Applied Physics Letters

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Cite as: Appl. Phys. Lett. **102**, 221604 (2013); https://doi.org/10.1063/1.4807793
Submitted: 21 March 2013 . Accepted: 11 May 2013 . Published Online: 07 June 2013

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APPLIED PHYSICS LETTERS **102**, 221604 (2013)

Towards an electro-magnetic field separation of deposited material implemented in an ion beam sputter process

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(Received 21 March 2013; accepted 11 May 2013; published online 7 June 2013)

Nowadays, Ion Beam Sputter (IBS) processes are very well optimized on an empirical basis. To achieve further progresses, a modification of the IBS process by guiding the coating material using an axial magnetic field and an additional electrical field has been studied. The electro-magnetic (EM) field leads to a significant change in plasma properties and deposition rate distributions, whereas an increase in deposition rate along the centerline of the axial EM field around 150% was observed. These fundamental studies on the prototype are the basis for the development of an applicable and workable design of a separation device.
[http://dx.doi.org/10.1063/1.4807793]

During the last decades, rapid growth in scientific research and industrial development of laser technology imposed ever increasing demands on optical thin film technology. For example, high precision interferometric laser measurement techniques require lowest loss optics.[1] State of the art dielectric optics with absorption values in sub ppm regimes at near-infrared (NIR)-wavelengths is indispensable for these laser applications. Currently, Ion Beam Sputtering (IBS) reaches highest-quality standards in optical thin films, allowing the production of lowest loss coatings in terms of scattering and absorption.[2] The IBS process has been highly optimized on an empirical basis to a high quality level. However, possibilities for further developments might be achieved by new fundamental optimization strategies. Considering typical losses in bulk materials, which are still orders of magnitude lower than in the corresponding coatings, an apparent potential for additional improvements can be expected. As a consequence, fundamental changes in process concept must be explored to achieve coatings with even improved properties.

An approach for improvements in coating quality is a well-defined control of the energy and species of adatoms forming the layer structure. In this context, topographical inclusions as a major origin of absorption and scatter losses in thin films can be traced back to macro-particles generated in the coating process itself. Therefore, besides a control of deposition species, a mitigation of macro-particles would offer a variety of advantages.

Our concept for an appropriate control and mitigation strategy in IBS processes is based on theoretical and experimental investigations in Filtered Vacuum Arc Deposition (FVAD) using bent magnetic or electrical filters in order to separate the cathode plasma flow from the so called macro-particles of the cathode material according to Aksenov *et al.*[3,4] In this concept, the cathode is equivalent to the target in IBS process. The applied magnetic field strength can only exert influence on charged particles of the deposition species. Due to their high inertia, the macro-particles are weakly influenced by the field, and they are moving along nearly straight lines contrary to the trajectory of the adatoms within plasma. Therefore, the unwanted particles are separated from the subsequent deposition process in this way.[5] In addition, the energy and species of deposited adatoms can be controlled by the parameters of the magnetic or electrical filter.

The purpose of this study is to evaluate the potentiality of electro-magnetic (EM)-guidance for an improvement of IBS coatings. The experiments are carried out in a specially constructed IBS unit applying a commercial Veeco high power ion source. The curvilinear shape of the magnetic field lines used to guide the ionized sputtered material is formed by a solenoid with a diameter of 25 cm. In the solenoid, a maximum magnetic field strength of 23 mT is achieved by applying a current of 300 A, which generates an axial magnetic field parallel to the target. The solenoid is bent slightly into a V shape with an angle of approximately 140° and allowed a line-of-sight trajectory from the target to the end of the solenoid. The opening of the first section of the solenoid (pre-collimation coil) is located 5 cm in front of the ion source collimating the ion beam onto the target. The second section of the solenoid collimates the sputtered species emitted from the target and guides it onto the substrate to be coated. The pre-collimation coil between the source and the target has 11 turns, with a total length of 10 cm, and the second part has 20 turns with a total length of 30 cm (Fig. 1).

When the pre-collimation coil is actuated, the electrons generated by the neutralizer are led into the pre-collimation coil and were guided along the magnetic field lines until they partially impacted perpendicularly on the target surface. In order to improve the efficiency of the guidance, i.e., to enhance the deposition rate, a bias plate is mounted.[6] The bias plate is formed as a curved strip, which covers a quarter of the solenoid's interior at the top. It is electrically insulated from the solenoid and kept at a DC bias voltage of approximately 80 V during the measurements.

