Effect of nitrogen plasma on the transport properties of *SI GaAs* photocathode

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In this paper we experimentally discuss the *nitrogen* and *air* plasma effect on the transport properties of semi-insulating *(SI) GaAs* photocathode in the semiconductor gas discharge structure. Discharge gap is filled with various pressures of *air* and *nitrogen* at different gap spacing *d* and cathode diameter *D*. Under the same discharge conditions, while the *N*-type *CVC* behaviors and low frequency oscillations in *air* are observed at the lower pressures, that behavior in *nitrogen* gas is generally encountered between p = 100 and 480 Torr. Besides, threshold electrical field E_{th} value at d = 525 μm is found to 9.4 kV/cm in the N_2-filled case. This value is higher than that in the *air*-filled case observed at d = 525 μm. Our results also provide important knowledge associated with plasma–surface interaction with low-energy *nitrogen* ions on the presence of an oxide or disturbed layer is encountered at the interface between the photocathode and the gas discharge plasma.

1. Introduction

Of recent years, *III-V* compound semiconductors have obtained great importance by experimental and theoretical workers. Most of them have been electronic and physical properties [1]. With this remark, *GaAs* still attract much attention in the qualified fabrication technology. Its electronic effective masses are in general very low, and the carrier interactions are favorable to obtain high-electronic velocities. Since than we have seen interesting to investigate and study the features and capacities offered by this material, and know the influence of the external conditions [2].

Research in this area is currently focused on the transport peculiarities of the semiconductors which are described by a nonlinear dependence of the current density *j* on the electrical field *E*. Most importantly negative differential conductivity (*NDC*) occurs [3]. According to the related studies [4-9], semiconductors used semiconductor–gas discharge structure (*SGDS*) is sophisticated nonlinear dynamic systems displaying current instabilities and self-organized formation of spatio-temporal patterns under the influence of strong electric fields. *SGDS* is composed of a photosensitive high resistivity semiconductor layer and a narrow plane-parallel discharge gap. As is known, the operation principle of the *SGDS* is dependent upon controlling the gas discharge through a high-resistivity semiconductor photocathode [6].

In [8] we observed complicated behaviour of the *SGDS* with a *SI-GaAs* photocathode in *air* and *neon* media. It is proved that the observed current oscillation is due to the *SI-GaAs* photocathode when a dc voltage of sufficient amplitude is applied to a system. As we stated previous publications [8,9]; *N*-shaped negative differential conductivity was observed within the range of high-electric fields. Therefore, when the applied voltage on *GaAs* photocathode reaches and exceeds the threshold value, low-frequency oscillations starts which was attributed to *EL2* centres in the volume of *SI GaAs* material that is produced nowadays using the liquid encapsulated technique [10,11].

It should be noted that we have experimentally examined the aforementioned complicated electrical behaviours of *GaAs* by a new-suggested method and our experimental results are in accordance with the measurements reported by other independent authors. In order to study the effect of nitrogen discharge on semiconductor transport properties, the experiments are carried out above mentioned method using *SI-GaAs* crystal.

At the present work, Nitrogen plasma has been operated and the interaction of plasma and semiconductor surface has been explored. Nitrogen plasmas have been generally exploited in separate researches and application fields. The application area of the nitrogen plasmas includes semiconductor fabrication, nitridation processes which are applied to form high quality oxynitride films to act as a boron diffusion barrier for the gate oxide [12].

We know that semiconductor surface properties can be changed by means of plasma treatment. In this study we report new experimental results on the transport properties of *SI GaAs* in *nitrogen* and *air* media. Thus the effect of layers formed on the surface of *GaAs* crystal is considered during treatment in nitrogen plasma. Furthermore, operation peculiarities of semiconductor photocathode in *nitrogen* and *air* non-thermal plasmas in a wide pressure range up to atmospheric pressures are presented by both electrical and optical emission methods in the *SGDS*.

