Nano Packaging Technology for Interconnect and Heat Dissipation

NANOPACK

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WORK PACKAGE 9 : Project Management

Publishable Summary

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PUBLISHABLE EXECUTIVE SUMMARY

NANOPACK is a European large-scale integrating project aiming at the development of new technologies and materials for low thermal resistance interfaces and electrical interconnects, by exploring the capabilities offered by nanotechnologies (such as carbon nanotubes, nanoparticles and nano-structured surfaces) and by using different mechanisms to enhance interparticle contact formation, compatible with high volume manufacturing technologies. Several key research areas relative to thermal management interconnects and packaging are addressed by European industrial and academic partners: thermal interface materials, assembly, reliability, and characterisation; supported by world class modeling and simulations. The benefits of the technologies will be evaluated in different applications to demonstrate improved performance of microprocessors, automotive and aerospace high-power electronics and radio-frequency switches.
While the phases of developments of highly thermally conductive materials and processes are now being tailored to fit the demonstrator designs, this fourth issue of the NANOPACK newsletter intends to present the major events of the project's and consortium's lives as well as the major advances in the fields of material & process developments, characterization and modelling activities.

➢ Progress in Material Developments

Overview of the materials (grease, adhesive, phase change materials) developed in the project (Chalmers and EVAC)
The objective of the material development phase is to produce free standing materials of different types with on one hand high intrinsic thermal conductivities but also on the other hand a good reliability and workability to reach low BLTs and therefore low total thermal resistances.

- CNT-based bi- and single-modal materials greases exhibiting thermal conductivities lower than 4 W/mK but allowing a good workability with 10 µm of BLT;
- Other greases have been designed for high BLTs (>75µm) on the basis of bi- and tri-modal combinations (CNT, micro Ag/graphite, silicone, epoxy). These greases have reach 12.3 W/mK of thermal conductivities;
- Electrically Conductive Adhesives (ECA) have been developed on the basis of bimodal fillers in bi-epoxy matrix with flexibilizer. They have a thermal conductivity of 10W/mK, a glass transition Tg>180℃, a low viscosity 60 Pa.s for workability a nd an electrical resistivity of $610^{-5}\Omega$.cm.
- CNT buckypaper films have been developed but, in spite of interesting mechanical properties, they exhibit low thermal conductivity <1,9 W/mK
- A bimodal Phase Change Material (PCM) using CNT and graphite as fillers has been developed and exhibits a thermal conductivity of 3,5 W/mK.
- a Smart-PCM (metal-polymer based PCM InSnBi/PI) has been developed and thermal conductivity as high as 18W/mK and resistance as low as 2-5 Kmm2/W have been achieved.

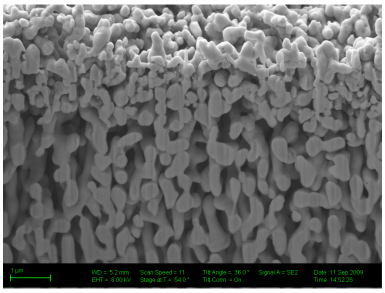
All these materials are now under intensive testing to estimate their reliability, temperature resistance and other environmental tests.

➢ Progress in Process Optimization

Hierarchically Nested Channel (IBM)
Integrating microchannels at the thermal interfaces of heat sinks, spreaders, and microprocessor chips can reduce bond line thickness, assembly pressure, and overall thermal resistance. The channels help control the flow of particle filled thermal interface materials (TIM) during the assembly squeeze. We demonstrated experimentally that HNC can improve thermal interfaces by enabling thinner bond lines with higher-performance (filled more highly) pastes at lower assembly pressure.

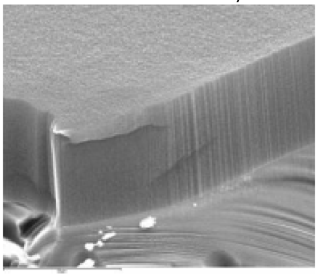
The effects are most dramatic in large-area applications, where a 90% or greater reduction in squeeze time can reduce assembly time and burn-in while enabling shorter cure times for adhesive TIM applications.
However, the relationship between channel geometry, material properties, and interfacial area is not fully understood. In the absence of meaningful analytical models, we develop a computational fluid dynamics approach to the non-Newtonian squeeze flow applied to rectangular 3D geometries. Experiments confirm the applicability of the models and illustrate the effect of viscoplasticity in highly loaded TIMs. Based on a first-principles thermal-fluidic model, the optimal width for a corner-to-corner channel is 608 µm for an 18x18 mm2 chip with 35 µm thick TIM bondline, or channel-to-chip size ratio of 0.068. This results will allow us to define the most suitable candidate for our demonstrator which will be built up in WP7.

