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Gettering improvements of minority-carrier lifetimes in solar grade silicon

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ABSTRACT

The minority-carrier lifetime in p-type solar-grade silicon (SoG-Si) produced by Elkem Solar was investigated after different types of heat treatment. Two groups of samples differing by the as-grown lifetimes were exposed to internal and phosphorus gettering using constant and variable temperature processes. Optimal heat-treatment parameters for each group of samples were then identified which improved the minority-carrier lifetimes to values higher than the minimum value needed for solar cells. Phosphorus gettering using a variable temperature process enhanced in particular the lifetime within each group, increasing in certain cases the lifetime from 3 up to 81 μs.

1. Introduction

Solar-grade silicon produced by the metallurgical route (SoG-Si) has recently attracted attention due to its low wafer cost and high-volume production. Simultaneously, the quality of this material has improved, and efficiencies of solar cells fabricated from SoG-Si have attained values of 16%–18% [1–3]. They remain, however, still lower than the highest efficiencies of multicrystalline Si (mc-Si) solar cells of 16%–20% [4], and monocrystalline Si solar cells of 18%–25% [5,6]. So there is room for improvements. The solar cell performance strongly depends on type and concentration of impurities, type of clusters and precipitates, and type and concentration of structural defects [1]. A convenient measure of the quality of the starting material is the minority-carrier lifetime. The minimum value of the minority carrier lifetime (τ) in as-grown multicrystalline silicon, needed in a profitable solar cell production, is estimated to be $\tau_{min} \approx 2$ μs. This value must subsequently be improved at least by a factor of 10 during the solar-cell production [7]. Several methods, such as external and internal gettering, may considerably improve the quality of defected silicon, especially for electronic applications. In the first mentioned case a phosphorus-doped layer [8], or a layer of Al [9,10] produced on one side of the wafer play the role of a gettering sink for impurities during high temperature heat treatment. The Al gettering method can considerably improve the lifetime in Czochralski Si [11], but its efficiency seems to be limited for low-cost multicrystalline silicon containing metallic impurities in high concentrations [12,13]. In the internal-gettering method intra-grain defects and, depending on the size of the grains, grain boundaries are important precipitating centres for impurities [14,15].

The minority-carrier lifetime in as-grown Elkem SoG-mcSi ingots varies between 40 and 55 μs [16]. For the present investigation, however, two ingots were grown in such a way as to increase the concentration of those impurities which are mostly present in commercial Elkem SoG-Si. Thus, the as-grown lifetimes in these ingots are lower than those in commercial Elkem SoG-mcSi or reference mc-Si [17].

The gettering efficiency depends on the quality of the as-grown silicon, e.g. type and concentration of contaminations, clusters, precipitates and structural defects. e.g. dislocations. An exhaustive investigation of the dependence of the gettering efficiency on all these sample parameters is, however, outside the scope of this investigation. Here we merely present experimental results from an investigation of the influence of different heat-treatment methods on the minority-carrier lifetime of p-type SoG-mcSi wafers produced by Elkem Solar.

2. Experimental details

The investigated ingots were made out of p-type 100% Elkem SoG-Si feedstock produced by the metallurgical route [18–20].

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The SoG-Si technology route followed by Elkem Solar was reported in Ref. [15]. The SoG-Si wafers, $6'' \times 6''$ in size, thickness of about 250 μm, were cut out of block-cast ingots grown by directional solidification. The wafers were always p-type, and their resistivity varied between 0.5 and 1 Ω cm. The wafers from Ingot 1 visually consist of larger grains and smaller areas of grain boundaries than those from Ingot 2. The typical grain size varies between 1 and 8 cm^2 and between 0.1 and 1.5 cm^2 for Ingot 1 and Ingot 2, respectively.

The distribution of the minority-carrier lifetime (τ) over the SoG-Si wafers was measured by the microwave photoconductivity-decay technique (μ-PCD) using a SEMILAB-2000 instrument. The 904 nm laser wavelength used penetrates into silicon to a depth of about 30 μm; thus the free carriers under investigation are generated close to the surface of the sample. The surface passivation was done chemically using an iodine/methanol solution. Before iodine passivation the sample surface was chemically polished using an CP-4 etchant ($HF:CH_3COOH:HNO_3$) for 3 min and etched in 10%-HF solution for 2 min. Subsequently, the samples were put into special plastic bags filled with the iodine/methanol solution. Air bubbles were removed from the liquid in order to provide a uniform passivation of the whole surface. In agreement with the recommendation of the instrument producer and Ref. [21] the minority-carrier lifetime measurements were carried out using a bias of continuous white light of 1000 $\mu W/cm^2$. Using this bias light a large number of excess carriers are continuously generated and recombine at the surface states. The surface states are thus continuously occupied, and the excess carriers generated by the excitation pulse have a much lower probability to recombine at surface states.

