Novel Control Schemes for PIAD Processes

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Plasma ion assisted deposition (PIAD) employing the Advanced Plasma Source (APS) is an important tool for the production of high quality optical interference coatings. Until present PIAD processes rely on recipes based on layer properties while there is still little knowledge on the plasma state. This paper gives a brief overview of first results on the development of concepts for control of the plasma source based on radiance monitoring. It is shown that quality and repeatability of a sensitive PIAD process (TiO_2 deposited at low plasma assistance) can be improved significantly compared to conventional control schemes.

1. Introduction

In various optical applications like imaging, metrology or laser technology interference coatings are required to provide specific spectral properties, e.g. for lenses, beam splitters or mirrors. Plasma ion assisted deposition (PIAD) is a technique offering a high level of flexibility in an area of opposing demands of high throughput on the one hand and high quality and repeatability on the other hand[1]. In PIAD, gridless plasma sources are employed that generate an energetic ion component to assist the growth process of various oxides and fluorides where typically the material is evaporated from crucibles by an electron beam. Until today, PIAD processes are configured according to recipes which were developed by empirical means based on layer properties. Increasing demands on quality and repeatability has driven this technological field to direct attention also on plasma properties and related methods for in-situ based control schemes. This conference paper shall give a brief overview on first results for novel concepts for radiance monitoring and control of a PIAD plasma source.

2. Experimental setup

The experiments were carried out in an industrial PIAD box coater equipped with a plasma source and an electron beam evaporator (Fig.1). This device serves as an experimental environment for detailed diagnostics of plasma properties [2]. For the results presented here, the setup for optical emission spectroscopy is the relevant one.

2.1. Advanced Plasma Source

The Advanced Plasma Source (APS) [3, 4] is a hot cathode DC glow discharge with an auxiliary magnetic field. Fig.1 gives an impression on the design of the source. The fundamental parameters of the source are gas flux Γ (typ. Ar + O_2), chamber pressure p, discharge voltage V_D and current I_D, anode voltage vs ground V_A, coil current I_C and cathode heating power P_H. An overview of plasma properties of the APS plume and dependencies

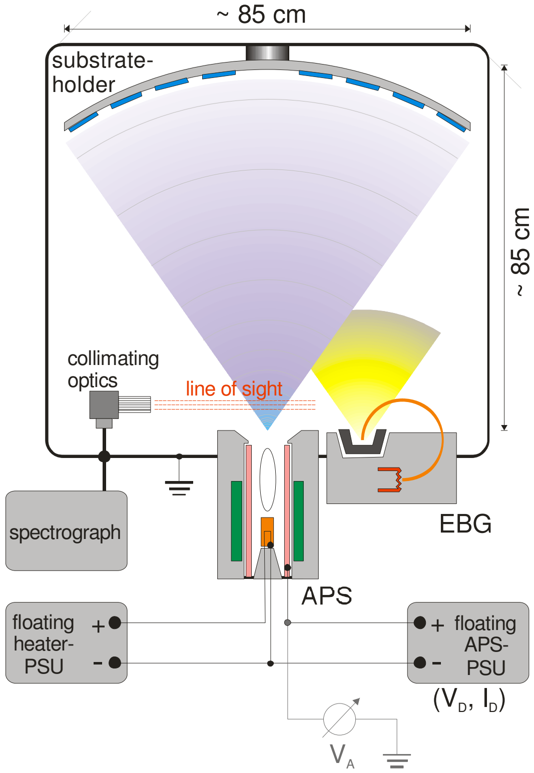

Fig. 1: Scheme of the box coater equipped with plasma source (APS), electron beam evaporator (EBG) and diagnostics (OES).

on the control parameters can be found in [2]. The APS generates an ion beam with particle energies of E_i=50..150eV due to plasma expansion. Part of the fast ion population emitted from the source is transformed into fast neutrals by resonant charge exchange with the background gas (typ. p≈20mPa) [5]. The DC concept using LaB_6 as cathode material on the one hand is found to be highly efficient – a degree of ionization in the source volume close to one has been confirmed recently [6] – but on the other hand it is characterised by drift behaviour during operation that requires to adopt dedicated control schemes.

