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ELECTRICAL INSTABILITY IN A SEMICONDUCTOR GaAs DISCHARGE SYSTEM

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Electrical instability in a semi-insulating (*SI*) *GaAs* plates of the semiconductor gas discharge gap system (*SGDGS*) is studied experimentally in a wide range of the gas pressures, interelectrode distances and different diameters of the cathode areas. While being driven with a stationary voltage, it generates current and discharge light emission (*DLE*) instabilities with different amplitudes of the oscillation. It is shown that under the experimental conditions the interelectrode distance played only a passive role and was not responsible for the appearance of the *DLE* instability. At the same time for different diameters *D* of the *GaAs* plate areas the expanded range of current and *DLE* oscillations are observed. *SGDGS* with an *N*-shaped *CVC* was analyzed using both the current and *DLE* data showing the electrical instability in the *GaAs* cathode. It was found that application of high feeding voltage to this cathode give rise to non-uniform spatial distribution of the *DLE*, which disturbed the operation of the system. The experiment presents also a new metod to study and visualization of the electrical instabilities in high-resistivity *GaAs* plates of large diameter.

I. INTRODUCTION

This article covers the electronic instability in semi-insulating (*SI*) *GaAs* at high applied dc voltages. The theory [1] and experiment [2] showed that the current flowing through a semiconductor can oscillate if a sufficiently high dc bias is applied to the sample. These oscillations are caused by domains of high electric field that travel from cathode to anode. Electronic phenomena that occur at a contact between a semiconductor and a gas discharge plasma have a number of special features and have been among the least investigated semiconductor contact phenomena. Penetration of a double electrical layers charge 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 makes it possible to control both the current and the radiation emitted by the gas discharge [3,4]. However, technological plasma devices [5,6] often use discharge cell in which the photo-sensitive cathode diameter is much larger than the distance between the cathode and anode. At present, there is extensive research aimed at establishing the optimum conditions for obtaining homogeneous discharges in various gases and various discharge gap geometries (see, e.g., [7,8]). Recently [9], we observed complicated behavior of a planar “semiconductor–gas-discharge gap” system (*SGDGS*) with a *SI-GaAs* cathode.

It is suggested that the observed current and discharge light emission (*DLE*) oscillation is due to the coupling of processes in two components, the *SI-GaAs* cathode and gas discharge gap when a dc voltage of a high enough magnitu-de is applied to a system. Distributed semiconducting media frequently exhibit the formation of self-organized localized structures, a classical example being offered by the spontaneous formation of field domains in systems with *N*-shaped current–voltage characteristics (*CVC*) [1]. Therefore, in this work, electrical instability in a *SI GaAs* cathode of the

SGDGS is studied experimentally in a wide range of the gas pressures *p* (28-550 Torr), interelectrode distances *d* (45-330 μm) and different diameters *D* (5-22 mm) for the first time to our knowledge. It is suggested that active properties of *SI GaAs* cathodes that manifest themselves at high electric fields play an important role in the observed phenomena. We remark also that *SGDGS* with a *SI GaAs* cathode can serve as fast converters of *IR* images to the visible [10]. Therefore, studying the stability of their operation is important for these and other technical applications [11].

