Pathways and Potentials for III–V on Si Tandem Solar Cells Realized Using a ZnO-Based Transparent Conductive Adhesive

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Abstract—This work presents a new type of transparent conductive adhesive and its electrical and optical properties with regards to an application in III-V on Silicon tandem solar cells. The developed adhesive is based on a doped ZnO and deposited by spray coating. The optical interconnection of the two sub-cells is identified as one of the major challenges due to the reflectance at the bond and possible approaches to reduce the reflectance are investigated by optical simulations. Regarding the electrical interconnection, an ITO-based contact layer reduced the lowest measured connecting resistivity from previously 17 $\Omega \cdot \text{cm}^2$ [1] down to 0.12 $\Omega \cdot \text{cm}^2$. It is shown that the homogeneity of the bond correlates with its conductivity and can be improved by adjusting the glueing process according to the calcination process of the adhesive. Taking both the electrical and optical parameters of the transparent conductive adhesive into account, the efficiency of a triple junction solar cell was estimated.

Index Terms—Electrical contact, tandem solar cell, transparent conductive adhesive.

I. INTRODUCTION

T HE highest photo-conversion efficiencies of photovoltaic devices are achieved by using multijunction solar cells. Silicon-based multijunction solar cells are a promising candidate for low-cost production. The most common materials, which are combined with silicon in order to form a multijunction solar cell, are either perovskites or III–V compound semiconductors. While perovskite-on-silicon solar cells show very promising results, the perovskite is very sensitive to humidity and its long-term stability is currently under investigation [2]. III–V on silicon tandem solar cells have the advantage, that both materials are already very well understood and both materials

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demonstrated their durability in space applications. However, combining the two materials poses some difficulties since the crystal lattices differ by 4% and their thermal expansion coefficients by a factor of 2. This makes the direct growth of III-V on silicon quite challenging. Direct wafer bonding avoids this problem but needs intensive surface preparation and clean room conditions which is challenging for a cost-efficient upscaling of such a process. Compared to wafer bonding and direct growth, using transparent, conductive adhesives (TCA) to join the different substrates is a promising alternative. Advantages are fewer restrictions regarding surface preparation and the possibility to upscale the processes easily. However, in order to be competitive with wafer-bonded or directly grown tandem solar cells, the TCA has to show excellent optical, electrical, and mechanical properties. Existing TCAs usually consist of a nonconductive transparent matrix, in which conductive particles are embedded. The particles can either be opaque (e.g., metals) [3] or transparent in the case of transparent conductive oxides (TCO) [4]. One drawback of this approach is that the particles should show a very narrow grain size distribution in order to ensure that most particles are in contact with both subcells (this criterion is relaxed if the conductive particles are flexible). This publication presents results on a particle-free TCO-based TCA, which is applied by spray coating.

In contrast to the existing TCAs, the described approach does not need the addition of conductive particles because the matrix itself becomes electrically conductive upon thermal annealing. The process is thereby much simpler and less complex than TCAs that need the addition of particles.

II. GENERAL REQUIREMENTS FOR TCA

In silicon-based tandem solar cells, the TCA has to be optically transparent starting from the wavelength where the top cell becomes transparent until the wavelength where the silicon bottom cell becomes transparent. In the case of a top cell with a band gap (E_G) of 1.7 eV, this would result in the wavelength range 730–1200 nm. Besides the transmission, the reflection at the interfaces is also of great importance and depends mainly on the refractive index of the TCA and the refractive indices of the top- and bottom-cell. This publication focuses on avoiding the reflection either by implementing anti-reflection coatings

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Fig. 1. Sketch of the separate resistances that add up to the connecting resistivity.

(ARCs) at the two semiconductor-TCA interfaces and/or by texturing the silicon surface.

The electrical impact of the TCA on the ohmic behavior of the device is schematically shown in Fig. 1. It consists of the specific resistance of the TCA itself ($R_{B, \text{TCA}}$) and the contact resistances of the TCA to both sub-cell surfaces ($R_{C, \text{top}}, R_{C, \text{bottom}}$). Combined, those resistivities result in the connecting resistivity, which is added to the solar cell by the TCA bond layer.

The electrical impact of the TCA on the tandem solar cell also depends on the properties of the device itself, since a lower current of the tandem solar cell leads consequently to a lower ohmic loss at the TCA bond layer. Cell concepts with a higher number of junctions typically possess a higher voltage and a lower current, which means that an increase in connecting resistivity is less critical for such devices.

