Plasma source based on an unbalanced magnetron sputtering system

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Abstract. The paper presents research results on the capabilities of an unbalanced magnetron sputtering (UMS) system with a coefficient of geometrical unbalance \(K_G=0.3\) to produce gas discharge plasma far from its target. Using argon as the working gas and silicon as the target material, it is shown that the proposed UMS system provides the generation of plasma with an ion current density of \(\approx 0.2\) mA/cm\(^2\) in the region of treated material at 440 mm from the Si target. The research data on the maximum power at which the UMS system produces high-density plasma without melting the Si target are also presented.

1. Introduction

Magnetron sputtering systems are an efficient tool for deposition of high-adhesion coatings [1] and plasma-assisted ion implantation [2] using an argon plasma generator [3] which provides preliminary surface cleaning of metal substrates and better penetration of atoms into their surface layers. In technological terms, it is, however, desirable to use as fewer plasma devices as possible: for example, only magnetron sputtering systems to provide surface cleaning as well as plasma-immersion doping and plasma-assisted coating deposition. To do this the ion current density from the plasma produced by a magnetron sputtering system must be higher than 0.2 mA/cm\(^2\) at an ion energy to a substrate from several to hundred electron-volts [4–7]. Here we study the possibility of producing gas discharge plasma of required density with an unbalanced magnetron sputtering system.

2. Experimental equipment and research technique

The unbalanced magnetron sputtering (UMS) system under study had a planar circular configuration; a simplified schematic of its cross-section is shown in figure 1 (a). The UMS system was mounted on one of the side flanges of a cylindrical vacuum chamber made of stainless steel with a diameter of 1200 mm and height of 600 mm. The cathode-target of the UMS system was a silicon disk of diameter 80 mm and thickness 8 mm mounted at the face of the UMS system casing (not shown in figure 1) by tightly pressing the target to a water-cooled copper base of thickness 2 mm which, being as such the face of the UMS system, separated the water-cooled volume of the magnetic system and the vacuum volume. The axially symmetric circular magnetic system was formed by an annular permanent magnet (NdFeB) and a cylindrical magnetic core (steel) with an axial channel for cooling water supply to the copper base-face.

Figure 1 (a) also shows a field pattern calculated for the magnetic system. It is seen that on the system axis, there is a point at which the magnetic field lines reverse their direction, and hence, the system is unbalanced. The calculated behavior of the magnetic field is confirmed by figure 1 (b),
which shows an image of the discharge and plasma produced in the UMS system. It is seen that the unbalanced field lines limit the electron scattering region because the unbalance distorts the arch shape of the field in the magnetic trap region (region of bright plasma glow), decrease the field in the radial direction, and allow electrons to leave the magnetic trap [8, 9]. The electrons escaped from the trap move to a substrate, rotating about the divergent unbalanced lines and ionizing the working gas (argon).

Figure 1. Simplified cross-sectional schematic of the UMS system with calculated magnetic field lines (a) and image of the discharge glow (b): 1 – Si target; 2 – water-cooled Cu base; 3 – annular permanent magnet; 4 – cylindrical magnetic core; 5 – balanced field lines; 6 – unbalanced field lines; 7 – grounded anode; 8 – cooling water channel; \( U_m \) – discharge power supply.

The magnetic field on the axis and at the cathode surface was measured with a meter based on Hall sensors. At the surface of the Si target, the axial (normal) component of the magnetic field was 0.095 T. At a distance of 11.4 mm along the axis, the magnetic field reversed its direction, reaching its maximum equal to 0.022 T at 28 mm from the target. Then, the axial component decreased gradually and vanished at 180 mm from the target. The measurements confirmed the calculation. The coefficient of geometrical unbalance for the UMS system was \( K_C = 0.3 \), being defined as the ratio between the distance along the system axis from the target surface to the point of field reversal and the average diameter of the target sputtering zone [10].

The anode of the UMS system was anode 7 (figure 1 (a)) as well as the entire grounded vacuum chamber. The argon pressure in the vacuum chamber was controlled by varying the gas flow rate to the chamber. The ion current density at the center of the chamber was measured using a one-sided plane probe with a conducting area of 200 cm\(^2\) located perpendicular to the UMS system axis at a distance of 440 mm from the target. The composition of the plasma produced in the UMS system, in particular the content of the ionized component of one or another element, was analyzed using a COLIBRI-2 multichannel atomic emission spectrometer in the region where treated objects were located. The test materials were NiTi substrates with a Ni content of 50.9 at %. The elemental composition of surface layers after treatment in different modes was analyzed using a Shkhuna-2 Auger spectrometer (Tomsk Polytechnic University).