We studied in *air* plasma because of its easier to use and availability, whereas *Nitrogen* is operated because of its molecular similarities with *air* apart from the presence of oxygen. However, oxygen molecules (*Air* is made up of *nitrogen* 78% and oxygen 21%) suppress nitrogen metastable species, and so atmospheric discharges have existence as streamer [13-15].

For this reason, non-uniform gas discharges are disadvantage of *air* discharges [14].

It is observed that the *CVC* and discharge light emission (*DLE*) in the *SGDS* dependent on the discharge parameters, such as the *nitrogen* pressure, the feeding voltage, and etc. The influence of the plasma on particular physical processes occurring in *SI GaAs* photocathode, the role of the semiconductor photocathode in stabilizing the discharge in planar devices and internal electric field distortion which affects the system characteristics are also studied in the paper

2. Experimental

The experiments are carried out on the system which is presented in Fig. 1 (Please see Refs. 8 and 27 for detail). In our earlier studies [8-9,16,27,32], we have compared transport properties of *SI GaAs* photocathode in the absence and in the presence of gas discharge gap. Both types of structures consecutively, operate with the same *GaAs* sample. From the similarity of the transport properties of two configurations, we can judge that the nonlinear electrical characteristics of current distributions in the unstable regions are similar as well.
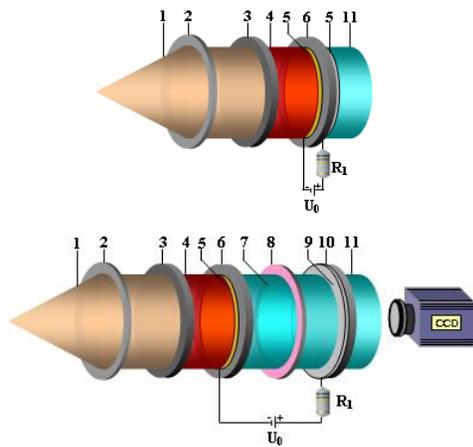
Fig. 1. Investigated structure (a) in the absence and (b) in the presence of a gas discharge gap: 1-incident light beam; 2- lens; 3-Si filter; 4- IR light beam; 5-semi-transparent Ni-layer; 6-GaAs cathode; 7-gas discharge gap; 8-mica foil; 9-transparent conductive SnO_2 contact; 10-flat glass disc; 11- UV- visible light beam.

In [8,27] we have experimentally studied the nonlinear characteristics of *SI-GaAs* in *Ne* media. In this study, we have experimentally measured nonlinear characteristics of *SI GaAs* photocathode in *air* and *nitrogen* media. In addition, we compare our results which are obtained in *air* and *nitrogen* plasma. *SGDS* is composed of a photosensitive high resistivity semiconductor layer and a narrow plane-parallel discharge gap. A gas layer is placed between the glass plate and the semiconductor photocathode in Fig. 1b [16]. In the experiments, a *SI-GaAs* [17], 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 photocathode. When applied high enough voltage V_0 between the *Ni* contact and the SnO_2 layer, a discharge is started in the gap. In this case, discharge corresponds to the homogenous Townsend regime. The surface of the *GaAs* photocathode was isolated from a flat anode by an insulating mica sheet with a circular aperture at its centre. Diameters of the effective electrode areas changes in the range of *D* = 5-22 mm. The *IR* light stimulates the photosensitive *GaAs* photocathode of the *SGDS* ensuring control of the current density and *DLE* from the gas discharge gap. In the experiments, *CVCs* are explored for a Townsend discharge in *nitrogen* at *dc* voltages of $U_0 \leq$ 2000 V and in a wide range up to atmospheric pressure $p \approx$ 28–690 Torr.

3. Results and discussion

Nitrogen plasma acts on the transport properties of the *SI GaAs* in different ways from *air* and changes the electrical properties and optical characteristics. In addition, plasma surface interaction results in the surface energy change and remove surface charged from the material. In the case of high resistivity of a semiconductor photocathode 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 gas-discharge plasma becomes important [17]. This carrier production takes place in a very thin skin layer (short-wavelength radiation, approximately 100 eV electrons and ions). One observes that the carriers which are aided by the field diffuse deep into the interior of the semiconductor, where they can modulate the conductance [20].

