

Local resolution of currents through electrical joints consisting of materials with different conductivity

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Abstract. Within this work the impact of contact materials with higher volume resistivity as leaded solder are investigated in terms of comparability of the current conduction through the joint. An approach was developed to experimentally determine the qualitative local current density by magnetic field imaging (MFI) at ribbon-to-ribbon contact samples. The result reveals that the MFI technique on a symmetric sample design allows the evaluation of the current paths in two-dimensional contact areas. Different resistivities of the contact material result in characteristic differences in current distribution through the joint. Low resistive $\text{Sn}_{60}\text{Pb}_{40}$ -soldered contacts exhibit localized current injection whereas the tested contact based on electrically conductive adhesives (ECAs) show an extended current flow through the ECA-based contact. A FEM-based simulation model to mimic the used setup was developed and confirmed the results by taking different contact material resistivities into account. For materials with resistivities larger than $1 \cdot 10^{-3} \Omega \cdot \text{cm}$ current injection was found to spread spatially within the tested contact geometry. Contact material development as well as contact design can benefit from that approach, allowing consumption and material composition optimization. A further advantage is the feasibility of the method to study production failures like inhomogeneous ECA distribution enabling a non-destructive monitoring of process stability and root cause analysis.

Keywords: Interconnection / ECA / solder / magnetic field imaging / simulation

1 Introduction

Today, leaded solder is the mature standard material for reliable and cost-efficient interconnection of double-sided contact silicon (Si) solar cells and module interconnection in the manufacturing process of modules [1]. Even if the lead-containing solder material is expected to be mainstream technology for the next 10 years, alternative lead-free materials will rise like electric conductive adhesives (ECA) or lead-free solder. A world photovoltaic (PV) market share for lead-free alternatives of around 45% is expected in less than 10 years indicating the demand for efficient, functional and cost-efficient new lead-free materials [1]. Reliability and costs are crucial to compete with leaded matured standard solder. In PV applications electrical contacts must resist harsh environmental conditions like thermo-mechanical stresses [2–5] or degradation due to exposure to moisture or reactive chemical compositions like acidic acid, depending on the encapsulation material [6,7]. Mechanical forces are able to separate electrical contacts which suffers by low adhesion or cohesion [8]. Chemical reactions can degrade electrical

contacts by corrosion as well [6]. If interconnection materials aging occurs either by long application time or by susceptibility to mechanical or chemical degradation a local separation of contacts can arise [9,10]. As consequence remaining intact electrical contacts act as a redundancy assuring the conduction of the full current. Accordingly, the current is conducted by a reduced contact area resulting in higher current densities. It is crucial for the reliability of the interconnection that the electrical contact is robust and persist even at higher stresses. Rising contact materials like ECAs must be designed carefully and tackle the challenge to form high-conductive electric joints whereas the consumption of silver must be minimized [11]. Due to the material design of a nonconductive matrix and conductive filler the bulk resistivity of an ECA is higher compared to a solder. In case of contact aging or degradation higher (bulk or contact) resistivities could be detrimental for redundant contacts due to increased power losses or accompanied thermal accelerated contact degradation. Therefore, new materials must be carefully tested in production as well as after accelerated aging. Usually, quantitative series resistance, qualitative Electroluminescence, I-V or series resistance imaging are used to characterize non-destructively interconnection status in terms of stability, defects or aging [12]. None of these

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techniques tests the electrical contact condition independent from the solar cell with local resolution. Hence, starting degradation with redundant contact cannot or hardly be investigated.

A novel approach to characterize the connection condition has been developed and tested for the assessment of electric contact materials. The needed measurement technique must be sensitive to electric currents in a two-dimensional joint as well as space-resolved enabling inspection of local current injection from one conductor through the joint into another conductor. Simplified test structures with no requirement of a solar cell were designed, suited to investigate two-dimensional joints in terms of their conduction homogeneity within the contact area. Magnetic field imaging (MFI) technique [13,14] has been applied to measure the magnetic flux density induced by electric currents along the joint. Our used characterization approach reached the needed sensitivity to resolve local current injection as well as differentiation of impacts by current injection and sample geometry. By evaluating the magnetic flux density, the current path within the contact area of a solder and an electrically conductive adhesive has been resolved revealing specific joint conduction characteristics. Accompanied simulations support the measured result that the difference in resistivity between solder and ECA is the key parameter of the observed current transport path differences. Generally, the presented method is applicable to all materials forming an electrical joint. The approach can also be modified by other ribbon dimensions (length, width) or substitution e.g., by a silver busbar. Furthermore, the contact area dimension is not a constraint but need technical improvements in spatial resolution if the contact dimensions are smaller than 2 cm. Hence, there are several degrees of freedom to modify the sample under test but the demand of precision in terms of set-up adjustment, sample fabrication and improved spatial resolution will increase.

