INLINE HIGH-RATE THERMAL EVAPORATION OF ALUMINUM FOR NOVEL INDUSTRIAL SOLAR CELL METALLIZATION

F. Heinemeyer[1], C. Mader[1], D. Münster[1], T. Dullweber[1], and R. Brendel[1,2]
[1] Institute for Solar Energy Research Hamelin (ISFH), Am Ohrberg 1, D-31860 Emmerthal, Germany
Tel +49 (0)5151 999 416, Fax: +49 (0)5151 999 400, e-mail: heinemeyer@isfh.de
[2] Institute for Solid-State Physics, University of Hannover, Appelstrasse 2, 30167 Hannover, Germany

ABSTRACT: We evaluate a novel high-throughput thermal evaporation system (ATON500, Applied Materials) for the aluminum metallization of solar cells. We demonstrate a maximum throughput of 720 wafers/h (156 × 156 mm² Si wafers coated with a 5 µm Al layer) applying dynamic deposition rates of up to 5 µm × m/min. By adjusting the individual aluminium evaporation rate for each evaporation boat, we achieve excellent thickness uniformity across the 50 cm-wide deposition area on the substrate carrier of ±3.4%. The specific contact resistance of an evaporated aluminium layer on a 0.5 Ωcm p-type Si wafer is determined to be 4 mΩcm^2 which is in the same range as Al contacts deposited by laboratory type evaporation systems. During deposition the wafer temperature increases up to 370°C at deposition rates of 2.9 µm × m/min, which is compatible with high-efficiency Si solar cell processes. By applying the high-rate thermal evaporation of aluminum to a buried-emitter rear-contact solar cell, we demonstrate a conversion efficiency of 20.6%. These results demonstrate the applicability of the inline evaporation system for the production of industrial high-efficiency solar cells.
Keywords: metallization, inline, contact, aluminum

1 INTRODUCTION

Inline high-rate thermal evaporation is used on an industrial scale since many years, for example, for the deposition of aluminum coatings on plastic foil wrapping in the food industry. For the metallization of solar cells Schott Solar AG used a batch evaporation system from 1992 to 1997 for aluminum deposition in a pilot production [1]. Apart from that only laboratory-type evaporation equipment has been used so far [2,3]. First results evaporating aluminum in a high throughput inline evaporation system as a solar cell metallization have been published recently [4]. In the photovoltaic industry, screen-printing is widely used for metallization. However, the advantages of aluminum evaporation are that the aluminum used for metallization is relatively inexpensive and has a better conductivity compared to screen-printing pastes. In addition, the contact resistance of evaporated aluminum to silicon is lower on highly doped substrates compared to screen-printed contacts. For industrial production aluminum contact deposition for rear side contacts will take place in one process step, compared with four steps (Ag pad printing, drying, Al printing, drying) in the case of screen printed contacts used so far.

2 THE EVAPORATION SYSTEM

We set up a small production-type evaporation system that is scalable to mass production at ISFH. In our new ATON 500 (Applied Materials) inline high-rate thermal evaporation system (Fig. 1), up to 720 Si wafers (156 × 156 mm²) are coated per hour under precise process control at 30 times higher deposition rates than in typical static evaporation systems. Deposition rates from 200 nm × m/min up to 10 µm × m/min are feasible. Individually controlled evaporation boats and wire feeds lead to high deposition uniformity of ± 3.4% on 500 mm deposition width. The homogeneity measurements and the evaporation principle are described elsewhere [5]. The system consists of a loading area, seven vacuum chambers and an unloading area and may be used either in a continuous or in an oscillating substrate flow mode (Fig. 2). The oscillating substrate flow simulates multiple serial evaporation chambers by passing the evaporator several times during one deposition.

Fig. 1: ATON 500 inline high-rate evaporation system installed at the ISFH.

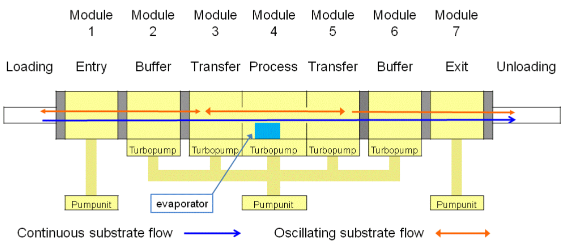

Fig. 2: Schematic drawing of the ATON 500 inline high-rate evaporation system. In continuous substrate flow, a user-defined number of carriers move through the system from the loading to the unloading zone by passing the evaporator only one time. In oscillating substrate flow, one carrier moves across the evaporator back und forth several times. This carrier leaves the system either at the unloading or at the loading zone, depending on the number of oscillations.

3 EXPERIMENTAL RESULTS

High evaporation rates that are required for high throughput cause a high heat-load for the solar cell due to the heat of condensation of the gaseous aluminum and due to the thermal radiation of the evaporator boats. In order to reduce the heat load, both, experiments and two-dimensional simulations with the finite-element method are conducted. As a result of our experiments, Fig. 3 shows maximum wafer temperatures for aluminum layers of different thickness values, deposited at various dynamic deposition rates (*ddr*). Layer thicknesses of 2.5 µm and 5 µm were deposited with 1 oscillation, 10 µm with 2 oscillations and the 20 µm aluminum layers were deposited with 4 oscillations across the evaporator.

