Study of non-thermal plasma discharge in semiconductor gas discharge electronic devices

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Current and discharge light emission (*DLE*) behaviors are studied experimentally in *neon* as a function of pressure *p* (30-760 Torr), interelectrode distances *d*(330 µm–530 µm) and diameter *D* (9 mm -18 mm) of the cathode in a semiconductor gas discharge electronic device (*SGDED*) with *GaAs* cathode. The discharge features of *neon* are investigated under low and atmospheric-pressures non-thermal microdischarge conditions. Experimental analysis has been made using *N*-shaped *CVCs* and time-dependent current and *DLE* to understand the features of *Ne*. Dynamic behavior of current is obtained within the feeding voltage of *U* = 200–1200 V under different *IR* light intensities incident on cathode material. If the applied electric field is much higher than the critical one, oscillatory behavior develops. While accelerating electrons produce ionizations with sufficient energies, the double layer acts as an internal source of charged particles. Current and *DLE* from the discharge burning up to atmospheric pressure in *Ne* usually has homogeneous form, however non-homogeneous *CVC* forms are observed under specific conditions.

1. Introduction

Particular interest has been given lately to the study of electronic microdischarge devices [1,2]. Some microplasma devices have been developed in environmental, *UV* radiation source and plasma-reactors fields [3]. In particular, it has been found that a planar semiconductor-discharge gap' (*SDG*) structure represents an experimentally flexible microelectronic device where patterning of electrical current may proceed at a quite low power density dissipated in the system [4].

Semiconductors which are frequently used in above mentioned devices are complex nonlinear dynamic systems which exhibit current instabilities and self-organized formation of spatio-temporal patterns under the influence of strong electric fields [5,6]. Semi-insulating (*SI*) *GaAs* is now being reconsidered as a promising material for radiation detectors, mostly due to greatly improved quality of the material. Negative differantial resistance (*NDR*) of the Current voltage characteristics (*CVCs)* was shown to originate from the microscopic properties of the bulk material [7] under non-termal plasma discharge conditions. In the case of *NDR* a longitudinal spatio-temporal instability leading to the formation of traveling field domains was discovered, which has become a well-known subject of applications as, for instance, in the Gunn effect [8]. Neumann [9] presented a review about the slow propagation of electric-field domains in *SI GaAs*. Low frequency oscillations (*LFO*) in *SI GaAs* samples consist of spontaneous oscillations due to a high applied electric field, characterized by pulses in the external current of the electric circuit. When an electric field above 1 kV/cm is applied to the *SI GaAs*, *LFO* [10] occurs as a result of the formation and propagation of a high-electric field domain, which is formed by the electric-field-enhanced capture of electrons by the *EL2* level [11]. In [12,13] we observed complicated behaviour of a *SGDED* with a *SI-GaAs* cathode.

If the *CVC* of the semiconductor cathode is a nonmonotonic one, instability develops in a semiconductor cathode, which may initiate formation of instabilities in the device. Such a case is considered in this work for *Ne* media. When the *CVC* of the semiconductor cathode is monotonic and the gas-discharge part does not display active properties, the device can be operated stably in a broad range of current density. This property of the system is used in *IR* image converters [14].

The present work is originally directed towards the some important results on electrical instability in the *SGDED* as functions of pressures *p* from 30 to 760 Torr, discharge gaps *d* (323-525 µm) and diameters *D* (9-18 mm) in *Ne* for the non- thermal plasma condition. The aim of this investigation is to detect, in more detail, the relation between the geometrical parameters and the discharge characteristics in *Ne* in order to provide the cell optimization. Presently, dielectric data for *Ne* is scarce, and the performance can only be predicted in terms of analogy [15]. *Ne* is often used in gas discharge applications including light sources, gas discharge lasers [16], plasma displays [17] and particle counters. Besides, the homogeneity of the *DLE* is very desirable for industrial applications, especially for surface treatment processes. Trunec et al [18] demonstrated that a diffuse dielectric barrier discharges (*DBD*) can be generated in *Ne* as well. But the character of the discharge remains unknown at this point of time.