2 Methodology

The design of a test structure for different connecting materials (ECA or solder) was developed with focus on considering critical material interfaces as well as a simple design requirement. As reported for encapsulated joints, after accelerated stressing of ECA based joints between solar cells and cell-interconnection ribbons structural aging can occur depending on the material composition and stress test conditions [10]. Preferentially the interface between the ECA and the cell-interconnection ribbon was found to be sensitive to accelerated aging after temperature cycle test (TCT) or damp heat test (DH). Sometimes cohesion fracture was observed for ECA whereas the interface to the solar cell metallization seems to be less affected by stresses. Consequential, the test structure design for this study must include the interfaces of ECA to the cell-interconnection ribbon. The test structure design has been defined by a symmetrical electrical joint between two identical cell-interconnection ribbons (further called as ribbon) like shown in Figure 1a. The electrical joint set-value based either on a solder joint or an ECA joint with a length of 5 cm

and a width equal to the ribbon width. Crucial for the design of the test structure is a straight alignment of the two ribbons to each other and the design should have flat ribbons on a length scale larger than the contact area (5 cm) due to the used measurement design. The flat outlying ribbons must be large enough to serve as a baseline allowing an alignment-proof to exclude sample distortion. To mechanically support the sample flatness an insulating layer were additionally added. For the experiments a coated Cu-ribbon with a width of 5 mm, a Cu-thickness of 0.3 mm and a Sn₆₀Pb₄₀ coating thickness of $\approx 23 \mu\text{m}$ was utilized. Within the study two joint materials with different given volume resistivities (around 3 orders of magnitude difference) were utilized to form electrical joints. A lead-free ECA with a given volume resistivity of $1 \cdot 10^{-2} \Omega \cdot \text{cm}$ was applied by a manual stencil technique. After application the curing in a lamination process took place at 150 °C and a pressure of 0.1 bar for 10 min. Sn₆₀Pb₄₀-solder based joints were manufactured by manual soldering the used ribbons, where a typical volume resistivity for Sn₆₀Pb₄₀-solder is $1.5 \cdot 10^{-5} \Omega \cdot \text{cm}$. Multiple samples were manufactured with the same condition of each electrical joint type. The resulting thickness of the contact between the ribbons is about 0.03 mm to 0.09 mm.

Analyzing electric currents laterally by magnetic field analysis have been reported previously [15]. By assuming a magnetostatic condition, the current densities $\mathbf{j}$ at position $\mathbf{r}'$ and the generated magnetic field density $\mathbf{B}$ at the position $\mathbf{r}$ are described by the Biot-Savart-law,

$$\mathbf{B}(\mathbf{r}) = \frac{\mu_0}{4\pi} \int \frac{\mathbf{j}(\mathbf{r}') \times (\mathbf{r} - \mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|^3} d^3\mathbf{r}', \quad (1)$$

where μ_0 is the permeability of free space [16]. In the following work only qualitative characteristics and relation of magnetic flux density to the current density ($\mathbf{j}$) and distance ($\mathbf{r}$) are considered. Magnetic field measurements have been performed by an MFI line-sensor by DenkWeit GmbH installed on a home-built 3D-motorized setup. Along his extension the line-sensor consists of multiple individual sensors arranged in a line where each sensor measures the $\mathbf{B}$ -field at his individual position. Accordingly, the line sensor generates a $\mathbf{B}$ -field profile. The spatial resolution of the line sensor is in the low mm-range due to the nature of the magnetic field dilatation and the arrangement of each single sensors along the line. The line sensor was positioned above the interconnection test structures and carefully aligned parallel and centered to the test structure as shown in Figure 1b. A parallel alignment is relevant to maintain the distance between the sensor and lower (upper) ribbon constant. The line sensor was kept fixed over the sample to generate a profile in x -direction. A movement of the sensor at constant height z along the y -direction is feasible and would generate an image. According to the symmetry of the sample an image would show additional geometrical impacts of the sample border. For simplicity this work was focused on the middle of the sample (see Fig. 1) by neglecting edge effects. Since the sensor was kept centered and fixed over the sample the measurement records the profile (magnetic flux density versus the position) along the center of the test structure. For generation of a magnetic field

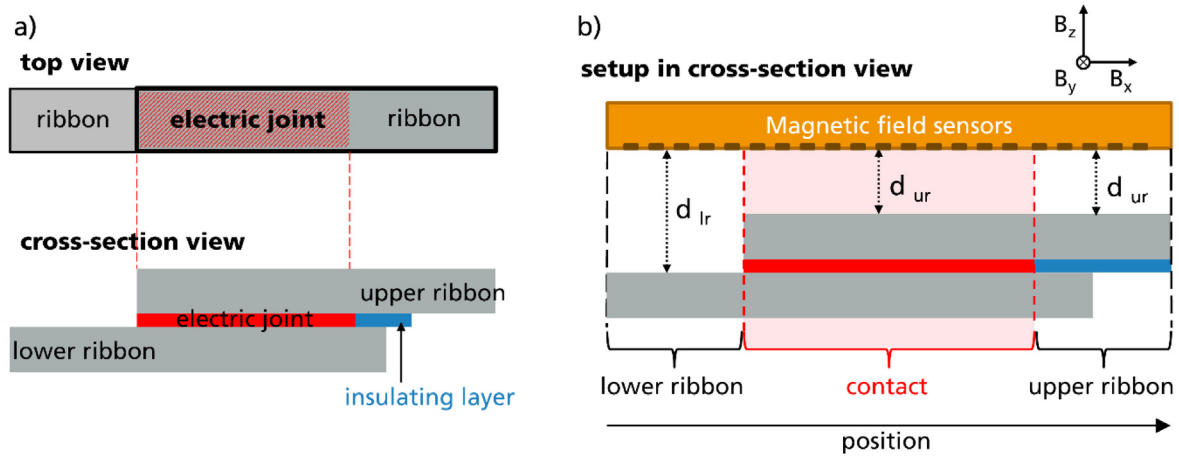


Fig. 1. Sample setup (a) drawn in top and cross-section view where the electrical joint between the upper and lower ribbon is red colored. (b) represents the measurement setup with the magnetic field line sensor parallel and centered to the test structure. Characteristic sample areas under investigation are indicated by brackets and distances from the sensor to the lower ribbon (d_{lr}) or upper ribbon (d_{ur}).

