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A Stable Discharge Glow in Gas Discharge System with Semiconducting Cathode

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Abstract. — A dc discharge generated between parallel plate electrodes are studied. The spatial stabilization of the gas discharge with the semiconducting Si_1 at 90 K have been studied in a wide range of the gas pressure p (21.3–466.5 hPa) and of inter-electrode distance d ($10 \mu\text{m} - 5 \text{mm}$) for the first time. The cathode was irradiated on the back-side with light in a particular wavelength range that was used to control the photoconductivity of the material. The semiconductor material was found to “stabilize” the discharge. The stable functioning of the ionization system at pressures of 21.3–466.5 hPa with a gap value of $10 - 100 \mu\text{m}$ and the photocurrent density about 10^{-4}A cm^{-2} is possible.

1. Introduction

Behaviour of planar gas discharge cells with photosensitive semiconducting cathodes [1, 2] is an essentially new subject of investigations in semiconductor physics and in gas discharge physics. In gas discharge physics, nearly for hundred years, gas discharges maintained between equipotential low-ohmic electrodes have been studied. In such a cell several stages and types of gas discharge were determined by the value of current passing through the gas discharge gap [3]. Using a semiconducting cathode having distributed resistance considerably changes the current distribution. The value of the transmitted current and the type of the discharge are determined by the uniformity of the resistivity distribution of the cathode and its thickness [4]. The ionization system has rather stable operation for a broad range of discharge current values, and the current density is stationary and homogeneous over the whole plane structure when an electrically homogeneous semiconductor cathode is used. This behaviour is not quite usual, because in other experimental realizations of a “semiconductor-discharge gap” structure current filamentation [5, 6] (*i.e.* an inhomogeneous distribution of the current density), and also rather complicated spatio-temporal behaviour of the current density have been observed [7, 8].

Electronic phenomena that occur at a contact between a semiconductor and a gas discharge plasma with negligible or no erosion and mass transfer have a number of special features and have been among the least investigated semiconductor contact phenomena. Penetration of

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the charge of a double electrical layer into the interior of a semiconductor results in a strong dependence of the value and spatial distribution of the current density on the state of the semiconductor and make it possible to control both the current and the glow emitted by the gas discharge. The study of the above system parameters is also important for practical use of the stable discharge [9–11].

At present, there is lack of experimental data concerning the general pattern of the phenomenon and especially of the dependence of the current stability on the gas discharge gap parameters for construction of a satisfactory stabilization theory. The results of a systematic investigation of the effects of pressure, the inter-electrode distances and other parameters are given in the present paper when the spatial stabilization is realized

A typical set of Current-Voltage Characteristics (CVC) of a planar discharge cell for different illumination intensities of a semiconducting cathode is shown in Figure 1. The CVC allow us to determine the cell parameters:

- 1) breakdown voltage U_B ;
- 2) variation of conductivity σ (or resistivity ρ) homogeneities of the semiconducting cathode at different illumination intensities (*i.e.* change of $\sigma = \partial J / \partial U$, or $\rho = \partial U / \partial J$ where J is the current density);
- 3) the voltage U_d at which the Stable Discharge Glow (SDG) is disturbed;
- 4) and the corresponding current value I_d .

As demonstrated in Figure 1, the potential drop across the discharge gap in this range was nearly constant and the electric field increased only at the semiconductor cathode. The resistance of the semiconductor cathode is dependent on its thickness in the range $10^5 - 10^8 \Omega$. The intensity of the gas discharge glow around the electrode depends on the total resistance of the circuit Ni–Si–air gap–SnO₂. Filamentation phenomenon can only be observed when the resistance of the semiconductor is less than a certain critical value for a given thickness. It was also observed that the critical resistance is dependent on the residual pressure of the system [9].

