ON THE WAY TO A COMPREHENSIVE APC LIBRARY: IDENTIFICATION OF PROCESS MODELS AND DESIGN OF CONTROLLERS FOR VACUUM COATING PROCESSES

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INTRODUCTION

Commercially available APC solutions are mainly adapted to the special requirements of semiconductor industries. They cannot be ported to other industrial sectors (especially photovoltaic manufacturing) without further ado.
The basics for the development of a generalizable APC library for Equipment Engineering Systems (EES) frameworks are created by analyzing various PVD process types, which are especially fundamental in photovoltaic manufacturing, to evaluate the suitability for a (retrofittable) classifiable APC solution. Such as generalizable APC library for EES frameworks is flexible in use and can be adapted to various production lines (e.g. semiconductor and automotive industries) with little effort.

The Fraunhofer FEP, together with the Department for Technical Information Systems at TU Dresden (TUD), AIS Automation GmbH, and Roth & Rau AG, are carrying out a joint project* »APC LIB« to develop controllers for in-line vacuum coating processes based on APC.
The objective of this project is to develop a universal controller library for coating processes that are used for manufacturing photovoltaic elements. This library enables an APC controller to be generated, based on the module principle, from individual controller components such as PID controllers or model based predictive controllers (so-called predictors).

DATA ACQUISITION, DATA STORAGE AND DATA ANALYSIS

At first software was developed for data acquisition and APC, with the focus on expandability and variability.
For data storage, for example, a new innovative database system was developed that takes into account the aforementioned aspects due to its ability to adapt to the circumstances of the different plant control systems.

Furthermore a powerful tool for process analysis was established [1]: the ADM (Advisory Data Modeling) tool. It was developed as an integrated tool for process analyzing, including an advisory module and a memory (i.e. experiment reproduction) function.
ADM provides mathematical statistical methods for identification of

- static processes
- dynamic processes and
- time series

which can be linked according to content, function or data. The interaction of the project partner's contributions to data generation, acquisition, storage and analysis within the extended APC-framework is sketched in fig. 1. An Equipment Engineering System (EES) framework is the control center for administration and configuration of the data streams. It is the base for the exchange of information between the process units and all additional components. In this way APC acts as a subset of an EES solution via the Controller Module. By this abstraction an open implementation platform for the APC controllers is supplied (different programming languages and software systems are possible) and users can modify the controller model or even design own models without altering the EES framework.