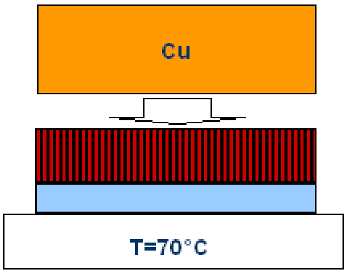
WLP nano-enhanced surface structuring by gold nano-sponge (IZM)
Nano-porous structures deposited by electroplating combine the advantage of a wafer level process with the benefit of a large contact area. The idea is to optimize bonding processes with respect to reduced bonding parameters and enhanced reliability.



The nanosponge technology was first investigated on Cu substrates. Now the structuring of the nanosponge was shown. On a basis of 5 µm Au a layer of 5 µm Au/Ag was deposited. The Ag was then etched and the Au-Nanosponge remained. The structuring of the Au-Nanosponge is needed to finally define certain TIM layer geometries on wafer scale. The development is now focussed on the mixing ratio of Au and Ag to form stable Au structures after etching. A silver content of 90 to 50 % was investigated. It was found that an Ag content of minimum 65 % is necessary to form a nano-porous Au structure after etching. With a silver content above 80% cracking takes place and above 90% also the gold is lost during etching.
In further work we will optimize the Au/Ag plating as well as the Ag dealloying. We will also investigate the bonding of nano-porous surfaces by adhesive attachment.

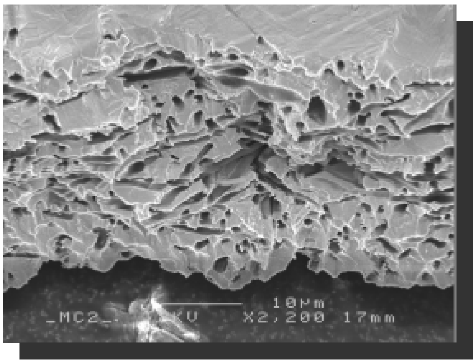
Vertically Aligned CNT (VACNT) based thermal interfaces (TRT)
In order to reduce the thermal resistance of CNT based materials, the use of VACNT is an attractive way to greatly improve thermal conductivity by lowering the number of junctions inside a thin film. VACNT obtained with plasma enhanced chemical vapor deposition (PECVD) and thermal chemical vapor deposition (TCVD) growth processes on silicon are currently under investigation for their thermal properties. A simple method





was developed in order to obtain composite like VACNT mats. The CNT assembly is brought in contact with fused paraffin (fusion temperature ~55℃), which spontaneously wets the CNTs. The low fusion temperature of the organic "matrix" allows the fabrication of interfaces using low temperature and pressure conditions process.
The reflow process implies re-heating of the film in contact with a copper substrate under small pressure (1.5 bar) and 75℃ temperature, a process compliant with low pressure applications. Thermal resistance measurements show values ranging from 2.2.10-6 to 6.15.10-6 m^2K/W corresponding to effective thermal conductivities from 1.6 to 9.3 W/mK depending on the initial length of the nanotubes and growth process.

Smart-TIM: metal-polymer composite (Chalmers)



The polymer-metal composite consists of two distinct phases; a highly porous polymer structure composed of individual polymer fibers, infused with a low melting temperature ternary alloy. The porous polymeric phase defines the final structure of the composite, i.e. film thickness and phase composition. Via infiltration of a low melting temperature alloy (LMTA) into the polymeric phase, a continuous vertical all-metal high thermally conductive network is formed from surface to surface in the composite film, suggesting high vertical thermal conductivity. Furthermore, the presence of LMTA at the composite surface ensures proper thermal contact with mating surfaces as the composite is heated above the melting temperature of the alloy, implying low thermal interface resistances.
The current version of this smart TIM (Polyimide fiber network and InSnBi 60℃ eutectic) exhibits extremely high thermal performance: Rth=1.2 Kmm²/W @ BLT=22µm equivalent of 18.7 W/mK as effective thermal conductivity. Future works will be focused on higher transition temperature alloys (160℃ eutectic).

