High Rate Electron Beam Evaporation of Functional Layers for Solar Cells

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ABSTRACT

The productivity enhancement of coating processes in the fabrication of solar cells is an urgent issue in order to meet the low cost requirements regarding their manufacturing. Often the introduced vacuum based coating technologies allow the deposition of functional layers only with insufficiently low rates.

Electron beam physical vapor deposition (EB-PVD) is a well introduced vacuum coating technology which allows superior coating rates. The inclusion of EB-PVD into the technological concepts of solar cell production opens up the possibility of drastic cost reduction of several coating steps.

This paper introduces examples of EB-PVD processes and their potential concerning photovoltaic applications. The coating of active layers of cells by EB-PVD will be discussed in detail with regard to coating rates and film properties. Large area solutions for highly productive coaters will be presented.

INTRODUCTION

The global energy consumption is increasing rapidly. In 2007 the global energy consumption has been reached 13 TW and it will grow to up to 30 TW in the year 2050 [1]. On the other hand the limitations of conventional energy resources accompanied with the problems of environmental pollution by combustion turbines are obvious. This is a challenge to open up new alternative resources of energy. And this is the well-known background of the current development of solar energy technologies and the growth of solar energy production. Therefore a considerable and worldwide increase of the photovoltaic power generation can be expected within the next few years.

It is unquestionable that strong efforts still have to be made in order to achieve an overcoming of the niche technology status of the solar energy production. For example progress regarding energy storage is required. A standardization of cells and modules has to be enforced. But first of all a comparability of solar energy production cost with conventional energy production cost is an absolute necessity. At present the cost per kWh is about a factor 5 more expensive than the cost of conventional energy [2]. Therefore the cost reduction by increased cell efficiency and/or increased productivity of the cell and module fabrication are the issues in order to achieve considerable portions of the whole energy production. In the following the focus will be set to possibilities of enhancing the productivity of solar cell fabrication.

In the last decade thin film solar cell fabrication technologies began to attack the exclusive position of wafer-based solar cell fabrication and gained a share of the market. While the production growth of wafer based solar cells is limited by the shortage of the silicon feedstock a rather non-braked spreading of thin film solar cell production can be observed [3]. The growth of its market position depends more or less on the capacity of the equipment manufacturers. Figure 1 shows the development of the whole production volume in the field of thin film photovoltaics over the last three years [4].

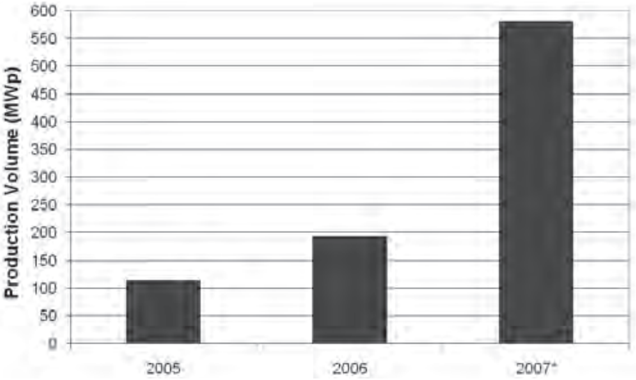

Figure 1: World wide thin film PV production volume from 2005 to 2007 (estimated value).

In the period between 2006 and 2007 thin film technologies crossed 10% of the total solar cell production. In this context thin film photovoltaics has become an important application field of PVD technologies. The necessity to search for highly productive coating steps which are scalable to large area inline concepts in order to achieve a remarkable production cost reduction helped to overcome the common introduction barrier of PVD which consists in rather high investment costs even though accompanied with low running costs.

In this paper EB-PVD will be considered regarding its capability to carry out advantageously coating steps of solar cell fabrication which are encountered in a high variety of

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cell concepts. EB-PVD is in the position of being an offered substitution technology which could replace firstly introduced technologies of minor productivity. In other industrial application fields EB-PVD is already established as a highly productive large area coating technology as for example in the reflector coating on metal strips or thermal barrier coating on turbine blades. Concerning these mentioned industrial applications inline concepts have been industrially introduced for some years [5], [6]. This allows the assumption that EB-PVD will become a strong technology in the field of solar cell production, too.

CONTACT LAYERS COATED BY EB-PVD

The contact layers of solar cells comprise metal layers as well as TCO layers. A long-term stable TCO coating process cannot be carried out by EB-PVD because of the thermal instability of the oxides under effecting electron beams. TCO layers have to be sputtered or deposited by CVD. But the coating of metal layers allows the application of high rate EB-PVD. Molybdenum coatings are suited as back contact of thin film solar cells on glass substrates or thin metal foils as stainless steel. Figure 2 shows the principle structure of the layerstack of a CIGS-cell containing an about 500 nm thick Mo-layer.

