8.
Semiconductors:
Theory

(references refer to the list of publications given in chapter 12)

A. DC Driven pin-Diodes and p-n-p-n Layer Devices

A. 8.1 General remarks

The considered devices are represented schematically in fig. 7.1a, b of the chapter Semiconductors: Experiment and have been modelled qualitatively on the basis of the device fig. 2.1 with the characteristics fig. 2.2 discussed in chapter A Model for Pattern. The corresponding model equations are of reaction-diffusion type and important solutions, also those referring to pin-diodes and p-n-p-n layer devices are discussed in the chapter Reaction-Diffusion Equations using the generalized FitzHugh-Nagumo (FHN) equation.

A semiconductor specific theoretical model for the formation of self-organized current filament has been proposed in [Pu010] but so far no experimental system has been detected where the model applies to.

A semi-quantitative semiconductor specific model for the experimentally investigated p^{+}-n+-p-n^{-} layer devices fig.71b of chapter Semiconductors: Experiment has been treated e.g. in [Pu020, Pu033]. The resulting model equation reads as

$$\tau_e \frac{\partial V_e(x,t)}{\partial t} = l_e^2 \frac{\partial^2 V_e(x,t)}{\partial x^2} - q\left(V_e(x,t), V_i(x,t)\right), \qquad (1)$$

$$\tau_p \frac{\partial \bar{p}\left(V_i(x,t), V(t)\right)}{\partial t} = l_p^2 \frac{\partial^2 \bar{p}\left(V_i(x,t), V(t)\right)}{\partial x^2} + Q\left(V_e(x,t), V_i(x,t), V(t)\right), \qquad (2)$$

$$V(t) = U_0 - R_0 l_y \int_0^{l_x} j\left(V_e(x,t), V_i(x,t)\right) dx. \qquad (3)$$

Here $\bar{p}\left(V_i(x,t), V(t)\right) = p_{n0} \exp\left((V(t) - V_i(x,t)) / V_T\right)$ can be interpreted as the hole concentration of the overall device being averaged along the *z*-direction ranging from 0 to l_z. Thereby p_{no} and V_T are known constants. τ_e is a dielectric relaxation time and comes into play via the capacity of the p^+-n^+ transition and the average resistivity of the n^+ layer. τ_p is the effective hole relaxation time of the overall device and is determined by the lifetime of the holes in the n^- region. The term l_e denotes the effective voltage diffusion length resulting from the finite lateral conductivity of the n^+ layer and $l_p = \sqrt{D_p \tau_p}$ is the effective diffusion length, with D_p as the diffusion coefficient of holes in the n^- region. Finally q and Q are functions that can be expresses by V_e and V_i. We not that j can be chosen as j_c which in turn can be calculated from V_e, V_i and V.

A.8.2 Graphical representation of selected results

The following is a series of figures reflecting main results that have been obtained theoretically in relation to the investigation of p-n-p-n -devices.

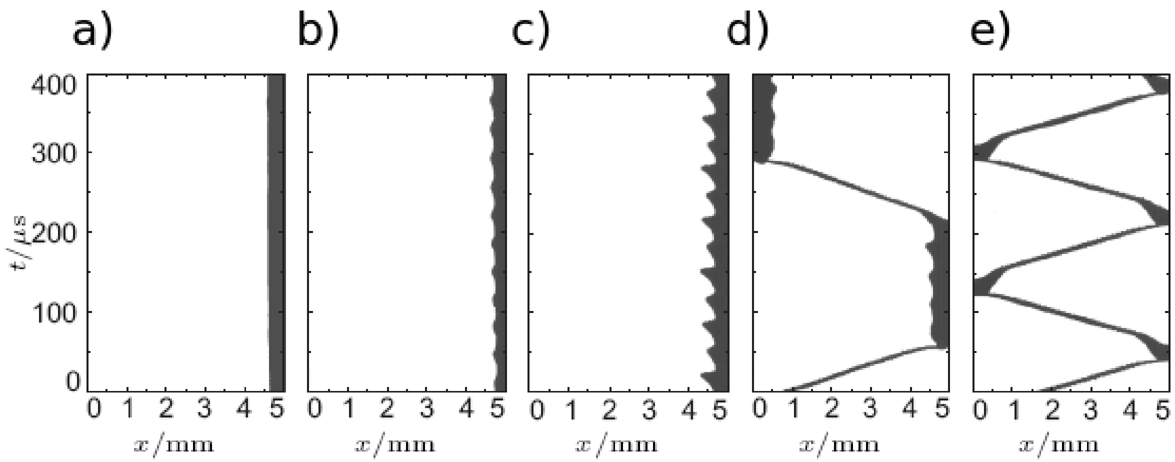

Fig. 8.1

Space time plot for the numerical solutions of the semiconductor specific equations (1-3) for the current density $j_c = j_c(x,t)$ in the quasi 1-dimensional p^+-n^+-p-n^- layer device fig. 7.1b of the chapter Semiconductors: Experiment. As parameters for the figures (a - e) those of the corresponding experimental patterns of fig. 7.2a-e have been chosen. As can be seen, without any fitting rather good agreement is obtained between the experimentally observed cascade of bifurcations depicted in fig. 7.2 and the numerical simulations. [Pu033]

