

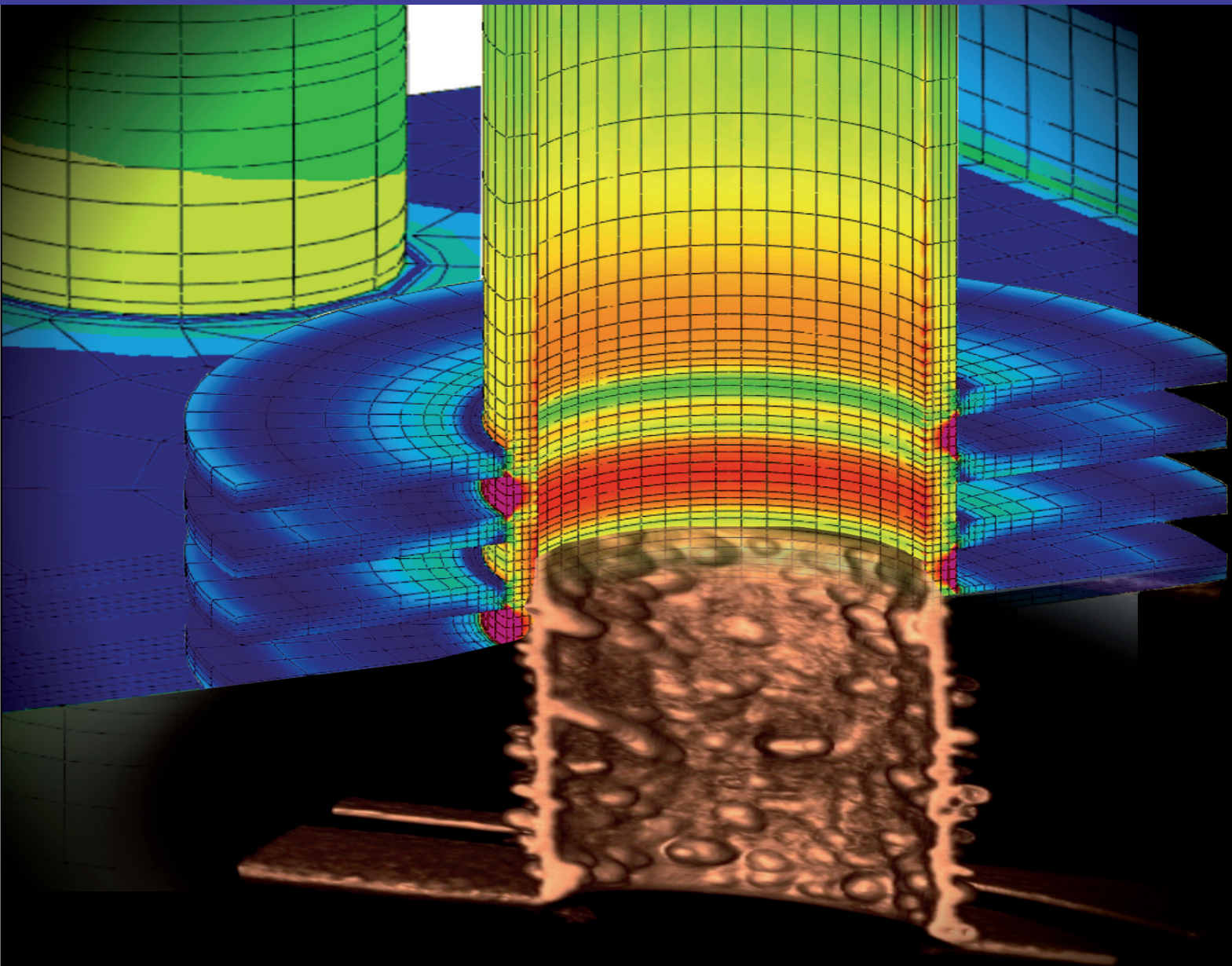


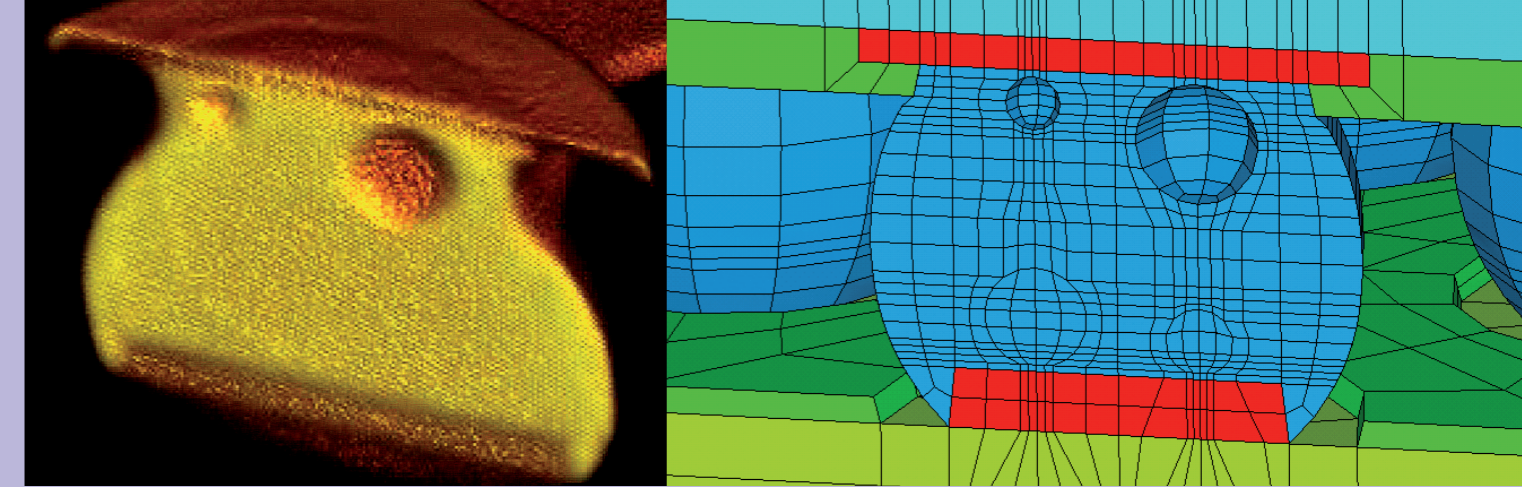
Fraunhofer

ENAS

FRAUNHOFER INSTITUTE FOR ELECTRONIC NANO SYSTEMS ENAS

MICRO MATERIALS CENTER





Nondestructive Analysis and Fully Parametric Modeling of Real Micro and Nano Structures

RELIABILITY RESEARCH

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SYMBIOSIS BETWEEN EXPERIMENT AND SIMULATION

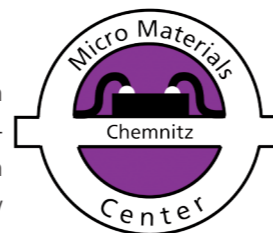
The actual developments of micro and nano technologies are fascinating. Undoubtedly they are playing a key role in today's product development and technical progress. With a large variety of different devices, different technologies and materials they enable the integration of mechanical, electrical, optical, chemical, biological, and other functions into one system on minimum space.

The Fraunhofer Institute for Electronic Nano Systems ENAS in Chemnitz focuses on research and development in the fields of Smart Systems Integration by using micro and nano technologies with partners in Germany, Europe and worldwide. Based on prospective industrial needs, Fraunhofer ENAS provides services in:

- ▶ Development, design and test of MEMS and NEMS (micro and nano electro mechanical systems)
- ▶ Wafer level packaging of MEMS and NEMS
- ▶ Metallization and interconnect systems for micro and nano electronics as well as 3D integration
- ▶ New sensor and system concepts with innovative material systems
- ▶ Integration of printed functionalities into systems
- ▶ Reliability, safety and security of micro and nano systems.

Micro Materials Center (MMC)

The competence and experience in the field of reliability research available at Fraunhofer ENAS has been the result of 25 years of industry related work. It started with studies on fracture and damage mechanics for lifetime estimations of big pressure vessels at the Institute of Mechanics. After founding the Micro Materials Center, these methodologies could be transferred and expanded into the field of electronics packaging during the 90s and grown further into micro and nano technologies after the turn of the century. Becoming part of Fraunhofer ENAS, the logical next step has been made by comprehensively covering the needs of smart systems integration as well.