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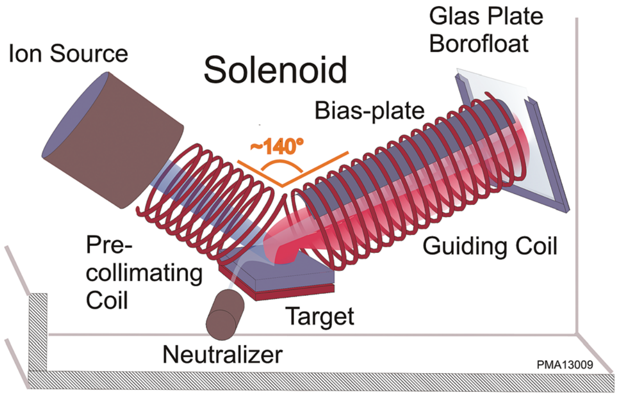

FIG. 1. Schematic drawing of the set-up.

In particular, the first study is focused on deposition experiments, measuring field-induced changes in the coating rate and the lateral distribution of coating material on substrates. Silicon, Tantalum, and Titanium are used as target materials. Silica, the established low index material, as well as Titania and Tantala, as high-index materials, were found to be promising candidates for low loss optics.[1] The coatings are produced under reactive conditions by injecting oxygen in the chamber during coating process.

In the center position of the solenoid outlet, the deposition rates are measured using a QCFO (Quartz-Crystal Frequency Oscillator), and the plasma conditions are analyzed using an RFA (Retarding Field Analyzer) to provide information about energy distribution and relative ion density of the plasma.

The experiments are mainly focused on investigations in the influence of the EM-fields on the coating material guidance.

The effect of the magnetic field on the plasma at the center of the solenoid exit is measured using an RFA. Fig. 2 shows the energy distribution of the ions during reactive sputtering of Titanium and Silicon, respectively.

It is observed that higher coil currents generate a shift of the maximum of the plasma energy distribution towards higher energies. Additionally, the measured energy distribution of Silicon resides partially in the negative regime. This irregularity may be caused by an energy offset based on a negative floating potential with respect to the plasma potential. This offset is created by the dielectric coating settling on the RFA aperture during subsequent measurements. Generally, the energy distributions cannot be interpreted in respect to a complete quantitative evaluation of the energy distribution. However, the integral of the distribution is proportional to the total ion current, and thus a measure of ion density for the plasma. Fig. 3 displays the ion current density during reactive sputtering under two different solenoid configurations for Silicon, Tantalum, and Titanium as a function of coil current, respectively.

These results indicate the influence of the pre-collimation coil. Concerning the curves of the total ion current, involving Silicon and Tantalum, the pre-collimation coil is deactivated. The curves for the Titanium target are measured with activated pre-collimation coil, as in experiments described before. The total ion currents of Titanium exceed the values of Silicon and Tantalum, significantly. The gain in total ion current of Titania can be traced back to the influence of the pre-collimating coil, which creates further magnetic field lines. These magnetic field lines form a superposition with the field lines from the guiding coil and an extension of the axial magnetic field lines. This extension in turn results in an amplification of the guiding effect. In general, the presence of the EM-fields leads to significantly higher total ion currents at the end of the solenoid. Without the EM field, the ion density flux is in the range of the detection limit of the RFA and rises with an increasing magnetic field continuously by more than one order of magnitude. The change in plasma density may be attributed to the ionization of the inert sputter gas Argon as well as the coating material. In the present experimental set-up, a separation of the ion species is not possible. Further information can be extract by comparison with QCFO and the properties of the produced coatings.

