# Application of transient interferometric mapping (TIM) technique for analysis of ns-time scale thermal and carrier dynamics in ESD protection devices

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# Outline

- Motivation
- Principle of Transient Interferometric Mapping (TIM)
- Application example of TIM
    - Thermal breakdown mechanism in ESD protection devices due current filaments
    - Analysis of carrier plasma spreading in 90nm CMOS SCR ESD protection device
    - Transient latch-up analysis in 90nm CMOS test chip
    - Failure analysis
- Conclusions

# Motivation

Experimental access to internal device parameters (temperature, carrier concentration, current density, electric field) is important for:

→ Finding critical places in devices - hot spots, thermo-mechanical stress,..

→Device structure and performance optimization

→ Verification of simulation results

→ Calibration of simulation models

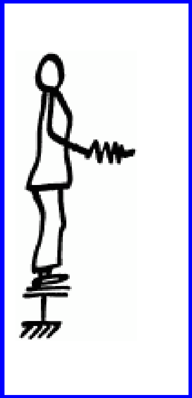
→ Prediction of device failure threshold

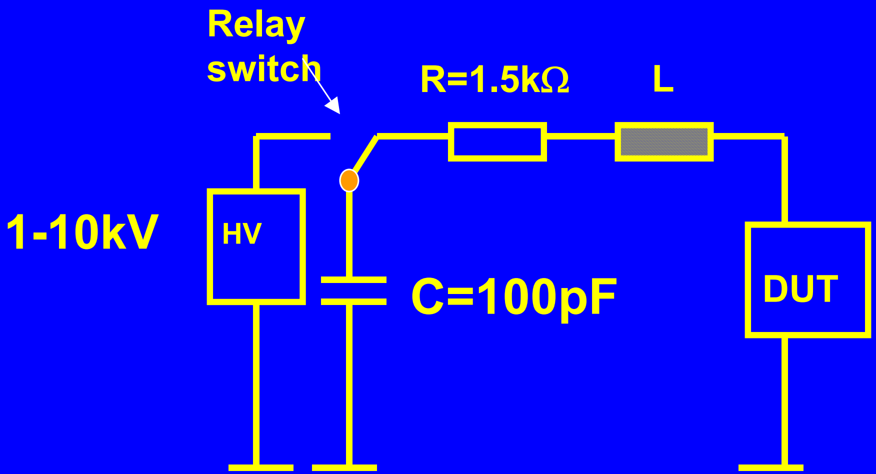
Thermal and high injection effects important in: power devices, electrostatic discharge (ESD) protection devices, etc...

⇒ TIM method provides µm space and ns time resolution and access to bulk properties from backside

# **Electrostatic discharge (ESD)**

## Human Body Model (HBM)





**Relay switch**

**R=1.5kΩ**

**L**

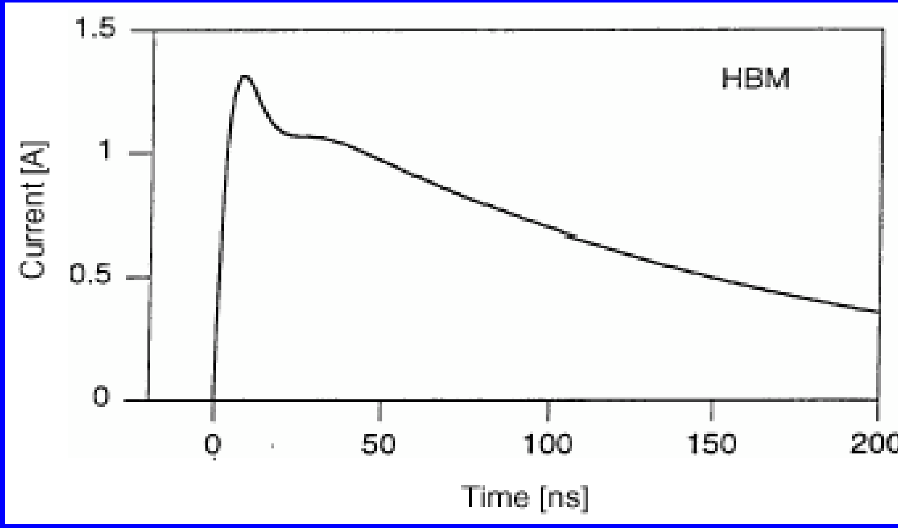
**1-10kV**

**HV**

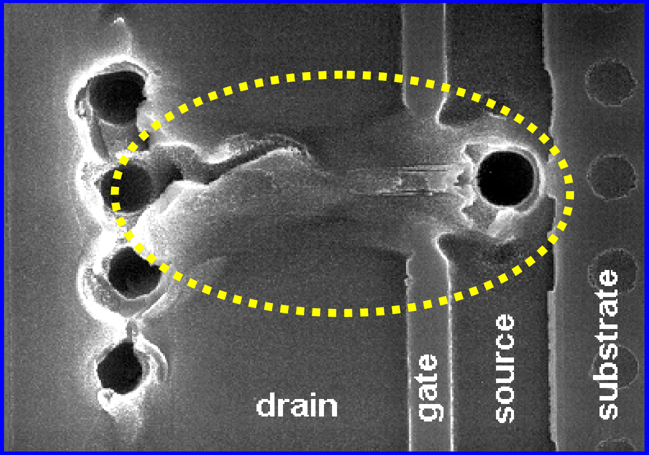
**C=100pF**

**DUT**

**1-5Amps@100ns**



**Catastrophic failure**



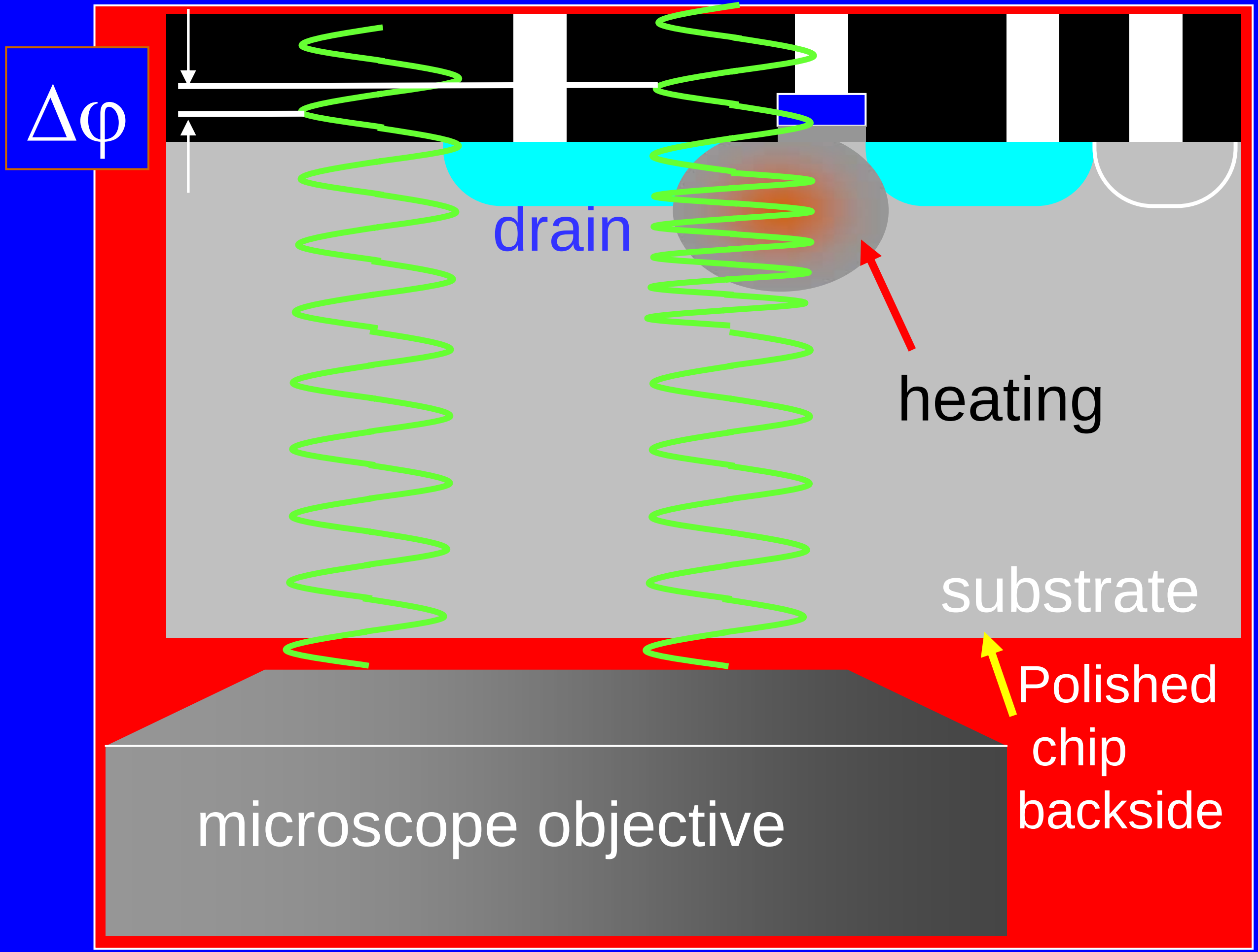
**[Courtesy W. Stadler, Infineon]**

[Amerasekera & Duvvury, 1995]

- ESD more and more important with scaling down technologies
- higher power dissipation densities in smaller volumes → higher temperatures up to silicon melting point