Additional to the electrical and optical properties, the mechanical stability of the TCA has to be sufficient to withstand all necessary process steps and ensure a long lifetime of the device in the final module.

III. EXPERIMENTAL

The developed TCA was characterized for its electrical and optical properties as well as its homogeneity in order to assess its potential application in silicon-based tandem solar cells.

Regarding the electrical characterization, the contact resistance of both sputtered and by spray pyrolysis deposited contact layers, which are implemented between the TCA and the subcells, was investigated. The connecting resistivity of the TCA in combination with the electrical contact layer was investigated in bonded test structures.

A. Test Structures for Investigation of Contact Resistance

In order to protect the surfaces of the two subcells from oxidation during the thermal annealing of the TCA and to facilitate the electrical contact formation, a contact layer is implemented at the two interfaces. As contact layer, both a sprayed and a sputtered TCO were investigated. The sprayed TCO is deposited by spray pyrolysis at a substrate temperature of 375 °C. The precursor solution is a 0.2-M solution of zinc acetylacetonate hydrate (Merck) in methanol (99% for synthesis, Carl Roth). The precursor solution further contains acetic acid (1:500 acetic acid:methanol) and InCl₃ (anhydrous, Alfa Aesar) with a In/Zn ratio of 3at%. The results of the sprayed TCO (indium doped zinc oxide, IZO) are compared to those of a



Fig. 2. Sketch of the sample structure for the electrical characterization of the contact layer.



Fig. 3. Structure of the silicon and III–V samples for the electrical characterization of the IZO/semiconductor contact.

sputtered tin doped indium oxide (ITO) contact layer, which is a widely used TCO in photovoltaic applications [5]. The ITO was deposited at room temperature by dc magnetron sputtering with a dc power of 200 W and 0.4 and 60 sccm oxygen and argon gas flow respectively. The composition of the ceramic target (Evochem) was 95:5 wt% In_2O_3 :SnO. In Fig. 2(a) sketch of the sample structure, which is used for both contact layers, is shown.

Both contact layers were tested on silicon and III–V surfaces. In case of silicon substrates, the contact layers were tested on p-type and n-type ¹/₄ 4" 1 Ω ·cm FZ silicon. The surface on the pand n-type substrates were coated with 100 nm of a highly doped polycrystalline silicon layer on top of a thin tunneling oxide (TOPCon [6]) with a doping concentration of 4×10^{19} cm⁻³ and -1×10^{20} cm⁻³ respectively. Regarding the III–V material, the contact layers were tested on p- and n-type GaAs, p-type Al_{0.3}Ga_{0.7}As (AlGaAs in the following), all with a doping concentration of $\pm 2 \times 10^{19}$ cm⁻³ and p-type Ga_{0.51}In_{0.49}P with a doping concentration of 9×10^{18} cm⁻³. All test structures represent materials that might need to be contacted in actual devices. The structure of the silicon and III–V samples for the electrical characterization is shown in Fig. 3.

For the sprayed IZO contact layers, the substrates were metalized on the rear side using Ti/Pd/Ag (50 nm/50 nm/1000 nm,

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deposited by thermal evaporation) and subsequently cleaned by performing a 2 min HF dip (1%). After cleaning they were immediately coated with \approx 100 nm of IZO. The IZO surface was then metalized again using Ti/Pd/Ag and the sample was cut into 5 × 5 mm² squares with a dicing saw. Each square was characterized for its resistance by measuring its I–V behavior. Since the contact layer has to withstand the subsequent glueing process, which includes hot-pressing at 300 °C for 30 min, the samples were annealed at 300 °C for 30 min and measured again. In order to obtain the contact resistance of the deposited layer to the test structure, a linear fit was performed. The resulting resistance includes also the contact resistance of the samples metallization as well as the resistance of the bulk material but compared to the measured values, these additional resistances can be neglected.

The III–V samples were processed in the same way, only the rear side metallization was adjusted such to form a low resistivity ohmic contact to the III–V substrate.

For the sputtered ITO contact layers, all sample structures were identical except that the substrates were coated with 100 nm ITO by sputtering (Evochem target with composition of 95/5wt% In_2O_3/SnO_2) and the samples were annealed at 200 °C for 2 min to improve the adhesion of the TiPdAg layer on the sputtered ITO (to avoid delamination of the metal during dicing).