Titanium deposition rates are measured by arranging a QCFO centered to the exit of the solenoid. The QCFO is mounted at the position of the RFA. The method can be used

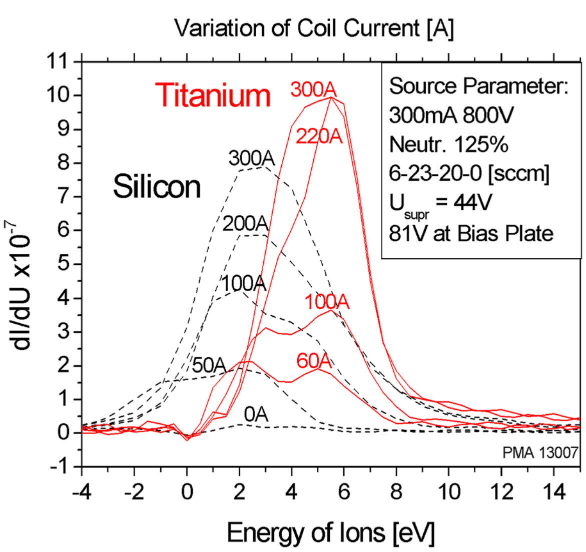

FIG. 2. Energy distribution of plasma at the exit of the solenoid in dependence of the EM field during reactive sputtering of Silicon and Titanium.

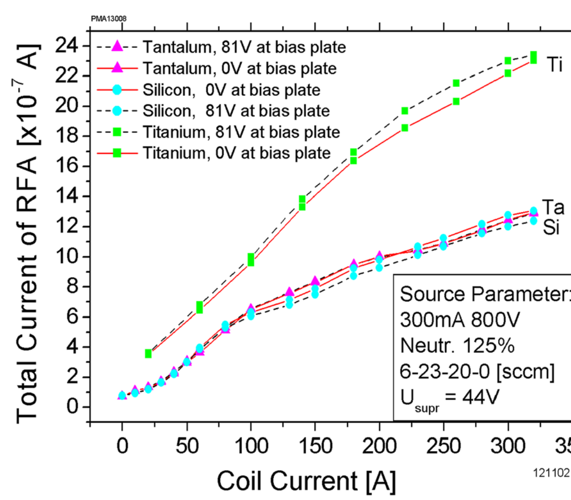

FIG. 3. Total ion current of the plasma at the exit of the solenoid in dependence of the EM field during reactive sputtering of Silicon, Tantalum, and Titanium under two different solenoid configurations.

to determine the total rate of neutral and charged species. The QCFO measurements correlate well with the results of RFA measurements. There is a significant gain in the deposition rate by a factor of 1.5 compared to the case without EM fields. This increase in deposition material along the centerline of the solenoid is also indicating a guiding effect caused by the EM field.

A complete picture of the EM field influence on the deposition can be attained on the basis of the lateral distribution of the coating material at the exit of the solenoid. The absolute thickness of the film is determined by evaluating transmission spectra at a well-defined measuring position using a spectral photometer. Planes ($230 \times 230\,\mathrm{mm}^2$) of Borofloat 33 glass from Schott are employed as substrates for these measurements. In all experiments, stable source parameters ($I_{Source} = 300\,\mathrm{mA}$ and $U_{Beam} = 800\,\mathrm{V}$) and stable gas conditions are adjusted. The results of the coating experiments are displayed in Figs. 4(a)–4(c) for Titania. In detail, Fig. 4(a) displays the background without an EM field; Fig. 4(b) shows the influence of the magnetic field and Fig. 4(c) the resulting thin film thickness distribution applying an EM field, respectively. The magnetic field causes a change in the spatial distribution of the coating material and leads to a significant increase in the deposition rate from $r_{max} = 0.028\,\mathrm{nm/s}$ to $r_{max} = 0.039\,\mathrm{nm/s}$. The electrical field of $U_{Bias} = 80\,\mathrm{V}$ induced an additional increase to $r_{max} = 0.053\,\mathrm{nm/s}$ for Titania. Such an increase in the deposition rate is in accordance to a previous study of Kwok *et al.*[6] In the experiments presented here, the relative patterns of coating material do not differ from those with an induced electric field; only the efficiency of the process increases. This fact can also be observed in the photocopies of the coatings, which are attached to the corresponding diagrams.