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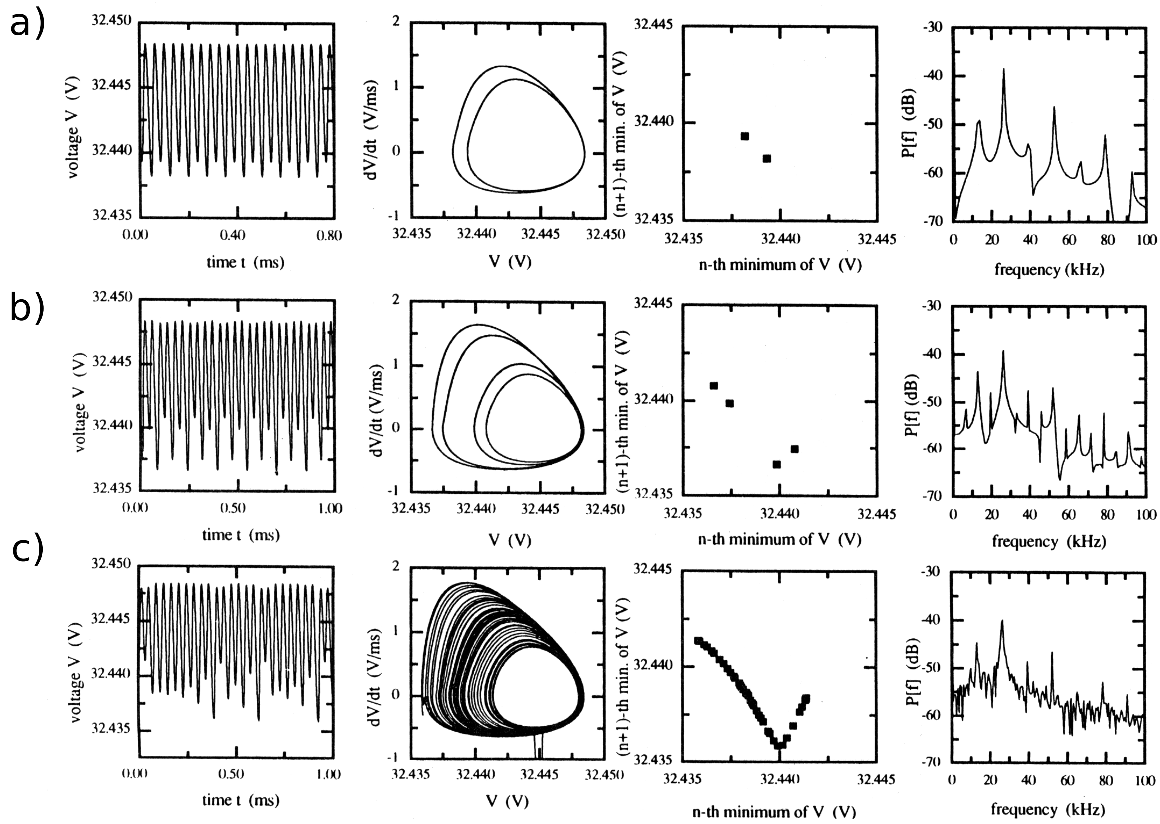

Fig. 8.2a-c

Dynamical behaviour of a breathing single filament being the numerical solution of the semiconductor specific equations (1-3) in the quasi 1-dimensional p^+-n^+-p-n^- layer device fig. 7.1b of the chapter Semiconductors: Experiment. The driving voltage is increased from (a) to (c). 1. column: voltage drop $\tilde{V}(t)$ at the device as a function of time; 2. column: corresponding time derivitve of $\tilde{V}(t)$ versus $\tilde{V}(t)$; 3. column: return map; 4. column: power spectrum of $\tilde{V}(t)$. [Pu033; Pu036]