In Figure 1, curves 1–3 represent the CVC for different resistance $R_1 - R_3$ of Si cathode (for different illumination intensities of light) and C, F, K represent the points that the SDG (a) ends and disturbances start (b). Figure 2 is a schematic diagram illustrating the range of stable operation of the cell, which is the generalization of the information obtained from the CVC in Figure 2. The voltage U across the discharge cell is plotted against the gas pressure. For a discharge breakdown voltage, curve A, is the well-known Paschen curve [12] at constant gap distance d (without illumination). The shaded area in Figure 2 shows the range of SDG. In Figure 2, R_1, R_2 are the two different resistivity values of the photoconductor corresponding to illumination intensities L_1, L_2 . The breakdown voltage U_B at a particular pressure p' is obtained from Paschen curve A (point E). The SDG can be observed up to voltages U_{d1} (point C) and U_{d2} (point F) for resistance R_1, R_2 respectively. Thus, the voltage at the point F and C characterizes the beginning of the stability disturbance for R_1, R_2 .

2. Experimental

The CVC of the gas discharge cell are obtained experimentally as functions of the gas pressure p (21.3 – 466.5 hPa), and inter-electrode distance d (10 μm – 5 mm), which were varied in sufficiently wide ranges for the first time.

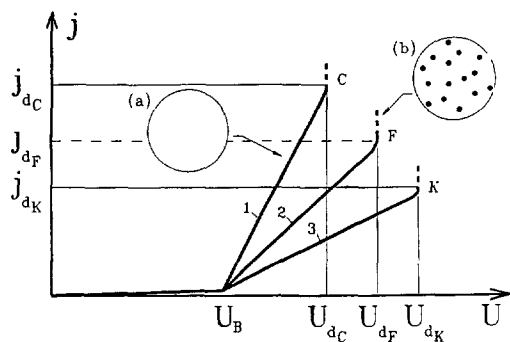


Fig. 1

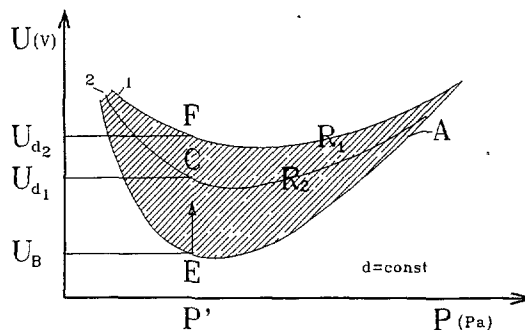


Fig. 2

Fig. 1. — A typical set of CVC of a planar discharge cell for different illumination intensities of the semiconducting cathode. Curves (1, 2) represent the CVC for different resistance of semiconducting cathode and C, F and K represent the points that the SDG (a) ends and disturbances start (b).

Fig. 2. — The schematic diagram showing the range of stable operation of the cell with semiconducting cathode. R_1 and R_2 are the two different resistance values of the cathode corresponding to two different illumination intensities. The breakdown voltage U_B at a particular pressure p' is obtained from Paschen curve A (point E) and SDG can be observed up to voltages U_{d1} (point C) and U_{d2} (point F) for R_1 and R_2 , respectively.

The material of the photosensitive cathode consists of platinum doped silicon [14]. The measurements were carried out by cooling the semiconductor down to 90 K. This was done to reduce the thermally generated carriers in the semiconductor. The diameter of Si plate is 30 mm and its thickness is 1 mm. This photodetector material has a maximum sensitivity at the wavelength $\lambda = 2.3 \mu\text{m}$. The illuminated side of the Si is covered with a highly conducting thin Ni film, which is transparent in the IR spectral range. The anode is a disk of glass (diameter 30 mm, the thickness 2 mm) coated with a thin layer of a transparent conductor SnO_2 . The semiconductor cathode is uniformly illuminated by the light of an incandescent lamp with a Si-filter in front, transmitting the wavelengths $1 \mu\text{m} < \lambda < 3 \mu\text{m}$. The maximum illumination intensity L_{max} is around $10^{-4} \text{ W cm}^{-2}$. Intensity of the light incident on cathode was changed by filters. The discharge gap of the cell was filled with atmospheric room air. In the IR region the photoconductivity in Si is attributed to platinum impurities. The applied voltage was adjusted using a sensitive rotator attached to a variable resistor to attain high uniformity of potential difference. The rate of change of voltage can be altered between 0.01 to 1 V s^{-1} . The maximum sensitivity for the current axis was $10^{-9} \text{ A cm}^{-1}$ and for the voltage axis it was around 0.5 V cm^{-1} .

