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Multioscillatory patterns in a hybrid semiconductor gas-discharge system

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A planar pattern forming semiconductor gas-discharge device is examined. While being driven with a stationary voltage, it generates patterns that contain domains oscillating with different frequencies. The multioscillatory pattern is formed in a sequence of bifurcations from the homogeneous stationary state. A nonlinear interaction between different parts of the pattern can be detected. It is suggested that the observed behavior is due to the coupling of processes in two nonlinear components, the gas-discharge gap and the semiconductor cathode fabricated from high resistance gallium arsenide.

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I. INTRODUCTION

Appearance of spontaneous oscillations is a rather common feature of systems maintained far from equilibrium. Such oscillations can be due to self-organization of systems with a small number of degrees of freedom [1] or of spatially extended media [2]. Ensembles of interacting oscillators that may exist in extended systems manifest a number of nonlinear phenomena such as global synchronization, frequency entraining, transitions to chaotic states, etc. (see, e.g., [3] and references therein). The destabilization of a homogeneously oscillating medium is known to give rise to the appearance of the coherent spatiotemporal behavior of the medium in the form of spiral and target patterns [2,4].

In the present work we show that a spatially extended oscillatory system may generate states that contain domains oscillating with different frequencies. The system under consideration here is a planar dc gas-discharge device with a cathode fabricated from a high resistive semiconductor. It has been shown previously that devices of this type demonstrate formation of various generic patterns [5–9]. Since the radiation intensity emitted by the discharge is almost proportional to the current density, formation of patterns in the spatial distribution of current can be observed by optical means. The important experimental advantage of these systems in studying the pattern formation in nonlinear media is the low value of power dissipation for the first bifurcation. Therefore, it is possible to study a hierarchy of bifurcations while the power driving the system is still low.

Previous investigations of these systems have shown the existence there of several modes of destabilization. If a high resistivity silicon electrode is applied as the cathode material and the structure operates at a temperature of about 90 K, the first bifurcation from the spatially homogeneous stationary state is of the Turing type [5,6]. Such a destabilization may create a spatially periodic structure. In contrast, for a system at room temperature where an undoped semi-insulating gallium arsenide (SI GaAs) is applied as a cathode material, a subcritical bifurcation to spatially homogeneous oscillations can be observed [9]. In the latter system, the leading bifurcation may also create spatial patterns, the basic element of which is an oscillating current filament [10]. In the present contribution, we study the situation where the oscillating filaments are created from a homogeneously oscillating state via a secondary bifurcation. For a small number of filaments in the active area, it has been revealed that they may oscillate at different frequencies, being at the same time in subharmonic resonance with the oscillating background. It is suggested that active properties of SI GaAs electrodes that manifest themselves at high electric fields play an important role in the observed phenomena.

II. EXPERIMENTAL SETUP AND RESULTS

A. Spatiotemporal patterns in the hybrid system

The setup used here (see Fig. 1) is similar to that applied earlier [9,10], where a planar dc-driven gas-discharge system with the SI GaAs cathode was studied at room temperature. In the present work, the width of the discharge gap is 0.5 mm, the diameter of the discharge channel is 30 mm, and the cathode is 1.5 mm thick [11]. The gap is filled with nitrogen, its pressure being varied in the range 40–60 hPa. For further details, see [9,10]. The images of the discharge glow are recorded with a standard video camera or, alternatively, with an intensified charge-coupled device camera when a short exposure time t_{exp} is needed. The specific conductivity of the SI GaAs electrode is spatially homogeneously controlled with light from a halogen lamp, due to the photoelectrical process in the semiconductor volume. It is set to a value of about $2.5\times10^{-7}(\Omega\ \mathrm{cm})^{-1}$, measured at small electric fields in the semiconductor, where its conductance is linear. Under these conditions, the bifurcation from a homogeneously oscillating state to a state with filaments on the oscillating background can be investigated by varying the supply voltage U_0 as a control parameter.

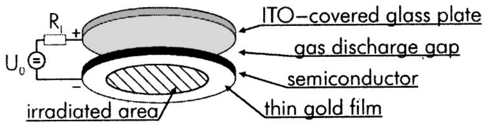

FIG. 1. Sketch of the experimental device. For explanation, see the text.

