The gettering effect of dielectric films for silicon solar cells

DOI:

[10.1109/PVSC.2017.8366084](https://doi.org/10.1109/PVSC.2017.8366084)

Document Version

Accepted author manuscript

[Link to publication record in Manchester Research Explorer](#)

Citation for published version (APA):

Liu, A. Y., Sun, C., Markevich, V., Peaker, A., Murphy, J. D., & Macdonald, D. (2017). The gettering effect of dielectric films for silicon solar cells. In *Proceedings of 44th IEEE Photovoltaic Specialists Conference*
<https://doi.org/10.1109/PVSC.2017.8366084>

Published in:

Proceedings of 44th IEEE Photovoltaic Specialists Conference

Citing this paper

Please note that where the full-text provided on Manchester Research Explorer is the Author Accepted Manuscript or Proof version this may differ from the final Published version. If citing, it is advised that you check and use the publisher's definitive version.

General rights

Copyright and moral rights for the publications made accessible in the Research Explorer are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

Takedown policy

If you believe that this document breaches copyright please refer to the University of Manchester's Takedown Procedures [<http://man.ac.uk/04Y6Bo>] or contact uml.scholarlycommunications@manchester.ac.uk providing relevant details, so we can investigate your claim.

The gettering effect of dielectric films for silicon solar cells

A. Y. Liu¹, C. Sun¹, V. P. Markevich², A. R. Peaker², J. D. Murphy³, and D. Macdonald¹

¹Research School of Engineering, Australian National University, Canberra, ACT, 2601, Australia

²Photon Science Institute, University of Manchester, Manchester, M13 9PL, United Kingdom

³School of Engineering, University of Warwick, Coventry, CV4 7AL, United Kingdom

Abstract — We present our recent findings on the strong gettering effect of dielectric films for removing impurities from the silicon bulk. Iron was used as a model impurity in silicon to study the gettering effects. The iron concentration in silicon is found to be significantly reduced after annealing silicon wafers coated with either plasma-enhanced chemical vapour deposited (PECVD) silicon nitride (SiN_x) films, or atomic layer deposited (ALD) aluminium oxide (Al_2O_3) films. Both PECVD SiN_x coated and ALD Al_2O_3 coated silicon wafers demonstrate largely diffusion-limited iron reduction rates at around 400°C, removing half of the bulk iron concentration within 30 min for a 160- μm thick silicon wafer with dielectric films on both sides. PECVD SiN_x films are shown to achieve diffusion-limited gettering of iron at temperatures below 700°C, meaning that 90% of iron can be gettering by the surface SiN_x films within 5 min for a 260- μm silicon wafer, or within 2 min for a 160- μm wafer at 700°C. Secondary ion mass spectrometry reveals that the gettering effect of PECVD SiN_x films is caused by impurity segregation into the bulk of the SiN_x films, and the gettering effect of ALD Al_2O_3 films comes from impurity accumulation at the $\text{Al}_2\text{O}_3/\text{Si}$ interfaces.

Index Terms — gettering, silicon, iron, silicon nitride, aluminium oxide, plasma enhanced chemical vapour deposition, atomic layer deposition.

I. INTRODUCTION

Improving the silicon bulk material quality for solar cells is a vital aspect for photovoltaic research and industry. Phosphorus diffusion gettering is commonly applied to remove unwanted impurities in silicon, and the gettering process is conveniently coupled with the formation of n+ regions near the silicon wafer surfaces. Effective gettering via phosphorus diffusion, however, relies on the full-area high-temperature heavy diffusion processes, with lighter diffusions or ion implanted phosphorus regions being much less effective at gettering [1-4]. Moreover, novel high efficiency cell architectures, for instance, heterojunction and passivating contact solar cells, no longer require heavy phosphorus or boron diffusion to form p-n junctions. The need for alternative gettering processes is therefore imminent. Solar cells based on n-type silicon could also benefit from alternative gettering approaches, as the gettering effectiveness of boron diffusion for the formation of p+ regions is thus far not well integrated into cell processing steps [5].