Before the gettering-heat treatments the wafers were divided into smaller pieces having irregular forms with areas between 10 and 30 cm^2. The minority-carrier lifetime of every sample was measured before heat treatments. The samples were treated according to the internal and external (phosphorus) gettering procedure using constant and variable temperature processes. The "slow cooling" process in a tube furnace and the "fast cooling" process in a rapid thermal annealing (RTA) system belong to the constant temperature processes, while the variable temperature process was carried out in the RTA system. The parameters of these processes are presented in Table 1. Each process is described in detail in the following section.

3. Methods of heat treatment

3.1. The "slow cooling" (SC) process

The "slow cooling" process was carried out using a "Vecstar" tube furnace in which the temperature was stabilised during half an hour before annealing. In order to avoid undesirable oxidation of the samples the treatments were performed in a nitrogen ambiance. The temperature of annealing was varied between 750 and 900 °C during the internal gettering, and was equal to 930 °C during the phosphorus gettering [7,22]. Several regimes of cooling were checked, and it was established that the best results were obtained for samples cooled very slowly. It means in practice, that after the furnace power was switched off the samples were cooled inside the furnace in the N_2 ambiance for several hours. The estimated cooling rate during this process was equal to 50 °C/h for the temperature range between 600 and 900 °C and 20 °C/h for $T < 600$ °C.

3.2. The "fast cooling" (FC) process

The "fast cooling" process was performed using a "Jipelec JetFirst" RTA system with N_2 or dry air ambiances. Inside the RTA chamber a graphite plate was installed on quartz pins on the top of which a monocrystalline wafer was mounted. The samples for heat treatment were placed on top of the silicon wafer. The sample temperature was simultaneously controlled by a chromel/alumel thermocouple and a pyrometer. The thermocouple probe tightly touched the back side of the graphite plate. Calibration of the temperature curves of the thermocouple and pyrometer was carried out before every series of heat treatment. The melting point of Ge was chosen as the calibration point. The difference between the temperature values measured by thermocouple and pyrometer did not exceed 10 °C for $T > 300$ °C. The maximum temperature during the "fast cooling" processes varied between 500 and 1200 °C. The plateau time at maximum temperature varied between 10 and 60 s. The estimated cooling rate of the cooling from the maximum temperature to 300 °C was between 10 and 20 °C/s.

3.3. The variable temperature process

Plekhanov et al. [23] has proposed a heat-treatment process consisting of several heating steps, which may significantly improve the lifetime properties of p-type Si (see Fig. 1). During the first step of this process the temperature is at its maximum, and the heat-treatment time must be long enough in order to dissolve all clusters and precipitates of, in particular, iron in p-type Si. The aim of the subsequent steps is to allow the interstitial Fe atoms, produced during the declustering, to effectively diffuse to the sample surface without being recaptured in clusters and precipitates inside the bulk. On the surface, an Al gettering layer is deposited which has to effectively collect the interstitial Fe ions, thereby purifying the bulk silicon and improving its lifetime. Plekhanov et al. considered a process in which the temperature from its maximum to its minimum value decreased in steps of 100 °C. Since the diffusivity and solubility of iron in silicon strongly depends on temperature in the temperature range between 700 and 1200 °C, the length of the sequential steps was gradually prolonged. Plekhanov et al. demonstrated theoretically that using the proposed approach the amount of recombination centres in the whole bulk could be reduced by several orders of

Table 1
Methods of heat treatment of SoG-Si used in the present work.

Heat treatment method	Temperature range (°C)	time at T_{max}	Cooling rate	Ambience	Type of process
Internal gettering					
Slow cooling process	750–900	0.5–4 h	20–50 °C/h	N_2	Constant temperature
Fast cooling process	500–1200	10–60 s	10–20 °C/s	Dry air or N_2	Constant temperature
Plekhanov's procedure	1000–1300	150–300 s	10 °C/s	Dry air	Variable temperature
P-gettering					
Slow cooling process	930	1 h	20–50 °C/h	Dry air	Constant temperature
Fast cooling process	500–1200	10–60 s	10–20 °C/s	Dry air	Constant temperature
Plekhanov's procedure	1000–1300	150–300 s	10 °C/s	Dry air	Variable temperature