2.2. Optical emission spectroscopy

The state of the source plasma in terms of optical emission is monitored by a system consisting of in-vacuum collimating optics and a broadband spectrograph. The optical head is placed in the chamber such to provide a horizontal line of sight right above the APS exit (Fig.1). It is oriented in a way to avoid recording of light from reflections or the EBG. For operation in deposition processes it is equipped with a multi-capillary aperture.

The compact spectrograph is an Avantes USB2-device featuring a nominal spectral range of about 200-1100nm at a spectral resolution of $\Delta\lambda_{res}\leq 1$nm which is sufficient to resolve the dominant emission lines in the argon/oxygen plasma. A homogeneous light source Labsphere USS-800S-035 is employed for absolute radiance calibration in the range $\lambda\in[300;1000]$nm.

2.3. Layer preparation and characterisation

As PIAD process a single layer of TiO_2 of thickness d=200nm deposited at a rate of 0.2nm/s is chosen. The stoichiometry of the layer material is obtained by evaporation of Ti_3O_5 and admixture of oxygen to the plasma through a gas inlet at the APS exit. TiO_2 is an ideal material for studies on the impact of plasma parameters on layer properties. Depending on ion energy and flux it features a pronounced transition of high porosity, low refractive index and tensile stress to compact, high index and compressive stress. For this study the APS configuration is chosen in a range were the variation of refractive index is most sensitive. For the gas fluxes of Γ_{Ar}=17sccm and Γ_{O2}=20sccm this is the case when $V_D\approx 65$V. Layers are prepared in series of 6 samples for each control method where the initial configuration uses a clean anode tube. Besides drifts of process parameters that may occur during one run, this approach addresses the run to run variation by changes due to the state of the process environment (impact of source condition, venting, etc.).

B270 glass substrates which a roughened on the backside are placed on the substrate holder at mid radius. This sample type is used to minimize backside reflection in ellipsometric analysis of layer properties. The measurements are carried out with a Woollam M-2000 spectroscopic ellipsometer. In order to obtain a good fit of ellipsometric parameters Ψ and δ we use a Cauchy model for the substrate, that is determined once on an uncoated sample, and a general oscillator model which is extended by surface roughness and grading of layer properties.

3. Concepts for plasma control

In a standard setup of a PIAD process employing the APS the operator is limited to settings of external parameters of the plasma source such as gas fluxes, electrical currents or voltages of the discharge or heating power delivered to the cathode. By external we mean that there is no explicit information about internal plasma parameters. In our experiment, settings on gas fluxes are kept fixed. Changes of electrode properties, i.e. coating of the anode tube or variation of electron emission of the cathode by oxygen poisoning or variation of temperature, result in a drift of working parameters. Conventional control methods are focussed on the APS parameters V_D, I_D, V_A and I_C. A voltage-current pair may be kept fixed where the two remaining parameters are the dependent ones.

We chose two of the conventional concepts. In the V_A/I_C approach a value of I_D is set and the coil current, i.e. the magnetic field, and discharge voltage are adapted to obtain the desired anode voltage. Since V_A is closely linked to the mean ion beam energy [2] and $I_D(U_D)$ is very sensitive on I_C, this method is often employed in production processes. Another concept (V_D/I_D) is to keep I_C and V_D fixed such that I_D and V_A adjust to values of a stable working point. From a basic physical point of view V_D and I_C may be regarded as fundamental parameters which primarily determine electron energy and electron transport. Electron kinetics in turn has a strong impact on the topology of the plasma potential which causes the formation of an ion beam. Further, as was shown in previous studies [2], the discharge current is not directly linked to the plasma beam properties.

For the first time regarding PIAD we have implemented control schemes which are based on in-situ monitoring of optical emission from the source plasma. The determination of plasma parameters like electron or neutral kinetics from OES data is a difficult task and requires complex collisional radiative modelling. First results on an argon plasma are described in [6] but the model employed needs substantial refinement for application in a coating process. The two control methods presented here are based on comparison of experimental data on electron and ion kinetics and optical emission. The state of the cathode being influenced by external heating power P_H was found to primarily affect mean electron energy [7]. A variation of electron energy, in particular the high energy part, has a strong impact on argon ion emission due to the high threshold energy for electron impact excitation. As a robust monitor signal a ratio of certain argon neutral and ion line radiances L_{ArI}/L_{ArII} was chosen. We operate the APS in V_D/I_D mode, but vary P_H such that L_{ArI}/L_{ArII} reaches a reference value, abbreviated as L_{Ar}/P_H. The variation of P_H during the deposition process is a rather unconventional approach and not intended by factory control algorithms.