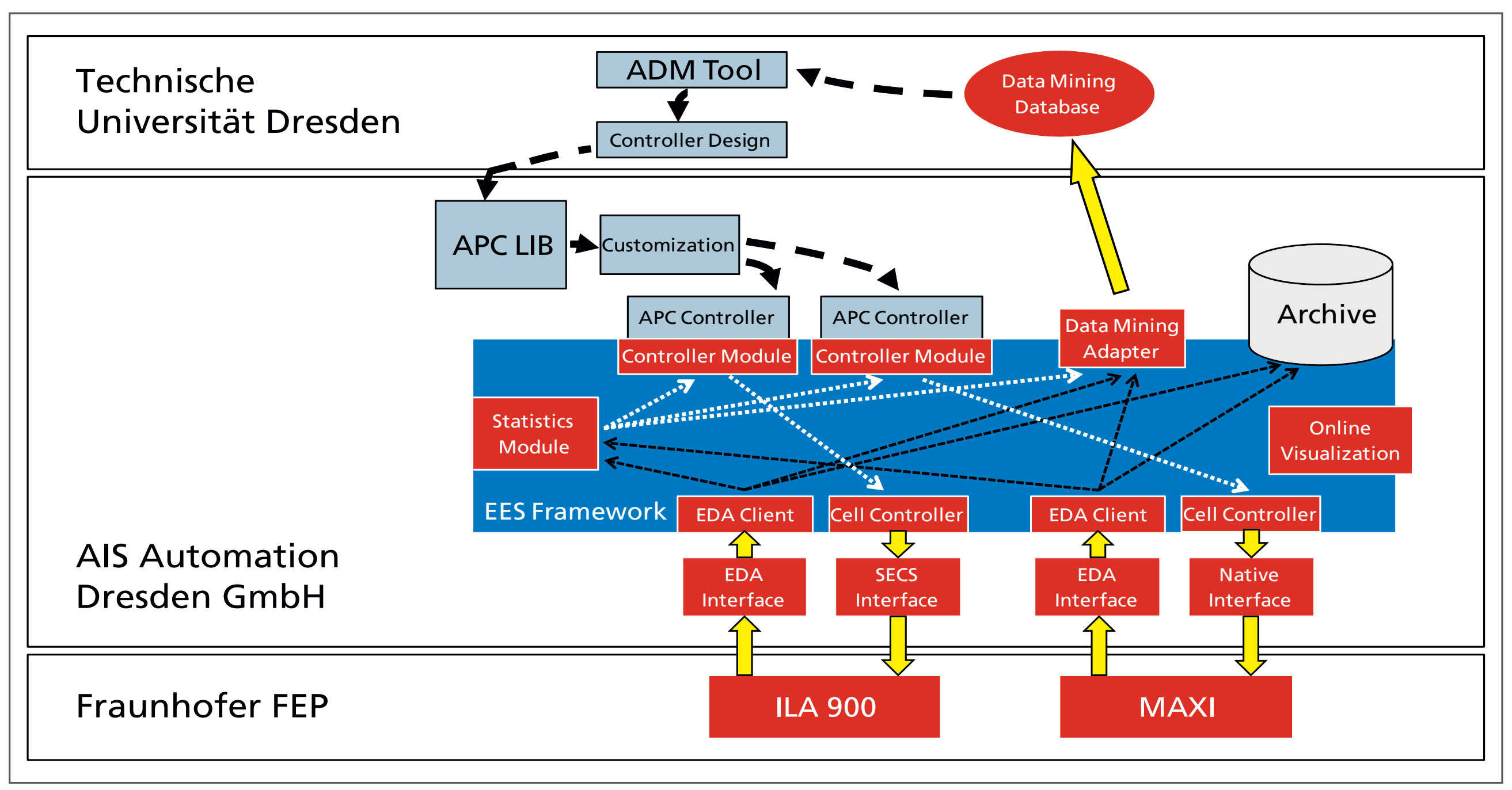

Figure 1:Extended APC-framework (chart of data generation, acquisition, storage and analysis).

PLANTS AND PROCESSES

The necessary process models were developed in conjunction with the project partners in extensive experiments using the MAXI – an in-line coating plant for metal sheets and metal strips – as well as the ILA 900 – a vertical in-line sputtering plant.

For this, experiments to identify the static and dynamic process models for different control paths were made. Furthermore validations of the control algorithms implemented by the project partners were carried out at the above mentioned plants.

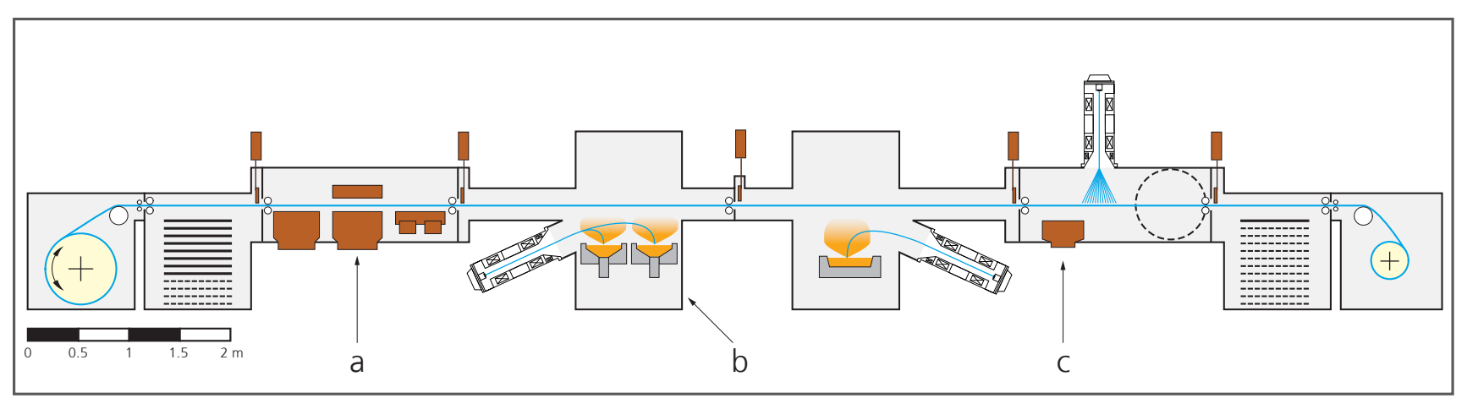

Figure 2: in-line coating plant for metal sheets and metal strips MAXI; a) pre-treatment station; b) coating station, c) in-situ measurement of layer thickness by X-ray fluorescence spectroscopy (XRF); sampling time 10s

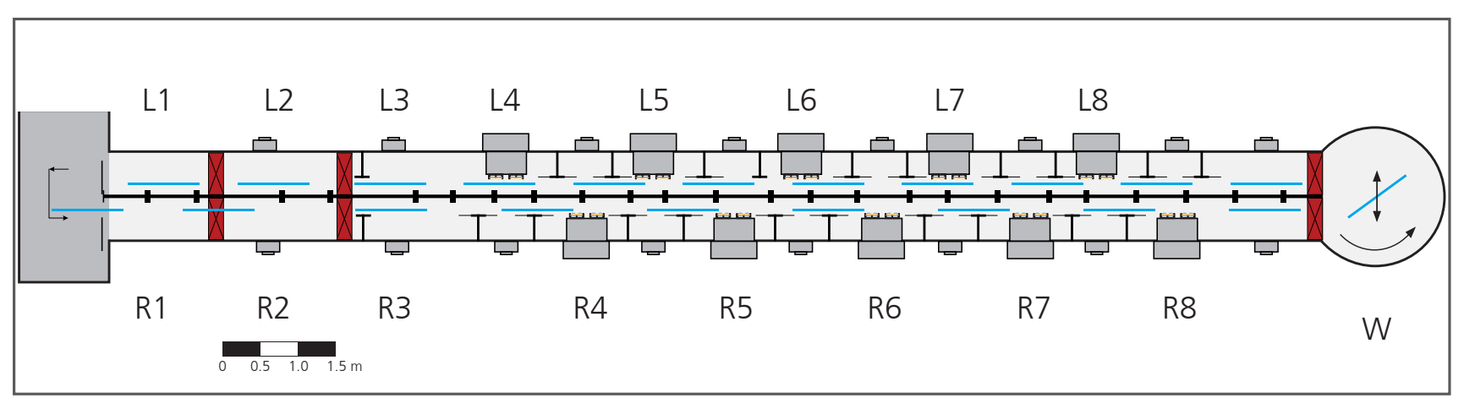

Figure 3: Vertical in-line sputtering plant ILA 900; chambers #2 & #3: pre-treatment stations; chambers #4…#8: coating stations