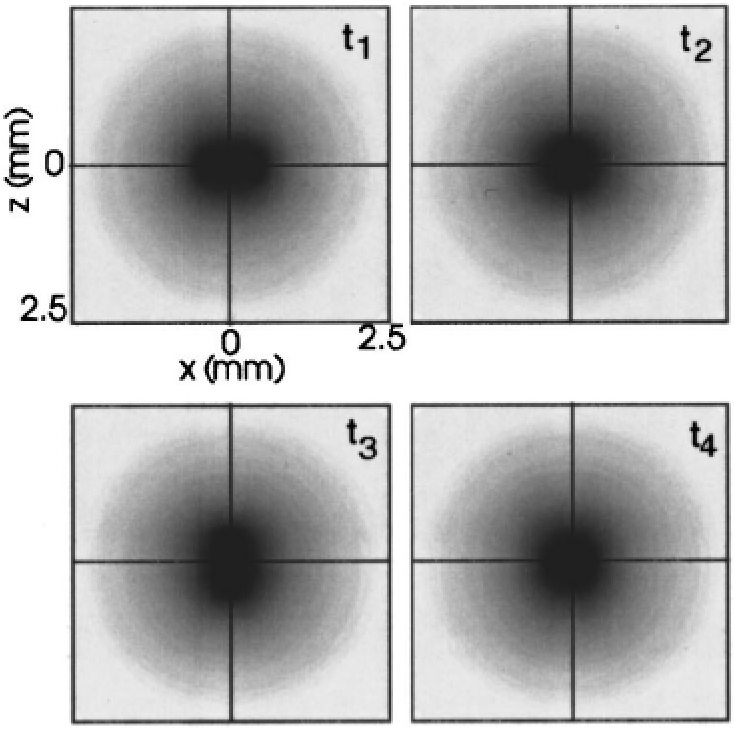

Fig. 8.3
Numerical solutions of the semiconductor specific equations (1-3) for V_e in the quasi 2-dimensional p^+-n^+-p-n^- layer device fig. 7.1b of the chapter Semiconductors: Experiment in the case of elliptically oscillating filaments periodically deforming first in in x and subsequently in y direction. [Pu054]

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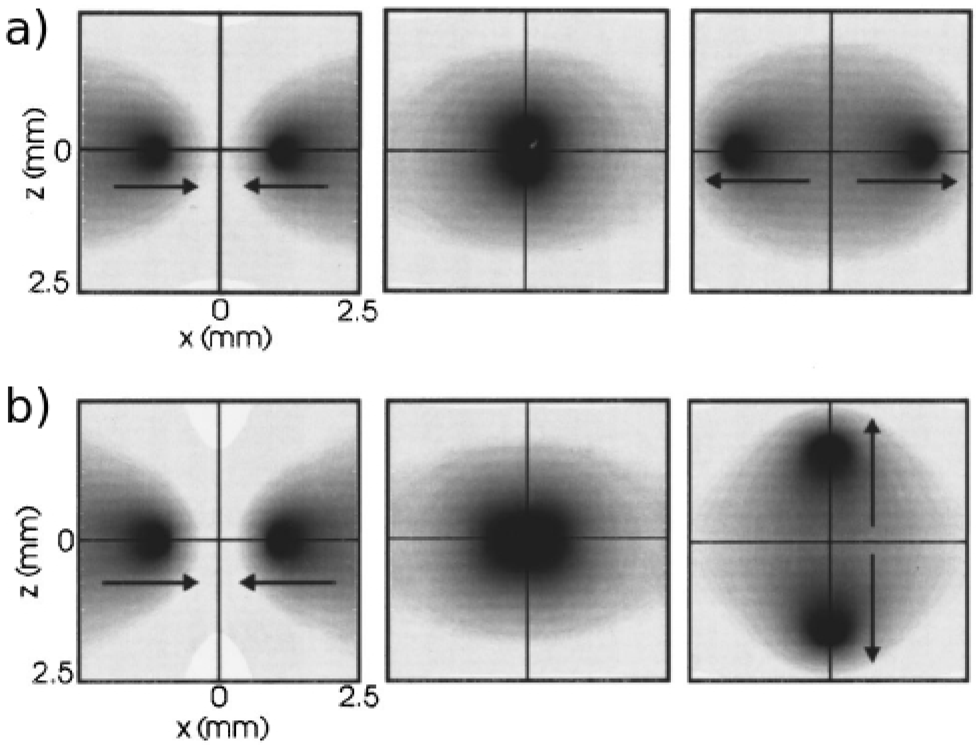

Fig. 8.4

Numerical solutions of the of the semiconductor specific equations (1-3) for V_e in the quasi 2-dimensional p^+-n^+-p-n^- layer device fig. 7.1b of the chapter Semiconductors: Experiment. In dependence of the chosen parameters, in the present case one observes a central collision of two travelling filaments with subsequent reflection (a) and vertically outgoing filaments (b). [Pu054]

A. 8.3 Listing of main results

With respect to the abbreviations used in the following listing of observed phenomena we refer to the Introduction.

