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Aging behaviour of laser welded Al-interconnections in crystalline silicon modules

Henning Schulte-Huxel [a,*], Susanne Blankemeyer [a], Robert Bock [a,1], Agnes Merkle [a], Sarah Kajari-Schröder [a], Rolf Brendel [a,b]

[a] Institute for Solar Energy Research Hamelin (ISFH), Am Ohrberg 1, D-31860 Emmerthal, Germany
[b] Department of Solar Energy, Institute of Solid-State Physics, Leibniz University of Hanover, Appelstrasse 2, D-30167 Hannover, Germany

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ABSTRACT

We investigate the artificial aging of PV modules interconnected with the aluminum-based mechanical and electrical laser interconnection (AMELI) process. AMELI forms a laser welded connection between the Al-metallization on the rear side of the solar cell and an Al-layer on an interconnector substrate. AMELI avoids soldering, conductive adhesives, and Ag-pastes. We investigate glass and encapsulant films as possible interconnector substrates that carry an Al-film. Modules processed with high temperature-deposited aluminum on the cells and an encapsulant as interconnector substrate do not degrade during 200 humidity-freeze cycles. The conversion efficiency η, the fill factor *FF*, the open circuit voltage V_{oc}, and the short circuit current I_{sc} are unaffected by the artificial aging within an accuracy of 1%.

1. Introduction

The development of new solar cell concepts, especially of high-efficiency back-contact solar cells, and decreasing wafer thickness approaching 100 μm or less, requires new concepts for module integration. During the last years different approaches have been developed for interconnection of back-contact solar cells [1–4]. They reduce the required handling and the high temperature inducing stress during soldering, which potentially induce micro-cracks. Nevertheless, all these novel approaches require expensive materials such as solderable metallization, e.g. plated Ag, Ag pastes, or conductive adhesives.

ISFH developed the aluminum-based mechanical and electrical laser interconnection (AMELI) process, which omits silver metallization, solder containing lead, or conductive adhesives [5,6]. A mechanical and electrical connection between an Al-metallization on the rear side of the solar cell and a structured Al-layer on an interconnector substrate is formed by a damage-free laser micro-welding process. This process is applicable to back-contact solar cells, contacting of very thin wafers, and to monolithic integration concepts [7].

Various interconnector substrate materials can be used if they are sufficiently transparent for the laser radiation. The preferred option is that the interconnector substrate remains in the module. Glass substrates and encapsulant films are therefore particularly suitable. With both types of interconnector substrates the AMELI process was shown to successfully integrate high-efficiency cells loss- and damage-free into modules [5,6]. However, loss-free interconnection is only the first step towards a new interconnection concept for PV modules: the modules also need to withstand the thermal cycling and humidity exposure that they will experience during a module's lifetime of more than 25 years.

In this paper we therefore investigate and compare the durability of the AMELI process under accelerated aging conditions. We compare modules that use the two different interconnector substrates glass and encapsulate film.

2. Experimental

2.1. Solar cells

We apply the AMELI process to interconnect high-efficiency solar cells, which accommodate both contacts on their rear side. The *n*-type back-junction back-contact (BJBC) solar cells developed at ISFH are processed on 12.5 × 12.5 cm² Czochralski-grown silicon wafers. These cells are metalized with aluminum using two different processes.

- Al_{ebeam} uses electron beam evaporation. We utilize a BAK-EVO system (Unaxis) with a calotte rotating at 20 rpm. A deposition rate of 5 nm/s is applied at a maximum temperature of 125 °C

* Corresponding author. Tel.: +49 5151 999303; fax: +49 5151 999400.
E-mail address: h.schulte-huxel@isfh.de (H. Schulte-Huxel).
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and a pressure below 6×10^{-6} mbar. The thickness of the Al-layer is 25 μm on the finished cell.

- $Al_{thermal}$ is a thermal evaporation process. This is done in a high rate in-line metallization system (Applied Materials, ATON 500). We utilize a dynamic deposition rate of 5 μm × m/min at a tray speed of 3 m/min and twelve oscillations for the 20-μm-thick Al-metallization. This evaporation process leads to a maximum Si-wafer temperature of about 350 °C.

The finished cells are annealed at 390 °C for 3 min and laser-diced in three parts each. Three sizes of laser diced cells are used depending on the number of fingers and the fingers' width on the solar cells rear side.

- D1: 34.4 cm^2 (2.7 × 12.5 cm^2).
- D2: 43.6 cm^2 (3.49 × 12.5 cm^2).
- D3: 51.7 cm^2 (3 equally sized cells parts of a 155.1 cm^2 pseudo-square cell).

Before module interconnection the *I–V*-characteristics of the solar cells are measured using a LOANA system (pv-tools).

2.2. Modules

Two types of interconnector substrates are used for interconnection. Both can be metalized and remain within the final module.