Fig. 2 shows the *CVC* and *CTC* (current time characteristic) of the *SI GaAs* photocathode while operating in *nitrogen*.
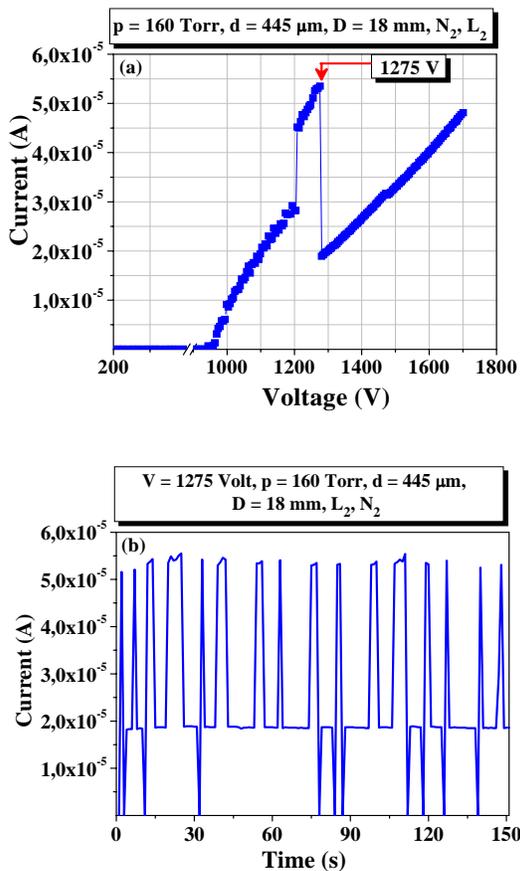
Fig. 2. (a) CVC with N-shaped of SI-GaAs photocathode under illumination intensity L₂. (b) CTC at a feeding voltage of 1275 V.

The experimental results were explained using the *CVC* and *CTC* of *SI GaAs* photocathode under Townsend discharge conditions in *nitrogen*. As it can be seen in Fig. 2a, instant current drop develop in *nitrogen* discharge for the pressure regime 160 Torr when the applied voltage is 1275 V. Fig. 2b presents a detailed study of the time-dependence characteristics of current behavior for 150 s where the photocathode is exposed to strong illumination intensity L_2 in the case of feeding voltage $V_0 = 1275$ V. The current pulsations with large amplitude are observed in a wide range of operating voltage including inside the *N*-shape region (1275 V) of *CVC* curve marked in Fig. 2a.

According to earlier studies [11,16] and on the background of previous studies, we can judge that current oscillations with large magnitude are connected by the dynamics of electrical domains (i.e. generation, motion along the sample, and damping at the contacts). Furthermore, stable and reproducible low frequency oscillation (*LFO*) is encountered under the voltage range of *NDC*. Obtained experimental results manifest that the origin of *LFO* in *SI GaAs* [21] is the electric field-enhanced capture of electrons by the *EL2* deep donor level [11].

Experimental parameters adjusted in such a way that a homogeneous Townsend discharge occurs in the discharge gap [22]. If the applied voltage V_0 comes close to the critical level V_{cr} from below, the current I in the *SGDS* reveals oscillations with relatively small amplitude. As shown in Fig. 2b, when the gap voltage exceeds the breakdown voltage (1000 Volt), the discharge current grows in time. Under the same discharge conditions, while the *N*-type *CVC* behaviors and low frequency oscillation (*LFO*) in *air* are observed at the lower pressures, that behavior in *nitrogen* gas is generally encountered between $p = 100$ and 480 Torr.

