Ultrasonic welding-
a connection technology for flexible thin film modules

Jeannette Wienke[1], Olaf Tober[2], Peter Buur[1], Wim Brieko[1],
[1]Energy Research Centre of the Netherlands , 1755 ZG Petten, The Netherlands,
[2]Institut für Solartechnologien, Im Technologiepark 7, D-15236 Frankfurt (Oder), Germany

ABSTRACT: Commercial ultrasonic welding equipment has been modified in such a way that it is applicable to flexible foils. Individual welding parameters, such as force, time and amplitude are optimised for the electrical connection of CISCuT (**CuInS**$_2$ on **Cu-T**apes) solar cells. By fine-tuning the ultrasonic welding force, we succeeded in making stable and reproducible connection between aluminium tape and the front contact respectively the copper back contact. As busbar material aluminium and copper metals have been tested. Outside the welding area no material changes were observed. Ultrasonic welding and encapsulation of the foils have not influenced the solar cell performance. The measured contact resistance is very low (<4 mΩ on 1.5 mm^2 contact area). It is possible to weld several tapes on short distances. Thermal cycling between -40°C and 80°C or 85%/85°C damp/heat exposure do not influence the electrical contact at the weld.
Keywords: Contact, Thin Film, $CuInS_2$

1 INTRODUCTION

Flexible foils are promising candidates to be used as substrate for cost-effective thin film PV since foils are cheap, lightweight and will broaden PV application area. Flexible PV foil requires careful treatment since PV cells on ≤100µm thick foils are extremely fragile and sensitive to mechanical, chemical and thermal stress. For that reason, the processes for electrical connection have to be reviewed. The electrical connection of tabs to thin film solar cells requires special conditions to prevent disruption of the thin layers and to prevent short-circuiting in case of metal foils. Additionally, it is required to establish good conductive contact at low temperature and without the application of additives, like solder flux. The purpose of this work is to demonstrate the feasibility of ultrasonic welding for electrical connection of flexible CIS solar cells.
Ultrasonic welding is a promising industrial technique for electrical interconnection of thin film PV on flexible foils. Metals are fused together by the simultaneous action of static and dynamic forces. The advantages of the ultrasonic welding technique are extremely short welding times (less then a second), no filler materials are needed and minimal electrical contact resistance with proper choice of materials. Moreover this principle is applied at room temperature. This work presents the applicability of ultrasonic welding for CIS solar cells on copper foil.
Therefore commercial Telsonic USP -10M/ CU-3/SG 25-500A ultrasonic welding equipment has been modified in such a way that it is applicable to flexible foils. The equipment has been redesigned to work with low welding force (≤1 N). Individual welding parameters, such as force, time and amplitude are optimised for several material combinations. The quality of the welded connection and its stability are investigated, the influence of the welding process on the CISCuT-cell performance has been studied.

2 EXPERIMENTAL

2.1 Ultrasonic welding equipment (see Fig. 1)

The commercial Telsonic USP-10M/CU-3/SG25-500A equipment has been modified by adjusting the welding force to lower values (≤1 N). The maximum input power (500 W) and welding frequency (36 kHz) are kept constant.
In addition a special substrate support table has been designed to fix flexible material. Single sonotrodes with variable areas (0.5 to 11 mm^2) or a combi-sonotrode with six different areas on a wheel (see Fig. 1) have been used.

For the connection of CISCuT cells welding forces between 2 and 4 N are applied. Usual welding times are between 0.35 and 0.6 seconds. Considering the dimensions of the busbars used as front contact, the 1.5 mm^2 area sonotrode derived to be most suitable.

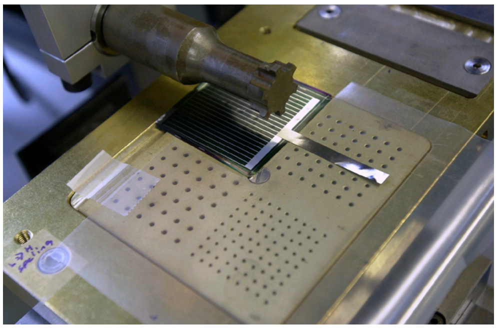

Figure 1: Modified Telsonic USP-10M/CU-3/SG 25-500A welding equipment

2.2 Solar cell material

CISCuT solar cells [1,2] prepared at the Institut für Solartechnologien (IST) have been used to investigate the feasibility of ultrasonic welding as connection tool for flexible cell material. From the quasiendless copper tape with a $CuInS_2$ absorber layer on top 400 mm² standard measurement devices have been prepared at IST.

