Multiple current filaments and filament confinement in silicon based PIN diodes

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Biography

- Patrick Scharf
  - 2012: Bachelor of Science in Applied Natural Science, Technical University Freiberg
  - 2014: Master of Science in Applied Natural Science, Thesis: “Optical and electrical defect spectroscopy on high-k-material – semiconductor interfaces”, Technical University Freiberg
  - Since 2015: PhD student at Fraunhofer Institute for Integrated Circuits IIS/EAS in Dresden

Abstract

- Electrostatic discharge (ESD) is one of the greatest reliability risks for modern electronics. Failures occur due to a high current injection. One of the dominant failure mechanisms during an ESD event is thermal runaway caused by an avalanche breakdown leading to an inhomogeneous current flow and a current filament. Investigations on the formation and motion of current filaments were carried out with the help of special test structures of silicon based PIN diodes using technology computer-aided design (TCAD) simulations and transmission line pulse (TLP) measurements. In thin structures the current filament gets constricted (filament confinement), which can lead to the formation of multiple current filaments.

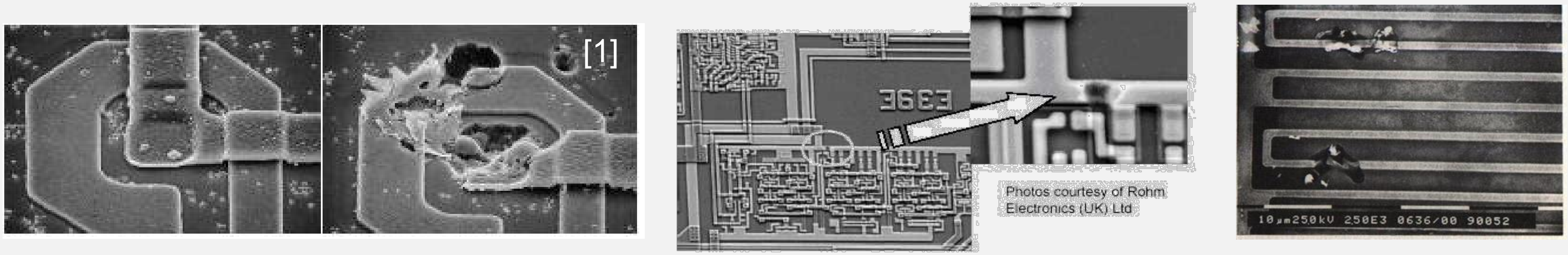
Outline

- Introduction to ESD
- TCAD Simulations
- TLP Measurements
- Comparison between simulation and measurement
- Results
- Conclusion

Introduction

- ESD is one of the main reliability risks for modern electronics
- ESD causes failure of semiconductor devices by an over-current effect
- Consequences for reliability under the influence of ESD
  - Dielectric Breakdown
  - Thermal failure due to localized power peaks
  - Parasitic switching of transistors (latch up)

Sensitivity of components to ESD



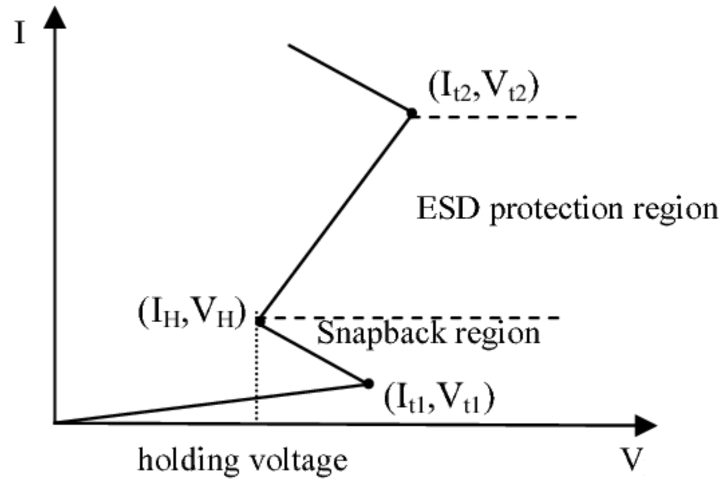
Example of an ESD damage to an IC

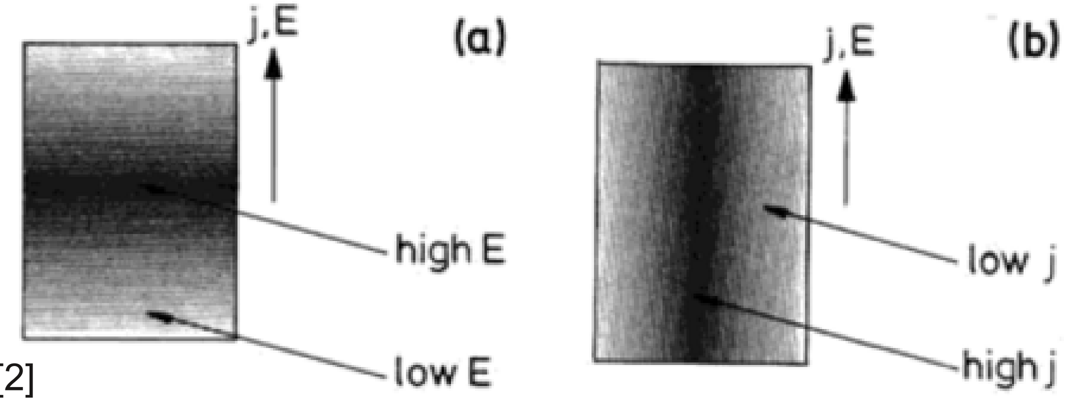
Introduction

- ESD protection necessary
- Several devices available
  - Diodes
  - MOSFET's
  - SCR's
- PIN(p-doped/intrinsic/n-doped) – diode
  - No current flow in reverse bias
  - Tolerates high voltages until breakdown
  - Junction breakdown due to avalanche
  - Carrier generation leads to current filament formation