Fig. 3 shows the *CVC* of *SGDS* under different pressures in N_2 plasma. When the N_2 pressure increased to 480 Torr, current fluctuations disappeared. It has been observed that the value of the discharge current decreased as the pressure increased, denoting that the cross section of the plasma became smaller [4].
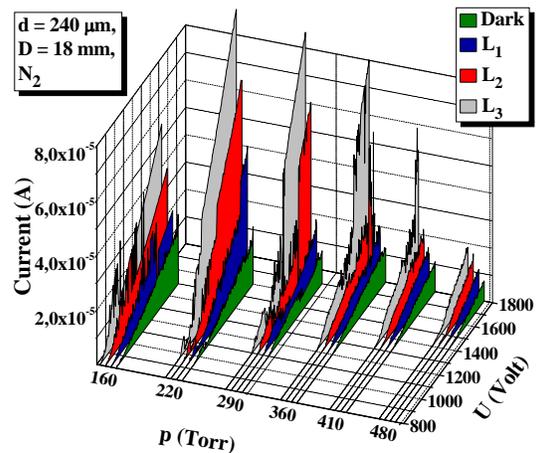
Fig. 3. CVCs of SI-GaAs photocathode for different pressure and illumination intensities in the case of d = 240 μm, D = 18 mm.

One can observe current oscillations which are caused by the formation of the fronts lies and movement of high-field domains in the bulk of the *SI GaAs* electrode when the applied voltage is high enough [10]. It is also assumed [17, 23-24] that the state with the moving planar domain may be destabilized, i.e. the phases of movement of the domains in different parts of the system can be different. It has been reported that formation of a travelling planar high-field domain in the semiconductor [10] is accompanied by charge separation processes in the bulk of the wafer.

Detailed information regarding to *CVCs* for variable interelectrode gaps are represented in Fig. 4 for *nitrogen* plasma. The experimental results in this study show that the gap spacing between electrodes can affect the discharge characteristics, including the *CVCs*, the discharge modes, etc., significantly with other parameters being constant.
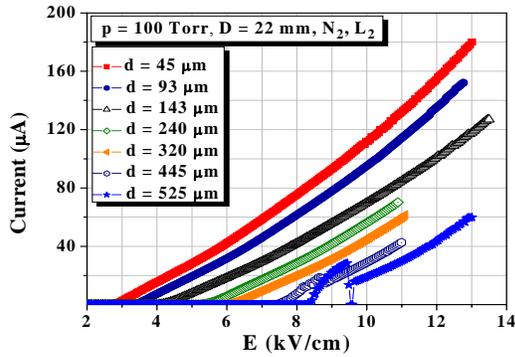
Fig. 4. CVCs of the SI GaAs as a function of d in N₂ media for L₂ at p = 100 Torr. The E_th are as follows: E_th = 8.7 kV/cm for d = 445 μm and E_th = 9.4 kV/cm for d = 525 μm.

There is an obvious difference for discharge behaviors in *nitrogen* and an *air*, which occur after plasma treatment of the *SI GaAs* under Townsend discharge conditions. N_2 play an important role on the transport properties of *SI GaAs*. The destabilization of current behaviour in a planar dc-driven structure is owing to the nonlinear transport properties of *GaAs* photocathode. At the same time, the results of separate studies [6] demonstrate that the electrode conductivity is important for the stability of the system. In this type of structure, the plasma–semiconductor electrical contact can play a definite role in the treatment of the surface at the interface.

Interactions of *nitrogen* plasmas with the *GaAs* surface effects the transport properties as shown in Fig.4. The *CVCs* are generally stable, as is to be expected in the small electrode. For discharge gaps smaller than 445 μm a uniform current behaviour can be obtained in the *SGDS*. When the electrode separation was increased to 445 and 525 μm, *N type NDC* appeared. The experimental observations show that the current stability for the case of small gap spacing becomes higher than that for the case with larger gap spacing.Besides, threshold electrical field E_{th} value at d = 525 μm is found to 9.4 kV/cm in the N_2-filled case. This value is higher than that in the *air*-filled case observed at d = 525 μm and in the *Ne*-filled case at d = 525 μm [25].