# Backside Transient Interferometric Mapping (TIM)

**IR laser, wavelength=1.3µm is transparent for Si**



*** Temperature and carrier conc. variations**

⇓

*** Change in refractive index**

⇓

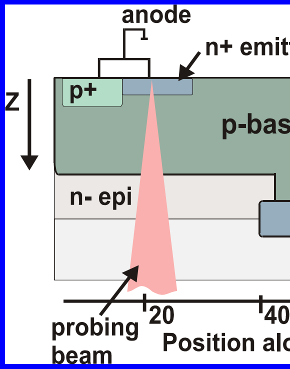
*** Optical phase shift Δφ**

⇓

*** Interferometric detection**

# General optical principle of TIM

## Optical phase shift (integral along the laser path):



$$\Delta\varphi(t)=\frac{4\pi}{\lambda}\int\left\{\frac{dn}{dT}\Delta T(z,t)+\left[\alpha_n\Delta n(z,t)+\alpha_p\Delta p(z,t)\right]\right\}dz$$

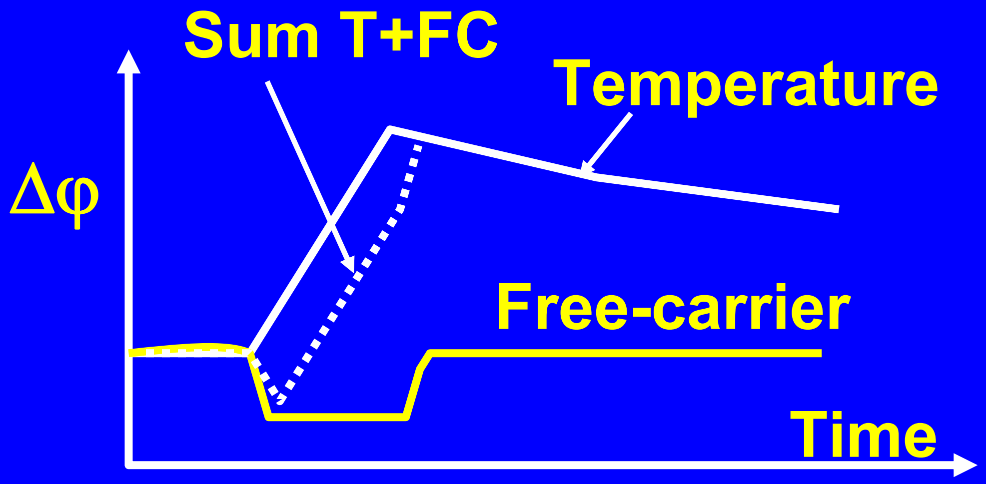
**Thermal contribution**
**>0**

**+**

**Free-carrier contribution**
**<0**

**Both components can be distinguished according to the sign and different time scales**

**Thermal component is dominant at high dissipated powers**



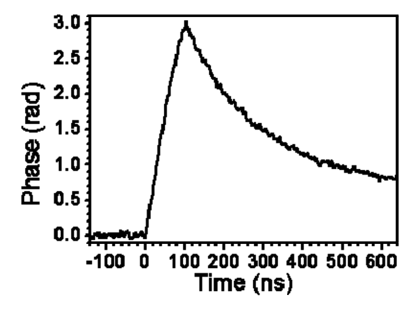
[Goldstein &,Rev.Sci. In. 64(1993)3009, D.Pogany & IEEE TED 49(2002)2070]

Method is quantitative:

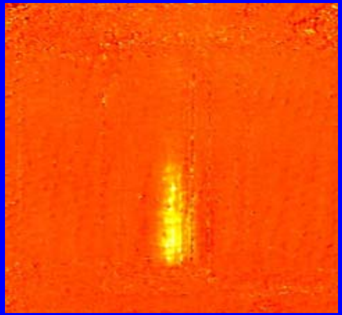
APEX postprocessor of Synopsis allows calculation of phase shift data from the simulated temperature and free carrier distributions of device simulation (TCAD) DESSIS

# Transient interferometric mapping (TIM) at TU Vienna:

- * Scanning heterodyne interferometer + Michelson
  - 3ns and 1.5µm resolution
  - phase shift transients recorded at each scanning position
  - repetitive stressing necessary for spatial imaging



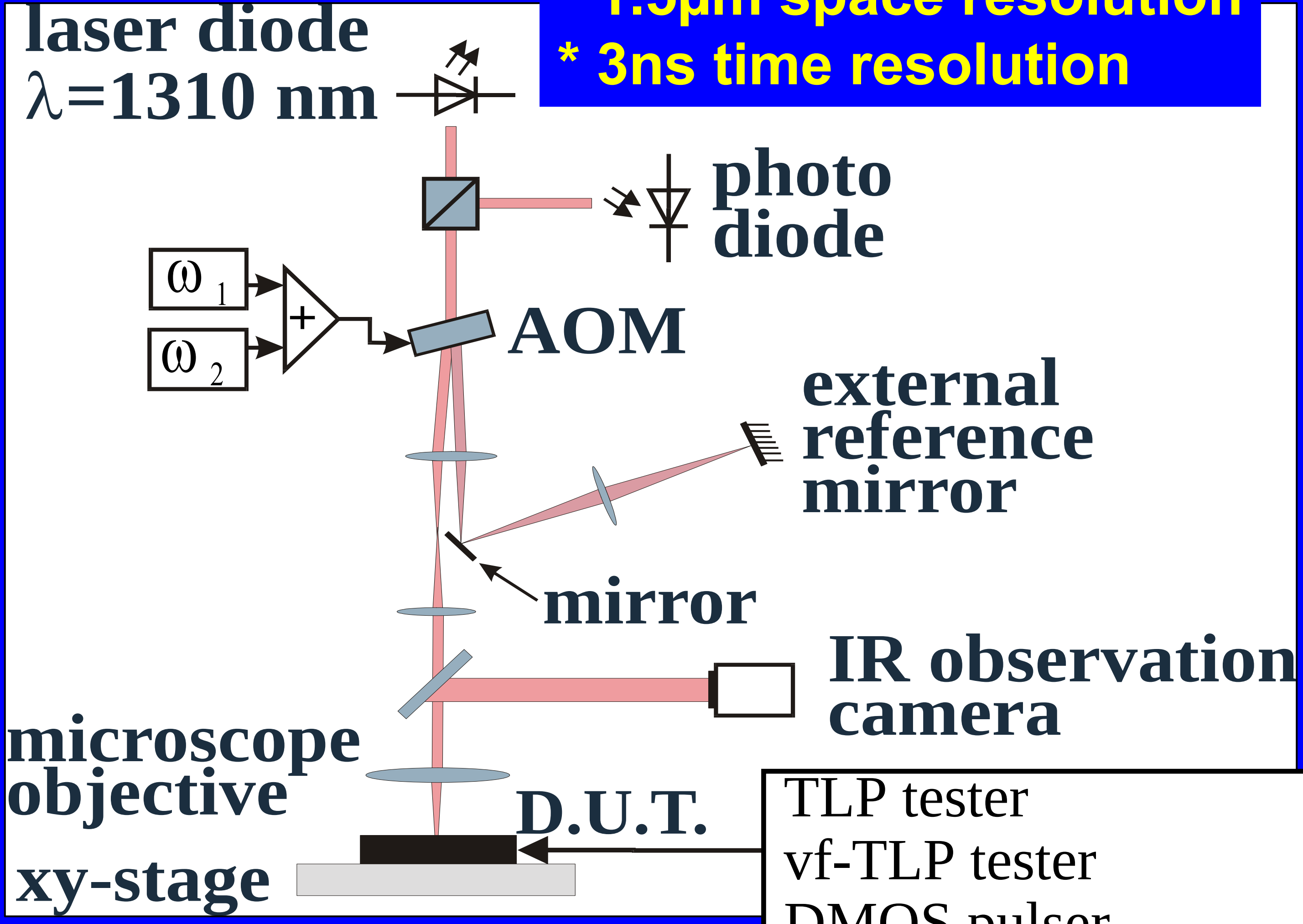
- * 2D holographic interferometric method
  - 5ns and 3µm resolution
  - one or two 2D images recorded per single stress pulse
  - single event thermal imaging
  - wafer level probing possible