2 EXPERIMENTAL PROCEDURE

In this work, we will compare transport properties of structures of the two types, one of which contains a *SGDGS* with a *SI GaAs* cathode [7]. Both structures sequentially operate with the same *SI -GaAs* sample. The setup used here is similar to that applied earlier [9], where a *SGDGS* with a *SI GaAs* (ρ ~10^8 Ωcm) cathode was studied at room temperature. The diameter and the thickness of the *GaAs* cathode were 50 mm and 1 mm, respectively. On the illuminated side of the cathode, a conducting vacuum-evaporated *Ni*-layer with approximately 40 nm thick was coated. This layer was transparent to the *IR* light. The anode was a disc of glass (with 50 mm diameter and 2 mm thickness) coated with a thin layer of a transparent conductor SnO_2 (i.e. in the *UV* and visible (blue) region). The sheet resistance of the SnO_2 layer is in the range between 15 and 20 Ω/ sq and that of the *Ni* film is of the order of 10 Ω/ sq. The resistances are negligible when compared with the sheet resistance of the *GaAs* layer, which is 1.5 x 10^8 Ω/ sq in the nonirradiated case. The discharge gap between the glass plate and the semiconductor is filled with atmospheric room air. By applying a high voltage V_0 between the *Ni* contact and the SnO_2 layer, a discharge is ignited in the gap. This corresponds to a discharge operating in the Townsend regime (this stable form of discharge is employed in spectral image converters [7,12] with photosensitive *GaAs* cathode possessing linear *CVC*s). For further details, see [9]. The two parts mainly specifying the properties of the system are a semiconductor and a gas layer. Using the data obtained under these conditions, it is possible to conclude that the current and *DLE* instabilities readily observed in the *SGDGS* are generated by the semiconductor element and, hence, can exist in the absence of *SGDGS* as well. The light of an incandescent lamp in front illuminates the cathode uniformly. The illumination intensity is varied in the range 10^{-6}–10^{-2} W/cm^2 by the use of neutral density filters. The total current *I* and *DLE* through the discharge cell and the voltage drop *V* between the electrodes are recorded simultaneously. The assessment of the light intensity was then based on analysis of the *DLE* (330–440 nm), recorded through a transparent anode. The *DLE* from the cell was measured using a computerized photon counting unit. The photomultiplier tube of the unit has a high sensitivity in the *UV*-blue region of the spectrum which coincides with the emission from the cell.

3. RESULTS AND DISCUSSION

The experimental results were tested by measuring the *CVC* curves for a Townsend discharge in an air at dc voltages $V_0 \leq 1000$ V and pressures $p \approx 28 \div 550$ Torr. Such a discharge is supported by the electrode processes and by the multiplication of the number of charged carriers in the gas volume due to the avalanche mechanism. Figure 1 shows the *CVC* of the *SGDGS* in parallel-plane geometry with different conductivity of the *SI GaAs* cathode, which was varied by its uniform illumination. We assume that a homogeneous stationary Townsend discharge [13] is established in the gap at appropriate breakdown voltage V_B. This mode of discharge is observed for low currents between the point of ignition and the point where negative differential conductivity (*NDR*) is observed in the gas characteristic. The *CVC* of the system is very close to a linear curve if $V > V_B$, reflecting the Ohmic behavior of the semiconductor cathode [14]. The voltage drop at the discharge gap for this discharge mode is independent of the current. Therefore, the slope of the *CVCs* provides the resistance of the *SI GaAs* cathode. Then, the specific conductivity can be computed from this resistance and the geometric dimensions.

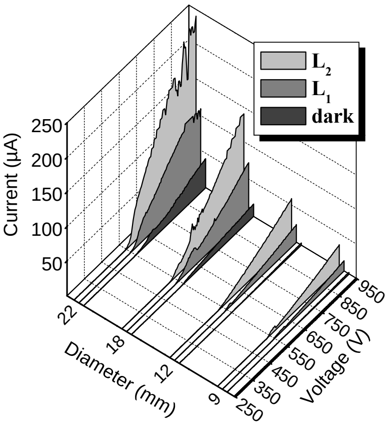

Fig.1. *CVC* of a semiconductor gas discharge structure in darkness and under a weak and a maximum illumination intensity L_1 and L_2, respectively. The curves represent the *CVC* for different diameters *D* of the *GaAs* photodetector

The resistivity of the *GaAs* semiconductor decreases monotonically when the intensity of the external irradiation is raised. At the same time for different diameters *D* of the cathode areas the expanded range of current oscillations are observed. Curves in figure 1 represent the *CVC* (i.e. in darkness and under a weak L_1 and maximum illlumination intensities of light L_2, respectively) when the resistivity of the semiconducting cathode is decreased from ρ_1 = 1.5 x 10^8 Ωcm to ρ_3 = 4 x 10^7 Ωcm through illumination. Figures 2a,b gives detailed information regarding the regions of current oscillations of the cell with respect to pressure when a dc voltage of a high enough magnitude is applied to a system. It should be noted that the voltage in the oscillation region is the potential drop across the semiconducting cathode, whereas the value from 0 to V_B is mainly the potential drop at the discharge gap.

