [4]. To minimize or eliminate undesirable effects, narrow the performance gap between mc-Si and mono-Si, and re-establish the cost advantage of cast mc-Si, it is crucial to investigate the impact of metal impurities and structural defects on the electrical properties of cast mc-Si. Iron is the most prevalent and electrically active transition metal contaminant in cast mc-Si, owing to its high solid solubility, strong non-radiative recombination cross-section, and frequent introduction during wafer handling and solar cell fabrication—particularly through direct contact with iron-containing tools, fixtures, and processing equipment [5]. As a result, iron contamination typically exceeds that of other metallic impurities in as-received mc-Si wafers, rendering it the dominant focus of both industrial quality control protocols and fundamental defect physics studies [6–9].



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A significant body of research demonstrates that the electrical properties of metallic impurities and structural defects in crystalline silicon are highly sensitive to high-temperature heating processes [10–13]. Our prior investigations have shown that the minority carrier lifetime decreases with increasing cooling rates, a phenomenon referred to as thermally induced degradation (TID) of the minority carrier lifetime [14,15]. This implies that the photoelectric conversion efficiency of solar cells may potentially be diminished during thermal processing steps involved in the fabrication of silicon wafer-based solar cells, such as phosphorus diffusion, annealing, and electrode sintering. It is widely accepted that the TID of the minority carrier lifetime arises from the formation of smaller and more dispersed recombination centers [10–12], substitutional boron atoms, and additional iron-related defects [16,17] during high-temperature treatments.

In order to further investigate the causes of TID, we employed photoluminescence (PL) imaging technology and a minority carrier lifetime testing system to study the influence of cooling rate during the thermal process on the recombination characteristics of grain boundaries and dislocation defects in cast mc-Si [18]. The results indicate that when mc-Si wafers are heated to high temperatures and subsequently cooled to ambient temperature at varying rates, both the Fe concentration and the density of recombination-active dislocations and grain boundaries increase with higher cooling rates, while the minority carrier lifetime decreases. Building upon prior research, this study still applied PL imaging techniques and the minority carrier lifetime testing system to analyze changes in the electroactivity of structural defects and Fe concentration in response to different heating temperatures.

2. Methods

Three p-type sister wafers (156 mm × 156 mm), fabricated from a cast mc-Si ingot supplied by Jinko Solar (Shangrao, Jiangxi, China), were selected for this analysis. These wafers, which are adjacent vertical slices derived from the same ingot, exhibit nearly identical initial crystal structures, grain morphologies, and chemical compositions. Their resistivity ranges between 1 and 3 Ω cm, with a thickness of 180 μm. The total iron concentration—including both Fe_i and Fe in precipitates—was quantified using inductively coupled plasma mass spectrometry (ICP-MS) on a NexION5000G instrument (PerkinElmer, Waltham, MA, USA) for the same batch of wafers and found to be $3.9 \times 10^{14} \text{ cm}^{-3}$. The Fe_i concentration was quantified independently using different lifetime measurement techniques, as detailed in the following section.

The first wafer was left unprocessed and served as a reference sample. Under the protection of high-purity argon gas, the second wafer was heated to 800 °C, while the third wafer was heated to 1000 °C. Both wafers were maintained at their respective temperatures for 30 min and subsequently cooled naturally to room temperature (with an average cooling rate of approximately 30 °C/s). Following heat treatment, the two wafers were immersed in a 10 wt.% hydrofluoric acid (HF) solution to remove the oxide layer from their surfaces. They were then rinsed with deionized water and dried using nitrogen gas.

The minority carrier lifetime was measured using the microwave-induced photoconductive decay (μ-PCD) method, and the Fe_i concentration was assessed through different lifetime measurement techniques [19–22]. The Fe_i concentration [Fe_i] can be determined by measuring the carrier lifetime before and after breaking Fe_i-B pairs in a boron-doped p-type silicon sample. The iron concentration is quantified by

$$[Fe_i] = C_{\mu\text{-PCD}} \left(\frac{1}{\tau_{\text{before}}} - \frac{1}{\tau_{\text{after}}} \right)$$

where τ_{before} and τ_{after} represent the lifetimes measured before and after dissociating the Fe_i-B pairs, respectively. The conversion factor $C_{\mu\text{-PCD}}$ depends on the injection level,

capture cross-sections of the Fe_i and $\text{Fe}_i\text{-B}$ states, and the doping concentration. According to the user manual, based on the injection level during the measurement of minority carrier lifetime, $C_{\mu\text{-PCD}}$ is $3.4 \times 10^{13} \mu\text{s}/\text{cm}^3$ [21].

