SELF-ORGANIZED QUASIPARTICLES AND OTHER PATTERNS IN PLANAR GAS- DISCHARGE SYSTEMS

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ABSTRACT

A summary is given for the work that has been done on pattern formation in planar ac- and dc- gas-discharge systems with high ohmic and dielectric barrier respectively at the Institute of Applied Physics at the University of Muenster. Well defined stationary and moving solitary filaments are observed that may be referred to as self-organized quasiparticles. Among others, filaments can be scattered, generated, or annihilated, and the formation of filament clusters ("molecules") is observed. For appropriate parameters filaments in the "gaseous" phase are observed, and the condensation of large assemblies to "crystalline" phase and "liquid" phase is recorded, too. Filaments may generate superstructures e.g. domain patterns. The experimental work demonstrates that a filament is a generic pattern. In addition, reference is made to non-filamentary patterns. Finally, a list of references referring to models and numerical treatment is presented.

I. Introduction

The evolution of self -organized patterns in gas-discharge systems is well known since the middle of the 18th century. It is amazing to observe that so far little attention has been paid to a systematic investigation of these patterns from the point of view of modern Nonlinear Dynamics and Pattern Formation. To fill this gap at the Institute of Applied Physics at the University of Muenster extensive experimental, theoretical and numerical investigations have been carried out for lateral ac- and dc-gas-discharge systems. In this paper we mainly concentrate on the experimental results thereby emphasising spatially well-localized large amplitude patterns that behave like quasiparticles as it turns out. A detailed discussion of the experimental results in terms of recent qualitative and quantitative models and reference to other work that is related to the work carried out at the Institute of Applied Physics will be done elsewhere.

Due to the spatial extension, because of the dissipation of electric energy and as result of the intrinsic nonlinearities of transport processes gas discharge systems may generate self-organized transient patterns and attractors. As electronic systems they can easily be driven far away from thermodynamic equilibrium. Also the formation of spatial patterns is supported by the absence of a reference system in the discharge gap in contrast e.g. to the rigid ion lattice in solid state devices. These properties make gas-discharge systems exceptional for studying self-organized patterns.

2. Experimental Set-Up

The experimental investigations have been carried out with four different devices:

- A quasi -1-dimensional dc-system operated at room temperature where the edge of a thin metallic plate is opposite to the edge of a thin high-ohmic semiconductor wafer. The electrodes are separated by a discharge gap with discharge length ranging from some 100 μm to some mm. The pressure of the gas is about 10-100 hPa. The driving voltage is up to about 1 kV .¹
- A quasi-2-dimensional dc-system operating at room temperature with a high-ohmic semiconductor layer with diameter in the range of some cm parallel to a glass plate coated with ITO and being transparent with respect to the radiation emitted from the discharge gap. Roughly the discharge length is 1 mm, the pressure 100 hPa, and the voltage up to 1 kV .²
- A quasi-2-dimensional dc-system similar to the former one. However, to increase the resistivity of the semiconductor the latter can be cooled down to about 90 K. In addition, the semiconductor resistivity can be controlled by an external IR-source. The discharge length ranges from about 100 μm to about 1 mm, the pressure is in the order of 100 hPa, and the voltage rises up to some kV .³
- A quasi -2-dimensional ac-system consisting of two parallel dielectric layers having a diameter in the order of several cm and a transparent ITO-contact at the outer sides. The dielectric plates are separated by a discharge space with a discharge length of approximately 1 mm. The pressure is in the order of some 100 hPa the amplitude of the driving voltage is up to some kV, and the period is in the range of 10^{-5} s.⁴

Among other things, self-organized patterns in the distribution of the discharge current do occur. These patterns can be observed optically due to the fact that excited states in the discharge gap emit light. Therefore, locally the current density distribution is reflected by the radiation density distribution which is approximately proportional to the current. All patterns listed below are recorded by optical means.

3. Experimental results

Table 1 gives a listing of patterns of the current distribution in the discharge space. These patterns consist of well-localized objects that may be referred to as quasiparticles.