B. Test Structures for Investigation of Resistivity of TCA

In order to investigate the connecting resistivity that would be added by implementing the developed TCA into tandem solar cells, silicon test structures were bonded. Since the characterization of the two contact layers (IZO and ITO) showed that the sputtered ITO performs better, this contact layer was chosen for the TCA-silicon interfaces. The silicon test structures are the same as for the analysis of the contact resistance with the only difference being that full 4" wafers were used. The rear side was again metalized using TiPdAg followed by a 2 min anneal at 200 °C. A short HF dip (1%) was performed prior to depositing 100 nm of ITO by sputtering. On top of the ITO, the adhesive layer was deposited by spray coating of the same precursor solution as described in Section III-A but at a substrate temperature of 125 °C, resulting in the adhesive layer. After coating two substrates, they are joined and placed inside a hot-press which applies a pressure of up to 129 N/cm² and a linear heating ramp up to 300 °C. After heating up, the sample is kept at 300 °C for 30 min. The thermal annealing of the adhesive layer is necessary to calcinate the adhesive layer and to form a conductive ZnO:In (IZO). After hot-pressing, the samples were diced into $5 \times 5 \text{ mm}^2$ squares and each square was characterized for its resistance.

C. Optical Simulation of Bond Layer

Losses due to parasitic absorption in the ZnO-based TCA layer are below 2% within the relevant wavelength range, as it has been already demonstrated [7]. Also, very promising results for a TiO₂-based ARC at the TCA-semiconductor interface have already been published [1]. In this publication, the feasibility of an ITO-based ARC as well as a textured silicon bottom

TABLE I OVERVIEW OF OPTICAL PARAMETERS USED FOR SIMULATIONS

Material	n @ 759 nm	Reference
GaAs	3.71	[8]
Silicon	3.71	[9]
ITO	1.93	In house: spectroscopic ellipsometry
ZnO-based TCA	1.78	[1]
	TCA	GaAs ARC ARC Si

Fig. 4. Sketch of the modeling regime for OPTOS simulation of planar/ textured interfaces.

solar cell are investigated by optical simulation. In Table I, the optical parameters of the materials used in the simulations are summarized.

For planar sample structures, the reflectance of the bond layer was calculated by the transfer matrix method.

In contrast to the planar samples, bond layers including textured surfaces (random pyramids) cannot be described by a transfer matrix simulation. Since the random pyramids scatter and redirect the light into different angles, the resulting reflectance at the bond interfaces is numerically calculated using the OPTOS formalism optics [10]. This formalism allows for the incoherent coupling of interfaces with different surface textures acting in different optical regimes. A sketch of the modeling regime for OPTOS is depicted in Fig. 4.

As the reflectance at the bond layer shall be investigated, the top and bottom cells are assumed to be nonabsorbing and semi-infinitely thick. As the absorption coefficient is relatively low in the investigated optical regime for both the top and the bottom cell, the error to the reflectance at the interface due to the assumption of no absorption is negligible. The highly doped contact layers (as shown in Fig. 3) are not included in the optical simulations since their absorption coefficient too is low within the relevant wavelength range and should not significantly affect the reflectance at the interfaces.

The TCA layer has shown to be inhomogeneous (thickness and porosity) and random pyramids introduce strong scattering, thus this layer was treated as the incoherent layer in the OPTOS formalism. The random pyramid interface matrix required for OPTOS was modeled according to Rodriguez [11] and Tucher [12], [13], and the front interface matrix was created with the transfer matrix method.

D. Test Structures for Analysis of Homogeneity

The homogeneity of the bond and the impact of the hotpressing parameters on the bond layer were investigated using silicon test structures. The used silicon wafers were 4" FZ silicon



Fig. 5. Exemplary I–V behavior for test structures coated with the sprayed IZO, before and after annealing for 30 min at 300 $^{\circ}$ C.

with shiny etched surfaces on both sides from Wacker Siltronic. The TCA layer was spray-coated at a substrate temperature of 100 °C. During the subsequent hot-pressing, the temperature and pressure ramps were varied. Compared to the bonding process described in Section III-B, a temperature plateau at 210 °C for 30 min was implemented during which a reduced pressure of 26 N/cm² was applied. Following the temperature plateau, the sample is heated up to 300 °C for 15 min while applying an increased pressure of up to 180 N/cm². The characterization of the bond layer was done by scanning acoustic microscopy using a 100MHz transducer [14].

