Grid current control in the unstable mode of plasma discharge

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Abstract. The paper presents the results of studies of the effect of grid current control of triode cesium-barium vapor modulator in the unstable mode of plasma discharge. The possibility of effective modulation of the current due to the development of nonlinear plasma structures formed during the excitation of the electronic instability of Bursian-Pierce is discovered. It is shown that in this mode, in the interelectrode gap, a potential distribution with a virtual cathode is formed, leading to a break of the electron current. In this case, the current in the triode changes almost instantaneously, since the process of the formation of a virtual cathode proceeds over a time of the order of the electron travel time through the gap. This is especially important for the successful practical application of triode modulators. The achieved high transient rates had a positive effect on the efficiency and frequency characteristics of the device. A high electric strength has been implemented, which allows to keep the triode in the locked state after a current break for a long time.

1. Introduction

Low-temperature plasma finds a wide practical application in devices used in the current control circuits of space and ground-based nuclear power plants, such as: modulators, thermionic converters, current and voltage stabilizers. One of the most important requirements for devices of this designation is the ability of trouble-free operation under conditions of high temperature and radiation load [1, 2].

The formation of nonlinear structures in the plasma of a triode modulator is associated with one of the fundamental phenomena in a confined collisionless plasma – development of the Bursian-Pierce instability [3]. As a result of the development of instability, the plasma enters a new state with a potential distribution that differs significantly from the initial one. The duration of this process is determined by the time of the electron mileage through the gap.

It is known [4], that the resulting self-consistent nonlinear oscillations are characterized by alternating slow and fast stages. During the slow stages, the ions are redistributed in space. At certain moments of slow stages, conditions arise for the development of Bursian-Pierce instability: a potential jump formed at the emitter, at which electrons are strongly accelerated, and electron beam moves in the plasma, which has a small velocity spread.

As a result of the development of instability, a current interruption may occur. This occurs when the electronic transient process ends with a state, if at a certain distance from the emitter an area with a negative potential (virtual cathode) forms, which leads to a strong limitation of the transmitted electron current. Since the process of the formation of a virtual cathode takes place over a time of the
order of the electron travel time through the gap, it can be said that the current changes instantaneously. The resulting structure is stable, at a slow stage it moves towards the collector and controls the electron current flowing through the triode.

2. Grid current control mechanism

The potential distribution associated with the formation of a virtual cathode leads to the formation of a potential well for electrons. At the stage of the formation of such a well, the capture of electrons into it can occur due to their interaction with a self-consistent unsteady electric field. As the depth of the potential well increases, the electron moving in it loses some of its energy, giving it away to the electric field [5]. With an increase in the size of the gap, the energy loss grows and there is a limiting gap, above which these losses are greater than the initial electron energy at the emitter. Electron capture has a significant effect on a potential well.

Knudsen discharge \((l_e,i \gg d)\), where \(l_e, i\) – mean free path of electrons and ions, \(d\) – interelectrode distance) with increasing current density above a certain critical value \(j_c\), turns into an unstable state and goes out, that the magnitude \(j_c\) turns out to be equal to the current density, which can be compensated with fully ionized cesium atoms. The plasma lifetime in the gap decreases as the current density increases above the values corresponding to the critical current. The characteristic time of plasma existence is several hundred microseconds and is much longer than the mileage time of atoms and ions between the electrodes and along the radius of the electrode.

This feature of the Knudsen high-current discharge in cesium and barium vapors is apparently associated with a large number of cesium atoms adsorbed on the electrodes. The discharge on the mixture of cesium and barium vapors is especially convenient for this purpose, because the barium film cathode allows obtaining a high emission current density (about tens A/cm\(^2\)) at low cesium pressures \((p_C \approx 10^4 \pm 10^3 \text{ torr})\) and thereby realize a high degree of gas ionization at small \((\approx 1,5 \pm 2 \text{ V})\) anode voltages. Due to the desorption of these atoms, an increased density in the discharge remains for some time. The transition to critical modes increases the efficiency of grid control. In this way the presence of the grid, which ignites and blocks the discharge after a spontaneous break, also creates additional convenience for registering the processes that occur. Without a grid, the discharge goes into auto-oscillation mode [6].

The reason for the fact that with an increase in the density of the discharge current above a certain limiting value, a spontaneous break in the current can be caused by the depletion of the neutral component due to the removal of atoms at high degrees of ionization.