The second OES-based algorithm uses the V_D/I_D mode for the APS at fixed P_H, but varies the target V_D such to obtain a reference value of oxygen radical emission: L_O/V_D. With the focus on absolute radiance data as a parameter for monitoring, the concept may be more prone to drifts due to changes in spectral sensitivity of the collecting optics compared to a line ratio technique.

4. Results and discussion

In order to apply in-situ OES based control schemes the factory control setup had to be augmented by input channels and measures to smoothly adjust APS parameters. Appropriate proportional-integral-differential control concepts were employed. Figures 2 and 3 illustrate the level of accuracy and typical behaviour of the control parameter pairs for the methods L_{Ar}/P_H and L_O/V_D. The argon line ratio can be kept at a value very close to the reference by strongly changing P_H (Fig.2). Not shown here is the variation of L_{ArI}/L_{ArII} in the conventional cases which shows excursions from the reference value in the order +/-5%. L_O is very sensitive to V_D such that slight changes are sufficient to keep it close to the target value. In general we found that the novel control schemes did not impose problems with respect to the stability of the PIAD process with the exception that the level of P_H partly resulted in initial oxygen poisoning of the cathode which is an issue unacceptable from the industrial application point of view.

For a brief description of the impact of control scheme on layer properties and repeatability of the PIAD process we restrict this presentation to the refractive index (Fig.4) and level of inhomogeneity of the layer (Fig.5). The layers deposited with the conventional approaches show similar absolute values for n and Δn. With the latter result we find a 1%-level of repeatability at present understood to be characteristic for PIAD. The conventional methods obviously differ in the level of density grading. It seems that the densification of layers is more constant during the deposition phase in V_A/I_C than in V_D/I_D mode. This result can be interpreted as a confirmation of V_A as a fundamental PIAD parameter.

For the OES based schemes we find two trends. While the L_{Ar}/P_H approach results in lower quality, i.e. more pronounced inhomogeneity, and lower repeatability, the opposite is the case for L_O/V_D. Probably the reduction of P_H resulted in a drop of ion beam flux as well (see also [2]). This result shall however not serve as an argument to abandon the idea of controlling mean electron energy: control of L_{ArI}/L_{ArII} by V_D remains as an option for future studies. The constant level of oxygen radical radiance on the contrary seems to indicate a stable plasma performance. The lowest value of Δn is obtained and grading is comparable to the V_A/I_C case. Larger values for n may be obtained by increasing V_D, i.e. in the framework of this concept, a higher setpoint for L_O.

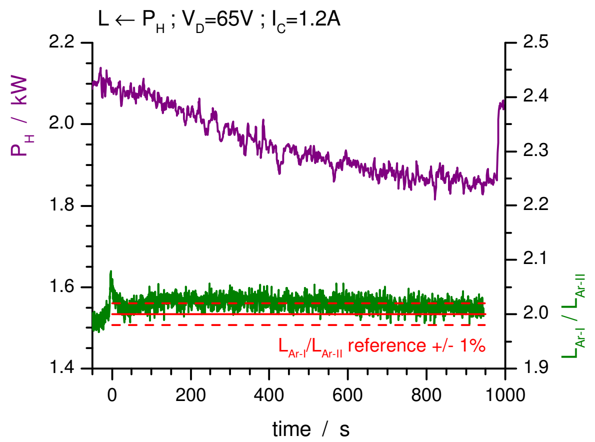

Fig. 2: Time traces of cathode heating power and radiance reference signal in L_{Ar}/P_H controlled deposition phase.