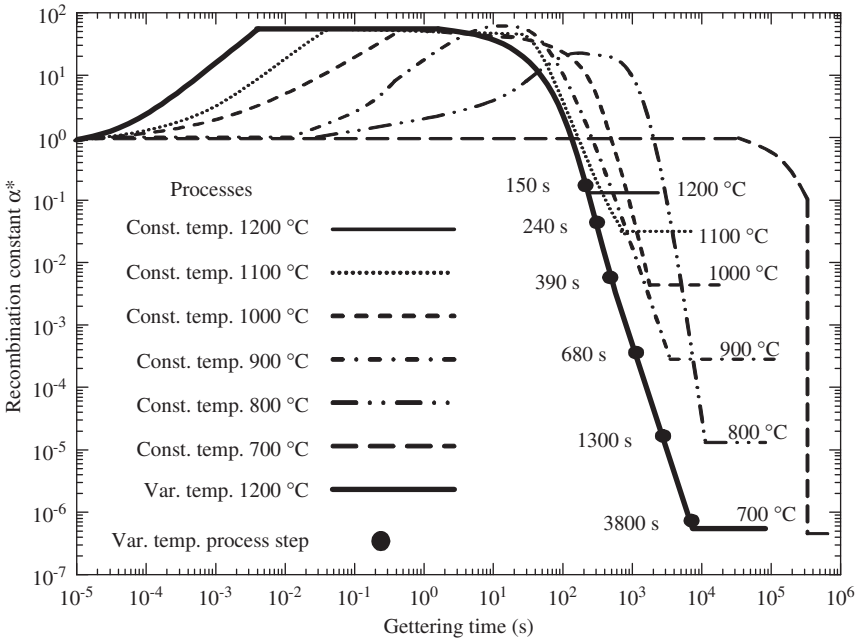

Fig. 1. A scheme of Al-gettering using the variable temperature (Plekhanov's) process with the maximum temperature of 1200 °C. The thin lines show the change of the recombination constant α^* during Al-gettering using constant temperature processes at different temperatures. The thick line corresponds to a variable temperature process in which the temperature decreased from 1200 to 700 °C in 100 °C steps, at the indicated temperature stepping-down points. Shown times and temperatures of variable process steps are taken from Ref. [22].

Table 2
An example of the variable temperature (Plekhanov's) process.

Step	T (°C)	time (s)	Cooling rate (°C/s)
1	1200	180	10
2	1100	100	10
3	1000	150	10
4	900	300	10
5	800	650	10
6	700	2500	20
7	20	stop	

magnitude. Following the method proposed by Plekhanov et al. we treated the samples by varying the maximum temperature between 1000 and 1300 °C, and by increasing the duration of the first step. The temperature of the last step remained constant (T=700 °C) for all treatments. The cooling rate between the steps was close to 10 °C/s. The whole process was performed using the RTA system which could provide the needed cooling rates. As an example of the variable temperature process, a process with a maximum temperature of 1200 °C is presented in Table 2. In this example, the first step is longer than the second step, while the duration of subsequent steps increases exponentially. It should be noted that such a procedure may be a more time- and energy-consuming process as compared to gettering processes presently used by the industry, but it is very useful as a method allowing to determine the maximum limit of the minority-carrier lifetime which can be achieved for different types of gettering. At such high temperatures Al atoms intermix with Si atoms, forming a high conductive Si–Al alloy layer which is difficultly removed from the Si surface. However, the Al–Si layer may be used as a back contact in solar cells.

3.4. Phosphorus gettering

Using a phosphorus containing paste ("SPP-P-0606" produced by "Filmtronic Inc.") a gettering layer was deposited on the top of a wafer through a 15×15 mm^2 square mask by screen printing. During the subsequent RTA at $T \geq 700$ °C for several hundred seconds the side with the phosphorus layer was exposed to the light of the halogen lamps of the RTA system. After heat treatment the samples were first etched in 10%–HF and CP-4 solutions, and the lifetimes were then measured on the side opposite to the phosphorus layer. The penetration depth of the laser pulse at the wavelength of 904 nm used during the μ-PCD measurement is about 30 μm, and with a thickness of the investigated wafers of about 250 μm and a P penetration depth of about 5 μm (T=930 °C; O_2/N_2 ambiance [24]), there will be no phosphorus in the depth range investigated during the μ-PCD measurements: The measured values of τ indeed reflect the minority-carrier lifetime of bulk silicon. In accordance with the instruction to the use of the phosphorus containing paste all phosphorus gettering processes were performed in a dry air ambiance.

4. Results and discussion

As mentioned above, two p-type, boron-doped, multicrystalline SoG-Si ingots with low minority-carrier lifetimes were chosen for the present investigation. A detailed characterisation of one of these ingots was given in Ref. [17]. Here, we will concentrate on the results of minority-carrier lifetime measurements examples of which are shown in Fig. 2. Several wafers were chosen from the top and bottom parts of Ingot 1, and from the top, middle and bottom parts of Ingot 2. From the μ-PCD data the lifetimes through most part of the Ingot 1 are higher than the minimum solar-cell limit, and vary between 2.4 and 3.4 μs. There is, however, a small region in the bottom part of Ingot 1 which has significantly lower lifetimes ($\tau \approx 0.3$ μs) than the minimum solar cell limit. These two regions of Ingot 1 are denoted the high lifetime region (HL1) and the low lifetime region (LL1), respectively. The lifetime values of the top part of Ingot 2 vary between 2.5 and 4.0 μs whereas the lifetime through the middle and bottom parts of Ingot 2 only varies weakly and attains values

