Effective Source of High Purity Gaseous Plasma

A.V. Vizir[1], M.V. Shandrikov[1], G.Yu. Yushkov[1], E.M. Oks[1,2]

[1]*Institute of High Current Electronics SB RAS, Tomsk, 2/3 Akademichesky ave., 634055 Russia,*
phone (3822) - 491776, fax (3822) - 492410,
e-mail: shandrikov@opee.hcei.tsc.ru
[2]*Tomsk State University of Control Systems and Radioelectronics, 40 Lenin ave., Tomsk, 634050, Russia*

Abstract – Results of experimental study of low-pressure, high-current gaseous discharge with electron emitter based on constricted arc discharge are presented. Physical features of plasma generation in such system are discussed. Special features of the electron emitter design provide a long lifetime due to decrease of arc cathode erosion rate, as well as decrease of contamination of gaseous plasma by metal ions, atoms and particles. The discharge voltage is 20–150 V and the discharge current is up to 20 A in DC mode. It is shown that simultaneous operating of three discharge systems provides formation of uniform and stable gaseous plasma in the volume of 1 m^3 with plasma density up to 10^{11} cm^{-3} at operating gas pressure in the vacuum chamber of 10^{-3} torr. The discharge system is characterized by high efficiency of energy utilization (about 140 eV/ion), plasma density uniformity, possibility to operate with chemically active gases, simplicity of set-up and maintenance and long lifetime.

1. Introduction

Glow and arc are the two basic types of a gaseous discharge, according to conventional classification. The difference between them is in external electrical parameters as well as in conditions of plasma generation and current passage. In the glow discharge, the gas ionization is realized by electrons emitted by the cathode as a result of secondary ion-electron emission. Since the coefficient of secondary emission is quite low (near 0.1 electron per ion) and grows with ion energy, for discharge maintenance a comparatively high discharge voltage is necessary. In the gaseous arc discharge, the cathode emission is thermionic. Therefore the high discharge voltage is not required.

Relatively high voltage of a glow discharge in most cases is undesirable, because it leads to intense ion sputtering of the cathode material and, as a result, contamination of gaseous plasma by the sputtering products. The fraction of metal ions in the glow discharge plasma can be as high as several percent [1, 2]. It was shown [3] that parameters of the low-pressure glow discharge can be improved by injection of electrons into the discharge plasma through a perforated part of the cathode wall. As an electron emitter, the plasma of auxiliary gaseous discharge with cold electrodes was used. In this way it was possible to decrease the hollow cathode glow discharge voltage from several hundred volts to 50 V, and to reduce the minimal operating pressure by order of magnitude. With the increase of the injected electron current [4], the transition of discharge parameters from values typical for a glow discharge to the ones appropriate to an arc, however, reached without thermionic emitter, is observed.

The gaseous plasma source described in this paper is based on the discharge with electron injection. The source design, together with the advantages of such type of discharge, provide high performance attributes of the device, such as high energy utilization efficiency, low operating pressure, low contamination of discharge plasma, long maintenance period and lifetime. The plasma source was used for production of uniform bulk plasma (1 m^3, 10^{11} cm^{-3}), and more dense plasma localized by magnetic field in a smaller volume.

2. Experimental Set-up

A schematic view of the plasma source electrode system is shown in Fig. 1.

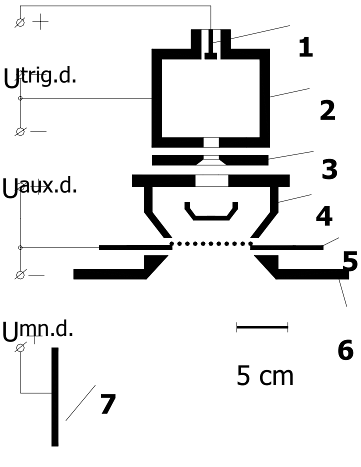

Fig. 1. Schematic view of the discharge system: 1 – igniter electrode; 2 – hollow cathode of the auxiliary discharge; 3, 6 – shields; 4 – intermediate electrode; 5 – mesh-like cathode of the main discharge and anode of the auxiliary discharge; 7 – anode of the main discharge

