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Self-sputtering of an inverted cylindrical magnetron for ion beam generation

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Abstract

The self-sputtering mode in high power pulsed magnetron discharges opens the possibility of generating plasma that contains mainly singly charged metal ions of the target (cathode) material. The main idea of a self-sputtering magnetron ion source is to utilize the dense plasma to extract ions from it and thus to form a beam of accelerated, purely singly charged metal ions. Such kind of metal ion source based on a planar magnetron has been reported in our previous, recent publication. The present paper describes the special features observed for the self-sputtering mode of an "inverted" cylindrical magnetron configuration formed by two coaxial cylindrical electrodes. This geometry appears attractive for a novel ion source design and its applications.

1. Introduction

The self-sputtering operation of planar magnetron is a special mode of discharge with high current density when gaseous ions are practically fully replaced by metal ions of the target material [1-3]. This special mode can be reached both in dc and pulsed mode. Pulsed self-sputtering is closely related to the recent development of high power impulse magnetron sputtering (with the acronym HIPIMS) which is used for metal ion etching as well as for the deposition of dense metal and compound films [4-6].

The main idea of a self-sputtering ion source is to utilize the dense plasma of the self-sputtering magnetron discharge, to extract ions from it and thus to form a beam of accelerated, purely singly charged metal ions. Such special kind of metal ion source has been recently reported in our previous publications [7-9]. Previous research made use of a planar magnetron configuration for ion beam extraction. The planar configuration is widely used in most film deposition equipment. It makes use of a planar (flat) target serving as the cathode of the discharge, a ring anode, and an arched magnetic field, which is typically obtained by using a permanent ring magnet at the near-cathode area. For ion sources design such planar configuration is not ideal or convenient and therefore a cylindrical magnetron discharge seems to better suited [10]. The electrode system of a cylindrical magnetron discharge is formed by two coaxial cylinders, serving as cathode and anode, and by a longitudinal magnetic field that could be obtained, for example, by a simple solenoid coil. This configuration is usually called "inverted magnetron", where the anode is the inner electrode of the discharge unit. Ions are extracted from the grid located at one end of cylinder.

The paper presents the results of investigations and describes the special features found for the self-sputtering mode of the magnetron discharge in cylindrical geometry. We will show that this arrangement is attractive to ion source design and applications.

2. Experimental setup

Similar to the experiments with the planar magnetron discharge [7-9], the experimental setup was based on modifications of LBNL's "Mevva V" ion source facility [11]. Here, however, the vacuum arc discharge unit was replaced by the cylindrical magnetron discharge unit shown in Fig. 1. The setup and basic electrical schematic of the experiment are shown in Fig. 2. Using the "Mevva" facility had two advantages. First, we could make use of the available high voltage power supplies, the time of flight (TOF) spectrometer, the magnetically suppressed Faraday

Fig. 1. Photo of the inverted cylindrical magnetron.

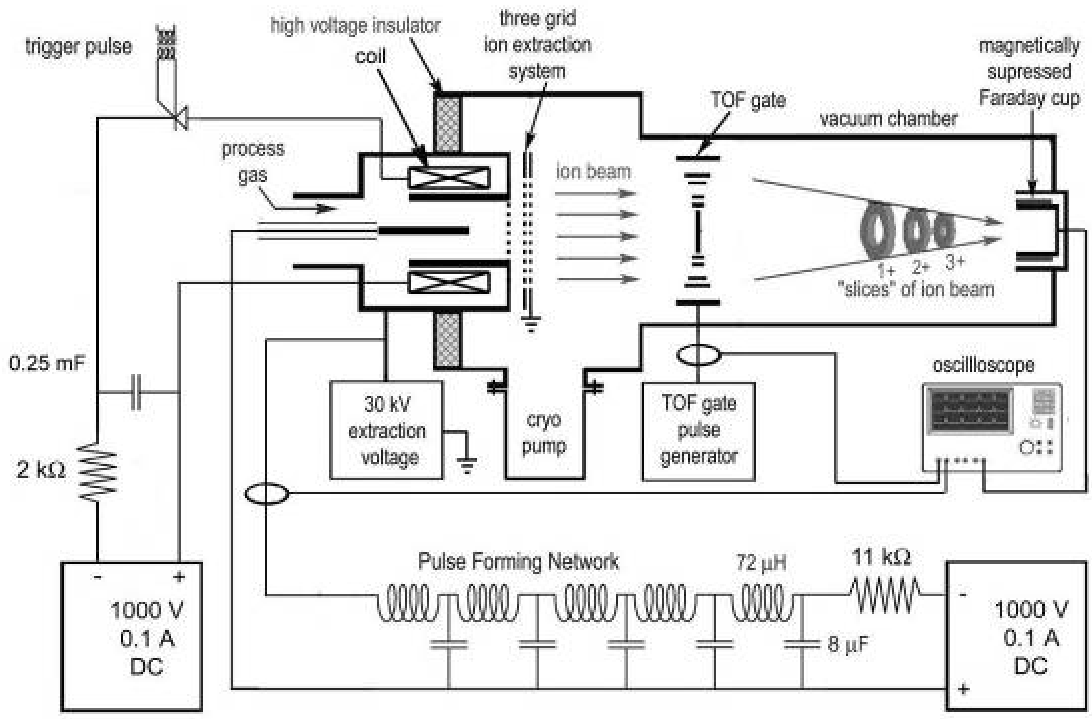

Fig. 2. Set up and basic electrical schematic of the experiment (geometrical dimensions are not to scale)

