Vacuum 143 (2017) 458–463

Contents lists available at ScienceDirect

Vacuum

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

Planar magnetron sputtering with supplementary electron injection

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ARTICLE INFO

Article history:
Received 14 December 2016
Received in revised form
8 February 2017
Accepted 13 February 2017
Available online 17 February 2017

Keywords:
Magnetron discharge
Target
Hollow cathode
Electron injection
Ion current

ABSTRACT

The characteristics of a magnetron discharge system enhanced by the supplementary injection of energetic electrons are presented. Two versions of a two-stage arrangement were explored: central electron injection and peripheral injection into the cathode layer from an auxiliary glow discharge located downstream of the plane of the sputter target. Electrons injected form the auxiliary discharge are accelerated in the cathode layer of the magnetron discharge to an energy sufficient for effective gas ionization and formation of dense plasma near the sputter target. The minimum operating pressure of the non-self-sustained magnetron discharge is 4×10^{-2} Pa at a discharge current of up to 400 mA. The two different embodiments, with central and peripheral electron injection, show stable operating modes differing in discharge voltage and plasma parameters.

1. Introduction

Magnetron sputtering systems with planar cylindrical targets have found wide use as tools for coating deposition for over 40 years. Their basic design has remained the same over the years [1–3], with minimum operating pressure generally in the range 4×10^{-1} to 1 Pa [4]. It is usual that the operating pressure for a magnetron discharge is set somewhat above the lower limit so as to provide a safety margin to decrease the risk of discharge extinction. At these pressures, the mean free path for atoms sputtered from the metal target is no greater than several centimeters, and only 35% of the sputtered material reaches the substrate with 65% depositing on the walls and other parts of the vacuum chamber or back onto the target [5]. Thus the effective distance between the target and substrate needs to be decreased. Another problem is the necessity to maintain a high discharge operating voltage for efficient target sputtering, typically 400–600 V, and increasing the sputtering rate requires that the operating voltage be yet further increased. However, increasing the electron energy decreases the effective ionization cross-section for plasma formation. On the other hand, the minimum operating voltage of a self-sustained discharge is limited to 300–350 V. Thus the magnetron discharge, although rather efficient in terms of technological processes, operates in a comparatively narrow range of operating pressure and voltage.

For the formation of coatings with new properties and superior quality, there is a need to extend this parameter range and to decrease the operating pressure by at least an order of magnitude. In attempts to decrease the operating pressure of a magnetron discharge through additional ionization, it has been proposed to use a hot spiral cathode (electron emitter) and an anode in the gap between the target and the substrate [6]. Despite a number of shortcomings (necessity to introduce additional electrodes, inability to operate in reactive gases, and thermal load on the substrate), this approach has allowed the minimum pressure to be decreased down to 6.5×10^{-2} Pa; the hot cathode current ranged typically from several to several tens of amperes. Another approach is to use hot hollow cathodes in the form of a tube or a set of tubes. However, because of the relatively low injected electron energy in this kind of discharge, it is necessary to provide an auxiliary discharge current at least 1.5–2 times greater than the main discharge current in order to sustain the magnetron discharge in

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http://dx.doi.org/10.1016/j.vacuum.2017.02.011
0042-207X/

the low pressure range. All these shortcomings can be eliminated by using a cold hollow cathode [7].

To decrease the limiting operating pressure of a magnetron discharge with planar target to less than 10^{-1} Pa, we propose a new two-stage magnetron discharge system with electron injection from an auxiliary discharge that utilizes a hollow cathode located downstream of the target plane. A distinguishing feature of this approach is that electrons injected from the auxiliary discharge are accelerated in the near-cathode layer of the magnetron discharge to energy sufficient for efficient gas ionization near the sputter target. The auxiliary plasma – glow discharge based on a cold hollow cathode – features simplicity, reliability, and a high degree of ionization due to electron oscillations.

2. Experimental

The overall dimensions of the source measure 95 mm in height and 100 mm in diameter. We have explored two versions of the discharge system (Fig. 1): one with central electron injection (Fig. 1a) and the other with peripheral injection (Fig. 1b). For peripheral injection, two emission holes were located opposite each other at a radius of 13.5 mm. The magnetron target was made of titanium and was 50 mm in diameter. The two discharge systems were identical in operational physical principles and differed only in location of their emission holes and in the auxiliary discharge configuration.