Today, the Micro Materials Center is able to assess and to evaluate the effects and interactions that lead to drift or degeneration of performance parameters and finally to the failure of the micro and nano systems. Strictly following the 'physics of failure' approach, potential yield distractors as well as risks concerning reliability, safety, and security of new technologies and products can be identified at the earliest time possible and lifetime models can be extracted. Being the result of direct cooperation, these findings directly support the development of new products and systems in industry (design for manufacturability and reliability). The ultimate goal of this effort is to fully optimize products based on numerical simulations avoiding all the time-consuming and expensive experiments prior to shipment qualification. This methodology of full 'virtual prototyping' would create new system solutions at a

fraction of current time and cost. The first real samples fabricated would immediately meet the yield and reliability requirements for the ramp-up into high volume production. What a vision! Fortunately, today's design practice for microelectronic circuits as well as for structural parts in the automotive industry already gives rise to optimism that virtual prototyping may also be feasible for the design of smart systems based on micro and nano technologies. Numerical simulations being as accurate as real sample tests provide the objective feasibility criterion. Key to achieving this is a truly symbiotic alliance between simulation and experiment. Only this way, all the numerical models can be calibrated as precisely and all results can be validated as realistically as needed. Professor Bernd Michel and the Micro Materials Center at Fraunhofer ENAS have pioneered this approach and continue to lead its advancement.



The European Center for Micro and Nano reliability (EUCEMAN) is the most comprehensive European research network on reliability of micro and nano technologies. Fraunhofer ENAS coordinates the activities of EUCEMAN at its main office in Berlin. Important research institutes and labs from many European countries have become very active in the EUCEMAN network (e.g. Austria, France, Germany, the Netherlands, Poland, Romania, Sweden, Switzerland, the United Kingdom). EUCEMAN has initiated numerous European projects and brings together the experts in the field of reliability research. The first World Congress 'MicroNanoReliability' attracted participants from more than 40 countries. More information on: <http://www.euceman.com>.

High Level Reliability Research for Industry and Education

The Micro Materials Center offers a large variety of R&D support services. Besides direct cooperation and participation in publicly funded joint projects, the services also include consultations, consulting, and scientific / engineering expert reviews in the various fields of reliability research for micro and nano technologies as well as concerning all related subjects of materials research, testing, and numerical simulation. The reference list of partners and customers shows many SMEs but also large companies and global players, like

AMD, Audi,	Globalfoundries,	Siemens,
BMW, Bosch,	Hella, Heraeus,	X-Fab,
Continental,	IBM, Infineon,	ZMD.

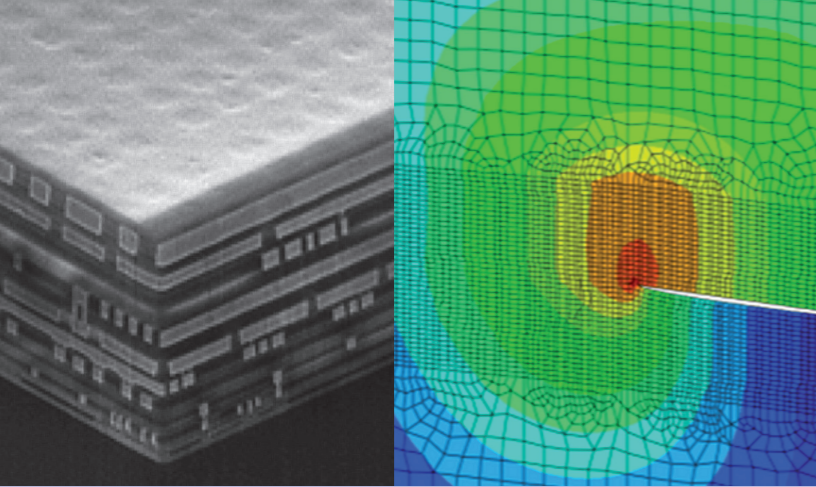
The Micro Materials Center has been working on regional, national, and international level, e.g.