The device is a two-stage system. The first stage is the auxiliary discharge (emitter) and the second stage is the main discharge. The plasma of the main discharge occupies the whole internal volume of the vacuum chamber. The auxiliary discharge functions between the hollow cathode 2 with small output aperture and the anode 5 made of tungsten mesh. The mesh-like anode of emitter is at the same time the cathode 5 of the main discharge. The auxiliary discharge voltage is 30–40 V and its current is 3–20 A. The anode 7 of the main discharge is placed inside the vacuum chamber. Alternatively, the grounded vacuum chamber itself can serve as an anode. However, the use of separate anode with sufficiently small surface area (1% of the total internal surface area of the chamber) increases an average path length of injected electrons, and consequently, the plasma density.

Operating gas is fed into the emitter cathode cavity. Presented results refer to argon as an operating gas. Nitrogen and oxygen also were tested. The auxiliary discharge is initiated by a high current gaseous discharge when a high voltage pulse (5 kV, 35 μs) is applied between igniter electrode 1 and hollow cathode 2. When the DC voltage is applied between the electrodes 2 and 5, the arc discharge with cathode spots is initiated between these electrodes. The emitter discharge voltage is about 30–40 V. In order to prevent the formation of a cathode spots on the outer cathode surface there is an insulated stainless steel shield 3 on the exterior surface of the cathode. The hollow cathode is made of magnesium. Between the emitter cathode output aperture and mesh-like anode 5, there is an insulated filter electrode 4. This electrode serves for intercepting macroparticles and neutrals of the emitter cathode material. Neutral metal ions are caught by the filter electrode surface because their mean free path is much longer than the dimensions of the electrode. Metal ions from cathode cavity don't overpass double electrostatic layer formed near emitter cathode output aperture. At the exit of the filter electrode, the electron flow is directed to the mesh. The injected electrons passed through the mesh (more than 70% of auxiliary discharge current), obtain an additional energy, corresponding to a cathode potential drop of the main discharge. This energy is quite sufficient for effective gas ionization in the volume of the vacuum chamber. The cross section of the elastic scattering by gas atoms substantially exceeds the ionization cross section of the operating gas. This leads to a situation in which the initial narrow beam of injected electrons is homogeneously scattered over the discharge-chamber volume. Main discharge plasma potential with respect to the grounded walls of the vacuum chamber is negative (1÷6 V) with respect to the grounded chamber in case of the chamber used as an anode, and positive (10÷20 V) in case of insulated anode. In the first case, the plasma is not contaminated by the chamber wall material at all. With separate anode, walls of the vacuum chamber are not subjected to intense sputtering, because the ion energy does not exceed 10–20 eV, which is close to the sputtering energy threshold.

The plasma potential was measured using emission probes made of a tungsten wire 50 μm thick. The plasma density was determined from the ion saturation current onto a moveable flat Langmuir probe with collecting surface area of 5 cm^2 on the distance of 40 cm from plasma source. The probe has an additional electrode serving to keep flat the emission surface of the plasma. The specific energy spent for production of an ion (energy per ion) was estimated from the average ion current density to the vacuum chamber walls. For this purpose, several probes were placed on the chamber walls. For exception of influence of emitting plasma surface expansion, a screen mesh over the probe was used. This mesh has a potential of grounded vacuum chamber.

3. Results and Discussion

The main discharge current-voltage characteristic (curve 1, Fig. 2) shows that the discharge current stops to increase at the discharge voltage about 60 V. The position of saturation point is determined by an average ionization length and depends on the size of the vacuum chamber, pressure of the operating gas and injected electrons energy. With vacuum chamber of larger size, the main discharge current saturation starts at higher voltage.