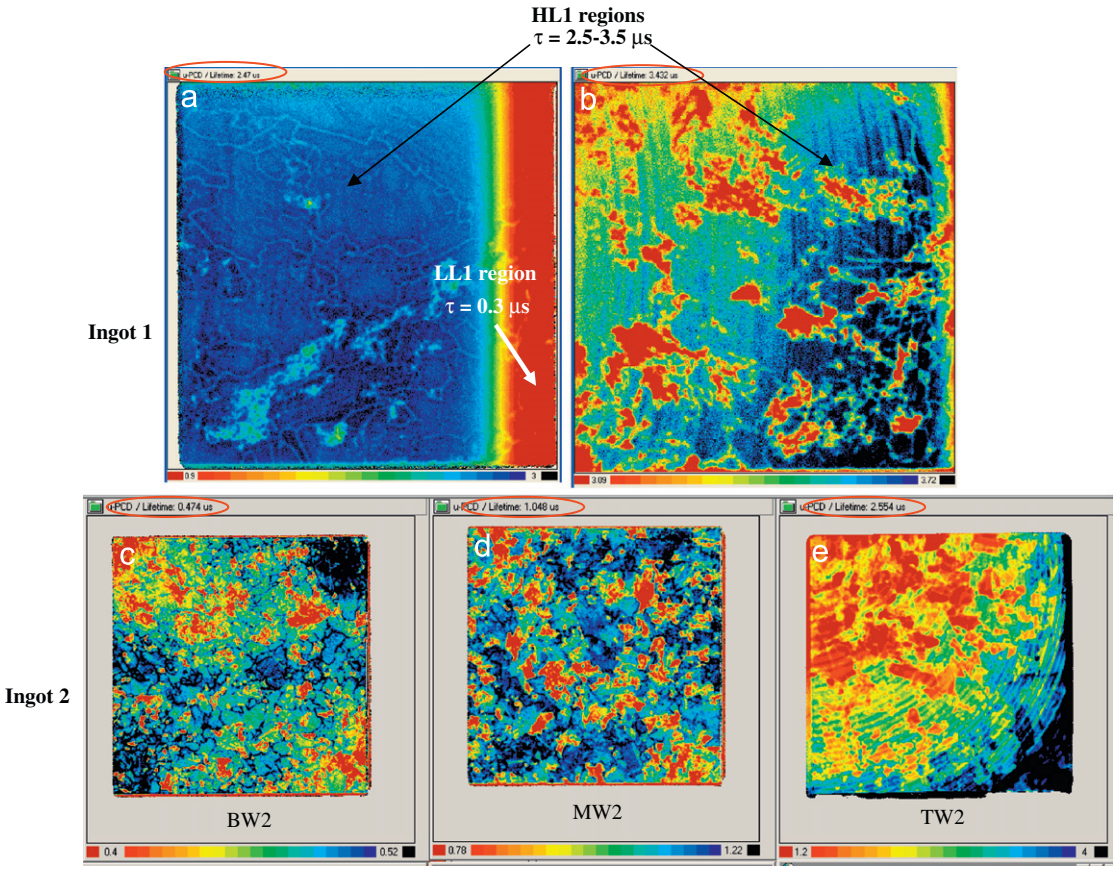

Fig. 2. Minority carrier lifetime mappings in wafers from different parts of Ingot 1 and 2. Ingot 1: bottom (a) and top (b) parts. Ingot 2: bottom (c), middle (d) and top (e) parts.

Table 3
Minority carrier lifetime (in μs) in different regions of the SoG-Si ingots after heat treatments.

Ingot region	As-grown	"Slow cooling"		"Fast cooling" at 1200 °C		"FC" at 800 °C	"FC" at 600 °C	Plekhanov's procedure	
		Internal gett. at 800 °C	P-gett. at 930 °C	Internal gett.	P-gett.	Internal get.	Internal gett.	Internal gett.	P-gett.
Ingot 1									
HL1	2.4–3.2	7	**16**	0.2	0.2	0.6	2.6	8.5[a]	**18**[a]
LL1	0.3	13	15	0.1	0.1	0.1	0.2	15[b]	**29**[a]
Ingot 2									
TW2	2.5–4	34	**60**	0.3	0.2	0.9	1.1	**68**[c]	**81**[c]
MW2	1	5.6	4	0.2	0.1	0.2	0.8	8.2[d]	**13**[c]
BW2	0.5	1	0.8	0.2	0.1	0.1	0.4	3.5[d]	**6.2**[c]

Maximum gettering temperature during Plekhanov's procedure:

[a] 1100 °C.
[b] 1000 °C.
[c] 1200 °C.
[d] 1300 °C.