Using the technique described in [6, 7] I-V curve of cesium-barium modulator (fig. 1) for one of the typical modes in which spontaneous current break is observed obtained (fig. 2). In the 0-1 area, the discharge is stable and the current-voltage characteristic can be registered by static methods. At point 1, the discharge current density reaches a limiting value at which the discharge loses stability and spontaneously goes out after a certain time after ignition by a positive grid pulse (fig.2, b, 1).

With further increase in the anode voltage (or decrease in the anode load), when the amount of current after ignition of the discharge is greater than the limit – the discharge goes into unstable burning mode. The section of the I-V curve above point 1 can be registered only by the pulse method.

The shape of the pulses of the discharge supercritical for different points of the I-V curve is presented in fig.2, b. It can be seen from the figure that a high-current Knudsen discharge on a mixture of cesium and barium vapors is characterized by an unusually long discharge time of up to several hundred microseconds. It is 1-2 orders of magnitude more than the free path of atoms (ions) through the interelectrode gap, which in these conditions is of the order of 4 \(\mu s\).

Measurements show that for the investigated pressure range the level of the critical current does not depend on \(p_\text{th}\), and is proportional to the pressure of cesium, which plays the role of the plasma-forming component. Thus, atoms that desorb from the surfaces of the anode and the grid make a significant contribution to the pulse duration of the critical current. Cesium atoms are characterized by a high degree of adsorption on surfaces. At a critical current density, atoms in the interelectrode gap are almost completely ionized, and it can be assumed that due to the electric fields that arise, the ions
are pumped out towards the cathode surface and leave the interelectrode gap. If the desorption of cesium from the surfaces did not occur, then after the time required for the passage of ions through the gap, the atoms would almost completely be thrown out of the gap and a current would break.

**Figure 1.** Cesium-barium triode modulator: 1 – cathode, 2 – anode, 3 – electron gun, 4 – grid, 5, 6 – thermocouples, 7 – cavity for pyrometry, 8, 9 – alundum insulation, 10 – sapphire window [8].

**Figure 2.** I-V curve of the triode modulator (a) and the shape of the discharge current pulses (b) in the unstable mode of discharge burning; points 1-9 correspond to the value of current in the pulse, A/cm²: 1 – 8.1; 2 – 9.5; 3 – 10.8; 4 – 12.8; 5 – 14.9; 6 – 16.2; 7 – 17.6; 8 – 19.6; 9 – 27. For stable mode point 0 has value of current about 1.5 A/cm². Grid potential regarding to the cathode is close to zero, $T_e = 1700$ K; $p_{Cs} = 8 \cdot 10^{-4}$ torr; $p_{Ba} = 2.6 \cdot 10^{-4}$ torr; time scale for pulses 1-3 – 50, 4-9 – 20 $\mu$s/cm.
Obtained results are in agreement with the energy parameters which previously were received and published in [8]:

- at an interelectrode distance of 4 mm and a cesium vapor pressure of $10^{-2}$ torr, the values of current density were up to 100 A/cm$^2$, the voltage losses in the open state were in the range of 0.8–2.5 V;
- stably modulated power 1.8 kW/cm$^2$ with an efficiency of more than 95%;
- operating modes were found in which, with an increase in the density of the modulated current, the electrical waste in the grid circuit fall. At anode voltage of 50 V, stable modulation was obtained at frequencies of 1–10 kHz with a specific electric power of 5 kW/cm$^2$ and an efficiency of more than 95%.

In this way the presence of the grid, which ignites and blocks the discharge after a spontaneous break, also creates additional convenience for registering the processes that occur. Without a grid, the discharge goes into auto-oscillation mode [7]. It turns out that the role of the grid is reduced to maintaining the locked state of the triode and ensuring high electrical strength, and reigniting the discharge is carried out by applying a positive pulse to the grid.

3. Conclusion
Results of studies of the effect of grid current control of triode cesium-barium vapor modulator in the unstable mode of plasma discharge are shown. It is shown that the plasma Cs-Ba modulator in the non-stationary mode is promising not only from the point of view of limiting parameters, but also from the point of view of control efficiency. In the triode modulator may be a situation when in the interelectrode gap, a potential distribution with a virtual cathode is formed, which leads to a break of the electron current. The features of transient processes in the mode of spontaneous discontinuity of the discharge current with limited ionization due to the lack of atoms are investigated. A significant effect of oscillatory processes on the efficiency of grid quenching was found. The achieved high transient rates had a positive effect on the efficiency and frequency characteristics of the instrument.

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