Table 1

pattern	description	reference
stationary isolated filaments	<ul style="list-style-type: none"> - well localized solitary current density filaments - bifurcation cascades with increasing and decreasing number of filaments 	dc-1-dim: 1,5-13 dc-2-dim: 2,14 ac-1-dim: 15 ac-2-dim: 9,16,17
tails of isolated filaments	<ul style="list-style-type: none"> - basic feature to allow for molecules and various other composite structures at least for dc-systems 	dc-2-dim: 18
stationary filament clusters	<ul style="list-style-type: none"> - well defined filaments stick together to form “molecules” - bifurcation cascades with increasing and decreasing number of filaments in “molecules” 	dc-2-dim: 2,14,19 ac-2-dim: 4,16,17
travelling isolated filaments	<ul style="list-style-type: none"> - single filament motion - bifurcation cascades with increasing and decreasing number of filaments - filament interaction: scattering, generation, annihilation - spontaneous generation - generation due to splitting - coexistence of moving and travelling filaments 	dc-1-dim: 9,11-13,20,21 dc-2-dim: 22,23 ac-1-dim: 9,11 ac-2-dim: 4,15,17,24
travelling isolated filament clusters	<ul style="list-style-type: none"> - moving “molecules” 	ac-2-dim: 4,16,25

pattern	description	reference
oscillating filaments	<ul style="list-style-type: none"> - periodic filament due to splitting with consecutive fading of the new filament - filaments at fixed positions are switched on and off in succession, periodic process, only one filament on at given time - periodically breathing filaments with intermediate dumb-bell shape - circular shape with varying diameter - rotating “molecules” 	dc-1-dim: 9,11,20 dc-2-dim: 2,26,27 ac-2-dim: 28
homogeneous dense filament structures	<ul style="list-style-type: none"> - stationary periodic filament pattern in 1-dim - stationary hexagonal filament pattern (“crystals”) - drifting hexagonal filament pattern - “liquid” state of filaments - “gaseous” state of filaments - “gaseous” state of molecules - rotating rings of filaments 	dc-1-dim: 7,10,29 dc-2-dim: 14,22,30 ac-2-dim: 4,9,11,17,24,31
inhomogeneous dense filament structures	<ul style="list-style-type: none"> - coexistence of gaseous state and “crystalline” or “liquid” filament state, respectively - coexistence of stationary filaments and filaments travelling on closed loops - domains of dense filament patterns surrounded by homogeneous discharge regions - grain boundaries 	dc-2-dim: 32 ac-2-dim: 4,17,24

Table 1: Filamentary patterns observed in 1-and 2-dimensional dc- and ac-gas-discharge systems.

3.1 Stationary isolated filaments

With increasing supply voltage an increasing number of well defined isolated stationary current filaments of solitary shape may appear in a cascade of subcritical bifurcations. This is the case for ac- and dc-systems. Due to identical shape and spatial localization a "centre of mass" can be attributed to the current filaments, and they can be referred to as quasiparticles in 1- or 2-dimensional space. These filaments are the basis for a rich variety of stationary and dynamical patterns that will be discussed in what follows.

3.2 Nonmonotonic tails of isolated filaments

In cases where the amplitude of the current filament is high enough nonmonotonic behaviour of the filament tails can be observed experimentally. This is a generic result also obtained from model calculations and, at least in dc-systems, is considered as the basic property of single filaments to allow for higher hierarchies of structures of which the filament is the basic element.

3.3 Stationary filament clusters

Due to nonmonotonic behaviour of filament tails neighbouring filaments may undergo repulsive and attractive interaction depending on distance. This can lead to isolated stationary filament clusters that we refer to as "molecules". For a large number of interacting filaments the "condensed" state can be organized (see below). The stationary filament clusters are observed in dc- and ac-systems.

3.4 Travelling isolated filaments

Isolated stationary filaments in dc- and ac-systems can undergo a bifurcation to moving filaments. Therefore, they may interact with each other, with the boundary and with inhomogeneities. The former two kinds of interactions are verified experimentally in dc- and ac-systems. Thereby, particle-like behaviour as generation, annihilation, scattering, and the formation of bound states is documented. This is the case in dc- as well as in ac-systems. In addition, the coexistence of moving and stationary filaments are observed in ac-systems. These findings strongly support the notion of a quasiparticle.