A1) SIO_2 DEPOSITION AT MAXI PLANT

One focus of the work on the MAXI was the SiO_2 deposition on steel strips. This layer system is particularly important for insulation and barrier layers for thin film photovoltaic systems on metal strips.
The Hollow cathode-Arc-Deposition (HAD) process (see fig. 5 for a 'live' impression) - a plasma-activated electron beam evaporation - was used to deposit the SiO_2 layers of the required quality.

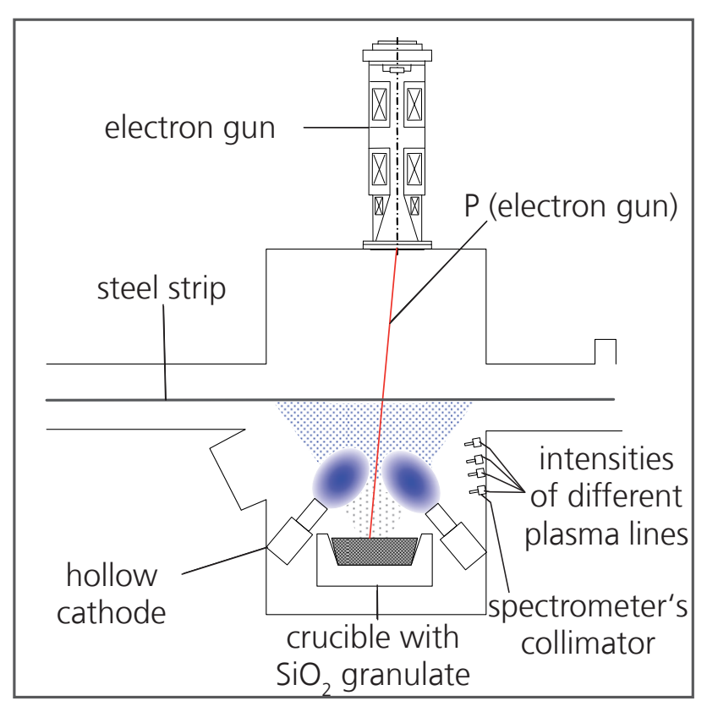

Figure 4: MAXI's coating station with HAD process and plasma diagnostics equipment

Figure 5: HAD process in action (crucible in the center; hollow cathodes at left and right side).

The electron beam (eb) power was used as the main actuating parameter, while the layer thickness was assigned to be the main process output quantity. Several spectral emission lines of Si or SiO were investigated to determine whether they are useful as auxiliary input quantities for a controller.
There is a large distance (4.25 m) between coating station and layer thickness measurement, which is typical for big inline coating plants.

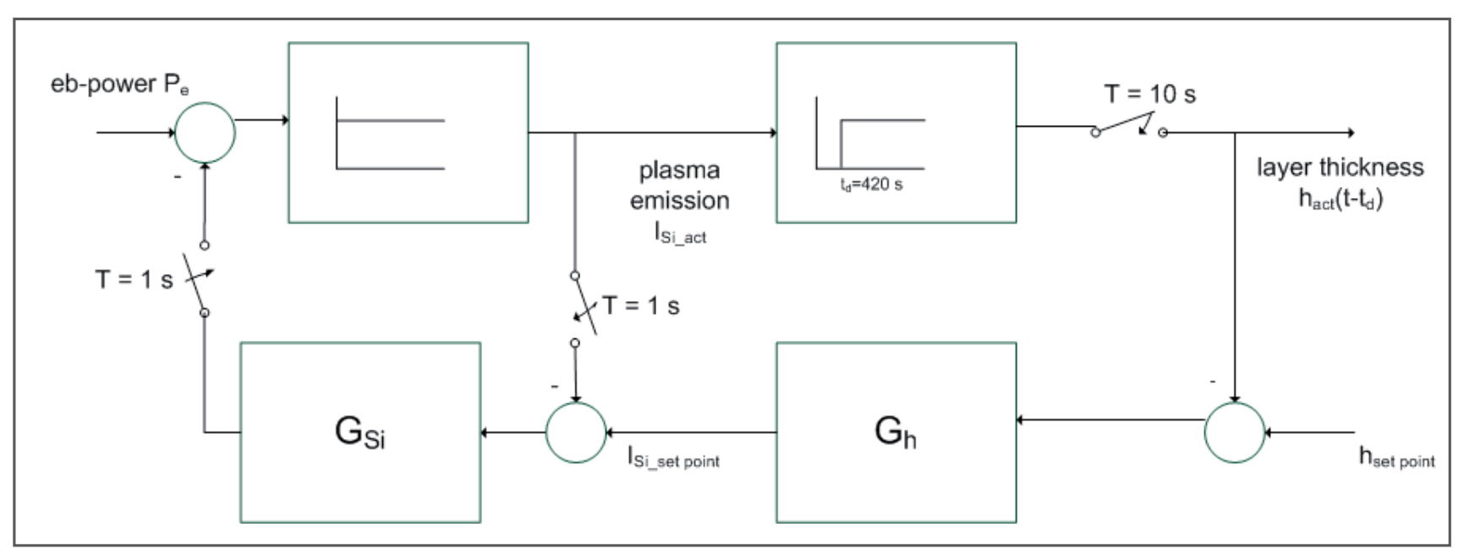

Figure 6: Possible design of a controller using an auxiliary controlling variable