by a DC current through the test structure both ends were electrically connected and a constant current of 6 A was applied using a Keithley 2462 SMU. The measured raw data curves of the magnetic flux density versus the distance were post-processed by subtraction of a (normalized to the minimum) baseline curve of the magnetic flux density. The distance between samples and sensor could not be precisely (μm -scale) controlled in the used setup. Therefore, the presented numbers of the magnetic flux density can only be compared quantitatively within the same record. Nevertheless, the used setup and conducted measurements allows samples to be compared in a qualitative manner. The magnetic flux density is a vectorial measure, and each direction of the 3-dimensions (x, y, z) is recorded independently. Figure 1b shows the orientation of the inertial system.

The software LTspice was used to calculate currents within the upper ribbon, lower ribbon and through the contact. Ribbon and contact have been modelled by a resistor mesh whereas the sample setup and material constants were used as input. Independently from the LTspice result, a finite-element method-based simulation of the static magnetic field was carried out with the software ANSYS version 2022R2. The analysis is based on the edge-flux formulation with voltage degree of freedom. For the geometric model, the test specimen consisting of connector and ECA as well as an air region must be modelled. The model was meshed with a suitable element size. Current is applied on the positive potential of the ribbon while the other side receives ground potential. The outer surfaces of the air still receive a magnetic flux parallel condition. The materials are considered continuous solids and were given their electrical conductivity and electrical permittivity.

3 Results

3.1 Soldered interconnection

Figure 2 shows the absolute of the magnetic flux density versus the position along the soldered test structure. Within

the graph the 3 characteristic sample areas (see Fig. 1b) are separated by dashed lines. On the left-hand side, the area represents the measurement above the lower ribbon and on the right-hand side above the upper ribbon.

According to the test sample setup, both areas represent resulting magnetic flux densities which are generated by the same current from solely the ribbon. Since the ribbon itself and therefore the ribbon cross-sectional area is equal for both areas the current density is the same. Consequently, the observable difference of around $24 \mu\text{T}$ between both areas must result exclusively from the difference in the distance. Since $d_{ur} < d_{lr}$ the magnetic flux density is larger at the right-hand side position of the upper ribbon. The area in between is the contact area where according to the sample scheme in Figure 1a a stack of the upper ribbon, the formed joint and the lower ribbon is present. Figure 2 shows on the left-hand side the contact area that the magnetic flux density increases by around $13 \mu\text{T}$ by $\approx 12 \text{ mm}$. Within 40 mm , the largest part of the contact area, the magnetic flux density shows a nearly constant value. At the right-hand side of the contact area the value increase again by around $12 \mu\text{T}$ within $\sim 12 \text{ mm}$ and reach the value observable in the bare upper ribbon. By comparison, within the soldered contact area 2 nearly equal steps (in width and height) of the magnetic flux density were found located at the start and the end of the contact area. Additionally, exclusively the baseline along the length of upper and lower ribbon outside the contact of the used test structure permits the fundamental discrimination of current density impact to the magnetic flux density from distance related artifacts (e.g., by distortion).

To calculate the current density reverse from the magnetic flux density is complex since the inverse magnetic problem solution is not unique [13]. The reason is that the measured magnetic flux density in a point $\mathbf{r}$ is the sum of all magnetic fields, missing information about the place $\mathbf{r}'$ of generation. One must consider the specific sample setup and boundary conditions for interpretation. Hence, the

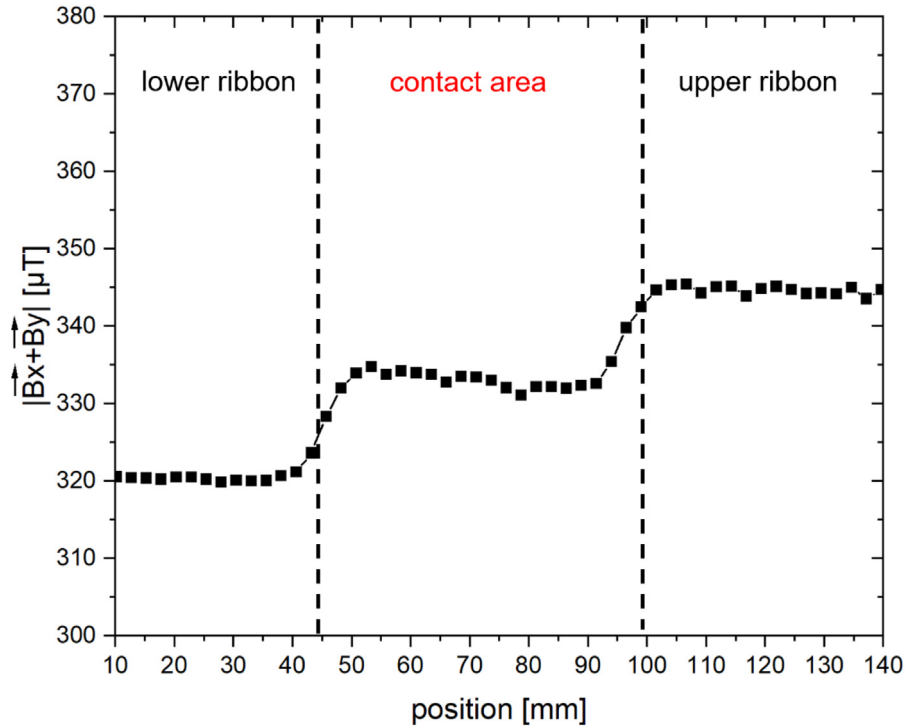


Fig. 2. Test sample with solder contact. Absolute value of the magnetic flux density versus the position along the bare lower, upper ribbon and the solder contact area. Dashed lines indicate the borders.

