Generation of Gaseous and Metal Ions in Vacuum Arc Discharge with the Longitudinal Hollow Anode in a Magnetic Field


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Abstract – The paper presents results of experimental investigations processes of generation mixed gaseous-metal ion beams extracted from plasma of vacuum arc discharge with a longitudinal hollow anode in magnetic field. Several cathode materials (Cu, Mo, Au) and argon as operating gas were used in experiments. It was shown that generations of gaseous ions basically take place in cavity of the hollow anode on significant distance from cathode surface. This fact is confirmed experimentally by observing rise the ratio between gaseous to metal ions in the extracted ion beam with increasing the length of the anode cavity. It was also determined that the arc plasma electrons provide mainly the ionization of gaseous molecules where as reduction the high charge states of metals ions is related with the charge exchange processes.

1. Introduction
In some specific modes of vacuum arc discharge (or more correctly arc discharge with cathodic spots), the total ion flux from the arc plasma may contain gaseous ions. Essential generation of the gaseous ions in such kind of arc could be reached either by enhancing of background pressure usually more than $1 \cdot 10^{-4}$ torr [1] or by decreasing pulse repetition rate of discharge current down to less than 0.1 s$^{-1}$[2], as well as the by introduction of an external magnetic field about 0.1 T [3]. At all these conditions value of gaseous ion fraction is comparable with fraction of metal ions. Appearance of gaseous ions also accompanies by significant reduction of multiply charged metal ions in the extracted beam [4]. Possibility to generate mixed gaseous-metal ion beams could be useful to for producing special surface layers, like titanium nitride, aluminium oxide and some others, where decreasing if high charge states is a way for controlling metal ion beam composition [5]. In spite of multiply experimental observations of this phenomena determination of basic physical principles still remains unclear. The main questions are the following: if gas ionization takes place in near cathode region or in the whole space of the anode cavity and also what is the reason for decrease the fraction of multiply charged metal ions.

So, the main goal of present work is investigation of process of gas ion generation in a vacuum arc discharge with an extended hollow anode in a magnetic field as well as determination of possible reasons influencing on decreasing of mean charge state of metal ions.

2. Experimental setup
For generation of gaseous-metal plasma in the ion source MEVVA-V.Ru [6] a special discharge module with extended hollow anode was used (Fig. 1). Cylindrical cathode 1 with diameter 6.4 mm was mounted on movable holder 2, which allows the moving of the cathode along the central axis of anode cavity 3. In that way, the distance between cathode 1 and emission electrode 4 could be varied from 1.5 to 30 cm. Magnetic coil 5 was also mounted on movable holder 2 axially with the cathode of a vacuum arc. Thus the geometric position of the maximum distribution in the magnetic field was matched with the position of the working surface of the cathode. In some experiments the deflecting anode shield 6 was used. The shield was located 4.5 cm from the cathode surface, suspended on pin 7 at single point. Removing the shield from line of sight of the cathode surface was produced by spinning the holder of the cathode on its axis. At that case when pin 7 was moved to the lowest position the shield moved downward by gravity. Vacuum arc discharge was ignited with auxiliary flash-over discharge. The power supply of a vacuum arc based on pulse forming network provided the current with amplitude up to 1 kA, pulse duration 250 µs, and repetition rate up to 10 s$^{-1}$. The pulsed magnetic field up to 0.5 T and

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duration of 1 ms produced by discharge capacitor bank through magnetic coil 5. Ignition of a vacuum arc discharge was carried out with a 330 µs delay on the leading edge of the magnetic field pulse. Thus, the discharge operated in the magnetic field, which was differed from the amplitude value no more than 10%. The beam was formed by ion-optical system at an accelerating voltage up to 50 kV, and voltage suppression of secondary electrons at several hundred volts. Mass-charge composition of the ion beam was measured by TOF mass spectrometer [7]. Argon of high purity was used as working gas, which was fed directly in the discharge unit of the ion source. Due to gas flowing though limited numbers of the holes in ion-optic system the operation pressure in discharge unit and background pressure in vacuum vessel were different on about one order of magnitude (10^-4 and 10^-5 torr, respectively). The pressure in the vacuum vessel has been provided by oil-free vacuum pumps.

3. Experimental results and discussion

All experiments were performed at magnetic field 0.4 T. Exceeding this value does not lead to any further changes of gaseous ions fraction and charge state distribution of metal ions. But the pressure of operating gas about 1 \cdot 10^{-4} \text{torr} resulted to appearance of argon ions in the beam even without magnetic field and seriously reduced the mean charge state of metal ions. Therefore in all experiments the pressure was no more then 5 \cdot 10^{-5} \text{torr}. It should be noted, that variation of the distance between the cathode and the anode and due to dependence of plasma density distribution from the configuration of magnetic field lines [8] is virtual to changing of the volume where the processes of the charged particles transport and their interactions with gas molecules is concentrated. Typical TOF spectrum of the extracted ion beam is shown in Fig. 2. In the study influence of cathode position on ion beam mass/charge composition cathode 1 together with coil 5 was moved toward to emission grid 4. During this experiment we assume that together with variation of linear distance important also to analyze changing of volume of space filled by arc plasma. Thus dependence of gaseous ion beam fractions on the operation volume has linear forms. The longer cathode-extraction grid distance the higher fraction of gaseous ions in the beam, that can reach even more then 50% in total beam current (see Fig. 3).