Introduction

- Current filamentation due to avalanche breakdown
  - Snapback IV-characteristics
  - Negative differential resistance leads to intrinsic instabilities
  - Inhomogeneous current flow
  - Junction breakdown due to thermal runaway





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TCAD simulations

➢ Introduction to TCAD

- TCAD (Technology Computer Aided Design)
- Device Simulation uses basic semiconductor equations
- Transport equations:

$$J_n = q \cdot (\mu_n \cdot n \cdot E + D_n \cdot \nabla n)$$
$$J_p = q \cdot (\mu_p \cdot p \cdot E - D_p \cdot \nabla p)$$

- Continuity equations:

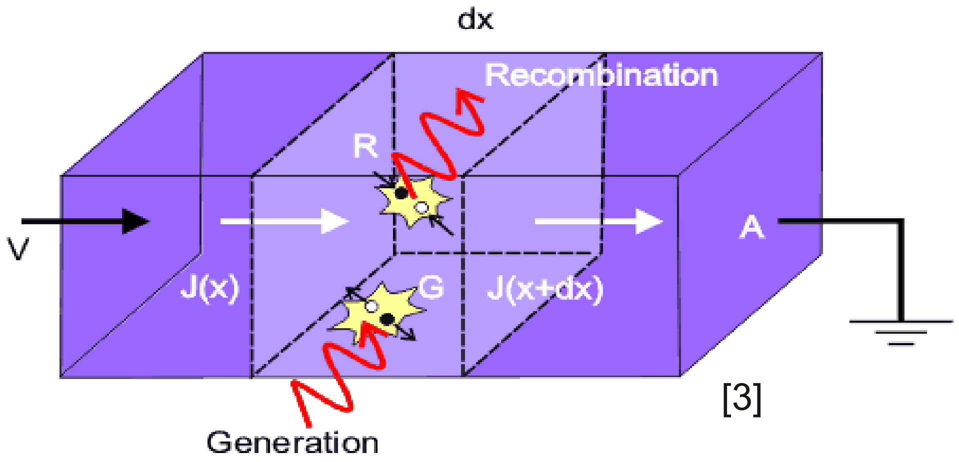
$$\partial_t n = G - R + q^{-1} \cdot \nabla J_n$$
$$\partial_t p = G - R - q^{-1} \cdot \nabla J_p$$

- Poisson equation:

$$\varepsilon \cdot \nabla E = -\rho$$

- Heat conduction equation:

$$\partial/\partial_t \, CL\, T - \nabla \cdot k \cdot \nabla T = q(T, J_n, J_p)$$



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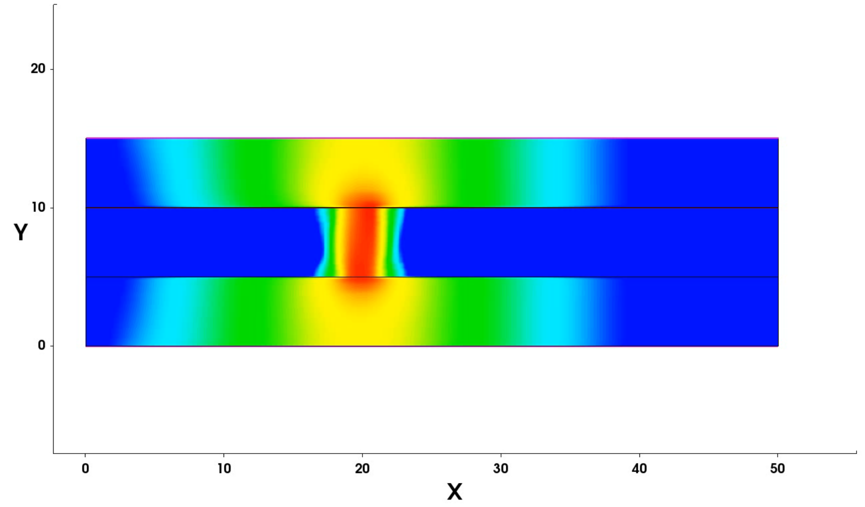
2D TCAD simulations

- In case of an ESD event
  - High current injection
  - Breakdown → voltage snapback
  - Filamentation
  - Self-heating
- 2D simulation
  - Moving current filament along x-axis
  - If the filament reaches an edge, voltage & temperature are increasing until the filament changes the direction
  - cross-section of a PIN(p+/n-/n+) diode