measured value of magnetic flux density within the contact area is the sum of fields generated from current densities 1st within the upper ribbon, 2nd the joint and 3th the lower ribbon. Boundary conditions are that the magnetic flux density could not decrease below the value in area lower ribbon or exceed the value in area upper ribbon. Consequently, if the value of the magnetic flux density (within the contact area) reaches the corresponding boundary value the causing current density must exist in equivalent (upper/lower) ribbon solely. Figure 2 exhibits in the contact area a magnetic flux density which is rather in the middle of the boundary conditions. Therefore, the 3 unknown current densities within the upper/lower ribbon and electric joint generate the magnetic field which sums up in the sensor height. By consideration, that the resistivity of copper ($1.7 \cdot 10^{-6} \Omega \cdot \text{cm}$ at room temperature [17]) is around an order of magnitude lower than that for $\text{Sn}_{60}\text{Pb}_{40}$ solder it is rather clear, that dominant current share is conducted by the two copper ribbons. Therefore, for simplification, the low current contribution share (within the parallel solder plane) will be neglected. Finally, taking the law of Biot-Savart and Kirchhoff's circuit laws into account, one can conclude for the solder contact in Figure 2 that within the contact area the upper and the lower ribbon conducts equal currents resulting in the observed nearly constant magnetic flux density. That behavior conforms up to an analog of one copper ribbon with a doubled cross-sectional area. Furthermore, the root cause of the two-step curve shape of the magnetic flux density along the contact area could be concluded by the same consideration. In Figure 2 the electrons drift (physical current direction) from the upper ribbon (source) to the

lower ribbon (drain). Regarding Kirchhoff's circuit laws the current split up in at least two dominant comparable shares in the ribbons. Both current shares combine primarily at the end within a few mm of the contact area. In the middle of the contact length no current transfer from one to the other ribbon takes place. For illustration, the test structure with concluded local current paths is drawn together with the magnetic flux density curve versus the position in Figure 3.

It has to be noticed, that the simplified discussion before includes several assumption and simplifications like negotiation of contributions from distant current densities ($j(\mathbf{r}')$), impact from small sample height inhomogeneities or limited lateral resolution of the sensor. Nevertheless, a qualitative description of the observed conduction characteristics indicates comprehensible the expected current transport properties of the solder contact. The approach demonstrates the feasibility to avoid distance-related artifacts caused by even slightly tilted samples enabling the inspection of transport within the contact area.

3.2 Electrically conductive adhesive interconnection

The determined resistivity of an ECA-based contact exhibits significant deviations [18]. Figure 4 shows for 10 samples the absolute magnetic flux density versus the position obtained from samples where the electric contact is formed by the ECA. Like in Figure 2, the 3 characteristic sample areas were indicated to identify the contact area. In comparison, all curves show a qualitatively comparable behavior. Therefore, the samples of the ECA group are manufactured comparable and show no large deviation.

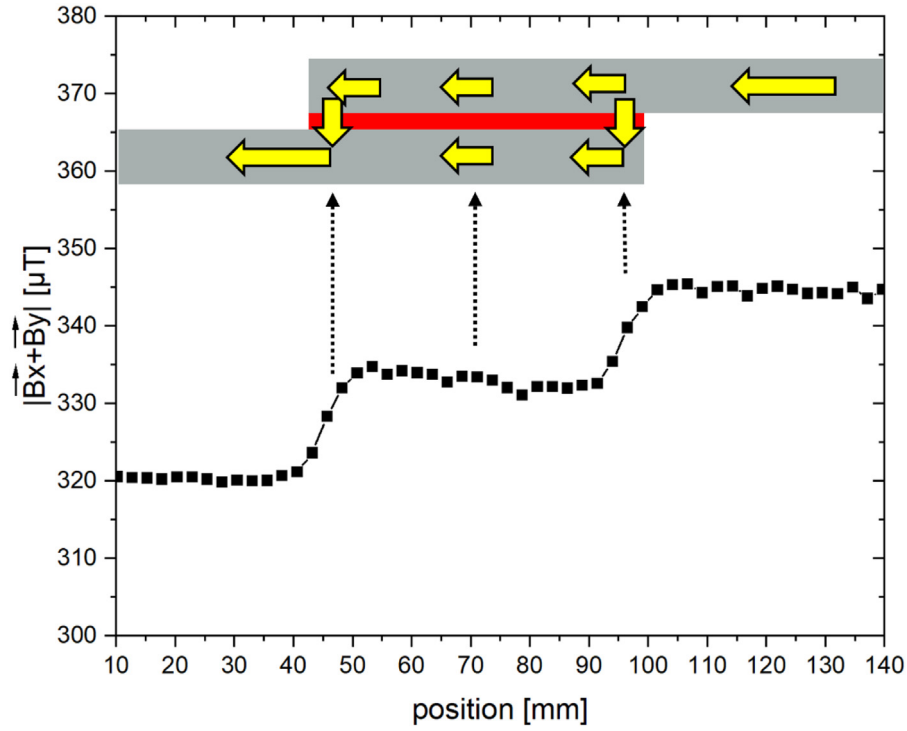


Fig. 3. Simplified drawing of the sample cross-section (see Fig. 1) aligned to the measurement from Figure 2. Yellow arrows represent the concluded current direction and allocated to the sample layer depth, respectively. The length of the yellow arrows indicates qualitatively the absolute current density at the equivalent position.

