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Thermal Challenges in Next Generation Electronic Systems- Summary of Panel Presentations and Discussions

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***Abstract*—The presentations made, as well as the discussions, in the panels at the workshop, *Thermal Challenges in Next Generation Electronic Systems (THERMES)*, are summarized in this paper. The panels dealt with diverse topics including thermal management roadmaps, microscale cooling systems, numerical modeling from the component to system levels, hardware for future high performance and internet computing architectures, and transport issues in the manufacturing of electronic packages. The focus of the panels was to identify barriers to further progress in each area that require the attention of the research community.**

I. Panel 1: Thermal Management Roadmaps

(A. Bar-Cohen, University of Maryland, and R. Mahajan, Intel Corporation)

A. Summary of Presentations

The panel session began with a presentation of the Thermal Management Roadmap that has emerged from the development of the 2002 NEMI Packaging Roadmap. The business and technology drivers for thermal packaging and the thermal challenges encountered in each of the five electronic product categories – low-cost, hand-held, cost-performance, high-performance, and harsh environment were discussed. Attention was then focused on the distinct thermal packaging building-blocks and the technology, as well as research, needs identified for each of these thermal components, including heat spreaders, interface materials, air-cooled heat sinks, liquid-cooled cold plates, direct "immersion" cooling, and vapor compression, as well as solid-state, refrigeration.

Another panelist presented a "CPU-focused" view of thermal management challenges and strategies, including the role of voltage scaling, architecture, and form-factor in establishing the cooling challenge. Through a brief review of typical thermal packaging approaches and metrics, various "thermal path" management and partitioning strategies were explored, with emphasis on addressing the thermal interfaces encountered in first-level and second-level packaging. A review of thermal challenges and opportunities concluded the presentation.

B. Critical Issues and Research Needs

1) Faster switching speeds and greater on-chip functionality, combined with a slowdown in voltage scaling, are leading to greater chip heat generation and significant nonuniformities in on-chip heat flux.
2) Rapid bifurcation in product categories and shrinking time-to-peak- production and time-to-end-of-life of electronic products are creating enormous cost pressure on packaging designs and fabrication.
3) Rapid exploitation of new technologies, materials, and manufacturing techniques will be needed to keep pace with thermal management demands.

The continued development of new and improved thermal management technology will require the combined efforts of industry-based development and university-based research with a focus on practical application. Extensive heat transfer, thermofluid, and thermomechanical research is needed to define new opportunities (i.e., path breaking) and to improve predictability and reliability (i.e., gap-filling).

Thermal Spreaders: Inexpensive high thermal conductivity, TCE-matched materials; Algorithms for optimizing thermal/thermomechanical design of thermal spreaders; Techniques for improved on-chip thermal spreading;Correlations and models for dry-out in micro-channels and micro-porous materials

Thermal Interface: Nanoparticle/Nanotube-filled thermal pastes, epoxies, and elastomers; Novel techniques and materials to minimize interfacial stresses; Correlations and analytic relations to predict fatigue life of bonded interfaces; Standardized method to characterize thermal performance of interface materials; Low-modulus, high-temperature phase change materials or microencapsulants

Heat Pipes: Flexible, high-flux, low-cost heat pipes for long thermal transport paths; Designs to reduce the gravitational orientation impact on heat pipe efficiency; Heat pipe technology capable of withstanding harsh environments; Sound numerical models and optimization tools

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Correlations and algorithm for design of thermosyphons (i.e., wickless heat pipe)

Air-Cooled Heat Sinks: Models and correlations for transition and low Reynolds number flow; Low Reynolds number turbulence models for use in CFD codes; Constraint-driven design and optimization procedures for heat sinks; Advanced manufacturing techniques for metal and composite material heat sinks; Concepts for higher-head moderate flow, low noise, compact fans; Novel, low power consumption, low acoustic emission micro-fans.