IV. RESULTS

A. Contact Resistance of Sprayed IZO

The measured I–V behavior before and after annealing of the tested contact layers on both silicon and III–V test structures is shown in Fig. 5. For better visualization, only exemplary I–V curves of each test structure are shown. The I–V characteristics of the silicon samples show ohmic behavior before and after the annealing. Regarding the III–V test structures, only p-type GaAs and p-type GaInP showed ohmic behavior (p-type GaAs only after annealing).

The obtained contact resistances of all measured samples of each test structure are plotted in Fig. 6. The results are plotted by means of a box plot with the box including the percentile range of 25-75% and the whiskers representing the standard deviation.

Fig. 6 shows that on n-type TOPCon the sprayed IZO forms a contact with moderate resistivity of around 0.2–0.3 Ω ·cm². The annealing leads to a wider distribution but the average contact resistivity does not change. The average value and its standard deviation is 0.24 ± 0.02 Ω ·cm² before and 0.24 ± 0.06 Ω ·cm² after annealing.

On p-type TOPCon, the contact resistance is slightly higher compared to the n-type substrate, which could be due to the lower doping concentration of the thin p-type polycrystalline silicon layer which is contacted by the sprayed IZO. Before annealing, the average contact resistance is $0.28 \pm 0.03 \ \Omega \cdot \text{cm}^2$. After annealing, the average contact resistance amounts to $0.35 \pm 0.03 \ \Omega \cdot \text{cm}^2$.



Fig. 6. Boxplot of the measured contact resistance of sprayed IZO the tested semiconductor materials.

When analyzing the contact resistance of the sprayed IZO on the III–V samples, ohmic behavior is only observed on p-type GaAs and p-type GaInP (see also Fig. 6). On p-type AlGaAs and n-type GaAs, the I–V curves showed a strong s-shape which did not allow for a linear fit. It can be seen that the contact resistance on the two III–V substrates is generally higher and shows a much broader distribution than on silicon. The average contact resistance on p-type GaAs is $0.88 \pm 0.83 \ \Omega \cdot \text{cm}^2$. On p-type GaInP, the average contact resistance amounts to $2.17 \pm 0.98 \ \Omega \cdot \text{cm}^2$.

In order to estimate the impact of the measured contact resistances of sprayed IZO on a tandem solar cell, the efficiency loss that would result from the added resistance was calculated. Assuming, that the device has an n-type TOPCon surface on the bottom cell and a p-type GaAs backside on the top cell (similar to the tandem structure in [15]), a total contact resistance of $1.1\,\Omega\cdot cm^2$ would be added as $R_{\rm C,\ top}$ and $R_{\rm C,\ bottom}$ (see Fig. 1). Even if the TCA $(R_{B, TCA})$ itself has a negligible resistivity, the connecting resistivity would be 1.1 $\Omega \cdot cm^2$. The connecting resistivity was added to a two-diode model of a dual junction $(E_{G, top}: 1.72 \text{ eV}, E_{G, bottom}: 1.12 \text{ eV})$ and a triple junction $(E_{G, top}: 1.90 \text{ eV}, E_{G, middle}: 1.43 \text{ eV}, E_{G, bottom}: 1.12 \text{ eV})$ solar cell as R_S [1]. If added to a dual junction solar cell, the connecting resistivity of 1.1 $\Omega \cdot cm^2$ would result in an absolute efficiency loss of 0.35%. Due to the lower overall current in a triple junction solar cell, this connecting resistivity would result in a loss of only 0.16%.

B. Contact Resistance of Sputtered ITO

The contact resistance of sputtered ITO was tested on p-type and n-type TOPCon as well as the four III–V test structures (n-type GaAs, p-type GaAs, p-type AlGaAs, and p-type GaInP). The contact resistance was measured before and after annealing at 300 °C for 30 min. The measured values are plotted in a boxplot (box including the 25–75% percentile range and the whiskers representing the standard deviation) in Fig. 7.



Fig. 7. Boxplot of the measured contact resistance of sputtered ITO on the tested semiconductor materials.

