ISSN: 2350-0328

International Journal of Advanced Research in Science, Engineering and Technology

Vol. 6, Issue 11 , November 2019

The study of Stability Combustion of the Gas Discharge in Sub-micron Gas-filled Cell with Semiconductor Electrode

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ABSTRACT: The spatial stabilization of a discharge in an air-filled cell with a semiconductor (gallium arsenide or silicon) electrode has been studied experimentally. The study was carried out in a wide range of residual pressures, interelectrode distances, and conductivities of the semiconductor. The loss of stability was primarily due to the formation of a space charge of positive ions in the discharge gap which changed the discharge from the Townsend to the glow type. When the semiconductor resistivity was high (in excess of 10^8 Ω cm), an instability of the current developed in the semiconductor under the influence of the ionizing components of the discharge plasma.

KEY WORDS: Steric stabilization current, resistivity semiconductor, semiconductor-gas discharge, the discharge cell, a photodetector, current-voltage characteristic of the semiconductor conductivity, voltage discharge ignition, self-sustained discharge Townsend.

I.INTRODUCTION

In recent time extends interest in the study of photovoltaic properties of gas-filled systems with semiconducting electrode (SGD-structure) with small interelectrode distances d≤0,1 mm [1-4]. Such devices have found practical use in high-speed infrared (IR) image converters of ionizing type, in particular for space-time diagnostics of infrared laser radiation. [5, 6]. This spatial distribution of current density in the small discharge gap is controlled by the semiconductor photodetector sensitive to IR illumination. For stationary discharge volume are important parameters along with the high-resistance semiconductor electrode, and the values of d and residual gas pressure P. So, with a decrease in d extends area of spatial stabilization of current and photoelectric amplification SGD-structure as a gas over a range of pressures, and in the values of permissible applied stress [7, 8].

In this work [9] the influence of the semiconducting cathode and interelectrode distance on the beginning of the gas ionization process has been investigated. The current voltage characteristics (CVC) of the narrow (d=60 μm) gas discharge gap with two kinds of electrodes (1) two metal electrodes; 2) gallium arsenide ($\rho \sim 10^8$ Ω·sm) has been used as the high-resistivity semiconducting cathode) are studied. The CVC are determined in a wide range of the gas pressures p=15÷700 Torr and constant voltage U=50÷700 V. Pashen's curves demonstrating, that the gas discharge occurs with difficulties in the narrow gap with metal electrodes, in contrast of the wide gap have been drawn. There is the sharp dependence of the striking voltage (Us) on pd in the range of pd=2÷30 mm Hg.

The structure of semiconductor – gas discharge plasma of low density has been investigated in this paper [10]. The current – voltage characteristics (CVC) of this system have been determined by the opposite polarities of direct (curred). Voltage and differend illumination intensities of semiconductor. It was detected the current rectification on the contact of semiconductor – gas discharge plasma. At was established the identity of the present CVC with the CVC of the lock contact.

In this paper we present the results of an experimental study of the stabilization of the discharge in a cell with silicon and gallium arsenide electrodes in a wide range of air pressure and the magnitude of the inter-electrode distance. It should be noted that in addition to scientific research such represent a significant practical value in the implementation of various technical options for use of the system semiconductor- gas discharge.

II.MATERIALS AND METHODS

Schema of the gas discharge cell with semiconducting cathode is shown in figure. 1. The total current through the discharge cell and the voltage drop between the electrodes is recorded simultaneously. The diameter of the high-resistivity ($\rho\div10^8\Omega$cm) GaAs photocathode is 25 mm and its thickness is 1 mm. The diameter of Si(Pt) plate is 30 mm and its thickness is 1 mm. This photodetector material has a maximum sensitivity at the wavelength λ=4,2 µm. The current voltage characteristic of the gas discharge cell are obtained experimentally as functions of the gas pressure p (20÷700), and interelectrode distance d (10µm ÷ 5 mm), which were varied in sufficiently wide ranges for the first time.

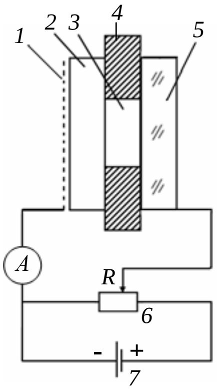

Figure 1. The basic scheme of the converter cell with a semiconductor photodetector: 1-transparent conducting Ni layer; 2-semiconductor photodetector; 3-gas discharge gap, 4—dielectric space, 5- transparent SnO_2 conductor; 6-externals resistance, 7-power supply.