2. Experimental

In *Ne* media, we compare transport properties two types of structures one of which contains a *SGDED* with a *SI GaAs* cathode [19]. Both structures (Fig.1) sequentially operate with the same *GaAs* sample. The *SGDED* have two main parts including a cathode and a gas layer which specifies the basic properties of the system.
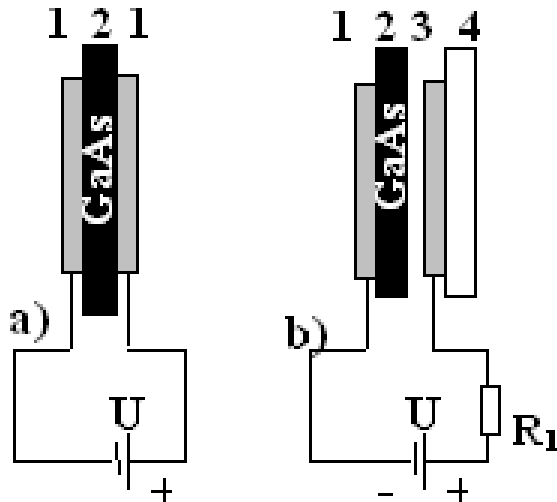

Fig. 1. Investigated structure (a) in the absence and (b)in the presence of a gas discharge gap: 1 – Ni contact; 2 - GaAs photocathode 3 – gas discharge gap; 4 - anode.

A gas layer is sandwiched between the glass plate and the semiconductor plate in Fig.1b (for more details, see Ref. [20]). In the experiments, a *SI GaAs* [14], an n-type high resistivity ($\rho \sim 10^8$ Ωcm) plate oriented (100) in the plane of natural growth of the crystal, is used as a semiconducting detector. The diameter and the thickness of the *GaAs* cathode are 50 mm and 1 mm, respectively. On the illuminated side of the detector, an approximately 40 nm thick vacuum-evaporated *Ni*-layer is coated. The anode is a disc of glass (with *D* = 50 mm and 2 mm thickness) coated with a thin layer of a transparent conductor SnO_2. The sheet resistivitiy of the SnO_2 layer is at the range of 15 and 20 Ω/sq and this value for *Ni* film is of the order of 10 Ω/sq. The discharge gap between the glass plate and the detector is filled with *Ne*. 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 operation in the Townsend regime. The surface of the *GaAs* cathode was separated from a flat anode by an insulating mica sheet with a circular aperture at its centre.

Diameters of the effective electrode areas, *D* (i.e. gas discharge gap or diameters of the circular through-aperture in the insulator) are 9 and 18 mm. The *IR* radiation excites the photosensitive *GaAs* cathode of the cell providing control of the current density and *DLE* from the gas discharge gap.

3. Results and discussion

We have studied current and optical *DLE* from non-thermal *dc* plasma in *SGDED* with *Ne* gas. Detailed analyses of the *DLE* have been performed by measuring the *CVC* curves for a Townsend discharge in *Ne* at *dc* voltages $V_0 \geq 1000$ V and pressures $p \approx 28 \div 760$ Torr. Strictly speaking, 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. We believe that a homogeneous stationary Townsend discharge [21] is established in the gap at appropriate breakdown voltage V_B. The electrical breakdown development is followed by the emission of light from the gas atoms, which de excite after collisions with free electrons. The intensive excitations of lower energy levels allow step-by-step ionization [22], which is significant for establishing the discharge at small over voltages and low pressures in rare gases. Note that in the stationary regime, the lower atomic energy levels are strongly populated due to the collisions of atoms with electrons [23].