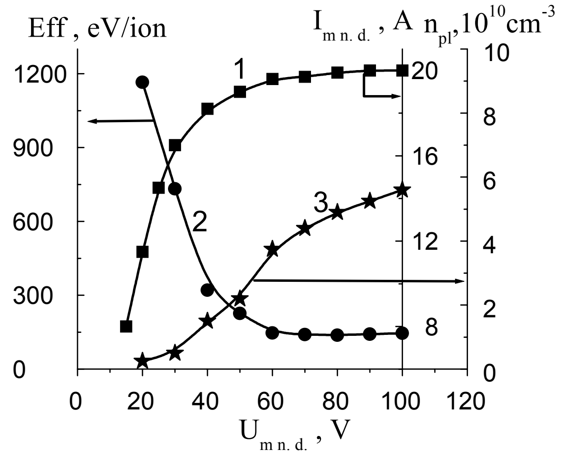

Fig. 2. Main discharge current (1), energy per ion (2) and bulk plasma density (3) versus the main discharge voltage. ($I_{\text{aux}} = 20$ A, $p = 5 \cdot 10^{-4}$ torr, argon)

The energy per ion was calculated as an electric energy input divided by total number of ions having hit the chamber in unit time. The addition to the energy of the auxiliary discharge was taken into account. With the increase of the main discharge voltage, from certain value, determined by a point of main discharge current saturation, the energy per ion (curve 2, Fig. 2) reaches its minimum and then slowly increases. The increase takes place because the plasma density (curve 3, Fig. 2) starts to increase slower than the power consumption by the main discharge.

The simultaneous operating of three discharge systems was realized. The main discharge current of each plasma source was 20 A. The optimal main discharge voltage was determined as a minimum of energy-per-ion curve. One common main discharge anode for three plasma sources was used. The spatial distribution of plasma density for this operating mode is shown in Fig. 3.

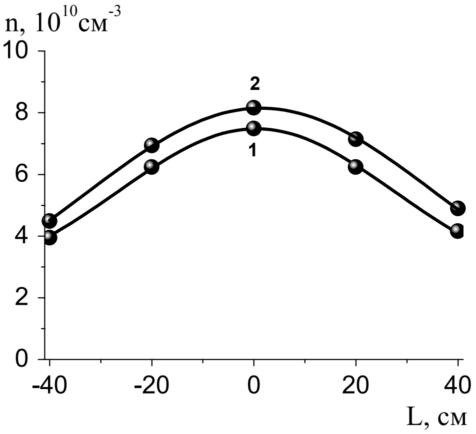

Fig. 3. Plasma density distribution. 1 – $U_{main} = 90$ V; 2 – $U_{main} = 110$ V ($I_{aux.d} = 3\times20$ A, $p = 2 \cdot 10^{-3}$ torr; argon)

The presented discharge system was used also for localized dense gaseous plasma generation in order to obtain high ion current density to collector. The main discharge plasma is confined by an axially oriented magnetic field created by two coils, a small, 20 cm diameter, placed around the source, and a large, 40 cm diameter coil in the ion collector region. The maximum value of a created magnetic field in the centers of coils is 10 mT. Ion collector made of stainless steel has a surface area of 500 cm^2. Plasma source-collector distance is 35 cm. Collector is negatively biased. The necessary value of the bias was determined from a current-voltage characteristic saturation point in the presence of a magnetic field. The vacuum chamber was made of non-magnetic material. With the maximum field of two coils, the plasma was concentrated mainly in the central area of the vacuum chamber and was almost absent on the chamber periphery.

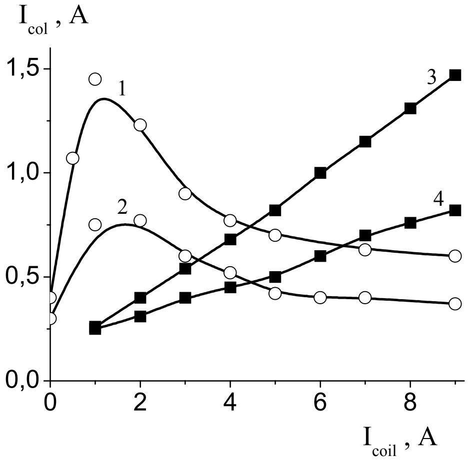

Fig. 4. Colector current versus the current of the magnetic coils: 1 – $I_{s.c} = 8$ A, 2 – $I_{s.c} = 4$ A, 3 – $I_{b.c} = 1$ A, 4 – $I_{b.c.} = 4$ A; $I_{aux.d.} = 10$ A, $U_{main} = 30$ V, $p = 4 \cdot 10^{-4}$ torr, $U_{col} = -150$ V, argon

Configuration and strength of magnetic field was optimized in order to get highest collector ion current.