# Scanning heterodyne interferometer

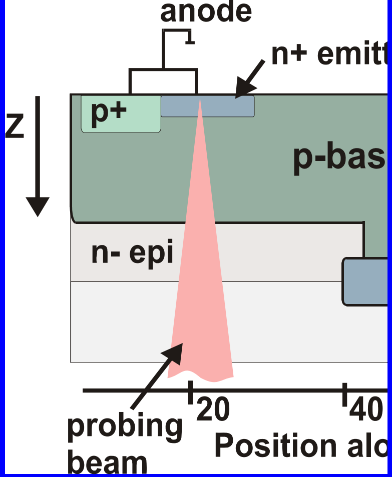
* 1.5µm space resolution

* 3ns time resolution



TLP tester
vf-TLP tester
DMOS pulser

HV source



**Spatial distribution:**

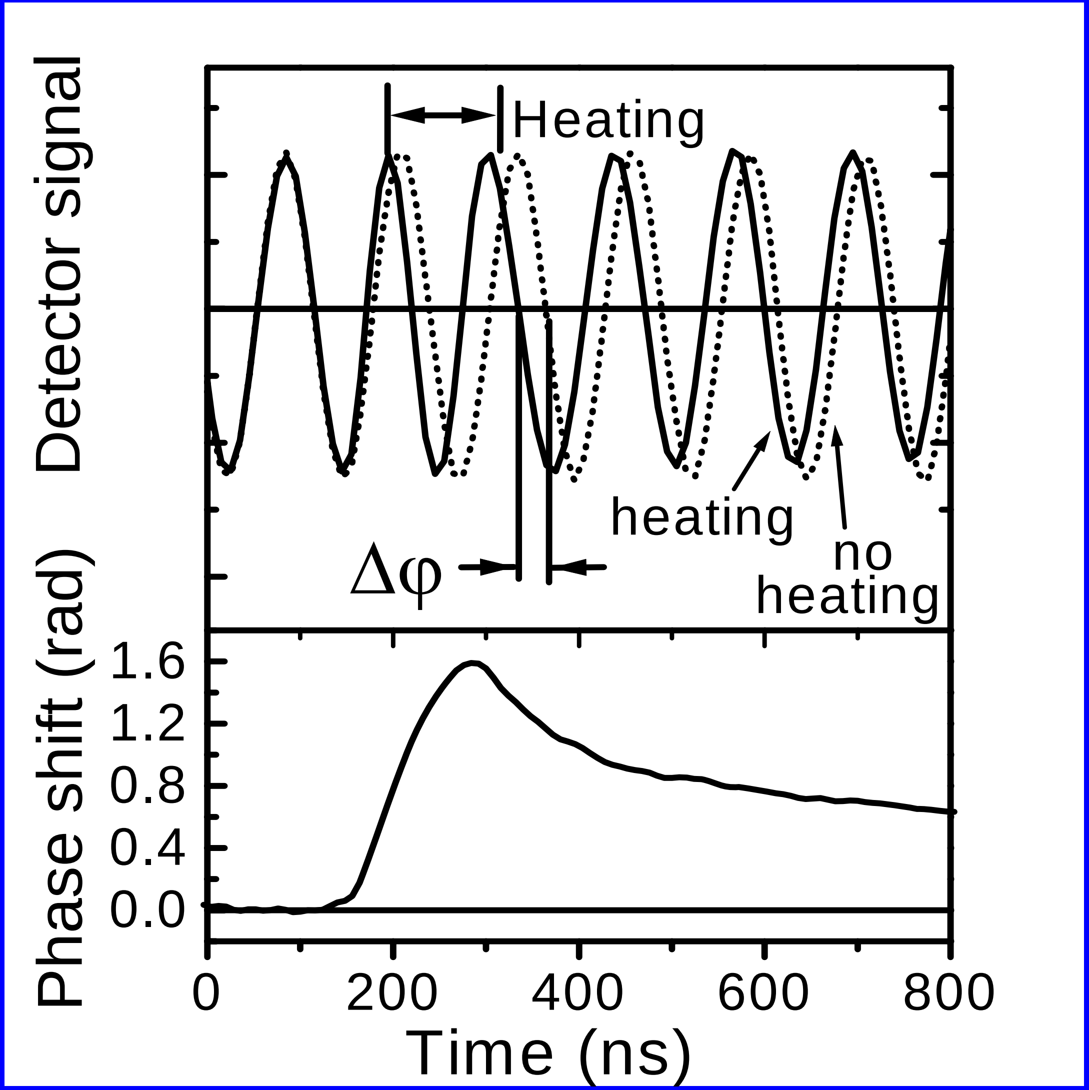
- periodical device stressing

- lateral device scanning

**Focused laser beam used**

Fürböck &, Microel. Rel. **40**(2000)1365]

# Scanning heterodyne interferometer: signal and phase shift



**Detector signal:**

$A \sin[2\Delta\omega t+\Delta\varphi(t)]$

- * **Time domain detection**
- * **Automated acquisition**
- * **FFT analysis**
- * **phase extraction insensitive to sample reflectivity**

[Fürböck &, J. Elstat, 49(2000)195]

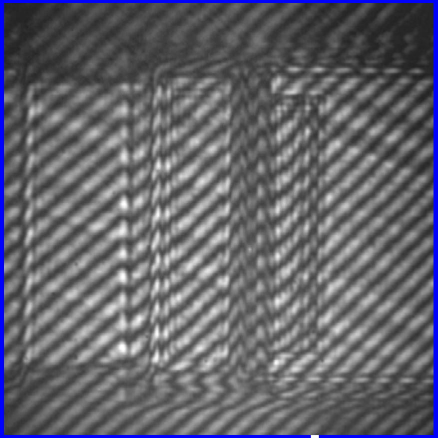
[M.Litzenberger &, IEEE TIM, 54(2005)2438]

# 2D TIM method: Phase extraction

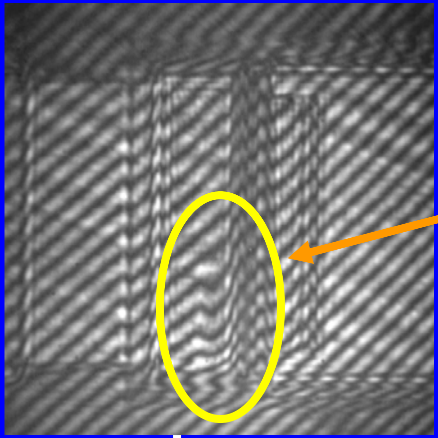
[D.Pogany &, IEEE EDL, 23(2002)606]

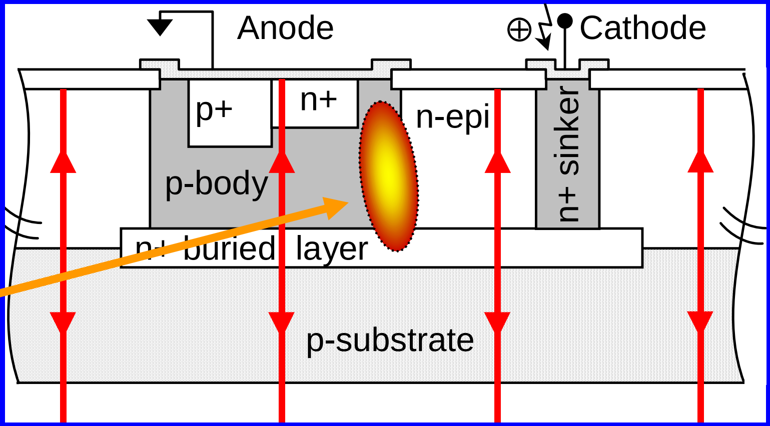
## Interferogram:

**Unstressed**



**Stressed**

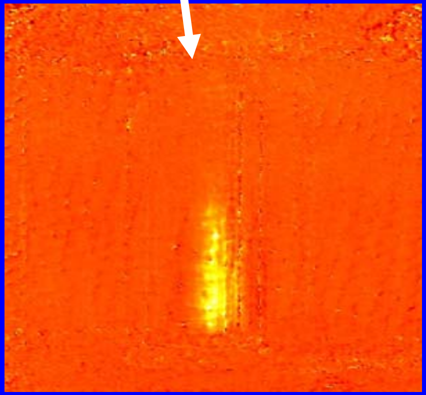




**Temperature-induced phase shift**

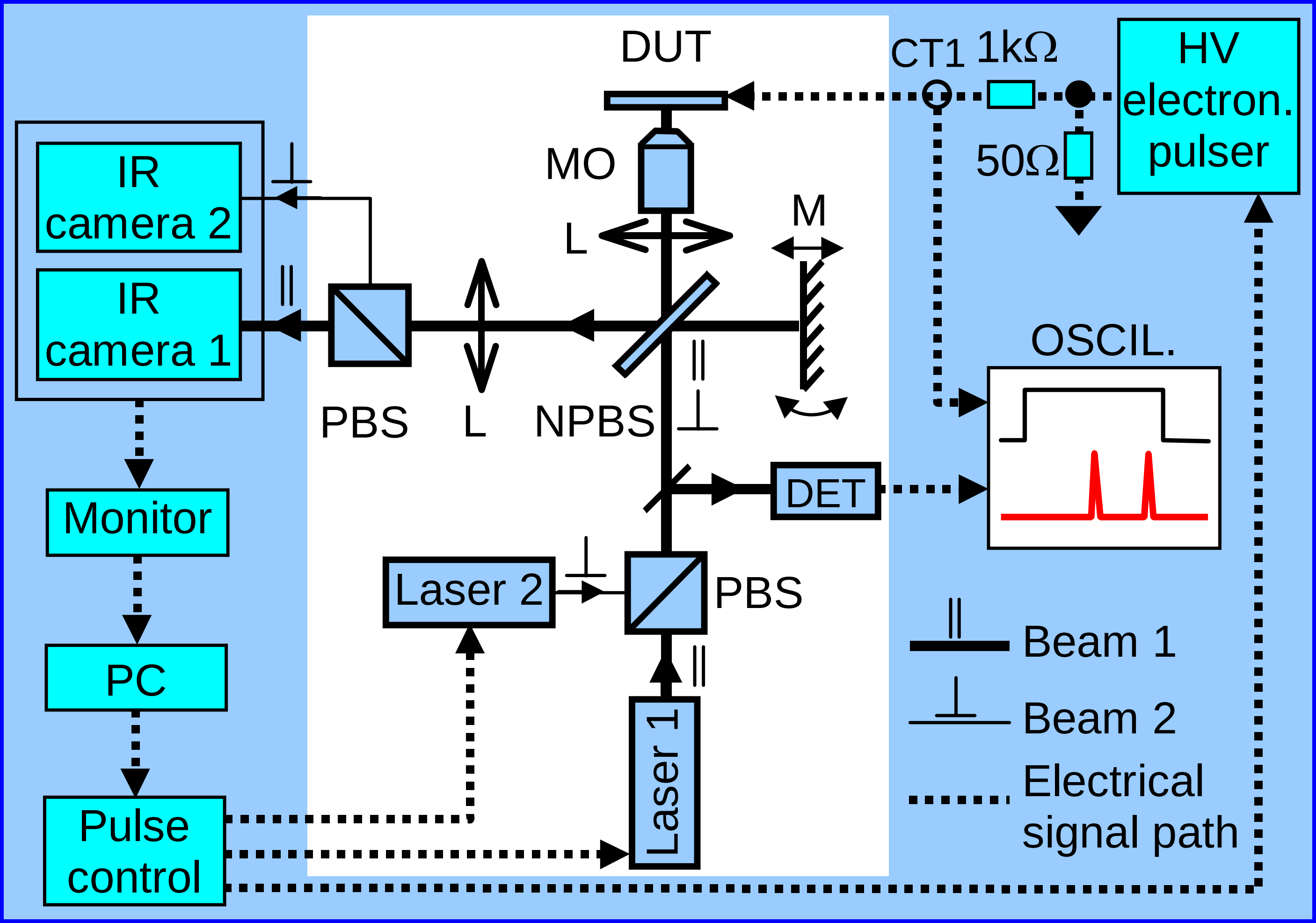
**Phase extraction based on FFT analysis**