- S_{glass} is a 1.1-mm-thick borosilicate glass (Borofloat, Schott). The glass is coated for the interconnection with a 20-μm-thick Al-layer using the in-line metallization system and a deposition rate of 5 μm × m/min at a tray speed of 1 m/min and four oscillations.
- S_{film} is a 450-μm-thick thermoplastic silicone encapsulant film (TECTOSIL, Wacker Chemie). A 10-μm-thick household Al-foil is attached thermally to the encapsulant and is used for the interconnection.

For the interconnection of the Al-metalized back-contact solar cells a spot weld is formed by laser irradiation through the transparent substrates, as shown in Fig. 1(a) and (b) for S_{glass} and S_{film}, respectively. The metalized rear side of the solar cell is held down to the Al-metallization on the substrate. A laser beam is then focused into their interface and forms the micro spot weld by melting and fusing both Al-layers. In the case of S_{glass} we use a laser (AviaX, Coherent) with a wavelength of 355 nm and a pulse duration of 20 ns. The weld spots are formed by eight pulses with pulse energies of 176 μJ, for further information see [5]. In the other case of substrate S_{film} we laser weld the Al-foil to the metallization of the solar cells with a disk-laser (Rofin StarCut Disk 100ICQ) having a wavelength of 1030 nm and a pulse duration of 1 μs. For interconnection single pulses with a pulse energy of 2.3 mJ are used, more details in [6].

For external connection we attach aluminum-clad copper conductor to the substrate metallization, see Fig. 2(b), and laminate the modules using the thermoplastic silicone encapsulant. Fig. 1(c) and (d) show the two different lay-ups of the finished modules depending on the interconnector substrate used.

- L_{glass} is used in the case of the glass substrate S_{glass}. The glass is at the rear side of the module (Fig. 1(c)).
- L_{film} is applied in the case of encapsulant substrate S_{film} with a front glass at the sunny side (Fig. 1(d)).

Two types of sheets are utilized in these lay-ups:

- F_{front} is a transparent frontsheet film (Isovoltaic 2754T).
- F_{back} is a white backsheet film (Isovoltaic 2442).

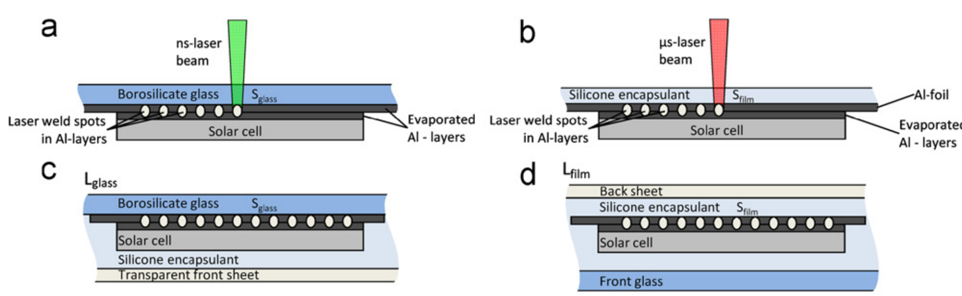

Fig. 1. (a) and (b) schematics of the laser bonding process with a glass S_{glass} and an encapsulant S_{film} as substrate, respectively. (c) Laminated final modules on a glass in lay-up L_{glass} and (d) on an encapsulant as substrate in lay-up L_{film} both with the sunny side down.

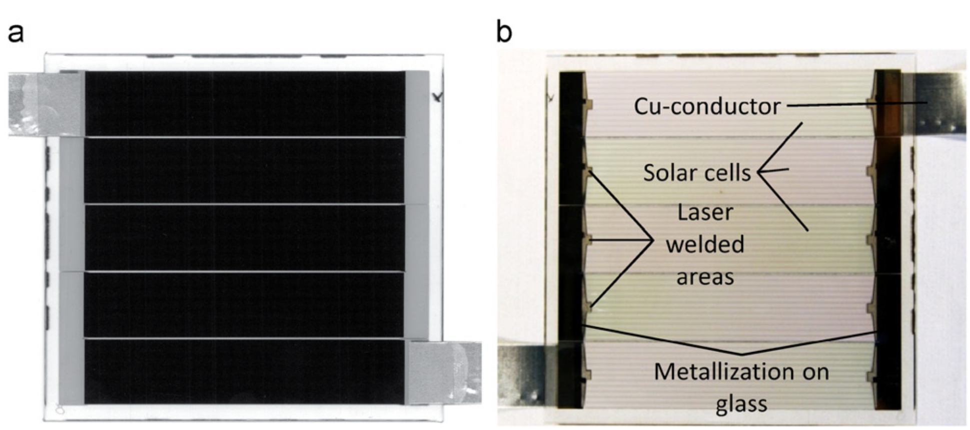

Fig. 2. Photographs of (a) the front and (b) rear side of the proof-of-concept module M1 on S_{glass}, adapted from [5].