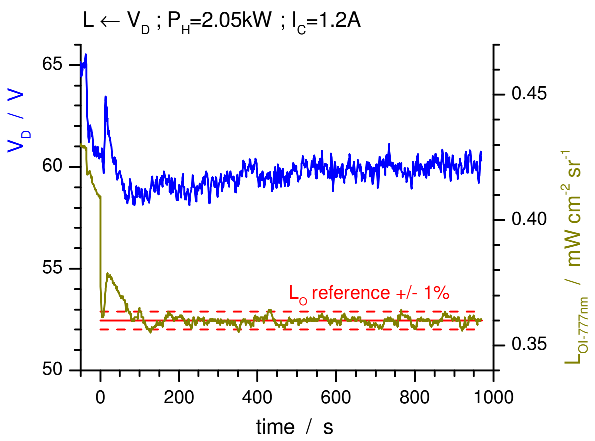

Fig. 3: Time traces of discharge voltage and radiance reference signal in L_O/P_H controlled deposition phase.

Our interpretation of these first results is that radiance monitoring is a reasonable candidate for characterisation of the source plasma. The complexity of emission spectra regarding its relationship to electron and neutral kinetics probably impedes the restriction to single spectral features. Further, the relationship of plasma parameters and external parameters is not completely resolved yet. Our first impression is that a variation of V_D is more beneficial than changing P_H. However, the latter is still thought of as a useful control variable that directly affects electron emission of the cathode. This is an important issue in particular when considering a runtime of industrial multilayer processes of many hours and reduction of cathode volume over its lifetime.

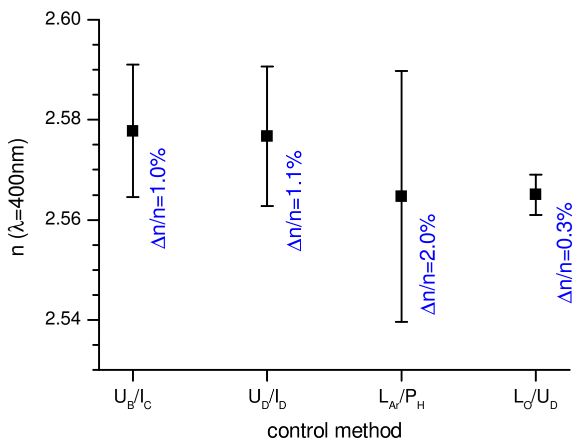

Fig. 4: Resulting absolute value and variation of refractive index obtained for deposition series using different control methods.

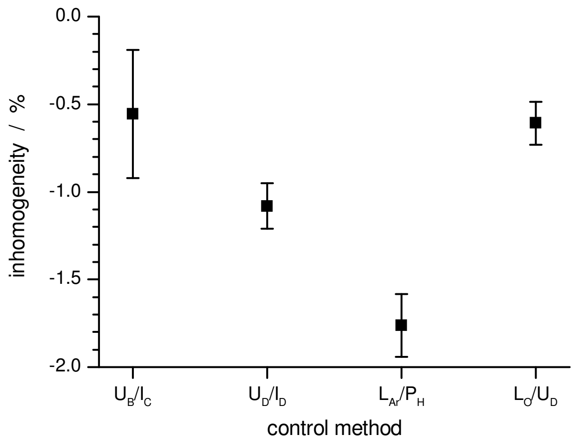

Fig. 5: Level of inhomogeneity obtained for deposition series using different control methods.

5. Summary and Outlook

PIAD employing the APS is a well-established tool for the production of optical coatings. Demands for improved quality, repeatability and yield have drawn attention towards detailed analysis of plasma parameters. Based on the present knowledge of APS plasmas we have implemented a system of radiance monitoring and control of the plasma source. Although the concepts developed are still quite simple, since only single spectral features are considered and single APS parameters are used as control variables, the results show that improved stability may be achieved compared to conventional methods. This is the case for the concept of adjusting discharge voltage such to maintain a reference level of oxygen radical radiance at the APS exit.

For the sake of robustness of diagnostics in an industrial environment the measurement of absolute radiance might be given up in favour of line ratio techniques. Radiance monitoring in this respect would be focussed rather on electron energy than density. An important development in the field of in-situ plasma diagnostics of electron density is the multipole resonance probe (MRP) which has been employed for tentative experiments in PIAD recently [8]. Our main goal of future work on PIAD is to combine OES and MRP to provide a detailed view on plasma properties during the deposition process and to setup control schemes suited for industrial demands.

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