From the physical point of view the most important feature of this kind of gas discharge is that space charge effects in the gap are small and do not cause a distortion of the electric field between the electrodes. Another characteristic property is a homogeneous distribution of the current density perpendicular to the current flow. This mode of discharge is observed for low currents between the point of ignition and the point where *NDR* is observed in the gas characteristic. The *CVC* of the structure is very close to a linear curve if $V_0 > V_B$, reflecting the ohmic behaviour of the semiconductor cathode as also observed in [24]. 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 *R* of the *SI GaAs* cathode. Then, the specific conductivity σ can be computed from *R* and the geometric dimensions. Initially, representative plots of *CVCs* in cases of illumination intensities and cell pressures are given in Fig. 2 (a) and (b).
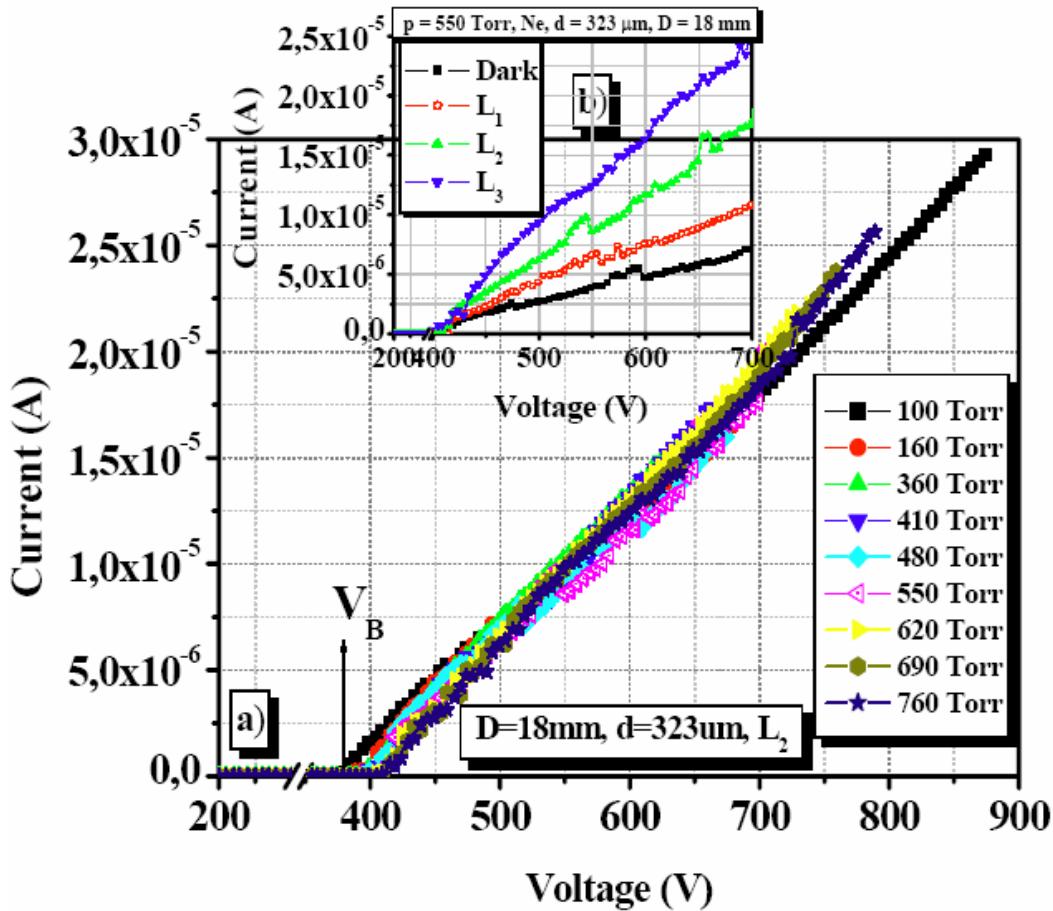
Fig. 2. (a) CVCs of the SGDED with GaAs cathode under moderate illumination intensity L_2 for different pressure p; (b) The inset shows the CVCs of the SGDED for different illumination intensities in the case of p = 550 Torr, d = 323 mm and D = 18 mm. The discharge gap d is filled with Ne.

According to the experiments, while higher voltages yield to high energetic electrons which are more able to cause impact collisions, higher pressures result in higher electron number densities and consequently more electron impact collisions. Fig. 2 (a) gives detailed information regarding the *CVC* of the *SGDED* in the wide pressure range up to atmospheric pressure *p* when a *dc* voltage of a high enough magnitude is applied to the system. The voltage value from V_B to feeding voltage V_0 applied to the electrodes 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.