The physical mechanism which gives rise to *N*-type *NDC* of the material is thought of the EL2 centers if the voltage is high enough to have a strong electric field [26]. On the other hand, electron concentration goes up due to the *NDC*, giving rise to enhance electron-trapping by *EL2* centers.

Apart from the above experimental analysis, optical *DLE* were also recorded in both media to characterize the N_2 discharge plasma. Simultaneously with the *CVCs*, the *DLE* intensity was recorded (i.e., radiation voltage characteristic). For the thin discharge gap of the *SGDS* the proportionality between the gas brightness and the current density *j* can be observed in a broad range of *j*. Variation of the discharge conditions can affect characteristics of the *DLE*. Therefore, the different *DLE* intensities which are

observed for N_2 and *air* microplasmas can be explained by the difference in the ionization cross section between N_2 and *air*.

Fig. 5 shows the distribution of light intensity emitted by the discharge with respect to the diameter of the *SI GaAs* photocathode. From a detailed view of the *DLE*, it can be seen that when the *DLE* behaviour are compared, the light emission is most intense in the *air* medium than the nitrogen medium. At the same time, the discharge intensity decreased when the *SI GaAs* photocathode diameter is decreased. This study in various gases provides a framework for understanding the transport properties of *SI GaAs* photocathode up to atmospheric pressures in the *SGDS*. Differences between *DLE* intensities are clearly visible in *air* and *Ne* [27]; however it is not easy to distinguish for N_2 and *air* in Fig. 5 for *D*= 22 mm.
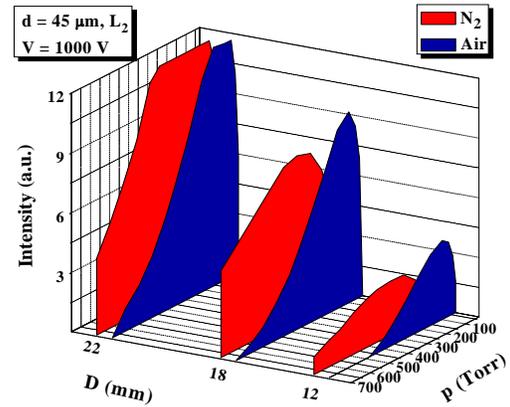
Fig. 5. DLEs of the discharges attained while operating in nitrogen and air media.

The *CVC* and *DLE* behaviour of *air* is more complex than N_2; this is likely owing to the oxygen, carbon dioxide and water vapour which further facilitate energy transfer to the neutrals as reported in Ref. [13]. According to Staack [13], *He*, *Ne* and *Ar* have lower electric fields than the molecular gases N_2 as a result of the fact that the amount of energy required to maintain sufficiently high electron temperatures and densities to have ionization rates balance losses is easier in atomic gases since there is no electron energy loss to molecular internal energy modes.

Experiments also show that the filaments appear in the system. In this filamentary regime plasma formations resulting in electrical conductivity are constricted to the microdischarges. By applying an electric field larger than the breakdown field local breakdown in the gap is initiated. Luo et. al [24] reported that the discharge happens with a relative high value of *α* as a result of the high electric field needed for the discharge in *nitrogen* or *air* at atmospheric pressure.

After critical current value (10^{-3} A), we have observed filament in the *SGDS*. In this case, *SGDS* is become unstable in the advantage of current filaments. In the relating patterns, *2D* and *3D* representations as well as

the profiles of those damages on the *GaAs* photocathode surface are shown in Fig. 6(a,b,c).

