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# Filamentation of Light Emission in an Infrared-Visible Image Converter with a Semiconductor Photodetector

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**Abstract**

This work studies the light emission patterns associated with the spatial modulation of the transversal distribution of the current density in a converter cell with a GaAs semiconductor cathode. Such light emission exhibits spatial structures of current filaments depending on the feeding voltage, illumination intensity, gas pressure and the surface treatment of the electrodes. When the current is increased above the stable limit, breakdown or small current filamentations begin. However, n-GaAs exhibits an S-shaped current-density-field relation due to impact ionization of carriers from shallow donors into the conduction band under high electric fields. The assessment of the filament formation is then based on analysis of the discharge light emission, recorded through a transparent anode. The filamentation 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.

## 1. Introduction

Among the different systems in the domain of natural science, special interest is directed towards pattern-formation phenomena in electronic media. Current filaments in semiconductors, the Belousov-Zhabotinskii reaction and biological morphogenesis are well-established examples [1]. Behavior of converter cells with photosensitive cathode is an essentially new subject of investigation that may be applied to IR imaging, high-speed photography, semiconductor physics and gas discharge physics [2,3]. The mechanism behind such an IR converter is based upon the discharge formation in the gap between a planar transparent anode and a semiconductor cathode. An infrared-visible image converter has a 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 photodetector is used. This behaviour is not quite usual, as current filamentation and other complicated spatio-temporal behavior of the current density have been observed in other experiments involving semiconductor discharge gap structures [1,4,6]. The physical reason is that a photosensitive detector is incorporated into these devices and operates in the external photoeffect mode. The light emission in the cell becomes unsteady as the current rises, i.e., either small regular oscillations or periodic repetitive breakdown occur. This instability arises because the space charge produces a decreasing current-voltage characteristic [4].

In the present paper, we give a visualization of the spatial patterns transverse to the current flow associated with the current filamentation (i.e. an inhomogeneous distribution of the current density). This is interesting from the point of view of the problem of formation of small-amplitude patterns in electronic systems. In this relation the subsequent transition to a filament pattern is also analyzed. On the other hand, small-amplitude patterns may serve in the considered system as an intermediate stage for the formation of high-amplitude patterns, composed of localized states.

## 2. Experimental

A schematic diagram of the setup with a converter cell is shown in Figure 1. A Cr-compensated GaAs ($\rho$ $\sim 10^7 \Omega$cm) plate was used as a semiconducting cathode. On the illuminated side of the cathode a transparent conducting vacuum evaporated Ni-layer was coated. The anode was a glass disk coated with a thin layer of a transparent conductor, $SnO_2$. A dc voltage of up to 2.2 kV was applied to the electrodes of the cell. The light of an incandescent lamp with a Si-filter in front uniformly illuminated the cathode, in the wavelength range 1.0 $\mu$m $< \lambda <$ 1.7 $\mu$m. In the IR region the photoconductivity in GaAs is attributed to Cr impurities. The discharge gap of the cell was filled with atmospheric room air. The assessment of the filamentation image formation is then based on analysis of the discharge light emission, recorded through a transparent anode with spatial resolution via their corresponding light emission. The brightness of the discharge light emission, in a good approximation, is linearly dependent on the current density of the discharge. The light emission is observed using a camera.

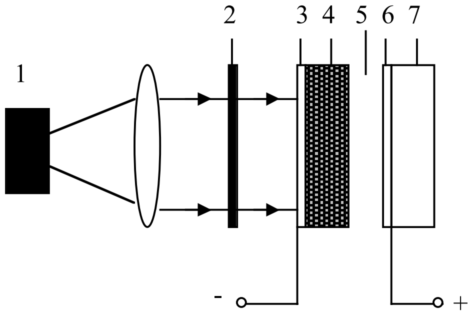

**Figure 1.** The basic scheme of the converter cell with a semiconductor photodetector: 1, light source; 2, Si filter; 3, transparent conducting Ni layer; 4, GaAs semiconductor photodetector; 5, air gap; 6, transparent conductor $SnO_2$; 7, glass disc.

