# MODELLING CURRENT FILAMENTATION DURING ESD EVENTS

Christoph Sohrmann, Patrick Scharf (Fraunhofer IIS/EAS, Dresden)
Steffen Holland (NXP, Hamburg)

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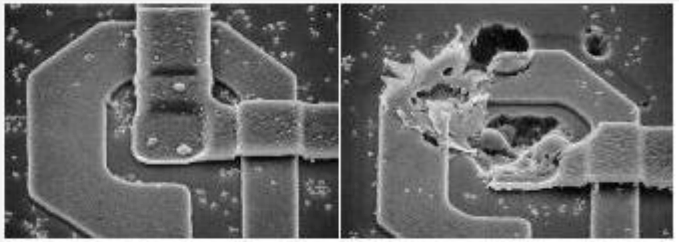
# OUTLINE

- Introduction to ESD
- Effects during ESD
- TCAD modeling
- New compact modeling approach
- Summary

# INTRODUCTION TO ESD

# Introduction to ESD
## Failure due to ESD

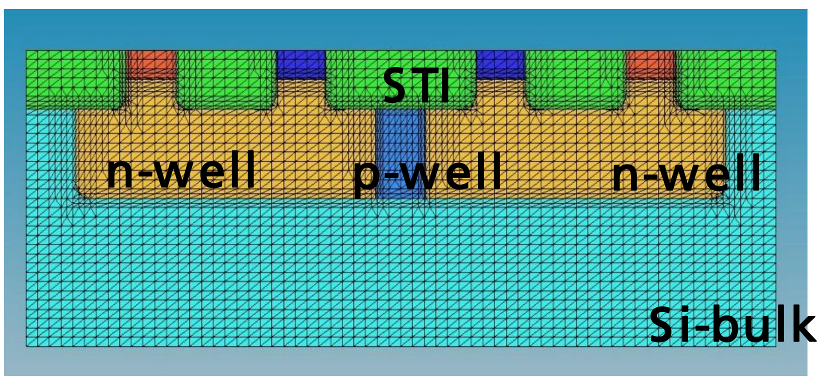
- Dielectric Breakdown of SiO2 at ~ 1e7 V/cm
- 200 Å gate oxide will breakdown at 20 V
- Carpet can charge a person with 20 kV
- ESD causes failure of semiconductor devices by an **over-current** effect

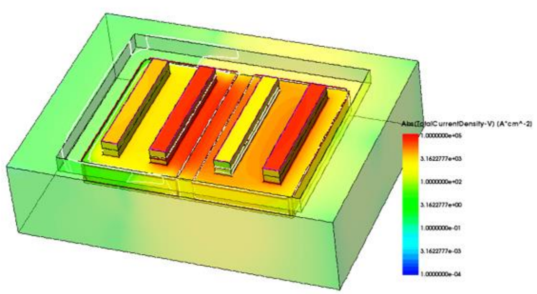


# Introduction to ESD
## Scope of this work

- **Short-term goal:**
  Optimization of discrete ESD protection devices

- **Mid-term goal:**
  Application of the method to other types of protection, e.g. SCRs





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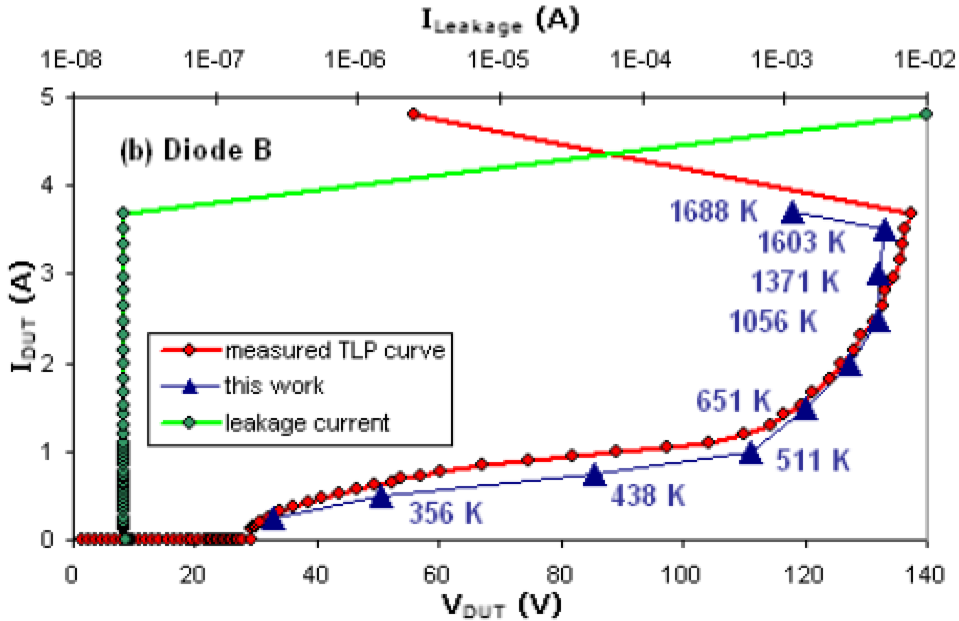
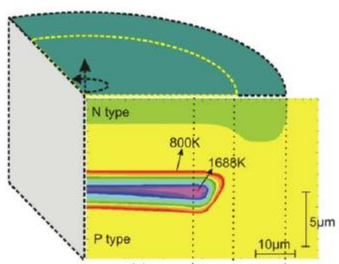
# EFFECTS DURING ESD EVENTS

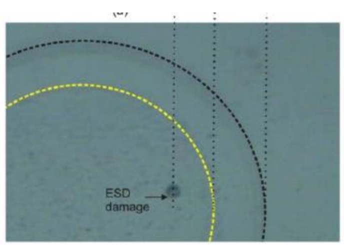
# Effects during ESD events
## What could possibly happen?

- **During an ESD event strange things can happen:**
  - Current flows at unexpected locations
  - Hotspot formation instead of uniform heating
  - Strong increase of voltage within the device