cups, and other components. Second, a direct comparison with the conventional vacuum arc ion source, so far the most prolific metal ion source, is readily doable.

The cathode (target) of the cylindrical magnetron was made from copper with an inner diameter of about 50 mm. The anode was a small tube of 5 mm outer diameter also made from copper; it was placed coaxially in the center of the cathode cylinder (Fig. 1). The working gas was supplied through the anode tube. The length of both cathode and anode was about 70 mm. A pulsed magnetic field up to 0.1 T was generated by a short solenoid coil placed on the outside of the cathode.

The pulsed magnetron discharge current was provided by a 3 Ω, 250 µs pulse-forming-network (PFN) charged up to 1000 V. In contrast to the case of a planar magnetron, which had a permanent ring magnet, the magnetic field was generated by a solenoid coil and hence an additional power supply was required. To simplify the situation, the PFN output was connected directly to the cathode and anode without any switch in the circuit. A thyristor switch was used to time the current through magnetic coil; the current was supplied by a capacitor bank total 250 µF. The ignition of the discharge was facilitated by pulsing the magnetic field.

Because of a small cathode bottom area of this inverted cylindrical magnetron it was possible to have better pressure drop between the discharge area and the ion extraction gap and we were able to operate under relatively lower pressure compared with the planar magnetron case. Argon was the only working gas used for the cylindrical magnetron experiments.

The extraction system was a simple, non-Pierce multi-aperture three-grid arrangement of the acceleration-deceleration type, where the accelerating grid distance was 1.28 cm and the diameter of each of the 163 holes was 4.7 mm. A fine mesh with 60% transmittance was spot-welded to the plasma-facing side of the first grid, resulting in a nominal extraction area of 17 cm^2.

The whole system operated at a potential of up to 30 kV above ground to allow extraction of ions from the self-sputtering plasma. In some experiments it was enhanced up to 45-50 kV. The grids were also used to limit gas flow conductance between the discharge zone and the main chamber, the latter being pumped by a 1500 l/s cryogenic pump.

3. Experimental results

Because the magnetic field also served to trigger the discharge, it was not possible to study the discharge under constant magnetic field conditions. The magnetic field changed as much as factor about 2 during the discharge. That might be one of the reasons for the "triangular" discharge pulse shape and the noisy burning voltage observed in these experiments (Fig.3). A discharge current up to 90 A in diffuse (not arcing mode) was reached.

As an essential difference to the planar magnetron case is the noise. The self-sputtering mode in a planar magnetron is associated with quiescent (low-noise) plasma: voltage, current, and ion collector currents exhibit low noise. For the inverted cylindrical magnetron, however, the level of plasma noise was rather high, which is also reflected in the noise of the ion beam current (Fig.4). The ion efficiency extraction

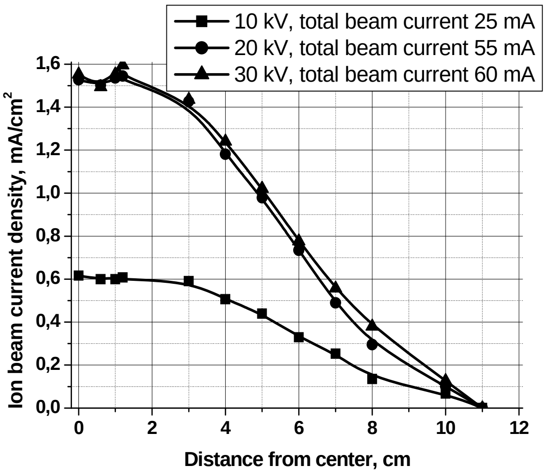

Fig. 5. Radial distribution of the ion beam current density; $p = 8*10^{-5}$ torr, $I_d = 90$ A.

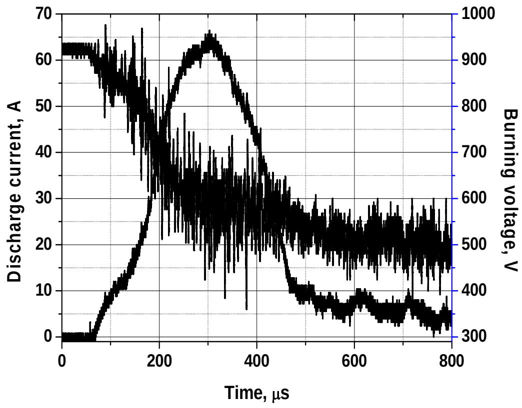

Fig. 3. Pulse shape of discharge current and voltage. Ar, $p = 8*10^{-5}$ torr.

for the cylinder magnetron was also essentially lower than for the planar magnetron. For the case of a discharge current of 80 A, the ion beam current was as high as150 mA, whereas the current did not exceed 60 mA for the cylinder case even when the discharge current exceeded 90 A.