## 3. Results and Discussion

The discharge light emission, in particular the total current, can be controlled over a rather broad range. It includes low current densities, $j \leq 1.5$ $\mu$A/cm$^2$, where the discharge operates in the Townsend regime. 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 electrical field between the electrodes [3].

Figure 2 (a,b) shows the evolution of the spatial patterns as they appear as a spatial modulation of the transversal distribution of the current density for a cell activated with two illumination intensities ($L_1 > L_2$), which lead to two resistances of the GaAs cathode. The spatial pattern of light emission intensity distribution was calculated from data obtained from a great number of vertical lines of the active part of the device. In Fig. 2 one can see a discharge light emission can be seen which is rather inhomogeneous in the $x$ and $y$ directions, and the spatial structure of the light emission in the $z$ direction consisting of different dark and bright regions. In nearly all cases the loss of stability of the current was coincident with the loss of uniformity of the discharge light emission and consequently affected strongly by the resolution of the images. Filament formation in the discharge deteriorates the properties of converter cell. Formation of patterns in the spatial distribution of the current was accompanied by the appearance of corresponding spatial distribution of the light emission in the visible range (330 – 460 nm), which was emitted by the discharge. The essential feature of this pattern formation is that electric current can be interactively controlled by the amplitude of the feed voltage and by the intensity of IR light, which irradiates the cathode, and thus governs its photoconductivity [3].