Therefore, the main problem of controlling such a process is the long dead time (of about 420s for a strip speed of 0.6 m/min) between actor and controlling variable measurement, because the process reacts very quickly compared to the dead time.
The static process characteristics were examined to decide, if a combination of (two coupled) control loops (see fig. 6) may overcome this problem:

- a slow and accurate control loop Gh with a long dead time for the real control variable and
- a quick supporting control loop GSi for an auxiliary control variable;

where the first control loop is used to calibrate the second one.

The following paths were investigated (see fig. 7):

a) dependency of the different plasma emission intensities from the eb-power,
b) dependency of the layer thickness from the plasma emission intensities and
c) dependency of the layer thickness from the eb-power.

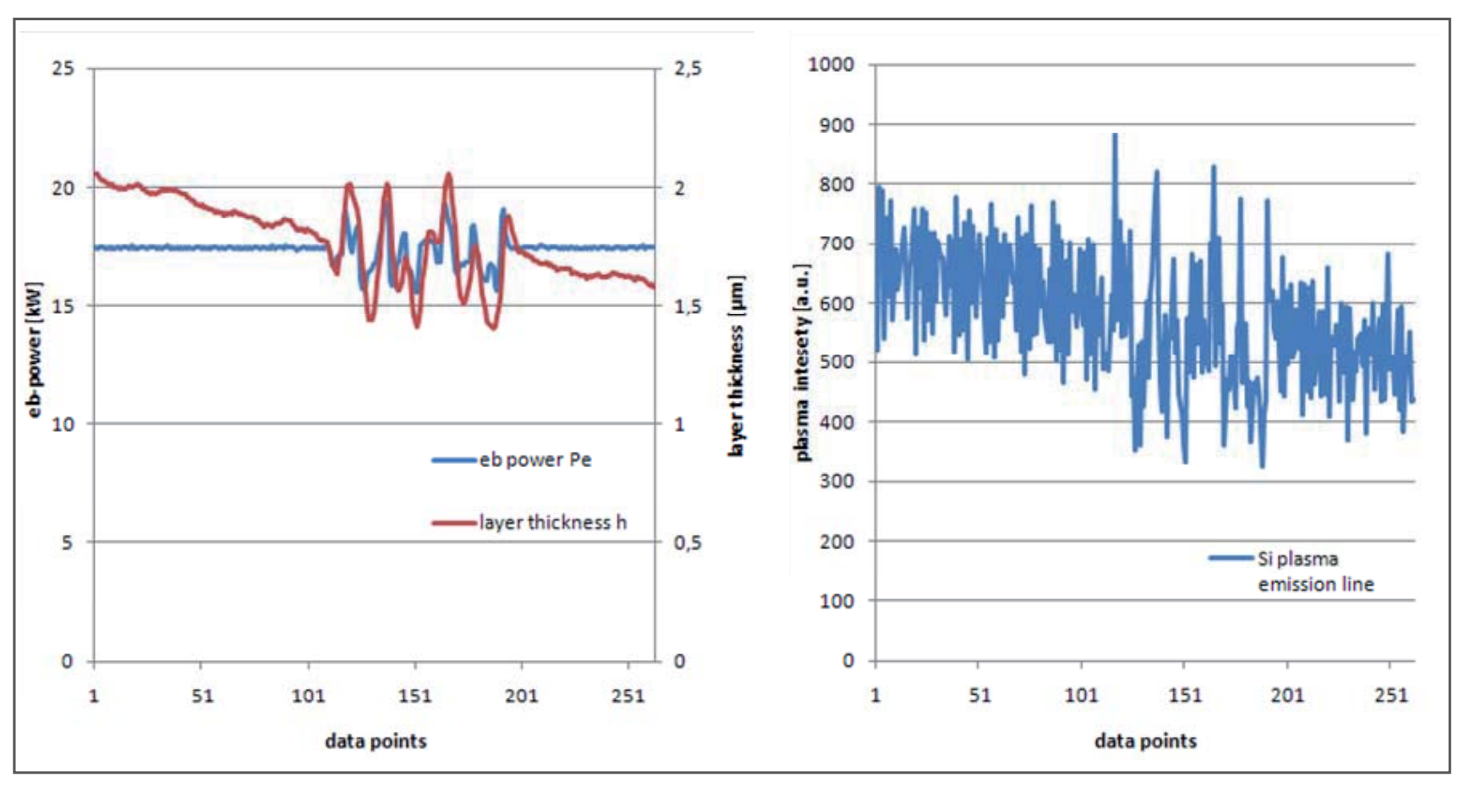

Figure 7: Long term experiments of SiO_2 deposition

To identify the static process characteristics several steps were carried out:

- preprocessing (dead time correction / trend correction / smooth filtering)
- analysis (correlation analysis / regression analysis).