We determined the current-voltage characteristics of a gas-discharge cell in which one of the electrodes was a semiconductor plate 1 mm thick and up to 1 cm^2 area with an external transparent ohmic contact. The second electrode was a SnO_2 film deposited on glass through which the discharge was observed. In one series of experiments the semiconductor electrode was chromium-compensated semiinsulating gallium arsenide. The measurements were carried out at room temperature. In another series of experiments, carried out after cooling to a temperature of 90 K, the electrode was made of platinum-doped silicon. In all cases after igniting a discharge an increase in the voltage ensured a uniform distribution of the discharge radiation along the electrode. A further gradual increase in the voltage brought the cell to a state of loss of the stability, which was manifested by a steep rise of the current simultaneously with the appearance of brighter spots against the background of the uniform radiation, which varied with time and with respect to their geometric positions. In nearly all cases the loss of stability of the current was coincident with the loss of uniformity of the discharge radiation.

III. RESULTS AND DISCUSSION

Figure 2 shows typical current-voltage characteristics of the cell recorded for different values of the conductivity of the semiconductor, which was varied by its uniform illumination through the transparent contact. These characteristics were used to find the discharge-ignition voltage U_{ig}, the voltage at which the discharge became unstable U_{un}, and the corresponding current j_{un}. There were individual differences between the current-voltage characteristics when the conditions were altered, particularly in the case of major changes of the discharge gap, of the conductivity of the semiconductor, and of the air pressure.

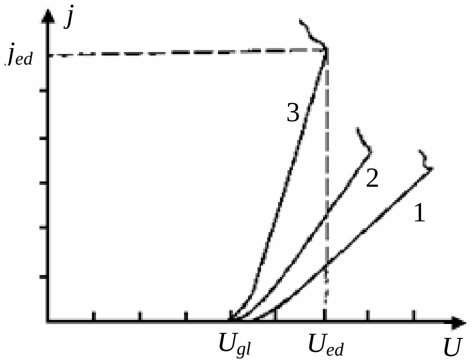

Figure.2.Typical current-voltage characteristics of a cell with a semiconductor electrode recorded at different rising (1,2,3) intensities of illumination of the electrode.

Figure 3a and 3b give dependences of the maximum current deduced from the current voltage characteristics in with a gallium arsenide electrode (a) and one with a silicon electrode (b) on the residual gas pressure when the interelectrode distance of 30 µm. The same figures give the voltage at which the discharge was ignited.

In discussing these experimental results we had to determine first which type of discharge we were dealing with in a cell with a semiconductor electrode. There were sufficient grounds for assuming that under dc conditions we were dealing with a self-sustained Townsend discharge, which was deduced, in particular, from the range of the current densities. The presence of a distributed resistance layer in the semiconductor was manifested in the following ways. First, this occurs at a specific surface, whicn in the case of the cathode determines the value of the coefficient γ in the Townsend theory. This coefficient has a strong. influence on the discharge ignition voltage. Since in the presence of a semiconductor electrode of sufficiently high resistivity the depth of penetration of the field into the semiconductor is considerably, we can expect a dependence of U_{ig} on the intensity of illumination of the semiconductor. Such a dependence was observed experimentally for gallium arsenide electrodes with a resistivity slightly higher than $10^8 \Omega \cdot$cm. We obtained a series of the current-voltage characteristics of a cell with such an electrode (Fig.4). The results indicate that the discnarge ignition voltage depends strongly on the intensity of illumination of the semiconductor electrode, and in the strongest, way upon transition away from the equilibrium dark current: The value of U_{ig}subsequently varies only slightly with an increase in the conductivity of the semiconductor electrode. The dependence of the charge ignition potential on the intensity of illumination of the semiconductor electrode can be explained qualitatively in terms of the increase in the electric field near the semiconductor surface due to a reduction in the screening length, which governs the dependences of the cathode processes on the illumination intensity. An analysis of the experimental results on the discharge ignition voltage, obtained for a gallium arsenide electrode with a resistivity $10^7 \Omega \cdot$cm, when the value of *Pd* is varied, demonstrates that these relationships are of the usual type, and that they fit the standard Paschen curves for a discharge between metal electrodes [7].In the case of a cell with a silicon electrode there is a considerable deviation from these standard curves.