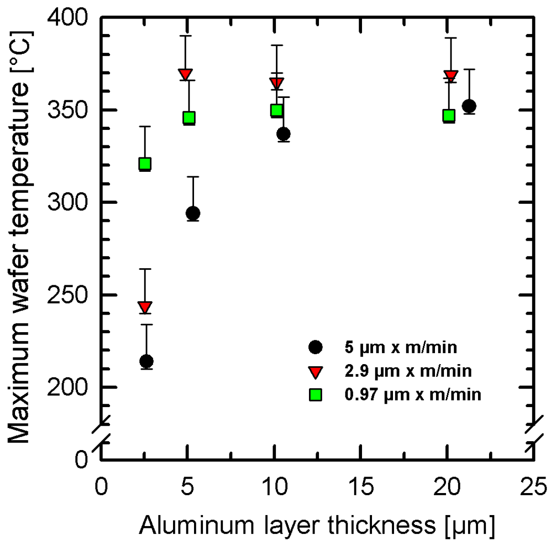

Fig. 3: Maximum temperature of a wafer as a function of aluminum layer thickness deposited at different dynamic deposition rates.

At an aluminum layer thicknesses of 2.5 µm (as used for example for the back contact of two-side-contacted solar cells) a deposition with a *ddr* of 0.97 µm × m/min leads to a maximum wafer temperature of 320°C, while a deposition with a ddr of 5 µm × m/min leads to a lower maximum temperature of 215°C. The dynamic deposition rate has thus a big impact on maximum wafer temperature for thin aluminum layers. This is due to thermal radiation from the evaporation boats that reaches the wafer prior to evaporating sufficient aluminum to significantly reduce the emissivity. The wafers spend more time without heat reflecting aluminum layer for slower carrier speed that are used for the smaller *ddr*s to achieve a constant layer thickness. Therefore the temperature is higher at small *ddr*s.

At an aluminum layer thickness of 20 µm (as required for rear-side interdigitated contacts of back-contact solar cells) the measured temperatures are between 350°C and 370°C. Here, the dynamic deposition rate has considerably less impact on wafer temperature. In this case, the power of heat condensation of the gaseous aluminum balances the radiation losses and is the controlling factor for the wafer temperature.

Using a higher number of oscillations (8 and 12, respectively) across the evaporator, simulating more evaporation chambers, lead to lower maximum wafer temperatures. For 20 µm aluminum layer thickness wafer temperatures decrease to 289°C and 232°C, respectively.

Therefore wafer temperatures depend on the aluminum layer thickness and the dynamic deposition rate used. In consequence the maximum allowed wafer temperature impact the number of required evaporation chambers. For all aluminum layer thicknesses from 2.5 µm up to 20 µm maximum wafer temperatures are below 370°C and therefore compatible to solar cell processes.

We perform contact resistance measurements using the transfer length method (TLM). Figure 4 shows the contact resistance measurements for a p-type FZ-Si wafer of 0.5 Ωcm resistivity. The specific contact resistance is 4 mΩcm^2 for ATON-coated samples (thermal evaporation). For comparison we also investigate samples that we metalize in a static laboratory-type system (BAK EVO with thermal und electron beam evaporation) and a deposition rate of 0.6 µm/min. These samples require subsequent heating to achieve a contact resistance as low as for the inline-evaporated samples. This is due to the fact that inline evaporation goes along with annealing during deposition of the aluminum layer due to the high deposition rate. Further annealing does not further reduce the specific contact resistance. However, ATON-coated samples with a higher resistivity of 1.5 Ωcm and 8 Ωcm, respectively, have specific contact resistances of 14 mΩcm^2 and 134 mΩcm^2, respectively. These values are only slightly lower than the contact resistances achieved for these materials with static evaporation (22 mΩcm^2 and 271 mΩcm^2, respectively). A more detailed analysis of inline-evaporated aluminum layers used as point contacts is given in Ref. 6.

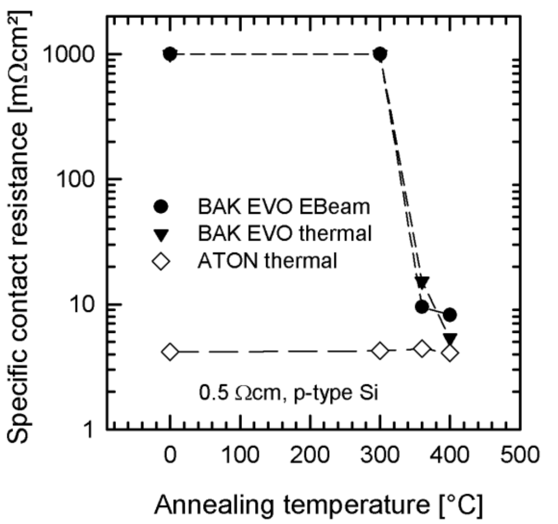

Fig. 4: Specific contact resistance measurements on a p-type wafer of 0.5 Ωcm resistivity. Samples were prepared in different laboratory-type static BAK systems (low deposition rates) and in the inline high-rate evaporation system ATON (high deposition rates).