- ▶ Competence Center 'Technologies for Electromobility' (Chemnitz)
- ▶ Spitzencluster 'Cool Silicon' (Germany)
- ▶ EU Joint Technology Initiative 'Clean Sky'
- ▶ European Green Car Initiative

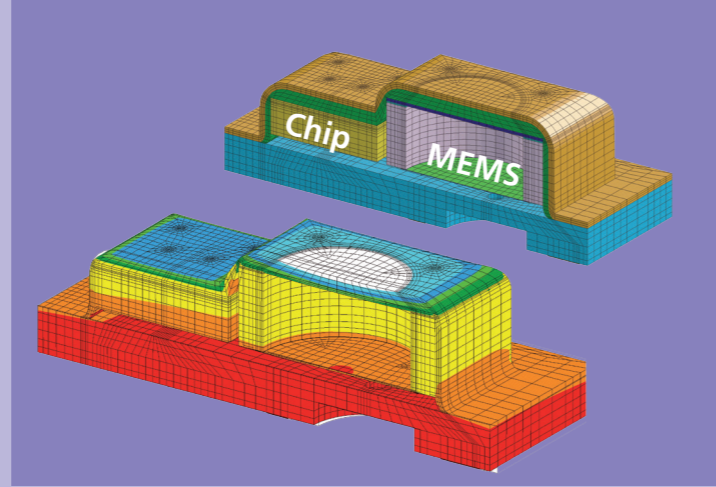
The Micro Materials Center is very active in technology platforms and initiatives:

- ▶ Dresden Fraunhofer Cluster Nanoanalytics and Silicon Saxony
- ▶ VDI/VDE-GMM (Germany)
- ▶ European Platform of Smart Systems (EPoSS) etc.

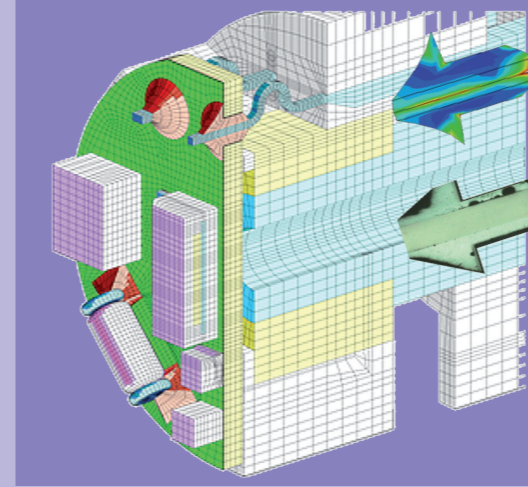
It contributes to university education through various activities and is editor of several journals (e.g. Microsystems Technologies Journal, M&N – Micromaterials and Nanomaterials).



