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Modeling and Control of Reactive Sputter Processes

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1 Introduction

Aim of the project is to develop methods for modeling, actuating, measuring and controlling low pressure plasma driven processes. Plasmas are mixtures of atoms, molecules and charged particles that are electrically neutral towards the outside. Low pressure plasmas operate at around 1 Pa and have a degree of ionisation of 10^{-5}. The mean heavy particle temperature complies with room temperature, but the mean electron energy reaches 30000 K. This pressure and temperature conditions enable surface treatment of anorganic and organic materials. This project will focus on deposition processes to create thin film layers. The deposition of thin film layers is described in the following.

2 Deposition Processes

Modern industrial products are increasingly refined by thin layers, which enable physical features that thick layers cannot sufficiently provide. Examples of thin film products include optical reflective layers, corrosion resistance layers, superconductive layers, hard coatings, magnetic coatings and integrated circuits. The technological processes for the generation of thin films require a vacuum in order to deposit solid components from a gas phase. Basically, there are two different process types in thin film technology:

- In **Chemical Vapor Deposition** (CVD) the material to be deposited is transported in a carrier gas, decays at the heated substrate area and build up a thin layer at the substrate. Weak point of this process type is the fact that the required precursor gases concerning metal or ceramic layers are often not realizable.

- The **Physical Vapour Deposition** (PVD) based on the sputtering of atoms from a solid object, the target, relinquished chemical reactions and is, therefore, not subject to the above mentioned restriction. In Physical Vapour Deposition the material to be deposited is located in the target solid body. The target is bombarded by ions of a non reacting working gas, which is usually argon. The ion current on the target caused by a plasma discharge leads to the sputtering of atoms from the target and in consequence to a flow of atoms from the target surface to the substrate surface. Figure 1 shows an experimental reactor for PVD processes.

In addition, PVD can be enhanced by one or more reactive gases to deposit more complex stoichiometries. This process type, called **Reactive Sputter Deposition** (RSD), is currently object of a research collaborative by the Institute for Electrical Engineering and Plasma Technology, the Institute of Theoretical Electrical Engineering and the Institute of Automation and Computer Control of the Ruhr-University Bochum.

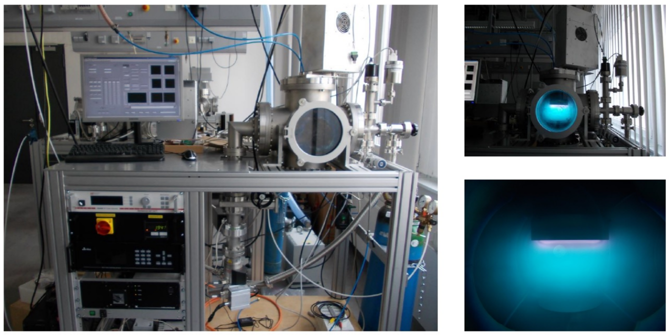

Figure 1: Experimental reactor (left) and plasma ignition (right)

3 Process Steps

The deposition process is a batch process with five process steps:

1. Goal of process **start-up** is to establish advantageous operating points for the plasma ignition and thin film growth, for example working pressure, surface temperatures, magnetic field configuration, matching conditions et cetera. These operating points are not necessarily the final operating points of the next process steps. Physics and control are comparatively simple at this process step and known modeling and control methods can be applied.

2. Next step is **plasma ignition and non steady state thin film growth**. During this phase process drifts occur because of couplings of subsystem (gas system, temperature system, et cetera) due to the plasma ignition (figure 2). These couplings lead to a non-linear system behaviour. Moreover the thin film properties change even at steady state plasma respectively subsystem working conditions.

3. Once **steady state thin film growth** shows, main task is to ensure process stability and suppress external disturbances. The project focuses on this process

step in order to find a correlation between particle energies and masses towards substrate and the achievable thin film properties combined with feedback control.

4. Last step of in-situ process control is process **shutdown** to extract the grown thin film. The shutdown consists of a high-precision timed shutdown of the plasma and closing a shutter in front of the substrate to prevent possible contaminations.