Comparing the obtained graph with the results for the sprayed IZO, it can be seen that the sputtered ITO before annealing shows much lower values on n-type TOPCon but slightly higher values on the p-type TOPCon. The average on n-type TOPCon amounts to $0.042 \pm 0.005 \ \Omega \cdot \text{cm}^2$ and $0.38 \pm 0.04 \ \Omega \cdot \text{cm}^2$ on p-type TOPCon. The higher contact resistance on p-type silicon can again be explained by the lower doping concentration. The annealing significantly affects the ITO/silicon contact, leading to an average contact resistance of $0.73 \pm 0.10 \ \Omega \cdot \text{cm}^2$ on n-type TOPCon and $2.69 \pm 0.32 \ \Omega \cdot \text{cm}^2$ on p-type TOPCon. This effect has also been observed elsewhere [16] and it is currently under investigation if the formation of a thin oxide at the silicon/ITO interface is responsible for the increase in contact resistance.

On the III–V substrates, only the p-type GaInP did not show ohmic behavior with sputtered ITO and is therefore not shown in Fig. 7. The contact resistances achieved on p-type GaAs, p-type AlGaAs, and n-type GaAs before and after annealing at 300 °C for 30 min are shown in a boxplot in Fig. 7.

It was found that the lowest contact resistance was achieved on p-type GaAs with the average before annealing being $0.011 \pm 0.001 \ \Omega \cdot \mathrm{cm}^2$ and after annealing being $0.016 \pm 0.009 \ \Omega \cdot \mathrm{cm}^2$. On p-type AlGaAs the sputtered ITO shows a contact resistance of $0.065 \pm 0.028 \ \Omega \cdot \mathrm{cm}^2$ and on n-type GaAs of $0.059 \pm 0.041 \ \Omega \cdot \mathrm{cm}^2$. After annealing, the contact resistance on p-type AlGaAs increased to $0.15 \pm 0.11 \ \Omega \cdot \mathrm{cm}^2$ and on n-type GaAs it increased to $0.30 \pm 0.13 \ \Omega \cdot \mathrm{cm}^2$. Considering again a device with an n-type TOPCon and p-type GaAs surface in contact with the TCA, these results (after annealing!) would amount to a minimum connecting resistivity of $0.75 \ \Omega \cdot \mathrm{cm}^2$. This minimum total series resistance is lower than the one calculated for sprayed IZO contact layers.

In a dual junction device, this minimum connecting resistivity would result in an absolute efficiency loss of 0.26%, in a threejunction device, it would cause an efficiency loss of 0.12%.

However, when analyzing the performance of the contact layer in a triple junction device, it can be seen that the sprayed



Fig. 8. Plot of measured connecting resistivities of bonded p-type and n-type TOPCon wafers. The broad distribution of measured resistances is correlated to inhomogeneities of the bond layer.

IZO contact layer only reduces the efficiency of the device by 0.04% absolute compared to the sputtered ITO contact layer while saving an additional vacuum process. This makes sprayed IZO an interesting candidate for low-cost manufacturing of glued tandem solar cells.

C. Resistivity of TCA

The analysis of the contact resistance of the sprayed and sputtered TCOs show that especially on III–V substrates the sputtered ITO showed lower contact resistance and was therefore chosen for the analysis of the connecting resistivity, which includes the resistivity of the adhesive layer. Two full 4" n-type TOPCon wafers and two full 4" p-type TOPCon wafers were therefore bonded according to the previously described bonding process (see Section III-B) and after the thermal annealing cut into 5×5 mm² squares. Each square was analyzed for its resistance and the obtained values are plotted in a box diagram. The resulting box diagram for n-type and p-type TOPCon can be seen in Fig. 8.

The impact of the higher contact resistance of sputtered ITO on p-TOPCon can be seen in Fig. 8. None of the bonded p-TOPCon samples shows a connecting resistivity below $1 \Omega \cdot cm^2$.

The wide spreading of the measured contact resistance is a result of the inhomogeneities in the bond (see Section IV-E). Areas that are poorly bonded show higher connecting resistivity, while areas with good bond properties and mechanical adherence also perform best from an electrical point of view. However, the lowest measured connecting resistivity for n-type TOPCon amounts to $0.12 \ \Omega \cdot \text{cm}^2$, which is a significant reduction compared to the previously reported lowest connecting resistivity of $17 \ \Omega \cdot \text{cm}^2$ for this type of TCA [1].