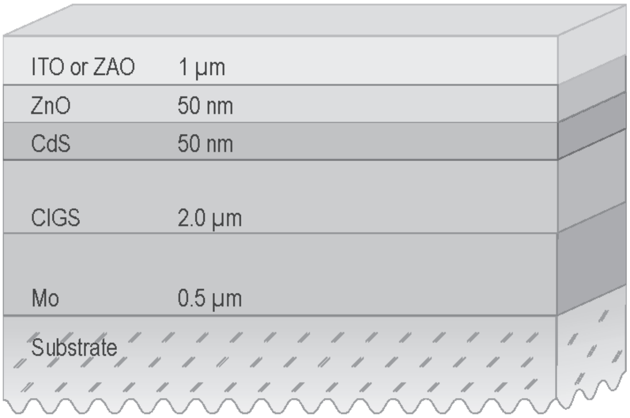

Figure 2: CIGS-cell layerstack containing a molybdenum back contact layer.

The molybdenum coatings as back contact of CIGS cells on soda lime glass substrates are well established because of their high thermal stability, mechanical strength, their electronic properties (conductivity) and the diffusion permeability for a certain amount of sodium into the CIGS absorber material. It increases the grain size of the CIGS-layer, provides a high degree of surface flatness and improves the efficiency of cells [7]. The introduced coating technology is magnetron sputtering. Table 1 compares some interesting issues of magnetron sputtering and electron beam evaporation of Mo on substrates having a width of 1.2 m. The table shows some remarkable advantages regarding EB-PVD. The first is the possibility to achieve a four times higher productivity with a comparable equipment. The second is the better material utilization. And the third is the remarkable price difference of the deposition material. Today the deposition material costs are the most important portion of the whole finishing costs per m² and in the case of sputtering with planar magnetrons they cause more than 73% of the finishing costs.

Several kinds of molybdenum have been tested as evaporation material. The price varied between 30 EUR/kg in the case of sintered molybdenum and 80 EUR/kg in the case of electron beam molten molybdenum. Sintered material was spitting under the effecting electron beam. A splashless evaporation only was possible with molybdenum which was prefabricated by electron beam melting.

A second application of contact coatings with prospects to become a domain of EB-PVD should be considered. This application refers to wafer-based solar cells. There are different kinds of wafer-based solar cells. They all need a back side metal contact which is deposited mostly by screen printing. In most of the cases the back side contact has to be coated nonstructured on the whole surface. The principle structure of one example of a wafer-based solar cell is shown in Figure 3.

Table 1: Comparison between EB-PVD and magnetron sputtering of molybdenum.

Feature	**EB-PVD**	**Magnetron sputtering**
Deposition direction	Up	Up, down, vertical
Equipment for 0.5µm at 1m/min	2 EB guns	3 WSM 1500
Equipment price ratio	3	: 2
Deposition rate Mo	2 000 nm x m/min	3 x 175 nm x m/min
Process power	2 x 55 kW = 110 kW	3 x 42 kW = 126 kW
Free surplus capacity	300%	5%

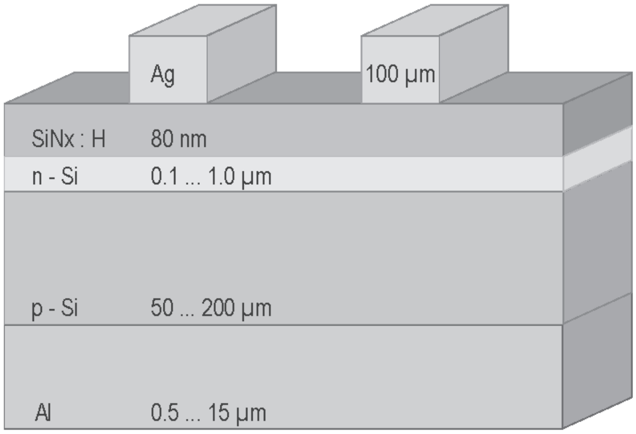

Figure 3: Example of a wafer-based solar cell.

The motivation regarding a substitution of the screen printing process at first is connected with the high cost pastes as coating material. The costs of these consumable materials during the process are about 10% of all production costs of the solar cell. Additives and minor purity of the pastes lead to minor contact quality and electrical losses. The deposition technique unavoidable leads to relatively thick layers. The difference in the thermal expansion coefficient between these thick contact layers and the wafer cause deformations of the wafer. Up to 15% wafer losses by damaging during screen printing has to be taken into account at the end of the production chain.