As can be observed from Fig.2, the range of current oscillations depend on the diameters *D* of the electrode areas. Considering these figures for the *SGDGS* with *GaAs* cathode at different diameters *D* of the electrode areas, one can note the following: ***a***) for small values of the diameters *D* (e.g. $D = 5$ mm) the current oscillations (i.e. starts at approximately $1,0x10^{-5}$ A) exists for the pressures (44÷160 Torr); ***b***) for large values of the diameters *D* (e.g. $D = 22$ mm) the current oscillations starts at approximately $1x10^{-4}$ A.

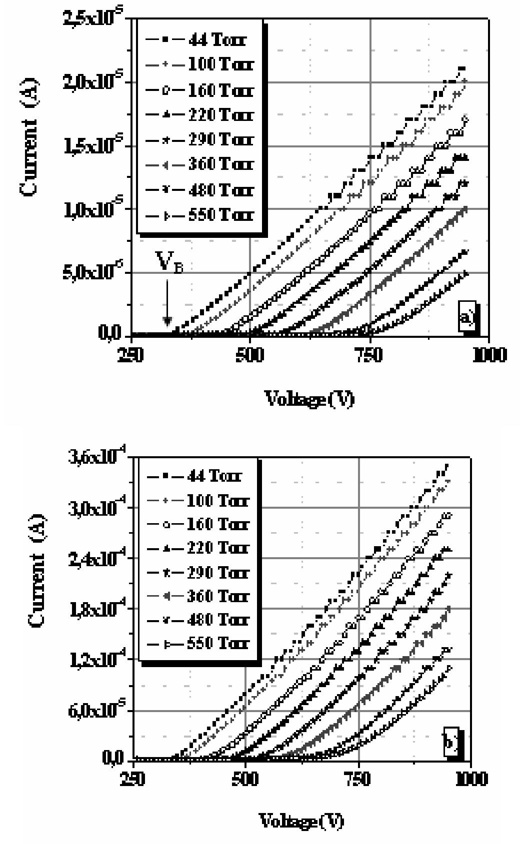

Fig.2 Regions of current oscillations with respect to pressure for a maximum illumination intensity L_2 and different diameters of the *GaAs* cathode: a) D =5 mm; b) D =22 mm. The 45 μm thick discharge gap *d* is filled with air.

An example of the *N*-type *NDR* in the *SI GaAs* cathode is shown in Fig.3. A change in the illumination intensity does not lead to a significant shift of the critical voltage V_{cr} at which the current *I* begins to drop with increasing voltage *V*. When the cathode was illuminated in the *IR* range (by light with $\lambda \geq 1$ μm passed through a silicon filter), the *N*-like character of the *CVC* curve was pronounced. When the voltage *V* approaches the threshold level V_{cr} from below, the current *I* in the structures exhibits oscillations of a relatively small amplitude. Such a behavior of *SI-GaAs* samples has been observed previously (see, e.g., recent review [2] devoted to the problem of domain instability in *SI GaAs*). For $V \geq V_{cr}$, the current usually oscillates in a broad range of voltages, whereby both regular and irregular variations can be observed. As is known, current pulsations of large amplitude in such materials are related to the dynamics of electrical domains (generation, motion along the sample, and damping at the contacts). It is suggested that electrical instability observed in the samples of this type is related to an increase in the rate of trapping carriers by *EL2* centers heated by the electric field [2].