Scheme of the gas discharge cell with semiconducting cathode is shown in Figure 3. In all cases after a gas breakdown 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.

It should be noted that during the illumination of the sample through the Ni contact the observed increase in photocurrent cannot be attributed to additional illumination by gas discharge itself. The direct measurements of a spectral composition of the gas discharge radiation

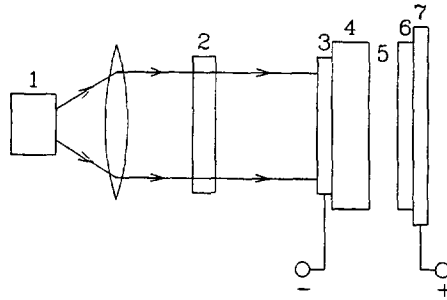


Fig. 3. — The basic scheme of the gas discharge cell with semiconducting cathode: (1) light source, (2) Si-filter, (3) transparent conducting Ni layer, (4) Si cathode, (5) air gap, (6) transparent conductor SnO_2 , (7) disk of glass.

in the range of $0.3\text{--}1.8\ \mu\text{m}$ were studied by Lebedeva *et al* [11]. The above radiation was observed only in the UV/blue spectrum ($0.336\text{--}0.45\ \mu\text{m}$), while in the IR region the glow was not revealed. Therefore we consider that the plasma radiation does not affect the photocurrent of the semiconductor.

3. Results and Discussion

Figure 4(a,b) shows the regions of SDG of the cell with respect to pressure for the system using Si cathode. The values of d are indicated on each figure. It should be noted that the voltage in the shaded region is the potential drop on the cathode, while the value from 0 to U_B is mainly the potential drop at the discharge gap. As it can be observed from Figure 4, the range of SDG can be expanded by increasing the conductivity of the cathode and the conductivity can be adjusted by the illumination intensity. The shaded area shows the expanded range of SDG, when the resistance is decreased from R_1 to R_2 through illumination, for the intensities L_1 30% of L_{max} and L_2 60% of L_{max} . The resistivity of semiconducting cathode is calculated from $C\text{--}V$ measurements. In the system cell the current density can be locally increased by illuminating the photoconducting semiconductor in the range of its sensitivity. This is followed by increasing the brightness of the discharge glow in the visible spectral range. The internal photoeffect mechanism in semiconductors is responsible for the broad range of the system sensitivity in the IR spectral range [11]. Considering these diagrams for the Si cathode at different values of the discharge gap length d (at $T \sim 90\ \text{K}$ shown in Fig. 4), one can note the followings:

- 1) In the ranges of relatively small d values ($26\text{--}100\ \mu\text{m}$) a wide range of SDG exists for the pressures ($21.3\text{--}466.5\ \text{hPa}$) and changing the resistance of the semiconducting cathode from $R_1 = 2 \times 10^8\ \Omega$ (corresponding to the illumination intensity L_1) to $R_2 = 1.2 \times 10^8\ \Omega$ (which corresponds to L_2) further expands SDG region.
- 2) The pressure region for the SDG is narrower ($21.3\text{--}466.5\ \text{hPa}$) and can never reach to the atmospheric pressures.
- 3) As a rule, a decrease of the resistivity of the semiconducting cathode due to illumination is found to increase the voltage range characterizing the stabilization region.