The individual cells have been accomplished by spray deposition of a CuI buffer layer and a ZnO:Al TCO layer by DC sputtering using (8x50) mm² masks.

2.3 Measurement techniques

Figure 2: Shear/peel test facility

The shear or peel strength are determined using a test facility with adjustable angle between 0 and 45° (see Fig. 2) with a maximum strength of 10 N.

The contact resistance has been measured by 4-point measurement with a Keithley 2400 sourcemeter.
The IV-performance has been measured using a Solar Constant 575 metal halogenide lamp from K.H. Steuernagel Lichttechnik GmbH. The IV-values were corrected by comparison with the IV-data of a reference CISCuT cell measured under a class A solar simulator.

3 RESULTS

3.1 Connection and encapsulation of CISCuT cells

The 4 cm^2 CISCuT-cells have been treated by first depositing the front contact material, by the connection of tabs to the front and backside of the cell and finally by encapsulation, as described below.

Front contact

Ultrasonic welding studies have been performed on different front contact materials:

i. Sputter deposition of 10 nm Cr followed by 3 µm Al (see Fig. 3)
ii. Electron beam deposition of 10 nm Ni followed by 3 µm Al
iii. Electron beam deposition of 10 nm Ni followed by 3 µm Cu (see Fig. 4)

Figure 3: Connected and encapsulated CISCuT cell: with sputtered NiAl busbar

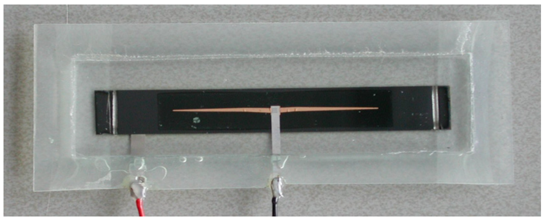

Figure 4: Connected and encapsulated CISCuT cell with electron beam deposited NiCu busbar

Front side connection,

25 µm thick aluminium tab has been welded to the different kinds of busbars:

i. and ii.

Despite a clearly different morphology (see Fig. 5), both sputtered and evaporated aluminium have successfully been connected using a welding force of 2 N and a welding time between 0.3 and 0.4 seconds. The shearing force measured for a tab welded on an aluminium busbar is usually ≤ 11 N.

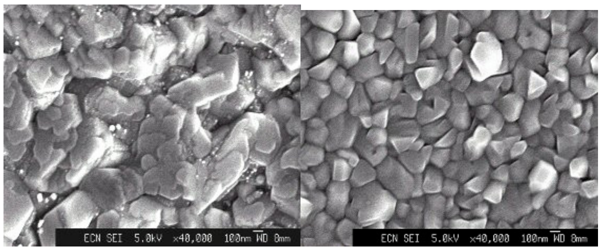

Figure 5: SEM photographs: Top-view of an aluminium busbar applied by sputtering (i) (left) and by electron beam deposition (ii) (right) (x40.000)

iii. The welding force used for the connection on an evaporated copper busbar was 3 N, the welding time 0.6 seconds. With approximately 5 N the shearing force appeared to be lower compared to aluminium contacts.

Back side connection

A 25 µm thick aluminium tab has successfully been welded to the copper tape with a welding force of 3-4 N and a welding time of 0.6 seconds.

Encapsulation

Encapsulation occured at a temperature of 150 °C. From front to back following materials have been used: 4 mm glass; 0,5 mm EVA; CISCuT-cell; 0,5 mm EVA; ICOSOLAR foil

All steps have been checked by measurement of IV-curves before and after the respective treatments A special adapted measurement equipment has been installed and successfully used.

3.2 IV-performance

The IV-graph (see Fig. 5) of a CISCuT-cell with sputtered NiAl front contact shows dark and light IV-curves before and after connection by ultrasonic welding.

The dark and light curves nearly coincide, showing that the ultrasonic welding process has not damaged the solar cell. The open circuit voltage and fill factor remain unchanged, whereas the short circuit current has even slightly increased from 18.0 mA/cm^2 to 18.6 mA/cm^2.