Fracture Mechanics at Nanometer Scale

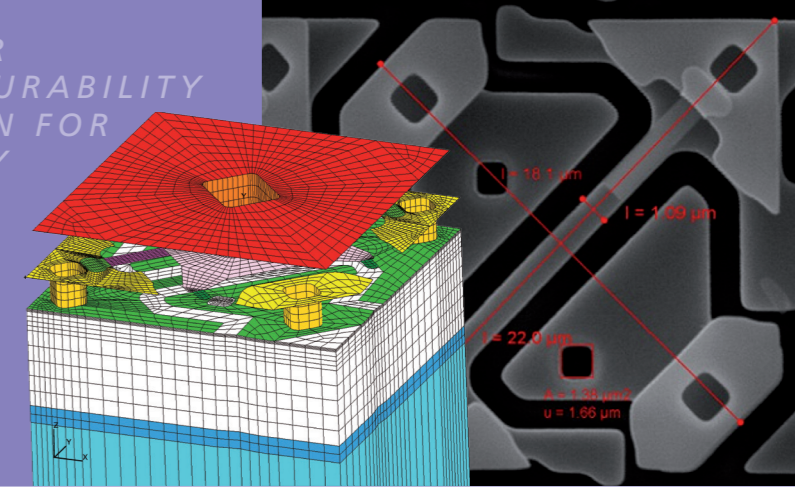


Virtual Prototyping for Smart Systems



Sensor and Actuator Systems for Automotive and Communication Applications

DESIGN FOR
MANUFACTURABILITY
AND DESIGN FOR
RELIABILITY



RELIABILITY FOR MICRO/NANO

Reliability for 3-D Nano Electronics

The years till 2020 are offering great challenges to back-end of line (BEoL) and electronics packaging technologies. The breakthroughs to be achieved in 3-D integration include the handling of very thin wafers for through-silicon via (3-D TSV) solutions in high volume production. They require full control of the **CHIP/PACKAGE INTERACTION (CPI)** also in ultra-dense packages with ultra-low-k (ULK) dielectrics. Micro Materials Center supports these efforts by feasibility assessments and reliability research. Leading edge finite element **SIMULATION METHODOLOGIES** are combined with advanced experimental techniques to apply state-of-the-art crack, fracture, and damage mechanics concepts to develop crack avoidance strategies based on the physics-of-failure approach.

The following aspects are becoming most important:

- ▶ Analysis and optimization of manufacturing (yield) and reliability in micro/nano systems
- ▶ Evaluation and prognosis of BEoL fracture strength, including ULK and nano-porous materials
- ▶ Complex analysis of 3-D systems integration incl. TSV, from the single via to the full module
- ▶ Application of fracture and damage mechanics in micro-, nano-, and even sub-nanometer structures (e.g. crack initiation in barrier layers)
- ▶ Crack and delamination prevention strategies

Applied simulation tools and methods:

- ▶ Extended FEM (X-FEM)
- ▶ Cohesive zone modeling (CZM) and virtual crack closing techniques (VCCT)
- ▶ Multi-scale and multi-level simulation

Reliability for Heterogeneous Micro/Nano Systems

The new effects of nano functional materials and components require **MULTI-FIELD COUPLING** in numerical simulation in order to analyze, evaluate, and forecast the reliability realistically. In addition, the complexity of the new functionalities with their multitude of new interactions necessitates the use of most effective **OPTIMIZATION ALGORITHMS** for the proper identification of all material parameters needed for modeling their behavior right.

Micro Materials Center has long been applying the following methodologies and is improving them:

- ▶ 3-D FE simulation of complex smart systems applying micro/nano technologies
- ▶ Characterization and modeling of multi-functional materials for micro and nano systems
- ▶ Thermo-mechanical assessments, reliability modeling, and life-time prognosis for components and full systems exposed to extremely large ranges in temperature
- ▶ Simulation of systems under a combination of temperature, moisture, electric current and voltage, fluidic, and structural loads in static and dynamic mode causing creep, fatigue etc.
- ▶ Optimal design of new structures for tests and service
- ▶ 'Design for reliability' support for technological innovation based on broad expert experience
- ▶ Derivation of standard solutions for micro/nano systems
- ▶ Automated DoE, optimization, and robustness analysis

AND CLEAN TECHNOLOGIES

Reliability for Advanced Mobility

All modern mobility concepts assume the use of smart systems and innovative material solutions as essential hardware basis. The service conditions of today's **AUTOMOTIVE, AIRCRAFT, AND SPACE APPLICATIONS** already drive the reliability requirements to the limits achieved so far. Safety concerns attached to the new features like high-energy batteries, 'drive by wire' or even by wireless communication, and ultra-compact high-power control systems further increase these challenges.

The Micro Materials Center actively contributes to the research in the following fields:

- ▶ Development of next generation battery management systems for fully electrical vehicles (EU project 'smartLIC')
- ▶ Lifetime prognosis and design optimization of structural components of fiber reinforced materials under complex loadings in dry and humid atmospheres (EU project 'CleanSky – Eco Design')
- ▶ Design for reliability of sensor networks for structural health monitoring of lightweight and fiber reinforced structures (national projects 'Nanett', 'CoolSilicon')
- ▶ Reliability of components for active flow control: simulation, measurements, and characterization of the fluid / structure interaction in micro-jet nozzles (EU project 'CleanSky – Smart Fixed Wing Aircraft')

Reliability of Energy Systems

Energy production and transport is the main focus of 'Clean Technologies', which combine high technologies with **ECOLOGICAL CONCEPTS**. Smart systems are key contributors as they provide sensing, controlling, and communication functionalities as needed autonomously and reliably.