New cell designs require contact layers with reduced thickness mostly between 1 µm and 3 µm. These are typical PVD-coating values. More and more double or triple layers are required in order to meet special features of the back contact surface as for instance solderability. Up to now the main contact layer of the stack is an aluminum layer. The top layer for example can be a thin silver layer. Depending on the required thickness of the sublayers an inline combination of two EB-PVD processes or of EB-PVD and sputtering can be arranged. With respect to a good passivation of the silicon surface the substrate temperature is the main limiting factor for the process. Commonly a critical wafer temperature of 350°C should not be exceeded during the deposition. The following EB-PVD process features contribute to heat up the wafers:

a) Condensation heat of the coating material,
b) Backscattered electrons from the crucible,
c) Heat radiation from the evaporant.

The contribution of the backscattered electrons to the thermal load can be considerably high if they are not caught by a bending magnetic field [8]. Figure 4 shows very impressive backscattered electron beams bent by a constant magnetic field. The seemingly five electron beams come from one EB gun. The dynamic deflection unit generates subsequently very fast patterns on five locations. The majority of the backscattered electrons do not reach the substrate, they collide with the cooled catcher wall. Such a well known configuration reduces the heat load of the wafers during the deposition drastically.

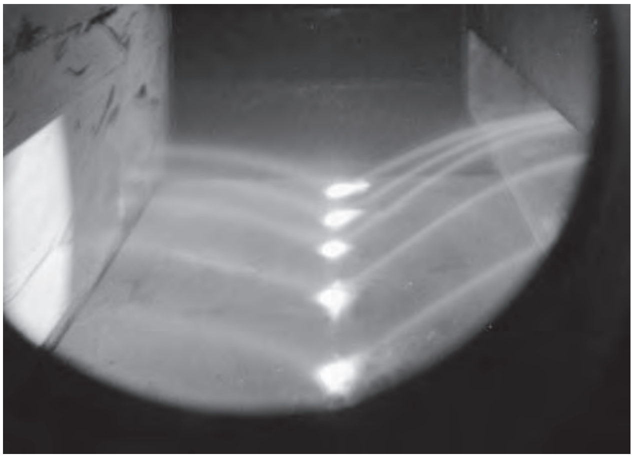

Figure 4: Bended backscattered electrons colliding with a catcher wall.

Figure 5 shows the calculated maximum temperature of silicon wafers having a thickness of 150 µm in the case of dynamic aluminum coating versus the layer thickness at a substrate speed of 1 m/min.

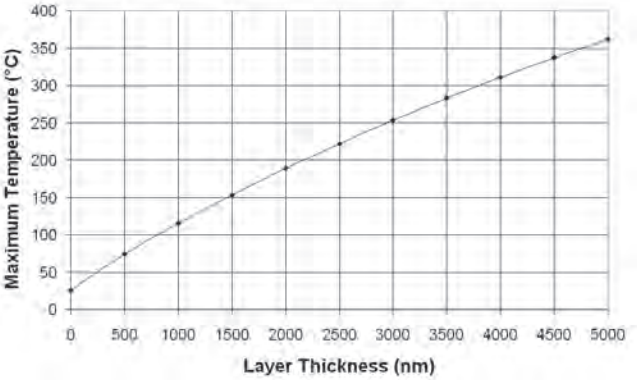

Figure 5: Temperature increase of 150 µm thick silicon wafers during EB-PVD of aluminum.

The coating process is assumed to start at a temperature of 25°C. Considered are condensation heat and radiation exchange of the substrate. This means that the calculation is done with the assumption that an additional heat load with backscattered electrons can be avoided and their thermal effect can be neglected.

In an R&D coating program wafers were coated in one run with about 2 µm thick aluminum and 0.2 µm thick silver sublayers. These experiments were carried out in a metal strip lab coater at VON ARDENNE. Figure 6 shows the scheme of this lab coater. In the coating experiments the strip served as means of transportation of a gondola which was bearing the wafers. In this way the dynamic deposition of wafers passing two processes in two adjoining chambers was possible.

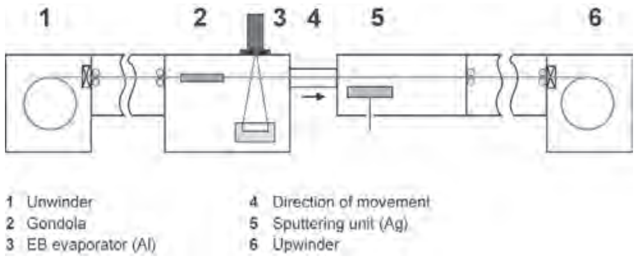

Figure 6: Scheme of the lab coater at VON ARDENNE.