In this paper, we present our recent findings of the strong gettering effect of the commonly used dielectric films for silicon solar cells, namely plasma enhanced chemical vapour deposited (PECVD) silicon nitride (SiN_x) films, recently published in Ref. [6], and atomic layer deposited (ALD)

aluminium oxide (Al_2O_3) films, recently published in Ref. [7]. Experimental evidence for the effective gettering capabilities of these two dielectric films is presented. Iron is used as a model impurity in silicon to demonstrate and assess the gettering effect, as dissolved interstitial iron (Fe_i) in silicon can be easily and accurately quantified using lifetime based techniques [8, 9]. Furthermore, iron is a common efficiency-limiting impurity in silicon solar cells [10]. The gettering effects of PECVD SiN_x films, and ALD Al_2O_3 films, are examined by monitoring the Fe_i concentrations ($[\text{Fe}_i]$) in the silicon wafer bulk for samples annealed with the respective film coatings, via photoconductance-based carrier lifetime measurements. The re-distribution of iron in the dielectric films and the near-surface regions of the underlying silicon wafer bulk is studied by secondary ion mass spectrometry (SIMS) depth profiling of the iron concentration. A comparison of the gettering kinetics and mechanisms for the two films is presented and discussed.

II. EXPERIMENTAL DETAILS

High quality boron-doped float-zone (FZ) silicon wafers, of 1 – 2 Ωcm , with well-controlled doses of implanted Fe, were used in this study. The wafers were 250 – 260 μm and 160 – 180 μm thick after saw damage etching in an alkaline solution. The targeted volumetric interstitial Fe concentration ($[\text{Fe}_i]$) varied from 2×10^{12} to $1 \times 10^{14} \text{ cm}^{-3}$. After ion implantation of Fe atoms, the wafers were annealed at 1000°C for 2 – 3 h to uniformly distribute Fe throughout the wafer thicknesses. Dry oxygen was chosen as the ambient gas to enable the growth of silicon dioxide (SiO_2) as surface passivation layers. Some samples were set aside as the SiO_2 controls.

A subset of the samples had the SiO_2 layers removed in dilute HF, and were then coated with either PECVD SiN_x films, or ALD Al_2O_3 films, on both sides. Details of the PECVD deposition can be found in Ref. [6], and ALD in Ref. [7]. It is worth mentioning that the deposition conditions were optimised for the surface passivation and antireflection purposes, not for the gettering effects.

Quasi-steady-state photoconductance (QSSPC) lifetime measurements [11] before and after breaking FeB pairs via illumination were used to determine the Fe_i concentrations in the Si bulk [8, 9, 12].

To study the Fe_i reduction kinetics, wafers with either SiN_x , Al_2O_3 , or SiO_2 coatings were co-annealed cumulatively, with

[Fe_i] measured after each annealing step using QSSPC. The SiN_x samples, with the SiO₂ controls, were annealed at 250 – 900°C; and the Al₂O₃ samples, including SiO₂ controls, were annealed at 425°C, a typical passivation activation temperature for the ALD Al₂O₃ films.

The re-distribution of Fe after annealing silicon wafers coated with different dielectric films was measured by SIMS depth profiling of the Fe concentration in the annealed SiN_x, Al₂O₃ or SiO₂ layer and the near surface region of the underlying Si substrate. SIMS measurements were conducted by Evans Analytical Group (EAG) Laboratories.

III. RESULTS AND DISCUSSION

A. Reduction kinetics of interstitial iron in silicon wafer bulk

When annealing silicon wafers coated with either PECVD SiN_x films, or ALD Al₂O₃ films, significant reductions of the interstitial Fe concentrations can be observed, as shown in Figs. 1 (400 – 425°C) and 2 (700°C).