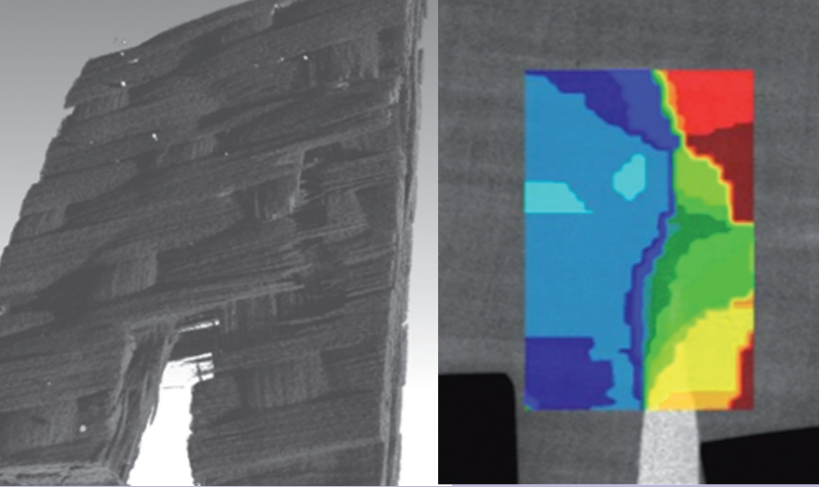
The Micro Materials Center deals with concepts and solutions for the specific reliability requirements in the fields of:

- ▶ Solar energy – Component, system, and interconnect reliability of large area organic and thin-film modules
- ▶ Oil, gas, and geothermal energy – Accelerated and combined testing for very high temperature systems
- ▶ Wind and water power (Desertec) – Longtime reliability under extreme environmental conditions (sea, desert climate)

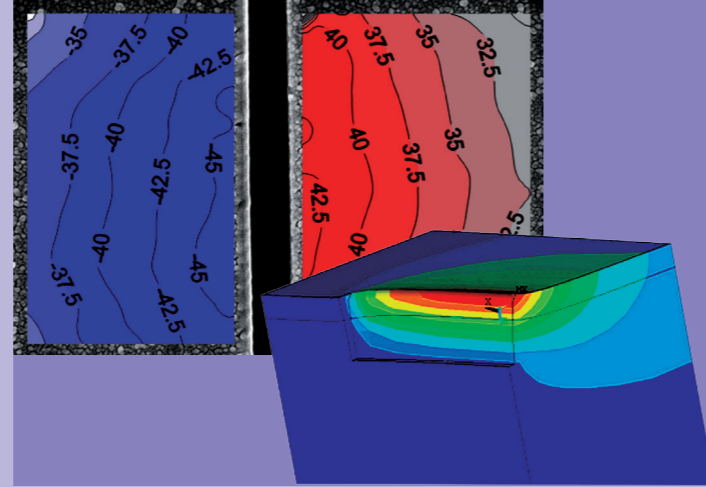
Reliability Methodologies for Safety and Security

Micro / nano technologies and smart systems are capable of adding valuable safety and security features to any kind of goods from small pills to big machines but also to buildings and complex infrastructure networks. Applying methodologies developed as part of the reliability research, the group of **MICRO AND NANO SECURITY** at Micro Materials Center deals with

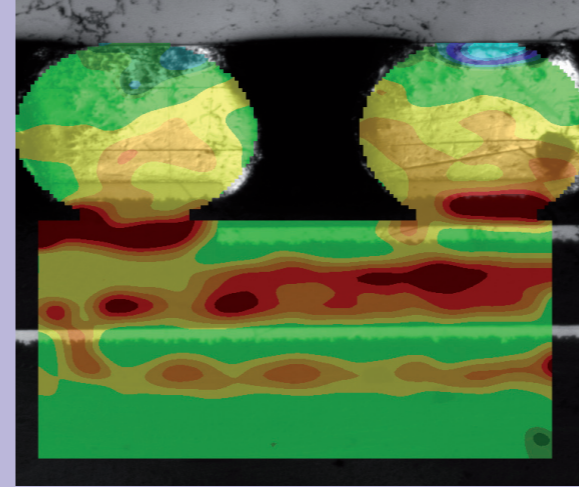
- ▶ Authentication and falsification of components, systems, documents (e.g. high security chips)
- ▶ Security, safety, and reliability of medical products (e.g. pacemakers)
- ▶ Security of buildings, manufacturing units, electrical power networks etc.