Measurements the time development of the ion beam composition showed, that even at 75 µs after discharge pulse it was possible to observe the ion beam, but only containing singly charged ions of argon (see Fig. 4). Apparently, these “slow” gaseous ions are generated in the discharge plasma as a result of ionization in decayed arc plasma. The process take place at a distance from the surface of the cathode, far then size of the region of electron pressure gradient influence, supported by Joule heating [9]. Therefore, the random thermal motion of ions in this field prevails over the hydrodynamic acceleration mechanism. There are two possible reasons for appearance of gaseous ions: electron ionization or charge exchange with multiply charged metal ions. To determine the main reason we made comparison of ion beam composition for different positions of deflected anode

Fig. 3. Ion beam composition. Au + Ar: 1 – metal fraction; 2 – metal ions mean charge state; 3 – gaseous fraction; 4 – admixtures (N, O, C) fraction. Discharge current 200 A, 250 µs, 5 pps

Fig. 4. Temporal development of the ion beam composition. Au + Ar: 1 – discharge current; 2 – metal fraction; 3 – ion current; 4 – gaseous fraction; 5 – admixtures (N, O, C) fraction. Accelerating voltage 33 kV. 15 cm between the cathode and the extraction grid
shield 6 (see Fig. 1). When the shield fully crosses cathode from extraction grid it does not influence on the arc operating but excludes the metal ion flux from the process of generation gaseous ion fraction. Comparison of ion beam spectra with opened plasma stream and closed stream is made in Fig. 5. It is clear that interception of the cathode plasma by shield does not exclude gaseous ions in the beam. If the shield was set to “semi-crossed” position the ion beam became unstable. This connects to the random nature of the cathode spots motion along the surface.

Because of chaotic movement of the cathode spots the plasma stream from the cathode could be many times both opened and screened during the pulse. For 20 random moments of measuring the ion beam spectrum the differences in the peaks amplitudes for $\text{Ar}^+$ was only 8%, whereas for $\text{Au}^+$ and $\text{Au}^{2+}$, it was more than 50% (Fig. 6). The high stability of this electron flow is due to necessity of keeping up the circuit of discharge current. So the ionization of argon molecules is basically produced by electron impact. Absence of reverse relationship between the ratio of the amplitudes of the spectral pikes of gas and metal ions excepts the charge exchange as the basic process of gaseous ions generation. In this experiment, such a source of ionization could be only the electrons from the arc plasma located near the walls of the anode. Weak influence of the cathode plasma stream on gaseous ion beam fraction could be considered as an experimental proves of preference for volume ionization to charge exchange process.

The dependencies of average charge state of gold ions $<Q>_{\text{Au}}$ and argon ion fractions from the plasma filled volume in a magnetic field have a different shape (Fig. 3). Changing the operating volume from 2 to 200 cm$^3$ reduces of $<Q>_{\text{Au}}$ in 1.5 times and at the same time increases of gaseous ions fraction only on 2%. The results of the measurement of average charge state ions of gold, depending on the distance between the cathode and the emission electrode are shown in Fig. 7. The value of $<Q>_{\text{Au}}$ reduced exponentially even at relatively low pressure and absence of a magnetic field (1), but much more strongly at presence of magnetic field (2). This effects show that the decrease of average charge state of metal ions does not have a dominant influence on gas ionization. The increasing the distance of metal ions transport toward extraction region is the reason of the rise of interactions of multi charged metal ions with gaseous molecules. Consequently the most possible reason of the losses of multi charged metal ions is the process of stepwise charge exchange [10].

4. Summary

The mixed gaseous-metal ion beam was extracted from plasma of cathodic arc discharge with a longitudinal hollow anode in magnetic field. The composition of the ion beam was investigated at different distances between the cathode and the ion extraction region. It was shown that the ionization of argon molecules is mainly produced by electron impact in the hollow anode space, at a distance from the surface of the cathode, greatly exceeding the size of “freezing” region [11]. The fraction of gaseous ions in the ion 

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Fig. 5. TOF spectrum of ion beam. $\text{Au} + \text{Ar}$. Accelerating voltage 33 kV. Discharge current 200 A, 250 $\mu$s, 5 pps. 150 $\mu$s after arc ignition. 15 cm between the cathode and the extraction grid

Fig. 6. TOF spectrum of ion beam. $\text{Au} + \text{Ar}$. Arc current 200 A, 250 $\mu$s, 5 pps. Accelerating voltage 33 kV. 150 $\mu$s after arc ignition. 15 cm between the cathode and the extraction region

Fig. 7. Mean charge state of metal ions. $\text{Au} + \text{Ar}$: 1 – pressure $5 \cdot 10^{-6}$ torr, no magnetic field; 2 – pressure $5 \cdot 10^{-6}$ torr, magnetic field 0.4 T. Arc current 200 A, 250 $\mu$s, 5 pps. Accelerating voltage 33 kV. 150 $\mu$s after arc ignition. 15 cm between the cathode and the extraction region
beam is directly proportional to the volume filled with plasma vacuum arc discharge in a magnetic field. Reduction of mean charge state of metal ions with increasing of distance between the vacuum arc cathode and the ion extraction region is the result of the charge exchange of multiply charged ions at collisions with gas molecules.

References