Pan et al. Proc. SISPAD 2010 p287

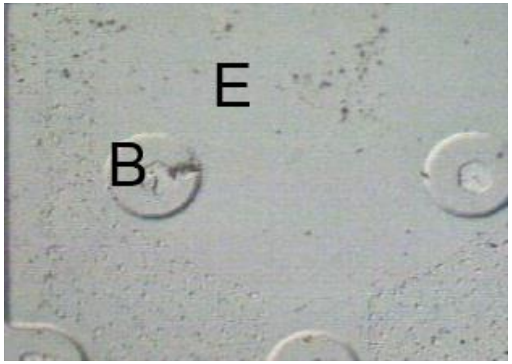


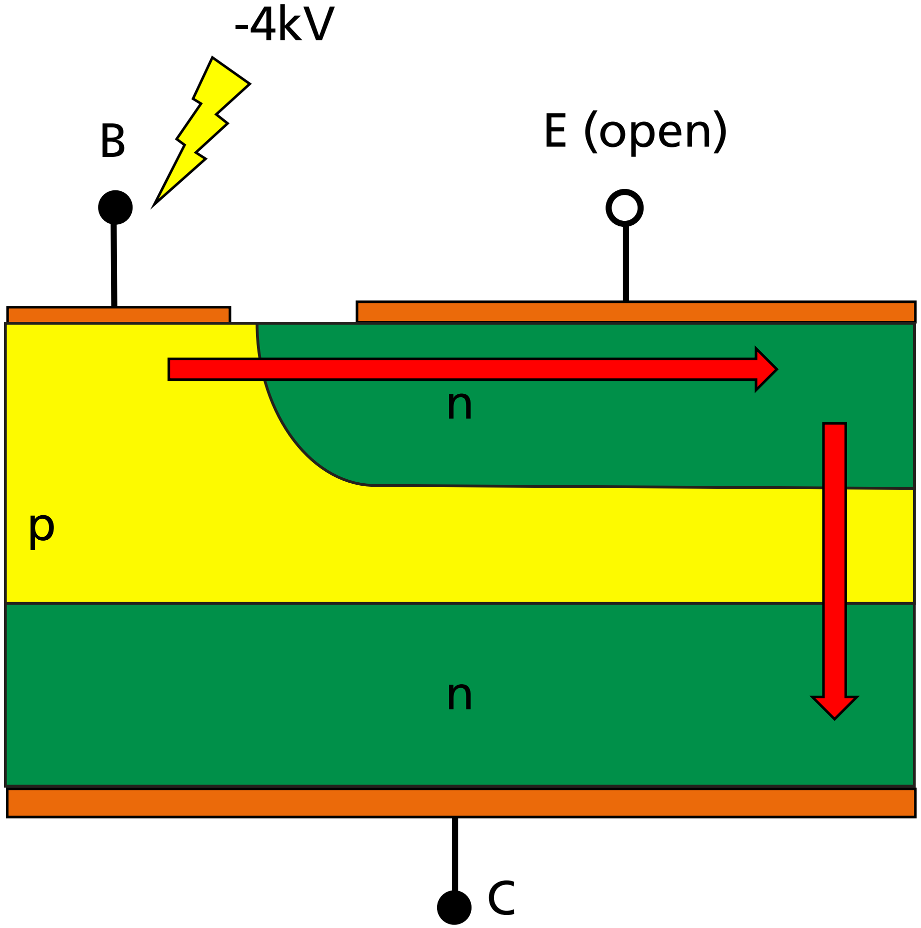



(b)

# Effects during ESD events
## Current flow at unexpected locations

- Vertical device geometry
- Negative ESD pulse is applied to the p-base
- Where does the current flow?
- If flows over the emitter!



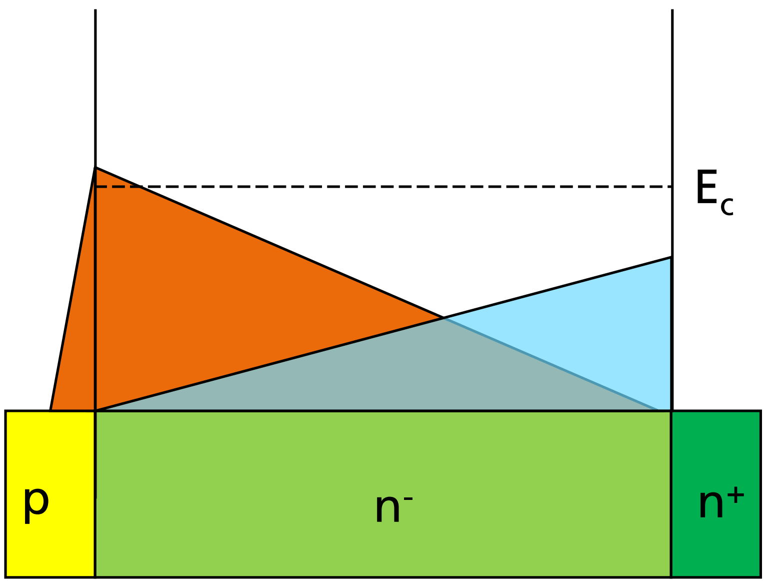
# Effects during ESD events

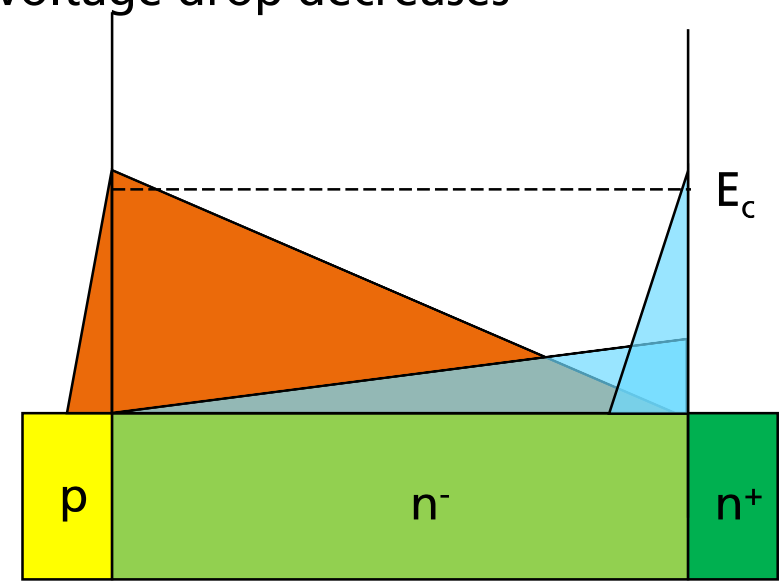
## Electric field of a simple diode

- $J = q \cdot n \cdot v$
  - Velocity saturates
- $J = q \cdot n \cdot v_{sat}$
  - $n$ must increase for rising J
    → rise of electric field
- Increase of electric field due to velocity saturation:
  - Avalanche at n- n+ interface creates holes

  → redistribution of electric field occurs

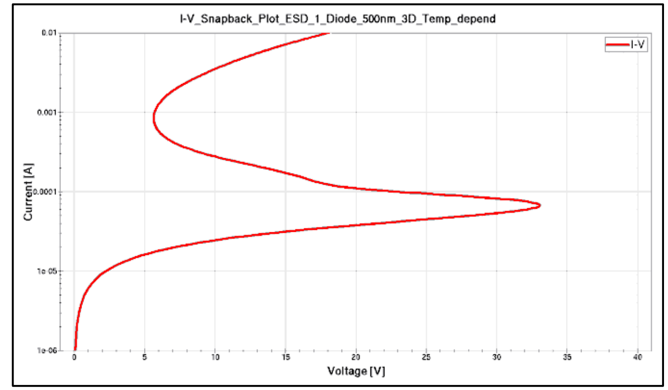
  → voltage drop decreases

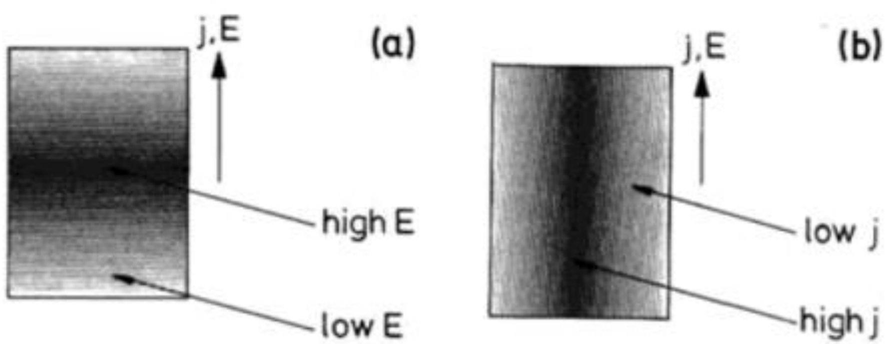


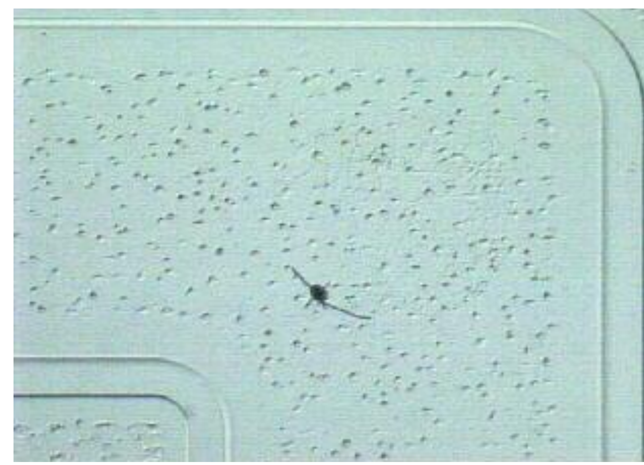



# Introduction to ESD
## Current filamentation

- Snapback IV-charactersistics
- NDR leads to intrinsic instabilities
- Inhomogeneous current flow
  → major cause of failure