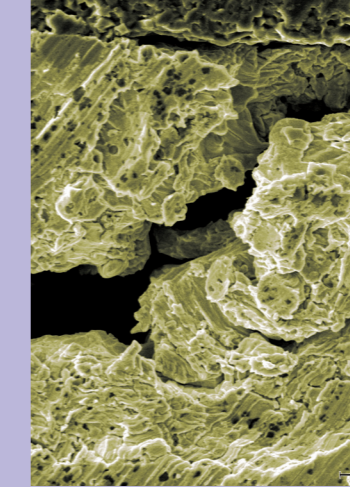
microDAC – Deformation Analysis at Crack Tip



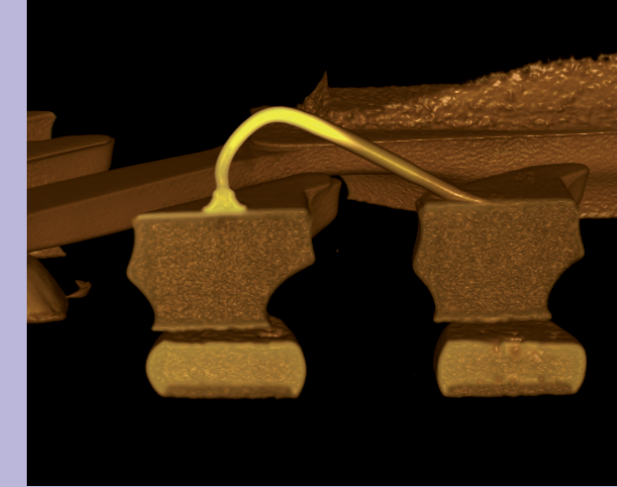
fibDAC – Stress Probing in Smallest Dimension



Inhomogeneous Deformation in Substrate



Analysis of Microstructures



Failure Analysis in Microsystems

WITHOUT EXPERIMENTAL ANALYSIS

Deformation Analysis for All Dimensions: From 'Sub-Nano' to 'Supra-Macro'

The Micro Materials Center has long been using innovative techniques based on latest advances in digital image correlation (DIC) for studying the thermo-mechanical failure mechanisms as well as for comprehensively evaluating movements and deformations in structures and materials of all sizes. The techniques of deformation analysis based on correlation in micro and nano scales, **MICRODAC™** and **NANO DAC**, have continuously been developed in close cooperation with CWM GmbH. They are also used for high precision calibration and validation of the finite element models and the simulation results with respect to deformation and movements. In summary, they offer the following options:

- ▶ Area of application: nanometer ... kilometer as well as micro-second ... years
- ▶ Measurement technique: in-situ, absolutely without repercussion
- ▶ Environmental conditions (temperature, humidity, protective gas, vacuum, vibration...) can freely be considered

Typical applications include:

- ▶ Deformation and shape diagnostics at the surface of materials and structures
- ▶ Temperature-dependent 3-D volume and deformation analysis by X-ray computer tomography (e.g. 'Nanotom')
- ▶ Crack tip detection and crack tracing
- ▶ Material characterization (Young's modulus, Poisson's ratio, thermal expansion coefficients etc.)
- ▶ Adhesion and related material parameters
- ▶ Stress analysis in multilayer systems.

Measurement of Film and Internal Stresses in Very Small Dimensions

Mechanical stresses may boost the performance of modern semiconductor devices. In some components of micro/nano systems, they even determine the function. On the other hand, they are often the root cause of degradation, fatigue, and failure in smart systems. In any case, mechanical stresses are structure-dependent local effects. Therefore, design, manufacturing, and test of functional and reliable smart systems require precise measurements of the stresses at local stage. The Micro Materials Center has been developing a series of stress analysis methods with high spatial resolution. They are also used for validating the stress results of finite element simulations performed to optimize the design of future smart systems.

