IN-LINE HIGH-RATE DEPOSITION OF ALUMINUM ONTO RISE SOLAR CELLS BY ELECTRON BEAM TECHNOLOGY

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ABSTRACT: This paper presents results on the contact formation to Rear Interdigitated Single Evaporation Emitter Wrap Through (RISE EWT) solar cells by electron beam high-rate evaporation of aluminum. In stationary depositions water cooled copper crucible and ceramic crucibles were used. The ceramic crucibles were found to be best suitable when regarding the electron beam power and the upper limit of the solar cell temperature of 400 °C. Using an in-line high-rate deposition equipment 20 µm-thick aluminum layers were deposited at dynamic deposition rates of 3.6 µm×m/min from ceramic crucibles onto RISE EWT solar cells. The cell temperature during deposition was measured and analyzed using 2-dimensional finite-element (FEM) simulations. The processed RISE EWT solar cells present efficiencies of up to 18.4 %, which equals the cell efficiencies of reference solar cells that are contacted at lower deposition rates at lab scale.

Keywords: Aluminum, Back contact, Electron beam evaporation, High deposition rate

1 INTRODUCTION

One of the most important issues in today’s industrial solar cell research activities is the reduction of costs per Watt peak due to an increase of efficiency and a decrease of process complexity and material consumption. The contact formation of solar cells has an important role herein, since the contact quality strongly influences the electrical parameters of a solar cell. Additionally, the use of precious metals like silver in case of screen printing or nickel, copper, and silver in case of plating makes the creation of contacts quite expensive.

Patterning of contacts is one of the technical challenges of this process step. The front contact lines must be as narrow as possible to cause only little shading. On the other hand the metal cross section must be large enough to carry the generated current with only few resistance losses.

Back contacted solar cells offer the opportunity to establish new metallization techniques. There is no need to care for shading losses. In case of passivated surfaces with isolating dielectric layers and local contact openings the interface area is independent of the metallized surface area. The well known methods like screen printing can be used for structuring the grid shape, and in some cases even self aligning processes can be applied for defining the grid outline.

The RISE EWT solar cell was introduced by Engelhart et al. in 2005 [1]. The cell is based on *p*-type mono crystalline silicon. The front surface exhibits a pyramidal surface texture and a silicon nitride surface passivation / anti reflective coating. Laser drilled holes connect the full area emitter on the front with a local emitter structure on the rear.

A characteristic feature of the RISE EWT cell is its structured rear surface. The shape of the grooves created by laser ablation of a protection layer and subsequent silicon etching defines the rear emitter location as well as the shape of the metal grids for both polarities. The borderline between the two contact polarities is represented by a steep flank between the two height levels of the surface. The local emitter on the rear is located inside the laser defined grooves including their walls. The non-diffused area on the rear is covered by a dielectric passivation layer consisting of a thermal silicon oxide and – depending on the embodiment of the cell – additional dielectric layers. Local contact openings created by laser ablation allow contacting the silicon base through the dielectric layer. The laser induced damage to the silicon surface is minimal. The metallization of the RISE EWT solar cell was designed in the lab as two layer structure consisting of 10–25 µm of aluminum and an additional thin layer serving as etch protection for the contact separation process (Figure 1).

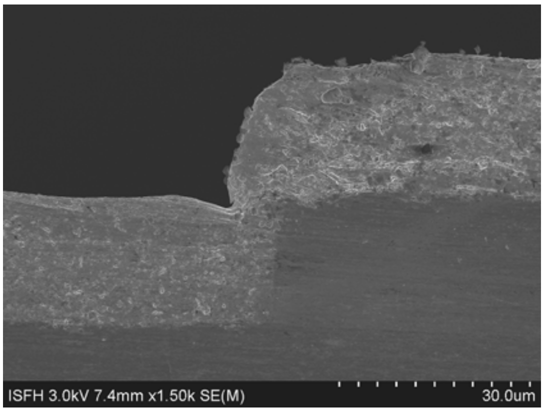

Figure 1: RISE EWT solar cell after aluminum metallization

During the contact separation the wafer is immersed in an aluminum etching solution to remove the metal at the borderline between the two height levels. The aluminum covers the whole rear wafer surface except for the flanks between the two height levels – see Figure 2.

We present the results of our study examining high-rate electron beam evaporation of aluminum using an industrial high throughput in-line tool for creating the metal contacts of the RISE EWT solar cell. It is shown that this method is well suitable for an industrial high efficiency solar cell process at low cost.