The PL imaging was performed using the PLI-1001A tester (Semilab, Budapest, Hungary) to visualize grain boundaries and dislocations, thereby assessing the recombination activity of structural defects. Subsequently, the samples were etched in an acid mixture solution ($\text{HF}:\text{HNO}_3 = 1:3$) to achieve a polished surface. The minority carrier lifetime was then measured by employing a surface-passivation technique, wherein the wafers were encapsulated in a plastic bag filled with a 0.08 mol/L iodine solution to minimize the influence of surface recombination.

3. Results and Discussion

3.1. Effect of Heating Temperatures on the Interstitial Iron Concentration

Figure 1 presents the distribution maps of Fe_i concentration in the wafers: (a) as-received, (b) after being heated at 800 °C and subsequently naturally cooled, and (c) after being heated at 1000 °C and subsequently naturally cooled.

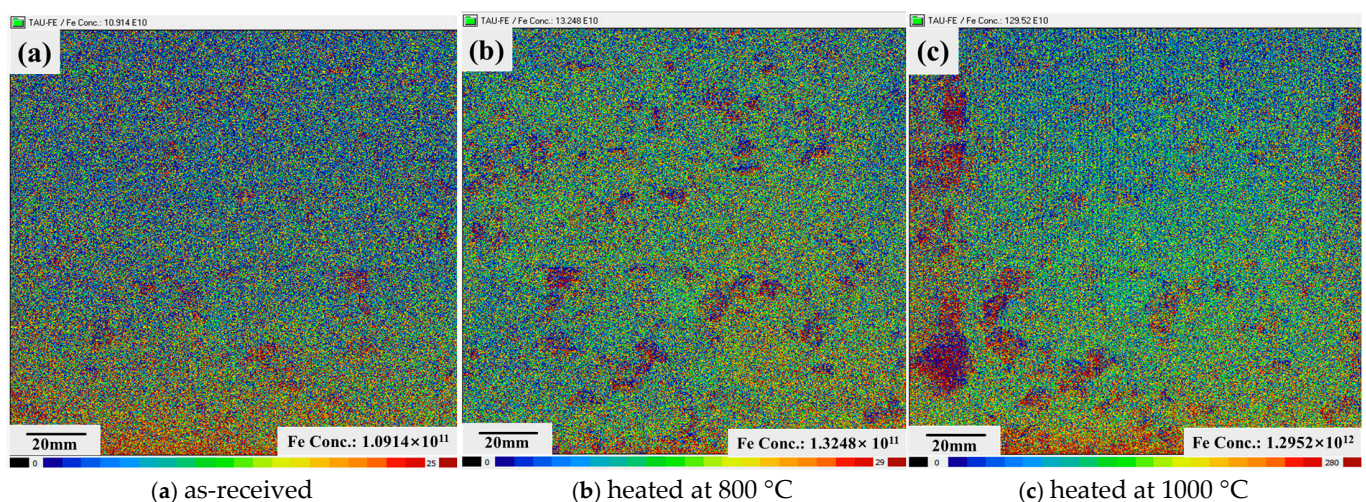


Figure 1. The Fe_i concentration maps and average Fe_i concentration in (a) the as-received wafer and its sister wafers: (b) after being heated at 800 °C and subsequently naturally cooled, and (c) after being heated at 1000 °C and subsequently naturally cooled. (Author’s note: resolution has been enhanced).

As illustrated in Figure 1, the Fe_i concentration exhibits a uniform and spatially homogeneous distribution in the as-received wafer as well as in the wafers subjected to thermal treatment at 800 °C and 1000 °C. The Fe_i concentration in the wafers increases to varying degrees after being subjected to heating at temperatures of 800 °C and 1000 °C, compared to the as-received wafer. Specifically, the Fe_i concentration increases with the rise in heating temperature. Following heat treatment at 800 °C and 1000 °C, the Fe_i concentration increased from $1.09 \times 10^{11} \text{ cm}^{-3}$ in the as-received wafer to $1.33 \times 10^{11} \text{ cm}^{-3}$ and $1.30 \times 10^{12} \text{ cm}^{-3}$, respectively, representing increases of 21.4% and 11.87 times. These observations are consistent with the previously published findings from our research group [14].