**Phase(Stressed) - Phase(Unstressed)** ⇒



# 2D TIM method

## Imaging at two time instants during a single shot



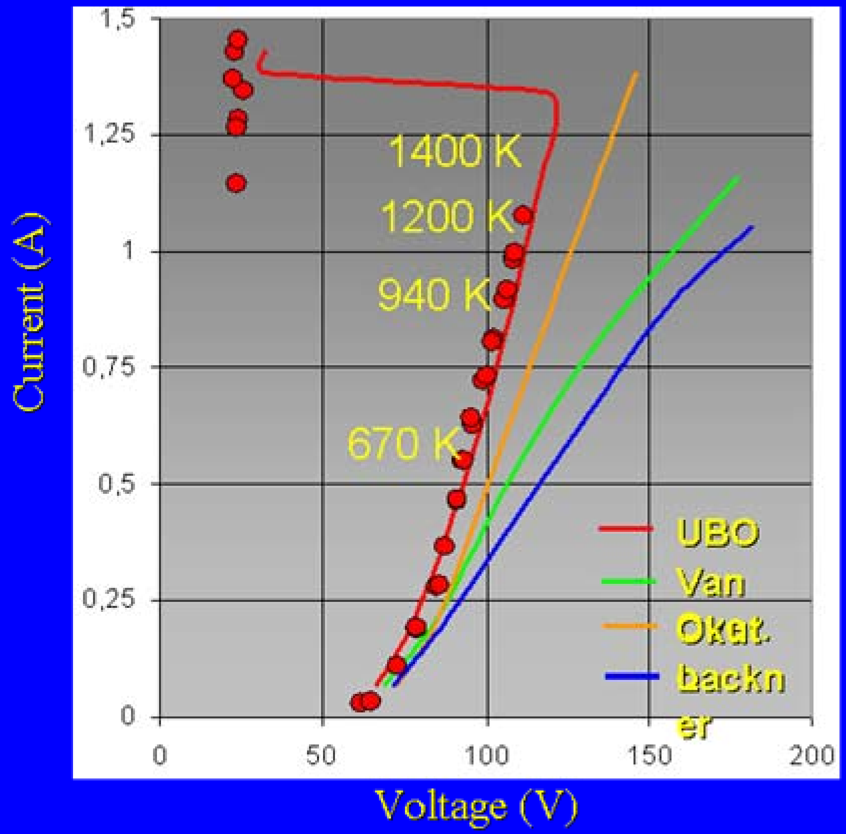
- orthogonally polarized laser beams
- laser pulse duration 5ns
- relative laser pulse delay 0 ns - 5 µs
- phase distribution at two time instants during single stress pulse

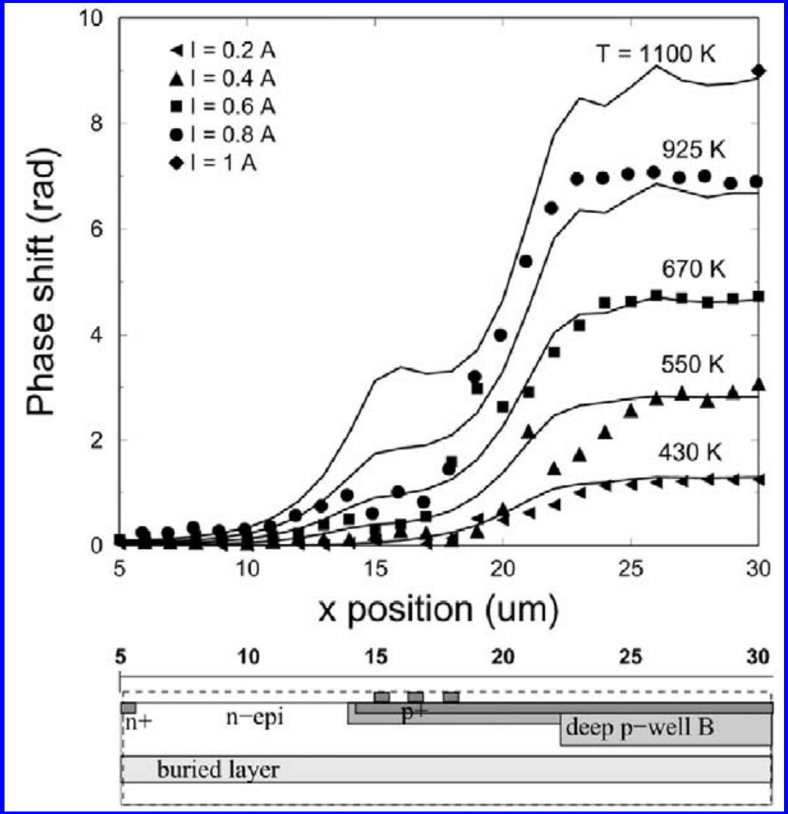
- non-repetitive phenomena (destructive)

[Dubec &, Microel.Reliab. 44(2004)1793]

# Model verification at high temperatures by TIM

## ESD protection diode : comparisom TIM vs. TCAD simulation

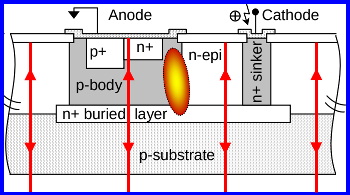




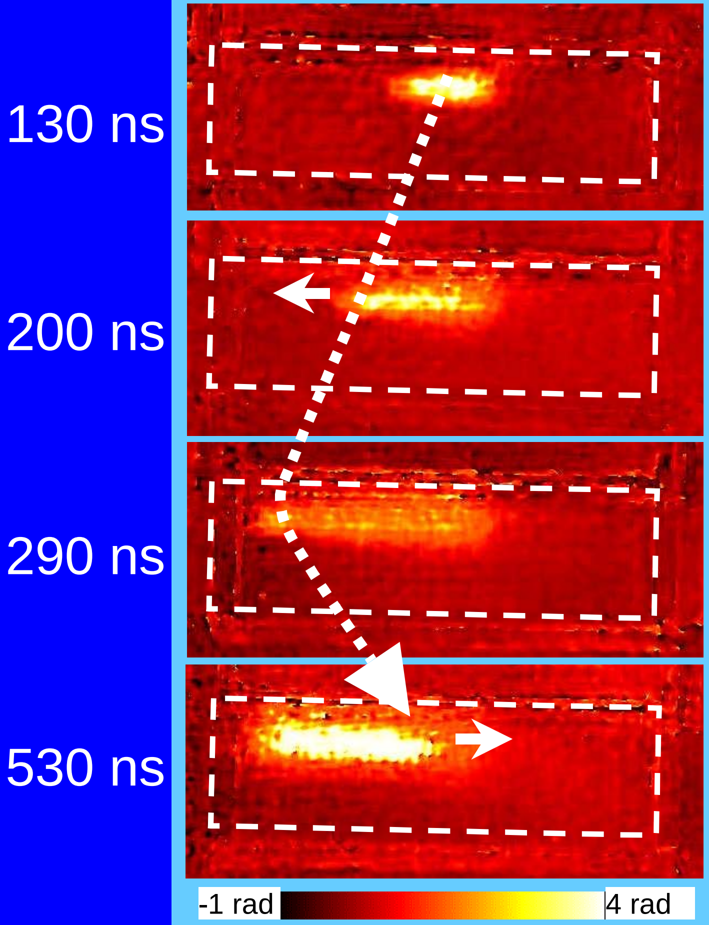
Up to 1100K models for impact ion. coeff. verified experimentally

[S. Reggiani et al. I3E EDL, vol.26 2005, p.916]