3. Results and discussion

Figure 2 shows current-voltage characteristics of the discharge in the UMS system, demonstrating a huge effect of the Ar pressure on the discharge parameters.
The current-voltage characteristics are ascending; that is, for increasing the discharge current the discharge voltage should be increased with the increase in the power of the UMS system. The most important characteristic of the UMS system is its capability of producing high-density plasma in the region of treated objects for their efficient heating, cleaning, doping of their surface, and plasma-assisted coating deposition. The plasma density was estimated from the saturation ion current density of the one-sided plane probe at its negative bias of 200 V with respect to the vacuum chamber. Figure 3 shows the dependence of the ion current density on the power of the UMS system at an operating pressure of 0.33 Pa.

As can be seen from figure 3, the designed UMS system is capable of providing ion current densities from the plasma which are sufficient to greatly influence the energy and structural phase states of the substrate and its modified surface layers even at the so large distance from the substrate as 440 mm. Our experiments show that in the UMS system, the use of a Si target tightly pressed to the Cu base and cooled through it does not allow a considerable increase in the power compared to that in figure 3 due to overheating and melting of the target.

Figure 4 shows an image of the Si target of the UMS system after its operation under the conditions indicated in figure 3 but at a power higher than 0.8 kW. It is seen that the target surface is melted and that the formed liquid droplet does not fall but flows down the target and becomes pointed at its end as if it were lying on the magnetic field lines near the target. Such a situation was observed in all experiments: the droplet of melted material was always held at the bottom of the target and the surface of its pointed end was similar to the configuration of magnetic field lines near the target.

We determined the maximum power at which the Si target of the UMS system with indirect cooling through the Cu base was not melted. Figure 5 shows the maximum power of the UMS system as a function of operating pressure.

Atomic emission spectrometry of the plasma produced by the UMS system in an operating mode with low Si target consumption at a dissipated power of 0.2 kW (the mode most used by the authors) suggests a rather low ionization degree of the plasma. This judgment is supported by experimental data on the ion current density from the plasma at respective Ar pressures. According to atomic emission spectrometry, almost the whole ion current is the current of Ar ions. The fraction of Si ions is low, lying on the verge of the spectrometer sensitivity (≤ 1 % of the Ar ions). The flow of the sputtered material in the region of the treated substrates is dominated by Si atoms. Thus, the high density of Ar ions in the plasma and the high content of Si ions in the substrate region make it possible to vary the elemental composition of modified surface layers by varying the bias applied to the substrates.
Figure 4. Image of the melted Si target of the UMS system.

Figure 5. Maximum power of the UMS system vs the operating pressure.

Figure 6 (a–d) shows Auger profiles of the chemical elements in NiTi surface layers treated in the plasma of the UMS system at a negative bias of 200 (a), 400 (b), 600 (c), and 1000 V (d) to the specimens with respect to the anode (vacuum chamber).

Figure 6. Auger profiles for NiTi after plasma treatment at a negative bias of 200 (a), 400 (b), 600 (c), and 1000 V (d).
It is seen from figure 6 that increasing the bias provides different modes of plasma immersion surface treatment of the material: deposition of a Si coating, plasma immersion ion doping and etching (surface cleaning) without coating deposition, and surface doping with Si. At a negative bias of 200 V (figure 6 (a)), a coating of thickness 600 nm is deposited on the surface with a considerable depth of Si penetration into the material (300 nm) and almost without any gas impurity (oxygen, carbon, etc.) contamination of the coating, suggesting that the plasma of the UMS system provides high-quality surface cleaning of the substrates [2]. At a negative bias of 400 V (figure 6 (b)), the coating is etched, but the depth of Si penetration into the material remains large (200–250 nm) with a maximum Si content of 60 at% [2]. Increasing the bias to 600 V (figure 6 (c)) decreases the depth of Si penetration into the NiTi substrate to 50–60 nm and the maximum Si content to less than 20 at%, suggesting that etching in this mode becomes more and more prevailing. Finally, at a negative bias of 1000 V (figure 6 (d)), the surface layer is fully etched such that the treatment represents surface etching and cleaning. The oxygen- and carbon-saturated thin (<10 nm) surface layer formed in this mode is likely due to the interaction of the elements with etching-activated titanium in air on removal of the specimens from the vacuum chamber.

4. Conclusion
Thus, our experiments demonstrate high efficiency of the proposed unbalanced magnetron sputtering system as a plasma source for realization of different types of surface treatment: coating deposition, doping, etching, and cleaning. This opens up new possibilities for simplifying the design of vacuum plasma setups and for increasing the technological efficiency of vacuum plasma treatment of metal articles.

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