A final comparison between the process model of the 'direct' path c) and those of the composed paths a) & b) shows a deviation of only 4.3%.

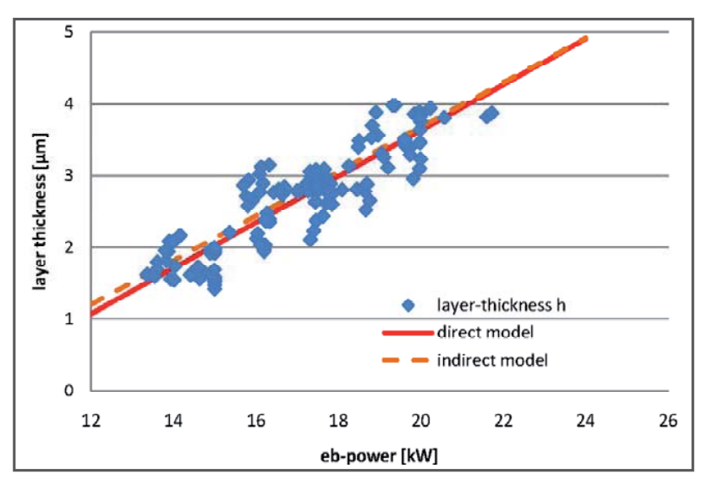

Figure 8: Comparison of process models

Therefore an employment of plasma spectral intensities as auxiliary control variable is possible to speed up the controller's reaction. An implementation of a prototype controller can be done after the dynamic characteristics of the process are also investigated.

A2) TIO_2 DEPOSITION AT MAXI PLANT

Based upon the experiences of process characterization and modeling of silica deposition, a prototype of a film thickness controller for the »titania on steel strip« coating process was developed.

The Spotless arc-Activated-Deposition (SAD) process (see fig. 10 for a 'live' impression) - also a plasma-activated electron beam evaporation - was used to deposit the TiO_2 layers reactively (in fully oxidized mode).

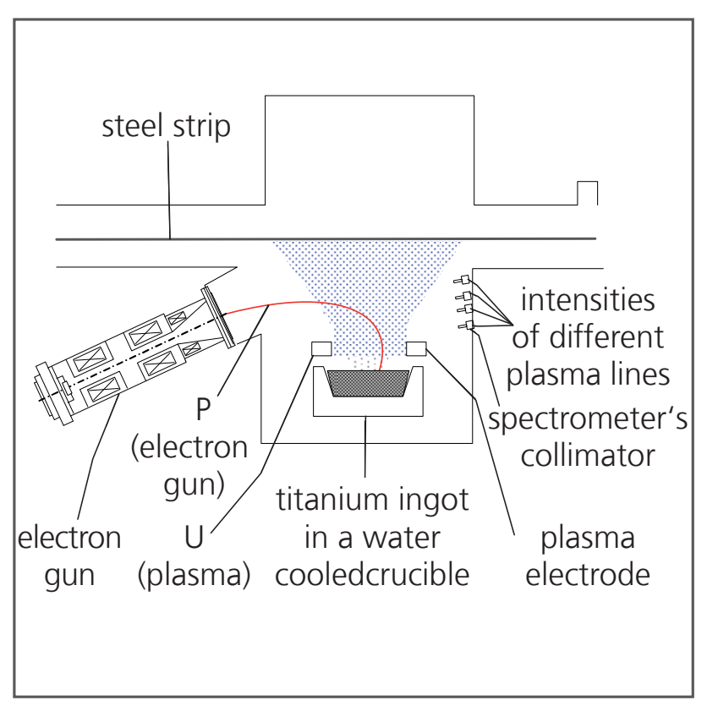

Figure 9: MAXI's coating station with SAD process and plasma diagnostics equipment

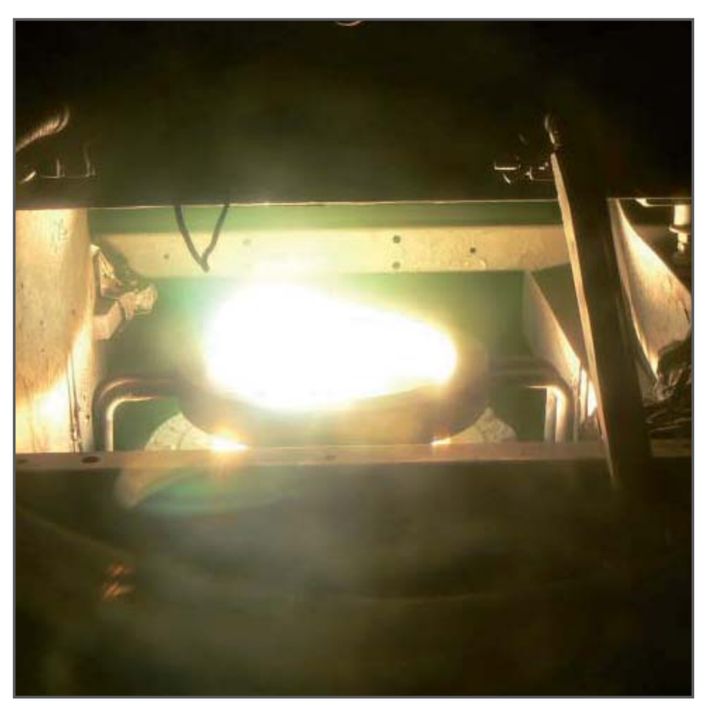

Figure 10: SAD process in action

A2) TIO_2 DEPOSITION AT MAXI PLANT (continued)

In order to compensate the large dead time occurring in the process, this controller was implemented as a Smith predictor and includes a feed-forward subsystem (scheme see fig. 11).

