Nano Packaging Technology for Interconnect and Heat Dissipation

NANOPACK

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Project n°216176
THEME 3 : Information and Communication Technologies

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WORK PACKAGE 1 : Systems and applications specifications

DELIVERABLE D1.3

PERFORMANCE EVALUATION METHOD

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WORK PACKAGE 1 : Systems and applications specifications

TASK 1.1
MATERIAL SPECIFICATIONS AND APPLICABLE CONSTRAINTS

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DISTRIBUTION LIST

WORK PACKAGE 1 : SYSTEMS AND APPLICATIONS SPECIFICATIONS

TASK 1.3
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1 ABBREVIATION / DEFINITION

TIM	Thermal Interface Material
SOI	Silicon On Insulator
CNT	Carbon Nano Tube
BLT	Bond Line Thickness
MCM	Multi-Chip Module
LCC	Life Cycle Cost
SCM	Single-Chip Module
Rth	Thermal Resistance
HP	Heat Pipe
RTD	Resistive Thermal device
CTE	Coefficient of Thermal Expansion
ECA	Electrically Conductive Adhesive
MEMS	Micro-Electro-Mechanical Systems
FIB	Focused Ion Beam
AFAM	Atomic Force Acoustic Microscopy
SthM	Scanning Thermal Microscopy

2 INTRODUCTION

This report illustrates the different characterisation methods envisaged by the partners with respect to their performance and realisation as given below in the table. This will be carried out in detail below.

Description of Work

- **T5.1: Definition and preparation of test specimens (BME, Chalmers, F-IZM, EVAC, Nanotest, Bosch, IEMN, VTT, TRT, IBM)**
  Test specimen preparation under consideration of relevant process parameters (according to material definitions → WP 1) for the various test methods carried out in tasks 5.2 - 5.5.
  - Bulk and bi-material test-specimens: for single material and interface properties
  - Special test structures: for heat-transfer on submicron scale and nano-analytics
- **T5.2: Electrical characterisation (Bosch, VTT, IBM)**
  Determination of electrical properties (drawing upon → WP 2, 3, 4 for processes and WP6 for simulations):
  - Magnitude and uniformity of electrical resistance across interconnect
- **T5.3: Thermal characterisation of test-systems by direct diffusivity measurements (BME, Bosch, F-IZM, TRT, IBM, MicReD, ICN, Nanotest)**
  Thermal conductivity and thermal interface resistance measurements by various static and transient techniques (feedback to → WP 2, 3, 7 for performance)
  - Construction of advanced testing equipment featuring localised heat injection and measurement with highest accuracy
  - Systematic variation of material and interface properties (defined by → WP 2, 3)
- **T5.4: Thermal characterisation by phonon scattering measurements (IEMN, ICN, F-IZM, VTT)**
  Measurement of heat-transfer on submicron scale (feedback to → WP 2, 3, 6)
  - Measurement of thermal conductivity by optical and acoustic techniques
  - Analysis of structure and measurement of thermal conductivity of nano-composites and nano-structures (from → WP 2, 3) by advanced microscopy techniques.
  - Establishment of structure-property correlation together with simulation
- **T5.5: Mechanical characterisation (BME, TRT, Bosch, F-IZM, Nanotest, Chalmers, FOAB)**
  Mechanical characterization of materials and interfaces as function of moisture and temperature (rheological, thermo-mechanical, diffusion, failure properties) (→ for WP 6)
  - Development of bi-material adhesion test-methods and test-apparatus
  - Extraction of critical data (energy release rate, phase angle) for reliability modelling
  - Reliability testing and failure analysis of test-specimens and test-systems

3 REVIEW OF PERFORMANCE METHODS

3.1 PARTICLE FILLED SYSTEMS

Due to the potentially high number of sample materials and potential sources that will be developed during the NanoPack project a well defined process for material selection and evaluation will be required. In order to quickly and efficiently make progress, poor performing materials will need to be eliminated before more time consuming tests with multiple partners are performed. For this reason the evaluation of materials is split into three distinct phases:

1) Preliminary phase where materials are compared to an accepted industry standard material,

2) Qualification phase where materials face a series of in depth tests and a

3) Demonstration phase with materials evaluation in application specific environments.

Here, the number of evaluated materials is to decrease and converge to the best in class materials/surfaces combinations, whereas testing methods and associated test-systems will become more refined during the project.

The **preliminary evaluation** is designed to quickly evaluate performance trends associated with changes in particle/matrix ratios or material choices. These tests are designed simply to evaluate the most important application and performance parameters by a high throughput screening process:

- bulk thermal conductivity,
- electrical conductivity,
- rheological properties (viscosity of mixture), and
- Structural analysis (metallographic sectioning & e.g. FIB, REM, etc).

Preliminary tests must meet or exceed performance of an industry standard material in order to be passed on to other partners for Qualification evaluation.

The **qualification phase** is intended to provide more detailed evaluation with respect to target applications such as

- minimum bondline thickness,
- a function of assembly load (for standard interface sizes) and
- thermo-mechanical properties (storage modulus, CTE, fracture properties) for adhesives and mono-metal interconnects.

Results from qualification testing are returned to material developers to enhance performance if possible (new mixtures must again pass preliminary tests). Materials that pass the more rigorous tests in the qualification phase are then supplied as demonstrator materials. Here, refined test-equipment along with test-systems featuring nano-enhanced surface properties come into use for joint evaluation.

The **demonstration phase is** used to evaluate target application performance and to establish

- evaluation on demonstrator level
- reliability characteristics,

Because these tests are the most time consuming and require more expensive test vehicles they will only be performed with top materials developed in NanoPack. A detailed chart showing the tests involved in during each phase for each type of material developed is shown in Table 1.

Material Type	Test Phase		
	Preliminary → Tests	Qualification → Tests	Demonstration Materials
Thermal Grease **Reference material: Shinetsu grease ?,**	1) Bulk thermal conductivity [Chalmers, EVAC, IZM, Bosch, BME, Micred, Nanotest] 2) Viscosity [IZM, who else?]	1) Bondline Rth verses thickness for standard interface sizes (12x12mm, [IZM, ?] 20x20mm and 50x50mm), flat and modified surface (HNC) [IBM] 2) Characterize level of trapped voids (temp cycle between glass slides) [IBM] 3) Bondline Rth verses modified interfaces: (flat layer, sintered layer, nanoporous layer), [IZM]	Bondline Rth for 1) Microprocessor TIM2 45x45mm, flat and modified surface (HNC) 2) High power RF switch 3) Power electronics module, flat and modified surface (HNC) 4) Reliability and stress testing
Thermal Adhesive **Reference material: Shinetsu adhesive?**	1) Bulk thermal conductivity [IZM, BME, Micred] 2) Viscosity during application [IZM, who else] Chalmers, EVAC, IZM, Bosch…?	1) Bondline Rth verses thickness for standard interface sizes (12,5x12,5mm, [IZM,] 20x20mm and 50x50mm), flat and modified surface (HNC) 2) Storage modulus (DMA) [Chalmers, IZM, BME,] 3) Adhesion strength (shear and tension), flat and modified surface (HNC) [Bosch, TRT] 4) Bondline Rth verses modified interfaces: (flat layer, sintered layer, nanoporous layer), [IZM,] 5) Fracture behaviour, thermo-mechanical properties [IZM, nanotest] 6) Structure Analyses (X-sections, FIB, REM, AFM, etc) [?, IZM]	Bondline Rth for 1) Flip chip microprocessor TIM1, flat and modified surface (HNC) 2) High power RF switch 3) Power electronics module, flat and modified surface (HNC) 4) Reliability and stress testing Tested by: IBM, Bosch, Thales, FOAB…?
Electrical Adhesive **Reference material: Dow Corning 6524**	1) Bulk electrical conductivity and or contact resistance [Chalmers, BME, Micred, IZM,Bosch] 2) Viscosity estimate [IZM, who else] Tested by: Chalmers, EVAC, IZM…?	1) Contact resistance on standard die size, flat and modified surface (HNC) 2) Storage modulus (DMA) 3) Shear and tension adhesion strength, flat and modified surface (HNC) [Bosch, TRT?] 4) Bondline Rth verses modified interfaces: (flat layer, sintered layer, nanoporous layer), [IZM] 5) Structure Analyses	1) Contact resistance of power electronics die, flat and modified surface (HNC)