5. If an **ex-situ process control** is needed, because important control variables are not measurable in-situ, the grown film can be analysed to predict reference variables for the next run.

Recapitulating from a control orientated point of view the process may be characterized as a non-linear hybrid system with a continuous in-situ control loop and a discontinuous ex-situ control loop. Aside from fragmentary models only very limited sensor signals are available in-situ. Moreover sensor probes only work in restricted process operating points or otherwise permanently fail, which also brings in concepts of fault tolerant control.

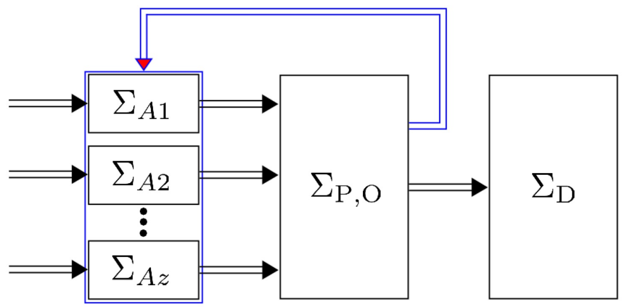

Figure 2: Crosscouplings between actuator systems Σ_{A_i} due to plasma ignition feedback starting from the plasma-surface system $\Sigma_{P,O}$. Σ_D describes the thin film formation

4 Project Aims

Although PVD and RSD have become indispensable in today's industry, the primarily focus of general research is on physical aspects of the processes. However advanced control methods are largely disregarded due to the lack of appropriate models and real-time diagnostic methods. Because of this state of research industrial applications have to be run in open loop or with heuristic feedback control, which leads to constraints in the accessible thin film quality and deposition rates. So the basic objective of this research project is to lift these restrictions and to enable a model-based feedback control of PVD and RSD.

Project Steps

1. Model

In order to run Reactive Sputter Processes by model-based control it is necessary to build a model of the overall process. The overall process consists of actuator systems, the plasma discharge, the plasma-surface interaction, the film formation and sensor systems. A first approach [1] to modeling of a reactive titan sputter process describes the main process mechanisms. It can be shown that the current models mainly describe the static behaviour rather than the dynamic behaviour of the system. Therefore, the first project aim provided by the Institute of Automation and Computer Control is

- **to develop a control orientated dynamic process model.**

For development and optimization of reactor concepts highly nonlinear scale models are needed, which focus on physical phenomena of the plasma discharge. So, the second part of the first project aim provided by the Institute of Theoretical Electrical Engineering is

- **to develop a physical orientated self-consistent global model of the plasma discharge.**

2. Experimental Setup

On a related note an experimental setup is required for parameter identification, validation of developed models and proving of the implemented control systems [2]. Thus the second project aim provided by the Institute for Electrical Engineering and Plasma Technology is

- **to develop an experimental setup with focus on real-time capable sensors.**

3. Control

Closely related to these two aims open loop and feedback control have to be realised. Based on the developed model and experimental setup control orientated analyses are needed to determine a control structure and define control procedures. Hence the third project aim provided by the Institute of Automation and Computer Control is

- **to realise open loop control by use of an electrical interface and process control system,**
- **to identify process parameters,**
- **to perform control orientated analyzes and**
- **to develop MIMO feedback control systems.**

This being the case, the overall goal is to ensure a stable growth process under well defined energetic conditions, which cause the desired thin film properties in a stationary deposition process.

References

[1] Woelfel, C.; Oberberg, M.; Lunze, J.; Awakowicz, P. *Control orientated modeling and analysis of a reactive (O2) sputter (Ti) process*, WELTPP-18, Kerkrade, 2015.

[2] Woelfel, C.; Oberberg, M.; Krueger, D.; Lunze, J.; Brinkmann, R.P.; Awakowicz, P. *Nutzung von Plasmadiagnostik zur Regelung eines reaktiven Sputterprozesses*, 23. Dresdner Vakuumtechnische Kolloquium (NDVaK) Beschichtung und Modifizierung von Kunststoffoberflächen, Dresden, 2015.