close to 1.0 and 0.5 μs, respectively. The wafers from Ingot 2 are denoted top wafers (TW2), middle wafers (MW2) and bottom wafers (BW2). Summarising the μ-PCD results, we may distinguish between five regions in Ingot 1 and 2: High and low lifetime regions in Ingot 1, and top, middle and bottom regions in Ingot 2, and join them in two big groups: One with as-grown lifetime values higher than 2 μs (HL1 and TW2) and one with lifetime values lower than 1 μs (LL1, MW2 and BW2). Average lifetime values of the as-grown and heat treated samples from all the above mentioned regions are collected in Table 3. Because the lifetime, measured by the μ-PCD method, is undervalued close to the sample edge, the data, corresponding to the edge area (about 2 mm from every sample side), were removed from the average lifetime calculations. The previous investigations of Ingot 1 [17] showed that the electrical properties of the HL1 region are mainly determined by transition metals such as Ti, Fe, Cu, Cr and Ni, and their clusters. In addition to transition metals the presence of S, Al, Zn and Na in different types of clusters were revealed in the LL1 region. Based on these data we suggested in Ref. [16] that the low lifetime of the LL1 region could be explained by the electrically active nature of sulphur-, aluminium-, zinc- and sodium-related centres.

4.1. "slow cooling" (SC) process

For a more convenient presentation of the results of internal gettering using the "slow cooling" process the results from the

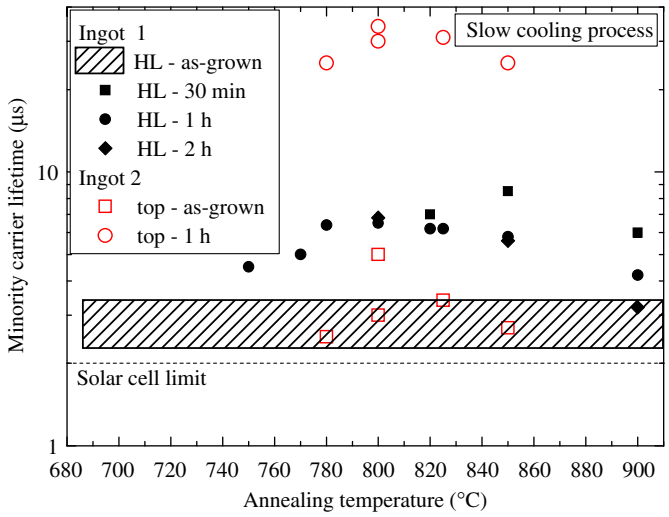

Fig. 3. Lifetimes in regions from the first group (HL1 and TW2) vs. gettering temperature after internal gettering using the "slow cooling" process. The hatched area shows as-grown lifetimes in the HL1 regions.

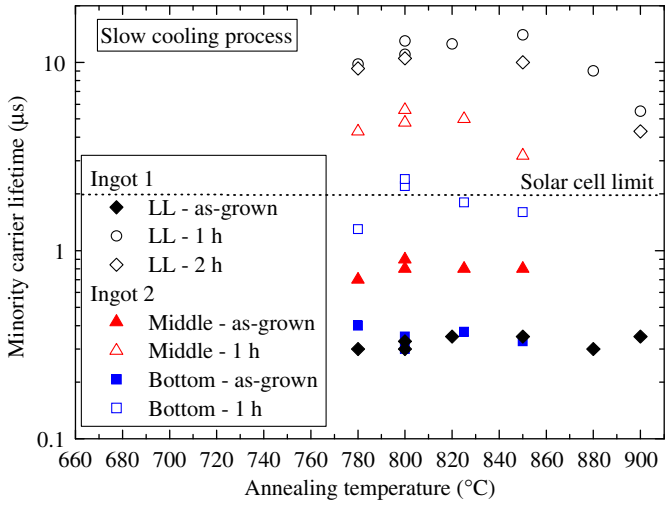

Fig. 4. Lifetimes in regions from the second group (LL1, MW2 and BW2) as a function of gettering temperatures after internal gettering using the "slow cooling" process. The hatched area covers the as-grown lifetimes in LL1 regions.

first and second group are split into Figs. 3 and 4, respectively. The consequences of the "slow cooling" process on samples from the first group are different from those from the second group: The lifetime values of the top region (TW2) from Ingot 2 have improved significantly (by 10 times), whereas the lifetime of the high lifetime region (HL1) from Ingot 1 has only improved a little (about 2–3 times). The gettering time (t_{get}) does not play a measurable role in the gettering temperature (T_{get}) range between 750 and 850 °C. However, for gettering at temperatures equal to or higher than 850 °C a 30 min process show better lifetimes than the longer processes, and heat treatments at a temperature of 900 °C for 2 hours result in a degradation of the lifetime of the HL1 region to the as-grown values. The highest lifetimes of the TW2 region are obtained after heat treatment at temperatures close to 800 °C. For the second group the "slow cooling" process works more effectively for the samples from Ingot 1 than from Ingot 2. The lifetime in the low lifetime region (LL1) from Ingot 1 increases by a factor of 30, and become considerably higher than the minimum solar cell limit. Heat treating samples from the middle (MW2) and bottom (BW2) regions from Ingot 2 only improves the lifetime values by a factor of 5–6, reaching the minimum solar cell limit. The best annealing parameters for the second group are similar to those for the first group: t_{get}=0.5–1 h and T_{get}=780–820 °C.