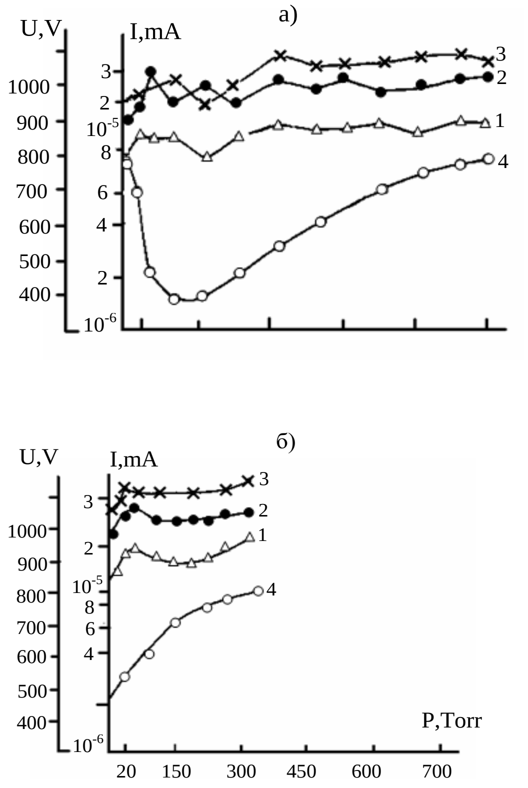

Figure 3. Dependences of the current corresponding j_{un}(1-3) and of the discharge ignition voltage U_{ig}(4) on the pressure in a cell with a semiconducting electrode made of gallium arsenide (a) and silicon, alloy platinum (b).

To the best of our knowledge, there is no published information on the discharge ignition potential for a cell with a semiconductor electrode. The special features of the semiconductor electrode are associated with its distributed resistance, which reacts to local changes of the current at each point in the discharge cross section as an element of a negative feedback loop which quenches fluctuations of the current. The lumped resistance of the circuit, on the other hand, reacts to the total electrode current and cannot experience an equally effective negative feedback. This circumstance primarily accounts for the stabilization of a discharge by a semiconductor electrode.

The loss of stability could be the reason for the change from the Townsend discharge to the glow discharge, i.e., for the change in the nature of the gas discharge itself. It is known [8] that the transition to the glow discharge is due to loss of uniformity of the electric field in the discharge gap as a result of the appearance of a space charge. In general, the distortion of the field along the lines of flow of the current can disrupt the homogeneity of the discharge along the cross section of the discharge gap. Even in

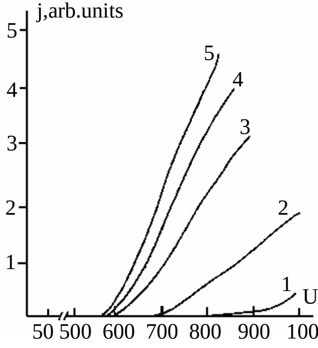

Figure. 4. Current-voltage characteristics of a cell with an electrode made of high-resistivity (in excess of 10^8 ? ·cm) gallium arsenide observed for increasing (1,2, 3, 4, 5) illumination intensity.

the case of the normal Townsend discharge, whose distinguishing feature is the absence of a space charge or negligible amount of it in the discharge gap, we could only with difficulty assume that the field is totally uniform. In fact, in most of the discharge gap the ionic current exceeds the electronic current because of the difference between the ion and electron mobilities, and because the concentration of ions is considerably higher than the electron density. Therefore, in the discharge all the space is basically filled with the positive charge of the ions. The transition from the Townsend discharge to the glow discharge, which is associated with a negative differential resistance region in the current-voltage characteristics, should be considered in accordance with the criterion of the absolute value of the space charge and of the degree of distortion of the electric field compared with the case in which the field is constant.

Approximate estimates indicate that the dependence of the field E on the distance along a line of current flow is given by

$$E = E_k\sqrt{1-x/l} \quad \textbf{(1)}$$

or

$$l = \mu_+ E^2{}_K / 8\pi j. \quad \textbf{(2)}$$

At the cathode the field E_K is maximal, but it decreases near the anode at an increasing rate with increasing current density. The quantity $l$is a certain effective length representing the degree of distortion of the field. When $l$becomes equal to the length of the discharge gap, the anode field vanishes and this circumstance is regarded as a criterion of the transition from the Townsend discharge to the glow discharge. The limiting current for the Townsend discharge j is given by

$$\frac{j}{p^2} \approx \frac{(\mu_+ p)U^2{}_{gl}}{8\pi(pd)} \quad (3)$$

A characteristic feature is that this maximum current does not depend on the gas pressure.