The following methods are available:

- ▶ **FIBDAC STRESS ANALYSIS** – a powerful method developed by Micro Materials Center. The assessment is based on the local stress release within the structure due to nano-scale trenches milled by focused ion beams (FIB) in the electron microscope. This method can be applied to nearly all materials and dimensions – avoiding the restriction of other methods.
- ▶ **MICRO AND NANO RAMAN** – Stress mapping in semiconductors, polymers and nano materials (e.g., carbon nano tubes, CNT) - also used in direct combination with FE simulation.
- ▶ Electron diffraction by **EBSD** detector for maximum spatial resolution in crystalline materials
- ▶ **STRESS SENSOR CHIPS** – online stress analysis in packages during manufacturing, test, and service.

NO RELIABILITY ASSESSMENT

Failure Expert Assessment, Damage Evaluation and Failure Avoidance Strategies

Microscopy and materialography at high level are the backbone of experimental analysis of real materials and devices. The Micro Materials Center can rely on 25 years of research activities in a wide range of practical applications as well as on the most modern tools and methods, e.g.

- ▶ Large variety of microscopic techniques (light, electron, laser scanning, fluorescence, ultrasonic, thermographic etc. microscopes)
- ▶ Micro/nano analysis tools: EDX, EBSD, FIB (Zeiss Auriga 60)
- ▶ 3-D X-ray computer tomography with sub-micron resolution, 3-D XCT ('Nanotom')
- ▶ Comprehensive materialography and structural analysis
- ▶ Volume correlation for materials/topography detection
- ▶ Measurement of geometric, thermo-mechanical, and electric parameters – in-situ within SEM, FIB, 3-D XCT but also under various combined real, test, and environmental conditions (temperature, moisture, vibration etc.).

These methods are also applied to **EXPERT REVIEWS** concerning the

- ▶ Determination of the real material, device, and product behavior
- ▶ Determination and evaluation of failure mechanisms and the reasons for damage, crack, and failure occurrence
- ▶ Determination of the extent of the damage
- ▶ Reconstruction of damage history and evolution
- ▶ Determination of root cause of failure and damage
- ▶ Practical help for failure prevention (e.g. crack avoidance, lifetime optimization, design optimization)

Accelerated Testing, Longtime Reliability, Environmental Tests

Assessing lifetime and fatigue of all the components is a very important requirement in the development and qualification of new micro and nano systems. The tests to be performed accordingly need to highly accelerate the failure initiation and propagation but must not change its mechanism compared to the real environmental and service conditions. The Micro Materials Center is engaged in developing accelerated tests covering the following loading factors separately but also simultaneously:

- ▶ Thermal conditions (constant, cycle, shock – diffusion, creep, fatigue, fracture etc.)
- ▶ Mechanical conditions (permanent loading, vibration, shock, drop...)
- ▶ Electrical conditions (high current, load cycles, pulses, ...)
- ▶ Environmental conditions (humidity, inert gas, vacuum, harsh environmental)

In order to validate accelerated fatigue tests, the Micro Materials Center operates the European **LAB FOR LONG-TERM RELIABILITY** in a former silver mine supported by companies like Siemens, Bosch, Infineon, etc.

Materials Reliability

Basis for virtual prototyping is the exact knowledge of the material behavior in response to the loads, the loading limits and the failure thresholds of all relevant parts of the system under development during fabrication, tests, and service. In most cases, **TIME-DEPENDENCE** and **NONLINEARITY** of micro structural phenomena, details of the manufacturing processes, and environmental effects (e.g. temperature, humidity, UV...) have to be taken into account.



Simulation and Experiment



Long-time Reliability Lab (in a former Silver Mine)



Accelerated Reliability Testing

Contact:

Fraunhofer Institute for Electronic Nano Systems ENAS
Department Micro Materials Center
Technologie-Campus 3
09126 Chemnitz
Germany

Head of the department Micro Materials Center

Prof. Dr. Sven Rzepka
Phone: +49 371 45001-421
Fax: +49 371 45001-521
Email: sven.rzepka@enas.fraunhofer.de
Web: <http://www.enas.fraunhofer.de/>

Front Page:

Symbiosis of Experiment and Simulation:

Reliability Evaluation of a RF Interconnect Via in Driver Assistance Systems

Photos:

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