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Abstract of the dissertation with the title „Metallization of Silicon Solar Cells with Passivating Contacts" by Jörg Schube

This work develops and analyzes innovative metallization and contact formation of next-generation silicon solar cells, namely silicon heterojunction (SHJ) and Tunnel Oxide Passivating Contact (TOPCon) cells. Thereby, the focus is set on metallization with reduced silver consumption along with extremely fast and effective contact formation techniques. For this purpose, the development of new printing approaches and a deep understanding of contact formation mechanisms using advanced characterization methods is necessary.

A new printing technique with large silver saving potential, called *FlexTrail* printing, is developed. Using the same nanoparticle-based inks as for inkjet printing, it allows for the application of very narrow metal electrodes down to 10 µm width on textured substrates and down to 8 µm width on planar surfaces. This minimizes shading-related losses, hence, enabling a SHJ cell efficiency of up to 23.7%. The wet ink laydown is reduced down to below 10 mg/cell, certainly offering a significant cost saving potential compared to state-of-the-art screen printing with a typical laydown of 100 mg/cell (busbarless).

Extremely fast intense pulsed light (IPL) is evaluated towards solar cell processing. Thereby, it is demonstrated that an entire replacement of time-consuming thermal post-metallization treatments is possible. IPL-induced electrical contact formation in finger-patterned metal electrodes printed on top of a SHJ substrate is investigated. The substrate absorbs pulsed light and, thus, heat is transferred to the metal/transparent conductive oxide (TCO) interface inducing sintering of metal particles. Additionally, it is demonstrated that the lateral conductivity of metal fingers is increased by heating due to light being directly absorbed in the metal electrode. Based on the knowledge of contact formation, IPL processes are developed allowing low finger resistances of down to 3.0 Ω/cm and contact resistivities of down to 2.7 mΩ·cm².

Furthermore, the impact of IPL on the SHJ is investigated. For this purpose, an in-situ temperature measurement setup is developed enabling to characterize the substrate temperature during millisecond-lasting IPL flashes. Peak temperatures are correlated with the SHJ passivation quality. For such contacts, an optimum peak temperature of 325°C is identified. It is tolerated by the temperature-sensitive SHJ due to the shortness of pulsed light. In comparison to thermal annealing, thus, up to 5 mV higher implied open-circuit voltages are achieved.

Using the findings of this work, busbarless IPL-processed SHJ cells are manufactured that outperform their thermally treated counterparts in terms of cell efficiency by up to $0.4\%_{abs}$. Thereby, curing, annealing, and light soaking is effectively combined in one single process step. IPL's efficiency advantage, high throughput potential, and compact design enable a cost of ownership saving potential of $6\%_{rel}$ compared to state-of-the-art thermal annealing and even a cost reduction potential of $2\%_{rel}$ on module level.

In order to make use of printed metal electrodes' full electrical potential, higher annealing temperatures are required than are compatible with the SHJ. They can be used, for example, in combination with temperature-tolerant TOPCon/TCO layer systems. Comprehensive microstructural analyses reveal that higher temperatures induce more effective particle sintering in printed electrodes. Therefore, thermal annealing is developed operating at temperatures of up to 350°C. This leads to lateral resistivities in the range of 3 µΩ·cm, comparable to those of high-temperature-processed contacts (temperatures of up to 800°C). Regarding contact formation at the metal/TCO interface, a contact formation model is presented. Thereby, the surface energy ratio of metal particles and TCO plays a crucial role. If the TCO layer's surface energy is too low, voids occur at the interface, hence, increasing the electrical contact resistivity.

Also in the case of TOPCon, IPL can replace thermal annealing. Both-sides TOPCon solar cells featuring front TCOs and screen-printed metal contacts are IPL-annealed. Thereby, high passivation quality and implied open-circuit voltages of up to 709.3 mV are obtained. This is similar to 709.4 mV as achieved in case of thermal annealing at 350°C. First results on lab-size cells reveal that IPL can achieve similar cell performance as thermal

annealing. The best TOPCon cell in this work is IPL-processed and has the potential for 21.6% conversion efficiency, demonstrating the applicability of IPL for TOPCon.