Summarizing the results of the internal gettering using the "slow cooling" process we may conclude that there is a critical temperature ($T_{get} \approx 850$ °C) and a critical time ($t_{get} \approx 1$ h) above which the minority carrier lifetime of SoG-Si degrades. Also for several regions (LL1 and TW2) there is an optimal temperature range in which gettering improves the lifetime by several factors. Significantly less improvement is found for the other regions in this temperature range.

There are several phenomena which might explain this effect, some of which will be briefly mentioned: Firstly, the optimal temperature might be too low to completely dissolve most of the electrically active clusters and precipitates into interstitial atoms. Secondly, the diffusivities of these elements in this temperature range could be too low, and the time of annealing too short to allow the interstitial atoms to diffuse far away from the initial clusters to the centres of internal gettering. Thirdly, during the "slow cooling" process the interstitial atoms, which did not diffuse sufficiently far away from the initial clusters during heating, could be recaptured by the clusters. Thus, we expect that a large amount of clusters and precipitates could remain undissolved after the "slow cooling" process. The significant improvement of the lifetime in the LL1 and TW2 regions indicates, however, a different nature of the dominant recombination centres in these regions as compared to those in the HL1, MW2 and BW2 regions. As mentioned previously, the low lifetime of the LL1 region has been explained by the electrical activity of sulphur-, aluminium-, zinc-, and sodium-related centres present in this region [17]. We can now conclude that the electrical activity of these centres is dramatically changed after the internal gettering.

4.2. Phosphorus gettering

The lifetimes after P-gettering at 930 °C of samples from the first group become higher than those after the internal gettering at 800 °C whereas the results of the internal and phosphorus gettering for the second group are similar (see column "Slow cooling" in Table 3). It was shown in Ref. [25]that in silicon the phosphorus gettering process (i) injects silicon interstitials into the bulk and (ii) induces dislocation network on the side predeposited by phosphorus. Silicon interstitials dissolve many metal precipitates by increasing the critical radius for the shrinkage of precipitates. Besides, silicon interstitials may kick out some metal impurities from substitutional to interstitial positions improving their dissolution and diffusivity in Si (out-diffusion phenomenon). This process is especially important at low temperature P-gettering when dislocations are not induced. On the other hand, a dislocation network effectively getters dissolved impurities during heat treatment. The results of the P-gettering for the first and second group of samples differ significantly: The lifetimes in the first group are close to the maximum values obtained by the variable temperature procedure, while the lifetimes in the second group are considerably lower (see Table 3). A comparison of the results of the phosphorus and internal getterings shows that after the P-gettering the lifetimes in the first group are higher than those after internal gettering, while the lifetimes after P-gettering and internal gettering in the second group are similar. Based on these considerations we may conclude that there is a considerable difference in the amount of gettering centres in the as-grown samples of the first and second group, and that these gettering centres are characterised by different capture cross-sections. Since the lifetimes in the samples from the second group after internal and P-getterings are similar, we may conclude that (i) the

as-grown samples from the second group have high concentrations of as-grown defects with high capture cross-sections and, as a result, a dislocation network induced by phosphorus diffusion does not drastically change the capture process of dissolved atoms, and (ii) Si self-interstitials do not play a dominant role in the gettering process. A similar conclusion has been made in Ref. [26], where the results of gettering using phosphorus diffusion, oxidation, nitridation and oxynitriditaion are compared. All these heat treatments introduce Si interstitials in silicon, but only phosphorus diffusion getters metallic impurities effectively, while the other processes do not. Opposite to the second group the samples from the first group show stronger lifetime inhancement after P-gettering as compared to internal gettering which indicates that they have a low concentration of gettering centres with high capture cross-section, and as a result, the dislocation network induced by the P-gettering as well as Si interstitials strongly influence the process of gettering.

4.3. "Fast cooling" (FC) process

To dissolve the clusters and precipitates in SoG-Si and, simultaneously, to increase the diffusivities of the impurity, gettering processes using the "fast cooling" process and variable temperature procedure were carried out at temperatures significantly higher than 800 °C. The results of internal gettering in the samples from the HL1 region using the "fast cooling" process are shown in Fig. 5. The internal gettering at $T_{get} < 600$ °C did not considerably change the lifetime values, while a dramatic degradation was observed at $T_{get} \geq 600$ °C. A similar picture was observed for other regions, e.g. the lifetime in the LL1 region decreased from 0.3 to 0.1 μs after annealing at 800 °C. This effect indicates that clusters and precipitates start to dissolve at temperatures higher than 600 °C. It can be expected that after the "fast cooling" process some of the dissolved atoms are frozen into interstitial sites. It is well established that many atoms, e.g. transition metals, in interstitial sites are effective lifetime killers. The P-gettering using the "fast cooling" process results in similar or worse results as compared to the internal gettering (see column "FC at 1200 °C" in Table 3).