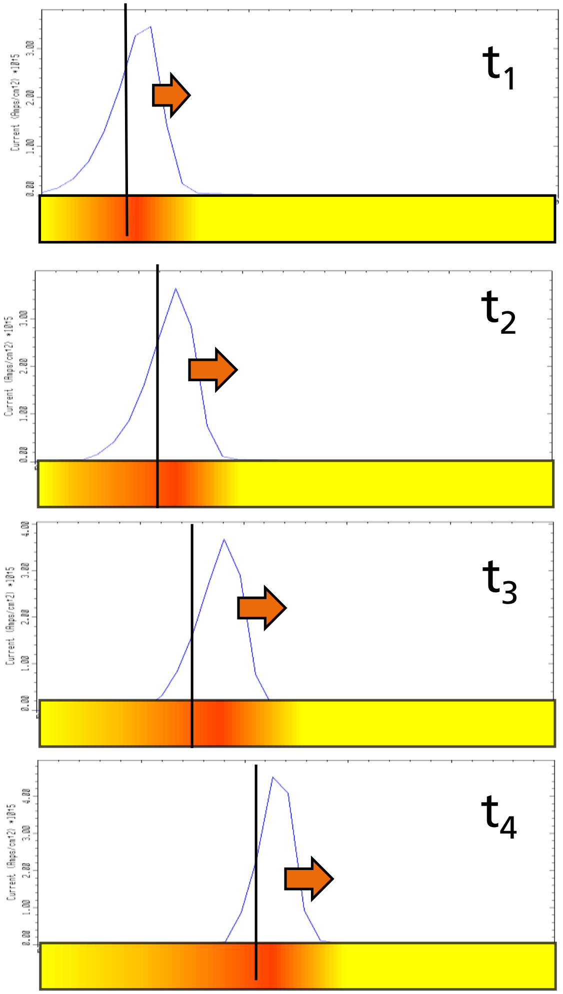



Schöll, E.. *Nonequilibrium phase transitions in semiconductors:*. Springer, 2012.

# Effects during ESD events
## Moving current filament

- Current filament forms and can move due to the temperature dependence of impact ionization coefficient

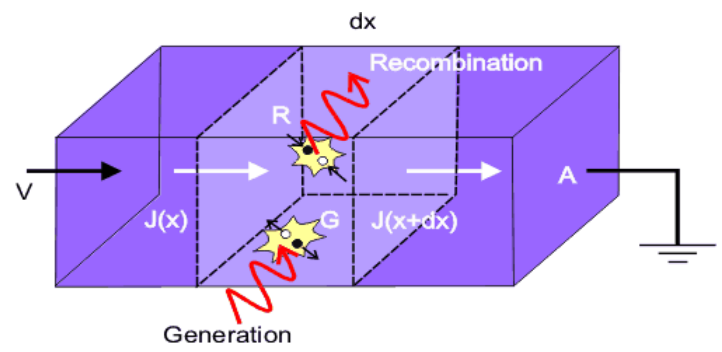
→ It's „surfing its own heat wave"



# TCAD MODELLING

# TCAD Modelling
## Introduction

- TCAD (Technology Computer Aided Design)
- Device Simulation using basic semiconductor equations
- **Transport equations:**
  - $\mathbf{J_n = q \cdot (\mu_n \cdot n \cdot E + D_n \cdot \nabla n)}$
  - $\mathbf{J_p = q \cdot \left(\mu_p \cdot p \cdot E - D_p \cdot \nabla p\right)}$
- **Continuity equations:**
  - $\mathbf{\partial_t n = G - R + q^{-1} \cdot \nabla J_n}$
  - $\mathbf{\partial_t p = G - R - q^{-1} \cdot \nabla J_p}$
- **Poisson equation:**
  - $\boldsymbol{\varepsilon \cdot \nabla E = -\rho}$



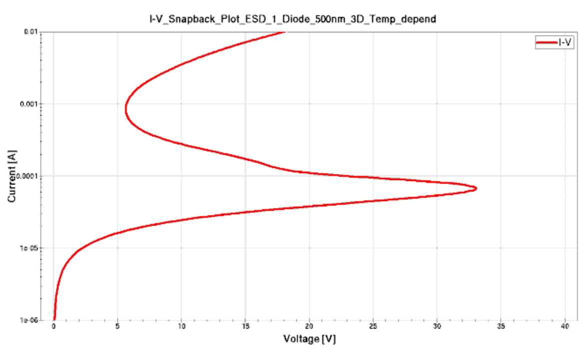

http://britneyspears.ac/physics/continuity/genrec.htm

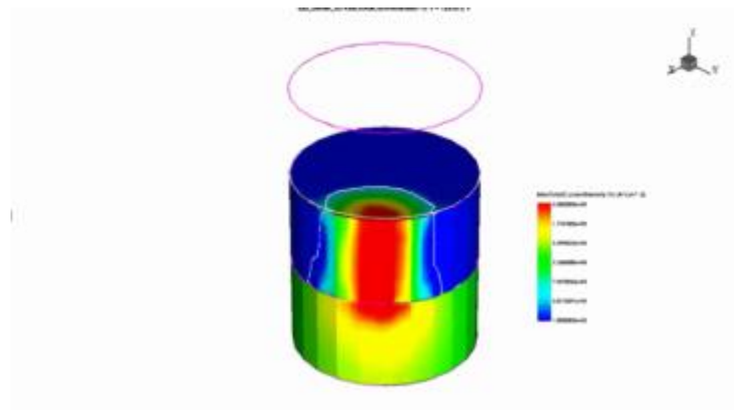
# TCAD Modelling
## Moving current filaments in 3D

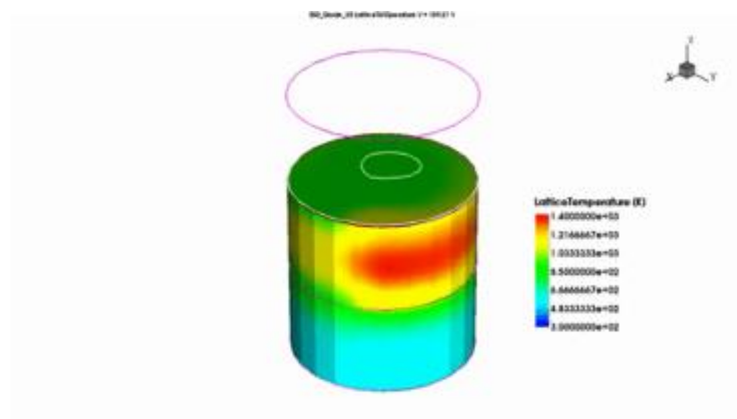
- **In case of ESD event:**
  - High current injection
  - Breakdown → voltage snapback
  - Current filamentation
  - Self-heating

  → filament starts moving

- **Example:**
  - pin-diode (p+/n/n+)