In the case of a cell with gallium arsenide we can assume approximately that the pressure dependence of the stability-loss current is weak (Fig. 3a). It follows from Eq. (3) that the dependence of this current on the combination of the quantities $U^2{}_{gl}/\partial^3$ should be li- near. This dependence is plotted in Fig. 5 for two values of the pressure (curves 1 and 2). The experimental points fit well, in accordance with the approximate expression (3), a straight line with a slope corresponding to the linear dependence.

The fact that curves 1 and 2 are not the same stems from the approximate nature of Eq. (3), which ignores the dependence of the ion mobility on the pressure and electric field. Accordingly, since Eq. (3) is an approximate equation, and since the loss of stability of a discharge is statistical in nature, we can assume that the suggested mechanism for the loss of stability is realized. The curves which we obtained correspond to low and moderate values of the intensity of illumination of the semiconductor electrode. We found that at high illumination intensities there is a change in the slope of the curve $j = f(U^2{}_{gl}/\partial^3)$ in the sublinear direction (curve 3), but the experimental points fit well a straight line plotted on a double logarithmic scale. This deviation could partly be due to a nonuniform carrier generation in the semiconductor as a result of illumination, so that the conductivity of the part of the semiconductor adjoining the discharge can have a much higher resistivity, which could affect the values of the current and ignition potential which were determined.

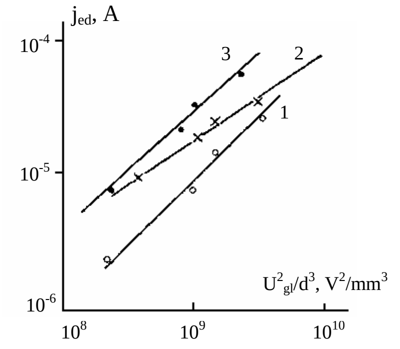

Figure 5. Dependence of the maximum current corresponding to the onset of an unstable discharge on the quantity Uig2/d3, obtained for different values of the gas pressure in a cell with a gallium arsenide electrode: 1, 2) in darkness; .1) during strong

Such measurements in the case of a silicon semiconductor electrode demonstrated the absence of the theoretically predicted behavior. The stability-loss voltage in this case behaves anomalously during illumination: A reduction in the electrode resistance increases, rather than decreases, the voltage at which the discharge becomes unstable (Fig. 3b).

The experimental results, taken as a whole, demonstrate that the spatial stability of the discharge in a cell with a photosensitive semiconductor electrode could be limited with respect to the distributed resistance on the low- and high-value sides. The physical nature of the current filamentation is different in these extreme cases. The loss of the spatial stability in a discharge is governed by space charges in the discharge gap and by the distortion of the electric field, typical of the transition to the glow discharge.

In the case of a high resistivity of a semiconductor electrode the ionizing effects of the active components of the discharge on the semiconductor become important. In fact, at very high values of resistivity of the electrode, and consequently low density of equilibrium carriers and photocarriers, the generation of carriers in a semiconductor under the influence of a gas-discharge plasma becomes important. This carrier generation occurs in a very thin skin layer (short-wave- length radiation, — 100-eV electrons, and ions). The carriers, aided by the field, then penetrate deep into the interior of the semiconductor, where they can modulate the conductance. The following process resulting in a local increase in the current then occurs. Modulation of the bulk of the semiconductor electrode and a reduction in its resistance increase the current in the plasma, and also increase the intensity of the radiation emitted by the gas and the flux of the ionizing particles, which in turn reduce to an even greater degree the resistance of the semiconductor in this range. Continuation of this process, which could be regarded as a positive feedback loop, gives rise to an S-shaped current-voltage characteristic of the semiconductor and of the current density in one or several local regions on the surface separating the semiconductor from the discharge gap. This stability loss mechanism was observed by us in semiinsulating gallium arsenide when it was illuminated. It manifested itself by spontaneous contraction of the radiation emitted by the gas discharge, initially distributed uniformly over the whole area, into a narrow region. The relevant calculations showed that this process occurs when the field intensity in the semiconductor exceeds a certain threshold value.

IV CONCLUSION

This mechanism of spatial destabilization of the discharge involves the development of fluctuations of the current in the semiconductor. It depends strongly on the state of its surface, i.e., on the sensitivity of the semiconductor material to strongly absorbed radiation emitted by the discharge gap, and, in particular, on the polarity of the applied voltage, on the effective surface recombination velocity, and on the presence of an oxide or disturbed layer at the interface between the semiconductor and the gas discharge plasma.

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