D. Optical Properties of ITO-Based ARC

The characterization of the electrical contact layers showed that the sputtered ITO forms a good electrical contact to the tested silicon and III–V materials. Since the ITO has a slightly



Fig. 9. Simulated reflectance of an ITO contact layer compared to no ARC and a TiO₂-based ARC implemented at the two semiconductor-TCA interfaces of the bond layer. By assuming the two semiconductor substrates to be of semi-infinite thickness, only the reflectance of the bond layer is simulated. On the right, a sketch of the simulated layer stack is shown.

higher refractive index compared to the IZO, it might additionally slightly reduce the reflectance at the TCA/subcell interfaces. In order to investigate the effect of a 100-nm thick ITO contact layer on the optical behavior, a transfer matrix simulation of the layer stack was performed. To isolate the reflectance at the TCA/semiconductor interfaces, the III–V top cell and the silicon bottom cell were assumed to be of semi-infinite thickness, the TCA's thickness was assumed to be 2 μ m based on SEM analysis of cross sections. The resulting reflectance is shown in Fig. 9, together with the already published reflectance of a TiO₂-based ARC [1].

The simulation shows that an ITO-based ARC would in fact reduce the reflectance at the bond slightly. By weighting the simulated reflectance with the AM1.5g spectrum, an average reflectance in the relevant wavelength range of 730–1200 nm of 18.5% (no ARC $\approx 21.5\%$) was determined.

The alternative to ARCs would be a textured silicon surface for the bottom solar cell. The layer stack, which was simulated by using geometrical optics, consisted again of semi-infinite silicon and GaAs substrates in order to only simulate the reflectance caused at the bond layer. At the two TCA-semiconductor interfaces an ITO- and a TiO₂-based ARC (100 nm and 94 nm thickness, respectively) were simulated and compared to no ARC. The silicon surface was assumed to have a random pyramids texture in all three cases with a typical pyramid height of 2 μ m. The TCA thickness is assumed to be 2 μ m from top to mid-pyramid (based on SEM characterization of cross sections). In Fig. 10, the resulting simulated reflectance of a textured silicon surface bonded to a planar GaAs surface is shown.

Within the wavelength range 730–1200 nm, the bond shows an average reflectance of 12.4 %, when weighted with the AM1.5g spectrum. By comparing this reflectance with the reflectance of the bonded planar surfaces, it can be seen that the texturing of the silicon surface does reduce the average reflectance. The limiting factor in this sample structure is the planar GaAs surface. Implementing an ITO-based ARC at this interface would reduce the



Fig. 10. Simulated reflectance at the bond interfaces; silicon surface is textured with random pyramids.



Fig. 11. SAM scan of bonded sample structure (4" silicon substrates) for measuring the connecting resistivity of TCA. (left). Bright areas are delaminated. On the right, the SAM scan is superimposed with a heatmap of the measured connecting resistivity. Delaminated areas are shown as hatched in the heatmap.

reflectance to 10.9%. Similar to the planar-planar test structure, a TiO_2 -based ARC is also most promising for the planar-textured test structure as it further decreases the weighted reflectance at the bond down to 2.5%.

E. Mechanical Properties and Homogeneity of TCA

The biggest difference between the presented ZnO-based TCA and polymer-based TCAs is that the ZnO-based TCA becomes conductive itself upon thermal annealing. In order to establish the conductivity, the adhesive layer has to be heated up to 240–300 °C [17]. During the annealing, the adhesive layer decomposes and forms ZnO. The added dopant (Indium, 3at%) increases the conductivity of the ZnO [18].

The thermal decomposition of the Zn-precursor, which is the main component of the adhesive layer, is accompanied by formation of allylene, acetone, and CO_2 according to [17], all products are gaseous at 300 °C. The gas formation is therefore needed in order to transform the Zn-precursor into ZnO.

The bond was characterized using a scanning acoustic microscope (SAM), which shows bonded areas dark and trapped gas/cavities bright.

In Fig. 11, an SAM scan of the sample bonded for measuring the connecting resistivity of the TCA is shown.



Fig. 12. SAM scan of sample (4" silicon substrates) bonded using the new pressing program, including temperature plateaus.

The SAM scan on the left shows large bright areas, where the formed gas is probably trapped within the bond layer. The image on the right in Fig. 11 shows the same SAM image with a heatmap of the measured connecting resistivity superimposed. It can be seen that those areas, that appeared bright in the SAM scan, also show very high connecting resistivities. Areas that appear dark in the SAM scan also showed low connecting resistivities. During the dicing, 22% of all cut squares delaminated, which is shown in Fig. 11 as a hatched area.