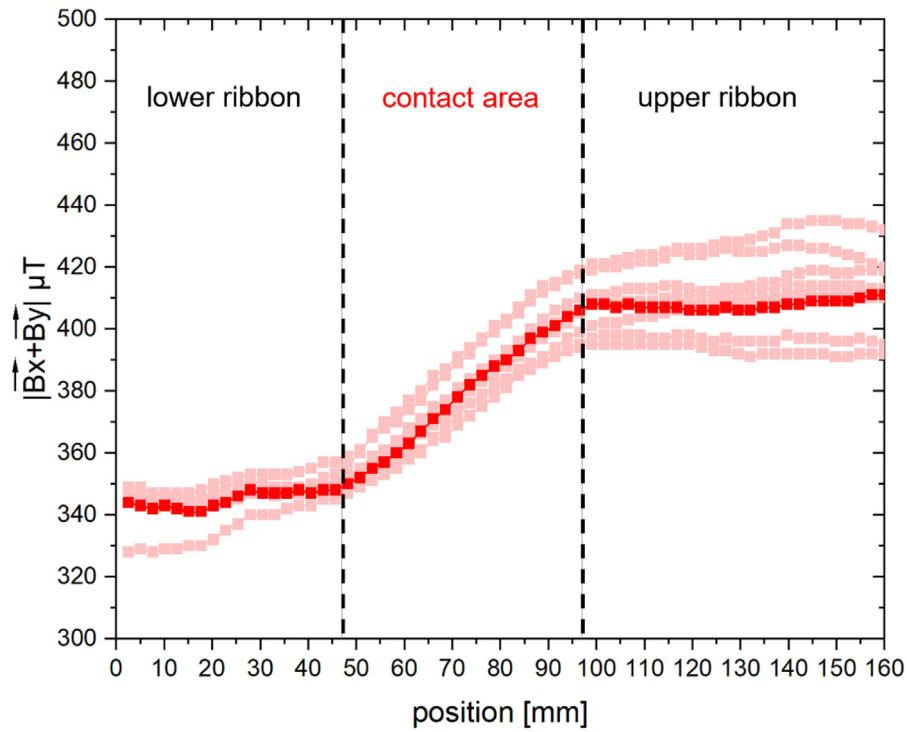


Fig. 4. 10 equal test samples with ECA-based contact. Absolute values of the magnetic flux density versus the position along the bare lower, upper ribbon and the ECA-based contact area. Dashed lines indicate the borders. One representative curve is plotted in dark red.

A representative curve out of the series of curves is highlighted in dark red color. Lower and upper ribbon area show an almost constant magnetic flux density. A tilt of the sample resulting in artifacts of the magnetic flux density in the contact area can be excluded. Hence, the curve within the contact area represents almost no sample tilt artifacts which would result in a constant slope increase or decrease. The magnetic flux densities along the total contact area length exhibit for all samples a linear curve or a constant slope, respectively. By a qualitative comparison to the soldered contact in Figure 2 a clear difference behavior is obvious and will be discussed below.

The method to draw a conclusion is analog to Section 3.1. The change in the absolute magnetic flux density, within the contact area, can be interpreted as a current transport. The current transport occurs through the ECA-based contact, from the upper ribbon into the lower ribbon. In particular, a current flow within the ECA contact plane can be neglected since the volume resistivity is 3 orders of magnitude higher than for the solder. Therefore, along the total contact area length, the constant slope of the curve indicates that the current density in the upper ribbon decreases linear. From a linear decrease can be concluded that the current density through the ECA-based contact is anywhere constant. Consequently, the ECA application during sample manufacturing is proven by this measurement to be homogenous in terms of contact formation along the total contact length. Finally, at the border between contact area and lower ribbon the total (source) current from the upper ribbon is transported into the lower ribbon. This current transport behavior differs strongly from the soldered contact where the current transport through the joint takes place within a mm-size length. This is clear evidence that the used ECA leads to a reduced maximum current injection density due to the ECA's higher resistance, compared to the solder. The high volume or contact resistance will limit the local current injection from the ribbon into the ECA. For the used ECA the limited current injection into the ECA results in a homogenous distribution of the current injection along the total contact length. The impact to the reliability of lower and higher conductive contact materials is not clear at this point. How the different homogeneity of contact current influences the aging need to be investigated. In case of adhesion or cohesion failure, smaller contact areas must conduct the same current. The current density and the power loss in these areas will increase. Consequently, it is obvious that low conductive materials must be designed and tested to resist larger current densities.