Sintering of Metals **Reference Material?**	1) Bulk thermal conductivity [IZM] 2) Porosity [IZM] 3) Shear strength to interfaces	1) Bondline Rth verses thickness for standard interface sizes ... [IZM, nanotest] 2) Thermo-mechanical properties for reliability [IZM, nanotest] 3) Structure Analyses (X-sections, FIB, REM, AFM, etc) [?, IZM	?
Nano-Interface Bonding **Reference Material?**	1) Porosity/ Structure [IZM] 2) Shear strength to interfaces	1) Bondline Rth verses thickness for standard interface sizes ...[IZM] 2) Thermo-mechanical properties for reliability [IZM] 3) Structure Analyses (X-sections, FIB, REM, AFM, etc) [?, IZM]	?
Nanofilms (Si membranes ~30nm thick, SOI structures, pastes with nano-particles) Reference material: ??		1) Thermal conductivity with 3□ method [ICN] 2) Impact of confined phonons on thermal conductivity using low frequency Raman scattering [ICN]	

Table 1 : TIM developed

3.2 ELECTRICAL CHARACTERISATION

Corresponds to task 5.2
Determination of electrical properties (drawing upon → WP 2, 3, 4 for processes and WP6 for simulations):

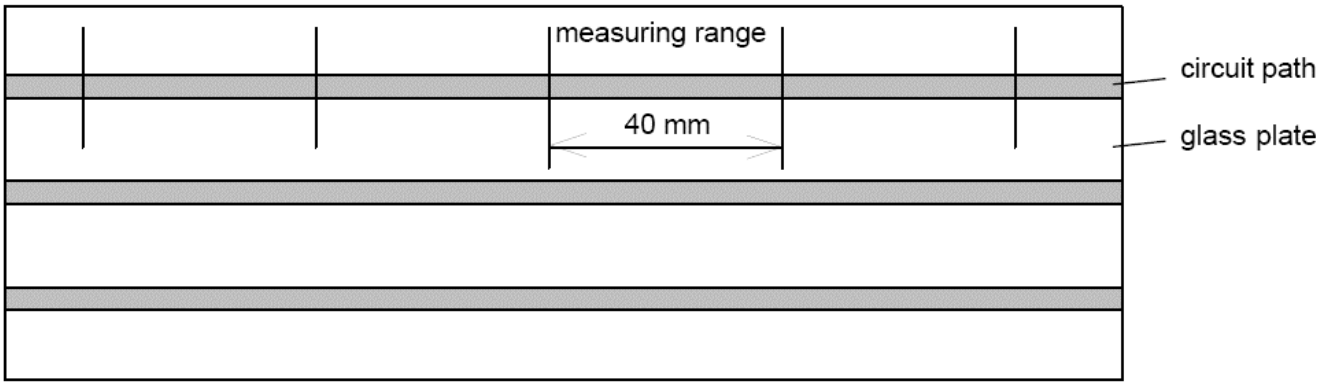
- Magnitude and uniformity of electrical resistance across interconnect

3.2.1 Contribution by Bosch

Although Bosch did not address electrically conductive adhesives in NanoPack, we could provide electrical characterisation of adhesives if they are interesting with respect to thermal performance. We will decide on a case to case basis if electrically conductive adhesives (ECA) will be characterised or not.
Bosch uses an in-house test specification for testing the specific electrical resistance of electrically conductive adhesives:

- We apply the given ECA as circuit paths (stripes) on a glass plate in a certain geometry (width about 2,5 mm, height varying between 50 µm and 250 µm). The exact geometry is measured after curing as it is needed to calculate the cross-sectional area (A) of each stripe (see figure below).

- After virtually dividing the circuit paths into fractions of 40 mm in length (L) we measure the resistance (R) of each path by means of four-wire method (applying voltage by two wires and measuring current by the other pair).
- The specific resistance of ECA is calculated by calculation using the equation $\rho = \frac{R \cdot A}{L}$



3.2.2 Contribution by VTT

Electrical properties of layered materials, SOI structures and related heater/thermometer elements will be characterized by IV-measurements and standard 4-point techniques. Lateral dimensions of the electrically active regions in the samples vary from sub-100 nm to few microns. Therefore, if accurate information on the actual material properties (sheet resistance, resistivity, carrier density) is required the measurements will be performed also on large area samples with Hall-bar or van der Pauw geometry (see *Figure 1*).

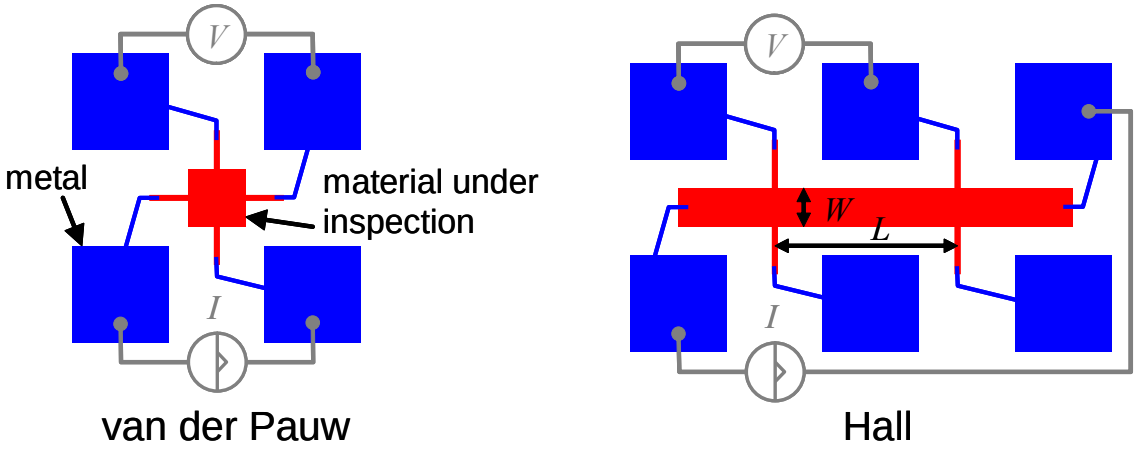


Figure 1 : Sheet resistance

Sheet resistance R_s measurement in van der Pauw and Hall geometry. In the former geometry $R_s = \pi/\ln(2) \times V/I$ and in the latter $R_s = L/W \times V/I$. Both structures also enable carrier density determination by application of perpendicular magnetic field.

3.2.3 Contribution by IBM

Electrical properties of particle filled interfaces and interfaces with surface enhancement will be made by 4-point measurements across the interface region. As depicted in Figure 2, a reference electrical current is passed through the interface with the first set of vertically aligned electrodes and a second set of electrodes is used to measure the voltage drop across the region the current flows. This allows an accurate measurement without interference from the resistance of the wiring leads. Regions of high particle concentrations within the interface such as along stacking lines between chip corners will be compared to measurements in more uniform regions such as between stacking lines. Using a standard digital multi-meter will allow sensitivity down to approximately 0.1 milliohm. Built in offset compensation functions within the multi-meter also allow the removal of thermoelectric effects. Dummy chain test samples with stacks of chips can also be used to multiply the effect of a single interface however these test samples do not provide localized measurements at different regions and thus are more suited for measuring the average resistance of the interface.

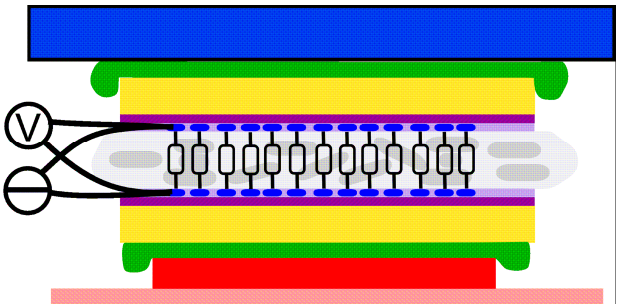


Figure 2 : Depiction of circuit and contacts used to measure electrical resistance of an interface. Current flows vertically between electrodes and voltage is measured at the two contacts.