The iron impurities in cast mc-Si predominantly exist in three forms: iron silicide precipitates, primary undissolved inclusions, and interstitial iron atoms [23]. The total iron concentration in cast mc-Si wafers used in this experiment is $3.9 \times 10^{14} \text{ cm}^{-3}$, encompassing all three aforementioned forms. However, the Fe_i concentration measured in this study specifically refers to the concentration of interstitial iron atoms alone. Additionally, Table 1 lists the total iron concentrations of previously tested samples, the solid solubility of iron in silicon at 800 °C and 1000 °C calculated using the formula of solid solubility of iron in

silicon [24]— $5 \times 10^{22} \exp(8.2-2.94 \text{ eV/k})$ ($900^\circ\text{C} < T < 1200^\circ\text{C}$)—and the Fe_i concentrations of each sample after heating at 800°C and 1000°C followed by natural cooling.

Table 1. Total iron concentration of wafers and calculated values of iron solid solubility in silicon and measured Fe_i concentration $[\text{Fe}_i]$ in wafers after heating at 800°C and 1000°C followed by natural cooling.

Heating Temperature	Total Iron Concentration (cm^{-3})	Iron Solid Solubility in Silicon Calculated by $5 \times 10^{22} \exp(8.2-2.94 \text{ eV/kT})$ [24]		Measured $[\text{Fe}_i]$ in Wafers		
		Calculated Values (cm^{-3})	Ratio of Total Iron Concentration (%)	Measured Values (cm^{-3})	Ratio of Fe Dissolved During Heating (%)	Ratio of Total Iron Concentration (%)
as-received	3.9×10^{14}			1.09×10^{11}		0.028%
800°C		2.9×10^{12}	0.75%	1.33×10^{11}	4.5%	0.034%
1000°C		4.1×10^{14}	>100%	1.30×10^{12}	0.33%	0.33%

It can be seen from Table 1 that, for the as-received wafer, the slow cooling process, which lasts approximately ten hours after directional solidification of the cast mc-Si, provides sufficient time for supersaturated metal impurities, which were dissolved at high temperatures, to aggregate and form coarse precipitates, thereby effectively purifying the silicon crystal matrix. At this time, the Fe_i concentration is relatively low. The measured value in this experiment is $1.09 \times 10^{11} \text{ cm}^{-3}$, accounting for only 0.028% of the total iron concentration.

For the wafer heated at 800°C , the relatively low heating temperature led to a calculated solid solubility of iron in silicon of $2.9 \times 10^{12} \text{ cm}^{-3}$, which corresponds to 0.75% of the total iron concentration. This implies that at 800°C , 0.75% of the total iron dissolve as interstitial iron atoms and be uniformly distributed within the silicon crystal lattice, while the majority of the remaining iron impurities remain as precipitates and inclusions in the silicon matrix. During the subsequent natural cooling process, only 4.5% of the interstitial iron atoms remained in the silicon lattice due to insufficient time for diffusion and precipitation. Consequently, 95.5% of the iron atoms re-precipitated during natural cooling. Although the retained interstitial iron atoms account for only 0.034% of the total iron content, this still resulted in a 21.4% increase in the Fe_i concentration in the ms-Si wafer compared to the as-received wafer.

For the wafer heated at 1000°C , the relatively high temperature increases the solid solubility of iron in silicon, exceeding the total iron concentration of wafer. This suggests that all iron impurities at 1000°C can dissolve into the crystal silicon lattice as interstitial iron atoms. During the subsequent natural cooling process, 0.33% of these interstitial iron atoms remain trapped within the silicon lattice due to insufficient time for diffusion and precipitation. Consequently, the Fe_i concentration in the sample reaches $1.30 \times 10^{12} \text{ cm}^{-3}$, which is approximately 11.87 times higher than that of the as-received wafer. From the above analysis, it is evident that as the heating temperature increases, more precipitates and impurities in the original cast mc-Si dissolve into the silicon matrix, leading to the generation of more interstitial iron atoms. Consequently, a larger proportion of these interstitial iron atoms remain within the silicon lattice after cooling.