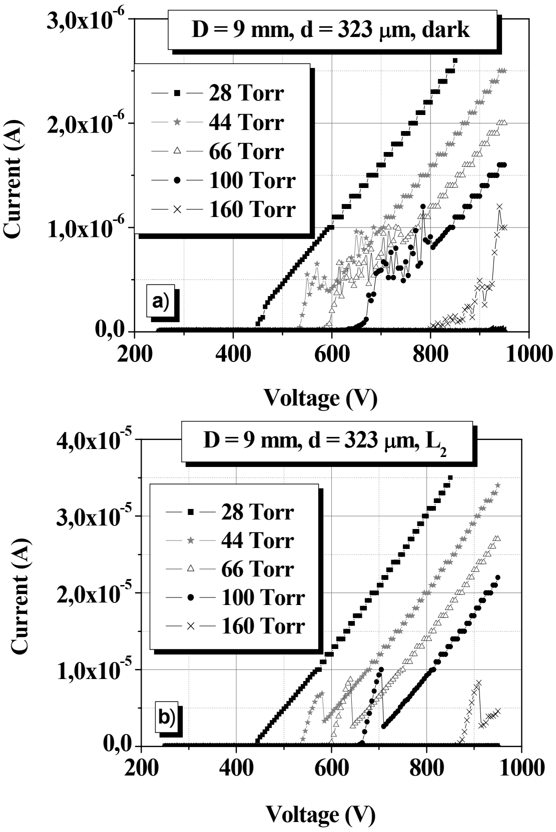

Fig.3 *N*-shaped *CVC*s of the *SGDGS* with *GaAs* cathode in darkness (a) and under a maximum illlumination intensity L_2 (b), respectively. The diameters of the *GaAs* cathode $D = 9$ mm and the 323 μm thick discharge gap *d* is filled with an air.

The electrical instability of the *GaAs* cathode in a planar *SGDGS* was analyzed using both the current and *DLE* data is shown in Fig.4. (This structure is the basic component of the infrared image converter; for details see, e.g., [10]). Three typical cases, for darkness and under a weak L_1 and a maximum L_2 illlumination of the cathode, are represented in Fig.4a. A comparison of our data for the *SGDGS* and data obtained by other authors for *SI GaAs* semiconductor [15] (in this case system differs from the well-known *SGDGS* [16] with *GaAs* cathode in that the emitting surface of the cathode facing to the gas discharge was coated with a thin metal film and served as the other contact) shows that the presence of the gas discharge region does not significantly modify the character of the charge transport in the system studied. Simultaneously with the *CVCs*, the *DLE* intensity was recorded. For the thin discharge gap of the cell the proportionality between the gas brightness and the current density *j* can be observed in broad range of *j*.

Figure 4b shows that the behaviour of the *DLE* in the *SGDGS* with different conductivity σ of the *GaAs* cathode is more sensitive to the current oscillation. Therefore the *DLE* is more clearly demonstrated the current instabilities in *SI GaAs* cathode. Comparison of the curves in Fig.4a,b gives evidence that the *N*-shaped *CVC*s of the *GaAs* cathode is retained in the *SGDGS*. In relation to these data, we notice that crystals of *SI GaAs* used in the experiments, were produced using the *LEC* (liquid encapsulated Czochralski) method [11]. So called ''pure'' semi-insulating crystals that are obtained by this technique are known to have a high resistance at room temperature due to the compensation of residual impurities by deep electronic levels of defects, the so called *EL*2 centers [11,14]. The presence of these defects is believed to give rise to the *N*-type *NDR* of the material and, as a consequence, to oscillations in current when a dc voltage of a high enough magnitude is applied to a sample [17]. The effect is governed by the increase of the efficiency of trapping the carriers by centers, while their kinetic energy grows at strong electric fields.