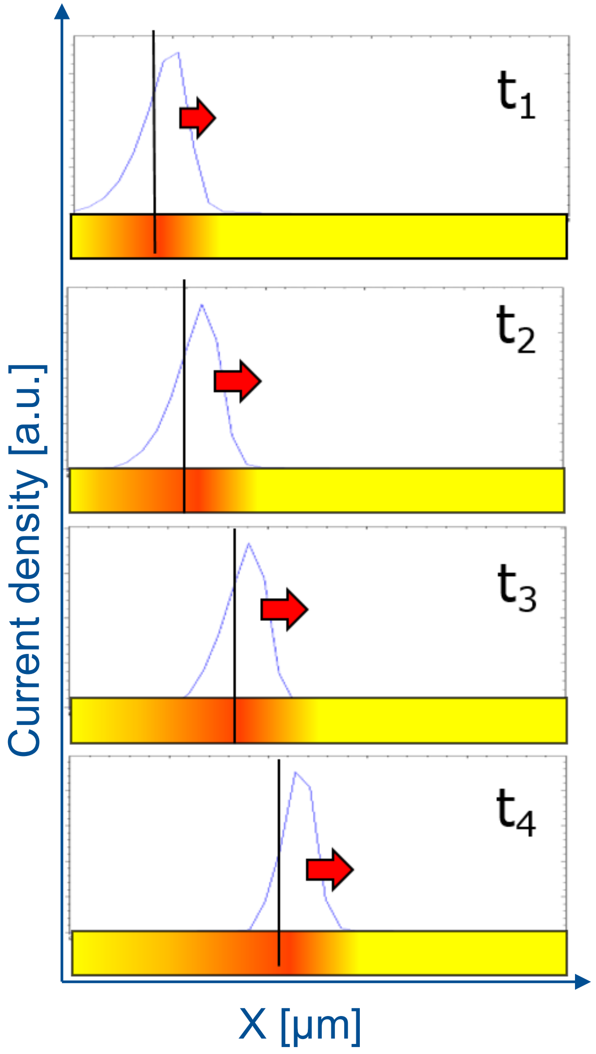
cross-section of a PIN(p+/n-/n+) diode



2D TCAD simulations

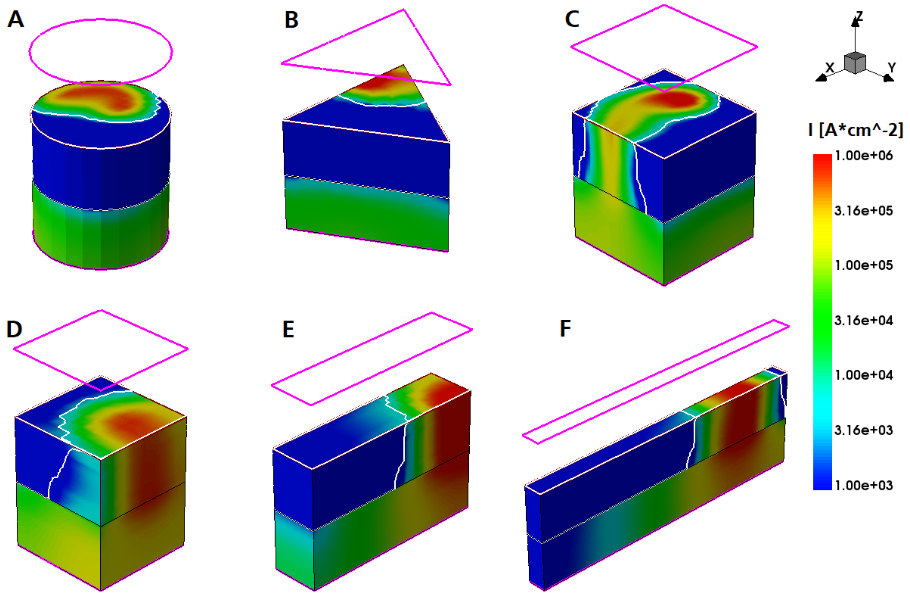
- Moving current filament
  - Current filament forms and can move due to the temperature dependence of impact ionization coefficient

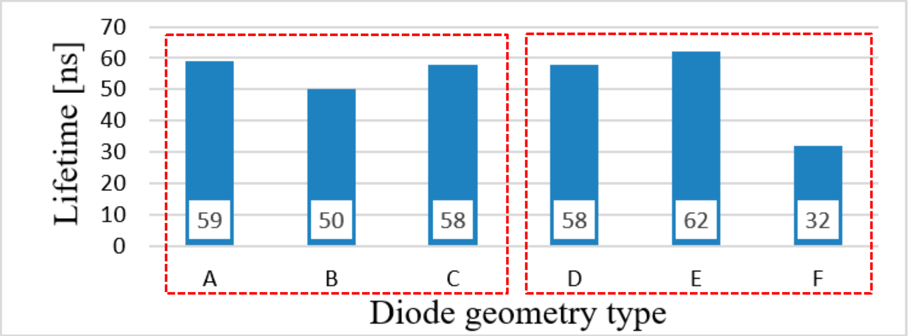
→ It's "surfing on its own heat wave"



3D TCAD simulations

- 3D simulations of PIN diodes
  - Same junction area for all geometries
  - A-C: different shape leads to different lifetimes
  - D-F: different ratio between volume and surface of the intrinsic zone leads to different lifetimes





TLP measurements

- Characterization of ESD protection structures
- Does not simulate any real world event
- Curve Tracing
  - Square Pulse
  - 50 – 500 ns
  - VF-TLP: < 10 ns
  - RT: 0.2 – 10 ns
- Results
  - Turn-on time, Snapback Voltage, On Resistance, Breakdown
  - Performance change due to different rise times