3.2. Effect of Heating Temperatures on the Recombination Activity of Structural Defects

Figure 2 presents the PL images of (a) the as-received wafer and its sister wafers: (b) after being heated to 800°C followed by natural cooling, and (c) after being heated to 1000°C followed by natural cooling, respectively. The purple and green colors in the images were automatically assigned by the equipment.

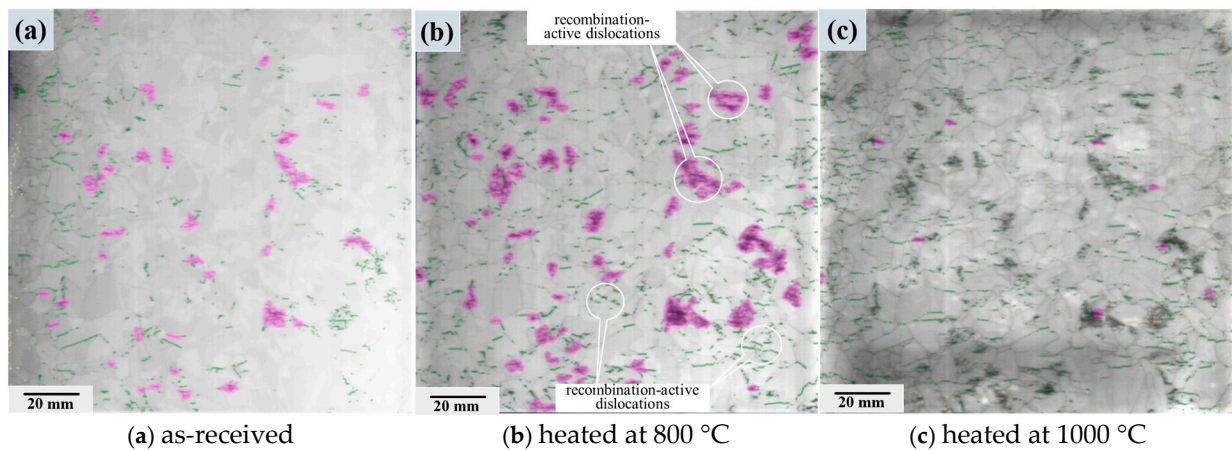


Figure 2. PL image of (a) the as-received wafer and its sister wafers: (b) after being heated at 800 °C and subsequently naturally cooled, and (c) after being heated at 1000 °C and subsequently naturally cooled.

The purple areas represent regions of recombination-active dislocations, where the carrier lifetime differs from that of the surrounding material by at least the lifetime value defined as the “defect area limit” (0.35 μ s). The ratio of the area of the purple region to the total area of the wafer is defined as “Defect Area Percent”. Similarly, the green areas indicate recombination-active grain boundary regions, and the corresponding area ratio is referred to as “Grain Defect Area Percent” [25]. PL images also exhibit “Dark Areas,” which refer to regions on the wafer where the carrier lifetime falls below the absolute threshold specified in the recipe, known as the “Dark Limit (1 μ s).” The proportion of these dark areas relative to the total wafer area is termed the “Dark Area Percent”. Table 2 summarizes the PL test results for the as-received wafer, along with wafer heated at 800 °C and 1000 °C, respectively.

Table 2. The PL test data for the as-received wafer, along with wafer heated at 800 °C and 1000 °C by PLI-1001A Tester.

Heating Temperature	Defect Area Percent (Marked in Purple)	Grain Defect Area Percent (Marked in Green)	Dark Area Percent
as-received	1.95%	1.26%	0.95%
800 °C	4.33%	3.05%	2.45%
1000 °C	0.15%	2.71%	83.30%

In the as-received wafer, as depicted in Figure 2a, both the proportion of recombination-active dislocations (marked in purple) and recombination-active grain boundaries (marked in green) are relatively low, with the Defect Area Percent and Grain Defect Area Percent being 1.95% and 1.26%, respectively, as shown in Table 2. This suggests that the defects in the as-received wafer exhibit favorable electrical properties. For the wafer heated at 800 °C, as illustrated in Figure 2b, there is a noticeable increase in both the purple and green regions. Specifically, the proportions of recombination-active dislocations and recombination-active grain boundaries rise to 4.33% and 3.05%, respectively, as indicated in Table 2. Compared to the as-received wafer, these represent increases of 122% and 142%. These findings indicate that the number of recombination-active dislocations and grain boundaries in the cast mc-Si wafers significantly increases after heating at 800 °C.