An interesting observation is encountered with respect to the pressure. Although current values increase as function of voltage for different illumination intensities in the inset of Fig. 2, the current variations are seen to be very stable for different pressure values in Fig. 2 (a). On the other hand, current nearly remains without any changing or shifting in the cases of different pressures. It means that one can adjusts any pressure value between 100 and 760 Torr for different voltage states in order to obtain the same current values. In fact, the breakdown voltages also changes very slightly for different pressure rates. Thus we believe that the system is independent from

the pressure for this regime. However we cannot say the same conclusions for the illumination intensities in Fig. 2 (b); indeed, the illumination scenarios applied to the system give different results which yields to different current stages.

If a critical threshold voltage V_{cr} is applied to the semiconductor sample, the free carrier concentration grows in an avalanche-like manner and the current increases by orders of magnitude at an almost constant voltage due to current oscillation. In the case of the discussed experimental condition the presented results give the first experimental evidence for the existence of the oscillations in *SGDED*.

A different type of *CVC* is shown in Fig. 3 (a). Here *LFOs* in the *SGDED* with *SI GaAs* cathode is observed different from the case in Fig. 2 (a). The weak and moderate illumination intensities are around $L_1 = 8 \times 10^{-4}$ Wcm^{-2} and $L_2 = 2,5 \times 10^{-2}$ Wcm^{-2}, respectively. A change in the illumination intensity leads to a significant shift at critical voltage V_{cr} where the current begins to drop (I_{dr}) with increasing voltage V_0.

Current and *DLE* from the discharge burning up to atmospheric pressure in *Ne* usually has homogeneous form. But under specific conditions *CVCs* can be non-

homogeneous form. The stabilization effect is closely related to the *CVC* of both the discharge gap and the semiconductor cathode, and also to the spatial distribution of the discharge current over the cathode area. However, we have chosen the experimental parameters for the *homogeneous Townsend discharge* can be generated in the active area of the system. When V_0 approaches to the threshold level V_{cr} from low voltage side in Fig. 3 (a), the current I in the structures exhibits oscillations of a relatively small amplitude in Fig. 3 (a). Such behavior of *SI-GaAs* samples has been observed previously [9,13] in an *air*. In order to make a comparison, we also carried out some experiments in *Ne* media. For $V_0 \geq V_{cr}$, the current usually oscillates in a broad range of voltages, whereby both regular and irregular variations can be observed.

When the discharge current slightly exceeds the critical value, the contraction occurs near one of the electrodes and evolves to the other electrode. For example in Ref [25] some experiment results with *Ar* and *Ne* are given and stepwise contraction taking place at the current increase is followed by a similar stepwise transition to the diffuse form, if the discharge current then decreases.
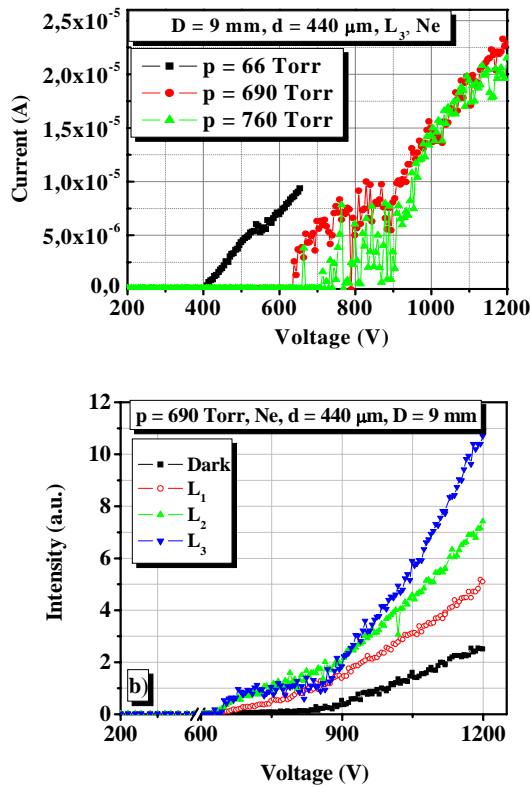

Fig. 3. (a) CVCs with N-type NDC of the SGDED at different pressure under strong illumination intensity of light L_3; (b) The behaviour of DLE of the SGDED for three ρ of the GaAs cathode for the Ne in the case of p= 690 Torr. The ρ_{sem} was changed from $7,3 \times 10^8$ Ωcm in the dark to 3×10^4 Ω cm at moderate illumination L_2.