Pu003: **Radehaus, Kardell, Baumann, Jäger, Purwins (1987)**

isolated stationary and travelling fs

theo: 2-k + gc, R^2 - num: stat **fs**

periodic pattern in R^2

theo: 2-k + gc, R^2 – num: stat periodic

bifurcation: Turing bifurcation and snaking

theo: 2-k + gc, R^2 - num: (stat hom) ↔ (stat period), Turing; snaking

electrodynamic derivation of a 2-component reaction-diffusion equation including global coupling - claim that certain planar semiconductor devices can be considered as r-d systems with respect to lateral patter formation - claim that the high ohmic resistively layer with monotonic current voltage characteristic supports spatially inhomogeneous patterns if it is in contact with an effective layer with S-shaped (current density)-(voltage) characteristic - possibly first explanation of the stabilization of a stationary current filaments in a semiconductor material based on local activation and lateral inhibition - first report of snaking - see also: Semiconductors: Experiment, Reaction-Diffusion Equations

Pu006: **Baumann, Symanczyk, Radehaus, Purwins, Jäger (1987)**

continuation of [Pu003] - the filament diameter is in good agreement with numerical results obtained from the 2-component reaction-diffusion equation - see also: Semiconductors: Experiment, Reaction-Diffusion Equations

Pu007: **Purwins, Klempt, Berkemeier (1987)**

theoretical and system specific semiconductor model describing the stabilization of stationary current filaments (for details see [Pu010]) - see also: Electrical Networks: Experiment and Theory, DC Gas-Discharge Systems: Experiment, Reaction-Diffusion Equations

Pu010: **Kardell, Radehaus, Dohmen, Purwins (1988)**

possibly the first development of a theoretical system specific semiconductor model describing the stabilization of stationary current filaments - model system for snaking in semoconductors

Pu020: **Niedernostheide, Kerner , Purwins (1992)**

isolated stationary and travelling fs

theo: 1d-SCD, $R_0 \neq 0$, I (p^+-n^+-p-n^- layer system) - stat , trav fs, semiconductor specific modelling (semi-quant)

isolated pendulating fs

theo: 1d-SCD, $R_0 \neq 0$, I - pend fs, semiconductor specific modelling (semi-quant)

interaction of fs: reflection

theo: 1d-SCD, $R_0 \neq 0$, I - ref at boundary, semiconductor specific modelling (semi-quant)

bifurcation: complex dynamical bifscenario

theo: 1d-SCD, $R_0 \neq 0$, I - complex dynamical bif scenario: essentially (hom stat state) ↔ (stat f) ↔ (pend f) ↔ (trav f), semiconductor specific modelling (semi-quant)

development of a semiconductor specific model being heavily based on the concept of local layer characteristics and lateral diffusion - description of the complex dynamical bifurcation scenario in 1- and 2-dimensional p-n-p-n semiconductor devices in the form of p^+-n^+-p-n^- diodes : (hom stat state) ↔ (stat DS) ↔ (pend DS) ↔ (trav DS) - see also: Semiconductors: Experiment

Pu025: **Niedernostheide, Dohmen Dohmen, Willebrand, Kerner, Purwins (1993)**

approximating the semiconductor specific model developed in [Pu020] in terms of the 2-component reaction-diffusion equation - similarity for semiconductor devices, electrical networks and gas-discharge systems - see also: Reaction-Diffusion Equations

Pu033: **Niedernostheide, Ardes, Or-Guil, Purwins (1994)**

isolated stationary and travelling fs

theo: 1d-SCD, $R_0 \neq 0$, I (p^+-n^+-p-n^- layer system) - semiconductor specific modelling: stat fs , trav fs (semi-quant)

isolated breathing and pendulating fs

theo: 1d-SCD, $R_0 \neq 0$, I - semiconductor specific modelling: pend fs, breath fs

interaction of fs: reflection

theo: 1d-SCD, $R_0 \neq 0$, I - refl at boundary, semiconductor specific modelling (semi-quant)

bifurcation of fs: complex scenario

theo: 1d-SCD, $R_0 \neq 0$, I - semiconductor specific modelling: complex bif scenario, essentially of the form (hom stat state) ↔ (stat f) ↔ (pend f) ↔ (trav f), (semi-quant); frequency doubling based on the dynamics of a breathing f

continuation of [Pu020 , Pu022, Pu030] - numerical solution of the semiconductor specific model developed in [Pu020] for p^+-n^+-p-n^- semiconductor devices: semi-quantitative agreement of the solutions with the experimentally observed complex bifurcation scenario, essentially being of the form: (homogeneous stationary state) ↔ (stationary filament) ↔ (pendulating filament) ↔ (travelling filament) reported e.g. in [Pu022] - numerical solutions of the same model again in p^+-n^+-p-n^- semiconductor devices: frequency doubling based on a breathing DS; the scenario is very similar to experimental results on frequency doubling that are reported in