# Current filament dynamics in ESD protection devices



Phase shift – measured



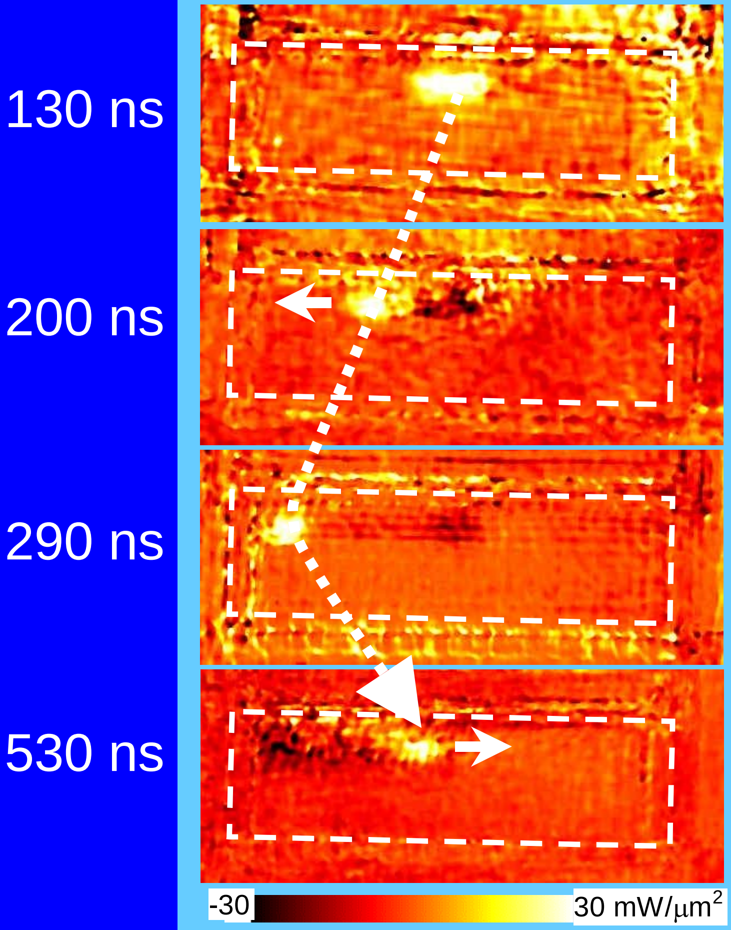
Filament has been created

Filament moves to left

Filament reflects from device corner

Filament moves back

P2D – extracted power density

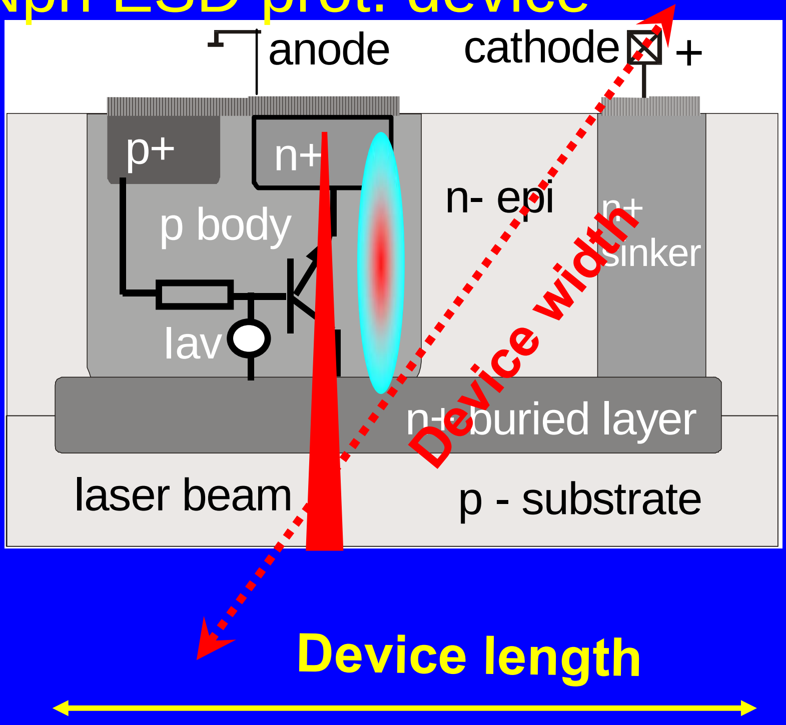


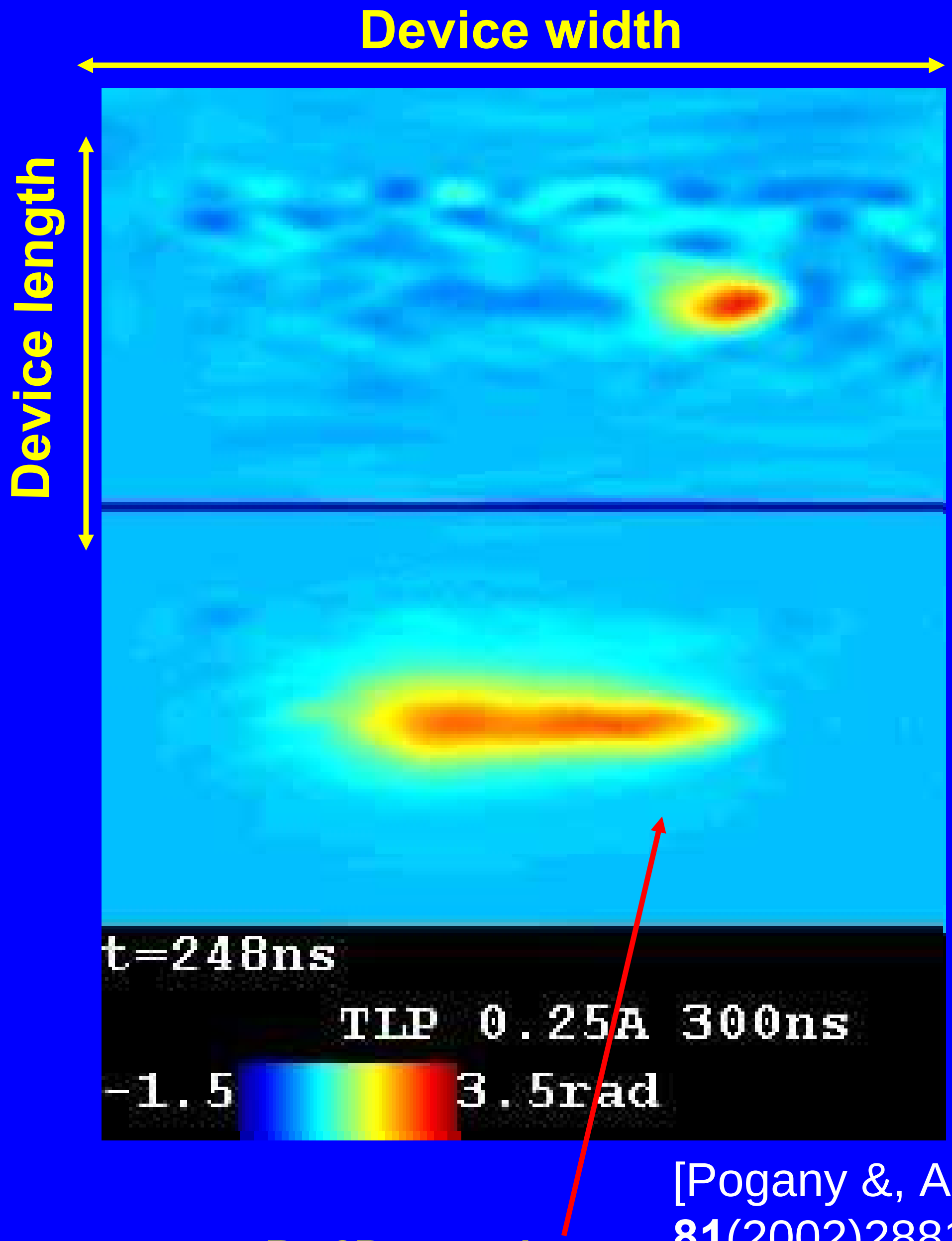
[Dubec &, Microel.Reliab. 44(2004)1793]

# Instantaneous power extraction from TIM measurements

**Filament movement along the device width**

Npn ESD prot. device





Calculated:

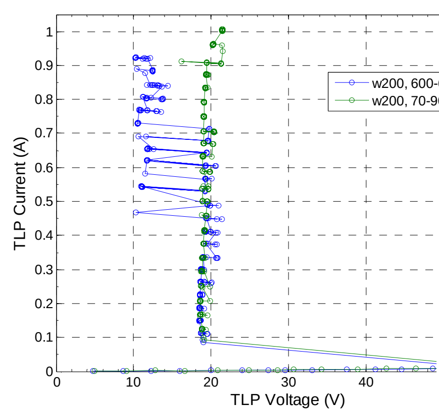
$P_{2D} \approx$ curr. density

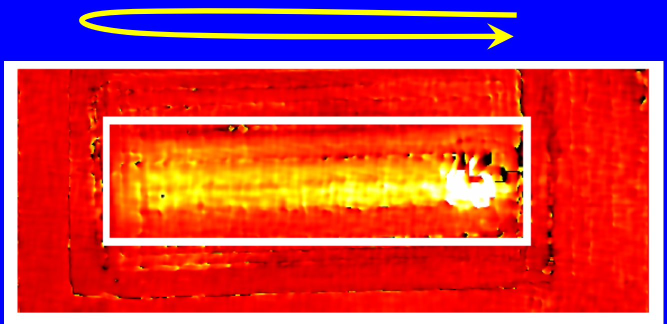
Measured:

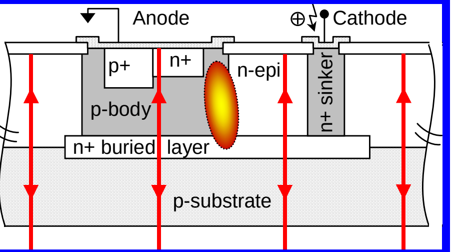
$\Delta\varphi$: memory effect

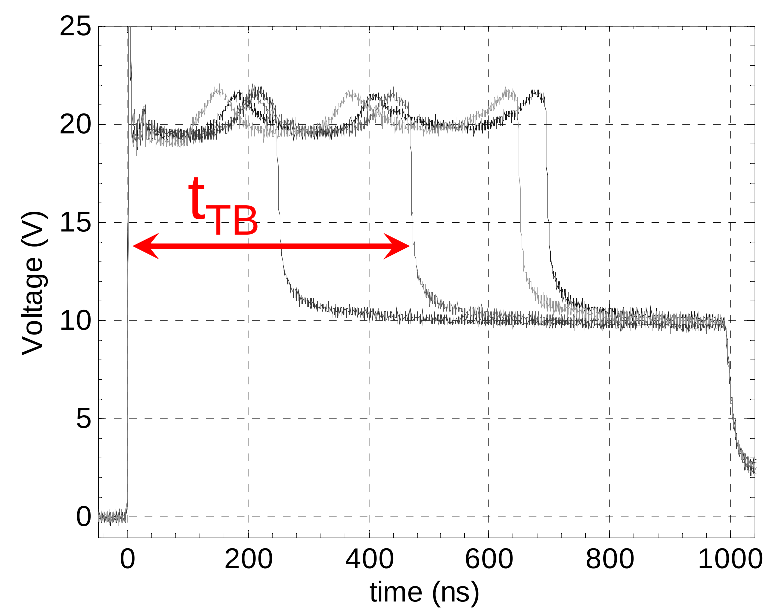
[Pogany &, App.Phys.Lett, **81**(2002)2881]

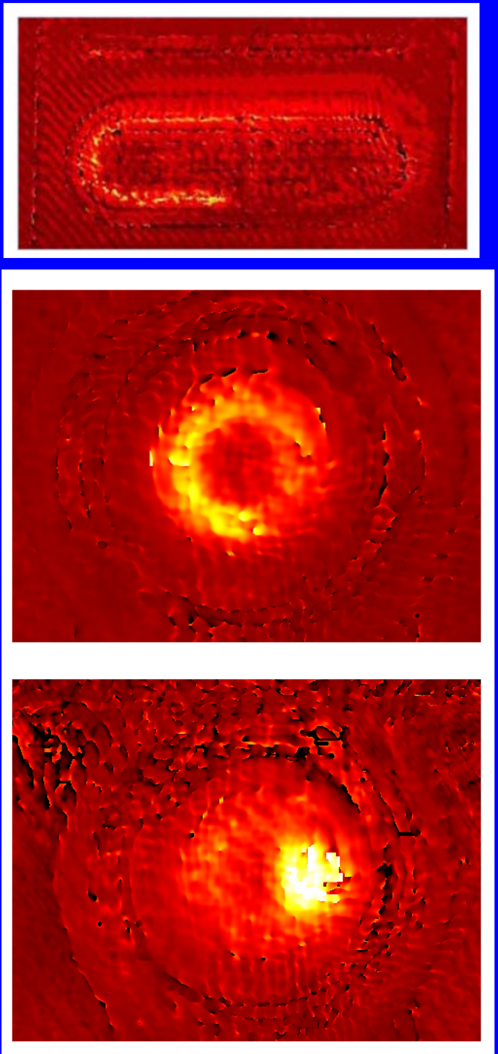
# Second breakdown due to stopped current filaments









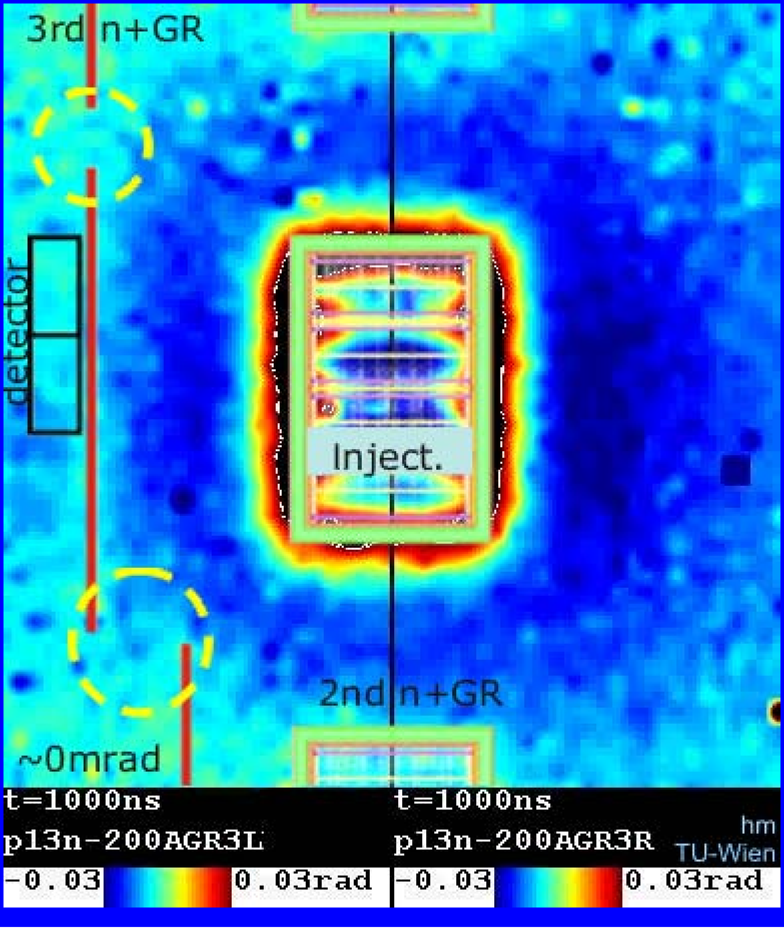


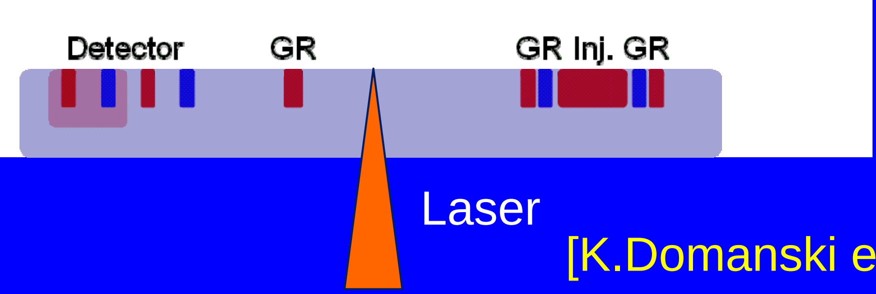
Optimized structures

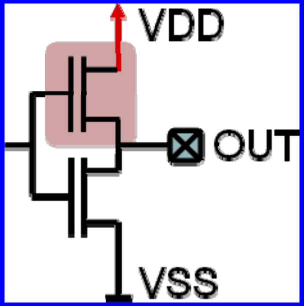
Thermal breakdown (TB) occurs when filament reaches an already preheated region (edge, or start position) → improving $t_{TB}$

[D. Johnsson &, IRPS08, p.240]