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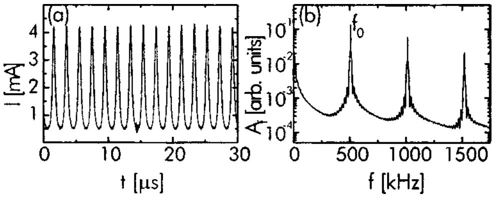

FIG. 2. An example of the time series (a) and the related frequency spectrum (b) of the global discharge current I for the state of homogeneous oscillation. The feeding voltage $U_0 = 580$ V.

The ignition of the discharge in the gas gap establishes a spatially homogeneous stationary Townsend discharge [12]. A further increase in the supply voltage U_0 beyond a certain threshold value leads to the bifurcation to a homogeneous oscillating state. The oscillation amplitude and frequency grow with increasing U_0 [9]. A representative example of the time series of the global discharge current in the oscillatory state is given in Fig. 2(a). The related frequency spectrum shows the typical features of an anharmonic oscillator [Fig. 2(b)]. The fundamental frequency in the case shown is $f_0 = 506.6$ kHz.

A further increase in voltage is followed by the appearance of bright spots in the discharge area [see the inset in Fig. 3(b)], which evidences filamentation of current. The characteristic diameter of a filament is of the order of 1 mm. The core of a filament is surrounded by a ring where the intensity of glow is lower than that for the background. The number of filaments increases with an increase in global current. The state with a small number of filaments is observed to be multistable, that is, depending on the system's prehistory, different numbers of filaments may exist for the same set of parameters. This evidences the subcriticality of the filamentation process.

The dynamics of states with different numbers of filaments may be quite different. The characteristic feature of a state with one filament is that the filament oscillates with half the background frequency f_0 (see Fig. 3). For a state with two filaments, there can be a situation where one filament oscillates with the frequency $f_0/2$, while the other has the frequency $f_0/3$ [the spikes belonging to these oscillators are labeled in Fig. 4(a) as (i) and (ii), respectively]. The phases of the oscillations of the localized objects may be locked (as shown here) to different phases of the oscillating background. For a pattern with three filaments, one can register a state where all of them oscillate with the frequency $f_0/3$ [bursts of these oscillators are marked in Fig. 4(b) as (i), (ii), and (iii), respectively]. Again, phases of their oscillations may be locked to different stages of the oscillation process for the background.

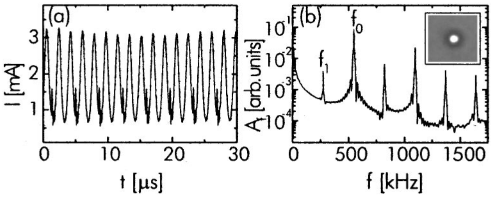

FIG. 3. A time series (a) and the related frequency spectrum (b) of the discharge current of a single filament on an oscillating background at a voltage of $U_0 = 600$ V. An image of the discharge glow (with $t_{exp} = 40$ ms) is shown in the inset, whose size is 8×8 mm^2.

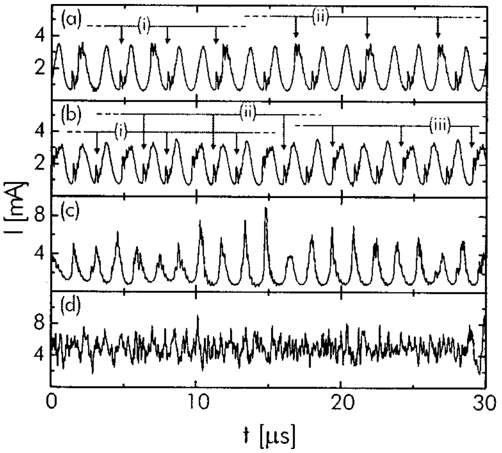

FIG. 4. Examples of time series of the global discharge current for cases of (a) two, (b) three, and (c) 21 filaments on an oscillating background, while (d) represents a state in which the complete area of the gas discharge is densely filled with filaments. The voltages are (a) 586 V, (b) 599 V, (c) 617 V, and (d) 760 V.