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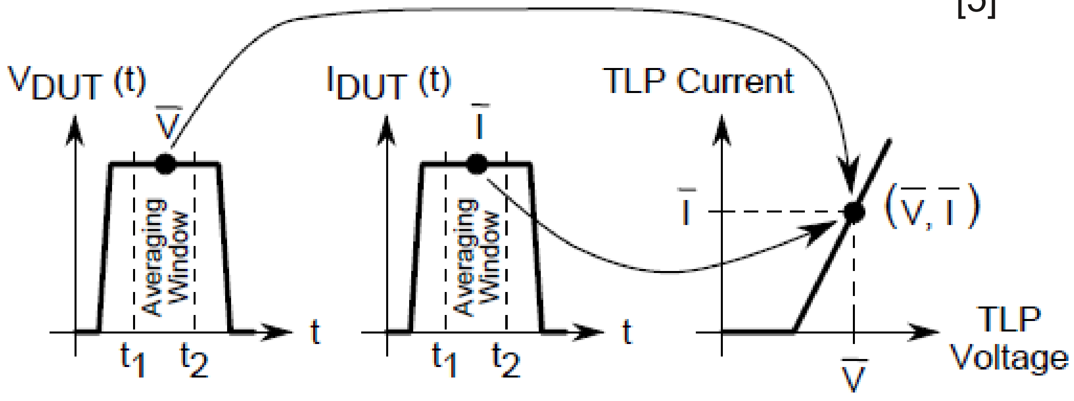
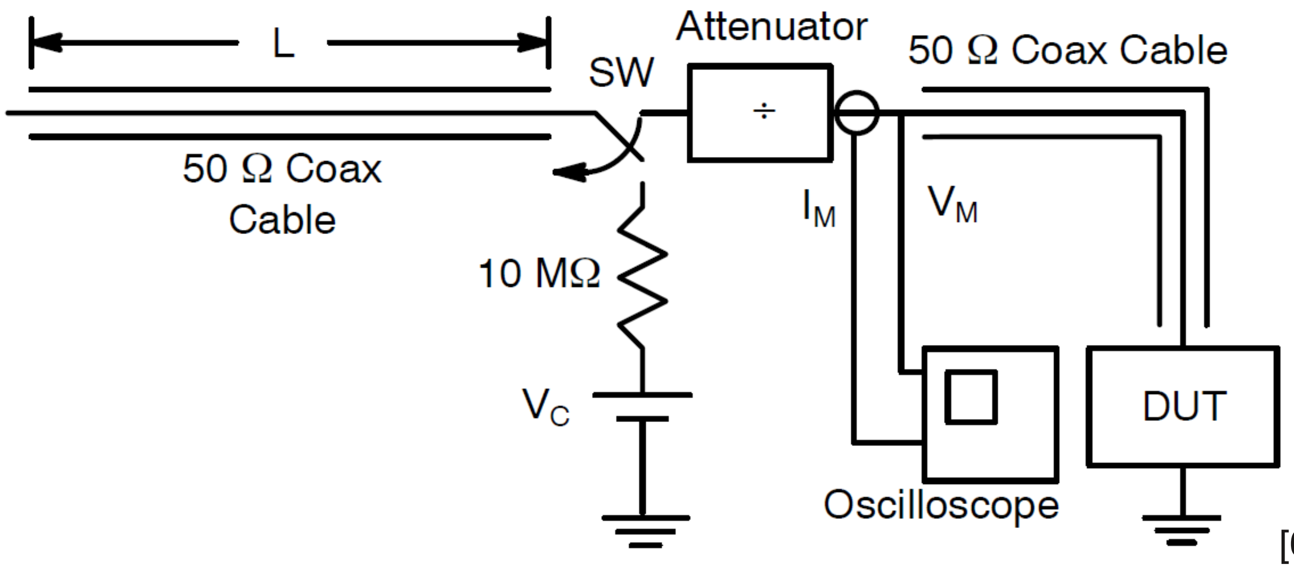


TLP measurements

- Transmission Line (Load/Charge Line) connected to power supply
- Switch closes → Discharge
- Square Pulse hits the DUT
- Measuring incident and reflected waveform (Time Domain Reflection)
- Repetition: Sequential TLP pulses produces an I/V Curve



