High ion current density plasma source for ion-assisted deposition of optical thin films

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A plasma source utilizing direct current (DC) voltage between an anode and a hot hollow cathode is employed to create high-density plasma. Plasma spatial distribution, ion energy, plasma neutralisation, and current densities are found to be separately tunable. Ion current densities > 0.5 mA/cm^2 have been demonstrated over coating areas > 1 m diameter. The primary advantage of plasma, as opposed to the ion source approach, is its ability to fill in the vacuum chamber and the couple with evaporant. This induces partial evaporant ionisation, providing uniform ion-assisted deposition over extended coating areas. Optical thin film properties deposited using the adapted high ion current plasma source are likewise described.

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Ionised plasma-assisted deposition provides a processing method that allows dense stable optical coatings to be deposited at room temperature. Such ion- or plasma-assisted processes can be effectively used in the vacuum processing of thin film coatings during electron beam, thermal, or sputter deposition.

Energy imparted by source to growing film enables the modification of microstructure, producing dense, near-stoichiometric films that are significantly more impervious to temperature and humidity variations than normal electron beam-deposited films. Materials like titania can be consistently deposited with high refractive indices without substrate heating, as they are considered harder and more robust.

However, a major difficulty in using ion- or plasma-assisted processes for production is achieving necessary uniformity and reproducibility in deposited film optical properties, particularly, over extended areas. There are a variety of sources for ion[1−4] and plasma[5,6], all of which rely on the generation of electrons confined within a magnetic field to stimulate ionisation of a working gas. Neutralisation of plasma is required to avoid charging effects and plasma voltage, and hence, variation in ion energy and localised discharges within the vacuum chamber. The primary advantage of plasma compared to the ion source approach is that the former fills the vacuum chamber and couples into the evaporant, inducing partial ionisation.

With a plasma source, high-density plasma is extracted via an electromagnetic field, offering wide coverage over a large substrate area. Commercial demands on optical coating production drive the need for higher throughput processes for applications, such as flat panel displays, liquid crystal display (LCD) projection systems, and visible/thermal control coatings for low-cost imaging systems. Meeting these demands requires coating over larger areas at low temperature. Additionally, optical thickness precision control is required to provide the necessary optical coating spectral performance. Production implementation of such high-throughput/precision processes requires uniformity over extended areas and reproducibility on a batch-to-batch basis.

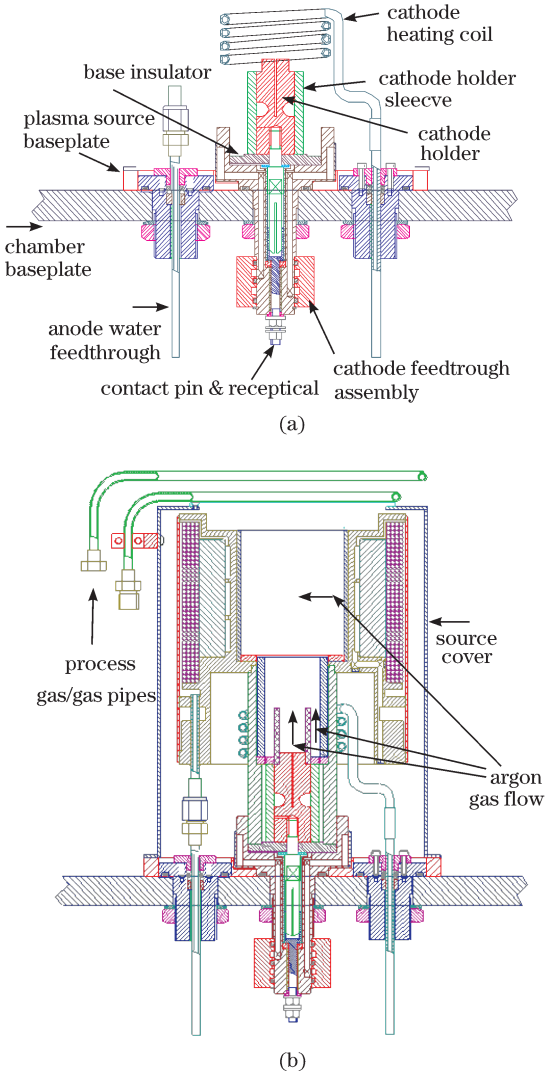

Fig. 1. (a) Plasma source base and cathode assembly, (b) cross section of plasma source showing cathode and anode assembly.