3.3 TERMAL CHARACTERISATION OF TEST-SYSTEMS BY DIRECT DIFFUSIVITY MEASUREMENTS

Corresponds to task 5.3
Thermal conductivity and thermal interface resistance measurements by various static and transient techniques (feedback to → WP 2, 3, 7 for performance)

- Construction of advanced testing equipment featuring localised heat injection and measurement with highest accuracy
- Systematic variation of material and interface properties (defined by → WP 2, 3)

3.3.1 Contribution of BME

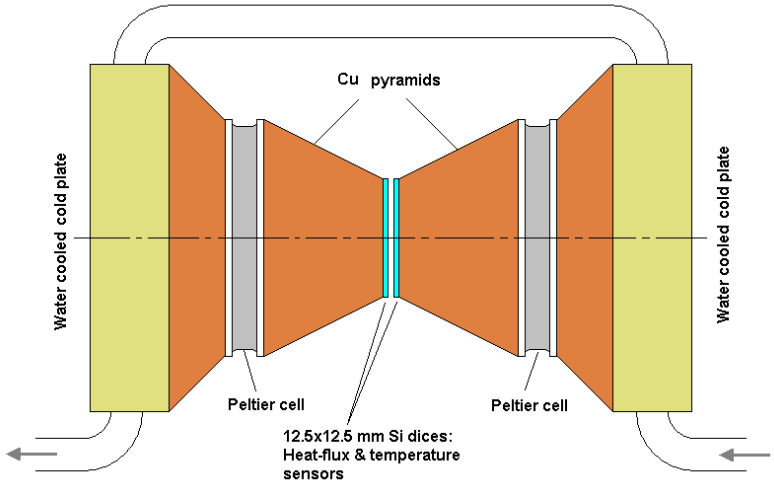


Figure 3 : Schematic of set-up

Advantage of symmetric structure: possibility to repeat the measurement in opposite heat-flow direction, eliminating a part of errors (*Figure 3*)
Why using Peltier cells: easy way to control and reverse heat flux
(24x24 mm unit 20-60 W)
Si sensor dices:
both the heat flux and the temperature are integrated/averaged for the whole area.
The temperature difference can be measured by a Wheatstone bridge.

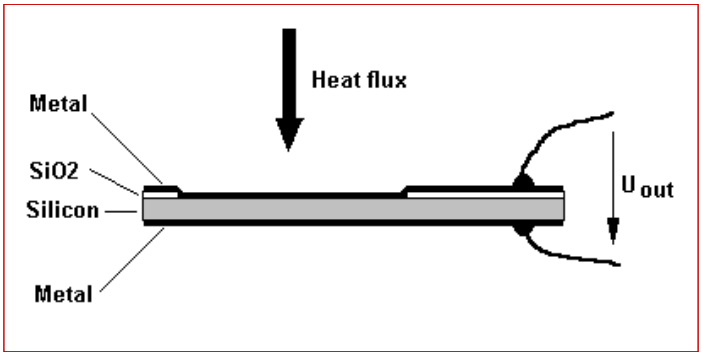


Figure 4 : Schematic of heat flux sensor

A gradient type sensor developed by our team for heat flux measurement with a sensitivity of S = 40…50 µV/W
For 1 cm2 area, 0.5 mm thickness sensor is Rth = 0.033 K/W.
The sensor is essentially a silicon resistor with two metal contacts, i.e. a resistor thermometer with a sensitivity of 0.87 %/K

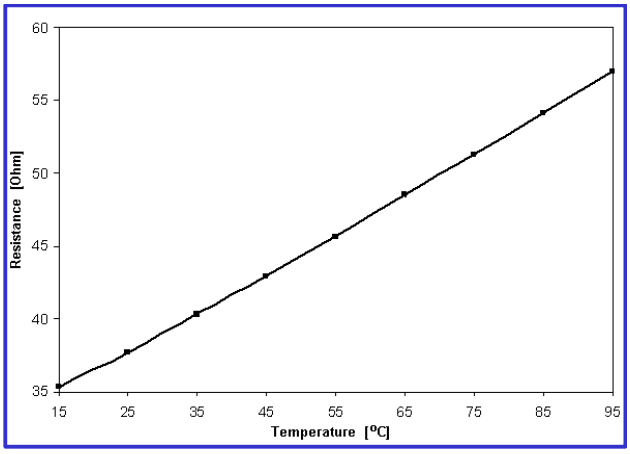


Figure 5 : Response of sensor

Feasibility calculations:

for a 1 cm2 sensor
S_{HFS} = 40 µV/W, range 0.1…25 W, noise rms ≈ 0.05 W
Rel = 2.5 Ω, I ≈ 40 mA (P = 4 mW) U=100 mV

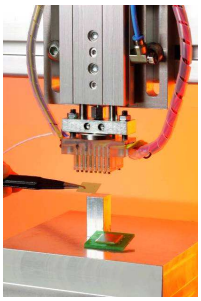
Expected temperature resolution:
ΔU = 5 µV → 0.005 % → ΔT = 0.006 K

Resolution of the Rth measurement 0.006 K/20 W = 0.0003 K/W
on 1 cm^2, 0.03 Kmm^2/W

Expectation for the most sensitive range: 2-5 Kmm^2/W, which is according to Nanopack specifications

3.3.2 Contribution of Nanotest and IZM

Test stand first generation will be enhanced:



A = 1.4 cm^2

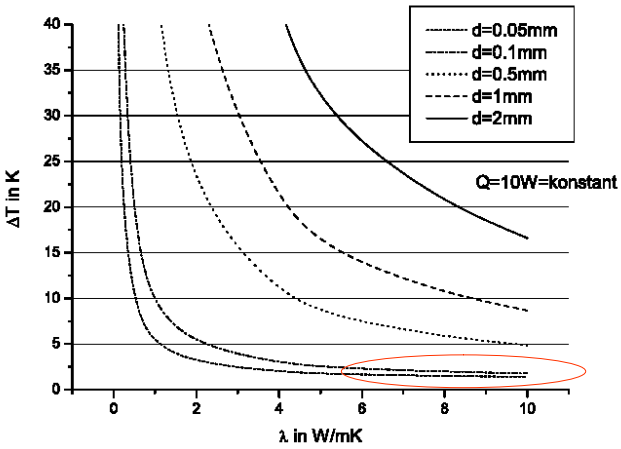


Figure 6 : Photo of Test stand: Red circle marks targeted region

Need to measure at least 2 different thicknesses. This yields the thermal conductivity as well as the thermal interface resistance at the intercept. The current design has been improved to measure the TIM thickness in-situ to sub-µm accuracy. This enables to measure pastes and pads. Adhesives need to be characterized a posteriori by cross sectioning, as a die tilt might occur. Thickness adjustment by spacers is insufficient at present.

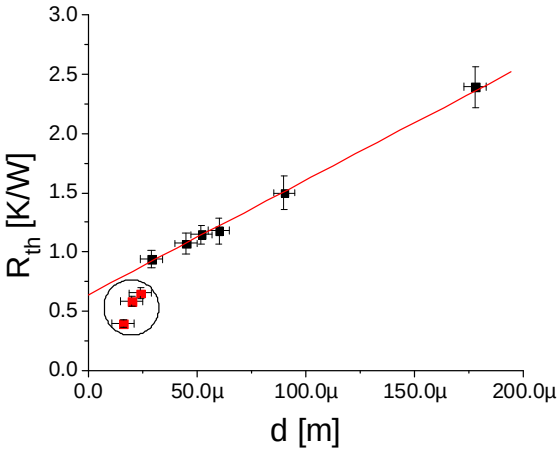


Figure 7 : Typical measurement result of good accuracy (here: Paste with 15 µm fillers).
The red circle shows the particle size effect which may be exploited for increased performance.

Failure analysis by cross sectioning gives important info about interface contact or process voids which, in combination with other failure analytical means (e.g. FIB) permits statements about interface resistance. Structure-property correlation could thus increase understanding about heat transfer

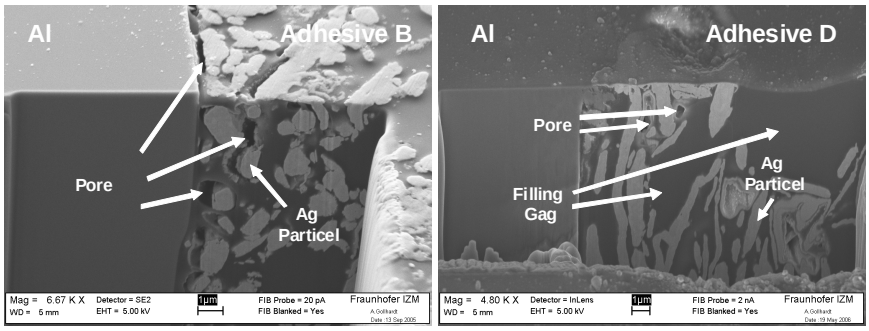


Figure 8 : Structural Analysis of Interface and conduction paths for 2 arbitrarily chosen adhesives by FIB analysis

Thin BLT and high TC entail a very accurate temperature measurement as can be seen below. In the range of the targeted values for TC the thermal resistance to be measured will be very low (Rth << 0.01 K/W).