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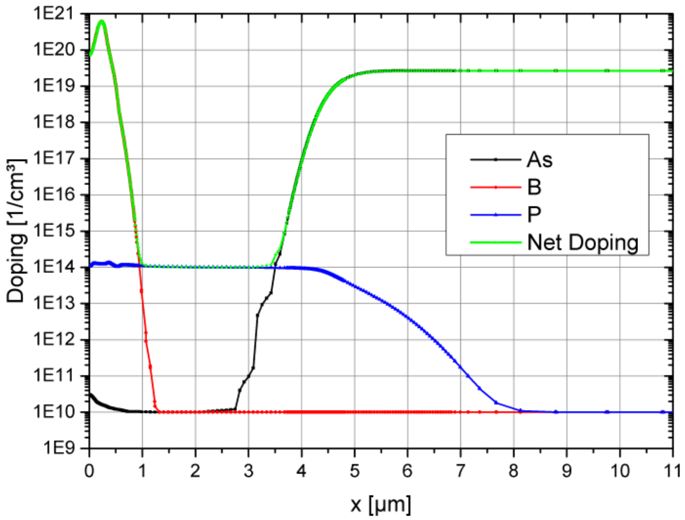
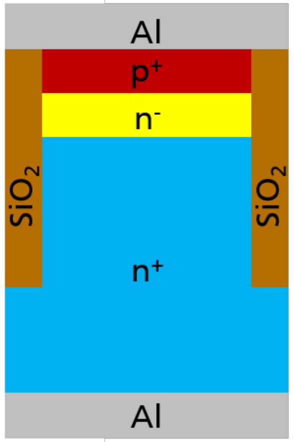
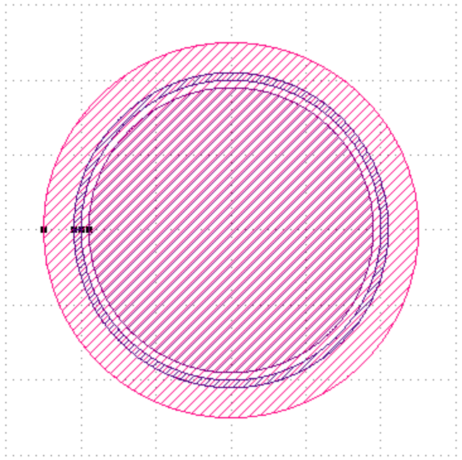
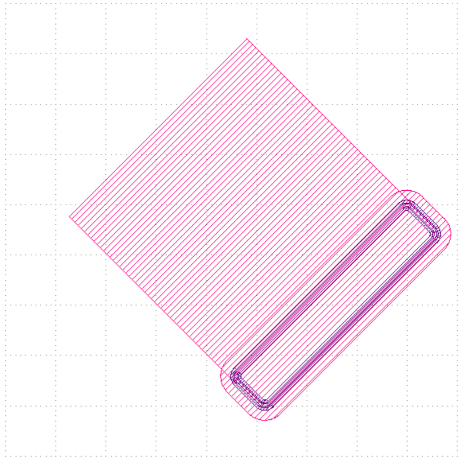
TLP measurements

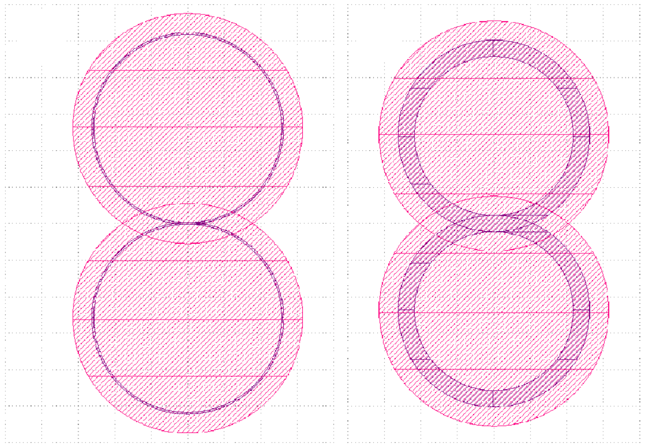
- Test structures
  - Circular diode: ø 20 µm
  - Hollow diode with rounded corners: 20 x 100 µm, PIN layer width of 2 µm
  - 8-shaped diodes with two different thicknesses of 2 µm and 10 µm







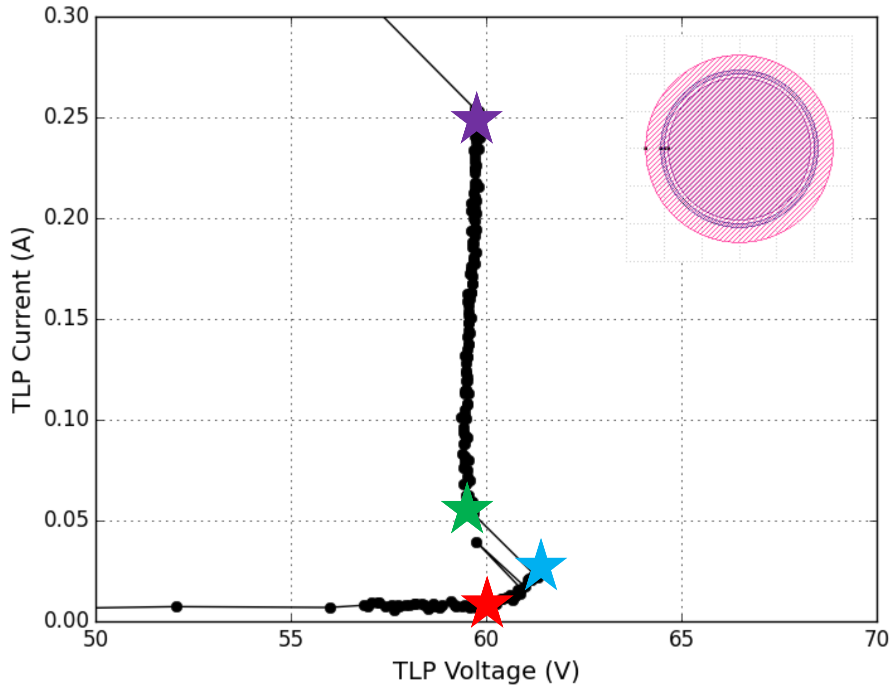




TLP measurements

- Circular diode
  - 100 ns square pulse
  - 10 ns rise/fall time
  - Reverse turn-on voltage of 60 V
  - Snapback from 62 V to 59 V
  - Around 250 mA the second non-reversible breakdown occurs