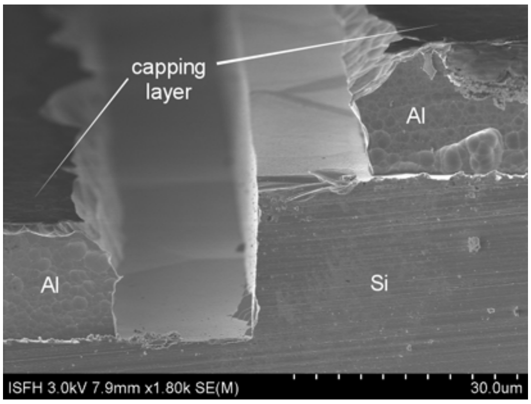

Figure 2: RISE EWT solar cell after contact separation

2 GENERAL PROCESS REQUIREMENTS

For the contact formation on RISE EWT cells we propose to use high-rate evaporation of aluminum using a high throughput electron beam in-line tool. Some technical requirements have to be fulfilled by the process. The deposition rate of the aluminum should be reasonably high, since it limits the throughput of the tool. With increasing deposition rate the substrate temperature rises as well. Here we are limited to 400 °C. The reason is that at higher temperatures the aluminum shortens the pn junction in the contact area. The metal locally spikes into the silicon surface creating highly conductive regions. As soon as these spikes penetrate the n+ region totally and reach the p basis, the solar cell is shunted.

Another requirement concerns the structure of the evaporated aluminum. The plane areas should possess a strong compactness comparable to bulk aluminum. Accordingly, the specific resistance should be low. On the other hand, the metal should be as thin and as porous as possible at the flanks of the groove structure to support the self aligning contact separation. For the process this means that the direction of the deposition should be mainly parallel to the silicon wafer normal. This is why sputtering is not well suited for contact formation on the RISE solar cell. In case of sputtering the metal particles reach the wafer surface from any direction and thus would cover the surface very homogeneously even in the area of the flanks.

3 EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Stationary aluminum deposition

The electron beam (EB) evaporation of aluminum using axial gun was evaluated in two different configurations. Stationary depositions were realized in a batch coater for pretests of three different types of crucibles: water cooled copper crucible, so called “hot” ceramic crucibles manufactured from aluminum oxide and from boron nitride. The electron beam was guided without a direction change in a direct shot into the crucible. The substrates were located about 300 mm above the evaporation pool only for the time of deposition using a transportation system (see Fig. 3).

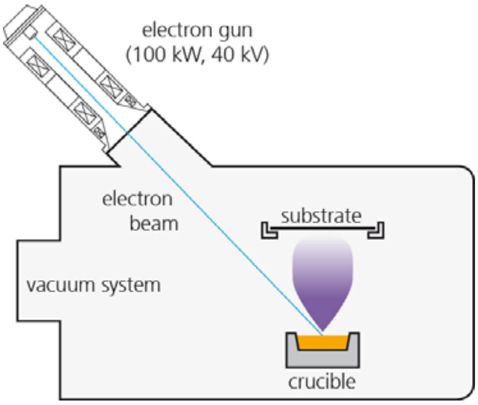

Figure 3: Equipment for evaporation with axial electron beam gun

The temperature was measured with NiCr/Ni-thermocouples which were fixed with ceramic glue. In Figure 4 is shown a characteristic temperature increase for a deposition with deposition rate 100 nm/s during aluminum evaporation from an aluminum oxide crucible. According to heat capacity of the used 180 µm silicon wafer and the heat input the temperature increases rapidly in the first ten seconds, after then the temperature converges a stationary value.

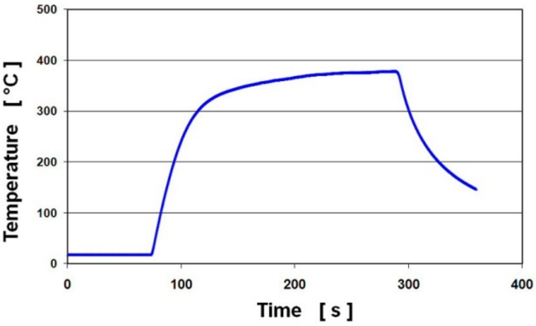

Figure 4: Characteristic temperature increase of silicon wafer during stationary aluminum deposition (100 nm/s)

The substrate temperature during deposition was simulated numerically. The simulation model is based on the heat flows during deposition, which are caused by the enthalpy of deposition and by heat radiation of the solar cell. The deviation between measured and simulated temperatures can be explained by parasitic heat flow (= heat flow additional to enthalpy of deposition) to the substrate, which are not included in the simulation. From measured temperature time curves the specific heat flows to the substrates were calculated for each crucible with two methods: In the first method the heat flow was calculated from the temperature increase immediately after start of deposition. In the second method the heat flow was estimated at steady state conditions from the balance of heat input and heat radiation. Table I shows the extracted parasitic heat flows for different types of crucibles for deposition rates to the substrate in the range 40 to 120 nm/s.