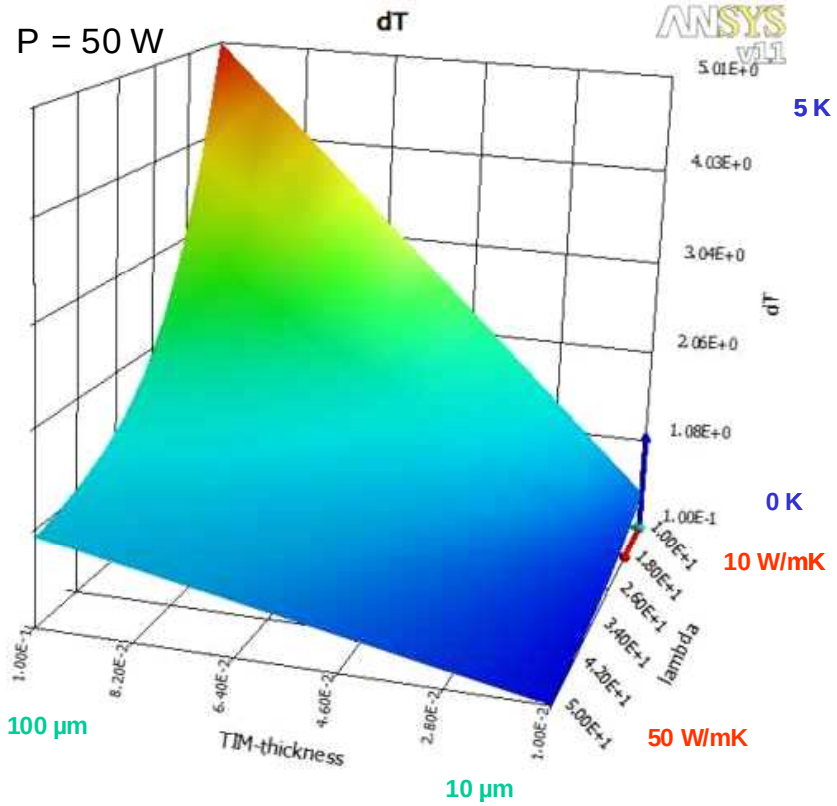


Figure 9 : Results
For P = 50 W and A = 1.4 cm2 the T-delta will be of the order of 0.1 K

This is very challenging and requires excellent novel characterisation methods to be developed. First, e.g. the input power could be increased, but there are obvious limits. Then there are basically two design variants, based on a steady state method which is in principle better suited for a direct determination of the conductivity. Transient methods measure the diffusivity, which does not differ so much for different materials as the thermal conductivity does.

Below a potential redesign which features some improvements is shown. Main advantage is the mechanical accuracy obtainable and the ease of manufacturing and processing.

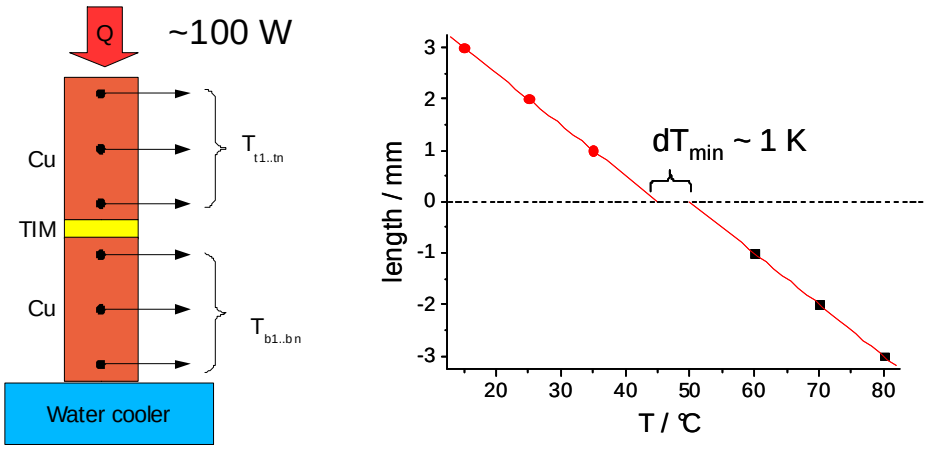


Figure 10 : Enhancement for high-throughput screening

Advantages:

- Standard components, cheap, discardable after use (important for adhesive)
- Working accuracy for adhesives as more than one thickness is measured
- In-situ measurement of thickness (δd < 0.5 µm) and pressure
- BLT can be adjusted easily also for adhesives, parallel plates assured
- Flow sensor by multiple T-measurement
- Calibration by simulation for parasitic effects
- Enhancement by T-sensor on front edge planned

Disadvantage:

- Measurement accuracy somewhat reduced, as T-flow measurement requires large T-drop through Cu-blocks.

It will be necessary to show the potential of this method, as it would be advantageous to be able to use it. An alternative method is outlined in report D1.3 and is similar to the test-system using parallel silicon dies with integrated T-sensor structures in thin-film technology. There possible limiting factors are the integrability of surface enhancement (which may still be overcome) and a lower mechanical precision. Both ways are envisaged to be pursued.

3.3.3 Contribution of Bosch

Bosch uses a standard transient measurement set-up for thermal conductivity (Netzsch LFA 447). Measurement error for bulk conductivity measurements has been proven to be +/- 4 %. Special analysis routines exist for measurement of two-layer specimens including thermal contact resistance (see figure below).

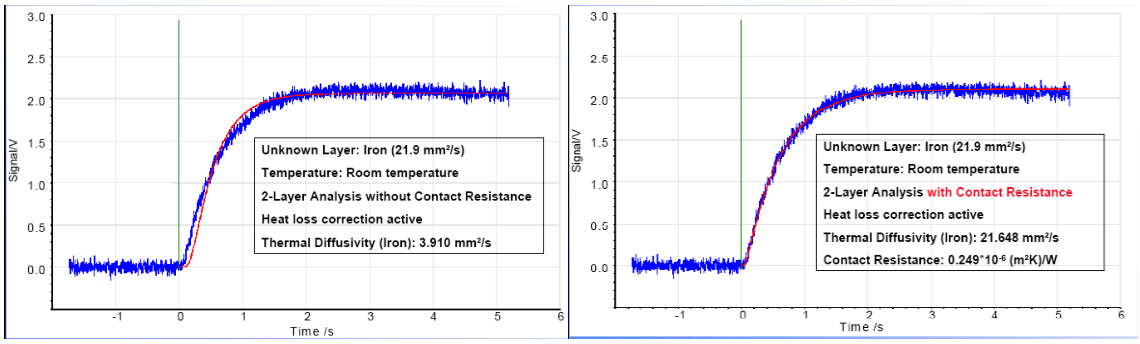


Figure 11 : Transient testing method of Bosch

We will test the applicability of this measurement system for analysis of sandwich structures made of real heat sink materials and state of art TIM. The following issues will be explored:

- Minimum contact resistance that can be measured for a given combination of substrate (e.g. Copper, alpha = 100 mm²/s) and TIM (alpha up to 50 mm²/s)
- Minimum thickness of graded interfaces that can be resolved using the analysis software

3.3.4 Contribution of IBM

Testing Methods for IBM microprocessor TIM1 and TIM2 applications

IBM Zurich Research Laboratory will utilize several different test methods to evaluate interface material properties and application performance. Product like test vehicles will be used for demonstrator type performance measurements and research test devices will be used to explore bulk material and particle stack properties. The application test vehicle resembles a typical flip chip packaged Silicon die with heater and sensor array on the opposite side as the TIM and liquid/cooler surface as shown in *Figure 12*.

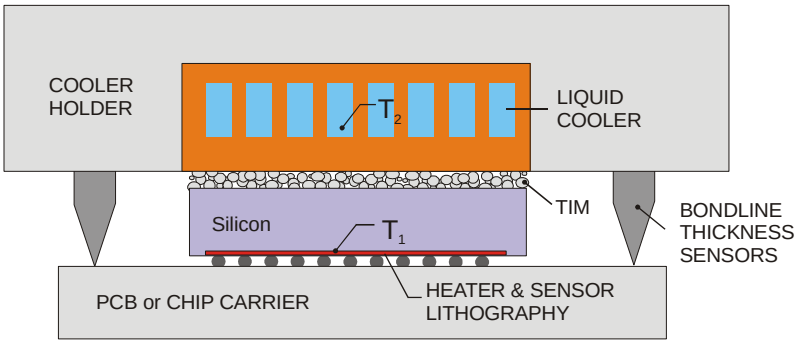


Figure 12 : Flip chip microprocessor TIM1 test vehicle.