Fig. 1(a) compares the Fe_i reduction kinetics in samples coated with different dielectric films – PECVD SiN_x, ALD Al₂O₃, or thermally grown SiO₂. The samples were of the same wafer thickness of 260 μm, and were annealed at a similar temperature of 400°C (SiN_x and SiO₂ samples) or 425°C (Al₂O₃ and SiO₂ samples). As shown in Fig. 1(a), the SiO₂ samples show a much slower rate of Fe_i reduction compared to the SiN_x and Al₂O₃ samples. As evident by the SIMS measurements in Section III B below, the substantial bulk Fe_i losses in the SiN_x and Al₂O₃ coated samples are caused by Fe_i gettering to the surface layers. Therefore, a diffusion-limited surface-loss model from Murphy and Falster [13] is used to fit the measured Fe_i reduction kinetics of the SiN_x and Al₂O₃ samples, with apparent dissolved Fe_i diffusivities being fitting parameters.

The 400°C annealed SiN_x sample yielded an apparent Fe_i diffusivity of 6.5×10^{-9} cm²/s, and the known Fe_i diffusivity from the literature is 9.6×10^{-9} cm²/s [14]. The 425°C annealed Al₂O₃ sample gave rise to an apparent Fe_i diffusivity of 5×10^{-9} cm²/s, and the reported Fe_i diffusivity is 1.5×10^{-8} cm²/s [14]. The Fe_i reduction kinetics in both SiN_x and Al₂O₃ coated samples are therefore close to diffusion-limited surface gettering processes, with the PECVD SiN_x films being a slightly faster gettering agent than the ALD Al₂O₃ films.

Fig. 1(b) illustrates the Fe_i reduction kinetics in thinner silicon wafers of 160 μm, which is more typical of the wafer thicknesses used for silicon solar cells nowadays. The silicon wafers were coated with either thermal SiO₂, or ALD Al₂O₃ of 20 nm or 80 nm. As a typical 20-nm Al₂O₃ film is too thin for SIMS analysis, the Fe_i kinetics of the 80-nm Al₂O₃ coated samples are examined and compared with the kinetics of 20-nm Al₂O₃ films, as shown in Fig. 1(b). This serves to ensure that the SIMS measurements on 80-nm Al₂O₃ films are

representative of the gettering behaviours of typical ALD Al₂O₃ films (commonly less than 30 nm).

As shown in Fig. 1(b), the samples coated with Al₂O₃ films, of either 20 nm or 80 nm, demonstrate a much faster Fe_i decline compared to the co-annealed SiO₂ sample in the initial stages. At this early stage, the Fe_i reduction kinetics can be fitted by the same diffusion-limited surface-gettering model [13] using a fitted diffusivity of 7×10^{-9} cm²/s. This is similar to the fitted diffusivity of the 260-μm Al₂O₃ sample shown in Fig. 1(a), indicating that the slower Fe_i kinetics in the 260-μm samples are largely due to the different wafer thicknesses. The Fe_i kinetics of the Al₂O₃ samples gradually slow down, the cause of which is unclear at this stage, as discussed in Ref. [7].

Fig. 1. Measured Fe_i reduction kinetics in the silicon wafer bulk for samples coated with PECVD SiN_x, ALD Al₂O₃, or thermal SiO₂, and cumulatively annealed at 400°C (SiN_x and SiO₂ samples) or 425°C (Al₂O₃ and SiO₂ samples). Fig. 1(a) plots the kinetics for wafers of 260 μm thick, with three different dielectric coatings. Fig. 1(b) shows the kinetics of 160-μm thick wafers, coated with either SiO₂, or Al₂O₃ of different thicknesses and two different initial Fe_i concentrations. The straight black lines are fittings to the experimental data based on a diffusion-limited surface-loss model, yielding fitted apparent Fe_i diffusivities [13].

As evident in Fig. 1(b), the SiO₂ sample again first shows little change in Fe_i concentration. With increasing annealing time, [Fe_i] reduction becomes faster. The initial slow change phase may be related to the nucleation of precipitation sites

that later facilitate Fe_i precipitation to take place, and thus a faster $[\text{Fe}_i]$ decline at later stages.