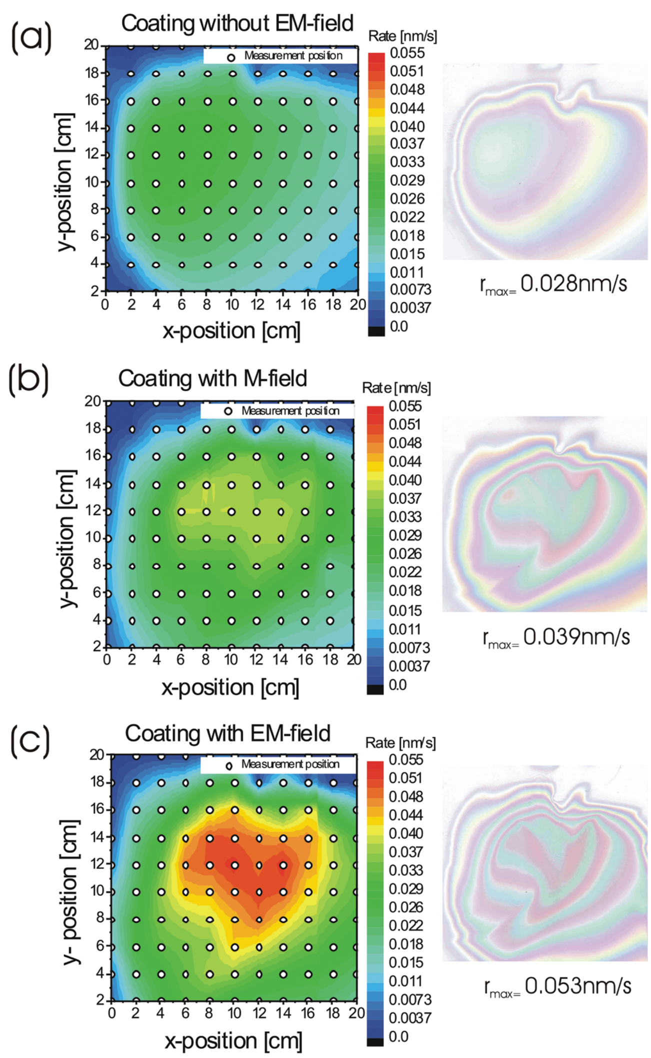

FIG. 4. Left image: 2D distribution of TiO_2 deposited on a glass plate at the exit of the solenoid after a deposition time of 4 h, right image: photocopy of the glass plate.

It has to be mentioned that measurements with Silicon as target material are conducted as well. Without the EM fields, in general Silica shows a higher value than Titania in deposition rate, which accounts for 0.048 nm/s. The local gain factor for the deposition rate of Titanium is calculated to be 1.89, whereas the gain factor for the deposition rate of Silica is nearly 1.34. These results indicate a dependency on the coating material, which originates from strongly different physical properties of each species (for instance: ionization energies).

Furthermore, investigations in the guidance of the total ion current are carried out by varying the current of the ion source. At the exit of the solenoid, the total ion current shows an increase approximately proportional to the source current, while keeping the coil current constant at 300A. Additionally, the influence of oxygen is investigated. A reduction from 50 sccm to 20 sccm oxygen flow leads to a 60% increase in the deposition rate. This effect is caused by the gain of the sputter yield at the target, and consequently, the lateral distribution of the coating material on the substrate does not change.

In conclusion, a significant increase in deposition material is achieved along the centerline of the solenoid, which indicates that the sputtered material is guided by the EM fields. RFA and QCFO measurements confirm an increased flux of ions and sputter material and thus guidance using the solenoid. Consequently, the control of coating material fluxes using EM fields is applicable in IBS processes. The study opens new ways to set up a practicable separation device for investigating and optimizing thin film layer growth in IBS. In contrast to FVAD, in which deposition material reaches a high degree of ionization in the plasma near to almost 100%,[7] the sputtered material of IBS coatings is believed to be hardly ionized. Typical ratios are estimated in a range from 10^{-4} (Ref. 8) up to a small percentage, depending on consistence and configuration of the target (metal or oxide).[9] In this context, further investigations of the degree of ionization in modified IBS process are intended. An additional step comprises the evaluations of high quality fused silica substrates with regard to the particle density and a proof of reduction of macro particles, which could not be verified in the framework of this preliminary study yet.

This work was financially supported by the Deutsche Forschungsgesellschaft (DFG) within the cluster of excellence 201 Quest.

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