4.4. The variable temperature process

To avoid freezing-in of the impurities at interstitial sites and to allow them to diffuse to the gettering centres we performed

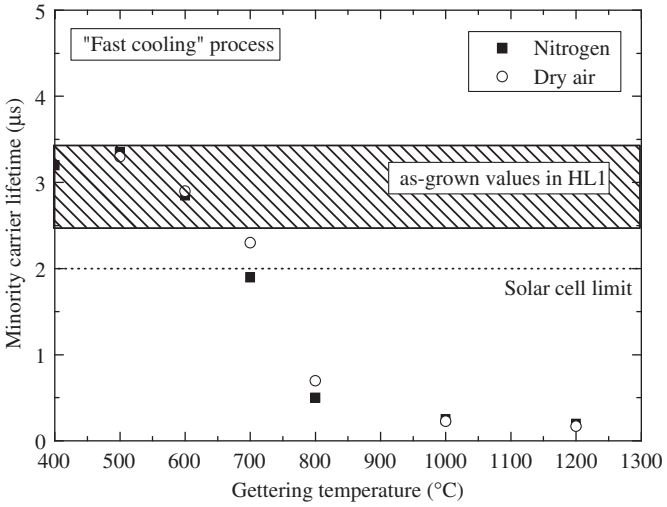

Fig. 5. Lifetimes in HL1 regions vs. gettering temperature after internal gettering using the "fast cooling" process in nitrogen and dry air ambiences. The hatched area shows the as-grown lifetimes in HL1 regions.

getterings using the variable-temperature process. The results of internal and phosphorus gettering using this procedure for samples from all regions of the investigated ingots are shown in Figs. 6 and 7. For most of the samples the lifetime after P-gettering is higher than that after internal gettering. This effect can be understood by reference to the difference in the distance which the interstitial atoms must diffuse before being gettered during these two types of gettering processes. Because the main sink of gettering during the P-gettering is the dislocation network close to the phosphorus layer on the sample surface the maximum distance is determined by the thickness of the wafers, and is not larger than 250 μm. If we assume that the main gettering centres during the internal gettering process are located at the grain boundaries, then the average distance from the clusters or precipitates to the gettering centres is several millimetres. Thus, the amount of interstitial atoms which can be gettered is significantly higher during the P-gettering process than during the internal gettering process. Here we would like to note, that the intra-grain dislocations are also the internal gettering centres and the distance between as-grown dislocations of a density of 1×10^6 cm^{-2} is about 100 μm. In Ref. [27] it is shown that during the high temperature treatment ($T > 0.8\ T_m$) the amount of dislocation may be significantly reduced. The evolution of dislocations in Elkem SoG-Si is an open question and requires further investigations. Therefore, in our considerations we mainly concentrated on the internal gettering by the grain boundaries.

As a result of phosphorus gettering the temperature dependence of the lifetimes shows a similar behaviour: An increase at low temperature and a decrease at higher temperatures. Such a behaviour is characteristic for a gettering process involving combined impurity release from cluster, impurity diffusion and impurity segregation [26]. Opposite to the P-gettering the results of the internal gettering are different for the different regions: The temperature dependences of the lifetime for the TW2 and HL1 regions resemble the phosphorus gettering results. The temperature dependence for the MW2 and BW2 regions does not have any maximum but the lifetime monotonically increases with gettering temperature. This result indicates a weak influence of the segregation mechanism on the gettering process. It can happen if the impurity solubilities in the lightly doped silicon and in the regions with high defect concentration are similar, and/or the defect density does not significantly change with temperature. The samples from LL1 region do not show any lifetime enhancement with gettering temperature which indicates that the total concentration of gettering centres starts decreasing at very low temperatures. The optimal temperature of internal gettering differs for the different regions: 1000 °C for low lifetime (LL1) and 1100 °C for high lifetime (HL1) regions from Ingot 1, and 1200 °C for top (TW2) and 1300 °C for middle (MW2) and bottom (BW2) regions from Ingot 2. This distribution of optimal gettering temperatures indicates that different elements and types of clusters and precipitates, or different types and concentrations of gettering centres are present in the two investigated ingots. This conclusion is also supported by the results from internal gettering using the "slow cooling" process, and our previous investigations [17]. Based on the variations of the optimal temperature we can conclude that (i) the dissociation energies of clusters and precipitates in Ingot 1 are lower than those in Ingot 2, and (ii) the gettering defects and dislocation centres are more stable in Ingot 2, especially in its low lifetime regions. The variation of the optimal gettering temperature for the P-gettering process is smaller than that for the internal gettering process: Between 1100 °C (all samples from Ingot 1) and 1200 °C (all samples from Ingot 2). The minority carrier lifetimes in the middle (MW2) and bottom (BW2) regions of Ingot 2 after the P-gettering process become higher than the minimum solar cell limit ($\tau_{min} \approx 2$ μs), namely 7 and 5 μs, respectively. It should be