Due to the thick silicon chip and variability in cooler performance, this test vehicle is only capable of providing average bondline performance data without localized information on non-uniformities in the bondline due to voids or particle stacking. Heating at the lower surface of the silicon is accomplished using a meandering thin film heater (~30nm gold) with interspersed resistive thermal devices (RTD) also based on meandering serpentine structures with 4-point connections (~30nm thick, 10um wide metal line). This allows a single metallization step to define heater and sensor devices. The typical resistance of a thin film RTD sensor is approximately 150 Ohm with a **sensitivity of 0.5ºC/Ohm**. Total thermal resistance or junction-to-air resistance is determined based on the temperature difference between the chip sensors and a set cooler temperature divided by the total power dissipated.

In order to estimate the interface resistance, the thermal resistance of the silicon and water cooler must be known or determined from additional calibration experiments and subtracted from the total resistance (often inducing the largest uncertainty). Inductive based displacement sensors, calibrated to zero before the interface material is applied, track the thickness of the interface as estimated from 4 points along the periphery of the system. Overall accuracy of interface resistance estimation is typically on the order of **+-1℃.mm ^{2}/W**. This test stand can also be used as an application demonstrator when a chip lid is inserted between the chip and cooler surface. With the lid inserted, the effect of a larger TIM2 area can also be investigated.

In order to increase the accuracy and area resolution of a thermal test an alternative test system will be developed with the capability to measure both thermal and electrical properties directly at both sides of the interface. This system uses two rectangular sensor chips with RTD sensors directly on both sides of the interface as shown in *Figure 13*. Heat is introduced below the chip stack by a thin film heater and a cooler is applied to the top of the chip stack. The temperature drop across the interface at specific locations is then measured by the RTD sensors, which have a similar design and performance as the test vehicle shown in *Figure 12*. In order to measure electrical resistance across the interface, the RTD is replace by a simple electrode with two contacts and a small current is applied between the upper and lower electrode allowing a 4-point measurement of voltage and current drop across the thin gap. An array of numerous sensors across the interface allows for investigation at locations that are known to have particle stacking non-uniformities such as the center point and along the lines between opposite corners of the square interface area.

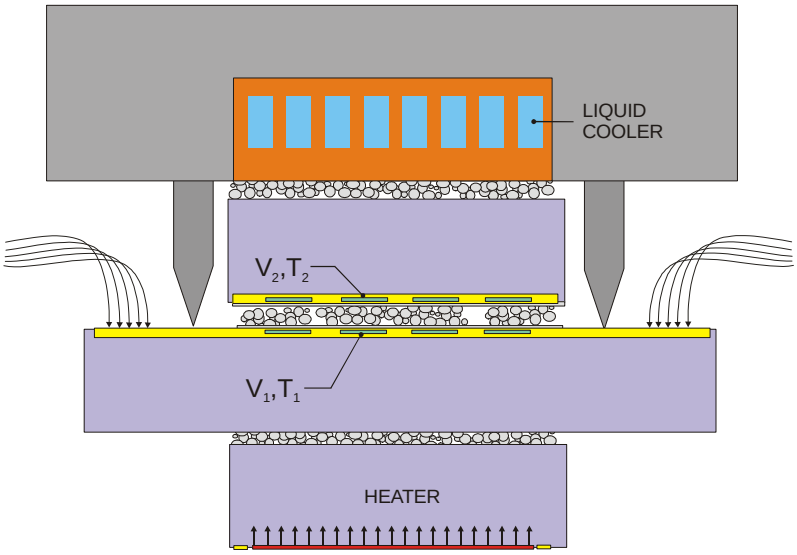


Figure 13 : Research test stand for investigation of interface material thermal and electrical properties.

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The material thermal performance is evaluated by reading the temperatures of the T1 sensors of the flip chip microchip TIM1 test vehicle for a given one-dimensional heat flux for a first gap width and a second gap width. The slope is used to determine the bulk parameters of the material while the extrapolated axis intersection is used to determine the boundary resistances after the resistance of the silicon chip has been subtracted. Readings are possible both in a static as well as transient fashion.

For the research test stand (*Figure 13*) two readings for the sensors above and below the interface are taken for two different interface thicknesses and also used to determine bulk and boundary resistances with a static heat flux. The configuration shown in *Figure 13* can also be used to determine the electrical resistance as function of gap thickness when a small current is applied between electrodes on opposite sides of the interface (see also Figure 2 in paragraph 3.2.3).

3.3.5 Contribution of TRT

Scanning Thermal Microscopy (SThM)
The scanning Thermal Microscope is an Atomic Force Microscope using a special probe with a platinum resistance deposited at the extremity of the tip. After calibration of the Pt resistance, the temperature measurement can be obtained with a spatial resolution of of the order of 100 nm. Measurements using a high resolution thermal Scanning Thermal Microscope have been achieved on devices and especially on high power transistors. The temperature has been measured at the transistor surface, close to the active layer and the spatial resolution allows a temperature mapping of the hot area between gate and drain. The following figure shows the temperature measured close to the active layer as a function of the power injected in the transistor.

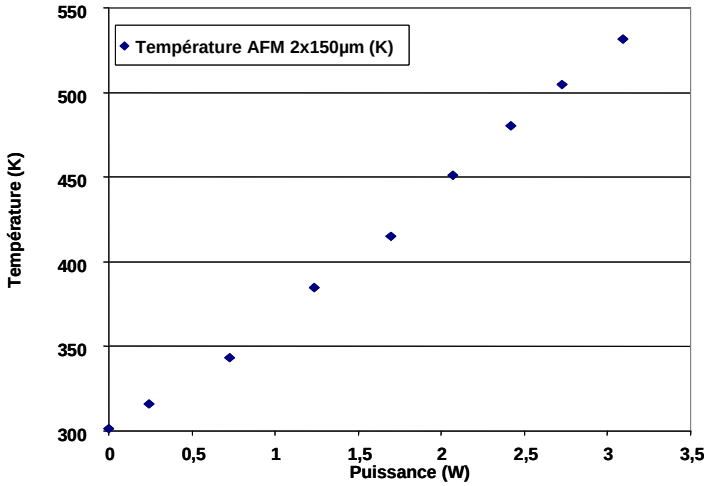

Figure 14 : Measurements of the thermal conductivity of Nanotubes and nanowires.

These special tips can be used to measure the thermal conductivity of nanotubes and nanowires. For such a purpose it is necessary to generate heat at the foot of the nanotube. To do it, one plans to use a Focused Ion Beam to get a local deposition of a platinum resistive wire used as a local heater. The temperature at the top of the nanowire can be measured using the SThM. Thermal conductivity can be deduced from these temperature measurements.

3.4 THERMAL CHARACTERISATION BY PHONON SCATTERING MEASUREMENTS

Corresponds to task 5.4
Measurement of heat-transfer on submicron scale (feedback to → WP 2, 3, 6)

- Measurement of thermal conductivity by optical and acoustic techniques
- Analysis of structure and measurement of thermal conductivity of nano-composites and nano-structures (from → WP 2, 3) by advanced microscopy techniques.
- Establishment of structure-property correlation together with simulation

3.4.1 Contribution by IEMN

IEMN provides ultrafast measurement methods which permit to measure thermal and acoustical properties of thin films (thickness comprise between a few 10 A and a few microns) with neither contact nor destruction.

Principle

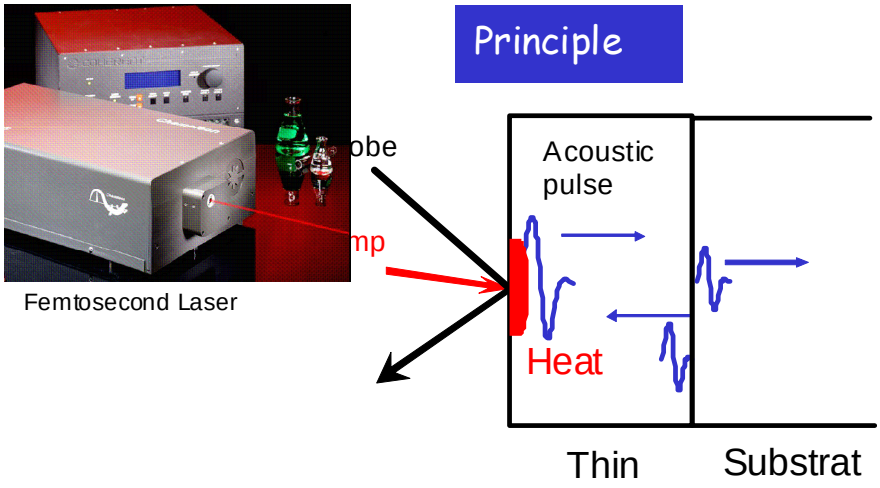

Figure 15 : Ultrafast measurement methods

The time-resolved measurements are performed by sending an ultrashort optical pulse issued from a femtosecond laser on an absorbing part of the sample. The light is absorbed and heat is deposited on the sample. The resulting thermal expansion produces a short acoustic pulse.