3.3 Simulation of contact with different volume resistivities

To proof these considerations a series of variations of the volume resistances for the material contacting equal high-conducting ribbons must be evaluated. The resistivity change should affect the current paths as well as the magnetic flux density profile along the contact under a transition of the observed curve shape of the investigated ECA to the solder curve shape. LTspice software have been

used to calculate local currents in the test structure with Sn₆₀Pb₄₀-solder and ECA to test the plausibility of the interpretation in Figures 3 and 5. The sample structure (along upper and lower ribbon and contact layer) has been modelled by a simplified resistor mesh by assuming an anisotropic conduction in the joint. Figure 6 shows the currents a) in the ribbons and b) through the contact for solder (filled symbols) and ECA (empty symbols). Figure 6 support the conclusion for the Sn₆₀Pb₄₀-solder contact that the current injection from the upper ribbon (black) through the contact (blue, filled symbols) takes place very locally (arrows in graph of Fig. 6b), balancing the currents to 3 A in each ribbon. For the volume resistivity, according to the used ECA, the current injection was found to be spatial distributed (Fig. 6b) and confirms qualitatively the prior experimental interpretation. Nevertheless, the result reveal that for a qualitative analogy of calculated and measured ECA curve characteristic a larger resistivity must be considered.

By mimic the experiment and to simulate the magnetic flux density the absolute current density needs to be calculated by finite element analysis (FEA) for the solder as well as the ECA contact. Figure 7 exhibit the cross-section of the structure whereas the color represents the absolute current density from the calculation in each segment. For clarity in the image the length of the contact has been reduced to 2 cm. The FEA simulated soldered and ECA-based contact characteristic corresponds to the expected behavior from Figure 6, confirms the developed model and enables the study of the magnetic flux density profiles.

Contact volume resistivity and contact length have been modified to study the quantitative impact on the generated absolute magnetic flux density by a FEA. Volume resistivities for the contact materials in the range from $1 \cdot 10^{-6} \Omega \cdot \text{cm}$ up to $1 \Omega \cdot \text{cm}$ were parameterized. Contact lengths of 0.5 cm, 2 cm and 5 cm (according to the experiment) have been simulated. Figure 8 show the obtained results. For narrow 0.5 cm contacts the simulated absolute magnetic flux density curves overlay each other and could not be distinguished by measurement. By increasing contact length of 2 cm and 5 cm the curves for different contact volume resistivities split up from curves shapes with two steps (low resistivity) to one step (high resistivity). The curve shape coincides qualitatively with the measured curve shapes (Figs. 3 and 5). For low volume resistivities the curve shape shows a very localized change of the magnetic flux density at the borders of the contact area. In the center, only a small slope can be noticed. With increasing volume resistivity of the contact material, the curve shape changes to a nearly constant slope. All curves intersect in the center of the contact.

One important outcome of the simulation is that the effective resistivity is the dominant parameter which determines the local current conduction through the contact area. The other important information is that the magnetic flux density curve characteristic is independent from contact material composition and structure as long as the contact size is larger than microstructural features of the joint composition. Consequently, the simulation predicts that a

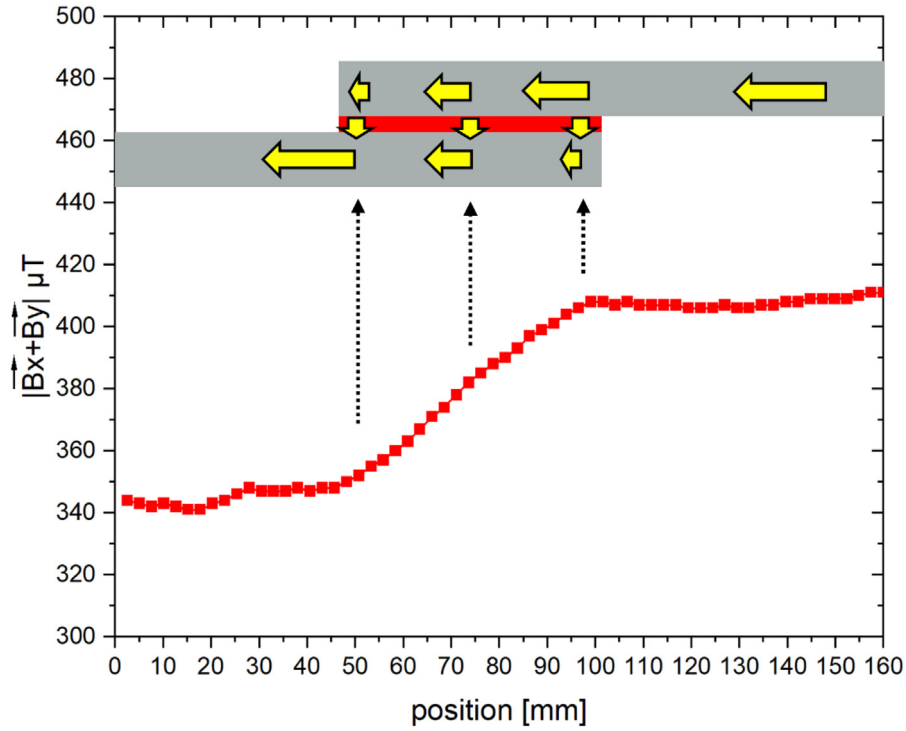


Fig. 5. Drawing of the sample cross-section (Fig. 1) aligned to the highlighted magnetic flux density curve from Figure 4. Yellow arrows represent the current direction allocated to the sample layer depth. The length of the yellow arrows qualitatively indicates the absolute current density at the position. For clarity, only 3 of multiple positions with current transport through the ECA-based contact could be drawn (denoted by the central black arrow).