Simultaneously with the *CVCs*, the *DLE* intensity was also recorded in the case of $p = 690$ Torr for different illumination intensities (Fig.3b). For thin discharge gap of the *SGDED*, the proportionality between the gas

brightness and the current density j can be observed in broad range of j. As also known from [12], current pulsations of large amplitude in such materials are related to the stable and reproducible *LFOs* are observed under the voltage range of *NDR* for non-thermal *Ne* plasma. Some higher order current oscillations and a chaotic behaviour are clearly observed under higher applied voltages. The primary amplitude of *LFO* is quantitatively explained by the ionized *EL2* concentration. These results prove that the origin of *LFO* in *SI-GaAs* [10] is the electric field-enhanced capture of electrons by the *EL2* deep donor level [9, 11].

Under the same discharge conditions, while the *N-type CVC* behaviours and *LFO* in *air* are observed at the lower pressures [20, 38], that behaviour in *Ne* gas is generally encountered between *p*=66-100 Torr. As a different feature from the case in *air*, such behaviours are also observed to atmospheric pressures (see curves for 690 Torr and 760 Torr in Fig. 3 (a). Even more dramatic effects can be expected, when gas molecules react with the surface material, producing an additional gas or surface component. Such reactions are to be expected, since reactive ions are readily created in plasma, especially in *air*. During discharge or development of the same, the secondary emission, described by Townsend's second coefficient γ, changes, because now not only the surface atoms are hit by electrons and ions, but also the gas molecules on the surface.

SI GaAs exhibits, at a field of about 1 kV/cm, a strong non-ohmic conduction and *NDR* is consequently suitable for the investigation of nonlinear systems and deterministic chaos. The dc *CVC* of the microdischarge shows several distinct regions. In our study, it is observed that when a dc electric field is applied to a *SI GaAs* crystal, *CVCs* become sublinear over about 450 V and then *LFOs* occur over about 520 V for L_1 as in Fig. 4 (a). The similarity of the transport properties in the *SGDED* and in a structure without a gas-filled gap [4] gives us a ground to suggest that the current and *DLE* oscillations in the unstable regions are similar as well. Therefore, by studying the *CVCs* and *DLE* we can judge the current instabilities in a structure without a gas-filled gap. The obtained characteristics define that *LFO* in *SI GaAs* samples consists of spontaneous oscillations due to a high applied electric field. Thus *LFOs* are due to electric-field-enhanced electron capture of *EL2* level [4] in *SI GaAs*.

It should also be noted that the current oscillations in the unstable regions may negatively affect the characteristics of instruments based on *SI-GaAs* [6].When the feeding voltage above 520 V is applied to the *SI GaAs*, *LFO* occurs. The *CVCs* show the onset of *NDR* region with *LFO's* which manifest themselves as apparent scatter in a dc measurement. The *NDR* has been originally proposed in order to explain *LFOs* observed under illumination due to field-enhanced recombination of excess carriers. Detailed information regarding to the time series of current pulsations inside the *N-shape region of CVCs* is represented in Fig. 4b. It is clear that the current pulsations inside *N-shape region* increase by increasing feeding voltage (see in Fig. 4 (a) and (b) *N-shape region of*