Pristine dislocations and grain boundaries—i.e., those free of metal decoration or aggregation—exhibit negligible electrical activity and therefore do not function as effective recombination centers; consequently, they exert minimal influence on the electrical properties of cast mc-Si [26–29]. In contrast, upon contamination by mobile metal impurities—most notably interstitial iron—their electronic activity increases markedly, transforming them into electrically active recombination sites. The electrical activity of

these defects, and consequently the electrical properties of silicon, are closely related to the aggregation state of metal impurities—particularly iron. Fine and dispersed precipitates or atomic aggregates significantly reduce the minority carrier diffusion length [5,6], and the associated dislocations and grain boundaries exhibit strong electrical activity.

For the as-received wafer, as discussed in Section 3.1, the slow cooling process, which lasts approximately ten hours following the directional solidification of cast mc-Si, allows supersaturated metal impurities such as iron to fully aggregate and form coarse precipitates. This process effectively purifies the silicon crystal matrix. Consequently, dislocations are seldom decorated by metallic impurities, and there is minimal spatial density of aggregation of metal precipitates at the grain boundaries. Moreover, the concentration of interstitial iron atoms remains relatively low, leading to reduced electrical activity of defects, which results in comparatively favorable electrical properties, as illustrated in Figure 2a and Table 2.

As analyzed in Section 3.1, heating cast mc-Si to 800 °C results in the dissolution of certain iron silicide precipitates and inclusions. During subsequent natural cooling, this process promotes the formation of finer and more uniformly distributed iron precipitates, accompanied by a 21.4% increase in Fe_i concentration relative to the as-received wafer. The resultant interstitial iron atoms, together with the finely dispersed precipitates, exhibit a heterogeneous distribution across grain interiors, dislocations, and grain boundary regions. This redistribution enhances the electrical activity of dislocations and grain boundaries, resulting in increased optical darkening observed in the PL image, as illustrated in Figure 2b and Table 2.

Figure 2c shows the PL image of the cast mc-Si wafer after being heated at 1000 °C and naturally cooled. By comparing Figure 2a,b, it can be observed that the purple areas have nearly disappeared, and the area of the green regions has increased compared with the as-received wafer, exhibiting an area comparable to that of the wafer heated at 800 °C. The data in Table 2 also correspond to the observations in the PL image. Compared with the as-received wafer, the Defect Area Percent (marked in purple) of the wafer heated at 1000 °C decreased from 1.95% to 0.15%, while the Grain Defect Area Percent (marked in green) increased from 1.26% to 2.71%, which is similar to the result obtained for the wafer heated at 800 °C. Although the wafer heated at 1000 °C appears to exhibit relatively good electrical properties, this is an illusion caused by the limitations of the PL testing method. From the PL image, it is evident that the grains, grain boundaries, and dislocations of the wafers heated at 1000 °C all appear grayish black. The test data in Table 2 show that the Dark Area Percent increased from 0.95% for the as-received wafers to 83.30%, representing an increase of approximately 8668%. This indicates that 83.30% of the wafer area has been affected by metal impurities—particularly iron contamination, leading to a significant drop in minority carrier lifetime to below 1 μ s. This decline suggests that the electrical activity of the matrix, dislocations, and grain boundaries is very high, which in turn results in poor overall electrical performance of the wafer. Why does the electrical performance of cast mc-Si wafer deteriorates significantly after heat treatment at 1000 °C? Furthermore, why does the PL measurement yield a low Defect Area Percent value (represented by the purple regions) that contradicts the actual electrical performance? As shown in Table 1, when the cast mc-Si wafer is heated to 1000 °C, all iron impurities dissolve into the silicon matrix. During the subsequent natural cooling process, due to the high cooling rate (approximately 30 °C/s) and significant degree of undercooling, the majority of the metal—particularly iron atoms that dissolved at high temperature—undergo uniform nucleation within the grains. At this stage, the rapid rate of metal—particularly iron precipitation—leads to the formation of an extremely fine and dispersed precipitate state of approximately 96.7% of the iron impurities, which are located at the grain boundaries, dislocations, and within the crystal grains. The remaining 3.3% of the iron impurities remain in atomic form, often referred to as “frozen” states, and are not only found at grain boundaries and dislocations