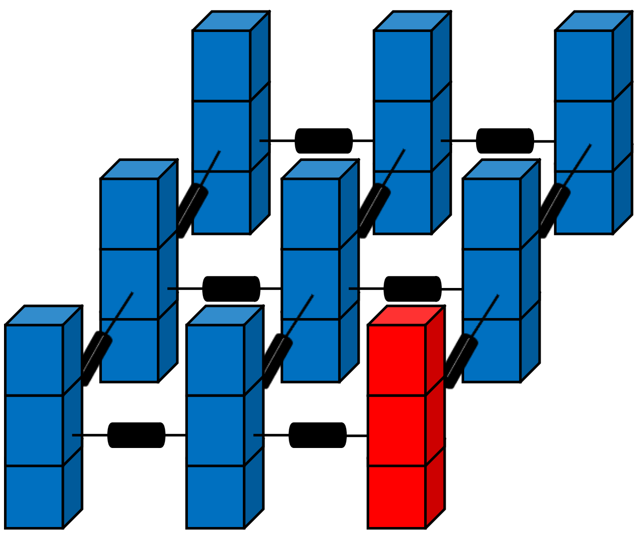





# TCAD Modelling
## Moving current filaments in 2D

### 3D Simulation

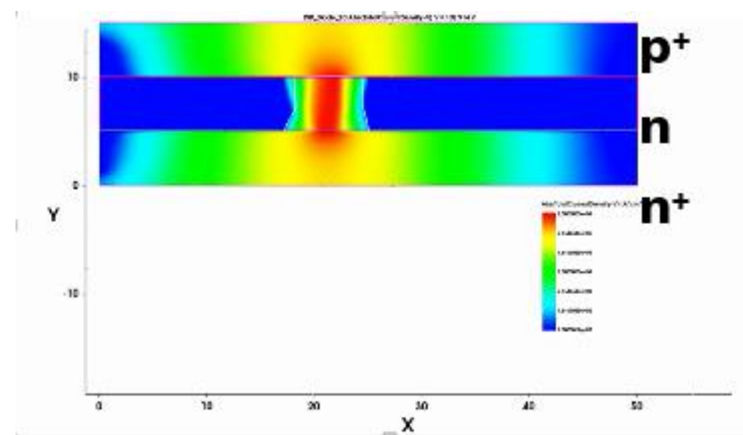
- Simulation time of several hours!!
- Symmetry of problem not exploited
  → too many useless vertices



### 2D Simulation

- Moving filament along x-axis
- When reaching an edge

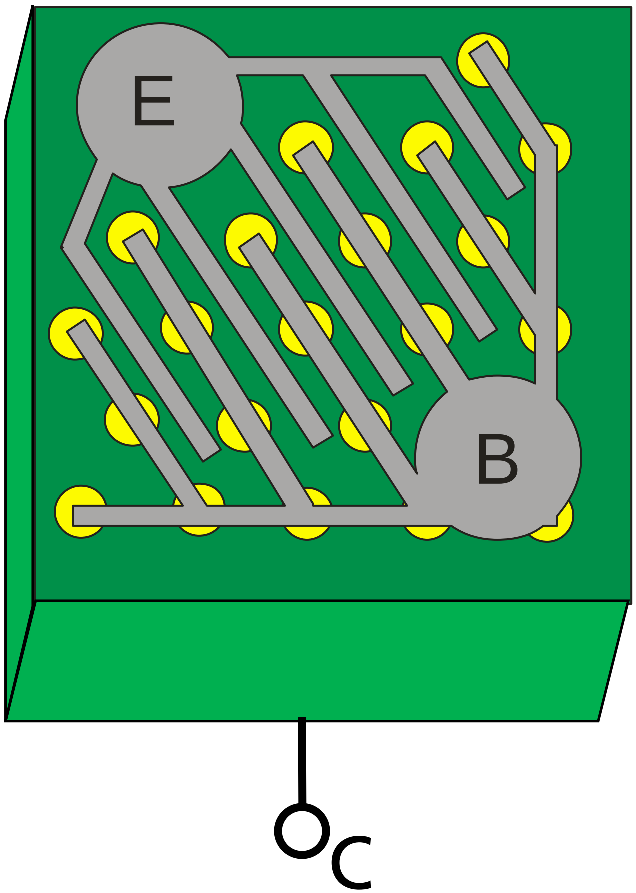
  → voltage & temperature increase until filament changes direction



# NEW COMPACT MODEL APPROACH

# New Compact Model
## Motivation

3D structure



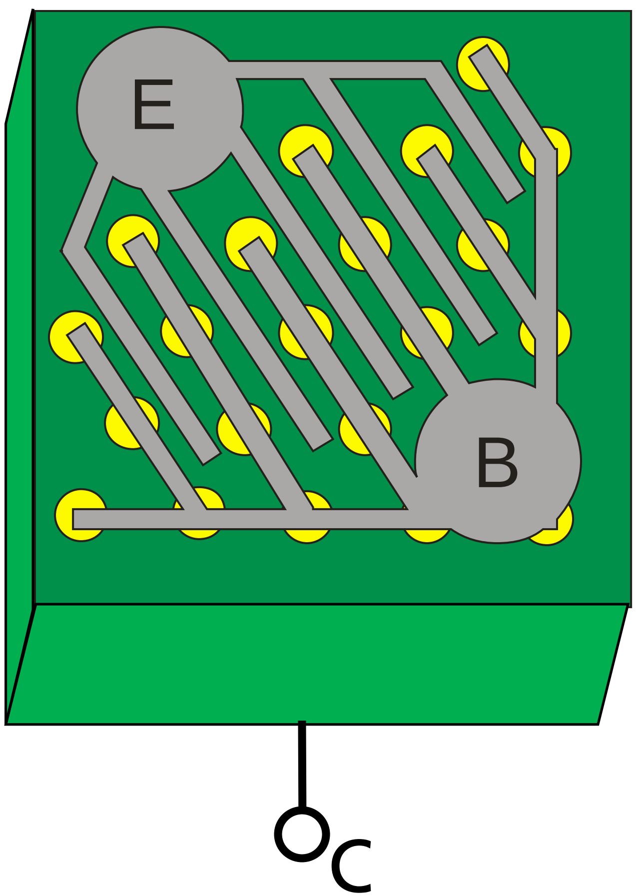

- Macroscopic behavior results from microscopic interactions
  - High currents → velocity saturation
  - High fields → avalanche generation
  - Fast dynamics → overshoot effects
  - NDR → current filamentation
  - ...
- Full description requires 3D model
  → solved with (expensive!) TCAD simulation