[Pu030] based on a pendulating filament - see also: Semiconductors: Experiment

Pu036: **Niedernostheide, Kreimer, Kukuk, Schulze, Purwins (1994)**
summary - material also contained in [Pu020 , Pu025, Pu033]

Pu054: **Niedernostheide, Or-Gui, Kleinkes, Purwins (1997)**
bifurcation: of fs

theo: 2d-SCD, I (p^+-n^+-p-n^- layer system) - semiconductor specific modelling, num: (stat f) ↔ (elliptically oscillating f) ↔ (trav f)

numerical solutions for a special bifurcation scenario using a semiconductor specific model - see also: Semiconductors: Experiment

Pu127: **Purwins, Amiranashvili (2007)**
summary - simple patterns: e.g. isolated solitary filaments and related DSs, stripes, hexagons and rotating spirals - patterns of higher complexity with solitary filaments and related DSs as elementary building blocks: e.g.”molecules” and “many body systems” in the form of crystal-, liquid-, gas-like arrangements, chains and nets - universal experimental behaviour for a ertain class of systems containing: planar ac and dc gas-discharge systems, electrical networks, semiconductor layer systems, chemical solutions and biological systems - theoretical definition of the corresponding universality class: writing down a 3-component reaction-diffusion system serving as a kind of normal form for the qualitative description of the experimentally observed self-organized patterns - illustration of the formation of solitary filaments and related DSs in planar electrical transport systems on the basis of the 2-component reaction diffusion equation - see also: Electrical Networks: Experiment and Theory, DC Gas-Discharge Systems: Experiment, AC Gas-Discharge Systems: Experiment, Gas-Discharge: Theory, Semiconductors: Experiment, Reaction-Diffusion Equations

B. Ac driven ZnS:Mn films

B. 8.1 General remarks

The device is depicted schematically in fig. 7.8 of the chapter Semiconductors: Experiment and has been modelled on the basis of various mechanisms for charge transport discussed also in that chapter. The semiconductor specific model includes first principle impact ionization calculations and modelling of charge carrier transport by a drift-diffusion equation (see e.g. [Pu096].

B. 8.2 Listing of main results

With respect to the abbreviations used in the following listing of observed phenomena we refer to the Introduction.

Pu044: **Goßen, Niedernostheide, Purwins (1995)**
qualitative discussion of experimentally observed patterns within the scope of the 2-component reaction diffusion system - see also: Semiconductors: Experiment

Pu088: **Raker, Kuhn, Kuligk, Fitzer, Redmer, Zuccaro, Niedernostheide, Purwins (2002)**
first principle impact ionization calculation - modelling carrier transport by a drift-diffusion model - comparison of the theoretical with the experimental dissipative currents - see also: Semiconductors: Experiment

Pu096: **Zuccaro, Raker, Niedernostheide, Kuhn, Purwins (2003)**
point defects are investigated by photo-depolarization-spectroscopy - specific experimental features of the latter correlate with self-organized patterns - modelling carrier transport by a drift-diffusion model and comparison of the theoretical and experimental dissipative currents - see also: Semiconductors: Experiment

Pu127: **Purwins, Amiranashvili (2007)**
summary - simple patterns: e.g. isolated solitary filaments and related LSs/DSs, stripes, hexagons and rotating spirals - patterns of higher complexity with solitary filaments and related LSs/DSs as elementary building blocks: e.g."molecules" and "many body systems" in the form of crystal-, liquid-, gas-like arrangements, chains and nets - universal experimental behaviour for a certain class of systems containing: planar ac and dc gas-discharge systems, electrical networks, semiconductor layer systems, chemical solutions and biological systems - theoretical definition of the corresponding universality class: writing down a 3-component reaction-diffusion system serving as a kind of normal form for the qualitative description of the experimentally observed self-organized patterns - illustration of the formation of solitary filaments and related LSs/DSs in planar electrical transport systems on the basis of the 2-component reaction diffusion equation - see also: Electrical Networks: Experiment and Theory, DC Gas-Discharge Systems: Experiment, AC Gas-Discharge Systems: Experiment, Gas-Discharge: Theory, Semiconductors: Experiment, Reaction-Diffusion Equations