The measured Fe_i kinetics and fitted apparent diffusivities in Fig. 1 show that, for a typical 160- μm wafer, a 30-min anneal at 400 – 425°C reduces the bulk Fe_i concentration by half. Iron has a moderate diffusivity in silicon. This reported gettering effect should be taken into account in studies that use PECVD SiN_x or ALD Al_2O_3 films as surface passivation coatings, to avoid misinterpretation. PECVD typically operates at 250 – 500°C, ALD Al_2O_3 films typically require a post-deposition anneal at 300 – 500°C, and the processing time ranges from minutes to tens of minutes. This means that the fabrication of these dielectric films could result in considerable bulk impurity gettering effects, depending on the processing conditions, as observed in Refs. [15, 16]. The external gettering of Fe_i during the passivation step could also explain lower Fe_i concentrations measured in multicrystalline silicon wafers passivated by PECVD SiN_x compared to temporary liquid passivation schemes [17, 18].

Fig. 2. Measured Fe_i reduction kinetics in 260- μm thick silicon wafers coated with either PECVD SiN_x or thermal SiO_2 , cumulatively annealed at 700°C. The straight black line is a fitting to the experimental data based on a diffusion-limited surface-loss model, yielding a fitted apparent Fe_i diffusivity [13].

Fig. 2 presents the Fe_i reduction kinetics at 700°C for the PECVD SiN_x and thermal SiO_2 coated samples. Similar to the 400°C results in Fig. 1, the SiN_x sample demonstrates a much faster Fe_i loss than the SiO_2 sample, and the loss kinetics can be fitted by the same diffusion-limited surface-loss model [13], using a fitted diffusivity that is close to the reported Fe_i diffusivity (fitted diffusivity is $4.5 \times 10^{-7} \text{ cm}^2/\text{s}$, and the reported Fe_i diffusivity is $3.4 \times 10^{-7} \text{ cm}^2/\text{s}$ [14]). This indicates a diffusion-limited surface-gettering process at 700°C for the PECVD SiN_x films. In fact, for PECVD SiN_x films the Fe_i reduction kinetics over a wide temperature range of 250 – 900°C have been investigated in Refs. [6, 15, 19], and the results show that the SiN_x gettering process is largely diffusion-limited for temperatures below 700°C. This helps to estimate the amount of bulk impurity loss for any given temperature profiles below 700°C.

As shown by the experimental data in Fig. 2, for a 260- μm silicon wafer coated with SiN_x films on both sides, the bulk Fe_i concentration is reduced by 90% after 5 min at 700°C. Modelling of the diffusion-limited surface-gettering process [13] predicates that, for a 160- μm wafer with SiN_x films on both sides, 90% of the bulk Fe_i is removed within 2 min at 700°C.

B. Re-distribution of iron

In order to understand the observed Fe_i reductions in the silicon wafer bulk (Figs. 1 and 2), SIMS analysis was conducted to reveal the re-distribution of Fe after annealing, in samples coated with different types of dielectric films and annealed for extended time to drive large bulk Fe_i reductions. Note that SIMS detects the total Fe concentration regardless of the electrical state, that is, SIMS detects both dissolved and precipitated Fe atoms.

It is observed that, all of the measured SIMS Fe profiles, in Figs. 3 and 4 and in Refs. [6, 7], demonstrate a near-surface Fe increase, for samples with or without previous bulk Fe contamination and with different film coatings. This suggests that this near-surface Fe increase does not come from the gettering of Fe from the silicon bulk, and is likely a measurement artefact in SIMS analysis, possibly caused by unintentional surface contamination during handling and processing.

Fig. 3. SIMS measurements of the total Fe distribution in (1) PECVD SiN_x coated silicon wafer with bulk Fe_i contamination of 10^{13} cm^{-3} ; (2) PECVD SiN_x coated silicon wafer with no bulk Fe_i contamination; and (3) thermally grown SiO_2 coated silicon wafer with bulk Fe_i contamination of 10^{13} cm^{-3} . All three samples were annealed at 700°C for 30min in N_2 . The upper curves are a qualitative measure of the Si matrixes (plotted against the y-axis on the right), which are used to indicate the positions of the SiN_x or SiO_2 films and the Si substrate in the depth profiles. The detection limits of total Fe in SiN_x , SiO_2 , and Si are marked by dashed lines.