**Can we simplify the problem AND keep the relevant physical effects… ?**

# New Compact Model

## Quasi 3D model

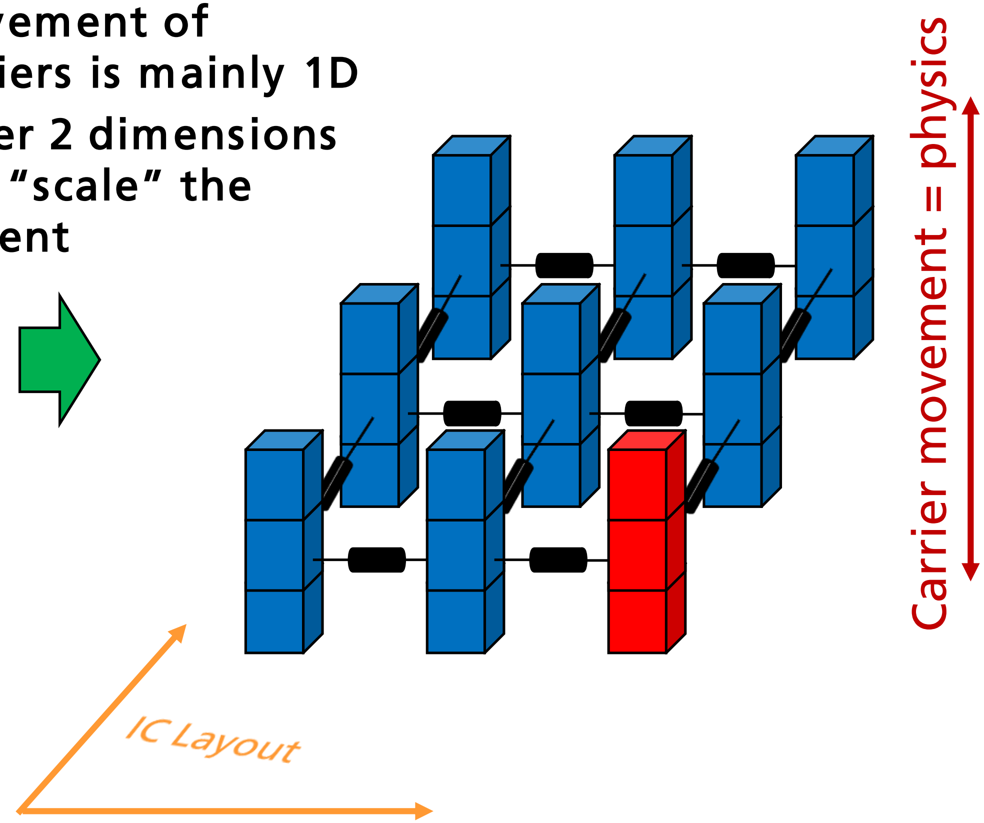
3D structure




**<u>Assumptions:</u>**

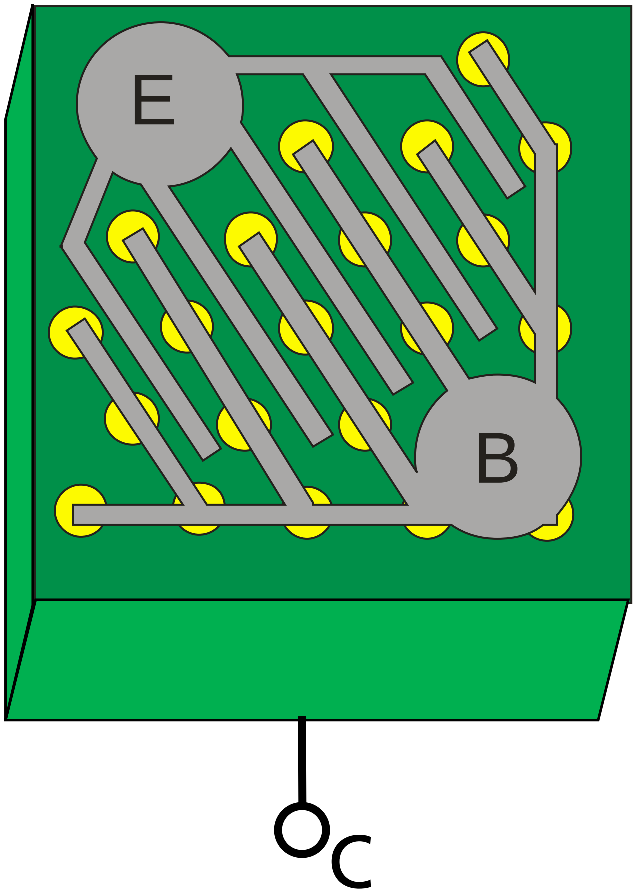
- **Movement of carriers is mainly 1D**
- **Other 2 dimensions just "scale" the current**

quasi-3D model



# New Compact Model
## Quasi 3D model

3D structure

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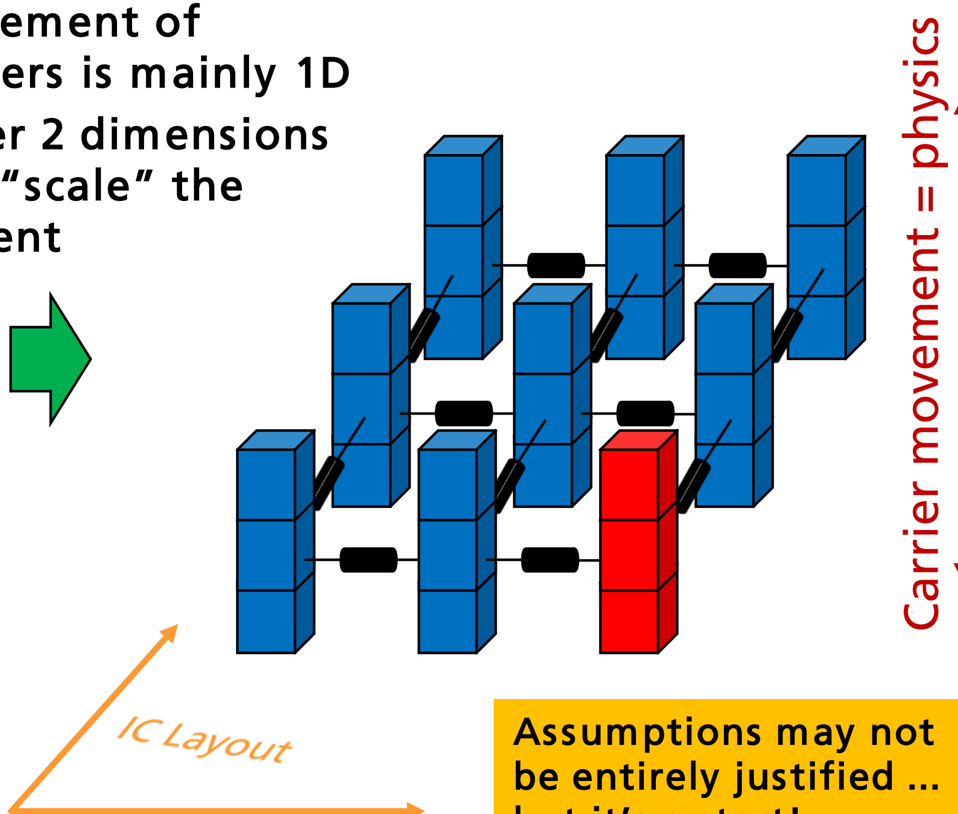
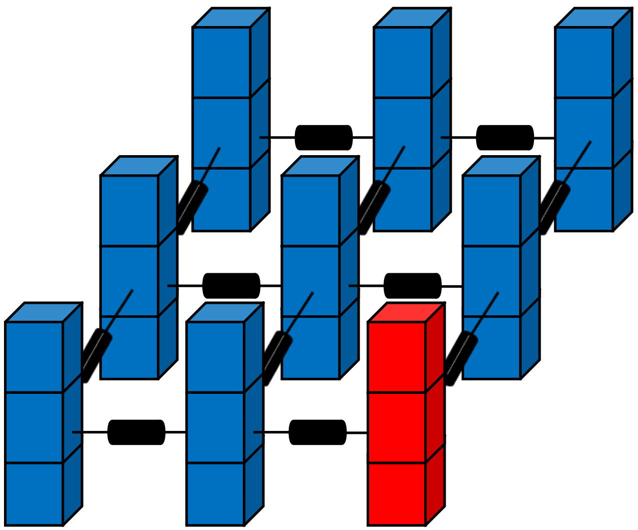
quasi-3D model



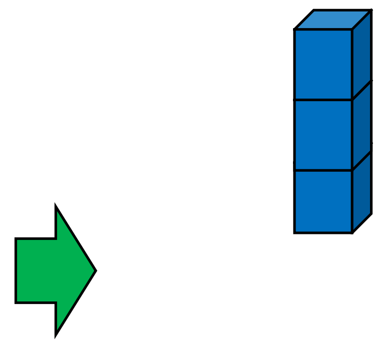

Assumptions may not be entirely justified ... but it's a start!

