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# Towards understanding the characteristics of Ag–Al spiking on boron-doped silicon for solar cells

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ABSTRACT

With this work, we introduce numeric three-dimensional simulation of metal spiking into highly boron-doped surfaces of n-type silicon solar cells, which is moreover performed with a simulation of the quasi-steady-state photoconductance technique. This setup serves as a virtual experiment to simulate the dark saturation current density $j_{0,\text{met}}$ of metallized boron-doped emitters with respect to metal spikes originating from the silver–aluminum (Ag–Al) contact. With the results obtained from this simulation model we approach quality and quantity of increased $j_{0,\text{met}}$ and give detailed insight to which degree a solar cell's performance is possibly harmed by this effect. We show that metal spikes penetrating into boron-doped emitters are of harmless nature concerning $j_{0,\text{met}}$ until their tips reach depths where boron doping concentration is lower than approximately $10^{18}$ cm$^{-3}$. Deeper spikes then lead to an exponential increase in $j_{0,\text{met}}$ as more and more carriers from emitter and also the base are able to diffuse to its tip and recombine there. With the help of $j_0$-results obtained experimentally in combination with the simulation results, we discuss the influence of spikes on emitter recombination, the benefits that can be achieved with deeper emitter doping profiles, and suggestions for the further development of pastes to contact boron-doped surfaces.

## 1. Introduction

As Shockley–Read–Hall (SRH) recombination on passivated solar cell surfaces reaches degrees where losses due to carrier recombination become negligible and bulk lifetimes improve further and further, the focus of recombination centers switches towards the metallized contacts of high efficiency solar cells with its indicator being the dark saturation current density beneath the metal contact $j_{0,\text{met}}$. In n-type silicon solar cells, the $p^+$-doped boron emitters are usually metallized by screen-printing and firing a silver (Ag) paste containing single-digit percentages of aluminum (Al) [1], which lowers the specific contact resistance [2]. During the firing process of the Ag–Al paste, the Al catalyzes the forming of much larger and deeper spikes [2–4] than in the case of pure Ag pastes, which are e.g. used for phosphorus-doped emitters in p-type silicon solar cells. As part of the overall dark saturation current density $j_0$, $j_{0,\text{met}}$ is a crucial recombination channel. However, the quantitative understanding of effects of metal spiking into emitter profiles has not yet been evolved to a satisfying level. Our target is to develop an advanced simulation model to cover this issue and to offer qualitative as well as quantitative results on the correlation between metal spikes and high $j_{0,\text{met}}$ measured on metallized boron-doped emitters. As the existing simulation models lack accuracy and predictability, we develop a three dimensional model with Sentaurus Device [5] to extract $j_{0,\text{met}}$ from a quasi-steady-state photoconductance (QSSPC) simulation, including the introduction of three-dimensional metal spikes into the emitter doping region.

This work builds onto research results on the influence of metal spikes on the emitter dark saturation current density $j_{0e}$ in terms of experiments and modeling, which have been shown in in the recent years. Increased $j_{0,\text{met}}$ on boron-doped emitters with screen-printed Ag–Al contacts (especially compared with Ag contacts on $n^+$-doped phosphorus emitters) was reported by several workgroups and in some cases attributed to highly recombination active spike-shaped metal crystallites of varying penetration depths [1–4,6,7], which mainly consist of Ag [3]. Crucial findings are that higher Al content in Ag–Al pastes presumably catalyzes spike formation and thus leads to an increased $j_{0,\text{met}}$ [1,3,4,8]. Further it was found, that shallow spikes (inside the

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emitter region) allow for lower specific contact resistance [3]. The dependence of the specific contact resistance on the doping profile is thoroughly modeled and measured by Lohmüller et al. [8].

In 2011, Edler et al. [9] first presented an approach to describe an increased reduction of open-circuit voltage $V_{OC}$ of n-type silicon solar cells beneath metal contacts on boron-doped emitters with a metal layer penetration into the silicon emitter region. In a subsequent publication in 2014 [7], Edler refined the results with a more advanced two-dimensional (2D) model performed with the simulation software ATLAS by Silvaco [10]. Here, the metal layer approach was explicitly explained and a variation of depths for a penetrating metal layer as a whole was shown and brought to consistency with measurement results on several boron and phosphorus doping profiles in its effect on $V_{OC}$. In 2014, the authors of the present work showed Sentaurus Device simulations approaching the increased $j_{0,\mathrm{met}}$ beneath contacts with a 2D geometric metal spiking model instead of a layer-like metal penetration [11]. The work at hand builds onto these results upgrading the models to three dimensions. In early 2015, Koduvelikulathu et al. [12] presented a spiking model on phosphorus-doped emitters with ATLAS. They also used a 2D geometric model of a metal spike, but restricted their investigation to the metal paste's influence on the parameters $V_{OC}$ and pseudo fill factor *pFF*.