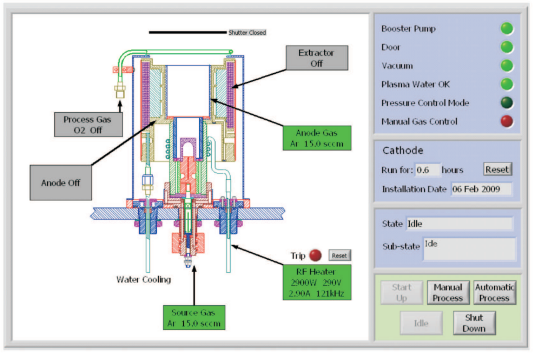

Fig. 2. Plasma source primary control screen.

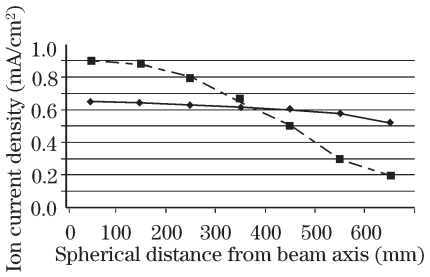

Fig. 3. Current density profiles at a spherical source to target distance of 50 cm using Ar for two extreme source running conditions. Source is located at the centre of baseplate.

(a) (b)

Fig. 4. Deposition system (a) chamber and (b) baseplate configuration showing the plasma source position with respect to electron gun sources.

As stated above, ionised plasma-assisted deposition[5,6] initiates a process that offers potential for large area coverage and low-temperature processing. The plasma source[6] described below provides a means for optimising spatial uniformity of plasma and hence, optical properties over extended areas. This is achieved without influencing other parameters necessary for reproducibility, primarily, ion momentum[7] and plasma neutralisation[6]. Construction and installation flexibility allows the plasma source to be placed at various baseplate positions to create optimal plasma.

Plasma source construction is demonstrated in Figs. 1(a) and (b). Figure 1(a) presents the assembly of cathode, comprising high-frequency (≈100 kHz) excitation of cathode emitter (lanthanum hexaboride) via a cathode heater coil. This generates thermionic electrons, ionising argon gas fed to both faces of the cathode, as shown in Fig. 1(b). This results in efficient plasma generation from all surfaces of the cathode emitter.

Evaporant plume overlap is observed for multiple material evaporation sources. The plasma source can be retrofitted into different coating system configurations.

Specific application of plasma source to ionised plasma-assisted electron beam deposition of precision colour separation edge filters over a coating area with 1-m diameter is described.

A detailed description of plasma source has been outlined in previous studies[6,8,9]. As demonstrated in Fig. 1, the plasma source features a modular construction containing various emitter configurations and output electromagnet coil geometries that are used to tune output plasma current density and spatial distribution for specific process requirements.

The source incorporates a thermionic emitter material heated by an induction coil, which likewise supplies radio-frequency energy within an electrically insulated cylindrical former. A cylindrical anode is concentric with the emitter and axially displaced, generating potential difference between anode and emitter. The potential difference between anode and ground and axial magnetic fields enables extraction of plasma from the source.

The induced axial magnetic field in the vicinity of the cathode (Fig. 1(a)) is de-coupled from a time invariant axial electromagnetic field at the anode (Fig. 1(b)). Plasma-confining magnetic fields within the anode and cathode regions provides a means for separate control of the plasma spatial distribution of plasma source within the chamber. This is achieved without influencing the momentum of ion, which is determined by the anode/cathode voltage, and plasma neutralisation, and determined by the cathode heater power to the electron emitter. As Fig. 1(b) illustrates, the decoupling of plasma-confining magnetic fields within the anode and cathode regions creates a means for separate control of the plasma spatial distribution within the chamber. This is achieved without influencing the ion momentum, as determined by the anode/cathode voltage, the plasma neutralisation, and the cathode heater power to the electron emitter.