but are also widely distributed within the grains. Consequently, the recombination-active regions throughout the crystal increase significantly, resulting in widespread contamination of the wafer by metallic impurities particularly iron. As a result, the electrical performance of the wafer is severely degraded. The Defect Area Percent (represented by the purple areas) is defined as “the area covered by dislocations where the minority carrier lifetime differs from the surrounding region by at least the value specified in the recipe as the ‘Defect Area Limit’.” The “Defect Area Limit” set by the PL tester is $0.35\ \mu\text{s}$. Due to the contamination of the silicon substrate by metallic impurities such as iron, the difference in minority carrier lifetime between dislocation regions and the surrounding areas is mostly below this threshold. As a result, in the PL imaging map of the tested wafer, the purple area accounts for only 0.15%, and the entire substrate, including grain boundaries and dislocations, appears gray-black. Meanwhile, the “Dark Area Percent” has increased dramatically from 0.95% in the as-received wafer to 83.30%, representing an increase of 8668%. This indicates a significant decline in the overall electrical quality of the wafer.

3.3. Effect of Heating Temperatures on the Minority Carrier Lifetime

Figure 3 shows the minority carrier lifetime mapping of (a) the as-received wafer and its sister wafers: (b) after heating to $800\ ^\circ\text{C}$ followed by natural cooling, and (c) after heating to $1000\ ^\circ\text{C}$ followed by natural cooling, respectively. As shown in Figure 3, the minority carrier lifetime of the as-received wafer is $10.60\ \mu\text{s}$. After heating to $800\ ^\circ\text{C}$ and subsequent natural cooling, the minority carrier lifetime decreases to $5.68\ \mu\text{s}$. When the wafer is heated to $1000\ ^\circ\text{C}$ and then naturally cooled, the minority carrier lifetime further decreases to $0.22\ \mu\text{s}$. These results indicate that high-temperature thermal treatment significantly reduces the minority carrier lifetime, with a more pronounced reduction at higher temperatures.

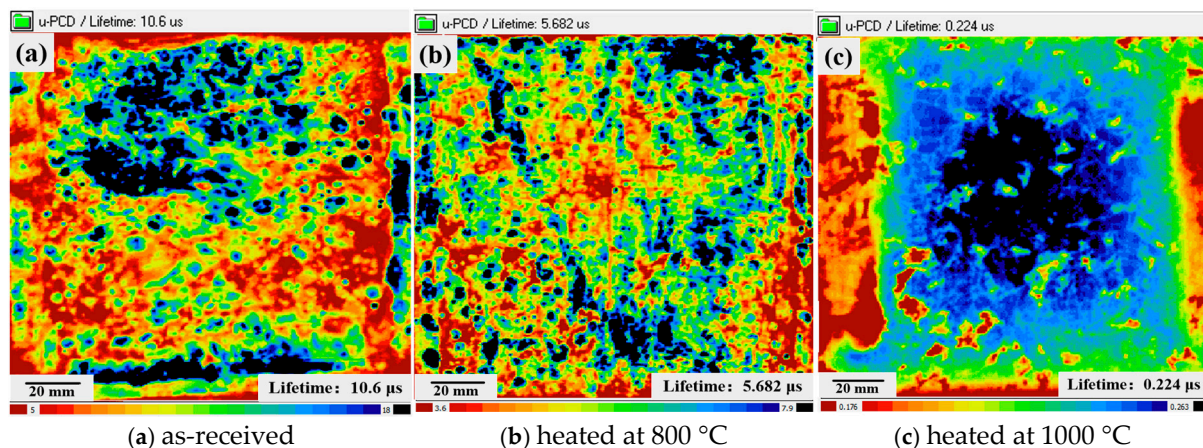


Figure 3. Minority carrier lifetime mapping and average lifetime of (a) the as-received wafer and its sister wafers: (b) after being heated at $800\ ^\circ\text{C}$ and subsequently naturally cooled, and (c) after being heated at $1000\ ^\circ\text{C}$ and subsequently naturally cooled.

