High-resolution interdigitated back contact solar cell inspection using Terahertz microprobes

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***Abstract* — Terahertz (THz) near-field microscopy is presented as a new characterization tool for photovoltaic applications: High-resolution sheet resistance measurements at interdigitated back-contact (IBC) solar cell samples are conducted, revealing previously undetectable features with lateral dimensions as small as a few tens of µm. Despite the very high maximum resolution the method is reasonably fast and suited for full wafer-scale inspection tasks.**

I. INTRODUCTION

DEVELOPMENTS in the photovoltaic market are driven by cost pressure and the need for ongoing solar cell efficiency improvements. A promising concept for performance enhancement is based on interdigitated back contact (IBC) cells. Front shading losses of the incident sunlight are avoided, as there is no metallization on the illuminated side. Accordingly, more care has to be taken of the rear-side structure of the cell, as it is responsible for the charge-carrier separation and extraction performance mainly determining the power conversion efficiency. IBC cell manufacturing processes solely based on cost-efficient screen printing patterning and metallization have been developed, recently leading to efficiencies as high as 20.7 % on 6-inch wafers [1]. The final structure of such devices contains selectively doped regions with dimensions in the range of just a few 100 µm [2]. Faults in the doping conformity of these small areas strongly affect the total cell efficiency. Hence, a full-wafer-scale and highly resolving method for sheet resistance imaging is urgently needed.

In this work we demonstrate a Terahertz near-field microscopy setup enabling sheet resistance measurements with a sub-wavelength resolution of 20 µm at IBC cell test structures.

II. RESULTS

Measurements are performed in a THz transmission setup based on a classic pump/probe scheme using 100 fs duration laser pulses at a central wavelength of 780 nm and a bias-free bimetal grating Schottky-field-emitter for THz generation. As described in earlier publications, a TeraSpike microprobe is used for photo-conductive THz near-field detection and scanned across the sample under test in a few µm distance [3]. The setup is schematically depicted in Fig. 1, showing also a blow-up of the microprobe-tip. The small electrode-spacing of just 2.5 µm at the cantilever tip, where the THz field is picked-up, and the close vicinity to the surface of interest enable highest resolution of a few µm. Minimum field invasiveness is achieved by a low thickness of the free-standing LT-GaAs cantilever of just 1 µm.

In this application, the sample property of interest is the lateral sheet resistance distribution of a thin doping layer on top of a homogeneous weakly background-doped silicon substrate.

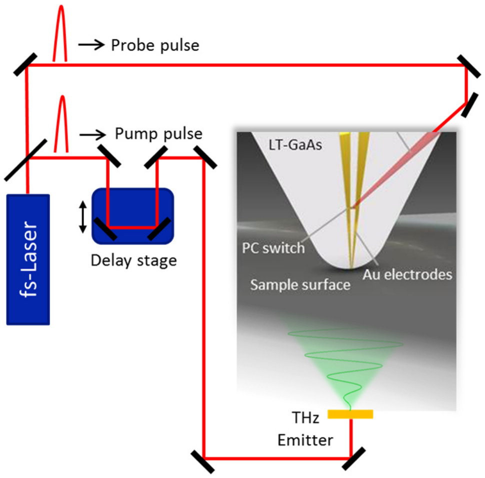

Fig. 1: Schematic of the THz near-field setup including a magnified image of the TeraSpike microprobe detector in close vicinity to the sample surface.

The sheet resistance R_{sh} is calculated from the measured THz transmission amplitude reduction by the doping layer [4] using the Tinkham formula (1). T_{SL} represents the transmitted amplitude through the doped sample areas while T_S is the reference value for the bare substrate. Further constants are the substrate refractive index n and the free-space impedance Z_0.

$$T = \frac{T_{SL}}{T_S} = \frac{1}{1 + \frac{Z_0}{R_{sh} \cdot (n+1)}} \qquad (1)$$

The results of THz sheet resistance measurements presented in this work demonstrate that this new approach goes considerably beyond the capabilities of the established techniques for solar cell sheet resistance imaging. While electrical four-point-probing (4pp) results are widely accepted as reference R_{sh} values for sufficiently homogeneous measurement spots, this method lacks the resolution and measurement speed for a complete IBC cell inspection. Thermography based on infrared transmission or reflection on the other hand is a fast camera-based technique [6], versatile for alignment tasks e.g., but difficult to use for the determination of absolute R_{sh} values, due to its strong dependence on surface morphology in terms of scattering and lens effects.

Therefore, THz near-field microscopy is proposed as a new inspection method for high-resolution large-area sheet resistance quantification. In the following, benefits of this approach are demonstrated at first at a dedicated test sample, featuring micron-scale R_{sh} variations and a relatively rough surface. Subsequently, the results from THz transmission measurements at IBC test samples are discussed that were produced using commercial manufacturing processes, as described in [7].