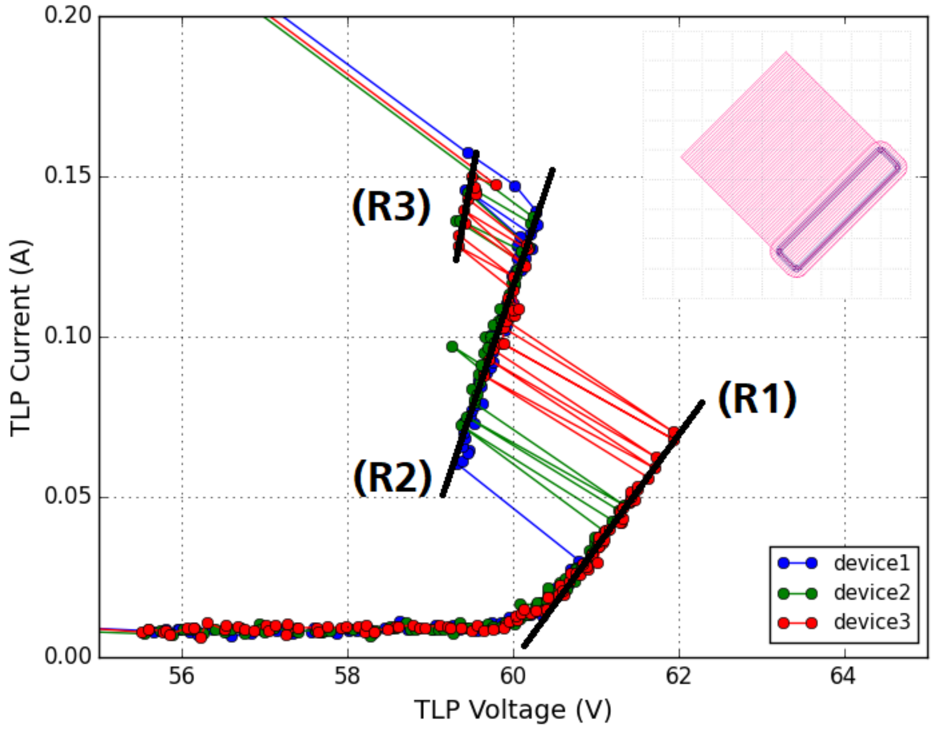
  → device is damaged
- Typical current-voltage characteristic for a full-area circular diode



TLP measurements

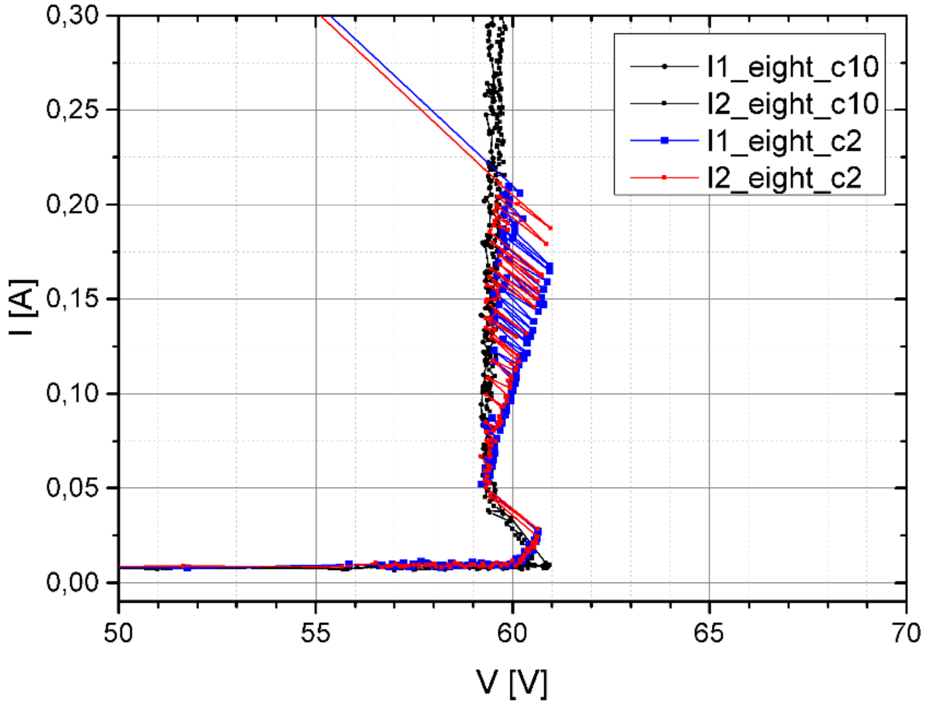
- Hollow diode
  - 3 measurements of the same device type
  - 100 ns square pulse
  - 10 ns rise/fall time
  - Reverse turn-on voltage of 60 V
  - Snapback from 62 V to 59 V
- Unexpected second voltage drop!
- 3 branches, which are related to 3 on-resistances

  → Multiple current filaments!?