Figure 5 gives the variation of breakdown voltage U_B with respect to the pressure for the interelectrode distance $30\ \mu\text{m}$. Figure 5 also shows the variation of the upper limits of current

SI-PHOTODETECTOR

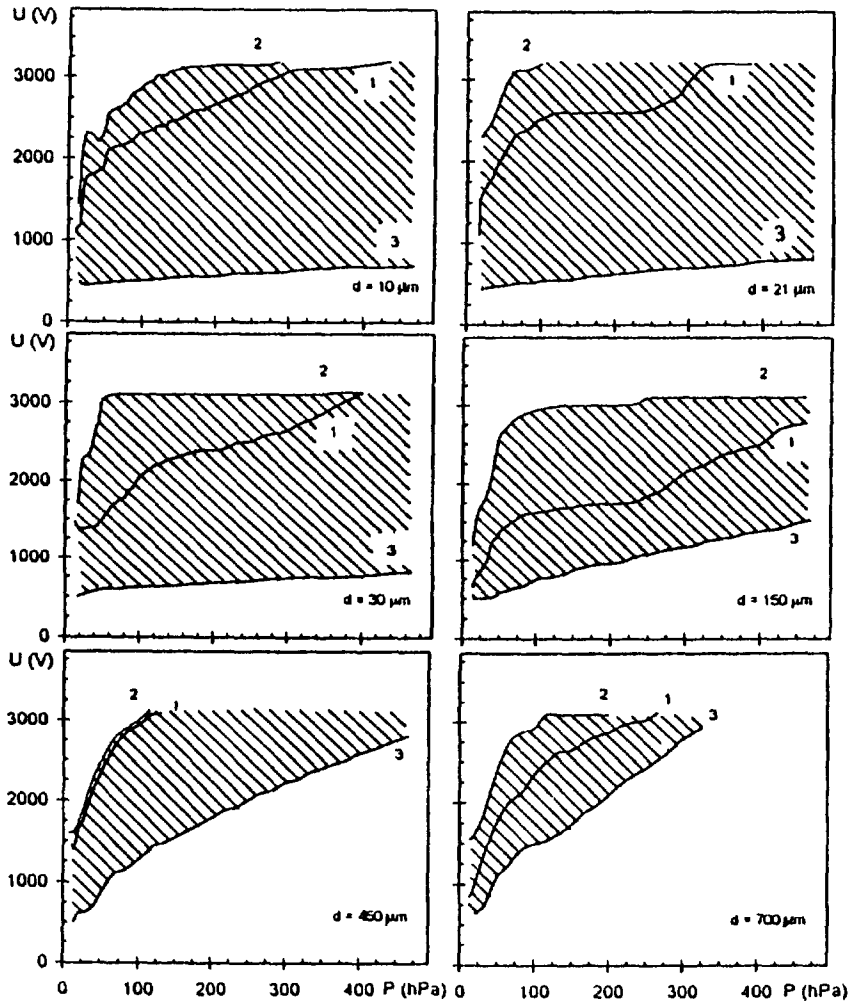


Fig. 4. — Regions of SDG for the resistances R_1, R_2 of a platinum-doped silicon cathode for the illumination intensities $L_1, L_2, T = 90$ K. Curves (1) and (2) correspond to two different voltage U_{d1} and U_{d2} respectively at which the SDG is disturbed. Curve (3) corresponds to breakdown voltage U_B at a particular pressure p .

I_ℓ values (above which the SDG can not be observed), for three different illumination intensities of light ($L_1 > L_2 > L_3$), which lead to three different resistances of Si cathode (R_1, R_2, R_3).

Figure 6 presents the dependence of voltage U_d at which the disturbance of stability starts on a wider range of gap values of the gas discharge for Si cathode. In most cases, the lack of dependence of the limiting current, I_ℓ , or at least the existence of a weak dependence on the pressure can be concluded. In some cases, however, the decrease in the limiting current I_ℓ was observed only for the large discharge gaps.