We also apply inline evaporation to a buried-emitter rear-contact solar cells [3]. This solar cell was first metallized with Al in the static BAK EVO system, then the

metallization layer was structured and all cell testing was done. Afterwards the metallization of this solar cell was etched back and a new aluminum layer was deposited in the inline ATON system, followed by structuring and cell testing.
Table I compares the solar cell parameters for both processes. The results are very similar. The I-V curve of the cell with the ATON metallization is shown in Fig. 5. The efficiency is 20.6 %.

Tab. I: Solar cell data of a buried-emitter rear-contact cell, first metallized in the static BAK system, etched and then metallized in the inline ATON system.

	V_{oc} [mV]	J_{sc} [mA/cm^2]	*FF* [%]	η [%]
BAK	644	41.1	78.3	20.8
ATON	649	41.3	77.0	**20.6**

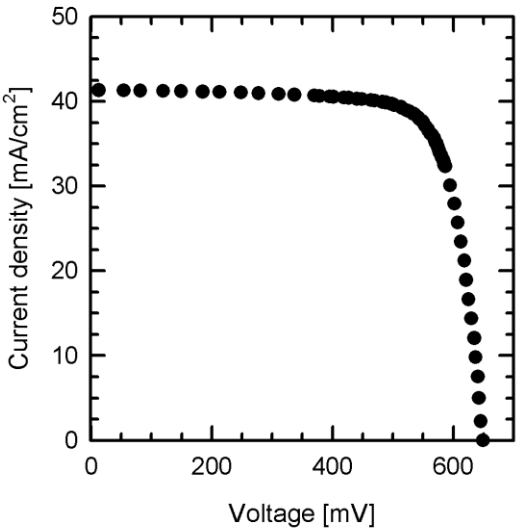

Fig. 5: I-V curve of a buried-emitter rear-contact solar cell (3.96 cm²) with 10µm aluminum layer, metallized in the ATON system showing a conversion efficiency of 20.6%.

4 SUMMARY

We have analyzed various thermal evaporation processes using a high-throughput inline evaporation system. Aluminium layer thickness values ranging from 1 µm to 20 µm were deposited. The thickness uniformity across the 500 mm wide deposition area is ±3.4%. The maximum deposition temperature varies from 200°C to 370°C and depends on the aluminium layer thickness and on the dynamic deposition rate. For thin layers high deposition rates lead to smaller deposition temperatures. Silicon wafers of low resistivity (0.5 Ωcm) have a specific contact resistance of 4 mΩcm² without subsequent annealing. Cell efficiencies of up to 20.6% were measured with inline evaporated metallization. This value is similar to that achieved with a static lab-type evaporation system. This demonstrates the applicability of the inline evaporation system to industrial high-efficiency solar cells.

5 ACKNOWLEDGEMENTS

Funding was provided by the State of Lower Saxony and the German Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) under Contract No. 0327666. The responsibility for contents of this publication is with the authors.

6 REFERENCES

[1] R. Hezel, W. Hoffmann, and K. Jaeger, " Recent advances in silicon inversion layer solar cells and their transfer to industrial pilot production", Proc. 10th European Photovoltaic Solar Energy Conference, 1991, pp. 511 - 514.

[2] P. Engelhart, N.-P. Harder, T. Neubert, H. Plagwitz, B. Fischer, R. Meyer, and R. Brendel, “Laser processing of 22% efficient back-contacted silicon solar cells”, 21st European Photovoltaic Solar Energy Conference, 2006, pp. 773- 776

[3] N.-P. Harder, V. Mertens, and R. Brendel, “Buried emitter solar cell structures: Decoupling of metallisation geometry and carrier collection geometry of back contact solar cells”, Physica Status Solidi (RRL) 2 (2008), Nr. 4, S. 148–150.

[4] J. Nekarda, D. Reinwand, A. Grohe, P. Hartmann, P. Preu, R. Trassl, and S. Wieder, “Industrial PVD Metallization for high efficiency crystalline silicon solar cells”, 34th IEEE Photovoltaic Specialists Conference, 2009

[5] F. Heinemeyer, C. Mader, D. Münster, T. Dullweber, N-P. Harder, and R. Brendel, “Inline high-rate thermal evaporation of aluminum as a novel solar cell metallisation scheme”, Proceedings 2nd metallization workshop, Konstanz 2010, in press.

[6] C. Mader, J. Müller, S. Gatz, T. Dullweber, and R. Brendel, “Rear-side point-contacts by inline thermal evaporation of aluminum”, 35th IEEE Photovoltaic Specialists Conference, 2010