Note that the duration of bursts of electric current corresponding to these localized oscillators is much shorter than the period of oscillations for the background. Thus, such an object gives a signal that varies rapidly in time as compared to the main period. The local current density in a filament can be estimated by comparing the current of the oscillating background with the amplitude of the burst of a solitary oscillator. Taking into account the difference in sizes of the corresponding domains, one finds that the peak density of current in a filament may be up to two orders of magnitude larger than that for the oscillating background.

The above examples of dynamics of a spatially structured state give evidence that the solitary oscillating filaments of current are in subharmonic resonance with the oscillating background. Additional information on these localized objects is obtained in experiments with a spatially restricted active area. In such experiments, only a small circular section of the semiconductor electrode is irradiated with light, keeping the conductivity of the semiconductor there at the same value as in the experiments described above, while the remaining nonirradiated part of the semiconductor has a conductivity about ten times lower. In this situation, the diameter of the effective discharge channel is comparable to the dimension of a filament. The spatially homogeneous oscillations of the background become suppressed (see Fig. 5), and the dynamics of the system is defined by a solitary filament. It can be seen that the fundamental frequency of a "free" localized oscillator—in the case considered it is 132.8 kHz—is substantially lower than that for a large homogeneously oscillating area. Therefore, the occurrence of subharmonic resonances in the cases represented in Figs. 3, 4(a), and 4(b) can be described as the frequency entraining of localized oscillators by a powerful driver, which here is the homogeneously oscillating domain. This nonlinear process

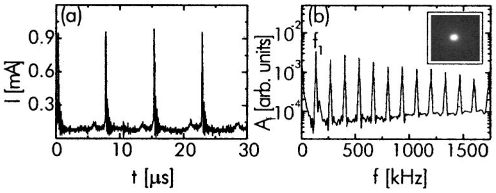

FIG. 5. Time series (a) and corresponding frequency spectrum (b) of the current for a spatially restricted active area containing one filament. Feeding voltage $U_0 = 600$ V. An image of the discharge glow (with $t_{exp} = 40$ ms) is shown in the inset, whose size is 8×8 mm^2.

detunes local oscillators and tends to synchronize them on subharmonic resonance frequencies of the driver.

When the number of filaments grows, the amplitude of the homogeneous background oscillation decreases gradually, because each newly created filament requires a certain area is ''taken'' from the background. Therefore, the strength of the oscillator that is formed by the background diminishes until it loses the capability to synchronize the filaments. Figure 4(c) refers to the developed stage of such a process. While the background oscillation can still be observed here, no periodicity in spiking of the current can be detected. When the voltage is raised further, more and more filaments are generated, until a stage is reached where the complete active area of the device is densely covered with filaments (which requires, in the case considered, more than 200 filaments). Consequently, the background oscillation vanishes, whereas the time series of the current [Fig. 4(d)] shows a seemingly irregular superposition of current spikes. When taking now an image of the discharge area with a relatively large exposure time [$t_{exp} = 40$ ms; see Fig. 6(d)], a dense liquidlike state of the ensemble of filaments is revealed. A sequence of images taken with a video frequency of 25 Hz evidences a permanent slow motion of filaments. Snapshots of the corresponding patterns taken with short exposure times yield informative data on the spatiotemporal behavior of the ensemble of pulsating filaments; see Figs. 6(a)–6(c). During a time interval of 100 ns (this is shorter than the duration of a current burst of a solitary oscillator, which is about 300 ns), only a few flashes due to localized oscillators can be detected [Fig. 6(a)]. Increase in t_{exp} causes an increase in the number of captured bursts; they seem to be scattered more or less uniformly across the active area [Fig. 6(b)]. These images show that bursts that are close to each other on the time axis are not neighbors in space. Therefore, the data seem to give evidence of the absence of phase synchronization of neighboring localized oscillators. At $t_{exp} = 10$ μs (which roughly corresponds to the oscillation period of a solitary filament), almost the complete discharge area is covered with flashes [Fig. 6(c)]. This image resembles the snapshot taken on the video frequency [Fig. 6(d)].