In the first chamber aluminum has been EB evaporated from a water-cooled copper crucible. In the second chamber the silver top layer for solderability has been coated by means of a planar ring magnetron. On the wafer substrate a fixed movable thermocouple allowed the measurement of the wafer temperature during the coating process. After the deposition the resistivity of the contact layerstack has been measured too. The layer thickness measurements were carried out on test substrates by profilometry. Figure 7 shows the gondola passing the magnetron.

Figure 7: Wafer bearing gondola passing the magnetron.

The double layer has been coated on 6-inch wafers having a thickness of 165 µm at a substrate speed of 1 m/min. Table 2 displays typical basic process parameters and a typical example of achieved coating results. The aluminum deposition by electron beam evaporation was carried out without any catching of backscattered electrons, i.e. under conditions of a considerable additional thermal load of the wafers.

Table 2: Basic process parameters and achieved coating results.

Feature	**EB-PVD of Al**	**DC Sputtering of Ag**
Coating system	Water-cooled Cu crucible	Planar ring magnetron
Process pressure	2 x 10^{-5} mbar	5 x 10^{-3} mbar
Process power	35 kW	2 kW
Layer thickness	1750 nm	170 nm
Temperature difference	269 K	55 K
Resistivity	2.7 x 10^{-8} Ohm·m	

After the coating process the wafers showed no deformations. Compared with the resistivity of bulk aluminum of 2.67 x 10^{-8} Ohm·m the achieved resistivity of the layerstack shows a very similar value. The comparison of the temperature increase during aluminum coating with values of Figure 5 for the same layer thickness shows that catching the back scattered electrons would lead to a remarkable decrease of the wafer temperatures.

EB-PVD OF SILICON ABSORBER LAYERS

The silicon-based solar cell has some advantages compared with other types of cells. It has the longest history of research and development. Efficiencies of more than 20% have been reached. Silicon is one of the best explored materials. Silicon is nontoxic. The availability of silicon is practically unlimited. The earth consists to about 15% of silicon. On the other hand the production of solar grade silicon is not inexpensive. The materials consumption in the case of wafer based silicon cells is rather high. The current shortage of silicon feedstock lead to an increased contribution of materials costs to the whole module costs, which amounts to more than 50%. Therefore efforts have been made to reduce the wafer thickness and to reduce the silicon losses by new wafer production methods (for example EFG ribbons [9]).

A very evident way to reduce the materials usage is the thin film design of silicon solar cells. One possibility is the silicon deposition on silicon wafers which have a porous surface and serve as carrier substrates. These at high temperature epitaxial grown silicon layers on silicon wafer carriers have a thickness of about 15 to 25 µm. The layers are processed as solar cells. After that they have to be removed from the reusable carrier substrate and to be attached to a glass carrier by means of a transparent glue. Cells which were deposited by CVD showed efficiencies up to 14% [10]. EB-PVD as alternative and highly productive coating process has come into discussion.

The other possibility is the direct silicon deposition on glass or ceramic substrates or on flexible substrates as stainless steel. Typically the coatings which have to be deposited at moderate substrate temperatures show an amorphous or nanocrystalline structure and they have to be recrystallized either by liquid phase crystallization (LPC) or by solid phase crystallization (SPC). Thin film polycrystalline silicon solar cells on glass have reached a large area production scale. Large area glass modules which are produced by CVD of a silicon-based layerstack achieve efficiencies in the order of 7% [11].

Lab scale experiments have shown that EB-PVD is a promising alternative in order to substitute low rate CVD with its hazardous source materials [12]. This was motivation for VON ARDENNE to order an experimental program at the Hahn Meitner Institute (HMI). Aim of this program was the investigation of the behavior of test cell parameters which have an electron beam evaporated silicon absorber layer. The cells have been coated at various conditions which are preferably tolerable for borosilicate glass. Figure 8 shows the principle structure of the test cell.

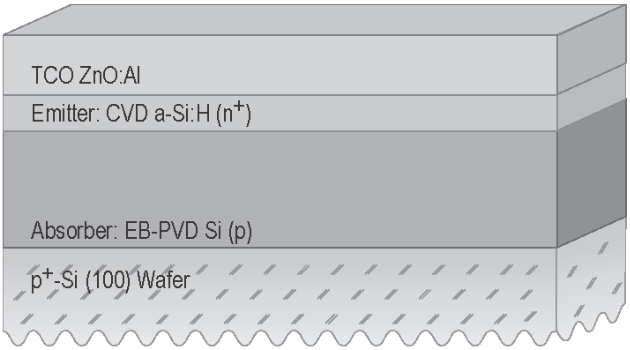

Figure 8: Principle structure of the test cell with EB evaporated absorber.