Table I: Parasitic heat fluxes from different crucibles to substrate

Type of crucible	Parasitic heat flux density [Wcm^{-2}]
Water cooled copper	0.5
Hot aluminum oxide	0.15
Hot boron nitride	0.06

The heat input for both ceramic crucibles is much lower than for the water cooled copper crucible. Especially in the case of the copper crucible the higher amount of backscattered electrons causes an unacceptable high parasitic thermal load in the used geometrical arrangement.

The deposited aluminum layer thickness was estimated gravimetrically and checked by single GD-OES measurements. From thickness and deposition time the stationary deposition rates were calculated. The different types of evaporation crucibles required different amounts of electron beam power for a definite deposition rate. Tab. II shows the required beam power for realizing a deposition rate of 100 nm/s with different crucibles.

Table II: Comparison of required beam power for realizing a deposition rate 100 nm/s

Type of crucible	Electron beam power [kW]
Water cooled copper	85
Hot aluminum oxide	10
Hot boron nitride	6

The amount of beam power in detail depends on several geometrical and electron beam parameters. But the comparison shows that the electron beam power is reduced remarkably by using the ceramic crucibles. By increasing the beam power the deposition rate was further increased to 800 nm/s. The two important technological parameters deposition rate and heat input are combined in Figure 5.

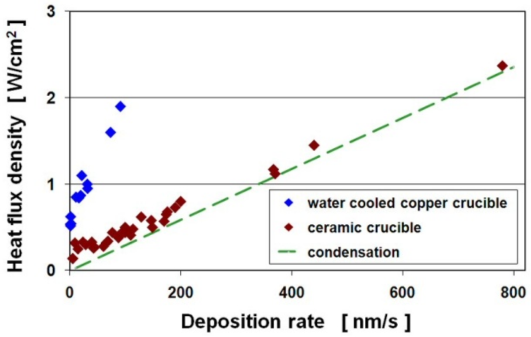

Figure 5: Relation of heat input and stationary deposition rate for aluminum electron beam evaporation from different types of crucibles

Figure 5 demonstrates that for water cooled copper crucible the deposition is connected with remarkable higher heat input in comparison with both types of ceramic crucibles. Both aluminum oxide and boron nitride crucibles show a performance which is close to the theoretical curve expected from heat input based on heat of condensation.

The electrical sheet resistance was measured for a first evaluation of the aluminum coatings on reference glass substrates with a four point probe device. The aluminum layers deposited from the water cooled copper and from the boron nitride crucibles showed specific electrical resistances in maximum only 10 % above the value for pure bulk aluminum. This shows the quality of the high-rate depositions in the batch coating equipment.

3.2 In-line aluminum deposition

In considerations of economical reasons (energy demand for evaporation, manufacturing cost, accessibility of high rates by keeping the temperature limits) and achievable layer quality the ceramic crucibles were chosen for the following in-line depositions in the Fraunhofer FEP coating equipment MAXI (see Fig. 6) [2,3].

Figure 6: In-line high-rate coating equipment “MAXI” at Fraunhofer FEP Dresden

The loading and unloading chamber, one EB-deposition chamber and a fourth chamber for single additional sputter depositions of the eight chamber equipment were used for our investigations. By using ceramic crucibles of a length of 530 mm the coating width was increased to more than 400 mm with only one EB-source. Figure 7 shows the achieved dynamic deposition rates.

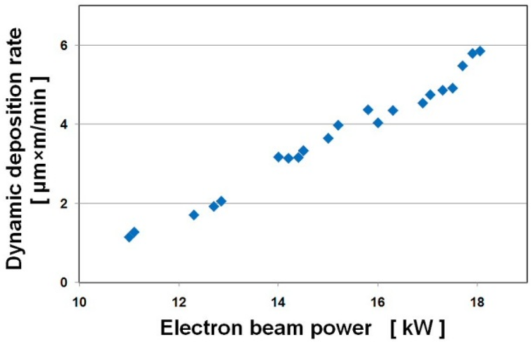

Figure 7: Dynamic deposition rate in dependency on electron beam power using boron nitride crucible

The substrate temperature during the coating process in the in-line equipment was recorded by using a data logger mounted and transported together with the wafer holder. The wafer temperature during deposition was simulated using two-dimensional finite-element simulations. The heat-conduction within the wafer is calculated by solving the two-dimensional differential equation of heat conduction of silicon. The boundary conditions are given by the heat flows during evaporation. A more detailed analysis of the temperature characteristics during in-line evaporation is given in reference [4].