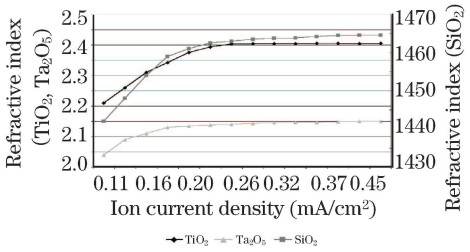

Fig. 5. TiO_2, Ta_2O_5, and SiO_2 refractive indices (@550 nm) as a function of ion current density.

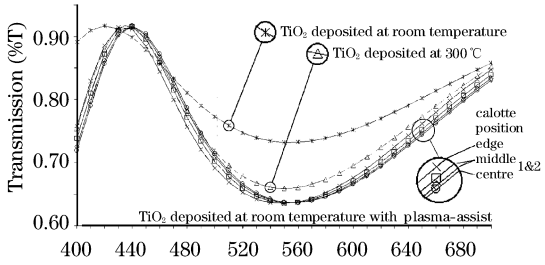

Fig. 6. Spectral transmission curves for TiO_2 deposited onto a hot substrate and cold substrates with and without plasma assistance.

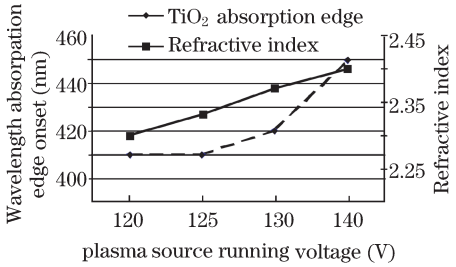

Fig. 7. Variation in TiO_2 refractive index and spectral position of absorption edge as a function of plasma source running voltage.

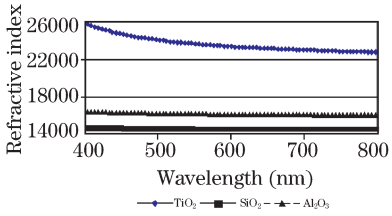

Fig. 8. Dispersion characteristics of plasma-assisted deposited TiO_2, SiO_2, and Al_2O_3.

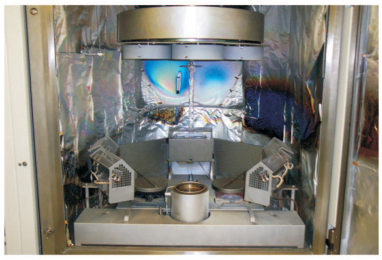

Fig. 9. Plasma source within a 1.2-m box coater configured with planetary tooling.

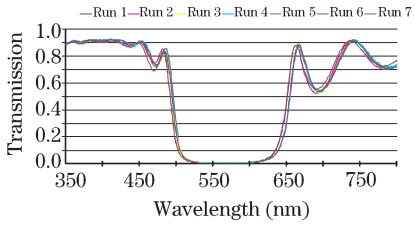

Fig. 10. Edge filter reproducibility (seven consecutive coating runs) for coating area edge position (coating area of 1.1-m diameter).

Reactive plasma is formed by injecting oxygen into the argon plasma at the output of plasma source (Fig. 1(b)), and is found suitable for the plasma-assisted deposition of oxide materials. Alternatively, nitrogen gas can be injected for the plasma-assisted deposition of nitride materials. And the width and height of the plasma source are 8 and 11 inch, respectively.

Additional boost in the plasma formation is achieved by the injection of additional argon into the anode region. The control of ion energy via voltage between the anode and cathode is attained by varying the argon flow to the anode region.

The source can be controlled either full-manually or automatically, and is linked with the main deposition chamber control system and water/pressure interlocks. Primary control screen is presented in Fig. 2. Specific running conditions for individual layers can be established through a recipe edit screen, while full data logging capability is enabled together with the ability to observe trends in selected parameters.