It has been found experimentally that with the gap of some tens of micrometers and with a semiconductor thickness of about 0.5 mm, the resistivity required for a discharge stabilization

Si-PHOTODETECTOR

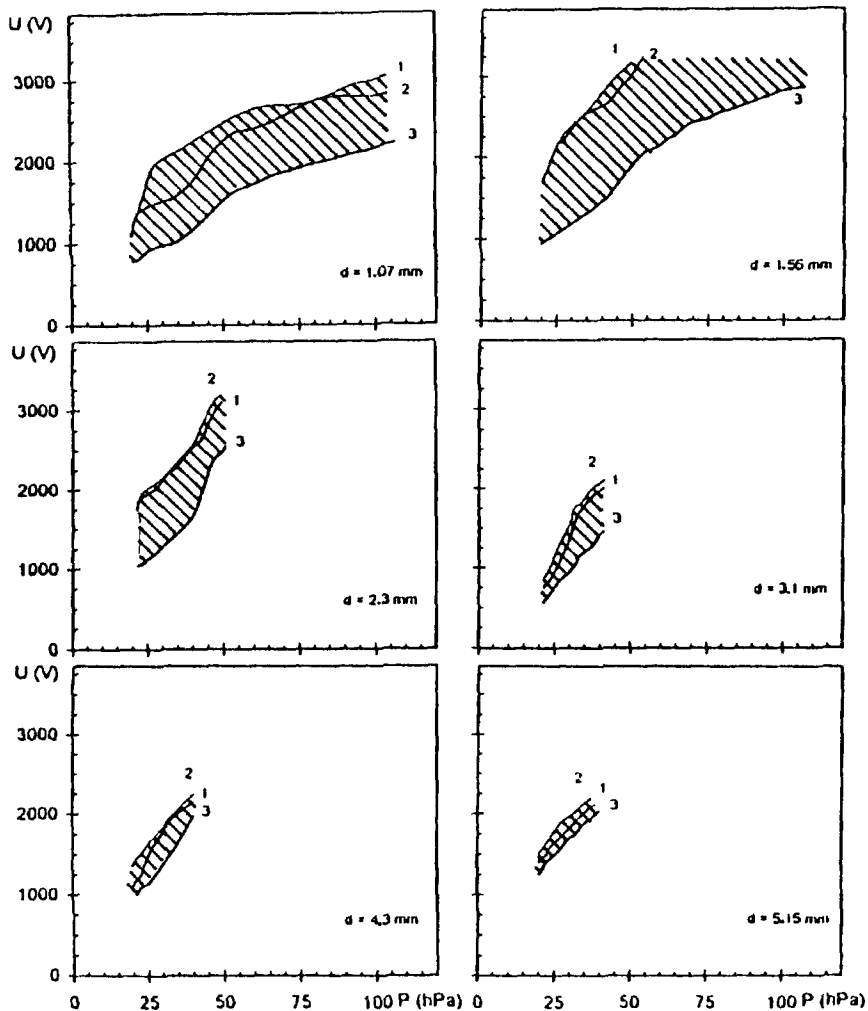


Fig. 4 — (Continued)

is equal to $10^6 - 10^7 \Omega\text{cm}$. The decrease of the resistivity due to illumination even by 3–4 order of magnitude was found not to cause the break of stabilization [9].

A qualitative characteristics of the phenomenon is as the following. with the fluctuation formed in the gap and accompanied by the current increase, there occurs the charge accumulation at the semiconductor-plasma interface leading to decrease the voltage on the discharge gap and to quenching of fluctuation, *i.e.* to the transition of the CVC of the discharge to the range of negative differential resistivity

In discussing these experimental results, it was primarily necessary to determine which type of discharge we were dealing with in a cell with a semiconductor cathode. 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