In both cases, the discharge circuit is a two-stage system with an auxiliary glow discharge, based on hollow cathode *9*, which ensures electron emission into the main region of the magnetron discharge whose operation in the low pressure range ($<10^{-1}$ Pa) without auxiliary discharge is problematic or impossible. Electrons injected through emission hole *1* to target *2* gain additional energy in the cathode layer of the magnetron discharge and provide efficient gas ionization near the target surface. Because the characteristic value of coefficient of secondary ion-electron emission γ for glow discharges is about 0.1, even a small flux of injected electrons can significantly influence the discharge operating conditions [8]. The outer and inner diameters of the hollow cathode were 6 and 4 mm respectively, chosen to provide a *pd* value optimal (here $pd = 4–5 \times 10^3$ Pa mm) for low-pressure operation [9]. The hollow cathode was insulated from magnetron system case *7* and from the electrodes of the main discharge by insulators *8*. A feature of the discharge power supply is that the anode of the auxiliary discharge serves simultaneously as the cathode of the magnetron discharge. The magnetron discharge with metal sputter target operates between cathode *2* and anode *5*. Ring magnets *3* with magnetic circuit *6* located in water-cooled case *4* produce an axially symmetric magnetic field of arch configuration. The maximum magnetic field on the system axis was 0.1 T. All other electrodes of the discharge system were also water cooled. The diameter of the emission hole in the target was 0.6 mm. In the first version (Fig. 1a), case *4* and target *2* were at the same potential. In the second version (Fig. 1b), the magnetron target was electrically insulated, and case *4* was held at a negative potential equal to the potential of the hollow cathode. The current to case *4* was limited by a 500 kΩ resistor. Emission holes of diameter 1.5 mm and coaxial with the hollow cathode form a cavity of inner diameter 8 mm, ensuring good conditions for stable operation of the auxiliary glow discharge at low discharge currents and decreasing the threshold for transition to hollow-cathode mode.

The residual gas pressure was 1×10^{-3} Pa. The working gas (argon) was supplied to the vacuum chamber through the hollow cathode of the auxiliary discharge. The operating pressure in the vacuum chamber was varied by varying the gas flow rate. The ion current density was measured using a movable plane Langmuir probe with a guard ring; the probe was made of nonmagnetic steel, and was of area 2.5 cm^2. The probe potential was 500 V. The magnetron discharge current was measured in its anode circuit, and the auxiliary discharge current was measured in its cathode circuit.

3. Results and discussion

Our investigations show that injection of high-energy electrons to the cathode layer region of the magnetron discharge greatly influences the discharge parameters. In general, for the same parameters, the electron injection either increases the current or decreases the voltage and pressure of the magnetron discharge. The effect of central electron injection on the magnetron discharge voltage is shown in Fig. 2. The magnetron discharge current I_{mn} was stabilized by the power supply at 100 and 200 mA, respectively.

It is seen that the higher the magnetron discharge current, the smaller the effect of electron injection on the characteristics of the

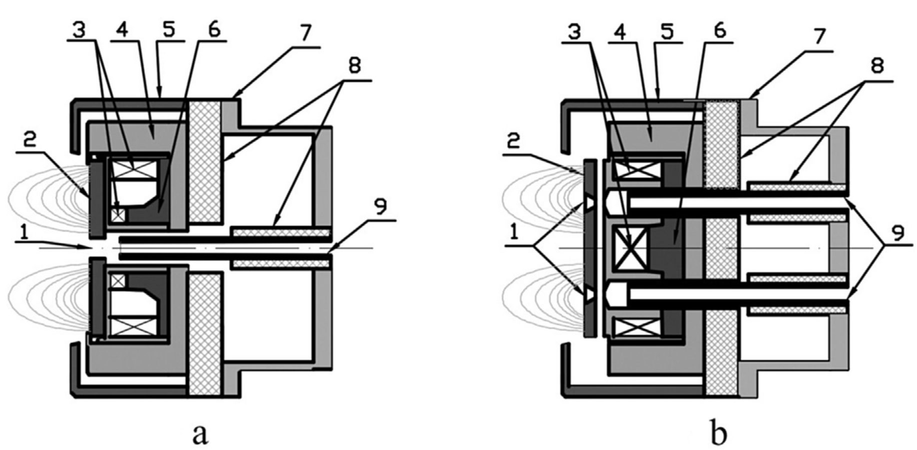

Fig. 1. Discharge systems with central (a) and peripheral electron injection (b): 1 – emission holes; 2 – target (cathode); 3 – magnets; 4 – magnetic circuit case; 5 – anode; 6 – magnetic circuit; 7 – magnetron system case; 8 – insulators; 9 – auxiliary discharge hollow cathode(s).