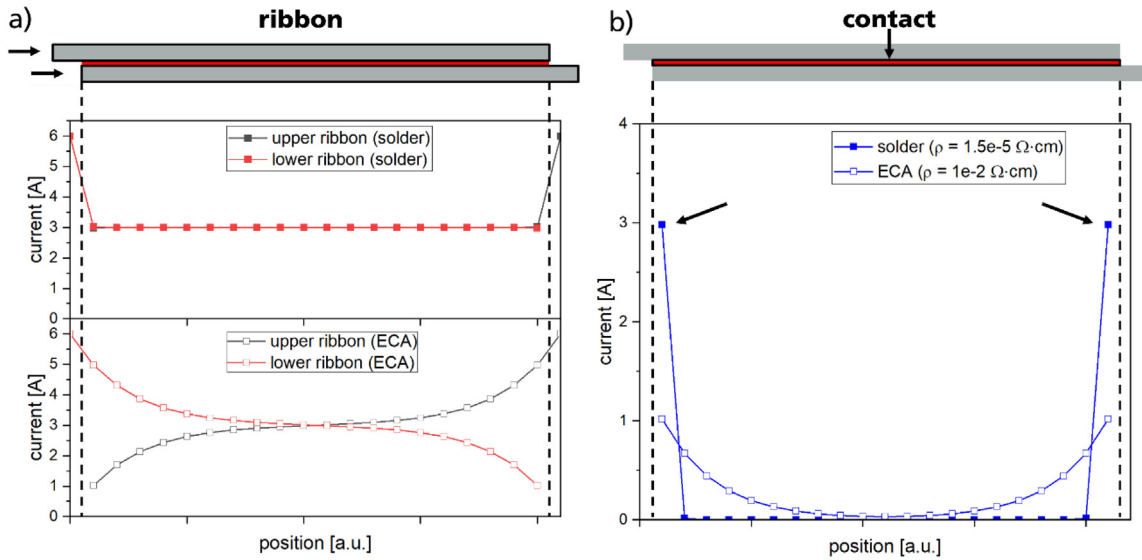


Fig. 6. Qualitative comparison of calculated local currents along the test structure a) in the upper (black) and lower (red) ribbon for $\text{Sn}_{60}\text{Pb}_{40}$ -solder (filled symbol) and used ECA (empty symbol). In b) the corresponding calculated current through the contact layer (from the upper into the lower ribbon) is shown in blue color. The schematic sample is drawn above the graphic as a guide to the eye whereas the arrows in the scheme point at the ribbons and the contact material.

high-conductive (or low-conductive) ECA will exhibit the same curve characteristic as a solder with the equal resistivity. It is relevant to note that within this study not all material type to resistance combinations have been experimentally studied.

Comparing the simulation with the experimental results, both characteristic curve shapes of the absolute magnetic flux density along the contact could be found in the simulation. The simulation confirms that the increase in the contact volume resistivity limits the current injection

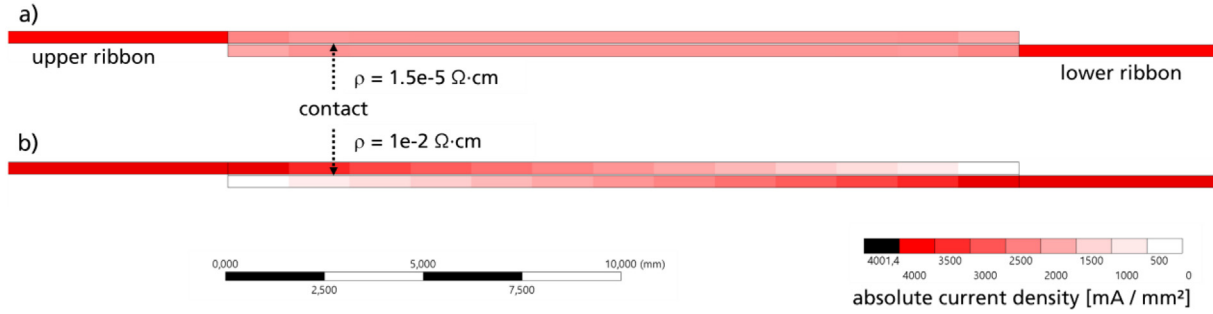


Fig. 7. Absolute current density calculated by finite element analysis (FEA) for a) solder and b) ECA-based contact cross-section of the test structure. FEA based on the experimental setup (contact length reduced to 2 cm for clarity in the illustration).