# New Compact Model
## Quasi 3D model

quasi-3D model



Compact model of 1D behavior

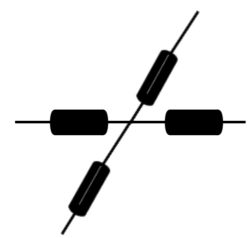


```
`include "disciplines.vams"

module simpleres(a, b);
  inout a, b;
  electrical a, b;
  parameter real r = 1000 from (0:inf);

  analog begin
    I(a,b) <+ V(a,b) / r;
  end
endmodule
```

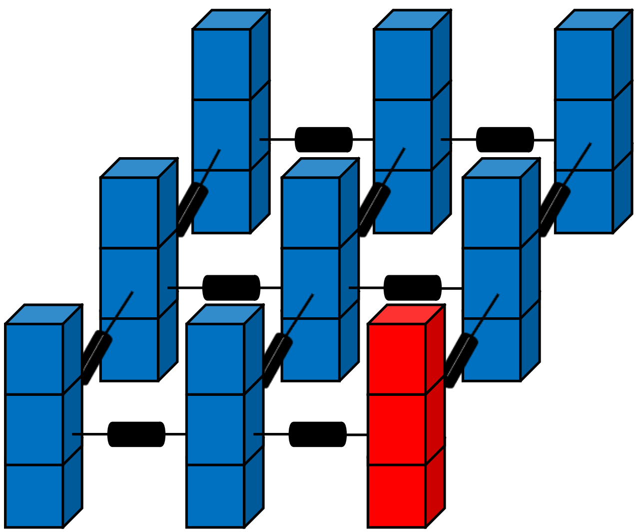
SPICE network



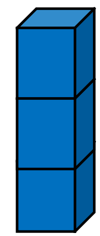
```
Cp0 #1 GND 126.379A
Cp1 Y:17 GND 40.5344A
Cp2 Y:16 GND 134.407A
Cp3 Y:15 GND 75.6834A
Cp4 Y:14 GND 71.8254A
Cp5 Y:13 GND 75.6834A
Cp6 Y:12 GND 71.8254A
Cp7 Y GND 106.974A
Rp0 Y:12 Y:17 0.329391
* Layer Metal1 terminals at
Rp1 Y:16 Y:17 0.041905
* Layer Metal1 terminals at
Rp2 Y:13 Y:17 0.329391
* Layer Metal1 terminals at
Rp3 Y Y:14 0.037626
* Layer Metal1 terminals at
Rp4 Y Y:12 0.032045
```

# New Compact Model
## Quasi 3D model

quasi-3D model



Compact model of 1D behavior



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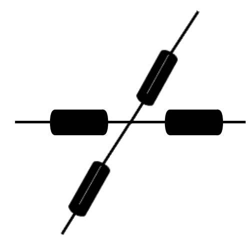
SPICE network



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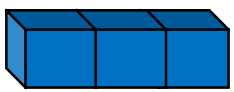
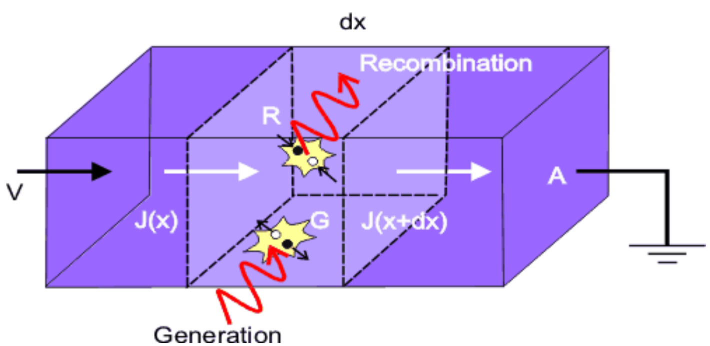
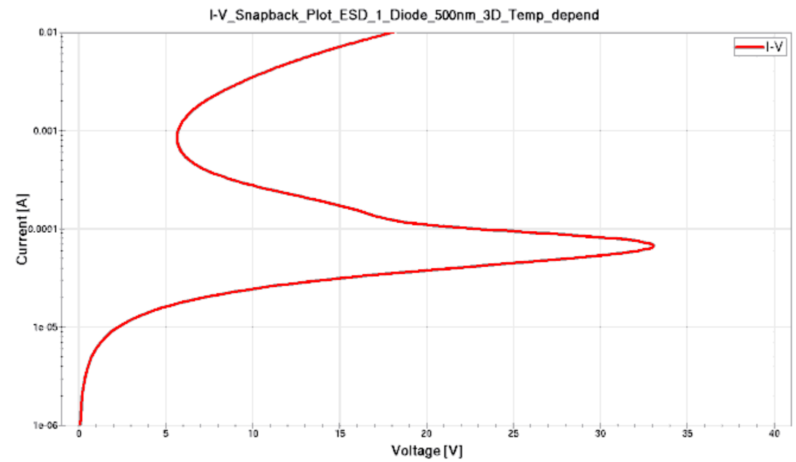
**Use SPICE solver !!**

# New Compact Model
## Compact 1D model

Compact model
of 1D behavior

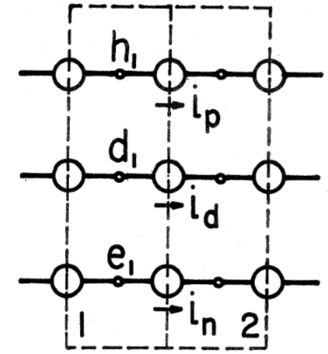




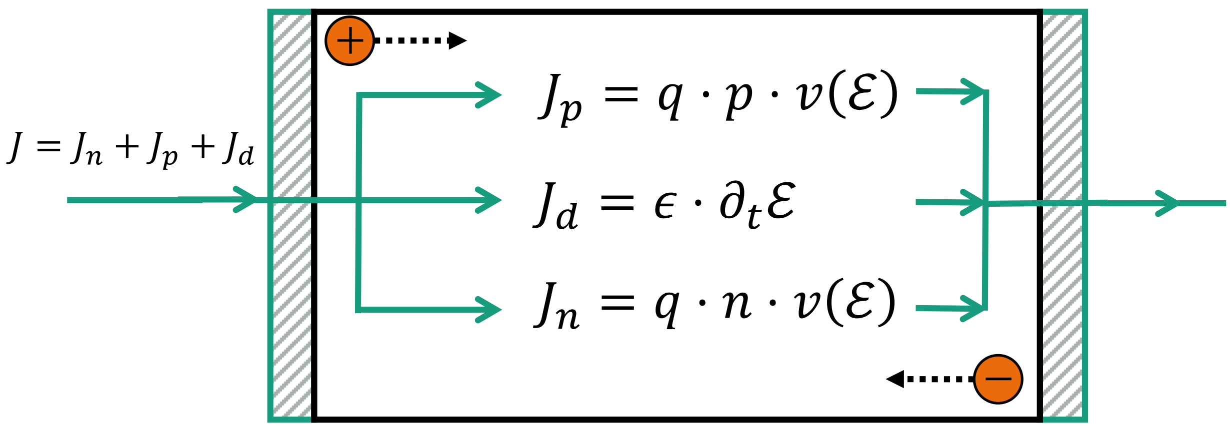




- **Physical model would be ideal …**
  - Generically applicable
  - Include geometric parameters
  - Get reasonable dynamic behaviour
  - Easy comparison with experiment/TCAD
  - Backlink to the real device