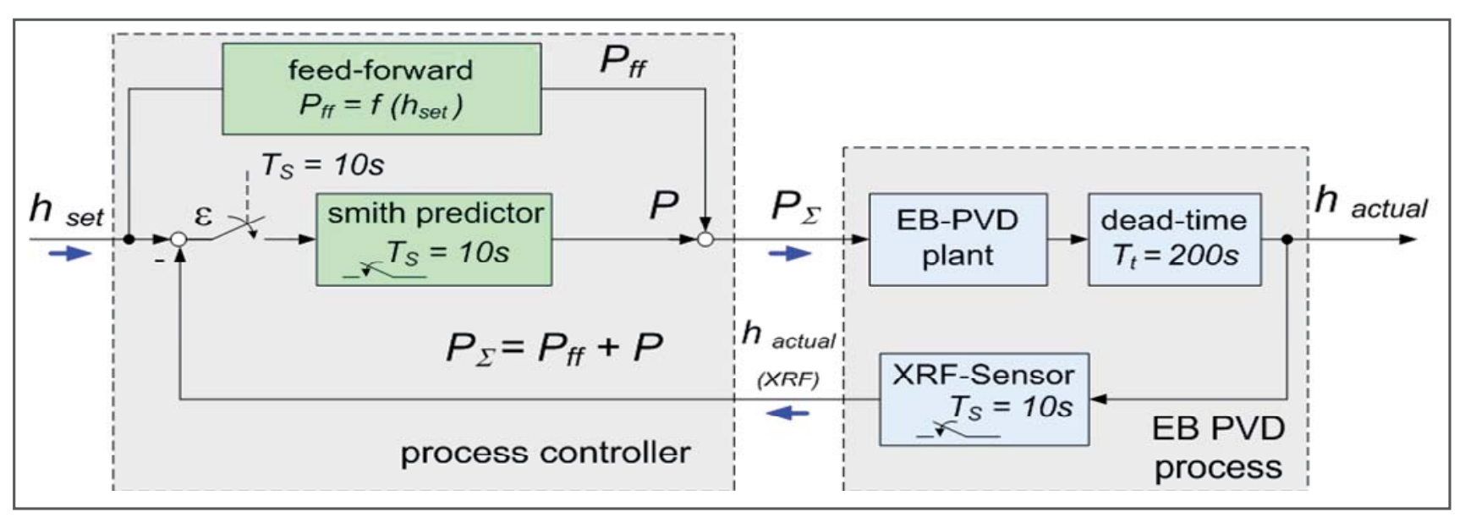

Figure 11: Prototype of a film thickness controller for a deposition by electron beam evaporation having large dead time (example 200 s).

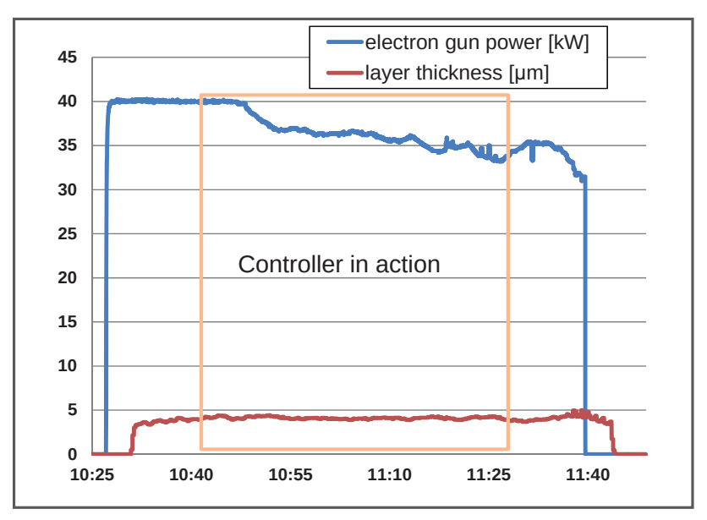

Figure 12: Results of controller testing

B) ZNO:AL AT ILA 900 PLANT

The sputtering of Transparent Conductive Oxide (TCO) layers for transparent front electrodes and window layers of solar cells was studied at the ILA 900.
Two process types were investigated: unregulated deposition using an oxide (sintered ceramic) target and reactive gas-controlled sputtering using a metal alloy target. Because reactive TCO sputtering is still believed to have a great potential due to the superior film properties (e.g. high conductivity and proper light scattering) [2], it took the center stage.