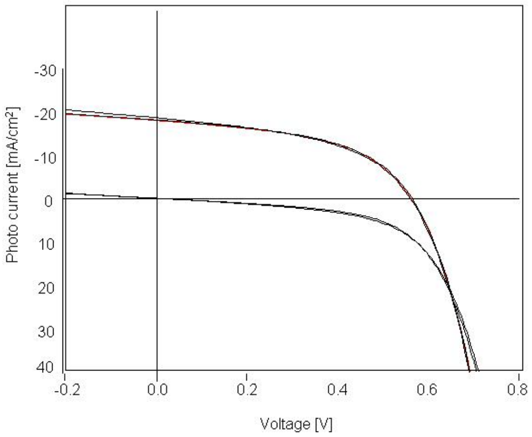

Figure 6: IV-curves before (black) and after (grey) tab application by ultrasonic welding (the I_{sc} and V_{oc} remained constant at 18 mA/cm^{2}and 0.56 V)

To study the influence of different busbar material on the IV-performance three different CISCuT-cells with similar initial photocurrent have been selected. Slight variations in the open circuit voltage are determined by the intrinsic cell characteristics.
Fig. 7 gives an overview of the IV-curves taken after connecting and encapsulation of the three cells. The similar short circuit current indicates that the contact resistance has not been influenced by variation of the busbar material.

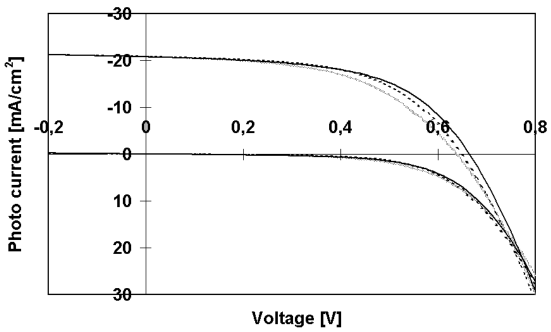

Figure 7: Influence of contact material on IV-performance of laminated cells
i. e-beam NiAl (black):
Isc= 20.8 mAcm^{-2}, Voc=664 mV, FF=56%, η=7.7%
ii. sputtered CrAl (dotted):
Isc=20.8 mAcm^{-2}, Voc=648 mV, FF=56%, η=7.5%
iii. e-beam NiCu (gray):
Isc=20.8 mAcm^{-2}, Voc=640 mV, FF=52%, η=6.9%

3.3 Stability testing

Test samples have been fabricated to study the contact resistance at the ultrasonic weld during aging.

i. Ultrasonic welding connection of two 50 µm thick aluminium foils (not laminated)
ii. CISCuT-dummy cells with broadened busbar to apply two tabs on the front side (laminated and not laminated) (see Fig. 8)

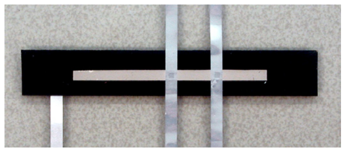

Figure 8: CISCuT cell with two front side aluminium tabs on 3µm aluminium to control the electrical contact at ultrasonic weld

The unlaminated aluminium foils where exposed to damp/heat 85 %/85 °C for 1000 hours. The initially measured contact resistance of 3.9±0.1 mΩ remained unchanged during the treatment.

The damp heat exposure of not laminated CISCuT dummy cells lead to the gradual damage of the aluminium busbar, which is finally reflected as disruption of the electrical pathway between the front side weldings. As long as the busbar was not completely damaged the resistance values remained unchanged giving an indication for the stability of the welding contact itself.
Laminated dummy cells show unchanged front contact resistance values after 1000 hours of damp/heat exposure.

Thermal cycling between -40 °C and 80 °C does not influence the electrical contact.

4 CONCLUSIONS

By fine-tuning the ultrasonic welding force, we succeeded in making stable and reproducible connection between aluminium tape and the front contact respectively the copper backside. As busbar material aluminium and copper metals could be used. Outside the welding area no material changes were observed. Ultrasonic welding and encapsulation of the foils do not adversely affect the solar cell performance. The measured contact resistance is very low (<4 mΩ on 1.5 mm^2 contact area). It is possible to weld several tapes on short distances. Thermal cycling between -40°C and 80°C or 85%/85°C damp/heat exposure do not influence the electrical contact at the weld.

4.3 References

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ACKNOWLEDGEMENTS:
This work is financially supported by the European Commission contract number N° ENK6-CT-2001-00519 (CISLINE).