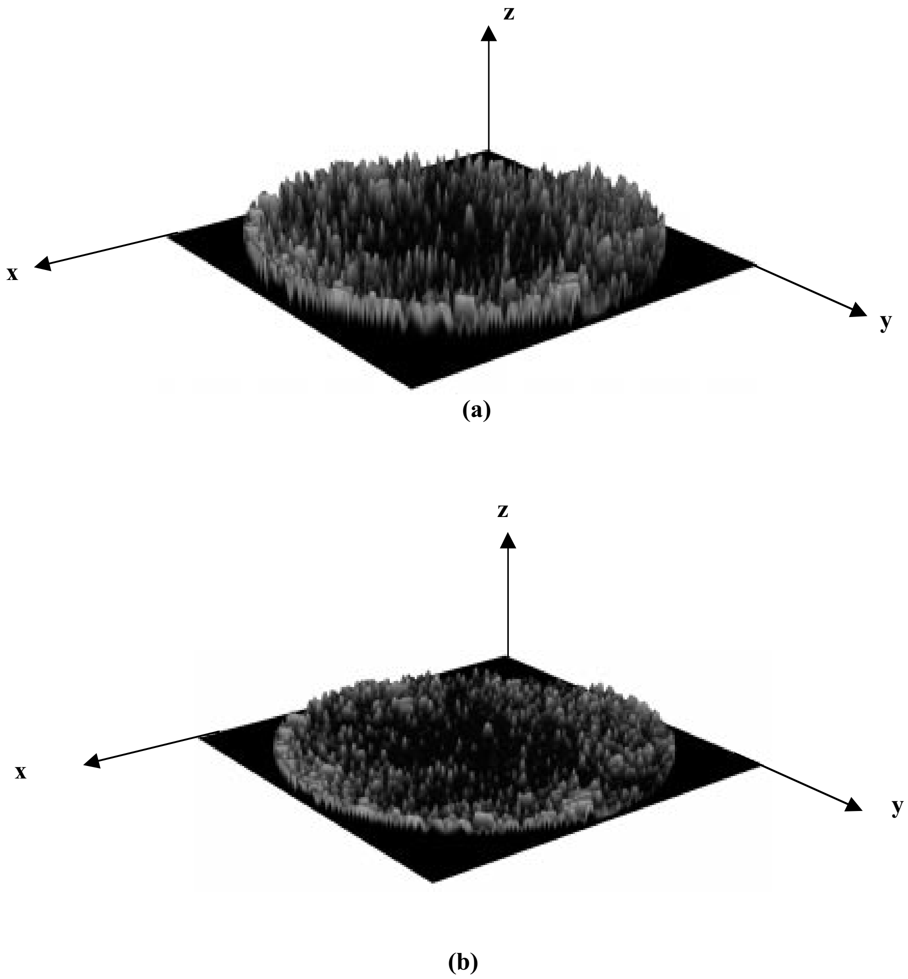

**Figure 2.** 3D filamentation pattern of the light emission in cell for different illumination intensities $L$: a) $L_1$= 4 mWcm$^{-2}$; b) $L_2$= 1.2 mWcm$^{-2}$; The radius of the cathode is $r$= 10 mm, where the other parameters are: $p$= 67 Torr, $d$ = 80 $\mu$m, $U_0$= 2.2 kV

The main mechanisms involved in current constriction in self-sustaining discharges are ionization or ionization-thermal instabilities, which develop in molecular and atomic gases, respectively. The filamentation images correspond to states of the system with various current density $j$ while the current is on the rise. The distribution of light emission reflects the lateral filament current density distribution. While increasing the controlling parameter further, the system can undergo further transitions, from a homogeneous light emission pattern then subsequently to filament patterns. This behavior can be explained by the transition from the Townsend mode of discharge to the glow mode. This transition is accompanied by the appearance of a negative differential resistance (NDR) of the discharge gap [5].

In Ref. [5] we get the expressions that characterize two different points of view and different quantitative criteria of stability for the mechanism of this process and its quantitative regularities. The following inequality was used as the limiting value of volume resistivity of the semiconductor :

$$\rho_{semicond} \geq V_d / jL. \tag{3.1}$$

Here, $L$ is the thickness of the cathode and $V_d/j$ is the discharge voltage over the discharge current density. It can be seen from (1) that to decrease the discharge current, a large $\rho$ - value is needed, and the stability has a low limit by voltage.

According to another point of view [2] a phenomenological consideration of CVC for the stability leads to the criterion

$$\rho_{semicond} \geq R_{NDR}/L. \tag{3.2}$$

Here, $R_{NDR}$ is the *NDR* of the gas discharge cell with the gap thickness $d$ and the parameters of gas-filled gap but without a distributed resistance. Condition (2) is independent of the current and, in general, to a great extent is similar to the monotony condition of CVC for a concentrated element with a NDR in series with the resistor. The $R_{NDR}$ value should be considered as a certain parameter determined experimentally, depending on the state and emission capacity of the cathode surface.

However, as reported earlier [1,8], n-GaAs exhibits an S-shaped current-density-field relation due to impact ionization of carriers from shallow donors into the conduction band under high electric fields. Such S-shaped negative differential conductivity has been shown to lead to the formation of current filaments in a variety of different semiconductor structures [1]. When diminishing the controlling parameter, the homogeneous state is restored. The filamentation pattern in this converter cell exhibits some specific peculiarities, which have been found throughout the investigated parameter space: We have exclusively observed filamentation patterns which can be considered as arrangements of spots which increased brightness of light emission. Another typical property of these filamentation patterns is the fact that they are not strictly stationary, but drift across the active area with a rather low velocity of about 0.3 mm/sec [6]. The velocity of a filament decreases with increasing gas pressure.

For a perfect performance with respect to efficiency, cathode quality and reproducibility, a homogeneous gas discharge is essential. Considerable difficulties were encountered in obtaining reproducible discharge operating voltages. At low pressures, the discharge voltage at currents below about 1 $\mu$A was found to drift badly as the discharge was operated. An aging procedure was adopted that resulted in reproducible voltages, i.e., the discharge was operated for 3 min at a current of 0.5 $\mu$A and a pressure of 67 Torr (see Fig. 3). 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 and gas temperature. 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.