3.5 Travelling filament clusters

In a collision of two solitary filaments a pair of filaments can be formed. During the collision process a phase destabilization with respect to the moment of breakdown occurs.

This leads to a symmetry breaking concerning the size of the two filaments. Pairs of filaments travel at velocities of about 10 m/s the smaller filament being the leading one. Besides pairs of filaments clusters of three and four filaments have been observed as well. Due to the internal symmetry of the latter clusters the velocity of these is lower than the velocity of pairs.

3.6 Oscillating filaments

Besides travelling filaments, various kinds of oscillatory behaviour have been exemplified experimentally. In dc-systems, filaments may undergo splitting but the second filament is not stable and disappears. This process is repeated periodically. In dc-systems, clusters of filaments do exist in such a way that the position of single filaments is fixed, but at a given instant of time only one filament is switched on while all the others are off. In a next step the adjacent filament is on and so forth. This dynamic is repeated periodically after all filaments have been switched on once. Breathing processes of isolated filaments have been observed in ac- as well as in dc-systems. In ac-systems, one has to deal with a breathing motion between rotationally symmetrical filaments and filaments of dump-bell shape. In addition, clusters of filaments may undergo rotation in dc- and ac-systems.

3.7 Homogeneous dense filament structures

A variety of patterns can be considered as consisting of dense arrangements of filaments. A natural structure is a large number of filaments covering the whole fundamental active area. On a spatial scale somewhat larger than the distance between single filaments these patterns may be considered as homogeneous. They may consist of stationary or moving filaments.

Stationary arrangements of filaments forming patterns of hexagonal symmetry are observed and can be referred to as "crystals". Dense patterns of moving filaments without long range order are seen and may be called "liquids". Finally, patterns consisting of less dense, uncorrelated filaments moving irregularly all over the fundamental active area have strong similarities to "ideal gases". By changing control parameters one may induce transitions between "solid", "liquid" and "gaseous" state very similar to phase transitions in matter consisting of atoms. It is interesting to remark that the gaseous state has been realized with molecules in ac-systems, too.

In addition, hexagonal arrangements of filaments may undergo a translatory motion with constant velocity in dc- and ac-systems. Also "liquids" with constant generation of filaments at the boundary are observed and correspondingly filaments are annihilated on their way to the center of the circular fundamental area. Again this is recorded in dc- and acsystems. We also mention that dense patterns in ac-systems have been observed consisting of filaments that rotate on circles with the centre of the circle in the centre of the circular fundamental active area. The speed of rotation of rings with different radius can be different.

3.8 Inhomogeneous dense filament structures

Dense filament patterns may exhibit superstructures. Recent experiments have given evidence for the coexistence of different phases e.g. of the "crystalline" and the "gaseous" state. In our findings a permanent exchange of atoms between the two aggregatstates takes place. Dense arrangements of filaments may be subdivided into stationary ones and into those travelling on closed loops that they do not leave. This is a manifestation of a memory effect. Pattens also may consist of nonstationary domains of hexagonal arrangements coexisting with regions of almost vanishing current density. "Grain boundaries" have been observed in stationary and moving hexagonal arrangements, as well.

4. Summary

The experimental results on the formation of filaments in planar gas discharge systems demonstrate clearly that filaments are a generic phenomenon and that the notion of a quasiparticle is a useful concept for the categorization and understanding of various stationary and dynamical patterns being self-organized in gas discharge systems. We mention that besides patterns made up of filaments, a large number of structures has been observed experimentally as there are low amplitude stripes, hexagons, target patterns and their zigzag destabilization, spiral patterns and their zigzag destabilization, strings etc. (1,4,13,22,33,3537). Also it is interesting to note that qualitative and quantitative models do exist describing many patterns and effects. E.g. isolated solitary filaments, corresponding bifurcation cascades, scattering, generation, annihilation, the formation of molecules, breathing filaments and so on are a natural outflow of these models.(6-8,10-12,14,16,28,34,38-52)

We mention that a lot of work has been done also with respect to structures that are not composed of filaments. With respect to this experimental work we refer to the literature. The filamentary structures have been treated analytically and numerically, as well. For this work we also refer to the literature.

5. Acknowledgements

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