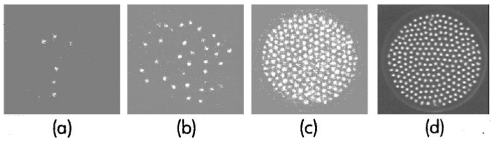

FIG. 6. Images of the discharge glow in a state where the complete discharge area is densely covered with filaments. The images (a)–(c) are taken with short exposure times of (a) $t_{exp} = 100$ ns, (b) $t_{exp} = 1$ μs, and (c) $t_{exp} = 10$ μs. The image (d) has an exposure time of $t_{exp} = 40$ ms. The feeding voltage $U_0 = 847$ V.

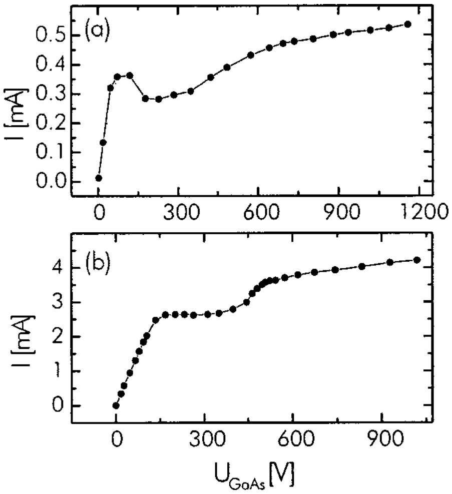

FIG. 7. Examples of current-voltage characteristics of the gallium arsenide cathode used in the experiments on the hybrid gas-discharge system for a weak (a) and a strong (b) irradiation.

B. Transport properties of SI GaAs cathode

Experiments carried out on the semiconductor electrodes separately have shown features in their conductance at high electric fields. To obtain the current-voltage characteristics of a SI GaAs electrode, the gas layer in the setup (see the sketch in Fig. 1) is replaced with an evaporated aluminum layer, other experimental conditions being close to those for the hybrid system. Examples of the characteristics obtained are shown in Fig. 7. Two typical cases, for a weak and strong illumination of the electrode, are represented there. In the first case [Fig. 7(a)], an expressed N-type shape of the characteristic is detected. In the case of a strong excitation of the electrode, which corresponds to the situation where multioscillatory patterns occur in the hybrid system, a slight decrease of current is also registered at the voltage increase [Fig. 7(b)]. The presented characteristics evidence the occurrence of negative differential resistance (NDR) of the semiconductor component of the hybrid structure. 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 $EL2$ centers [13]. 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 [14,15]. 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. Os-

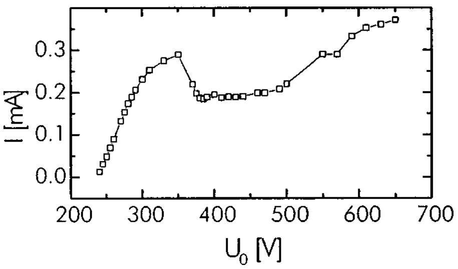

FIG. 8. Current-voltage characteristic of the compound semiconductor gas-discharge system for a weak irradiation. The 100 μm thick discharge gap is filled with Ar, the pressure being 200 hPa. The material for the semiconductor electrode is the same that is used to obtain the data shown in Fig. 7.

cillations there are related to the formation, traveling, and decay of domains of high electric field in a sample [15].

It is well known, however, that the conductance of a high resistance semiconductor can crucially depend on the kind of contacts to a sample. To verify if the N-type NDR of applied SI GaAs samples exists, when one contact to a sample (namely, the anode) is the gas-discharge plasma, experiments have been done where the gas-discharge part operates in a stable mode. The stability of the discharge is provided there by using a setup with a thin discharge gap. (This structure is the basic component of the infrared image converter; for details see, e.g., [16]). An example of the current-voltage characteristic of the device with a 100 μm discharge gap and the SI GaAs cathode is shown in Fig. 8. Comparison of the curves in Figs. 7 and 8 gives evidence that the characteristic N-type NDR of the GaAs cathode is retained in the hybrid system. Therefore, the nonlinearity of the cathode can influence the processes of formation of the spatiotemporal patterns in the compound system, where the gas-discharge part plays the active role.