As shown in Fig. 3, a high concentration of Fe is detected in the SiN_x film for the Fe_i-contaminated SiN_x sample, whereas the Fe concentration in the SiO₂ layer in Fe_i-contaminated co-annealed SiO₂ sample is below the detection limit. This is consistent with the lifetime measurements (Fig. 2 and Ref. [6]) that the SiO₂ sample only experienced a small decrease in the bulk Fe_i concentration after a 700°C 30-min anneal, and hence the majority of Fe_i still remains in the silicon wafer bulk, at a concentration well below the detection limit of SIMS for quantifying Fe in Si.

The high Fe concentration in the SiN_x film is shown to arise from the Si bulk, by comparing the SIMS Fe profiles in SiN_x samples with or without previous bulk Fe_i contamination (Fig. 3). The bulk Fe_i-contaminated sample shows a much higher concentration of Fe in the SiN_x film, indicating that this high Fe concentration does not come from the PECVD SiN_x deposition or the subsequent annealing processes, but rather from Fe previously distributed in the Si bulk in the interstitial form (i.e. Fe_i), that is, Fe_i is gettered to the SiN_x film from the Si bulk upon annealing. The quantitative Fe concentration in the SiN_x film from SIMS measurements is also found to be similar to the bulk Fe_i reduction measured from QSSPC, further confirming that Fe_i is gettered from the silicon bulk to the surface SiN_x films.

The uniform Fe distribution in the SiN_x film (shown in Fig. 3), and the effectiveness of SiN_x gettering at temperatures where the Fe_i solubilities are well above the bulk Fe_i concentrations (shown in Refs. [6, 15]), indicate that the SiN_x gettering process is driven by impurity segregation into the PECVD SiN_x films.

The observed [Fe_i] reductions in PECVD SiN_x coated samples were previously conjectured to be due to the hydrogenation of Fe [15, 19] (and the Refs within). This hypothesis, however, was later found to be inconsistent with the results from deep-level transient spectroscopy (DLTS) analysis of the annealed silicon wafers, and thermal stability studies of the Fe_i reductions, as detailed in Ref. [6]. The SIMS measurements of the Fe re-distribution provide conclusive evidence for the gettering effect of PECVD SiN_x films, ruling out the previous hydrogenation hypothesis. Our results do not exclude the possibility of hydrogenation of the silicon from the SiN_x film, but the involvement of hydrogen is not necessary to explain the kinetics of the interstitial iron reduction observed.

Fig. 4 presents the SIMS results of ALD Al₂O₃ coated and thermal SiO₂ coated samples, co-annealed at 425°C for an extended 18 h. After the long cumulative anneals, both Fe_i-contaminated samples, with either Al₂O₃ or SiO₂ coatings, show a significant reduction in the bulk Fe_i concentration (Fig. 1 and Ref. [7]). The SIMS profiles of the two Fe_i-contaminated samples both demonstrate large Fe peaks at the Al₂O₃/Si or SiO₂/Si interface. The quantitative Fe concentrations in these Fe peaks from SIMS measurements show general agreement with the losses of bulk Fe_i concentrations determined from QSSPC lifetime

measurements, indicating that the Fe peaks source from Fe_i originally distributed in the silicon bulk.

Fig. 4. SIMS measurements of the total Fe distribution in (1) ALD Al₂O₃ coated silicon wafer with bulk Fe_i contamination of 10¹⁴ cm⁻³; (2) ALD Al₂O₃ coated silicon wafer with no bulk Fe_i contamination; and (3) thermally grown SiO₂ coated silicon wafer with bulk Fe_i contamination of 10¹³ cm⁻³. All three samples were cumulatively annealed at 425°C for a total of 18h in air. The upper curves are a qualitative measure of the Al and Si matrixes (plotted against the y-axis on the right), which are used to indicate the positions of the Al₂O₃ or SiO₂ films and the Si substrate in the depth profiles. The detection limits of total Fe in Al₂O₃, SiO₂, and Si are marked by dashed lines.

It is well known in the literature that Fe-silicide precipitates tend to form at the SiO₂/Si interfaces (see, for example, Ref. [10]). The observed Fe peak at the SiO₂/Si interface for the thermal SiO₂ coated sample is therefore likely due to Fe_i precipitation, as the solubility of Fe_i at 425°C is in the range of 10⁵ cm⁻³ [14] to 10⁸ cm⁻³ (from extrapolation [20]), providing sufficient driving force for relaxation precipitation to take place.