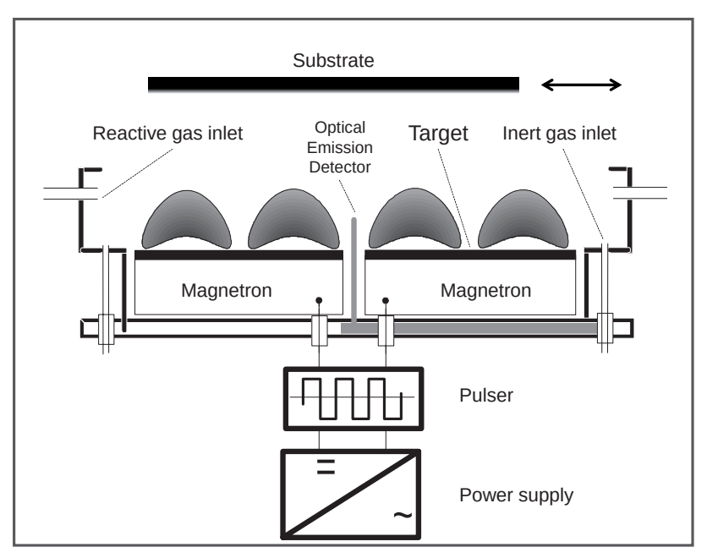

Figure 13: ILA 900's coating station dual-magnetron sputter and plasma diagnostics equipment

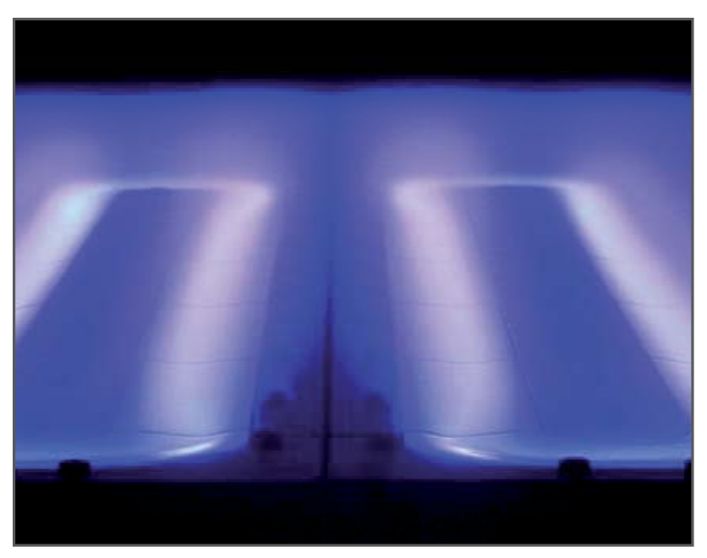

Figure 14: Bipolar sputtering process in action

Using a Dual-Magnetron-Sputter (DMS) system aluminum doped zinc oxide layers (ZnO:Al) were reactively deposited from a metal alloy target in transition mode.
The reactive process was stabilized at the desired working point (setpoint) by a fast control loop using special hardware controllers like PCU ^{plus} or S-PCU developed in Fraunhofer FEP. Both units are able to use (also) information from the plasma delivered by the Optical Emission Detector (OED) to adjust the reactive gas flow for up to 4 channels.

Figure 15: Process Control Unit – PCU ^{plus}

Figure 16: Spectrometric Process Control Unit – S-PCU (front and rear view)

The dependencies of several output quantities (layer characteristics like resistivity, thickness and absorbance) either from actuating parameters (mainly sputter power and reactive working point) or secondary input quantities:

a) plasma properties like oxygen content and emission lines;
b) process properties like impedance, gas flows and total pressure;
c) plant properties like chamber temperatures

were analyzed using the ADM software to develop an appropriate APC solution (setpoint tracing, model adaption).