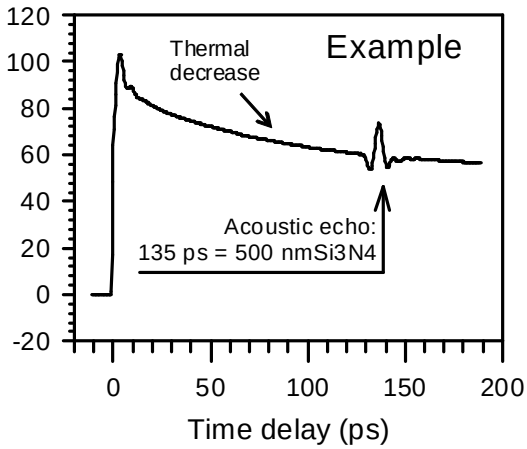

Figure 16 : Resulting thermal expansion

Then two phenomena happen: heat diffuses in the sample and the acoustic pulse propagates in the sample at the sound velocity. Both phenomena can be monitored using a second optical pulse time-delayed in respect with the first one using an optical delay line. As shown on the graph, the sample reflectivity provides informations about acoustical and thermal properties. The reflectivity first shows a step at t=0 a delay which corresponds to the absorption of the pump pulse. The sample is heated and as it is hotter than normally it reflects differently the probe light. The slow decrease which follows results from the thermal diffusion. From this decrease it is possible to deduce the thermal properties of the thin layer.

Measured quantity
The same graph also shows an acoustic echo detected at the sample surface after one round trip in the 500 nm thick SiN layer. From the time-delay we can measure the longitudinal sound velocity and from that the **elastic modulus** of the thin layer. A comparison between successive echoes let us characterize any interface from the acoustic point of view. Thin layer means here a layer whose **thickness is comprise between a few 10 A and a few microns.** Both techniques are **compatible with complex stacks**. In thermal measurements a complex stack would require a complete numerical modeling of the thermal resistance. In acoustic measurements, as echoes arrived at different delays, it is possible to access to the successive layers independently.

3.4.2 Contribution by ICN

The 3ω method

The 3ω technique is an alternative method for measuring the thermal conductivity of single layers, interfaces and bulk materials. The obtained data and its interpretation will be used as an input and for comparison with models of WP6.
The technique is based on the 4-wire- or Kelvin-method for resistance measurements. Both the heat flux and the temperature drop are determined from one element, functioning both as heater and as thermometer. The heater/thermometer element is a metal line with four contact pads, two for 1ω current input and the other two for 3ω signal measurement (/output). The line width, length and the size of the pads are designed according to the sample structure and patterned with lithography (see D1.2 for details).
During the measurement, an AC current modulated at 1ω is applied to the heater and generates a thermal wave with 2ω frequency by Joule heating. With this 2ω heat flux, an AC temperature component is induced. Under the condition that the thermal resistance between the metal line and the sample surface is ignorable, the metal line can be assumed at the same temperature with the sample

surface beneath it. Therefore, there is also an AC temperature component in the metal line. Taking advantage of the temperature dependent property of the electrical resistance in the metal, the metal line can act as a thermometer to measure the AC temperature rise at the sample surface. The variation of metal resistance with the 2ω AC temperature contributes to form a third harmonic (3ω) voltage signal according to the equation $V_{3\omega}=I_{1\omega}*R_{2\omega}$. The 3ω voltage signal, although orders of magnitude smaller than the first harmonic (1ω) input voltage, is prominent against the background noise at the same harmonic and can be picked up by the phase lock-in technique.

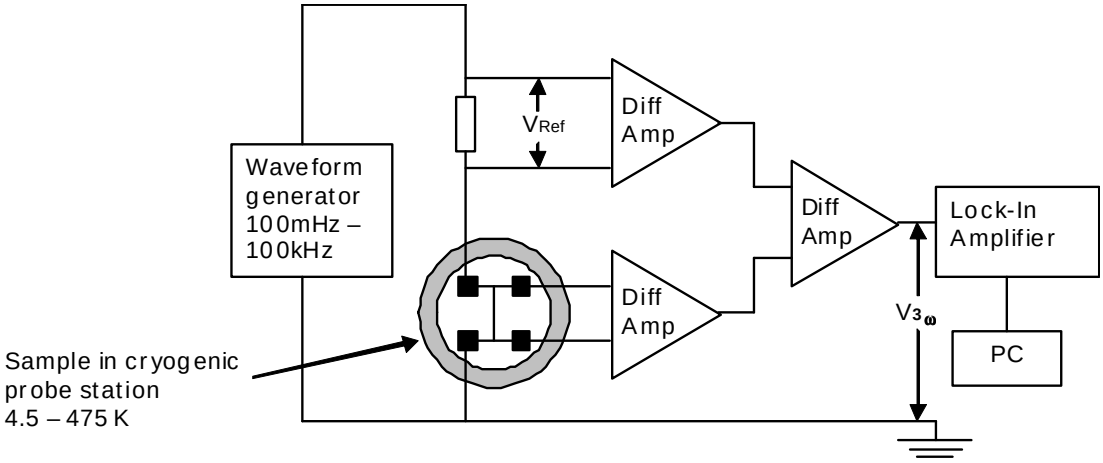

Figure 17 : Schematic of the proposed 3ω set-up for temperature range 5 to 450K

Low frequency micro-Raman scattering

In NANOPACK micro-Raman scattering will be used for local measurements of phonon scattering for out of plane conductivity as a function of wave vector to understand their properties and role in thermal transport in nano-electronic relevant materials and structures. Emphasis will be placed on acoustic phonons, which basically determine two aspects in the performance of electronic devices: the thermal conduction and the charge carrier mobility. Moreover, in thin slabs phonons are expected to be confined due to the acoustic mismatch. In turn, confined phonons are expected to have a smaller group velocity than bulk phonons impairing heat dissipation. These confined acoustic phonons may be partly responsible for the poor agreement between theory and experiment in nano-thermal transport.

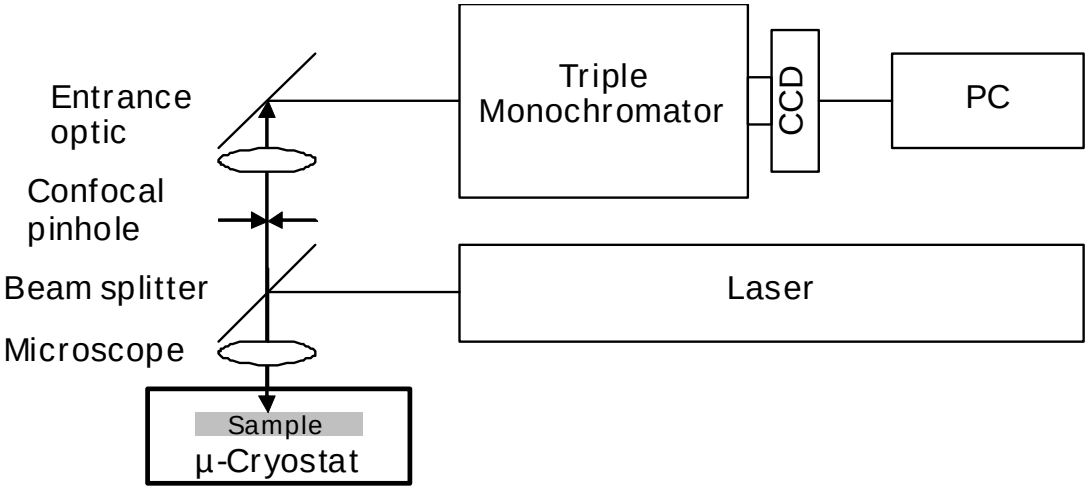

Figure 18 : Schematic of the µ-Raman set-up for temperature range 5 to 300K

Criteria	State of the Art	NANOPACK goals
3-omega method in nm-scale	Measurements of a few W/mK in III- V semiconductor alloy epitaxial fims of 700 nm thickness.	Keep the sensitivity of few W/mK applied to crystalline samples with sub 100 nm thickness.
Use confined acoustic phonon data for thermal simulations in the nanoscale	None available. Confined phonons have recently been observed in 30 nm thin films of SOI.	Provide measurements to underpin simulation tools and enhance their predictive nature for thermal properties in the nm-scale

Table 2 : Nanopack goals

3.4.3 Contribution by IZM

Feasibility studies of Nano-Raman technique in cooperation with partners. As this technique will be available at IZM from mid 2007 only, chances and limits will be commented on later.