The above experimental results are closely related to those presented in Sections 3.1 and 3.2: (1) According to the experimental results in Section 3.1, when cast mc-Si is subjected to high-temperature heating, the iron precipitates within the material either partially or completely dissolve, releasing a significant amount of Fe_i atoms and thereby increasing the Fe_i concentration in silicon. Although both the dissolved iron precipitates and Fe_i atoms act as deep-level centers, Fe_i atoms exhibit a more dispersed distribution within the crystal lattice. This leads to an increased spatial density of deep-level centers, which in turn significantly reduces the minority carrier lifetime in cast mc-Si. The extent of this effect correlates positively with the heating temperature—higher temperatures result

in greater Fe atoms release and more pronounced degradation of minority carrier lifetime. (2) In this study, after the cast mc-Si is heated at a high temperature and subsequently naturally cooled, compared to the slow cooling process following directional solidification of the original cast mc-Si, the newly formed iron precipitates are finer and more dispersed due to the higher cooling rate, greater degree of undercooling, and increased nucleation rate. Consequently, the spatial density of deep-level centers within the silicon crystal also rises. Furthermore, an increase in heating temperature and cooling rate leads to a higher spatial density of iron precipitates and a more significant reduction in minority carrier lifetime. (3) As shown in the experimental results presented in Section 3.2, high-temperature heating enhances the density of recombination-active grain dislocations and boundaries in cast mc-Si, which consequently leads to a reduction in the minority carrier lifetime. This effect becomes more pronounced with increasing heating temperature, as a higher temperature results in a greater increase in recombination-active defects, thereby causing a more significant decrease in minority carrier lifetime. This may adversely affect the photovoltaic conversion efficiency of resulting solar cells.

The cooling process can induce dislocation multiplication and enhance the population of recombination-active dislocations. To identify the dominant mechanism underlying the observed increase in recombination-active dislocation density, the research team conducted a controlled thermal annealing experiment using a batch of as-cast mc-Si wafers. The samples were heated to 1000 °C, held isothermally for 30 min, and subsequently cooled to room temperature at a precisely controlled rate of 0.05 °C/s. Quantitative characterization revealed that, following annealing, the average dislocation density increased by only 3.5%, whereas the recombination-active dislocation density rose by 169% [18]. This pronounced disparity strongly suggests that the surge in recombination-active dislocations is primarily attributable not to a general increase in dislocation density, but to the decoration of pre-existing dislocations by metallic impurities—most notably interstitial iron.

The thermodynamic and kinetic principles governing the dissolution of metal precipitates during thermal process in crystalline silicon—and the influence of impurity aggregation versus dispersion on electrical properties—are fundamentally universal across transition metal impurities. Consequently, the experimentally observed relationship between heating temperature, the quantitative and qualitative features of PL imaging, and electrical properties of cast mc-Silicon is broadly applicable to other metal impurities.

4. Conclusions

We investigated the effects of heating temperatures on the Fe_i concentration, electrical activity of structural defects, and minority carrier lifetime in cast mc-Si. PL imaging and minority carrier lifetime measurements revealed that after heating the cast mc-Si wafer at 800 °C followed by natural cooling, the Fe_i concentration increased by 21.4%, the recombination-active dislocations and grain boundaries increased by 121% and 142%, respectively, the “dark area percent” increased by 158%, and the minority carrier lifetime decreased by 46.6%. When the wafer was heated at 1000 °C followed by natural cooling, the Fe_i concentration increased by 11.87 times, and the “dark area percent” increased by 8668%, indicating severe metal impurity—particularly iron contamination across the entire wafer and an extremely low minority carrier lifetime (0.224 μ s). These experimental results demonstrate that heating cast mc-Si wafers above 800 °C leads to an increase in Fe_i concentration as well as in the density of recombination-active structural defects, which in turn reduces the minority carrier lifetime. Higher heating temperatures result in greater increases in Fe_i concentration and the density of electrically active defects, leading to more pronounced degradation of minority carrier lifetime.

The results confirmed that high-temperature thermal processing induces both an increase in interstitial iron concentration and electrically active defect density in crystalline silicon, resulting in reduced minority carrier lifetime. Concurrently, it promotes deformation and defect generation within the silicon wafer. Collectively, these effects degrade the power conversion efficiency and operational longevity of photovoltaic cells. Accordingly, minimizing high-temperature thermal exposure during crystalline silicon photovoltaic cell fabrication is strongly recommended.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

PL	Photoluminescence
Fe _i	The interstitial iron
mc-Si	Multicrystalline silicon
mono-Si	Monocrystalline silicon
TID	Thermally induced degradation
ICP-MS	Inductively coupled plasma mass spectrometry
μ-PCD	Microwave-induced photoconductive decay

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