As shown in Fig. 4, an Al₂O₃ coated sample without previous bulk Fe_i contamination illustrates no such Fe peak at the Al₂O₃/Si interface. This further confirms that the Fe peak observed in the Fe_i-contaminated Al₂O₃ sample comes from the gettering of Fe_i from the silicon bulk.

The underlying mechanism for the accumulation of Fe at the Al₂O₃/Si interface remains unknown at this stage. As an ultra-thin silicon oxide (SiO_x) layer is known to reside at the ALD Al₂O₃/Si interface [21], this Fe peak may be caused by Fe_i precipitation at the SiO_x/Si interface, similar to the Fe_i precipitation at the thermal SiO₂/Si interface discussed above. However, the ALD Al₂O₃ and thermal SiO₂ samples show very different Fe_i loss kinetics, as can be seen in Fig. 1. Hence, Fe accumulation at the ALD Al₂O₃/Si interface could be caused by a different mechanism, for example, by impurity

segregation at the $\text{Al}_2\text{O}_3/\text{Si}$ interface. Further temperature-dependent gettering studies will be required to assess the hypotheses.

IV. SUMMARY

This paper presents experimental evidence for the strong gettering effects of the commonly used dielectric films for silicon solar cells: PECVD silicon nitride and ALD aluminium oxide films. The gettering process is found to be largely diffusion-limited for both films near 400°C . The PECVD silicon nitride films are shown to result in diffusion-limited gettering effects at temperatures below 700°C . The measured interstitial iron reduction kinetics indicate that significant impurity gettering can be achieved by the dielectric films at moderate temperatures within minutes to tens of minutes, depending on the impurity diffusivity in silicon. International impurity gettering to dielectric films at low temperatures could be a viable alternative to high temperature gettering and may be particularly useful in the development of novel silicon-based solar cells.

Although the two films demonstrate similar diffusion-limited gettering processes at around 400°C , the underlying gettering mechanisms are different: PECVD silicon nitride films relocate bulk impurities into the films via segregation gettering, and ALD aluminium oxide films getter impurities via impurity accumulation at the $\text{Al}_2\text{O}_3/\text{Si}$ interfaces.

ACKNOWLEDGEMENT

This work has been supported by the Australian Renewable Energy Agency (ARENA) through project RND009. Author C Sun acknowledges the financial support from Australian Centre for Advanced Photovoltaics. The work in the UK is supported by the Engineering and Physical Sciences Research Council via the SuperSilicon PV project (EP/M024911/1). We acknowledge access to NCRIS facilities (ANFF and the Heavy Ion Accelerator Capability) at the Australian National University.