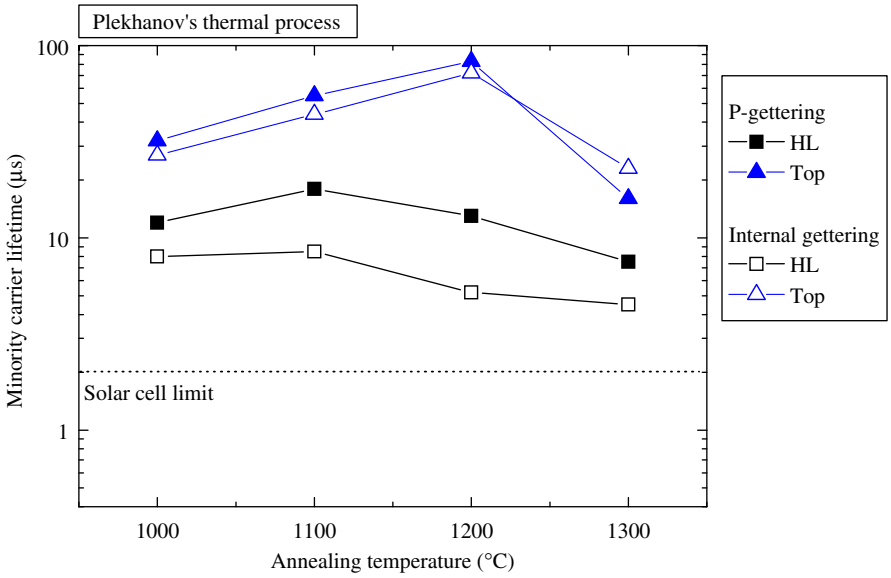

Fig. 6. Results of internal and P-gettering processes for the first group's samples using the Plekhanov's procedure. The *x*-axis presents the maximum temperature during the Plekhanov's procedure.

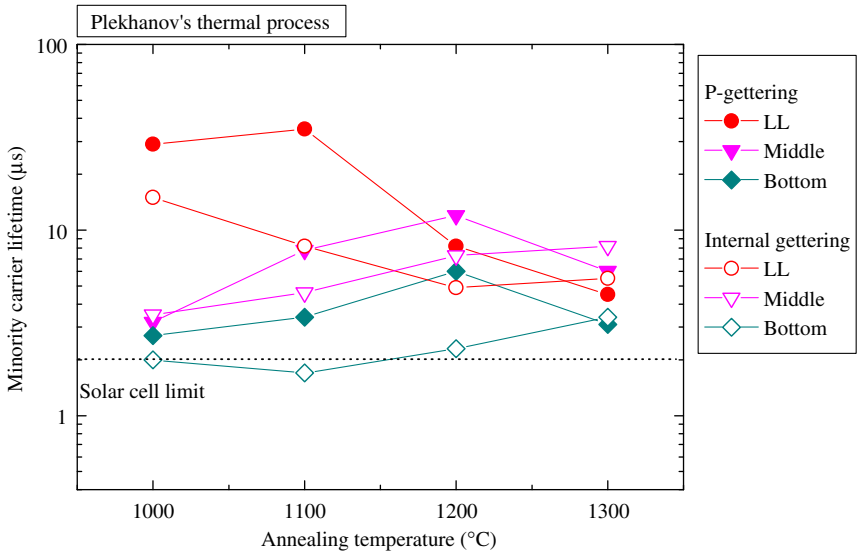

Fig. 7. Results of internal and P-gettering processes for the second group's samples using the Plekhanov procedure. The *x*-axis presents the maximum temperature during the Plekhanov procedure.

noted that after the P-gettering process the lifetime in the low lifetime (LL1) region from Ingot 1 improved from 0.3 to 28 μs and became comparable to the best lifetime values in the high lifetime (HL1) region. In Table 3 the data marked in bold show the best lifetime values obtained for each region of the ingots.

5. Conclusions

Gettering methods and their parameters for SoG-Si wafers with different as-grown minority-carrier lifetimes produced by Elkem Solar were optimised. Based on as-grown values of minority carrier lifetime the investigated ingot regions were divided into two groups. The regions in the first group are characterised by as-grown lifetimes above the minimum solar-cell limit (lifetime $> \tau_{min} \approx 2$ μs). In these regions significantly increased lifetimes are found as a result of internal and phosphorus gettering using either (i) a constant temperature process at $T_{get}=800$ °C and $T_{get}=930$ °C, respectively, or (ii) the variable-temperature process with maximum temperature in the temperature range between 1100 and 1200 °C. Lifetime improvements as a result of the variable-temperature process from 3–7 μs up to 60 with internal gettering and to 81 μs with phosphorus gettering were found. For all regions from the second group, the optimal process is a phosphorus gettering process using the variable temperature process with a maximum temperature between 1100 and 1200 °C. This procedure considerably enhanced the minority carrier lifetime as compared to the constant temperature gettering. After heat treatments the lifetime in most parts of the ingots becomes higher than the minimum solar cell limit.

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