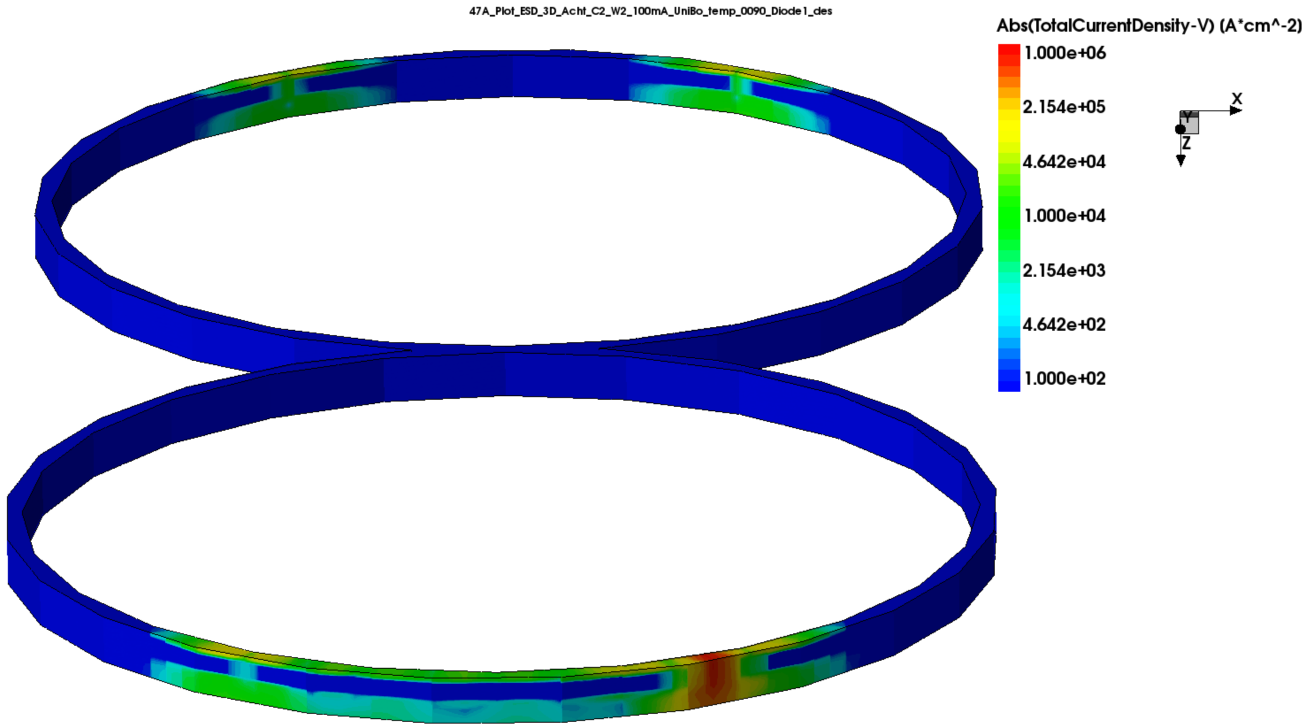
TLP measurements

- 8-shaped diodes
  - TLP pulse analogous
  - I-V characteristic for diode with 10 µm thickness as expected
  - For diode with 2 µm thickness an unexpected second branch occurs
  - Second branch, which is related to a second on-resistance
  - Indicates formation of several current filaments



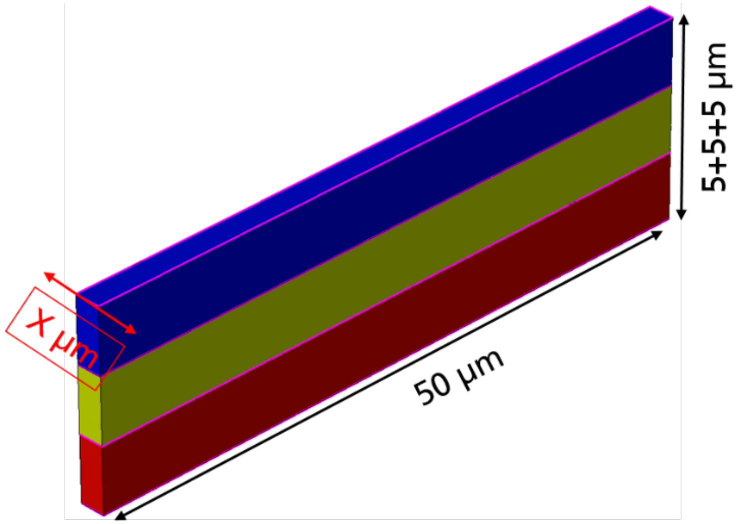
Comparison between simulation and measurement

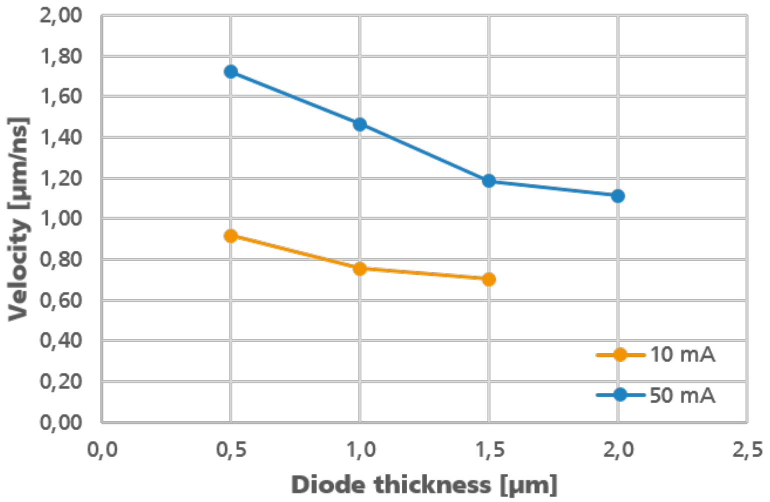
- TCAD simulation of 8-shaped diode with a thickness of 2 µm
  - Formation and motion of multiple filaments observed
  - Splitting and unifying of filaments possible
  - Effect of thin structures?



