Surface & Coatings Technology 267 (2015) 105–110

Contents lists available at ScienceDirect

Surface & Coatings Technology

journal homepage: www.elsevier.com/locate/surfcoat

Enhanced hollow cathode plasma source for assisted low pressure electron beam deposition processes

David Child [a],*, Des Gibson [a], Frank Placido [a], Ewan Waddell [b]

[a] Institute of Advanced Technologies, University of the West of Scotland, Scottish Universities Physics Alliance, Paisley, PA1 2BE, Scotland, UK
[b] Thin Film Solutions Ltd., Block 7, West of Scotland Science Park, Kelvin Campus, Maryhill Road, Glasgow, G20 0SP, Scotland, UK

ARTICLE INFO

Available online 19 December 2014

Keywords:
Hollow cathode
Plasma source
Double layer
Magnetic field
Pressure differential

ABSTRACT

A self-sustaining hollow cathode plasma source has been demonstrated to operate at an order of magnitude lower deposition pressure than previously reported, enabling plasma ion-assisted electron beam deposition at pressures of ≈2.0E-4 mbar.

This method uses a restrictor plate to create a pressure differential in gas flow between a hollow cathode region and the main deposition area. The cathode operates in higher density plasma, enhancing the hollow cathode effect and enabling self-sustaining plasma formation at lower gas pressures in the deposition region. It is also demonstrated that ion energy distribution and current density at the substrate plane can be varied by changing the orifice geometry and/ or gas flow.

It has been shown that by varying the restrictor orifice the proportion of thermalised ions to translational ions can be reduced, thereby reducing both substrate heating by typically 60% and defect incorporation into the deposited film. This is significant when coating low temperature materials such as plastics. Moreover the variation in ion current density over the calotte area can also be controlled by varying the geometry of the restrictor plate.

The hollow cathode design described in this work utilises both the interior and exterior cathode surfaces, with the additional electrons generated removing the need for a separate neutralising source as verified by Langmuir probe measurement of electron and ion densities at the substrate plane.

The effects on plasma assisted electron beam deposited TiO_2 film optical and mechanical properties have been assessed and correlated with plasma source characteristics.

In contrast to other hollow cathode plasma source configurations, this system has a converging magnetic field allowing electron concentration within the orifice.

1. Introduction

Plasmas are used extensively in thin film coating techniques to etch, clean and assist film growth and densification [1,2]. Production of plasma by hollow cathodes is well categorised [3–6], however, only at chamber pressures greater than 2.0 x 10^{-3} mbar - for example, as used in sputter deposition systems.

However, achieving a dense thin film microstructure by plasma ion-assisted electron beam deposition (PIAD) is adversely affected by increasing gas pressure [7], with pressures ≤2 x 10^{-4} mbar regarded as optimum [8].

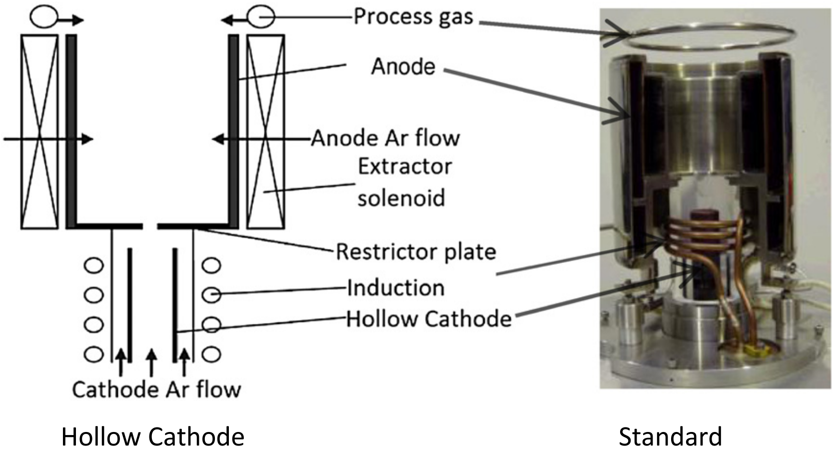
Moreover, low surface temperature for sensitive substrates such as plastic require minimised heat input by either increasing the ratio of translational to isotropic thermalised ions, use of thermal barriers and/ or efficient substrate cooling. It is difficult to achieve dense high refractive index, low absorption TiO_2 films at deposition temperatures less than 300 °C [9] without PIAD which provides a means of depositing fully dense TiO_2 films at room temperature. Optimised plasma ion energy distribution and current densities are critical to achieving effective deposited film densification, with ion/atom ratio for maximum densification dependent on the ion energy [10]. Excessive ion energies lead to film sputtering with consequent surface damage and unwanted inclusions. As these values vary with the material and thickness deposited, there is a need to match ion energy distribution and current density to the process.