CVCs at 530–580 Volt). It is a commonly observed phenomenon in gas-discharge systems that an increase in current may be accompanied by a decrease in voltage that supports the discharge. As a result, there appears a branch on the *CVC* with negative slope, *dI/dU*,
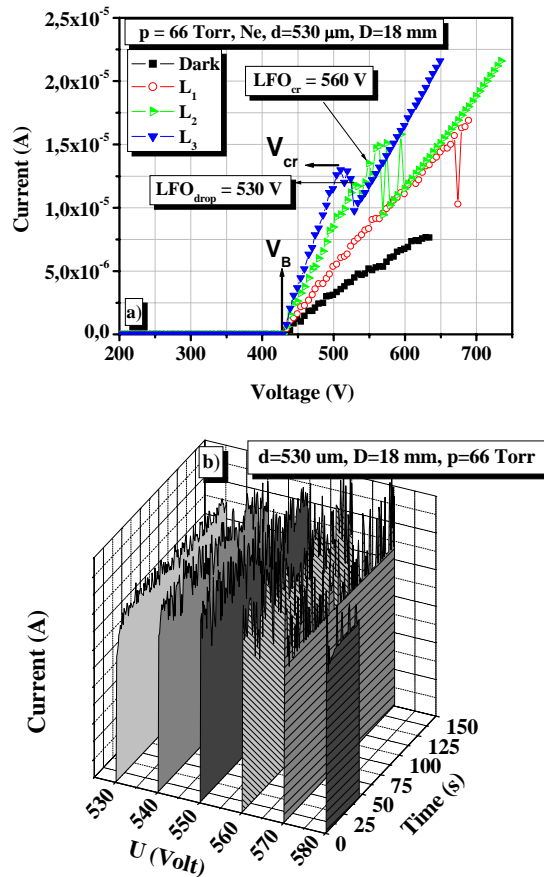

Fig. 4. (a) Typical CVC of SGDED shows three regimes: (i) linear region ($V_0 \leq 450$ V), (ii) sublinear region (450 V $\leq V_0 \leq$ 520 V) and (iii) small oscillations ($V_0 \geq 520$ V) for L_1; (b) Time dependence of current oscillations (i.e. inside N-shape region of CVCs) in the SGDED under weak illumination intensity L_1 and different feeding voltages U_0.

which corresponds to an arising of the *NDR* in the system [26]. In principle the aim is to obtain a stable and an intensive *DLE* at the desired atmospheric pressures, since the system becomes cheaper when it works at atmospheric pressures, eliminating the requirement at low pressure condition. A comparison of our data for the *SGDED* and data obtained by other authors for *SI GaAs* [4] shows that the presence of the gas discharge region in *Ne* media does not significantly modify the character of the charge transport in the system studied.

In this regard, it is possible to produce gas discharges up to atmospheric pressure by means of *SGDED* with very moderate voltages so that a wide area of plasma applications becomes feasible under reasonable

conditions. Non-thermal microdischarge devices attract much attention owing to several advantageous characteristics. However, more investigations are needed to find the optimal discharge parameters and operating conditions of such microdischarge devices concerning their radiation efficiency and power as well as their stable operation and lifetime.

4. Conclusions

The experimental results of the non-thermal plasma discharge in the *SGDED* for *Ne* are reported. The analyses of gas discharge have been carried out using time-dependent current and *DLE* in the *Ne* media. The dependence of the current and *DLE* on the plasma operating parameters (i.e. pressure, voltage, electrode separation, and gas type) are investigated. Current and *DLE* from the discharge burning up to atmospheric pressure in *Ne* usually has homogeneous form, however non-homogeneous *CVC* forms are observed under specific conditions. Under the experimental conditions, formation of instabilities at the expense of the semiconductor cathode is caused by the *N*-type *NDR*. We suppose that the origin of the instabilities is due to the formation and movement of high-field domains in the bulk of the *SI GaAs* cathode. These experiments and their analyses are believed to open the way to a study of the dynamic features of the system at high voltages since we can quantitatively define the most relevant underlying properties. By doing it, it is of importance to have knowledge in peculiarities of operation of these non-linear systems, in order to provide their stable and controllable operation up to the atmospheric pressure. However, one still needs much work to understand the optimal operation conditions and to determine the thresholds of different physical regimes for the response of the system in the cases of different parameter sets.

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