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Approaches to Reduce the Impact of Edge Recombination in Si Lifetime Samples With Emitter

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Abstract. The injection-dependent effective excess carrier lifetime is an important quantity to describe recombination characteristics in silicon. When measured with the photo-conductance decay technique it is known that for specific sample structures and sizes edge recombination can strongly affect the measured injection-dependent lifetime. Especially in lifetime samples involving an (induced) *pn*-junction edge recombination can become a dominant effect limiting lifetime towards low injection. We present different approaches to structure samples in order to suppress the detrimental effect of edge recombination on lifetime at low injection.

Keywords: Edge Recombination, Injection-Dependent Effective Lifetime, Edge Passivation

1. Introduction

Often, effective charge carrier lifetime (τ_{eff}) is assumed to reflect different recombination channels (intrinsic, bulk defects, surface) in a 'global way', however, lateral inhomogeneity and especially poorly-passivated edges (and scratches) may seriously influence the observed injection dependence. Hence sample size should be 'sufficiently' large to guarantee for an undisturbed analysis. In a sample in which minority carriers' lateral transport is governed by bulk diffusion only, their diffusion length determines the necessary distance between measurement area (WCT-120: ~30 mm diameter [1]) and edges, typically a few mm, allowing for easy-to-handle samples of ~50×50 mm^2. However, in structures resulting in spatial carrier separation, like an inversion layer (e.g. negatively charged dielectric layers like AlO_x/SiN_y stacks on n-type substrates) [2] or a (poly-Si/TOPCon) emitter [3,4], lateral minority carrier transport is not limited by bulk diffusion. Bulk minority carriers can then be transported in those layers as majorities across large distances towards the edges. This is exemplarily demonstrated in Fig. 1, where $\tau_{eff}(\Delta n)$ curves of n-type samples with boron emitter (p^+) are shown that were cut smaller by laser step by step resulting in unpassivated edges. Edge recombination in such samples mainly influences $\tau_{eff}(\Delta n)$ for low injection whereby the exact sample size determines which injection range is actually impacted. It is evident that the analysis of such edge-impacted $\tau_{eff}(\Delta n)$ curves is prone to error and misinterpretation, in particular towards low injection.

Edge recombination has long been recognized as a loss mechanism in silicon solar cells [5,6,7]. Proposed strategies to suppress it include increasing the distance between active area and cell edges, and reducing recombination velocity at the latter. Both strategies can also be applied to lifetime samples, either by using large samples or samples with well passivated edges. Using sufficiently large samples is an obvious solution that is also justified for single investigations. However, when lifetime samples are used in long-term stability studies, the limitation to parallelize investigations due to additional space requirements presents a clear disadvantage. As an alternative, all processing steps could be performed on small samples, allowing the emitter formation and the deposition of passivation layers to provide a certain degree of edge passivation. However, many processing steps are designed and optimized for entire wafers, and from a homogeneity perspective, it may be advantageous to cut out a central, more homogeneous region for later analysis.

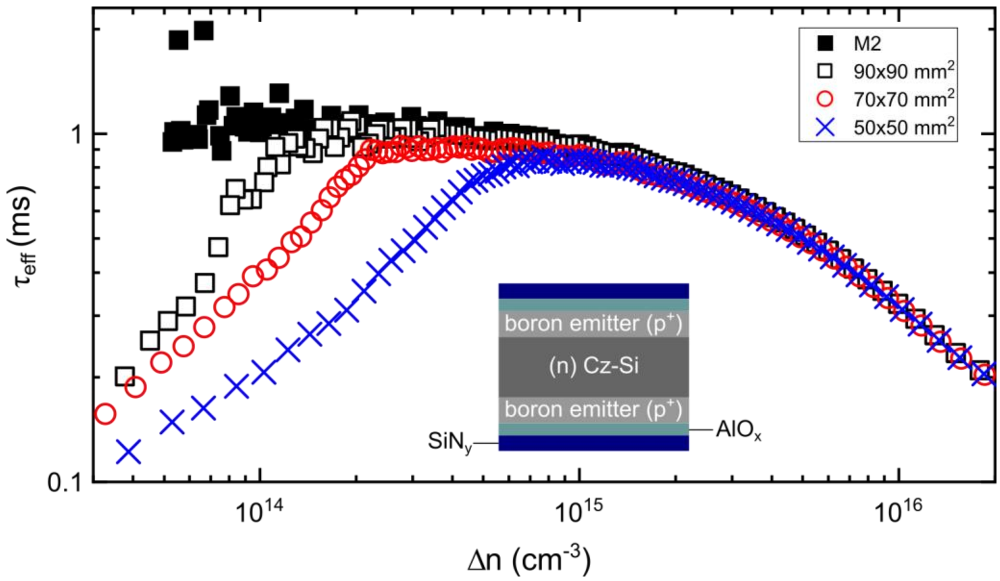

Figure 1. *Injection-dependent $\tau_{eff}(\Delta n)$ curves of a symmetrical n-type Cz-Si lifetime sample with boron emitter. The sample was subsequently reduced in size from M2 (~156x156 mm^2) to 50x50 mm^2 by laser cutting.*