# TLU analysis in 90nm CMOS structures

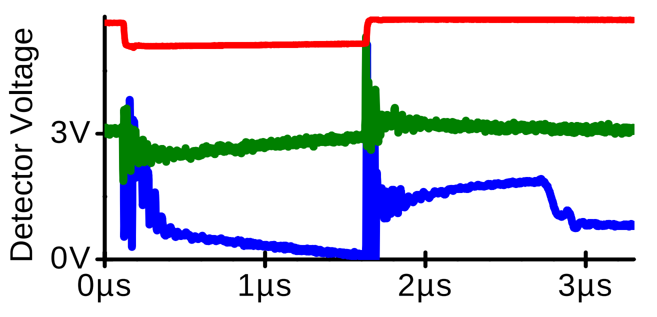


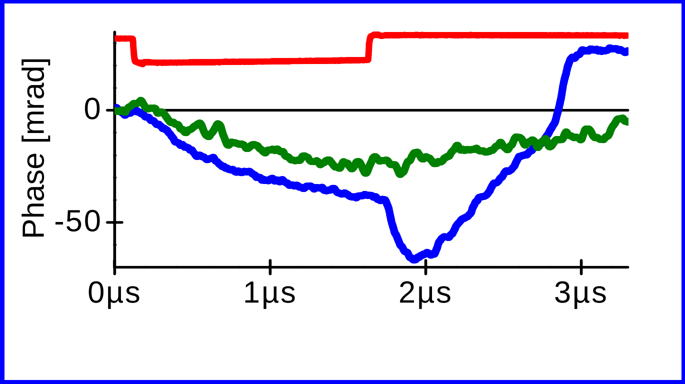




* Invertor sensitivity to Latch –up is studued

* Injector diode emulates substrate current injection



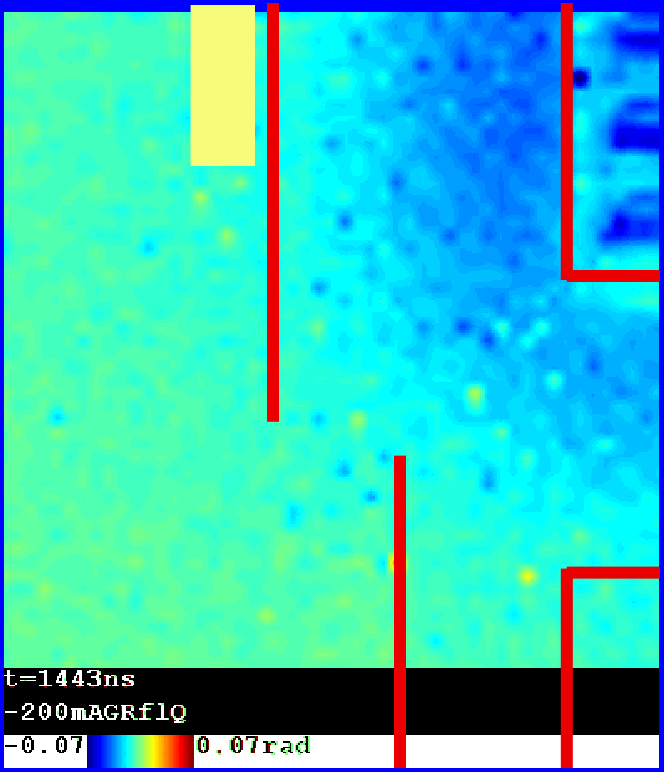


[K.Domanski et al. EOS/ESD’07, p.347]

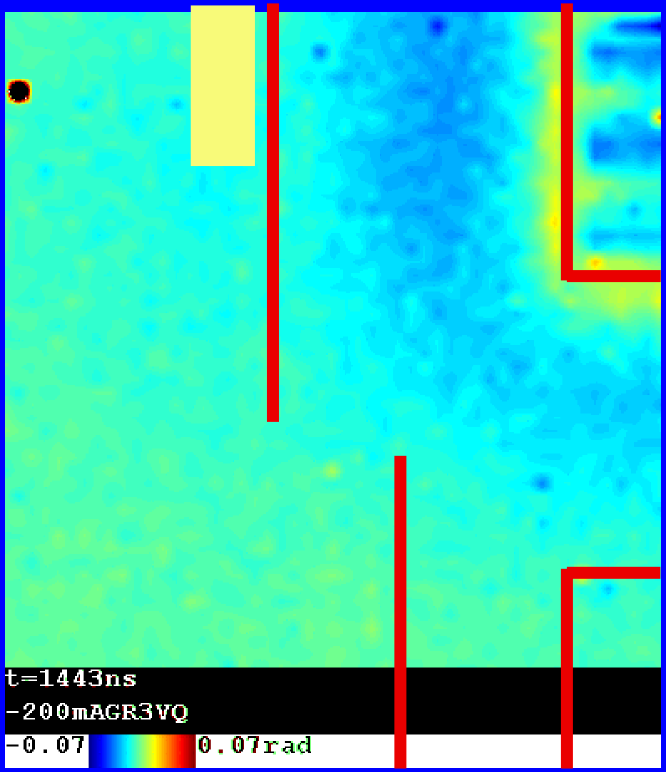
# Carrier an heat distribution during TLU event: effect of guard rings studied

**Guard Ring floating:**

[K.Domanski et al. EOS/ESD’07, p.347]



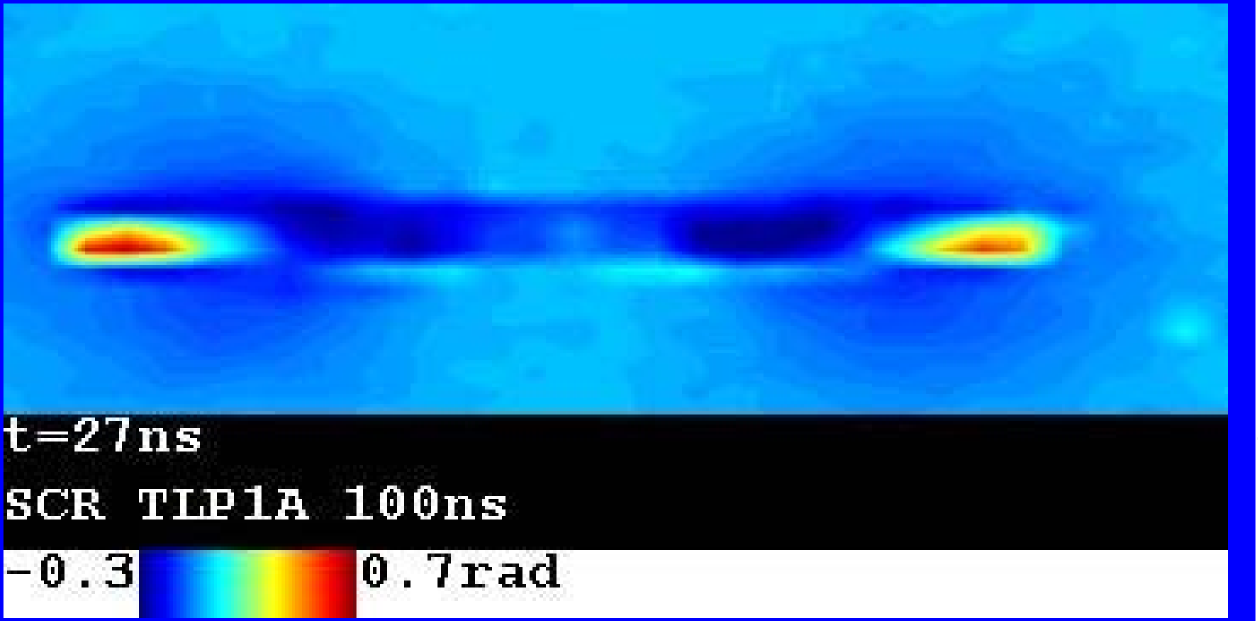
**Guard Ring 3V:**

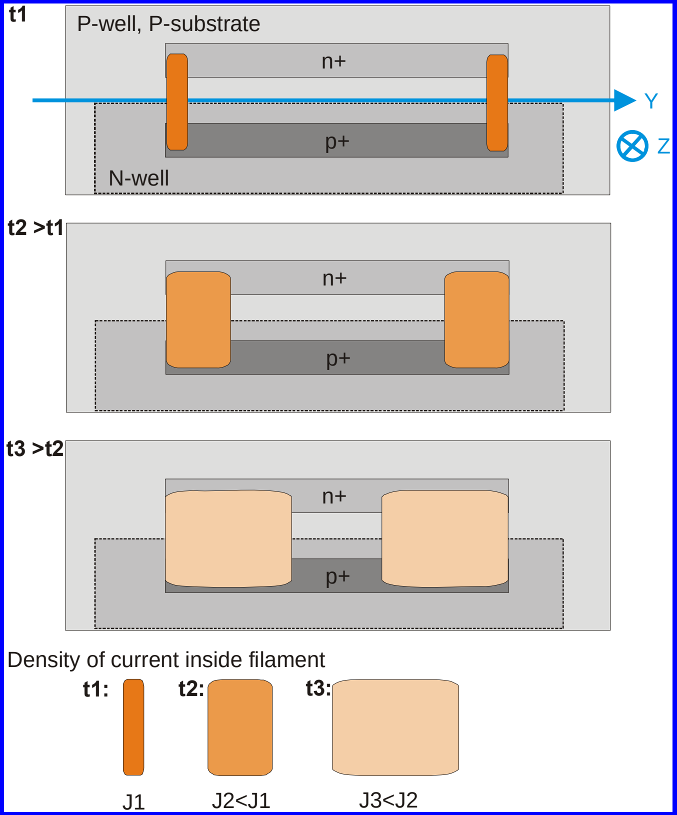


**-200mA pulse of 1623ns**

- **Carrier diffusion length can be experimentally determined ≈100µm (≈1µs) → calibration of simulator**
- **Guard ring effect demonstrated –still carrent via substrate**

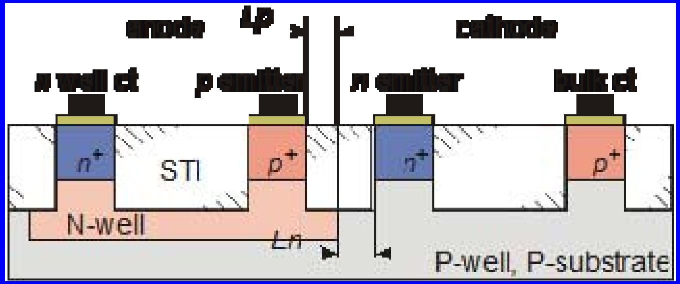
# 90 nm CMOS SCR study: spreading of the on state