Figure 8 shows the measured and simulated temperatures of 180 µm RISE EWT solar cells during the in-line deposition of a 21 µm-thick Al layer at a dynamic deposition rate of 3.6 µm×m/min. This dynamic deposition rate is connected with a stationary rate of 210 nm/s in central deposition zone. According with the upper temperature limit the maximum temperature was below 400 °C. By adaptation of an optimized electron beam guiding and the dynamic deposition method the heat input was minimized in comparison with the above described stationary deposition experiments.

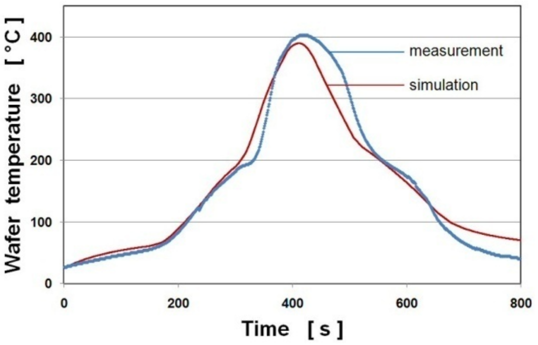

Figure 8: Temperature of a RISE EWT solar cell during in-line electron beam evaporation using a boron nitride crucible. The dynamic deposition rate is of 3.6 µm×m/min.

The stability of the deposition rate respectively the aspired layer thickness could be demonstrated within ± 6 % during an uninterrupted eight hour experiment. Only slight manual corrections of the beam power were done according to the measured values of deposition rate monitor. This represents the stability of the installed electron beam evaporation process.

3.3 Cell Results

Lifetime measurements at samples passivated with silicon nitride and silicon oxide, respectively, do not show any observable degradation due to the high energy electron beam used during the coating experiments.

RISE EWT solar cells were processed according to the process described in Ref. [5]. The aluminum depositions of reference cells were realized using a standard laboratory batch coater with a transverse electron gun realizing an aluminum deposition rate of about 5 nm/s. Table III shows the solar cell parameters open-circuit voltage V_{oc}, short-circuit current density J_{sc}, fill factor FF and cell efficiency η of the best RISE EWT solar cells. Both, the cell parameters of reference cells and of cells fabricated in the in-line coating equipment with high-rate electron beam evaporation are shown in Tab. III.

The cell parameters of the cells that were contacted using the in-line equipment correspond within deviations lower than one percent with the parameters of the reference cells. This demonstrates that the aluminum metallization with high rates of 3.6 µm m/min in an in-line equipment does not reduce the relevant parameters of the solar cells.

Table III: Parameters of best RISE EWT solar cells manufactured with different metallization rates. The designated cell area is 4 cm².

Parameter		Reference	High-rate deposition
V_{OC}	(mV)	630	629
J_{SC}	(mA/cm^2)	39.9	39.6
FF	(%)	74	74
η	(%)	18.5	18.4

The gap to the highest reported value of 21.4 % [6] demonstrated with RISE EWT solar cells so far results from less complex processing. The solar cells used in this study had a non-passivated rear emitter, a reason for lower open-circuit voltages, short current densities and efficiencies. Additionally, all solar cells produced during our study show unusually high temperature stability. This is an indication for the existence of an undesired interface layer beneath the aluminum, resulting in a too high series resistance, potentially a bad surface passivation and thus low cell efficiency. The analysis of this effect is not yet finished.

4 SUMMARY

Electron beam high-rate deposition with aluminum was tested for the metallization of RISE EWT solar cells. Different types of crucibles (water cooled copper crucible, ceramic crucibles) were proved in stationary deposition experiments. According to heat load, power input and layer properties the ceramic crucibles were chosen for following dynamic coatings. In an in-line coating plant the metallization with 20 µm aluminum layers was realized at dynamic deposition rate of 3.6 µm×m/min maintaining the temperature limit of 400 °C. The temperature increase during dynamic depositions was investigated and analyzed with 2-dimensional FEM calculations. Processed solar cells present efficiencies up to 18.4 %. The solar cell parameters reveal identical values in comparison to the laboratory metallization step which was solved at remarkably lower deposition rates. The developed metallization with industrial deposition rates in pilot in-line equipment was realized without any solar cell efficiency loss.

5 REFERENCES

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