Summary and outlook

In the present work, pattern-formation phenomena in a planar dc gas-discharge system with a high-ohmic electrode, operating in two different regimes are investigated analytically and numerically on the basis of the suitable reaction-diffusion systems. In particular, front propagation into an unstable state as well as Turing patterns and solitary localized structures (dissipative solitons (DSs)) are investigated in details.

Reaction-diffusion systems are widely used to describe pattern-formation phenomena in variety of biological, chemical as well as physical systems. A brief review of such systems, their properties and solutions is presented in the Chapter 1 of the thesis.

The experimental gas-discharge system in question also exhibits a large variety of self-organized patterns and is a good candidate for a fundamental investigation of general properties of pattern formation in nonlinear spatially extended dissipative systems. The experimental set-up and typical patterns, arising in the system are discussed in the Chapter 2. In contrast to the good qualitative understanding of experimentally observed patterns, the system with the high-ohmic cathode has been never investigated quantitatively on the basis of gas-discharge specific microscopically-based transport equations. Such a description is developed in the Part I of this thesis on the base of classical drift-diffusion discharge model in the Townsend mode of the discharge operation.

The key problem is that the experimental phenomena are observed on a macroscopic time scale (of the order of 10^{-3} s or longer), whereas the drift-diffusion approximation is on the microscopic time scale. A direct numerical solution of the full 3D drift-diffusion equations on macroscopical times is very time consuming or even impossible and a reduction of the drift-diffusion model is desirable. Such a reduction is developed in the Chapter 3 using the fact that the axial dimension of the discharge cell in question is small as compared to the radial dimension. Two-scale approach allows then to separate off the axial and radial effects. The reduction is possible if the source voltage exceeds the breakdown voltage to a small extent only.

The drift-diffusion equations are simplified to a two-component reaction-diffusion system, that incorporates only radial coordinates and slow temporal

dynamics. All numerical coefficients in this RD system can be quantitatively calculated, that is, our predictions can be compared with experimental data.

The derived set of RD equations is much better suited for an analytical and numerical investigation of the experimental systems than the full drift-diffusion set of equations. In particular, in the obtained RD system the solution in full three-dimensional space has to be implemented numerically only for two space coordinates because the axial dependence is taken into account analytically.

The most important nontrivial solutions of the two-component RD system are those for nonlinear ionization fronts (transition waves), which propagate along the discharge plane away from the point of ignition. Properties and peculiarities of ionization fronts in one and two spatial dimensions are investigated in Chapter 4.

Ionization fronts turn out to be transition waves between unstable and stable system states. The fronts propagate along the electrodes, their form depends on system parameters but not on the seed fluctuation. Propagation of such fronts is often referred to as a front propagation into unstable state. The fronts of such a type are well known in the literature, where, however, typically one-component RD systems are discussed. It is known that for such front propagation problems the propagating front always relaxes to a unique shape and velocity, if the initial profile, arising e.g., trough a local initial perturbation, is steep enough. Depending on nonlinearities, two regimes of front propagation can be distinguished: To the first front type belongs behavior where the velocity is determined by linearization about the unstable state. Such fronts are called pulled or linear marginal stable. In the other type, the front propagation is driven by nonlinearities. This regime is referred to as pushed or nonlinear marginal stable.

The feature of our two-component system is the presence of both pulled and pushed regimes. The transition between both propagation regimes depending on the system parameters is investigated in details. Furthermore, velocity selection problem is considered and the influence of initial conditions on the asymptotic front velocity is discussed.

The present approach is a first step in the quantitative description of pattern formation in planar DC gas-discharge systems. In the second step the treatment has to be extended from the Townsend mode of operation to the glow discharge mode where the patterns are actually observed. However, the case of glow operation mode is much more complicated as this of Townsend mode. At present it can be considered only in frames of a phenomenological RD system. In this thesis, the phenomenological two- and three-component RD systems are investigated in Part II. Both systems are an extension of FitzHugh-Nagumo model and allow the qualitative understanding of a wide variety of interesting experimentally observed phenomena in the gas-discharge

system. This work is focused on stationary spatial Turing structures in both systems, as well as on possible destabilizations of single DS in the three-component model.

In Chapter 6 super- and sub-critical Turing instability is discussed for both systems. Moreover, results, obtained from two-component RD system with an integral term are compared with patterns, observed in an ac-driven barrier discharge system (DBD), which also is known to produce a large amount of varying patterns. As the RD model is not specific for this type gas-discharge system, we cannot draw any quantitative comparisons. However, a qualitative comparison is possible.

The comparison of the observed patterns in the experiment and in the RD-model agrees remarkably. The appearance of spots, bright ones as well as dark ones, occurs via subcritical Turing bifurcation limited by integral inhibition. The intermediate patterns in both cases consist of branched stripe-like patterns with a spatial scale inherited from the spots.

Furthermore, considering the development of the amplitude patterns for the experiment and for the RD-model one can see that in both cases, all bifurcations — from a homogeneous state to a structured one and vice versa — are subcritical. In the course of the high-amplitude patterns the amplitude changes continuously.