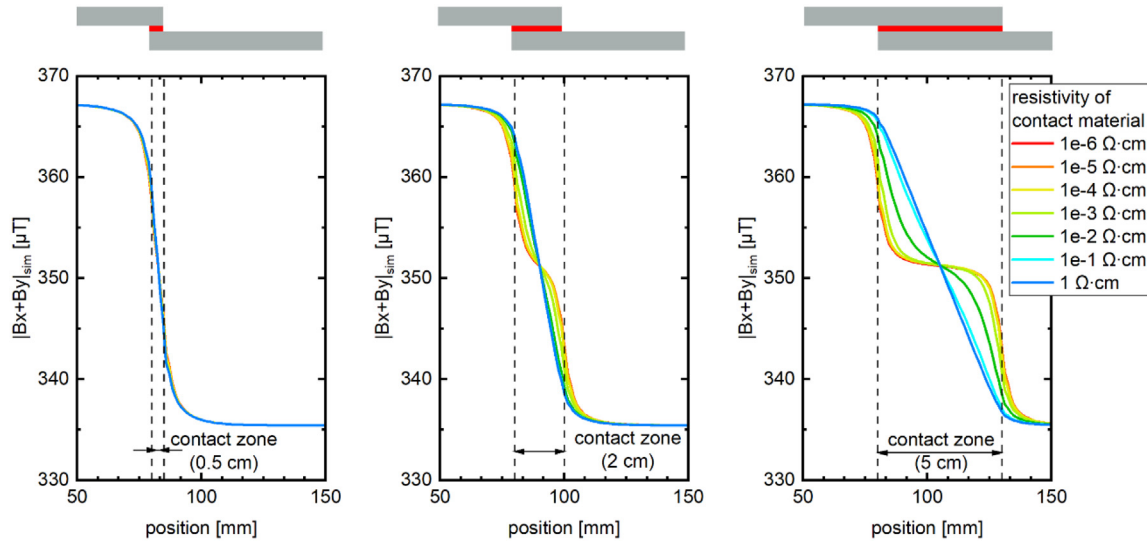


Fig. 8. FE-simulation of the absolute magnetic flux density to mimic qualitatively the experiment setup for different contact material volume resistivities and contact length of 0.5 cm, 2 cm and 5 cm. The schematic designs are shown above each graph according to Figure 1.

from the high-conducting ribbon into the contact material and result in a spatial extended current injection for high resistive contact materials. For the given simulation structure geometry, the current transport strongly changes for values around $1 \cdot 10^{-2} \Omega \cdot \text{cm}$. Therefore, the simulation also qualitatively confirms the experimental results by comparison the curve shapes for volume resistivities of $1 \cdot 10^{-2} \Omega \cdot \text{cm}$ (ECA) and $1.5 \cdot 10^{-5} \Omega \cdot \text{cm}$ ($\text{Sn}_{60}\text{Pb}_{40}$ -solder).

One can notice from the simulations that the calculated curve shape for a high-resistive material with a volume resistivity of $1 \cdot 10^{-2} \Omega \cdot \text{cm}$ differs from measured curve shape (see Fig. 5). The current injection within the simulated high-resistive ECA-based contact is not homogeneous distributed as experimentally found. The fact can be explained by the impact of the contact resistivity which was neglected in the simulation but is significant for current injection characteristics of high-resistive contact materials. Therefore, volume resistivity as well as contact resistivity must be known to optimize the simulation. Hence, the result demonstrates the benefit of the used

magnetic field measurement approach for locally resolved contact current characterization.

4 Conclusion

In this work a novel approach has been tested to investigate electric contacts of materials used in photovoltaic applications regarding the spatially resolved currents in a joint and local current injection from one conductor through the joint into another conductor. By means of the magnetic field imaging method and a specific sample design this method has been successfully tested for two contact materials with different volume resistivities, a high-conductive $\text{Sn}_{60}\text{Pb}_{40}$ -solder and a low-conductive electrically conductive adhesive (ECA). It could be shown that this sensitive measurement approach allows the robust reduction of measurement artifacts and enables reliable results. On the example of a $\text{Sn}_{60}\text{Pb}_{40}$ -solder interconnection a general workflow, sample design and interpretation were introduced and successfully applied to describe the measured conduction

and local current injection. By simulation, which mimicked the experiment, the experimentally concluded current injection from a copper ribbon through a high-conductive $\text{Sn}_{60}\text{Pb}_{40}$ -solder ($1.5 \cdot 10^{-5} \Omega \cdot \text{cm}$) interconnection into a copper ribbon could be confirmed qualitatively. The simulations showed that the resistivity of the contact material is the dominant parameter for the current distribution in the contact. Characteristic profiles of the simulated and measured magnetic flux density correlate to the effective bulk resistivity. According to simulations, when the volume resistivity of the contact material increases, the current injection into copper ribbons gets spatially extended for values larger than $\approx 1 \cdot 10^{-3} \Omega \cdot \text{cm}$. Therefore, different contact material types (solder or ECA) with equal resistivities will exhibit the same behavior. The predicted characteristic for a low-conductive material was found experimentally and qualitatively confirmed by application of the measurement approach by investigating a low-conductive ECA ($1 \cdot 10^{-2} \Omega \cdot \text{cm}$) as a contacting material.

In conclusion, the promising result demonstrate a further approach to support the development of robust, cost-effective and sustainable contacts for PV application. The approach enables a deep non-destructive insight in the contact function, the current transport and current injection in contacts between conductors. The method is limited by the spatial resolution of the used sensor to the mm-scale which restricts the resolution of small-size contact points. Nevertheless, multiple applications can be studied with this method, such as ECA application homogeneity, new ECA formulations and their functionalization. Based on the validated simulation, geometric variables and material requirements can be used for optimizations and identified design candidates can be evaluated with our developed method. Furthermore, the non-destructive character of the approach can be used to study the contact reliability by time dependent measurements in combination with accelerated aging stress.

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Author contribution statement

Stephan Großer: Measurement design, data evaluation and writing of paper. Matthias Pander and Ulli Zeller: simulation, support writing, proof-reading. Bengt Jäckel: discussion, proof-reading.

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