The surface treatment employed in our study, which causes the presence of a considerably disturbed layer at the contact between the semiconductor and the gas plasma, renders the discharge relatively insensitive to the local properties of the semiconductor surface and ensures retention of a considerable field-emission current. It is for this reason there is a high degree of uniformity of the current density and of the discharge light emission along the surface of the cathode. Also, by carefully polishing the cathode and by limiting the energy input of preceding discharge the constriction of the discharge light emission could be avoided [7].

Starting from a well developed filamentation pattern in system cell, a further increase in $j$ due to increased IR light intensity may initiate different scenarios in the system's evolution, as dependent on parameters. In the case of the filamentation patterns discussed above, bright spots become successively pronounced and finally they become nonstationary as the resistance of the GaAs cathode decreases. That is, the spots undergo a transition from state where they are strictly embedded in the lattice determined by the filament structure to a state where the spots become progressively solitary and mobile.

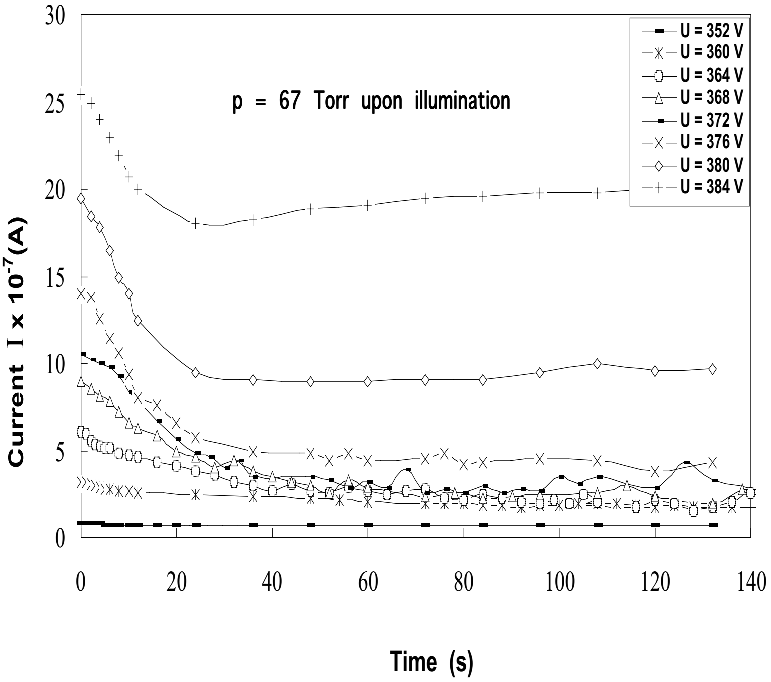

**Figure 3.** The variation of aging current of the converter cell with respect to time for the system using a GaAs : Cr semiconductor cathode.

The accumulation of positive ions in the gap has as consequence that the longitudinal electric field, that is, the field along the current, varies in the interelectrode space. The same is true also for densities of charge carriers in the discharge domain. To build an image of the current in such a system, one must then inevitably to deal with a 3D representation of physical processes in it. Such variables as local electric field and densities of charge carriers in the gap will appear in the model. This approach is evidently difficult for a theoretical analysis. In order to simplify the problem, one can examine the formation of patterns which are lateral to current direction, which can be interpreted on the basis of a 2D model [1,8].

The filamentation depends strongly on the state of the cathode 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 of nonequilibrium carriers in the cathode and on the presence of an oxide or disturbed layer at the interface between the cathode and the gas discharge plasma.

Studies of the characteristics of such systems showed that current and light emission filamentation are strongly affected by the resolution of the IR images. By irradiating the semiconductor cathode with IR light it is possible to displace the filaments spatially. The width and the light density of the filaments are almost the same for a certain parameter set. The filament shape does not change with the system parameters. The results obtained can be used to improve the output characteristics of converters.

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