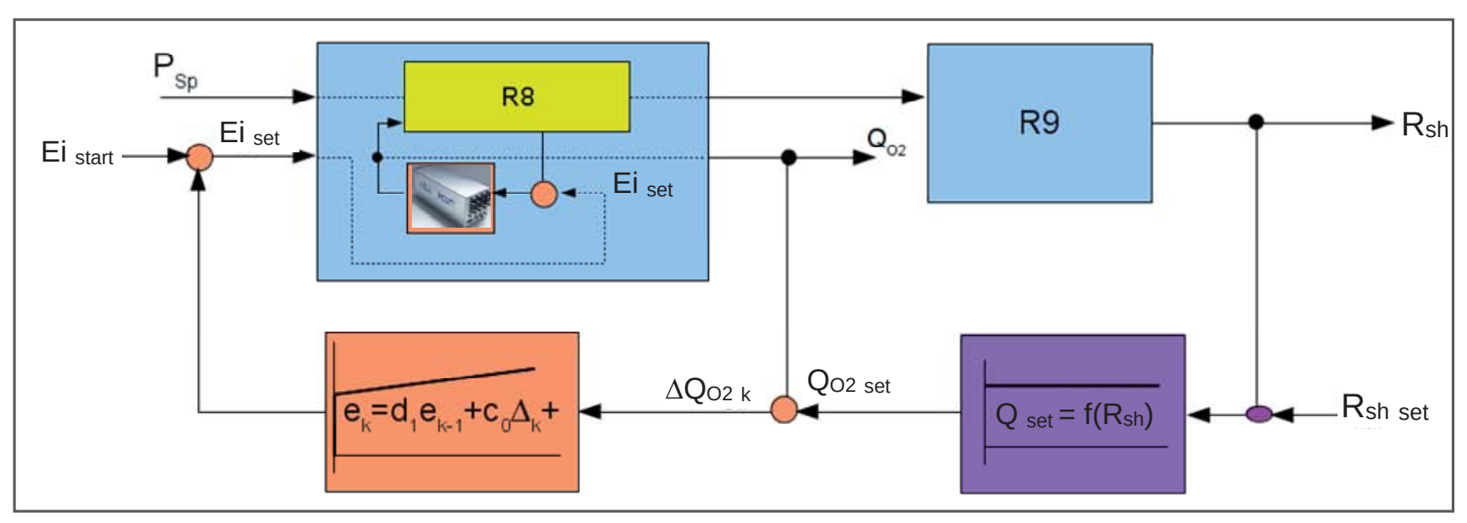

Figure 17: Prototype of an APC readjustment for reactive sputtering with built-in capability of model adaption.

The goal of the research was to stabilize the sheet resistance Rsh within the required uniformity by adjusting appropriate process parameter(s) (e.g. the working point Ei or sputtering power Psp). This should again be done by using information obtained rather directly from the coating chamber R8 than from the distant measurement compartment R9. The sum of reactive gas (oxygen) flow QO_2 was identified to be a suitable 'direct' information.

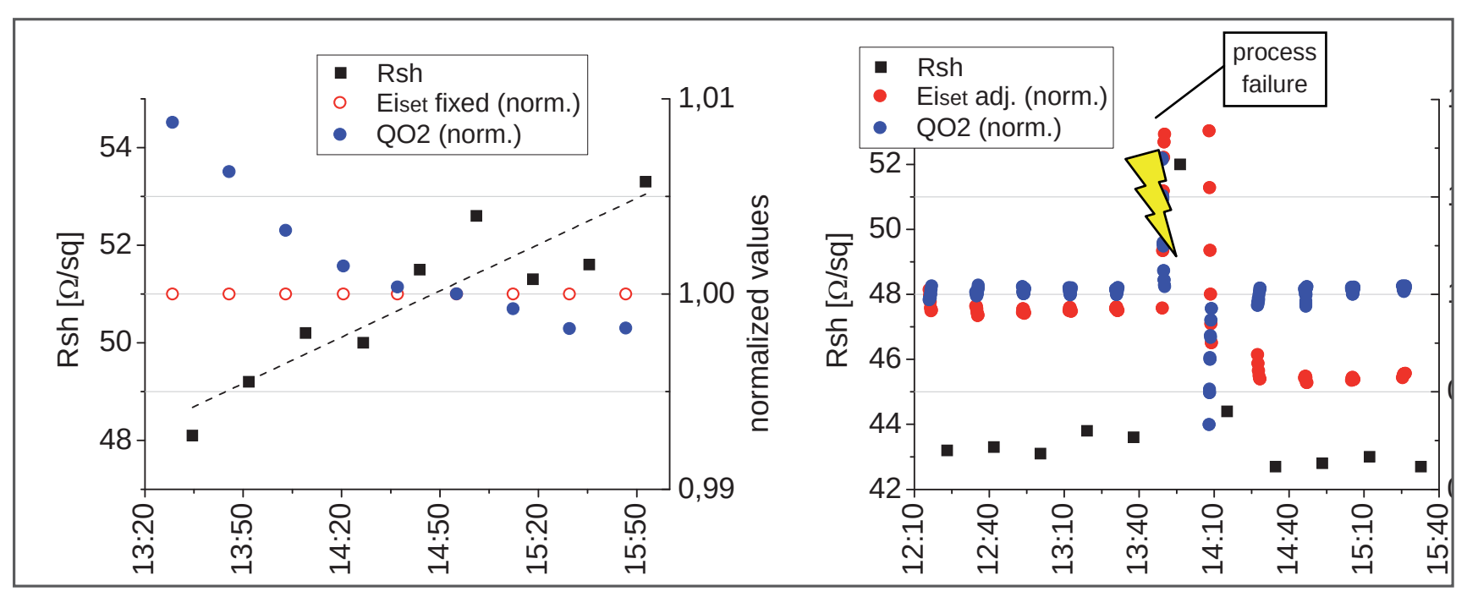

Figure 18: Long term experiments of ZnO:Al deposition (left: without readjustment / right: adjustment of working point Ei active) Resistance was measured approx. 7 minutes after start of process (dead time)!

The prototype of an APC readjustment of the fast control loop (scheme see fig. 17) consist of two paths:

- inner: adjustment of the working point Ei in dependence of the oxygen flow QO_2, which contains recursive parts and is robust enough to bear an adaption of its parameters, and
- outer: tuning the setpoint of the inner path QO_2 set in dependence of the sheet resistance Rsh (measured with considerable dead time).

Therefore this prefiguration is (also) especially suitable for discontinuous deposition processes.
This design was proven to be effective in several long time experiments (see fig. 18):

- without any active readjustment showing the undesired drift of sheet resistance;
- with active inner path only resulting in an already sufficient uniformity of sheet resistance;
- with both paths active yielding in even better uniformity.

CONTACT

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