Despite the efforts to describe the effect of spikes on boron-doped emitters, to date no publication is able to describe the effects on the dark saturation current in a consistent three dimensional physical model. This is the motivation of the presented work as it offers a much more consistent and reliable physical approach.

In the following section we introduce the basic assumptions of our work and the perspective of our approach. The simulation model is explained in Section 3, followed by the experimental background in Section 4. Simulation and measurement results are presented in Section 5. A thorough discussion of the results and a conclusion is provided in Sections 6 and 7.

## 2. Approach

The most descriptive parameter for the recombination at metallized emitters is the dark saturation current density beneath the metal contact $j_{0,\mathrm{met}}$, as $V_{OC}$ is affected by further influence of other cell components, for example the passivated areas. Therefore, we develop a method to simulate $j_{0,\mathrm{met}}$ for the metallized emitter regions including metal spiking. From microstructural investigations with scanning electron microscopy (SEM) we know that Ag spikes are formed in the shape of inverted pyramids, see Fig. 1 and References [4,13], which can reach towards or beyond the pn-junction. Our observed coverage of spikes yields an average of around 1% resulting from 30 images (with 983 $\mu m^2$ size each) taken from one silicon wafer after wet-chemically etching the Ag–Al bulk contact, the glass layer, the passivation layer, and all spikes [8].

Ag pastes tend to form only small spikes which consequently remain in shallow depths compared to the emitter profile depth, as can be seen in the SEM image in Fig. 2. As we will see later – and has also been shown in the above-mentioned references [7,12] – the impact of shallow spikes on $j_{0,\mathrm{met}}$ or $V_{OC}$ is small to none.

Unlike Edler et al., who model a planar metal layer evolving in penetration depth to explain observed $V_{OC}$ losses, we apply a model taking the 3D geometry of the spike into account. By replicating the actual (inverted pyramid) geometry of the spikes with Sentaurus Device [5], we want to get insight into the events taking place when spikes penetrate deeper into boron-doped emitter regions. We use a 2D and a 3D model to show the errors resulting from dimensionally simplified geometries. Our simulation setup of choice is a virtual QSSPC [14] simulation setup which will be explained in the next paragraph.

## 3. Simulation method

We emulate the experimental technique of the injection-dependent carrier lifetime measurements with Sentaurus Device, which can be done, e.g., using the QSSPC measurement technique developed by Sinton et al. [15]. $j_{0,\mathrm{met}}$ is extracted as described in Eq. (1). A quartered upper section of a QSSPC simulation symmetry element is depicted in Fig. 3(a), a 2D-cross-section through the spike tip plane in Fig. 2(b).

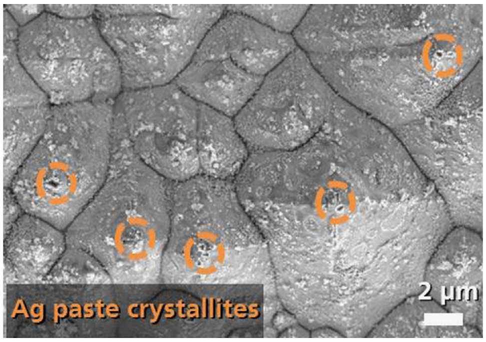

**Fig. 2.** SEM image of a phosphorus-doped surface after etching away the Ag contact, the glass layer, the passivation layer, and all spikes. Remaining spike imprints in orange circles; image taken from Ref. [8]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

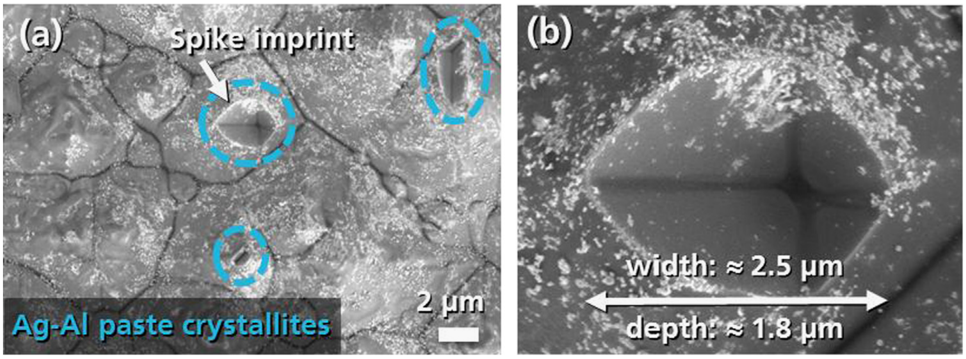

**Fig. 1.** (a) Scanning electron microscopy (SEM) image of a boron-doped emitter surface after etching away the Ag–Al contact, the glass layer, the passivation layer, and all spikes. Remaining spikes imprints in blue circles; (b) image crop of the largest imprint with the shape of an inverted pyramid. The dark shadows indicate the inverse pyramid's edges. Image taken from Ref. [8]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)