III. DISCUSSION

A previous study of a gas-discharge system with a SI GaAs cathode [9] revealed that the first destabilization there commonly gives rise to spatially homogeneous oscillations. The properties of this oscillatory instability are mainly determined by the density of electric current. In particular, oscillations may exist at a relatively low voltage drop on the semiconductor component when a strong irradiation of the SI GaAs electrode is applied, so that the current density is high. These observations, together with the data of the present work, show the existence of the oscillatory instability in the range of control parameters where the semiconductor electrode plays no active role. The experimental data, together with theoretical considerations of the problem of stability of the hybrid system [17], suggest that it is the nonlinearity of the gas-discharge (which is of the S type) that is responsible for the effect. We also mention in this context the study of oscillating discharges in long tubes (see, e.g., [18]).

In our experiments, the first localized structures appear on the oscillating background as soon as the transition from the linear to the NDR section of the current-voltage characteristic is reached as the voltage increases. This fact permits us to suggest that the nonlinearity of the semiconductor is, for the data presented, a decisive ingredient in the process of spatial pattern formation. To clarify the mechanism of the observed phenomena, a theoretical analysis of the dynamics of an extended system that consists of two parts, which are characterized by S- and N-type nonlinearities in the current-voltage characteristics, is required.

While such a theoretical approach is lacking at present, we suggest interpreting the first stages of formation of the complicated patterns in the studied case as follows. At a small feeding voltage, the system is in the nonconducting state, because the voltage is too low to support a self-sustained gas-discharge in the gap. At some (critical) voltage the discharge is ignited in the gap, so that an electric current is established in the device. At a small current density and at a low electric field in the semiconductor cathode, the system is stable: Here, the current density is too low for a destabilization of the homogeneous stationary state of current in the gap, and the electric field inside the semiconductor cathode is less than the critical one for the appearance of electrical domain instability in the semiconductor volume.

The case where the first destabilization of the system occurs due to the active properties of the discharge gap can be considered as follows. An increase in the intensity of irradiation of the semicondutor cathode is accompanied by current growth. At some critical value of current density, the system is destabilized in favor of the oscillatory instability [9]. In addition to a dc bias, the semiconductor cathode is, therefore, acted on by the oscillating voltage. If, then, the amplitude of the feeding voltage U_0 increases, the voltage drop in the semiconductor component becomes closer to the critical value for the electrical domain instability to occur. One should expect that peculiarities in the dynamics of the oscillating discharge current due to the nonlinear behavior of the cathode appear first in those phases of the oscillation where the voltage drop in the semiconductor is near the maximum. (For this stage of the oscillation process, the voltage in the discharge gap is near its minimal value.) It is just at this stage of the oscillation process that a feature in the system's dynamics can be registered, when both parts of the system start to interact; see the oscilloscopic trace in Fig. 3. The important experimental finding related to the corresponding stage of the system's evolution is that the interaction creates pulsating filaments of electric current. It has been found that, for a small number of filaments, their dynamics may be considered as the process of entraining the localized oscillators by a powerful driver, the primary oscillation.

There arises the question, however, of what can be the mechanism of formation of the pulsating filaments. Answering this question requires further research. We have to point out, however, that the existence of the phenomenon evidences the appearance of a transversal instability in the layered system; in other words, the one-dimensional spatial distribution of electrical field in the semiconductor cathode (which is observed either when the device is stable, or when the mode of homogeneous oscillations is observed) becomes, at some stage of variation in the control parameters, unstable.

In relation to the observation of such interesting phenomena as the appearance of subharmonic resonances, and locking of the phases of localized oscillators to different phases of the driver, it should be recalled that the generation of subharmonics of the main frequency was found earlier while studying transport processes in crystals of SI GaAs at a dc voltage (see the corresponding references in the recent review [19]).

We conclude finally that the case studied in the present work gives an interesting example of self-organization of a laterally extended system. The interaction of two nonlinear components produces nonstationary patterns whose different parts may oscillate on different frequencies.

ACKNOWLEDGMENTS

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