Fig. 2a) shows the THz transmission based sheet resistance measurement data of a p-type mc-Si sample that was locally doped using single laser-pulses and exhibits R_{sh} variations on a sub 100 µm scale, thus too small for the inspection using standard four-point-probes. The darker spot positions (marked with an arrow in Fig. 2a) stem from a double exposure to the doping-laser and show a significant reduction in sheet resistance. This laser-doping process is known to modify the surface morphology in the order of a few µm, thus in the order of the operational wavelength of thermography-setups. For the corresponding thermography-measurements displayed in Fig. 2b) we have ceased to quantify the R_{sh} values, as diffraction of the infrared light occurring at the surface texture results in misleading values and even shows seemingly increased sheet resistance at the stronger doped spots. Micron-scale surface textures hinder the extraction of absolute R_{sh} values from thermography images, but are less influential for the proposed THz inspection approach, due to the larger wavelengths.

In the investigated application case of interdigitated back contact cell test structures the layer of interest is the highly doped rear-side of cells made from n-type Cz-Silicon. Via selective boron and phosphorous diffusion processes the back surface field (BSF, n^+) and emitter region (p^+) are created, having lateral dimensions in the order of a few 100 µm. As schematically depicted in Fig. 3c), the single fingers feature additional heavily p^{++} and n^{++} doped regions.

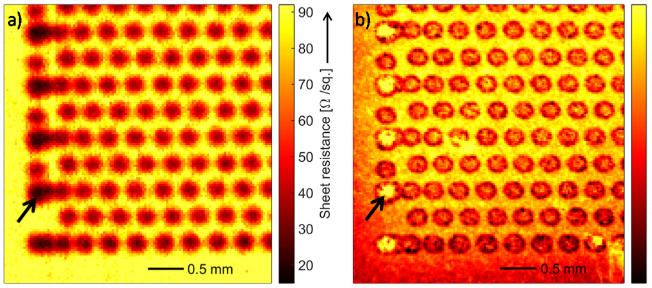

Fig. 2: Sheet resistance image of a locally laser-doped test-sample, a) obtained via THz near-field microscopy and b) via thermography imaging. The arrows mark exemplary spots with higher doping that have been exposed to the doping-laser pulses twice.

Fig. 3a) and b) display the measured sheet resistance of an IBC cell with a resolution of 20 µm. The separate finger structures and various doping levels are clearly resolved and distinct features can be observed. A large-scale variation of R_{sh} of the p^+ doped region is observable in Fig. 3a) as a continuous decrease in sheet resistance of the bright emitter region from left to right. This variation is attributed to inhomogeneity in the patterning process. In addition, a slight misalignment of the different diffusion processes is observed: The p^{++} doped region shows a small left-shift compared to the p^+ doped emitter region. A more detailed inspection reveals variations on the sub-100 µm scale, visible as darker shaded horizontal lines in Fig. 3b). Test measurements at a rotated sample and the observation of small temporal shifts in the transmitted THz pulse confirm that the origin of these variations lies in incompletely cured sawing damages from the wafer cutting process.

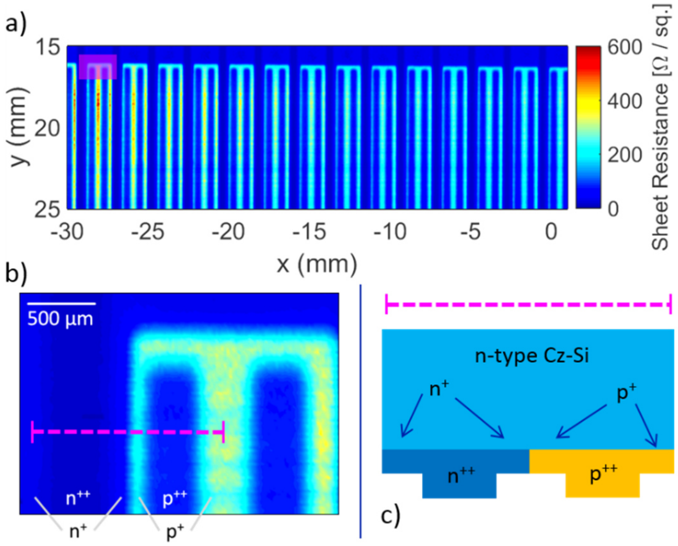

Fig. 3: a) Sheet resistance mapping of an IBC test sample obtained with THz near-field microscopy, b) zoom onto a single finger and c) schematic of the doping levels across a finger along the marked line in (b).

III. SUMMARY

In this work the capability as well as the necessity of monitoring micron-scale doping patterns on large-scale IBC solar cells using THz microprobes has been presented. THz near-field measurements enable the detailed inspection of doping layer structures and the detection of large- and small-scale inhomogeneities. As a result, cell manufacturers and process developers are getting a better control of production processes, which will finally help to reduce production costs and increase cell performance.

The method is not limited to solar cell applications, but can also be used for the examination of a vast variety of conductive thin-films on THz-transparent substrates. This covers the inspection of ITO layers or metal-meshes for display or sensor applications as well as quality control and sheet resistance measurements of graphene sheets.

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