# New Compact Model
## Compact 1D model




- **We created a model based on previous work of:**
- Linvill, J.G., "Lumped Models of Transistors and Diodes," in Proceedings of the IRE , vol.46, no.6, pp.1141-1152, June 1958
- Sah, C.-T., "The equivalent circuit model in solid-state electronics—III: Conduction and displacement currents." Solid-State Electronics 13.12 (1970): 1547-1575.
- Arendt, A., "The RCI model—A general model for semiconductor devices," in Electron Devices, IEEE Transactions on , vol.20, no.1, pp.5-12, Jan 1973
- Caruso, A.; Spirito, P.; Vitale, G., "Negative resistance induced by avalanche injection in bulk semiconductors," in Electron Devices, IEEE Transactions on , vol.21, no.9, pp.578-586, Sep 1974



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# New Compact Model
## Compact 1D model

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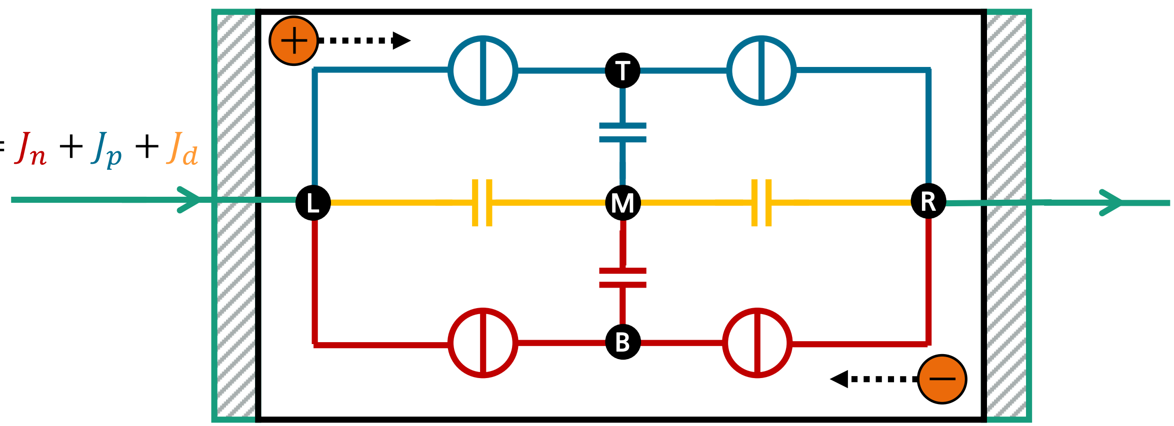
$J = J_n + J_p + J_d$




- Lumped-charge model
- Describes only excess carriers $n_e$ and $p_e$ (difference to thermal equilibrium)
- Includes displacement current AND Poisson equation in center rail
- Junctions can be treated inside the current sources (maybe not?)

# New Compact Model

## Compact 1D model

**M**

$$J_d^{LM} - J_d^{MR} + J_p^{TM} - J_n^{MB} = 0$$

$$\epsilon\, \nabla \mathcal{E}_M = q(n_e - p_e)$$

**L → M**

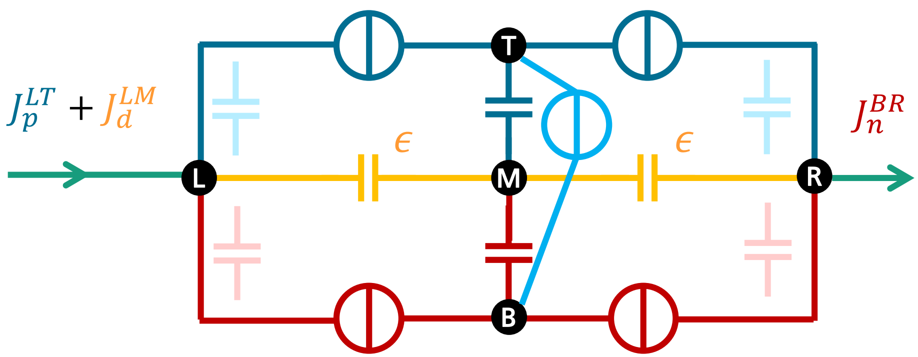
$$J_d^{LM} = \epsilon\, \dot{U}_{LM} = \epsilon\, \dot{\mathcal{E}}_{LM}$$

$$-\nabla J_p^T = q\, \dot{U}_{TM} = q\, \dot{p}_e$$

**M → R**

$$J_d^{MR} = \epsilon\, \dot{U}_{MR} = \epsilon\, \dot{\mathcal{E}}_{MR}$$

$$J = J_n^{LB} + J_p^{LT} + J_d^{LM}$$




$$J_n^{BR} + J_p^{TR} + J_d^{MR} = J$$

**T → B**

$$\nabla J_d^T = -\nabla J_d^B = \alpha_n |J_n^B| + \alpha_p |J_p^T|$$

$$\nabla J_n^B = q\, \dot{U}_{MB} = q\, \dot{n}_e$$

- Transport equations
- Continuity equations
- Poisson equation
- Impact ionization
- Junction carrier densities





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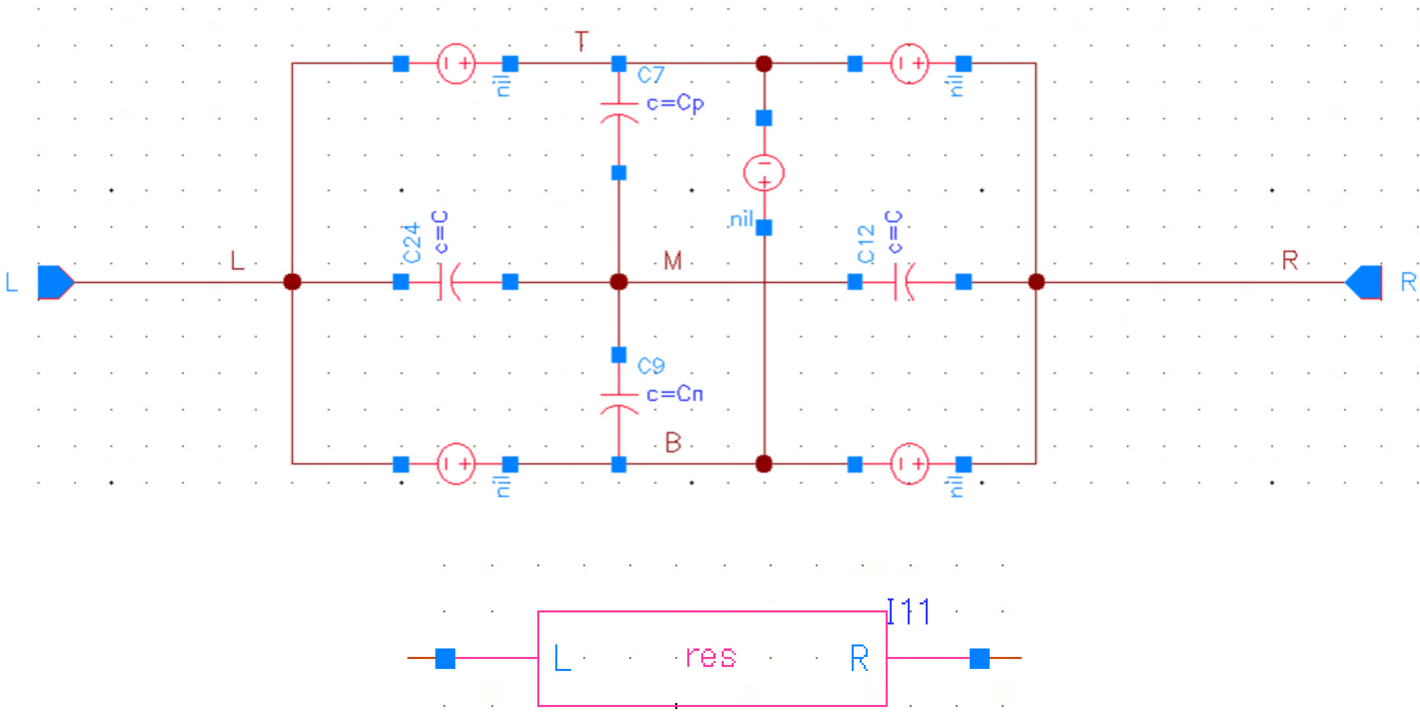
# New Compact Model
## Cadence schematic