The Doping of the EB evaporated silicon layers resulted from coevaporation of boron by means of an effusion cell. Subsequently a hydrogen plasma passivation has been carried out. After coating the whole layerstack and manufacturing test cells the cell parameters have been measured and compared relatively to each other. The process parameter variations and their range of good results are shown in Table 3.

Table 3: Parameter variation of the silicon EB-PVD process.

Process parameter	Variation range	Range of good results
Substrate temperature	450°C to 700°C	> 550°C
Base pressure (air inlet)	(3×10^{-9} to 1×10^{-5}) mbar	< 5×10^{-6} mbar
Coating rate	40 nm/min to 480 nm/min	Whole range, best results at 480 nm/min
Substrate bias	-50 V to +20 V	Whole range

With the following parameters a quasi epitaxial silicon absorber layer growth has been achieved:

Process pressure:	1×10^{-6} mbar,
Substrate temperature:	600°C,
EB-power:	2.5 kW,
Boron doping:	3×10^{16} cm^{-3}
Substrate bias:	-10 V,
Deposition rate:	approx. 150 nm/min.

Figure 9 shows the cell parameters and characteristic of a typical test cell with good results. The layer thickness of the silicon absorber layer amounted to 2200 nm.

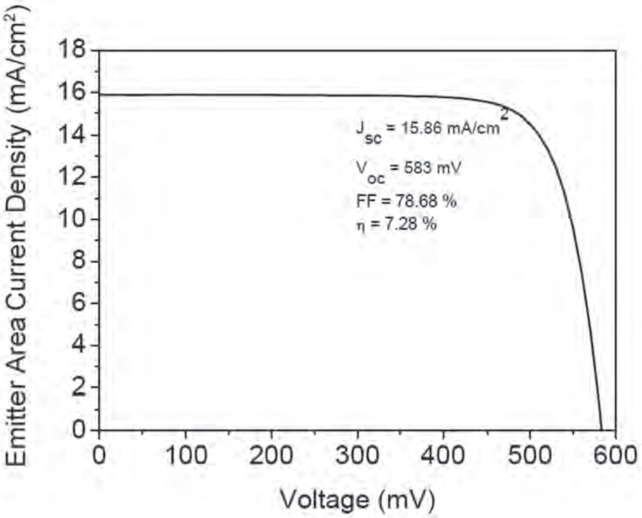

Figure 9: I-V-characteristic of a typical test cell from the HMI research program.

CONCLUSIONS

The substitution of the sputtering process of molybdenum contact layers by EB-PVD has the potential of a drastic cost reduction in the solar cell fabrication caused by the difference in the coating material costs. Furthermore EB-PVD allows a considerable increase of the operational capacity of PVD coaters which is caused by the attainable high coating rates.

The second advantageous application of EB-PVD is the back side metallization of wafer-based solar cells. In this case EB-PVD is a substitution technology of the screen printing process. Contact layerstacks with a solderable surface can be deposited in one run without breaking the vacuum. Excellent resistivity can be achieved. The thermal load of the wafer during the deposition is a critical issue which requires catching of backscattered electrons.

EB-PVD of silicon absorber layers of polycrystalline thin film Si based cells and modules has become a real possibility to reduce the materials consumption of expensive solar grade silicon. EB-PVD of solar grade silicon is possible with at least one order of magnitude higher deposition rates than CVD. The experimental program has shown that quasi epitaxial deposition can be achieved at industrially controllable process conditions. Furthermore it is possible to recrystallize EB evaporated silicon layers by SPC or LPC in the case of deposition at lower substrate temperatures.

There are very similar requirements for all three discussed applications regarding a productive large area EB-PVD solution. The first is an inline configuration with short cycle time and dynamic deposition of moved substrates in successive coating steps. This requires a modular designed coater concept which comprises a matched number of treatment and coating stations and a carrier transportation of the substrates (wafers or glass modules having a coating width up to 1.2 m) from the lock-in to the lock-out station.

The second is a sufficient stocking of coating material in order to guarantee long-term production cycles of 120 to 150 h without interruption. The third is a suitable vacuum pumping system which maintains low EB process pressures and sufficient gas separation between occasionally combined different coating technologies. In the case of EB evaporation of silicon absorber layers and doped layerstacks a start value of the productivity between 50 and 100 modules per hour having a size of 1.4 m² can be expected as first step of industrial introduction. A special solution regarding backside metallization of wafer-based solar cells allows a productivity of up to 5000 wafers per hour. First coaters have been ordered.

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