Hence, it would be a great advantage if one could prepare larger samples in such a way that the impact of edge recombination is limited in small subsamples with lateral minority carrier transport layers even with insufficient edge passivation. In this study, two different approaches were investigated to enable the laser cutting of samples after processing. These approaches are based on the emitter window concept, which utilizes an undiffused region close to the edges to reduce edge recombination by interrupting the bulk minority carrier's transport channel [8,9]. The two methods, the etch-back and sunken emitter approaches, are evaluated in terms of passivation quality and compared to a sample without any edge passivation as well as one with AlO_x edge passivation.

2. Experimental

In this study, samples were analyzed that were fabricated from phosphorous-doped Cz-Si wafers with a specific resistivity of 2–3 Ω cm. All samples underwent BBr_3 diffusion, resulting in a boron emitter with a sheet resistance of 155 Ω/sq. Four different sample groups were investigated. The first group, serving as a reference without any edge passivation, consists of samples that were laser cut without any additional or prior treatments. In the second group, samples were cleaved using a diamond scribe, which is expected to introduce less damage than laser cutting. Subsequently, the surfaces (including the edges) were passivated via an ALD (atomic layer deposition) process with 25 nm AlO_x, followed by annealing at 400°C for 30 min. The saturation of dangling bonds and the formation of negative charges within the AlO_x is known to result in a combination of chemical and field-effect passivation both on surface and specifically on edges as well [10,11]. Two additional groups were processed to enable potential post-processing size reduction without resulting in increased edge recombination. To achieve this, the emitter was restricted to a central region of the sample, ensuring that newly formed edges in the adjacent undiffused region are not connected to the measurement area via an efficient transport channel for bulk minority carriers. It is crucial that the passivation layers were deposited with appropriate masking as well to prevent inversion passivation in the edge regions without emitter. The process flow of the etch-back and sunken emitter approaches is shown in

Fig. 2. In the etch-back approach, the emitter was confined to a central region after diffusion through a masked etching step in KOH. In contrast, the sunken emitter approach utilizes a mask as diffusion barrier during emitter formation to spatially restrict the emitter to the center of the sample. For both processes, PECVD (plasma-enhanced chemical vapor deposition) SiN_Y was used as mask, which was deposited on the sample using a corresponding shadow mask laser cut from a silicon wafer.