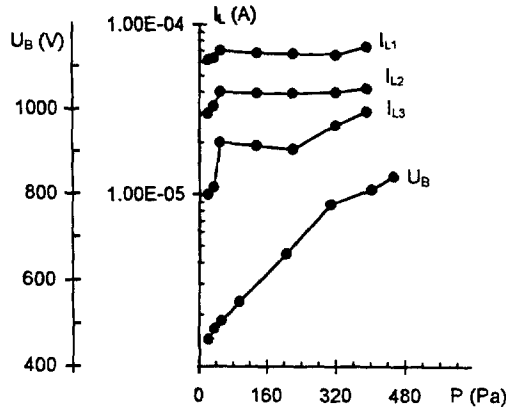


Fig. 5. — The breakdown voltage U_B and limiting current I_l dependence on the value of residual pressure at the length of the discharge gap of $d = 30 \mu\text{m}$. Curves (1, 2, 3) correspond to three different resistances $R_1 = 5 \times 10^7 \Omega$, $R_2 = 1.2 \times 10^8 \Omega$, $R_3 = 2 \times 10^8 \Omega$ of Si cathode.

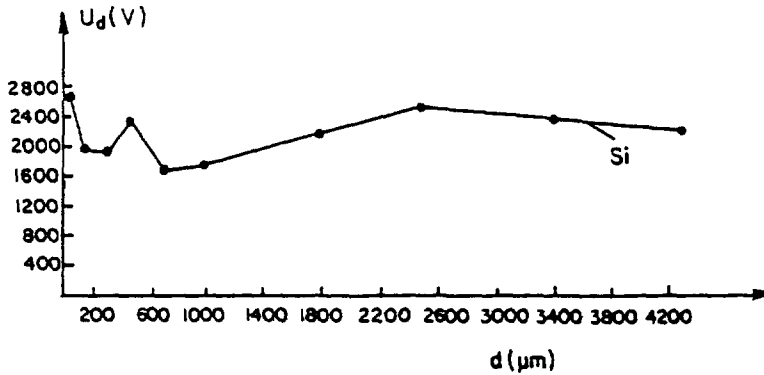


Fig. 6. — The dependence of the stability disturbance voltage U_d on gas discharge gap d for Pu doped Si semiconducting cathode.

ways. It occurs at a specific surface, which in the case of the cathode determines the value of the coefficient γ in the Townsend theory [14].

Thus, the presence of a semiconducting cathode affects the gas breakdown not specifically through the γ coefficient, and the condition of transition from a Townsend semi-self-maintained discharge to the Townsend self-maintained discharge is a common case provided the equality $I = I_0 e^{\alpha d} / [1 - \gamma(e^{\alpha d} - 1)]$ or $\gamma(e^{\alpha d} - 1) = 1$ is satisfied, where I is the discharge gap current, I_0 is the initial current caused by external ionizer, α is the ionization Townsend coefficient characterizing the volume ionization, γ is the effective coefficient of a secondary emission from cathode which can be due to positive ions, photons and metastable atoms generated in gas by electron impact excitation.

This coefficient has a strong influence on the discharge breakdown voltage. An analysis of the experimental results on the breakdown voltage, obtained for a GaAs cathode with a resistivity $10^8 \Omega \text{ cm}$, 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 [15]. In the case of a cell with Si cathode there is a considerable deviation from the above mentioned standard curves. To the best of our knowledge, there is no published information

on the discharge breakdown potential for a cell with a semiconductor cathode. The special features of the semiconductor cathode 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 concentrated external limiting 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 cathode.

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 [12] 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 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 assume with difficulty 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 CVC, 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. The reverse transition from the glow discharge to the Townsend one is accompanied by a hysteresis loop. In practice one of the most important properties of the cell was the stability of the CVC during illumination. Investigations of the current kinetics indicated that after the end of charging of the cell with semiconducting cathode, the current varied rapidly with time for several second. The nature of the current kinetics was a function of the current direction and magnitude. After several second, the CVC became stable and did not change for ten minutes in the low-current range. The voltage corresponding to zero current remained constant for exposures exceeding 1 h.