- Cadence schematic of the compact model





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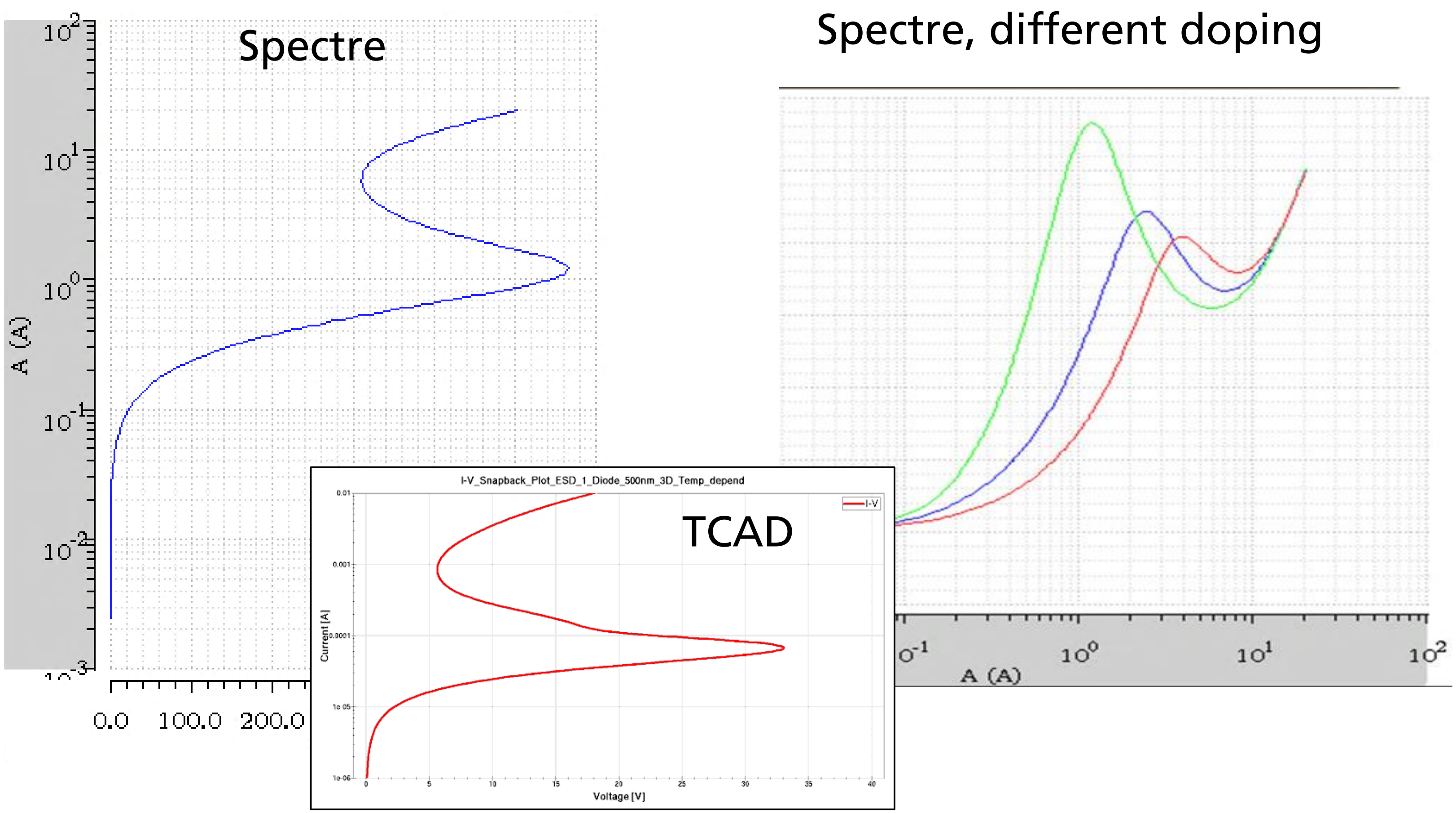
# New Compact Model
## Results of the compact model





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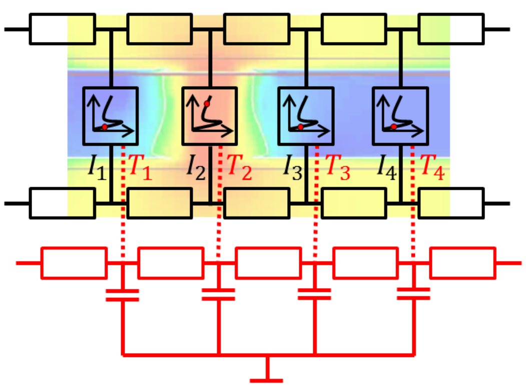
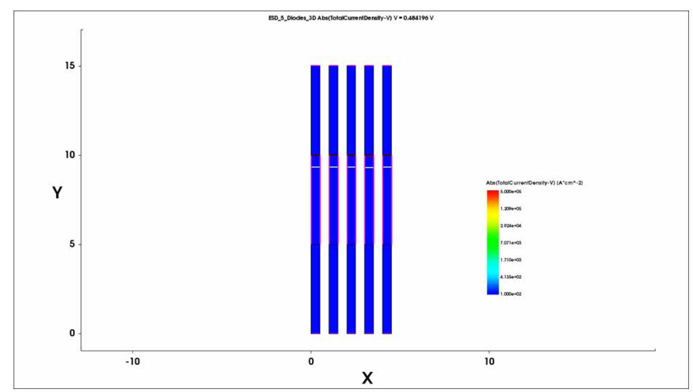
# New Compact Model
## Outlook

### Discretization
- Full separation of the diode to discretize the problem
- Get IV characteristics of each part
- Electrical compact model + thermal coupling circuit




### TCAD Results
- Single diodes going on and off after another
- Hopping of filament occurs
- Current chooses "coldest" diode
- Limitations due to complexity

→ Compact model required!



# SUMMARY

# Summary

- **General:**
  - ESD is a current event which can severely damage semiconductors
  - Inhomogeneous current filamentation is one main problem for device reliability … and very hard to predict!
  - TCAD gives behaviour in great detail → but too slow for real devices
- **Achievements:**
  - We created a physics-based compact quasi-3D model for Spectre
  - Implementation shows good agreements with 1D behaviour
- **Next steps:**
  Combine compact models according to IC layout and thermal net

RESIST

Arbeitskreis Modellierung von Systemen und Parameterextraktion
Modeling of Systems and Parameter Extraction Working Group
MOS-AK

GEFÖRDERT VOM

Bundesministerium
für Bildung
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Thanks!