In this letter, the measurements of ion current density and ion energy were performed with Faraday cups and Langmuir probes, respectively. Figure 3 illustrates the ion current density for extremes of plasma source running conditions as a function of spherical distance from the beam axis for narrow (25° half-angle) and wide (65° half-angle) coverage. Ion energy typically corresponds to 60% of the anode to earth voltage.

Experimental work was conducted in a Satis 380 box coater equipped with a plasma source located halfway between the electron gun positions, as demonstrated in Fig. 4. The chamber was pumped by a Pfeiffer 2000 s^{-1} turbo pump supplemented by a Meissner baffle for efficient water pumping. Film thickness and deposition rate monitoring was conducted via a commercial deposition controller. Two 6-kW electron beam sources were employed for the evaporation of coatings. The properties of various single films were characterized using various plasma conditions and material evaporation rates.

Variation of TiO_2, Ta_2O_5, and SiO_2 refractive indices (@550 nm) as a function of ion current density is presented in Fig. 5. Data indicates a threshold value at which constant refractive index is achieved. This result is in accordance with the requirement for minimum ion/adatom ratio to achieve film densification for a given material deposition rate. Deposition rates for TiO_2, Ta_2O_5, and SiO_2 are 6, 8, and 10 A/s, respectively.

The TiO_2 films which were evaporated at various deposition rates on borosilicate glass witnessed pieces situated across a substrate calotte with a diameter of 700 mm. Spectral transmission curves were plotted, and consequently, refractive index and dispersion characteristics were calculated. Figure 6 illustrates the transmission spectral curves. Spectral characteristics for non-plasma assist and substrates that were coated at 300 °C were included as well for comparison.

The refractive index achieved for plasma-assisted deposited TiO_2 was 2.40 at 550 nm. For comparison, the index of TiO_2 was 2.20 and 2.30 for deposition at room temperature, respectively, and 300 °C at substrate temperatures.

Figure 7 indicates the variation in TiO_2 refractive index and spectral position of absorption edge as a function of plasma source-running voltage.

Figure 8 demonstrates the dispersion characteristics of plasma-assisted deposited TiO_2, SiO_2, and Al_2O_3.

Implementation of a plasma source in a 1.2-m box coater is presented in Fig. 9, by using a planetary tooling configuration. Seven repeat runs of the edge filter is shown in Fig. 10, illustrating better uniformity compared to $< \pm 1\%$.

A versatile plasma source has been described for ionised plasma-assisted deposition of thin films. Independent magnetic field confinement in the cathode and anode regions of plasma source creates a means of controlling the plasma spatial distribution within the vacuum chamber. This is achieved without significantly influencing

other prime plasma source parameters, which influence the uniformity/reproducibility of resulting film optical properties, thereby overcoming one of the problems associated with plasma sources.

Resulting uniformity/reproducibility in optical properties has been demonstrated for single layer thin films. The plasma source is likewise employed for assisted deposition of multilayer filters.

References

1. P. J. Martin, H. A. Macleod, R. P. Netterfield, C. G. Pacey, and W. G. Sainty, Appl. Opt. **22,** 178 (1983).
2. M. L. Fulton, Proc. SPIE **2253,** 374 (1994).
3. B. G. Bovard, *Thin Films for Optical Systems* F. R. Flory, (ed.) (Marcel Dekker, New York, 1994).
4. H. R. Kaufman, R. S. Robinson, and R. I. Seddon, J. Vac. Sci. Technol. **A5** (4), 2081 (1987).
5. A. Zoller, S. Beisswenger, R. Golzelmann and K. Matl, Proc. SPIE **2253,** 394 (1994).
6. D. R. Gibson, D. Yates, J. O'Driscoll, and J. Allen, in *Proceedings of SVC Conference.* (2002).
7. J. D. Targrove, L. J. Lingg, and H. A Macleod, *Optical Interference Coatings* (Washington Optical Society of America, Tucsen, 1988), p268.
8. D. R. Gibson, in *Proceedings of SVC Conference*(2002).
9. D. R. Gibson, Patent No. EP 1154459 A2.