3.4.4 Contribution of TRT

Temperature measurements with Raman Spectroscopy
Micro-Raman can be used to measure the local temperature on a sample with high spatial resolution (<1 µm). At finite temperatures (T>0), inelastically scattered light can be observed on both sides of the Rayleigh peak (elastic scattering), referring to Stokes (energy loss) and anti-Stokes (energy gain) processes. The temperature is related to the intensity ratio between Stokes and anti-Stokes peaks following the simple formula:

$$\frac{I_S}{I_{AS}} = C \exp\left(\frac{\hbar\omega}{kT}\right)$$

where C is a calibration factor (C~1) and ω the phonon frequency ($\omega=2\pi cq$, q is the wavenumber or Raman shift in cm^{-1} and c is the celerity of light).
It is worth mentioning that Raman signals from a thin layer are generally weak. In particular, I_{AS} is weaker than I_S and is usually not detectable at high Raman shift. The temperature measurements can be performed with Raman peaks located below 600 cm^{-1} and the accuracy on T will depend on the intensity of the anti-Stokes signal. It is then desirable to select a material presenting a strong Raman signal.

NanoRaman microscopy: In the proximity of nanometer-spaced metallic structures the electric field induced by light can be greatly enhanced. This leads to the development of specific techniques such as SERS (Surface Enhanced Raman Scattering) or TERS (Tip enhanced Raman Scattering) which allow a local determination of structural properties as well as temperature measurement.

3.5 MECHANICAL CHARACTERISATION

Corresponds to task 5.5
Mechanical characterization of materials and interfaces as function of moisture and temperature (rheological, thermo-mechanical, diffusion, failure properties) (→ for WP 6)
- Development of bi-material adhesion test-methods and test-apparatus
- Extraction of critical data (energy release rate, phase angle) for reliability modelling

Reliability testing and failure analysis of test-specimens and test-systems

3.5.1 Contribution by Bosch

Bosch will perform the following tests depending on actual material consistency:
For adhesives:
- Viscosity of uncured adhesive (plate-plate geometry in either rotating or oscillating mode)
- Adhesion testing by lap shear testing with evaluation of shear strain at break
- Tensile testing (tensile stress and tensile strain at break)
- Hardness (scale depending on material)
- Coefficient of thermal expansion
- Optionally dynamic mechanical analysis (temperature dependent modulus)

For greases:
- Viscosity (plate-plate geometry in either rotating or oscillating mode)

For gap fillers:
- Viscosity of uncured material, if provided as liquid (plate-plate geometry in either rotating or oscillating mode)
- Tensile testing (tensile stress and tensile strain at break)
- Hardness (scale depending on material) or penetration
- Compression set
- Coefficient of thermal expansion
- Optionally dynamic mechanical analysis (temperature dependent modulus)

All properties will be measured in initial state (as received) as well as after certain ageing tests (e.g. high temperature storage as specified in D1.1). Most test procedures will follow ISO or EN standards. But, not all properties will be measured with each provided material. We will decide on a case by case basis which material properties will be measured.

3.5.2 Contribution by TRT

Testing methods of HP MEMS switches

As widely publicized in the literature, one of the main identified failure modes for HP MEM switches is thermal management. Higher power leads obviously to higher power dissipation requirements. Temperature increase is critical in the bridge since this part of the switch is relatively isolated

thermalwise. This can lead to destruction of the bridge, or at least, significant evolution of the mechanical material properties of the bridge, leading to dysfunction (evolution of the beam stiffness for example).
Other failure modes are contact degradation (not applicable to capacitive switches), mechanical shocks experienced during repeated switching cycles (not particular to high power MEMS), electro-migration at the materials interfaces (this phenomenon is accelerated with higher power), stiction between the dielectric layer and the metal (generally due to charging effects in the dielectric layer and leads to failure of the switch locked in the downward position), organic deposits and contamination, oxidizing, humidity (accelerate the failure mechanisms described above).

Two types of measurements will be performed on the RF-MEMS switches:

1. Microwave characterisation

S parameters of the switches under RF probes will be measured with a vector network analyzer, in ON and OFF states, before and after packaging, in the 0-20 GHz frequency range. These parameters allow to estimate:

- the insertion losses (expected: < 0.3 dB)
- the isolation (expected: > 25 dB)
- the actuation voltage (expected: < 20 V) and the switching time (expected: < 1 µs) will also be measured.

2. Power handling assessment and reliability testing

Thanks to the test bench depicted below, an analysis of the RF performances will be carried according to two main parameters:

- the RF power to commute (expected: > 25 W)
- the number of commutation cycles (expected: > 10^{12} cycles)

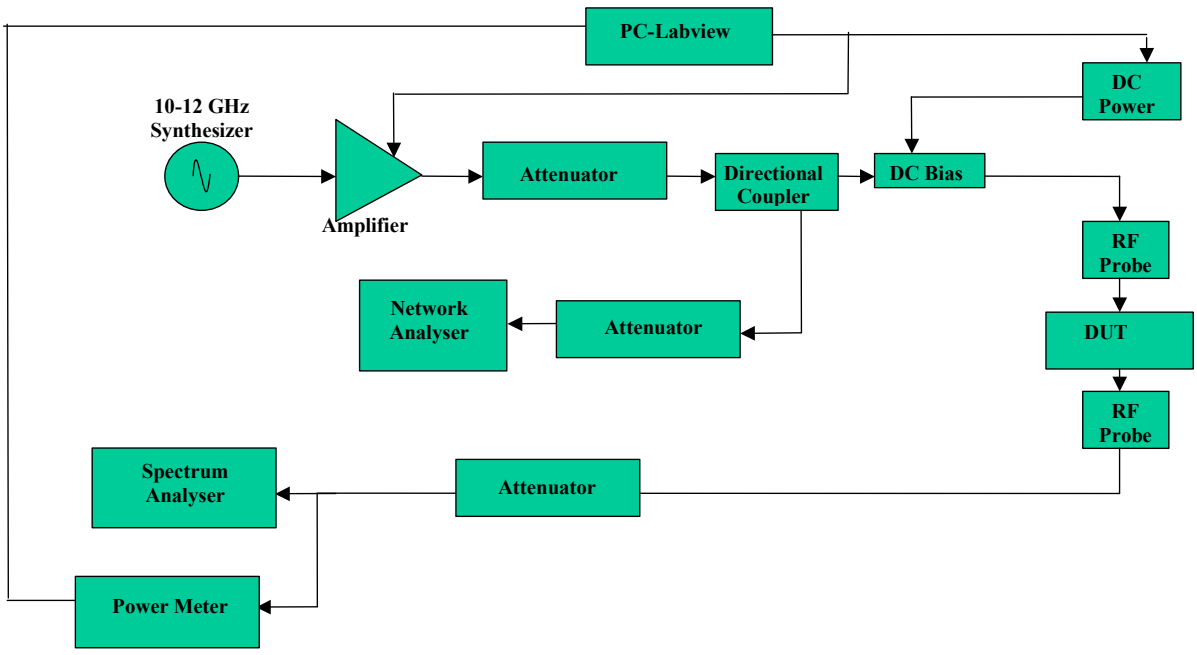

Figure 19 : Characterization bench for microwave measurements and reliability testing of HP MEMS switch

The power handling of the MEM shunt capacitive switches will be measured at 10 GHz, an intermediate frequency with respect to the targeted range (0 – 20 GHz). The microwave signal is generated by a synthesizer and amplified. It passes through a directional coupler. The coupled port is connected to a spectrum analyzer for monitoring the input power. A DC bias tee is used to superimpose to the signal a DC signal for switch actuation. The apparatus is connected to the switches through microprobes. Output signal passes through an isolator to remove the DC bias, and protect the network analyser. The signal is attenuated to enter the network analyser.

Defining a reliability test for the switch is not easy because a large number of parameters can be varied. Most obvious ones are the power level (it is to be noted that in the literature, most switches are cycled under 'cold switching' i.e. only 1 mW input power), the frequency, or more generally the characteristics of the input RF signal (CW, pulsed, arbitrary load cycle), and characteristics of the control voltage. A similar test bench as for power handling assessment will be used but a PC with a control software is added to generate a periodic signal switching ON and OFF the component every 1 to 10 ms.

Apart from that, TRT will also take part in materials characterization (e.g. nanoindentation) and with advanced analytical methods for structure evaluation.