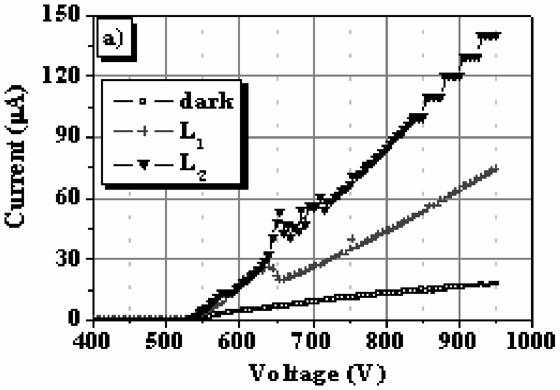

Fig. 4a CVC of the system with a *GaAs* cathode for three resistivity of the semiconducting cathode for p = 44 Torr, D = 18 mm, d = 323 μm: in darkness and under a weak and a maximum illumination intensities L_1 and L_2, respectively.

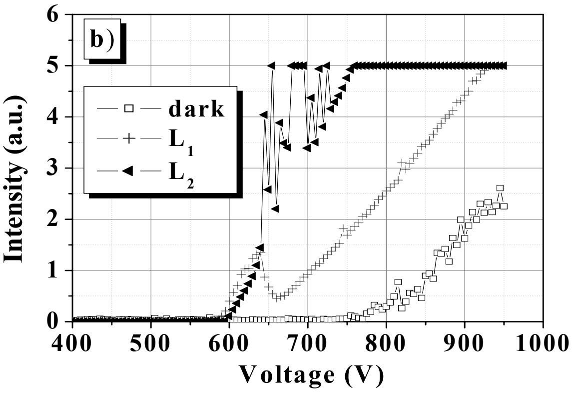

Fig. 4b The behaviour of *DLE* of a *SGDGS* for three resistivity of the semiconducting cathode for p = 44 Torr, D = 18 mm, d = 323 μm: in darkness and under a weak and a maximum illumination intensities of light L_1 and L_2, respectively.

The similarity of the transport properties in the *SGDGS* and in a structure without a gas-filled gap [15] gives us ground to suggest that the current and *DLE* oscillations in the unstable regions are similar as well. Therefore, by studying the *CVC*s and *DLE* observed in the *SGDGS*, we can judge the current instabilities in a structure without a gas-filled gap. As is known, the nature of instability of the stationary current in *SI-GaAs* with an *N*-like *NDR* characteristic is related to the formation and motion of electrical domains. This instability may give rise to a complicated pattern of charge transfer in the semiconductor, thus revealing a new property of systems with the *N*-like *NDR* characteristic. These dynamics of the current instabilities resembles structures of the "guiding center" type extensively studied in the case of chemical reactors featuring oscillatory reaction regimes [18]. It should also be noted that the current oscillations in the unstable regions may negatively affect the characteristics of instruments based on *SI-GaAs* [19].

4 CONCLUSION

The dependence of the current and *DLE* instabilities in a *SGDGS* on control parameters is investigated. It is found that active properties of *SI GaAs* cathodes that manifest themselves at high electric fields play an important role in the observed phenomena. It is believed that the presence of the deep electronic levels of defects, the so called *EL*2 centers, give rise to the *N*-type *NDR* of the material, as a consequence, to oscillations in *DLE* when a dc voltage of a high enough magnitude is applied to a *GaAs* cathode. Thus, the current instability with low-frequency oscillations that are due to dynamical of electrical domains, namely, by their generation, movement and decaying are observed in the system. It should be noted that under the experimental conditions the discharge gap played only a passive role and was not responsible for the appearance of the current instability. Our experimental investigations also confirm that by studying the *CVC*s and *DLE* observed in the *SGDGS*, we can judge the current instabilities in a structure without a gas-filled gap. The experiment presents also a new metod to study of the electrical instabilities in high resistivity semiconductor plates of large diameter.

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