Fig. 4 shows the dependencies of the ion current on the current of the coils. The character of the curves for large, collector coil (curves 1, 2) and for small, source coil (curves 3, 4), can be explained as follows. The collector current depends on simultaneous influence of two factors. First is the plasma confinement improvement with the increase of magnetic field. Second is that with increasing of a magnetic field an axial plasma potential gradient is formed. This electric field is directed from the region of strong magnetic field to weak field. Such potential gradient originates from the fact that the magnetic field pushes electrons out from intense magnetic field. It leads in turn to formation of positive space charge in this region. This potential gradient causes the leaving of ions from this region.

In the range of a weak magnetic field (less than 1 mT) the plasma confinement has the dominant influence. As the whole plasma becomes magnetized, leaving of ions from collector region due to the potential gradient starts to have an influence. The similar dependence for small magnetic coil, located at the source (curves 3, 4), has no maximum. Both factors (plasma confinement and potential gradient formation) leads to increase of ion collector current.

With optimum magnetic field, the collector ion current increases in a factor of 5 and reaches 1.5 A with main discharge current of 10 A and voltage as low as 30 V.

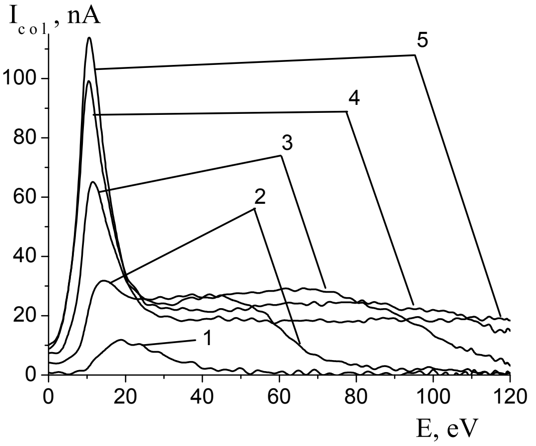

Fig. 5. Spectrums of electrons of the main discharge plasma. 1 – $U_{main} = 0$ V; 2 – $U_{main} = 20$ V; 3 – $U_{main} = 50$ V; 4 – $U_{main} = 70$ V; 5 – $U_{main} = 100$ V; $I_{aux} = 3$ A, $p = 6 \cdot 10^{-4}$ torr, argon

The measurements of electron and ion energy spectrum from the main discharge plasma with use of the electrostatic analyzer of Hughes-Rojansky [5] were carried out. The analyzer previously was gauged by means of filament emitter electrons. Plasma source – analyzer distance was 40 cm. In Fig. 5 the electron spectra from the bulk plasma for several values of main discharge voltage are presented. A spectrum consists of two groups. The first group is plasma electrons and the second is electrons, having the directed energy, obtained as a result of acceleration in the cathode potential drop of the main discharge. With the increase of main discharge voltage the maximal energy of electrons increases too. The energy spread of ions extracted from the plasma was less than 4 eV.

Two components of contamination of gaseous plasma can be distinguished. First is the erosion the electron emitter cathode and second is sputtering of main discharge cathode. Sputtering of grounded parts of the vacuum vessel should not contribute to contamination because the plasma potential accelerates the ions to the energy that is lower than the sputtering threshold. The contamination by the emitter cathode material was estimated by calculating the amount of emitter cathode material atoms coming out of its output aperture without the filter electrode barrier. Cathode erosion rate was taken from [6]. The ratio of flows of metal atoms and ions to gas ions appeared to be $2 \cdot 10^{-4}$. This value also was checked by depositing the film of cathode material on the sample placed right in front of the output aperture of the emitter cathode. Since the gas flow regime at the filter electrode is not viscous, the filter electrode should reduce the contamination at least by order of magnitude.

The contamination by the main discharge cathode mesh material strongly depends on the discharge voltage. With the voltage of 30 V, the energy of ions bombarding the mesh is near the sputtering threshold. At the same time, this voltage is enough to produce sufficiently high collector ion current (Fig. 4).

4. Acknowledgments

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