In order to allow the formed gas to leave the bond layer, a temperature plateau was added to the pressing program at that temperature, where based on the chemical reactions, gas formation is expected (30 min @ 210 °C). The resulting SAM scan of a sample bonded with the adjusted pressing program is shown in Fig. 12.

The SAM scan shows a more homogeneous bond. During the dicing of this sample, only 2.75% of all cut samples delaminated. By comparing the scan with the sample bonded using the old pressing program, it can be seen that there are no large "bubbles" trapped in between the wafers. The areas that still look inhomogeneous (lower right corner) are at least partly bonded in between the gas channels.

V. SIMULATION OF ZNO-BONDED MULTIJUNCTION SOLAR CELLS

The simulated impact of the developed ZnO-based TCA on a dual junction solar cell was already shown elsewhere [1]. Since the impact of the added series resistance of the TCA is directly linked to the current of the bonded solar cell, the simulation was again carried out for a triple junction (3J) solar cell, which has a lower current than the dual junction solar cell. The simulation was carried out by adding the connecting resistivity of the TCA as series resistance to a two-diode model of a 3J solar cell ($E_{G, top}$: 1.90 eV, $E_{G, middle}$: 1.43 eV, $E_{G, bottom}$: 1.12 eV) that included one two-diode model for each junction. The simulation model was in the first step fitted to the results of the bonded reference from [15]. In a second step, the optical losses (varied from 0–30%) were directly subtracted from the bottom silicon subcell current. The connecting resistivity of the TCA layer was



Fig. 13. Simulation of the efficiency of a triple junction solar cell (corresponding to [15]) where the direct wafer bond is replaced by the developed TCA bond layer, including optical and electrical losses. Already achieved values for connecting resitivity and the simulated reflectance at the bond (of planar bonded samples) are indicated by hatched lines.

added as series resistance (evenly distributed across the three two-diode models of the junctions) and was varied from 0 to $30 \ \Omega \cdot \text{cm}^2$. The resulting efficiency map is shown in Fig. 13. Within the map, already achieved values for series resistance (no ARC & ITO as ARC) are combined with the simulated reflectance of the bond and marked by a star. The influence of a TiO₂-based ARC on the series resistance is currently under investigation, the optical effect of this ARC is indicated by a dashed line.

It should be noted that the simulation does not show the potential of 3J solar cells but an estimation of what can be expected if the direct wafer bond in an existing 3J solar cell [15] would be replaced by the developed TCA bond layer. Compared to the direct wafer bond, in which the top and bottom cell are directly in contact, an added interlayer will introduce an additional series resistance and (depending on its optical properties) optical losses. The simulation in Fig. 13 shows that for the ZnO-based TCA in combination with an ITO-based ARC the electrical losses are already very small. The optical losses could be overcome by implementing a TiO₂-based ARC, if its electrical properties are sufficient.

VI. CONCLUSION

The electrical and optical aspects of a TCA interconnection for III–V on Si tandem solar cells with spray coated IZO have been discussed theoretically and evaluated based on experimental data. It has been shown that major hurdles for achieving high efficiencies can be overcome or have already been overcome with this system. In addition, the process is quite simple and potentially cost-efficient and the presented lowest measured connecting resistivity of $0.12 \ \Omega \cdot \text{cm}^2$ is comparable to the electrical properties of polymer-based TCAs [19].

Based on the current results of the developed TCA, we suggest that the sputtered ITO contact layer tends to be the most promising contact layer for a first glued tandem solar cell. However, it

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should be kept in mind that this will also lead to a reflectance at the bond of approximately 18.5% for planar bond interfaces and 12.4% if the silicon bottom cell is textured. This problem of reflectance at planar TCA-sub cell interfaces is also present in polymer-based TCAs [20] and has to be mitigated to allow for high-efficiency TCA bonded tandem solar cells.

A TiO2-based ARC at the TCA-sub cell interfaces would be very effective in reducing the reflectance in case of the ZnObased TCA. The impact of a TiO₂ layer on the electrical behavior of the bond is currently under investigation.

Further, it was shown that by adjusting the pressing process according to the stages of thermal decomposition of the adhesive layer the bond shows improved homogeneity.

The next steps in the development of the ZnO-based TCA also include the fabrication of actual III-V on silicon test structures that will allow the measurement of the TCA's electrical and optical properties in a test structure that resembles the later device more accurately.

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