Considerable difficulties were encountered in obtaining reproducible discharge operating voltages. Especially at low pressures, the discharge voltage at currents below about $1 \mu\text{A}$ was found to drift badly as the discharge was operated. An aging procedure was adopted that resulted in reproducible voltages. The aging current was chosen to give a laterally uniform discharge, *i.e.* no visible constriction. In addition, an increase in the low-current operating voltage was observed following discharge operation at high currents. This effect is attributed to a reduction in the gas density and, thereby, a reduction in the ionization rates resulting from changes in the cathode. The return to the low-current operating voltages was observed to correspond to the recovery time constant of 5–10 min for the cathode. For this reason, an effort was made to minimize the time required for CVC at the higher currents

It was estimated that the dependence of the field E on the distance along a line of current flow is given by [12]

$$E = \frac{E_c \sqrt{1-x}}{l} \quad (1)$$

or

$$l = \frac{\mu_+ E_c^2}{8pj} \quad (2)$$

where E_c is the field near the cathode.

E_c increases in the regions closer to the cathode, however, near the anode the field gets smaller and the current density increases. The plane xd , where the extrapolative quantity E of d becomes zero, for low currents and is situated far from the limits of discharge gap. The quantity l is a certain effective length representing the degree of distortion of the field. The vanishing of the field at the anode, namely when $l = d$, can be considered to be the criterion for a strong field distribution. This corresponds to the current density $j = \mu_+ E_c^2 / (8\pi d)$. If j is further increased, then, when $l < d$, the field becomes zero within the gap. In this case, the basic assumptions become invalid. Thus, the limiting current for the transition from the Townsend discharge to the glow discharge approximately corresponds to the following expression:

$$j/p^2 \cong \frac{(\mu_+ p) U_B^2}{8\pi (pd)^3} \quad (3)$$

where we use the relations $j = \mu_+ E_c^2 / 8pd$, $E_c d \sim U_B$. It is interesting to note that if the pressure and field dependences of ion's mobility are neglected, the limiting current of the discharge is almost independent of pressure. In our experiments, we have observed that this is valid in a wide range of pressures as seen in Figure 4.

The experimental data show mainly that the spatial stability of the discharge glowing in the cell with semiconducting cathode have the limitations both for small and large distributed resistance values. In these regions, the physical nature of the current filamentation is different. The disturbance of spatial stability in discharge is determined by the bulk charges in the gas discharge gap that causes a considerable distortion of electric field, typical of the transition to the glow discharge. An approximate criterion of "strong distortion" is the decrease of field strength down to zero on the anode, *i.e.* at the edge of the discharge gap. The maximum current transmitted by discharge without a strong field distortion is observed in the case of low resistance. The value of the current in this case depends only on the mobility of positive ions and interelectrode distance.

In the case of a high resistivity of a semiconductor cathode, the ionizing effect of the active components of the discharge on the semiconductor becomes important. In fact, at very high values of resistivity of the cathode, 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. Such a carrier generation occurs in a very thin skin layer (short-wavelength radiation, ~ 100 eV electrons, and ions). The carriers, aided by the field, then deeply penetrate into of the semiconductor, where they can modulate the conductance. The following process resulting in a local increase in the current then occurs. The modulation of the bulk of the semiconductor cathode and a reduction in its resistance increase the current in the plasma, and also increase the intensity of the glow 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 CVC 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 semi-insulating GaAs when it was illuminated [16]. It manifested itself by spontaneous contraction of the radiation emitted by the gas discharge, initially distributed uniformly over 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.

This mechanism of spatial stabilization 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.

As a rule, if we used semiconductor as an anode, then the glow stability usually causes a disturbance at lower applied voltages. This is probably due to the electron bombardment of the cathode surface. In our experiments the observed current concentration does not lead to a destructive disturbance of the semiconductor.

Acknowledgments

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