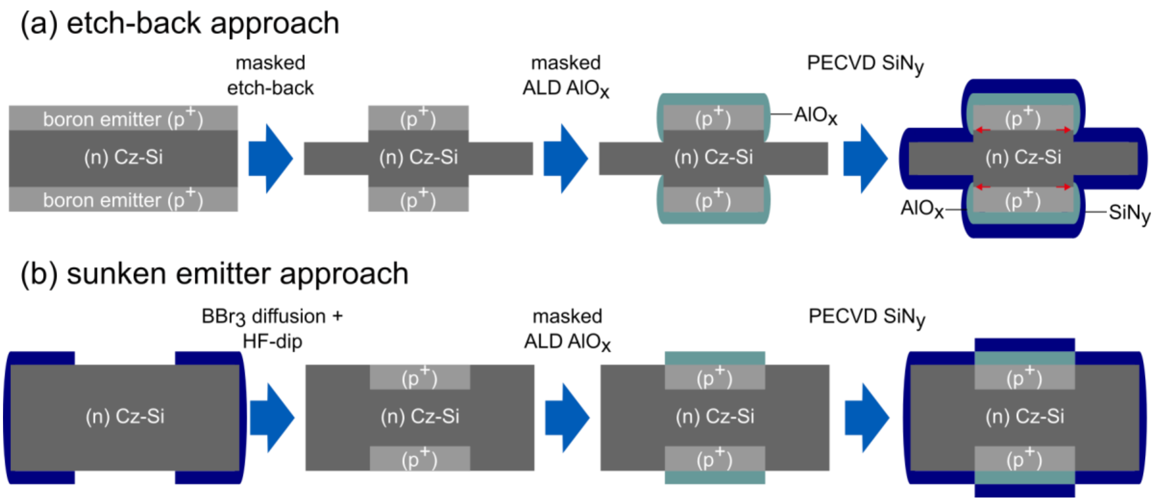

Figure 2. *Process flow for the (a) etch-back and (b) sunken emitter approach.*

3. Results and Discussion

The injection-dependent lifetime curves of samples from the different groups are shown in Fig. 3. It is evident that the laser-cut sample without any edge passivation, represented by black squares, exhibits the strongest limitation in low injection for a sample size of 50x50 mm^2. The region below $\Delta n = 10^{15}$ cm^{-3} is strongly dominated by edge recombination.

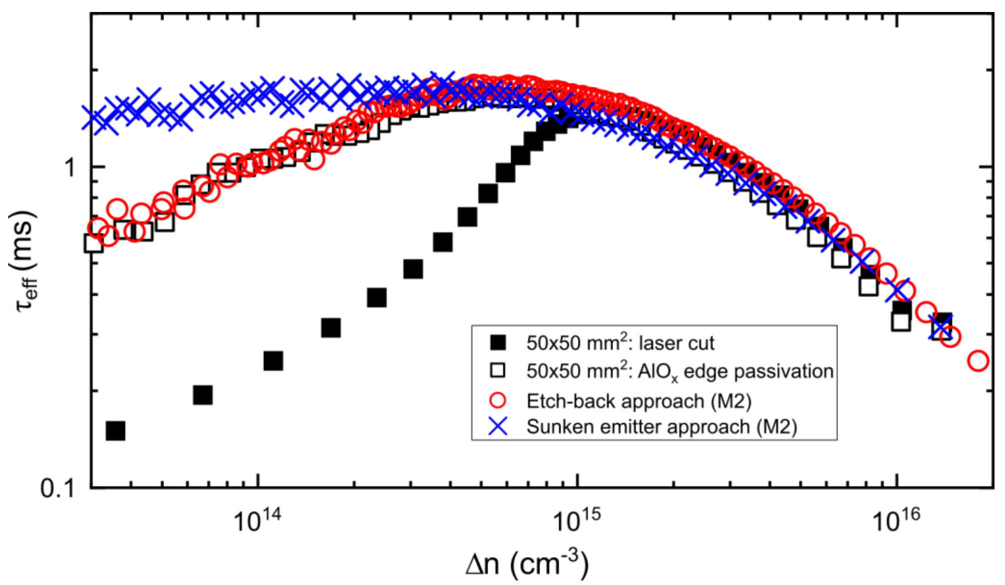

Figure 3. *Injection-dependent $\tau_{eff}(\Delta n)$ curves of samples with different levels of edge passivation.*

Edge passivation using ALD AlO_x can mitigate this limitation. The curve, represented by open squares, still shows a noticeable lifetime drop towards low injection compared to the sample in Fig. 1 in M2 format. However, this drop occurs only below $\Delta n = 5\cdot10^{14}$ cm^{-3} and is less pronounced than for the sample without edge passivation. Notably, the shape of the

$\tau_{eff}(\Delta n)$ curve for the etch-back sample, represented by red circles, is almost identical to that of the sample with AlO_x-passivated edges even though this sample is still in M2 format. This can be explained by the fact that the etch-back approach creates new “inner” edges due to the etching process, as indicated by red arrows in Fig. 2. Although these new edges constitute only a relatively small fraction of the total edges, they include the space charge region of the *pn-junction. Since the carrier concentrations of holes and electrons are approximately equal in* this region, the recombination rate at these inner edges is maximal. Consequently, the "inner" edges dominate the behavior of the etch-back sample. These edges were also passivated using ALD AlO_x (and PECVD SiN_Y), leading to a nearly identical response compared to the 50x50 mm^2 sample with AlO_x passivation. The sunken emitter approach shows no lifetime limitations towards low injection. The injection-dependent $\tau_{eff}(\Delta n)$ curve, shown as blue crosses in Fig. 3, reaches a plateau at low injection levels comparable to the sample in Fig. 1 in M2 format. The fact that no new edges are formed utilizing the sunken emitter approach seems to be beneficial.