- **Progress in characterizations**

Characterization of very low Rth thermal interfaces is an increasingly challenging task as the values to be measured are getting smaller and smaller. The methodologies that existed before the NANOPACK project were simply inappropriate to measure very small Rth values. This was proven by some measurements that the NANOPACK project started with. A Round-Robin test was initiated by IZM to check the reliability of the small Rth measuring capability of the various partners, and the result was even more disappointing than we had expected: the measured results on the same samples have shown a more than 100% spread at the different NANOPACK partner locations.
Different requirements have to be fulfilled when equipment or part manufacturers have to compare TIM products of different vendors. In this case the very complex physical methods are already not appropriate: easy to use, relatively fast but accurate methods are needed. Most of the methods developed in the NANOPACK consortium are targeting such applications. The new setups need to consider the application specific need, i.e. mimic the interface area and shape of typical electronic packages and resemble typical assembly conditions (pressure). In addition the setups should allow implementation of NANOPACK's surface modification technologies and be suitable for the complete range of TIM materials, i.e. adhesives, pastes, greases, phase change material, which are either electrically insulating or conductive. This broad spectrum of measurement requirements obviously can not be addressed by a single tool.
A benchmarking of the methodologies has been performed among the partners who have tested the same materials (one grease, one adhesive and one PCM). The results are compared with each other in terms of the measured thermal conductivity values and interface thermal resistances. The correlation between the results is significantly better than it was at the beginning of the project. The observed spread between the results was in the magnitude of 20-40%. This is not only a result of the inaccuracies of the methodologies, but the process influences play a significant role, too.
The Thermal Interface Materials developed in the frame of NANOPACK rely very often on low-dimension based materials (nanocomposites) such as metallic nanoparticles or graphitic structures such as carbon nanofibres or carbon nanotubes. The fundamental physics being the ground for the use of these materials is that the heat transport is modified when tackling this scale in comparison to the usual one. Unfortunately, data such as the phonon mean free paths, phonon interface transmission coefficients, electron-phonon coupling constants or composite material phonon average velocity are not always perfectly known, which is an issue for the simulations that one wants to perform in order to optimize the Thermal Interface Material fabrication. We have identified some techniques that are able to help to measure some of the missing data such as Raman spectroscopy, nanoscale 3 omega method and time-resolved picosecond acoustics experiments.

Progress in Modelling and Simulations

Several simulation tools are used to define limitations of heat transfer in nanoparticle systems with a fluid matrix and potential mechanisms to increase heat transfer between particles and or the matrix.

Three different numerical tools are used to evaluate the thermal performance of different Nanopack materials, including those used as matrices, fillers and common interacting surfaces. The thermal performance is measured in terms of the effective thermal conductivity, the interface thermal conductance (i.e. inverse of thermal resistance) of the composite material and surface arrangements, and their vibrational density of states (DOS). The numerical tools consist of an effective medium approximation program, molecular dynamics (MD) and FDTD (finite difference time domain) method.

The effective thermal conductivity of several representative thermal greases is obtained using an effective medium approximation (EMA) model. Based on the results obtained from the EMA, the thermal conductance of different thermal greases composed by carbon nanotubes (CNTs) and different polymers are estimated using MD.

Efforts are spent to better understand the different molecular mechanisms to increase heat dissipation. We have analyzed the effect of functionalizing the surface of SiO2 with –OH, -O molecules and self-assemble monolayers (SAMs). Then we have analyzed the effect of surface enlargement (by nanobeams) on the thermal conductance and on the vibration rectification of surface atoms. This new study is carried out by means of MD simulations. Furthermore, we compare our results in terms of density of states with estimations obtained using the FDTD method.

From these results, we have found that the interface resistance between CNTs and difference matrices (i.e. Glycerol, PDMS, and an Epoxy) and the CNTs aspect ratio play an important role on limiting the maximum effective thermal conductivity of the composite material. Moreover, from the data provided from EVAC we have found that further enhancements in the effective thermal conductivity on different thermal greases could be achieved just by increasing the aspect ratio of the CNTs currently used. From this, we recommend that additional experimental efforts should be given to characterize this property. Lastly, we have found that surface enlargement also contributes to significantly reduce the interface resistance on surfaces as a function of the nanobeam length. The importance of this result is that it corresponds to a general mechanism that can be activated between any surface and polymer.