Results

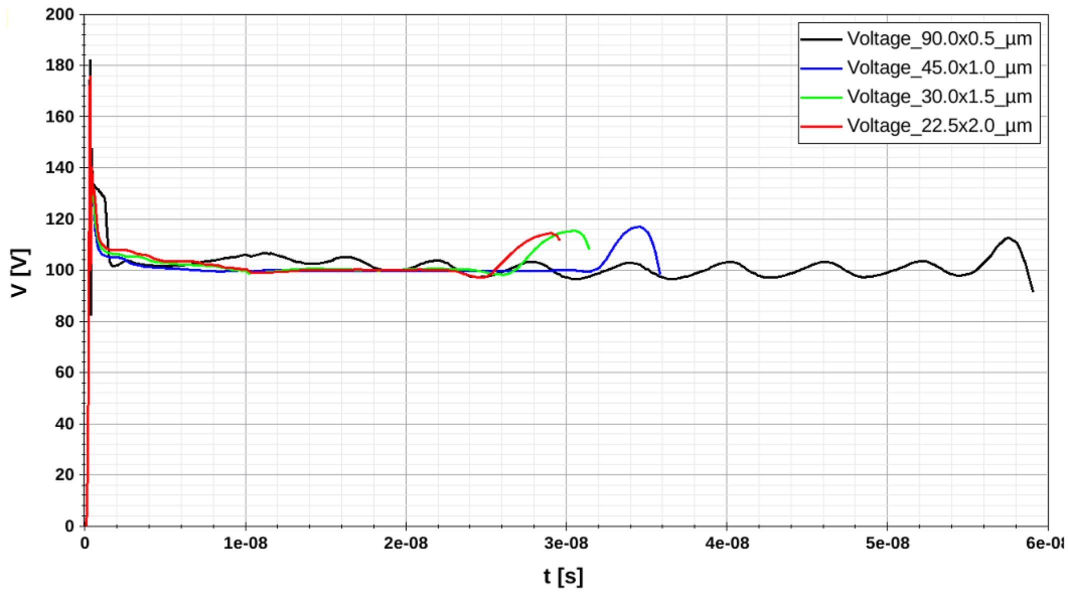
- Simulation of very thin test structures
  - Filament velocity depends on current injection
  - Lower thickness leads to higher velocity up to 2 µm/ns → Filament confinement
  - Avalanche region is expanded → multiple filaments can occur





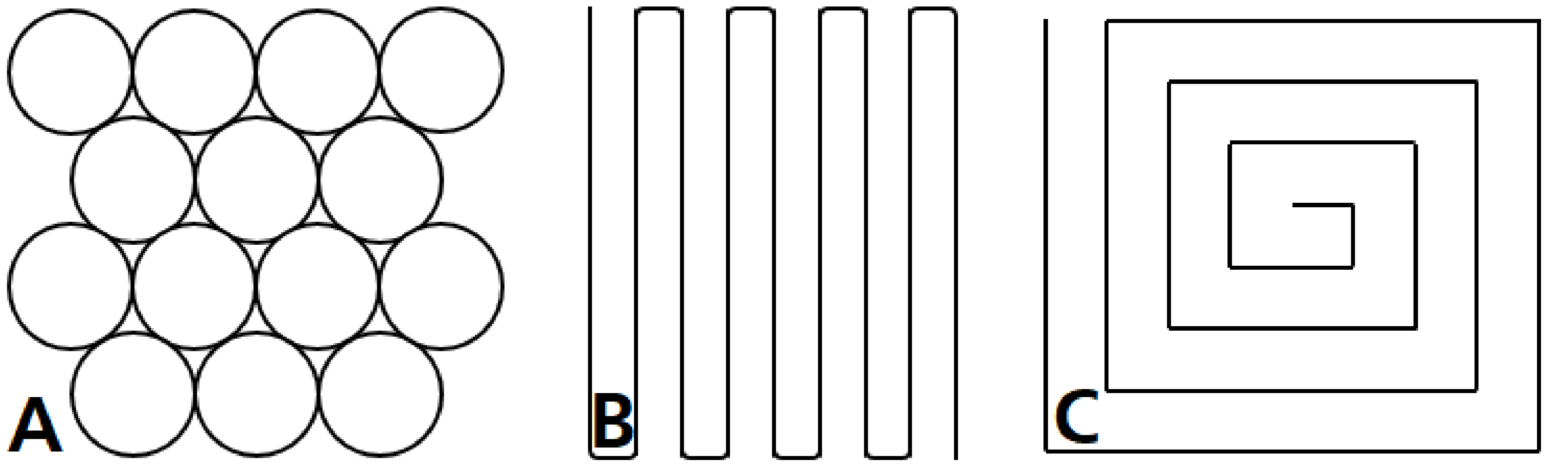
Results

- Lifetime investigations
  - Test structures with different length and thickness but same ratio of junction area and volume
  - Lifetime increases for thinner devices
  - Higher velocity of current filament causes less self-heating



Results

- Design recommendations
- Narrow ESD protection structures with sufficient length are recommended
- Chip area is expensive → good ratio between diode surface and chip area
  - Designs analogous to cooling fins would be advantageous
  - Keeping the current filament moving



Conclusion

- ESD events on PIN diodes were investigated with TCAD simulations and TLP measurements
- Influence of different geometries on the formation and motion of the current filament were discussed
- TLP measurements were done for three different test structures
  - Circular diode: typical snapback behavior
  - Hollow diode: three on-resistances
  - 8-shaped diode: two on-resistances
- Comparison with 3D TCAD simulations
  - Indicates the formation and motion of multiple filaments at the same time
  - Very thin structures show a higher filament velocity and a better lifetime

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