Characterisation of a Cavity-Hollow Cathode as Plasma-Assisted Sputtering Source

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1. Introduction

Plasma-assisted growth of thin films is a well-established method for both applied and basic research. Various techniques have become conventional in this field, such as dc and rf magnetron or chemical vapour deposition [1,2]. Recently, a simple sputtering source was proposed [3] which utilises the so-called cavity-hollow cathode post-discharge. Material consumption efficiency, low-cost and simple operation are advantages of this geometry, mainly for the deposition of ferromagnetic materials. In spite of a long-lasting experience with hollow-cathode discharges, their use as sputtering sources requires further characterisation.

In this contribution we present experimental results concerning the diagnostics of a hollow-cathode plasma source used for the growth of Ni thin films on dielectric substrates.

2. Experimental details

The sputtering source is schematically shown in Fig. 1. It is currently used in the Innsbruck Plasma Physics Laboratory to deposit ferromagnetic Ni films on various amorphous and crystalline substrates. Such a configuration was recently briefly investigated, starting from its current-voltage (I-V) characteristic and its optical emission features [3].

In our experiment, in a cylindrical glass tube (1), two 25-mm diameter Ni disks (2, 4 in Fig. 1) are used to enclose a cylindrical cathode cavity (3) with a volume of 1.4 cm³ within the spacer (8). The lower electrode (2) has a central cylindrical hole (5) with 2.5 mm diameter to enhance the ionisation rate inside the cathode chamber by the subsequent oscillatory motion of electrons there [4]. A 6 cm diameter ring

Fig.1. Schematic diagram of the cavity-hollow cathode
anode (13) was co-axially inserted 1 cm away from the nozzle, close to the film substrate (located in position 12). Ar gas was introduced in front of the nozzle through appropriate inlets (7, 9, 10). Power was applied to the cathode via electrode 6. Under normal operation, a conically shaped glowing plasma jet (11) was created in front of the cathode, in which the particle motion is controlled by electrical and pressure gradients.

A 0.05 mm diameter cylindrical tungsten Langmuir probe was used to measure the plasma density and potential at the substrate position (2 cm in front of the cathode) from its $I-V$ characteristic for different pressures and discharge currents. The ion energy distribution function (IVDF) in the same region was derived from the $I-V$ characteristic of a movable four-grid retarding-field energy analyser (RFEA). This is shown schematically in Fig. 2 together with the potential profile within. The RFEA consists of four square-shaped planar grids, made of 30 μm diameter stainless steel wires, with 62% transparency for a mesh size of 150 μm [5]. The grids are parallel to each other and stacked on top of a plane collector. Grid No. 1, which faces the plasma, has an aperture of 3 mm in diameter, while grids No. 2, 3 and 4, each with an aperture of 4 mm diameter, are spot-welded on 0.1 mm thick holders. Electrical insulation between the grids and the collector is achieved using 20 μm-thick mica sheets spacers. The spacing between grids 2, 3 and 4 was 200 μm, except for 300 μm between grids 1 and 2. The collector is biased at a constant potential of −78 V, while the potential of the electron repelling grid (No. 4) was −80 V. The potential of the energy discriminating grid (No. 2) was swept from −25 V to +25 V and the current was registered as a function of the sweep voltage. IVDFs were computed from the plots of the ion current versus the potential of the energy discriminating grid.

3. Results and discussion

Diagnostics was performed under realistic pressure and current conditions used for sputtering (0.02 – 0.1 mbar and 25 – 50 mA, respectively). Langmuir probe measurements showed that the electron temperature on the cathode axis decreases from around 1 eV in the nozzle

![Fig. 2. Schematic diagram of the four-grid RFEA and the potential profile inside it.](image)
exit plane to 0.65 eV at 2 cm, i.e., at the substrate site. The axial profile of the plasma density (see Fig. 3) shows a monotonous decrease within the same spatial interval for pressures ranging between 3 and 10 mbar. The slope of the decrease of plasma density is pressure-dependent. The IVDF was derived from the equation [5]:

\[
f(v) = \frac{M}{eS} \left( -\frac{dI(E)}{dE} \right) = \frac{M}{e^2S} \left( -\frac{dI(\varphi_s)}{d\varphi} \right)
\]

where \( E \) and \( M \) are ion energy and mass, respectively. The final value of \( f(v) \) was corrected for the overall transparency of the RFEA. In the following, we will express \( f(v) \) in terms of energy rather than ion velocity, since the principle of RFEA is based on energy discrimination. The true \( f(E) \) dependence can be easily found using the equation \( E = Mv^2/2 \).

Fig. 3 Axial plasma density profiles for various pressures.

The energy dependence of IVDF for different axial distances from the cathode is shown in Fig. 4. Measurements have been performed for a discharge current of 40 mA and an Ar pressure of 6.8x10^{-2} mbar. \( f(v) \) has a maximum at approximately 6 eV irrespective of the distance from the cathode. A similar shape of the IVDF is found when \( f(v) \) is plotted for different pressures at a point situated 1.8 cm in front of the cathode. It is interesting to note that the IVDF tends to narrow and shift towards higher velocities, under lower range discharge pressures. The operation of the hollow-cathode sputtering source in the high-
pressure range is affected by significant noise, which is evident in Fig. 5 for the plots corresponding to pressures in excess of $5 \times 10^{-2}$ mbar.

4. Conclusion

Langmuir probe and RFEA measurements were performed to diagnose the post-discharge Ar plasma jet in the front of the hollow-cathode sputtering source in the $10^{-2}$ mbar range. Due to the expansion of the plasma jet leaving the exit nozzle, electron temperature, plasma density, and ion velocity distribution functions show a rapid monotonous decrease along 2 cm on the hollow-cathode axis. The maximum height and minimum full-width half-maximum of the IVDF occur under the conditions of discharge pressures in the low $10^{-2}$ mbar range. The $f(v)$ dependence flattens for pressures in the high $10^{-2}$ mbar range.

Our results suggest that, apart from the well-known advantages, the hollow-cathode sputtering source brings the additional benefit of substrate bombardment with energetic particles during deposition. As is known, preparation of textured thin films often requires substrate bombardment with ion or neutrals during deposition to increase ad-atom mobility at the substrate site. In conclusion, the hollow-cathode discharge may be operated as a sputtering source in the low $10^{-2}$ mbar range, under the conditions of intense substrate bombardment to prepare crystal grade thin films, including ferromagnetic ones. Further energy and mass-resolved spectroscopy measurements are planned to characterize the condensation species at the substrate site.

Acknowledgements

One of the authors (I. T.) expresses his gratitude for the possibility to work at the Plasma Physics Laboratory of the Institute for Ion Physics at the University of Innsbruck, Austria. This work was supported by the Fonds zur Förderung der wissenschaftlichen Forschung (Austria) under grant No. P-14545-PHY.

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