NANOPACK Workshops

08:20	**09:40**	**Session 3.1** **Special session: Nanopack I**
08:20	08:40	[41] "Presentation and status of the NANOPACK project", Sebastien Demoustier, Afshin Ziaei
08:40	09:00	[29] "Electro-Thermal Modeling of Nano-Scale Devices", Dragica Vasileska, Katerina Raleva, Stephen Goodnick
09:00	09:20	[47] "Effects of Quantum Corrections and Isotope Scattering on Silicon Thermal Properties", Javier Goicochea, Marcela Madrid, Cristina Amon
09:20	09:40	[46] "Directional Thermal Conductivity of a Thin Si Suspended Membrane with Stretched Ge Quantum Dots", Jean-Numa Gillet, Bahram Djafari Rouhani, Yan Pennec
09:40	10:00	Break
10:00	**10:40**	**Invited speaker:** **Vladimir Székely** *BUTE, Hungary* "Thermal Transient Measurements: the State of the Art"

10:40	**12:00**	**Session 3.2** **Special session: Nanopack II (Thermal interface materials)**
10:40	11:00	[35] "Characterization of Metal Micro-Textured Thermal Interface Materials", Roger Kempers, Alan Lyons, Anthony Robinson
11:00	11:20	[39] "Carbon Nanotube Enhanced Thermally Conductive Phase Change Material For Heat Dissipation", Xinhe Tang, Ernst Hammel, Werner Reiter
11:20	11:40	[40] "Method for In-Situ Reliability Testing of TIM Samples", András Vass-Várnai, Zoltán Sárkány, Marta Rencz
11:40	12:00	[26] "Progress in Thermal Characterisation Methods and Thermal Interface Technology within the "Nanopack" Project", Bernhard Wunderle, Mohamad Abo Ras, Raul Mrossko, Daniel May,
12:00	**12:20**	**Closing remarks Bernard Courtois**

Two special NANOPACK sessions were held during the 15th International Workshop on Thermal Investigations of ICs and Systems, THERMINIC, in Leuven, Belgium, on 9th October 2009.

Nine scientific papers related to NANOPACK subjects were presented and discussed by project partners and external speakers. These sessions were a very good opportunity to discuss and compare the different approaches, and will serve to gain new ideas to achieve the goals of the NANOPACK projects.

On 1st July 2009, IBM organized for the consortium a very successful workshop on keys aspects of thermal management and packaging issues in electronics from system point of view down to nanoelectronics.
The consortium was very pleased to listen to expert speakers from IBM such as the Dr. W. Riess (on Nanotechnology and Si nanowires overview), Dr. B. Michel (Thermodynamics of datacenters and Green IT), Dr. M. Despont (More than Moore by (N)MEMS on CMOS), Dr. T. Brunschwile (Interlayer cooling in vertically integrated packages) and to exchange on various hot topics from nanoscale heat transport to the user's view of integration issues with Dr. B. Agostini, ABB (Thermal management challenges in power electronics), Dr. J. Walther, ETH (Hybrid atomistic/continuum simulations of Carbon Nanotubes in water environment) and Prof. Müller-Plathe, Darmstadt University (Molecular Simulation of Thermal Transport).

➢ **NANOPACK Publications**

In the last months, several NANOPACK partners such as BME, IBM and IEMN have published results related to the project in international refereed journals:
- E.H. El Boudouti et al., Acoustic waves in solids and fluids layered materials, Review paper, Surface Science Reports 64, 471-594 (2009)
- Y. Pennec et al., Phonon transport and waveguiding in a phononic crystal made up of cylindrical dots on a this homogeneous plate, Physical Review B 80, 144302/1-7 (2009)
- V. Székely et al., "Design of a static TIM tester" Accepted to be published In: ASME Journal of Electronic Packaging (JEP)
- P. A. E. Schoen et al., "Hydrogen-Bond Enhanced Thermal Energy Transport at Functionalized, Hydrophobic and Hydrophilic Silica-Water Interfaces", Chem. Phys. Lett. 476, 4, (2009).
- M.Hu et al., "Thermal Rectification at Water/Functionalized Silica Interfaces", Appl. Phys. Lett. 95, 151903 (2009).
- M.Hu et al., "Water Nano-Confinement Induced Thermal Enhancement at Hydrophilic Quartz Interfaces," Nanoletters (accepted for publication).

ICN and the NANOPACK consortium wish to relay the announcement of the ICREA Workshop on Phonon Engineering, to be held on 25th – 28th May 2010 in Barcelona and covering several NANOPACK-related subjects such as nanophononics, energy conversion, micro- / nano-scale thermal management, phononic crystals, photon-phonon interactions in low dimensions, electron-phonon interactions in low dimensions, phonons in metrology…

➢ **Further information**

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