In the Chapter 7 stability of a single DS is investigated in details. A linear stability analysis is performed and critical eigenfunctions, which could have an influence on the dynamics of the stationary DS are found. Then the destabilizations of the single DS, caused by these critical modes are discussed. The influence of the mode leading to breathing DSs is discussed in the section 7.2. These breathing solitons can be considered as a result of a Hopf bifurcation of a single stationary DS if one gradually changes a control parameter, e.g., the time constant of the second inhibitor. In this case the stationary DS bifurcates to the oscillatory one either with a constant or increasing amplitude, in the latter case the soliton collapses to a homogeneous stable state. This situation was analyzed performing two-time-scale expansion in the vicinity of the bifurcation point and the corresponding amplitude equation, being a normal form of the Hopf bifurcation, is derived. The information about the system behavior in the vicinity of the bifurcation point is now contained in the complex coefficients of this equation. The latter are the functions of the stationary solution and breathing eigenfunction and can be easily calculated from the original system. Depending on the sign of the coefficients this equation shows the two instability scenarios. We also have calculated the full system as well as the reduced amplitude equation numerically. The results show that both approaches are in good agreement.

Notice that the derived amplitude equation is a well-known normal form of Hopf bifurcation, studied in details for the steady-state solution of a set of

ordinary differential equations. In our case, in contrast, the instability of non-homogeneous stationary solution in two spatial dimension is discussed, what makes the considered problem more complicated. Furthermore, the amplitude equation being presented here was derived in a general form and therefore can be applied to other equations of reaction-diffusion type where a breathing instability takes place.

In the section 7.3 travelling DSs are studied. It was shown that the transition from stationary to moving state can occur due to a change of shape of the DSs. This is tested on the basis of the model equations by varying a parameter which can be related to the global supply voltage of the experimental system and afterwards solving the equations numerically. The results show the linear dependance of the square of the filament velocity on the control parameter, together with a change of the shape of the DSs. These results are compared with the experiments in a qualitative way.

The dynamics of current filaments in a planar dc gas-discharge system with high ohmic semiconductor electrode is considered. As experimentally observed DSs are subject to a strong influence of noise, the deterministic part of the dynamics of the filaments cannot be measured directly. To overcome this problem, methods of stochastic data analysis have been applied. As a result, the deterministic and stochastic parts of the dynamics have been separated and the intrinsic velocity of the filament has been obtained. The analysis shows that a single filament can undergo a transition from a stationary, purely noise driven state to a state with a finite intrinsic velocity due to a change of the system parameters. We identify this scenario as a drift-bifurcation. In the case discussed here, the drift-bifurcation is accompanied by a change of the shape of the DSs, which is related to the chosen control parameter which is the global voltage applied to the discharge cell. We have shown that beyond the bifurcation point the square of the velocity of the filament exhibits a linear dependence on the control parameter.

The qualitative agreement of the experimental system and the theoretical model is remarkable. One can conclude that the drift-bifurcation of DSs can occur in rather general scenarios in which the destabilization is accompanied or induced by a significant but continuous change of the shape of the DSs, induced by varying an appropriate control parameter.

A more complicated situation, when two critical modes become unstable simultaneously is numerically studied in the section 7.4. It is shown that in the vicinity of the codim=2 point, different combination of movement and breathing can be observed depending on control parameters. In particular, a solution in form of moving with a constant velocity and breathing with a constant amplitude DS is observed. To the best of our knowledge there is the first observation of such a phenomenon in two-dimensional RD system with cubic nonlinearity and is the interesting subject of further investigations.

Finally, a long-time dynamics of the DS in the situation with several unstable modes is briefly discussed in section 7.5.

In summary, the current work concerns analytical and numerical studies of pattern formation that are motivated the dc gas-discharge system but also can be applied to other RD systems. Two different discharge regimes are considered on the base of two reaction-diffusion systems. Propagating fronts, stationary Turing patterns, spirals, moving and breathing DSs as well as their combination are discussed in the work and compared qualitatively with the experimental findings. Notice that the most results, presented in this thesis are derived in general form and can be applied to other RD systems, showing similar instability scenarios. Furthermore, the two-component system, derived for the low-current Townsend mode allows the direct comparison with the experiment and is a first step in the quantitative description of pattern formation in planar dc gas-discharge systems.

List of illustrations used in the introduction

Figure	Letter	Source
Fig. 1	a	Photographer: Marek Szymocha, downloaded from: http://www.nordlicht.ch/aurora/gallery/bigpic/60Marek/60.html
	b	see [Nettesheim et al., 1993]
	c	see [Jun et al., 2000]
	d	Photographer: Johnny Jensen, downloaded from: http://www.jjphoto.dk/fish_archive/aquarium_salt/pomacanthus_imperator.htm
	e	see [Ouyang and Swinney, 1991]
	f	see [Ammelt et al., 1997]
	g	downloaded from: http://www.tcd.ie/Physics/Schools/what/materials/foam/shapes.html
	h	see [Ouyang and Swinney, 1991]
	i	downloaded from: http://www.uni-muenster.de/Physik.AP/Lange/Natrium.htm, see also [Ackemann and Lange, 2001]
	j	downloaded from: http://desert.bgu.ac.il/desert/bo/contentnet/siteimgs/rings1_s.jpg, see also [Meron et al., 2004]
	k	see [Vanag and Epstein, 2004]
	l	see [Astrov and Purwins, 2001]

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