-electron-hole plasma spreads with time to sides and to substrate

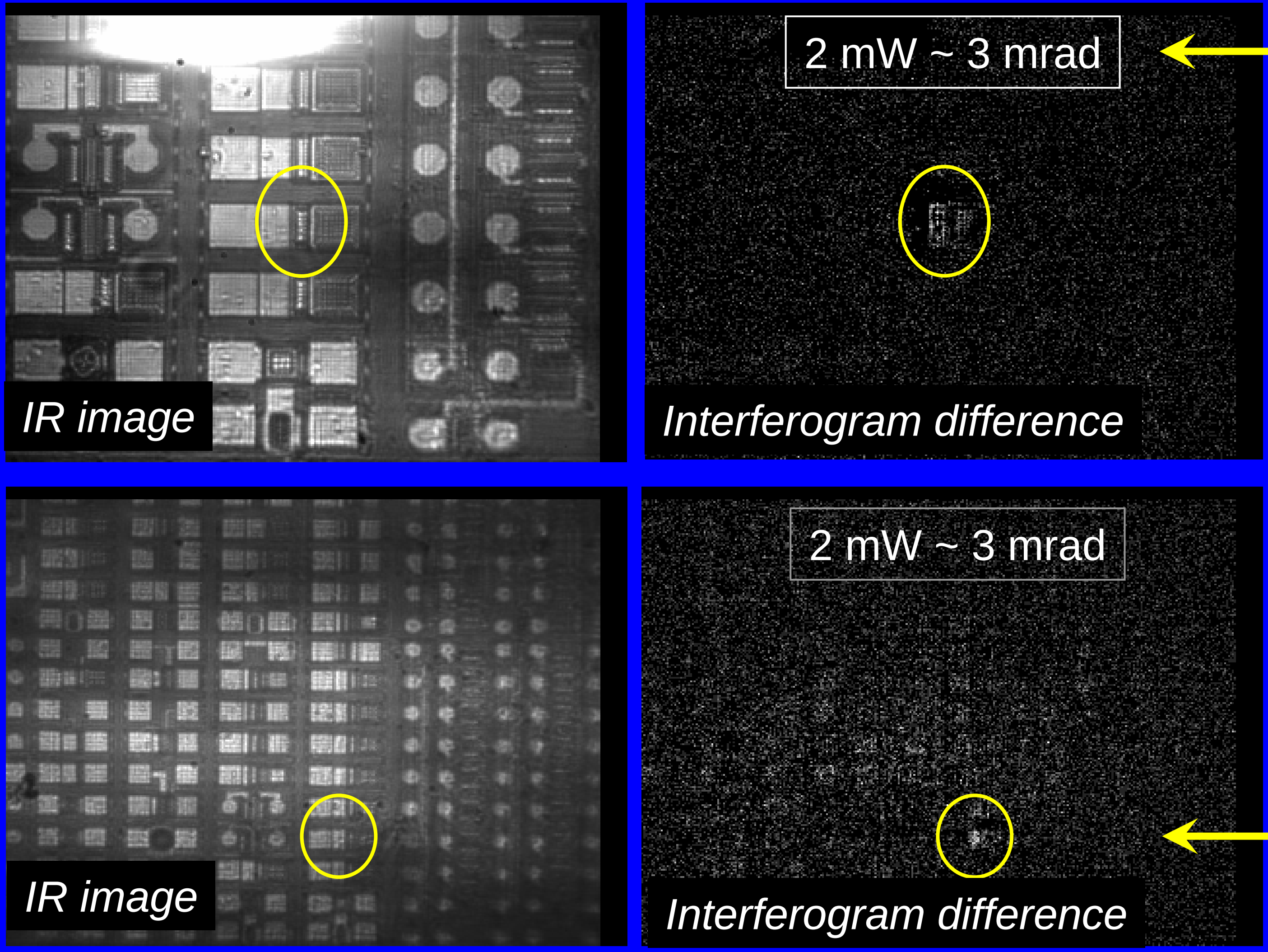
- heating follows with a delay the current flow



[K.Esmark et al, IRPS08, p.247]

# ESD failure detection using 2D TIM method

## – rough position detection in a large field of view



*FOV*
*1.6x1.3 mm*

Stroboscopic detection using repetitive pulses + stabized Michelson interferometer

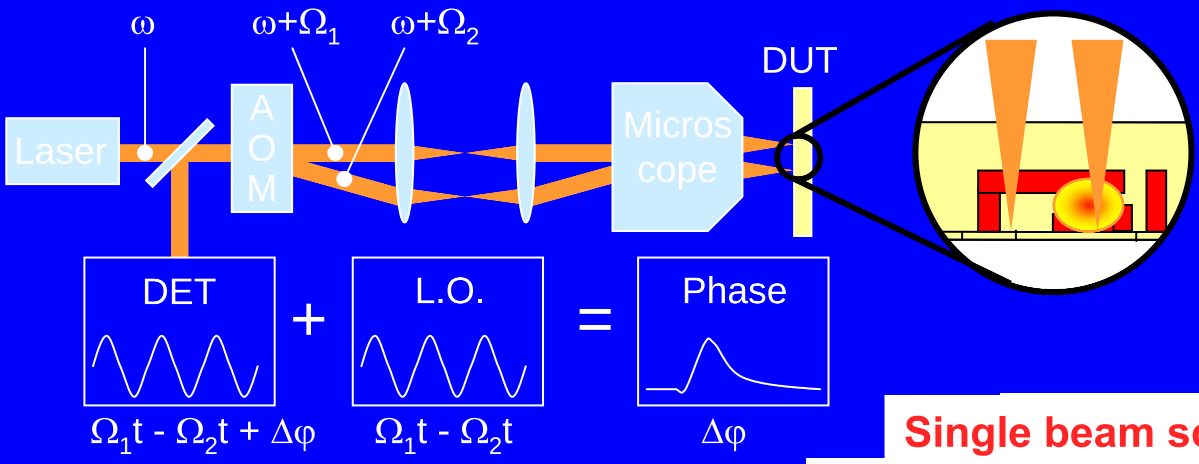
*FOV*
*3x2.5 mm*

Testing on npn transistor

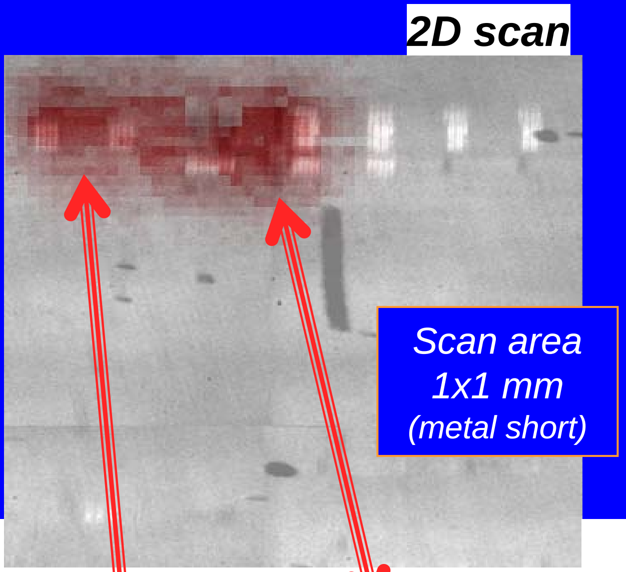
[V.Dubec et al. , Microel. Reliab, 47(2007)1549]

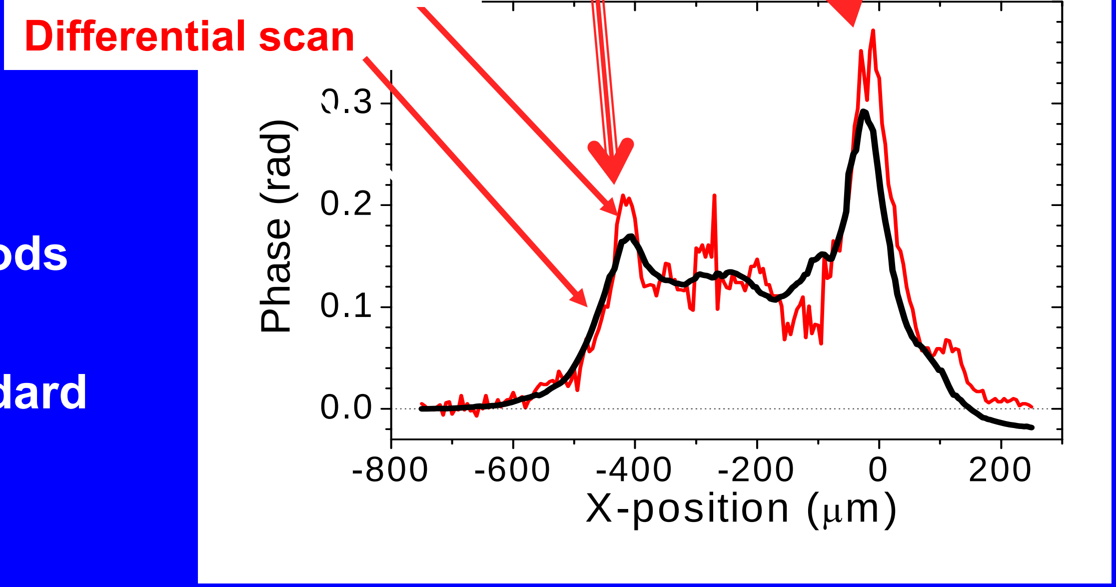
# Scanning TIM technique for failure analysis - metal short detection

[V.Dubec et al. , Microel. Reliab, 47(2007)1549]



- power resolution up to 50 μW
- spatial resolution 2 μm
- comparable to standard FA methods (e.g. TIVA)
- possible to combine FA with standard TIM for ESD analysis





# Conclusions

TIM :

– free carrier and thermal dynamics can be detected with ns time and µm space resolution

– understanding device physics and for device layout optimisation

- used for calibration and verification of device simulation models under high current and high temperature conditions

- failure analysis application

- other applications include thermal mapping of GaN HEMTs, lasers [J.Kuzmik &, APL 2003, IEEE TED 2005, SSE 2006,…]