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
\[
\tau_e \frac{\partial V_e(x,t)}{\partial t} = l_e^2 \frac{\partial^2 V_e(x,t)}{\partial x^2} - q|V_e(x,t), V_i(x,t)|, \tag{1}
\]

\[
\tau_p \frac{\partial p|V_i(x,t), V(t)|}{\partial t} = l_p^2 \frac{\partial^2 p|V_i(x,t), V(t)|}{\partial x^2} + Q|V_e(x,t), V_i(x,t), V(t)|, \tag{2}
\]

\[
V(t) = U_0 - R_0 \int_0^l j|V_e(x,t), V_i(x,t)| \, dx. \tag{3}
\]

Here, \( p(V_i(x,t), V(t)) = p_{n0} \exp\left( (V(t) - V_i(x,t)) / V_T \right) \) can be interpreted as the hole concentration of the overall device being averaged along the z-direction ranging from 0 to \( l_z \). Thereby, \( p_{n0} \) and \( V_T \) are known constants. \( \tau_e \) 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. \( \tau_p \) 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]
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 derivative 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 $p^+\text{-}n^-\text{-}p\text{-}n^+$ layer device fig. 7.1b of the chapter *Semiconductors: Experiment* in the case of elliptically oscillating filaments periodically deforming first in x and subsequently in y direction. [Pu054]
Fig. 8.4
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 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 pattern 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 semiconductors
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 bif scenario
  theo: 1d-SCD, $R_0 \neq 0$, $I$ - complex dynamical bif scenario: essentially
  (hom stat state) $\leftrightarrow$ (stat f) $\leftrightarrow$ (pend f) $\leftrightarrow$ (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) $\leftrightarrow$ (stat DS) $\leftrightarrow$ (pend DS) $\leftrightarrow$ (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) $\leftrightarrow$ (stat f)
  $\leftrightarrow$ (pend f) $\leftrightarrow$ (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) $\leftrightarrow$ (stationary filament)
  $\leftrightarrow$ (pendulating filament) $\leftrightarrow$ (travelling filament) reported e.g. in [Pu022] -
numeral 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

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 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 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.

qualitative discussion of experimentally observed patterns within the scope of the 2-component reaction diffusion system - see also: Semiconductors: Experiment

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

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

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