3.5.3 Contribution by Nanotest

Mechanical characterization of materials and interfaces as function of moisture and temperature (thermo-mechanical, failure properties) (for WP 6)

Mechanical characterization of materials with nanofillers by tensile tests, nanoindentation methods are carried out. The results will feed into WP6. Data are required for simulation approaches. The focus is laid on the correct description of viscoplastic and viscoelastic properties. In addition nanoanalytical methods for will be applied to derive mechanical parameters i.e. AFAM (atomic force acoustic microscopy)

The interface issue will be addressed by development of bi-material adhesion test-methods and test-apparatus. A test specimen for interface fracture mechanics will be designed. Adaptation to microtesting equipment will be designed, tested and applied to the relevant material pairings.

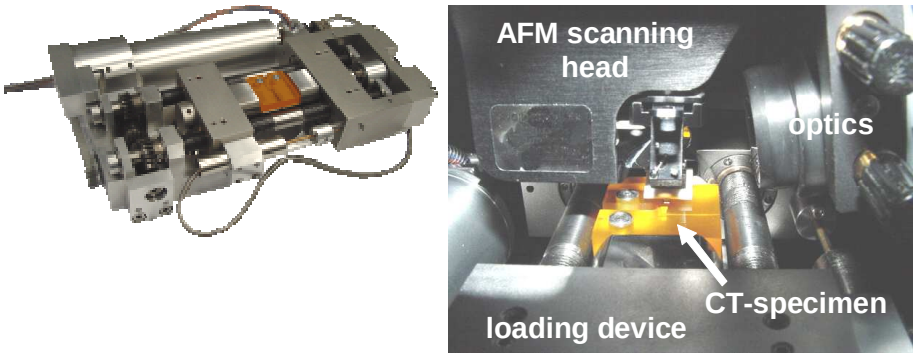

Figure 20 : Microtensile test stand under atomic force microscope

As the final result the extraction of critical data (energy release rate, phase angle) for reliability modeling will be derived from testing. The methods should be applied for reliability testing and failure analysis of test-specimens and test-systems.

Therefore high resolution strain field measurements at interfaces have to be measured. Microtensile testing devices will be adapted to the relevant test-systems so that high resolution images for failure modeling can be derived.

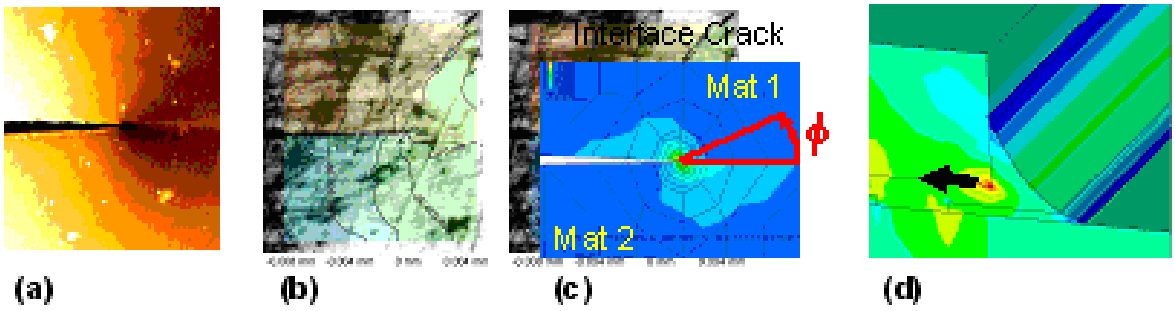

Figure 21 : High resolution strain field measurements and finite element solutions to be matched

In addition Focused-Ion Beam based residual stress measurement will be developed to meet the requirements from microelectronics and microsystem technologies. Up to now the method is not fully applicable to the required accuracy of a view nanometers.

3.5.4 Contribution by IZM

First, materials need to be characterised in their thermo-mechanical properties which could determine their behaviour during reliability testing. This means e.g. adhesive characterisation as a function of temperature and moisture.
Relevant quantities are:

- coefficient of thermal expansion
- storage modulus
- glass transition temperature
- fracture toughness

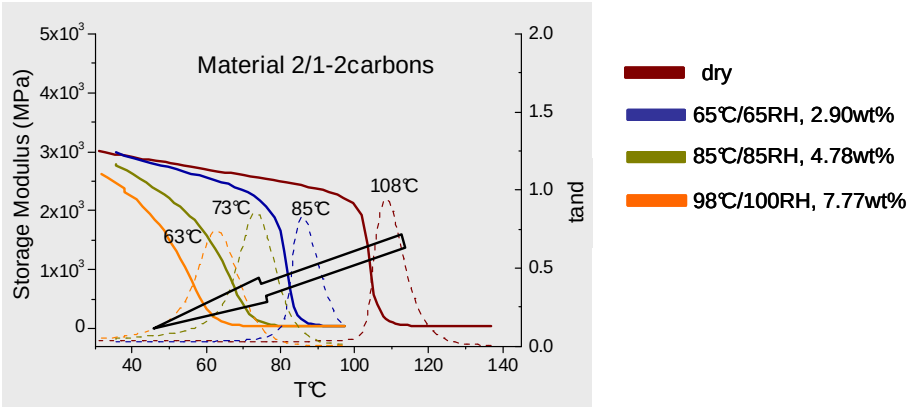

Figure 22 : Severe decrease of Tg as a function of moisture conditioning for an epoxy-based adhesive

Fracture mechanical properties are of special interest for determination on specimen level. Special specimen geometries need to be designed to evaluate interface failure. Here, new geometries and test-stands need to be devised.

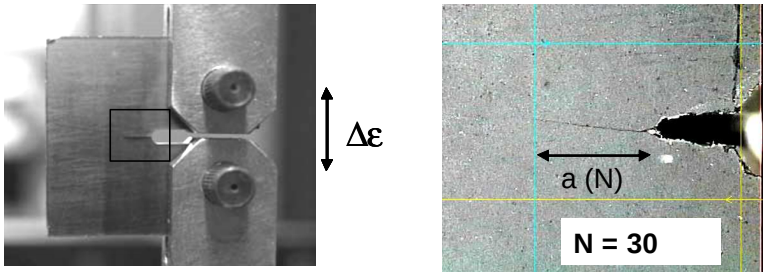

Figure 23 : Time honoured test specimen for crack propagation and extraction of fracture mechanical quantities

Desired plots for lifetime prediction are as given below. A simulatively accessible failure criterion, as e.g. the energy release rate can be put in correlation to the crack propagation rate via a Paris-Erdogan law. Simulation and experiment will have to go together at specimen level in order for the lifetime model to be applied to a demonstrator. These experiments are aimed to be carried out also under moisture and temperature variation.

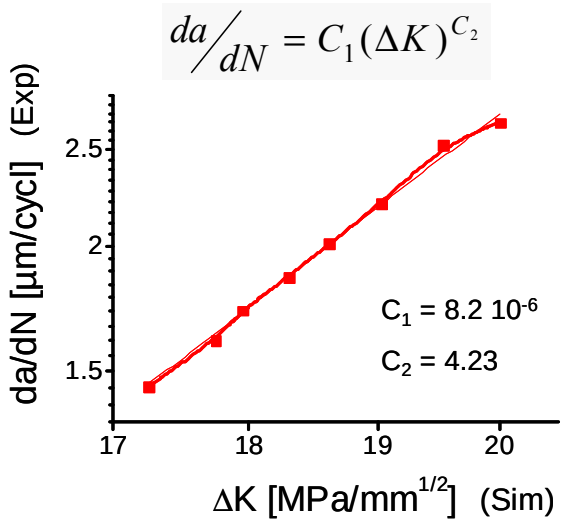

Figure 24 : Paris-Erdogan relationship for lifetime model for a particle filled epoxy resin

The crack propagation rate as function of the crack tip parameter allows then also to predict the reliability of the TIM layer in the test-specimens. Still, the conduction of this experiments requires the elaborate crack-tracing methods developed also in this workpackage, as the exact position of the crack tip needs to be measured on the micro- and nanoscale to calculate back to the crack tip fields determining the crack growth behaviour.

4 CONCLUSION

This report has provided a selection of methodology and characterization techniques for **WP5 (Metrology and characterization)** T0+9 -> T0+30.

The objectives of WP5 are :

- Design, development, calibration, benchmarking and standardisation of methods and test specimens for rapid and systematic determination of thermal and mechanical bulk and interface properties by various advanced experimental techniques
- Critical material data for the material pairings to describe interface reliability

WP5 will allow to characterise the thermal interface materials developed in WP 2 and WP 3 along with their process dependence in their thermal, electrical and thermo-mechanical properties.