REFERENCES

- [1] E. Cho, Y.-W. Ok, L. D. Dahal, A. Das, V. Upadhyaya, and A. Rohatgi, "Comparison of POCl_3 diffusion and phosphorus ion-implantation induced gettering in crystalline Si solar cells," *Solar Energy Materials and Solar Cells*, vol. 157, pp. 245-249, 2016.
- [2] H. S. Laine, V. Vähäniissi, Z. Liu, H. Huang, E. Magaña, A. E. Morishige, *et al.*, "Finite- vs. infinite-source emitters in silicon photovoltaics: Effect on transition metal gettering," in *2016 IEEE 43rd Photovoltaic Specialists Conference (PVSC)*, 2016, pp. 0678-0680.
- [3] M. Kim, H. Li, D. Payne, S. Wenham, B. Hallam, and M. Abbott, "Application of high efficiency emitters to multicrystalline silicon," presented at the 32nd European Photovoltaic Solar Energy Conference and Exhibition, Munich, Germany, 2016.
- [4] V. Vähäniissi, A. Haarahiltunen, M. Yli-Koski, and H. Savin, "Gettering of Iron in Silicon Solar Cells With Implanted Emitters," *IEEE Journal of Photovoltaics*, vol. 4, pp. 142-147, 2014.
- [5] S. P. Phang, W. Liang, B. Wolpensinger, M. A. Kessler, and D. Macdonald, "Tradeoffs Between Impurity Gettering, Bulk Degradation, and Surface Passivation of Boron-Rich Layers on Silicon Solar Cells," *IEEE Journal of Photovoltaics*, vol. 3, pp. 261-266, 2013.
- [6] A. Y. Liu, C. Sun, V. P. Markevich, A. R. Peaker, J. D. Murphy, and D. Macdonald, "Gettering of interstitial iron in silicon by plasma-enhanced chemical vapour deposited silicon nitride films," *Journal of Applied Physics*, vol. 120, 193103, 2016.
- [7] A. Y. Liu and D. Macdonald, "Impurity gettering effect of atomic layer deposited aluminium oxide films on silicon wafers," *Applied Physics Letters*, vol. 110, 191604, 2017.
- [8] G. Zoth and W. Bergholz, "A fast, preparation-free method to detect iron in silicon," *Journal of Applied Physics*, vol. 67, pp. 6764-6771, 1990.
- [9] D. H. Macdonald, L. J. Geerligs, and A. Azzizi, "Iron detection in crystalline silicon by carrier lifetime measurements for arbitrary injection and doping," *Journal of Applied Physics*, vol. 95, pp. 1021-1028, 2004.
- [10] A. A. Istratov, H. Hieslmair, and E. R. Weber, "Iron contamination in silicon technology," *Applied Physics A*, vol. 70, pp. 489-534, 2000.
- [11] R. A. Sinton and A. Cuevas, "Contactless determination of current-voltage characteristics and minority-carrier lifetimes in semiconductors from quasi-steady-state photoconductance data," *Applied Physics Letters*, vol. 69, pp. 2510-2512, 1996.
- [12] L. Geerligs and D. Macdonald, "Dynamics of light-induced FeB pair dissociation in crystalline silicon," *Applied Physics Letters*, vol. 85, p. 5227, 2004.
- [13] J. D. Murphy and R. J. Falster, "The relaxation behaviour of supersaturated iron in single-crystal silicon at 500 to 750°C ," *Journal of Applied Physics*, vol. 112, 113506, 2012.
- [14] A. A. Istratov, H. Hieslmair, and E. R. Weber, "Iron and its complexes in silicon," *Applied Physics A*, vol. 69, pp. 13-44, 1999.
- [15] A. Liu, C. Sun, and D. Macdonald, "Hydrogen passivation of interstitial iron in boron-doped multicrystalline silicon during annealing," *Journal of Applied Physics*, vol. 116, 194902, 2014.
- [16] S. P. Phang and D. Macdonald, "Direct comparison of boron, phosphorus, and aluminum gettering of iron in crystalline silicon," *J. Appl. Phys.*, vol. 109, 073521, 2011.
- [17] P. Karzel, A. Frey, S. Fritz, and G. Hahn, "Influence of hydrogen on interstitial iron concentration in multicrystalline silicon during annealing steps," *Journal of Applied Physics*, vol. 113, 114903, 2013.
- [18] M. Al-Amin and J. D. Murphy, "Passivation Effects on Low-Temperature Gettering in Multicrystalline Silicon," *IEEE Journal of Photovoltaics*, vol. 7, pp. 68-77, 2017.
- [19] C. Sun, A. Liu, S. P. Phang, F. E. Rougieux, and D. Macdonald, "Charge states of the reactants in the hydrogen passivation of interstitial iron in P-type crystalline silicon," *Journal of Applied Physics*, vol. 118, 085709, 2015.

- [20] J. D. Murphy and R. J. Falster, "Contamination of silicon by iron at temperatures below 800 °C," *Phys. Status Solidi RRL*, vol. 5, pp. 370-372, 2011.
- [21] F. Werner, B. Veith, D. Zielke, L. Kühnemund, C. Tegenkamp, M. Seibt, *et al.*, "Electronic and chemical properties of the c-Si/Al₂O₃ interface," *Journal of Applied Physics*, vol. 109, 113701, 2011.