The idea behind the etch-back and sunken emitter approaches is motivated by the goal of enabling subsequent size reduction of the samples without requiring additional edge passivation. This is achieved by ensuring that the newly created edges are separated from the emitter, which serves as the transport channel for bulk minority carriers, by an undiffused frame. To verify whether this approach is successful, samples fabricated according to the process flow shown in Fig. 2 were subjected to laser cutting after processing. The effect of subsequent size reduction on the injection-dependent $\tau_{eff}(\Delta n)$ curves is presented in Fig. 4. It is evident that for both the etch-back and sunken emitter approaches, the shape of $\tau_{eff}(\Delta n)$ remains unchanged as long as the laser cut is performed at a sufficient distance from the emitter (shown for a minimum of 5 mm in each case). However, if the laser cut is made within the emitter region (shown for the etch-back approach) or directly adjacent to it (shown for the sunken emitter approach), the typical lifetime limitations at low injection arises due to increased edge recombination.

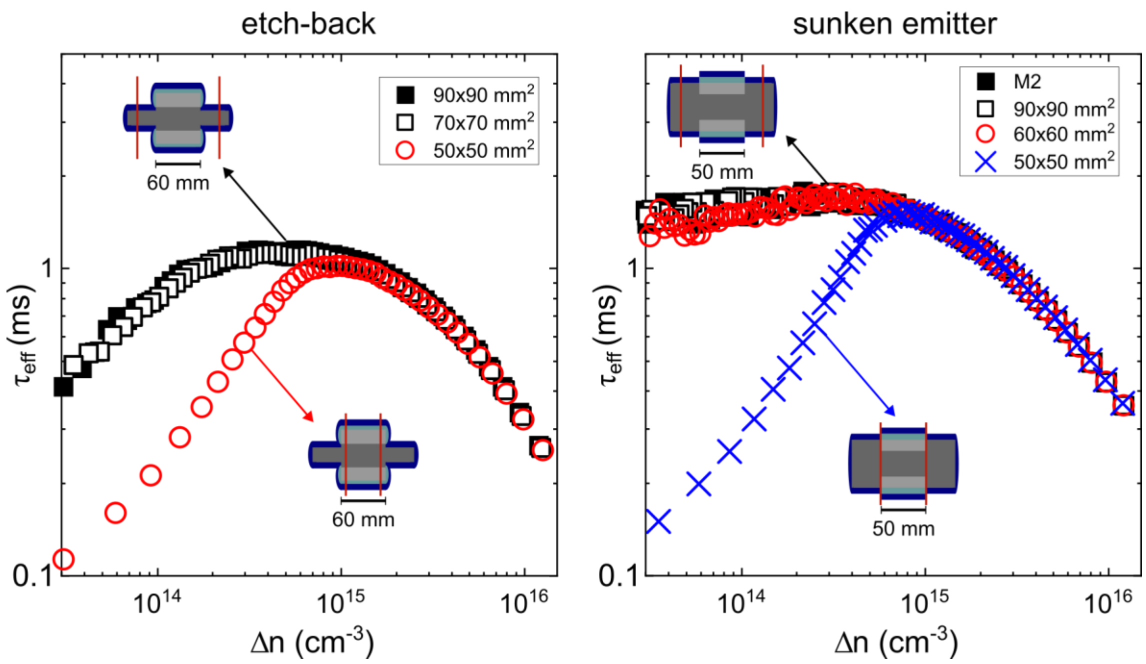

Figure 4. *Injection-dependent $\tau_{eff}(\Delta n)$ curves of samples utilizing the etch-back and sunken emitter approach with subsequent size reduction by laser cutting.*

4. Conclusion

Lifetime samples with a pn-junction exhibit strong limitations of $\tau_{eff}(\Delta n)$ at low injection due to increased edge recombination. Among the approaches presented in this work to mitigate edge-related effects, the sunken emitter approach appears to provide the most effective way to decouple the PCD measurement area from insufficiently passivated outer edges. While edge passivation using dielectric layers (as seen in the AlO_x-passivated reference sample and the etch-back approach) visibly reduces the impact of edge recombination, it does not completely suppress it. In contrast, the sunken emitter approach shows no injection-dependent limitation at low injection for the tested structures. Additionally, it allows for post-processing sample size reduction by laser cutting without additional passivation, provided that a sufficient distance between the laser cut and the emitter is maintained.

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Author contributions

D. Bäurle: formal analysis, investigation, validation, visualization, conceptualization, writing – original draft; **A. Herguth**: conceptualization, validation, supervision, project administration, writing – review & editing; **G. Hahn**: supervision, funding acquisition, writing – review & editing

Competing interests

The authors declare that they have no competing interests.

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