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

D. Pogany, S. Bychikhin, M. Heer, W. Mamanee, V. Dubec, E. Gornik

Institute for Solid State Electronics, Vienna University of Technology


Infineon Technologies, Am Campeon, Neubiberg, Germany

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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)

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

[Courtesy W. Stadler, Infineon]

[Amerasekera & Duvvury, 1995]
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 $\Delta \phi$
  ↓
* 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.

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**

- **laser diode** $\lambda=1310$ nm
- **photo diode**
- **AOM**
- **external reference mirror**
- **mirror**
- **IR observation camera**
- **microscope objective**
- **xy-stage**
- **D.U.T.**
- **TLP tester**
- **vf-TLP tester**
- **DMOS pulser**
- **HV source**

* 1.5µm space resolution
* 3ns time resolution

**Spatial distribution:**
- periodical device stressing
- lateral device scanning

Forböck & 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

Interferogram:

Unstressed  Stressed

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 \(\mu s\)
- phase distribution at two time instants during single stress pulse
- non-repetitive phenomena (destructive)

Model verification at high temperatures by TIM

ESD protection diode: comparison TIM vs. TCAD simulation

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

Current filament dynamics in ESD protection devices

Phase shift – measured

130 ns
Filament has been created

200 ns
Filament moves to left

290 ns
Filament reflects from device corner

530 ns
Filament moves back

P2D – extracted power density

Instantaneous power extraction from TIM measurements

Filament movement along the device width
Npn ESD prot. device

Measured: Δϕ: memory effect
Calculated: $P_{2D} \approx \text{curr. density}$

By 2D scanning

Device width
Device length

[D. Pogany, TU Vienna, Toulouse 2009]

Second breakdown due to stopped current filaments

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

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

D.Pogany, TU Vienna, Toulouse 2009
TLU analysis in 90nm CMOS structures

* Inverter sensitivity to Latch–up is studied
* 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:

Guard Ring 3V:

-200mA pulse of 1623ns

[K.Domanski et al. EOS/ESD’07, p.347]

• Carrier diffusion length can be experimentally determined
  \( \approx 100\mu m \) \( \approx 1\mu s \) → calibration of simulator

• Guard ring effect demonstrated –still current via substrate

D.Pogany, TU Vienna, Toulouse 2009
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

[IR image] 2 mW ~ 3 mrad
[Interferogram difference] FOV 1.6x1.3 mm

Stroboscopic detection using repetitive pulses + stabilized Michelson interferometer

[IR image] 2 mW ~ 3 mrad
[Interferogram difference] 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 $\mu$W
- spatial resolution 2 $\mu$m
- comparable to standard FA methods (e.g. TIVA)
- possible to combine FA with standard TIM for ESD analysis

D.Pogany, TU Vienna, Toulouse 2009
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,...]