Figure 5 presents the radial distribution of the ion beam current density as measured with a movable Faraday cup. Unlike to the planar magnetron case, the ring discharge structure is not visible in the cylindrical magnetron.

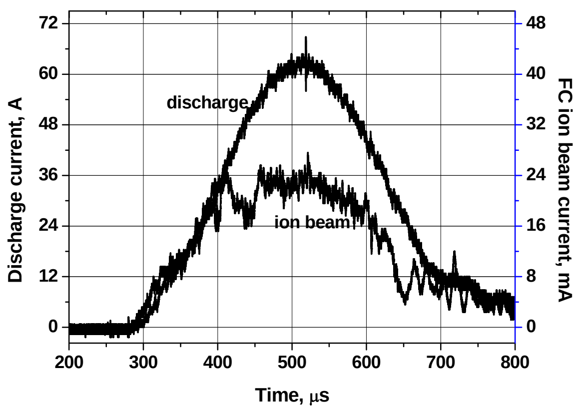

Fig. 4. Pulse shapes of discharge current and beam current. Ar, $p=8*10^{-5}$ torr. $U_a = 30$ kV.

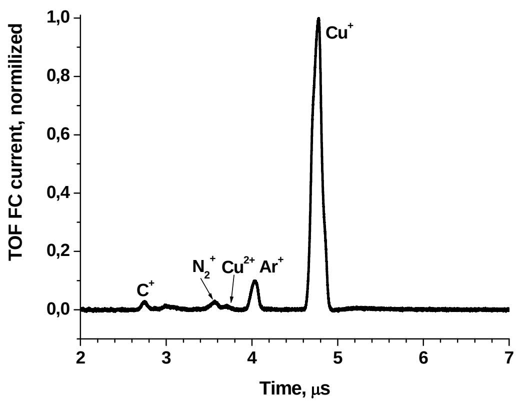

Fig. **6**. Time-of-flight (TOF) ion beam spectrum. Ar, $p = 8*10^{-5}$ torr, $I_d = 90$ A, $U_a = 30$ kV, measured 250 µs after discharge ignition.

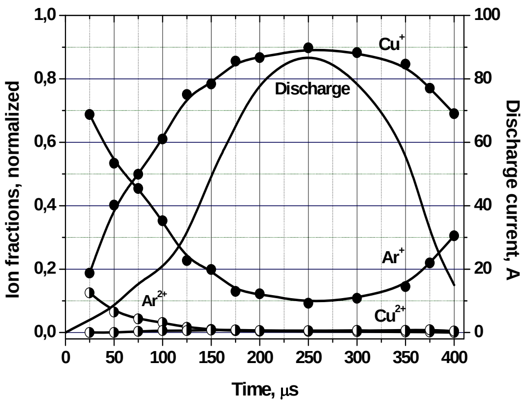

Fig.7. Temporal development of metal and gaseous ion beam fractions corresponding to the discharge current pulse shape. Ar, p= 8*10^{-5} torr, I_d= 90 A, U_a= 30 kV.

The next two figures, Fig. 6 and Fig.7, present the results of experiments investigating the development of the ion beam's charge state composition during the discharge pulse. The results show for the cylindrical magnetron case that it is possible to reach conditions when metal ions dominate over the gaseous ions. However, the situation is not as clear cut as it was with the planar magnetron.

The gas ions were displaced and replaced later in the pulse when considering the inverted cylindrical magnetron compared to the planar magnetron case. then for the flat magnetron case. Additionally, the ratio of metal to gas ions is remains smaller for the cylindrical magnetron. This may well be associated with the directionality of the sputtering process where sputtered atoms are preferentially emitted normal to the target surface, generally obeying a cosine-like angular distribution.

Conclusions

The results obtained with an inverted cylindrical magnetron discharge follow the general trends previously seen with a planar magnetron operating in self-sputtering mode. The cylindrical magnetron features self-sputtering and can serve as the feedstock plasma for an ion source. In both cases, metal ions can be extracted. However, the inverted cylindrical magnetron discharge delivers lower ion extraction current, and the discharge and ion current exhibits greater noise (fluctuations) and instabilities. There is a need to operate at much higher discharge currents due to the greater cathode area, this, however, is limited by the increasing likelihood for a glow to arc transition. In the present configuration it was shown that the pulsed magnetic field can be used to trigger the discharge pulses. However, such field may not be optimized for ion source operation.

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