Fig. 6 shows damaged *GaAs* surface result from high current glow to filamentary discharge transition regions for 620 Torr in *air* media. For the measured currents in our system, a constriction of the discharge and transition to a filamentary discharge is observed. At the transitional stage from glow to filamentary discharge, a filament mode occurs; current decreases instantaneously and the surface of *GaAs* photocathode get damaged.
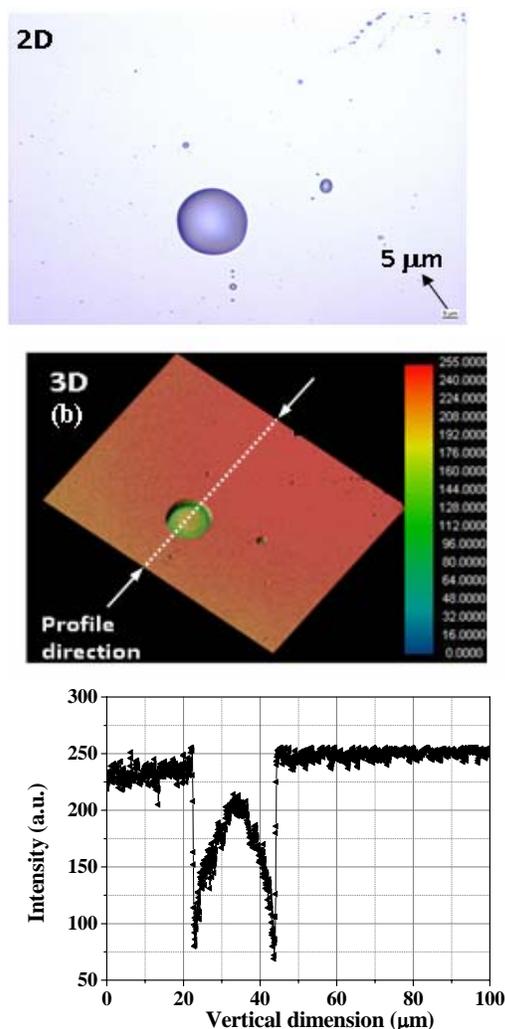
Fig. 6. (a,b,c) 2D and 3D surface pattern of damaged GaAs and variation of DLE intensity profile (i.e. gray levels) from indicated direction at 620 Torr in an air.

According to Kogelschatz and Fridman [28,29], the exact reasoning and physics for this is under investigation and may be concerned with thermal effects such as temperature gradients along the length of the positive column. A transition from glow to a filamentary discharge takes place for higher electrical fields [28,29]. Because

these filaments distorted *GaAs* surface, it is seen local damage on the surface of *GaAs* surface.

Shuvalov *et.al.* [30] reported that more complex changes can take place with dissolution of surface oxide layers or interactions (e.g., with thin metal films covering the semiconductor surface as well as these simple thermal processes]). Further, thermal processing can also give rise to recovery and recrystallisation, and can lead to enrichment in the crystalline quality of the nearsurface region [30]. In the *air* plasma, active oxygen species changes the electrode surface layer. Further, active oxygen species brings about the buildup of oxygenated carbon centers in the surface layer [31]. Discharge instabilities leading oscillations and the formation of the current filaments cause damage on the device operation owing to the space charge effects and interactions of plasmas with *GaAs* photocathode [32]. It should be noted that this kind of current oscillations may negatively affect the characteristics of instruments based on *SI GaAs* [33].

4. Conclusions

In this work, we concentrated both the effect of defects on the carrier transport in *air* and N_2 non-thermal plasma and *GaAs* surface modification by the active species which were identified as oxygen

atoms in *air* plasmas. We believe that the damages on the surface are primarily due to the effectiveness of sputtering and physico-chemical interactions in the discharge gap during the transition from glow to filamentary. At the same time, the observed damage phenomenon can be attributed to the change of recombination processes due to bombardment of the photodetector surface by the charged plasma particles. Thus, the current filaments in the unstable regions may negatively affect the characteristics of devices based on *SI GaAs*. Under the same discharge conditions, while the *N*-type *CVC* behaviours and low frequency oscillation (*LFO*) in *air* are observed at the lower pressures, that behaviour in *nitrogen* gas is generally encountered between $p = 100$ and 480 Torr. These observations justify the effect of nitrogen discharge on semiconductor transport properties and ooperation peculiarities of semiconductor photocathode in nitrogen non-thermal plasma. The optimization of parameters is discussed

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