This paper describes a methodology to vary the ion energy distribution and current density based on a differential pressure effect, utilising a thermionic lanthanum hexaboride (LaB_6) hollow cathode. Operation is typically at 2 x 10^{-3} mbar pressure in a self-sustaining mode, with deposition pressures of typically 2 x 10^{-4} mbar) [11]. Langmuir probe and Faraday cup measurements of plasma characteristics are described, characterising the ion energy distribution, ion density and neutralisation. TiO_2 films have been deposited using plasma-assisted electron beam deposition and resulting films characterised as a function of plasma ion energy, current density and plasma source operating voltages.

---

* Corresponding author. Tel.: +44 141 8483 444, +44 7564 106826(mob); fax: +44 141 848 3627.
E-mail addresses: david.child@uws.ac.uk (D. Child), des.gibson@uws.ac.uk (D. Gibson), frank.placido@uws.ac.uk (F. Placido), ewan.waddell@thinfs.com (E. Waddell).

http://dx.doi.org/10.1016/j.surfcoat.2014.12.030
0257-8972/© 2014 Elsevier B.V. All rights reserved.



Hollow Cathode Standard

Fig. 1. Hollow cathode schematic with restrictor plate in position and actual cross sections of standard plasma source.

Changes in ion energy with restrictor plate geometry used to achieve pressure differential are described.

2. Experimental arrangements

2.1. Plasma source description

Fig. 1 is a schematic of the hollow cathode plasma source and an actual axial cross section of the standard Thin Film Solutions broad beam plasma source [12]. This shows a 40 mm long by 19 mm internal diameter lanthanum hexaboride hollow cathode contained in a 44.5 mm diameter boron nitrate chamber surrounded by a start-up induction heater coil [11]. The cathode arrangement and argon flow distribution is modified to (a) provide a source of ions for the hollow cathode effect and (b) maximise thermionic electron generation from the cathode interior and exterior. The orifice in the restrictor plate increases the pressure by an order of magnitude in the cathode area. Additional argon can be introduced above the restrictor plate into the anode area for secondary ionisation. Oxygen gas flow is provided through an annular ring directly above the plasma source, maximising generation of ionised oxygen.

Two types of restrictor plate were tested, shown in Fig. 2; a single 10 mm diameter orifice and a 6 × 4.1 mm diameter multi-orifice plate having the same orifice cross section area but with increased wall area. The small hole to the right is for probe access.

The standard fitment extractor solenoid at 30 A produces magnetic field values of 24 mT in the orifice and 16 mT at the center of the hollow cathode measured with a Hurst GM08 gaussmeter. Typical cathode discharge currents are 10 to 30 A at 140 V to 220 V anode to cathode voltage respectively with total gas flow rates between 5 and 30 sccm. The discharge power supply is a standard constant current supply without arc suppression and is found to provide reliable stable operation. The calotte substrate holder is 497 mm above the orifice and axially offset by 354 mm.

2.2. Design of experiment (DOE)

A DOE based on an American Society for Quality Excel template [13] established the inter-relationship between cathode current, cathode/ anode/ process gas and the influence on plasma characteristics. Plasma-assisted electron beam deposition was carried out using a Satis Vacuum AG 380 box coater. DOE high/low values chosen were cathode current 17.5/12.5 A, cathode gas (Ar) 4/3 sccms, anode gas (Ar) 4/3 sccms, process gas (O_2) 15/10 sccms, with a measured 12 mT constant magnetic field at the restrictor plate with a single 10 mm orifice.

At these gas flows the deposition chamber pressure was in the range 2 to 2.5×10^{-4} mbar and a base pressure of 2×10^{-6} mbar with no gas flow. The experimental order was randomised to reduce bias from unaccounted factors such as chamber temperature rise and pumping variations. A further experiment examined the relationship between

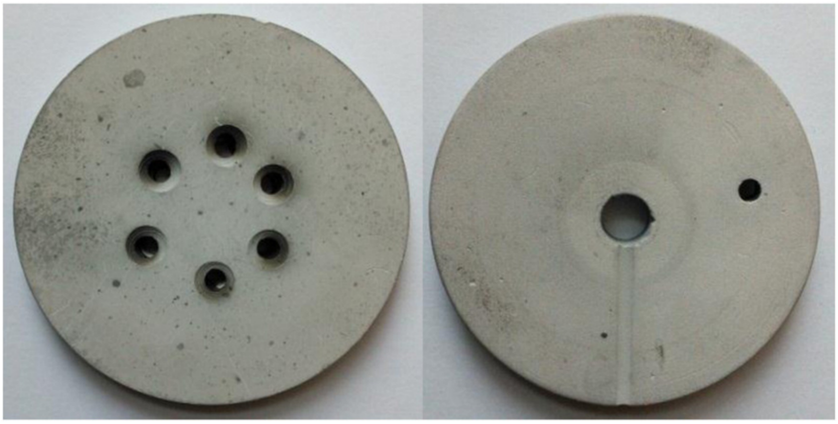


Fig. 2. Changing geometry of restrictor plate enables ion energy distribution to be varied.