Water Cooled Cold-Plates: MEMS and meso-scale components to create low-cost, low-noise, water-to-air heat exchangers; MEMS and meso-scale components to create low cost, package-size cold plates;

Methods to enable direct water cooling of chips or chip packages

Direct Liquid Immersion: Single-phase and two-phase heat transfer correlations for new dielectric coolants; Dielectric, high thermal performance nanofluids; Convective and phase change cooling correlations for highly nonuniform heat fluxes; Characterization of boiling and two-phase flow in narrow passages and 3-D structures; MEMS and meso-scale components to enhance convective and ebullient heat transfer; Correlations and models for evaporative spray cooling heat transfer

Sub-Ambient and Refrigeration Cooling: Highly reliable miniaturized components such as compressors, condensers, and evaporators;

MEMS and meso-scale components to create low-cost, low noise refrigerators; MEMS and meso-scale components to create low-cost, package-size cold plates; Improved thermoelectric materials and fabrication techniques.

Low Temperature Refrigeration: Application of Auto-refrigerating Cascade (ARC) systems; Application of mechanically cascaded (two-stage) refrigeration systems.

II. Panel 2. Microscale Cooling Systems – Successes, Barriers, and Integration With Electronic Devices

(V. P. Carey, University of California at Berkeley, K. C. Toh, Nanyang Technological University, Singapore, D. W. Copeland, Fujitsu Laboratories of America, and S. J. Kim, Korea Advanced Institute of Science and Technology)

The panel explored the progress of microscale cooling technology since its introduction roughly two decades ago. Panelists presented their views in the following areas: Summary of research on microchannels and micro heat pipes, including experimental, analytical and numerical work; Barriers and challenges to practitioners, including difficulties encountered and promising areas of application; Novel concepts evolved, including combinations of various mechanisms and on-board active cooling systems; and Future directions, including the development of analysis tools at all scales.

Discussions centered on the interest in on-board cooling systems, adequacy of current modeling techniques, and practicality of the current devices in overcoming the challenges highlighted. The critical issue that emerged is the need for closer collaboration between academic researchers and industry in order to facilitate successful implementation of devices. Research needs must be better balanced between studies of fundamental mechanisms and enhancement of heat transfer, and other aspects of practical microscale cooling systems. Possible hurdles toward broader penetration of this technology are the need for research teams to have capabilities in a multitude of disciplines, and the disparity between development times for cooling systems compared with rapidly evolving electronic device technologies.

A. Summary of Presentations

Ever since the pioneering work of Tuckerman and Pease [1], there has been the expectation that microchannel heat exchangers will be the breakthrough that would enable thermal management engineers to keep up with the rapid pace of advances in electronic devices. The panel explored how well the technology has lived up to its promise, the technological and experimental successes and barriers, and especially the degree to which this technology is ready for integration into the next generation of electronic packages.

Research in microchannels and micro heat pipes in the past two decades was summarized. In the 1980s, investigators had already achieved heat fluxes close to 1000 W/cm^2 (junction-to-ambient thermal resistances of 0.07 $°C/W$) in microchannels with water. Over the next ten years, much of the work concentrated on obtaining a better understanding of the microscale flow and heat transfer phenomena, as well as proposing designs that could be better integrated with electronic packages and systems. The areas of investigation have included the choice of working fluid (air, water, FCs); single-phase and two-phase flows; channel geometry and optimization; manifold design with single or multi-layered channels in parallel or counter flow; choice of channel substrate material; and methods of microfabrication. For flow and heat transfer behavior, studies have focused on determination of the friction characteristics, laminar/turbulent transitions, maximum heat flux in single phase or critical heat flux in two-phase flows; and means for reduction of the high pressure drop. In analytical and numerical work, the focus was on deviation from macroscale flow behavior; correlations for momentum and heat transport that take into account the influence of viscous dissipation; and explanations for interface behavior such as the electric double layer.

It was noted that heat pipes are not complete cooling systems, but are merely efficient transport devices. They are useful as heat spreaders for obtaining a uniform temperature distribution in very high heat flux applications. Micro heat pipes use the sharp corners in their internal structure (instead of a wick) for liquid return by capillary action, and usually involve flat plate or vapor chamber configurations, or an array of aligned micro heat pipes. Past studies have concentrated on design of the internal structure, liquid-solid contact, wetting angle and fill quantity, transport limits, liquid/vapor pressure and velocity fields and temperature distributions. Applications have included incorporation into heat sink bases, and for achieving temperature uniformity in laser diode arrays. They have often been combined with microchannels, either in an external or internal arrangement for a complete cooling system.

The main barriers and challenges encountered by practitioners in trying to functionalize microchannel cooling technology were outlined, and areas of potential research identified. The main challenges are:

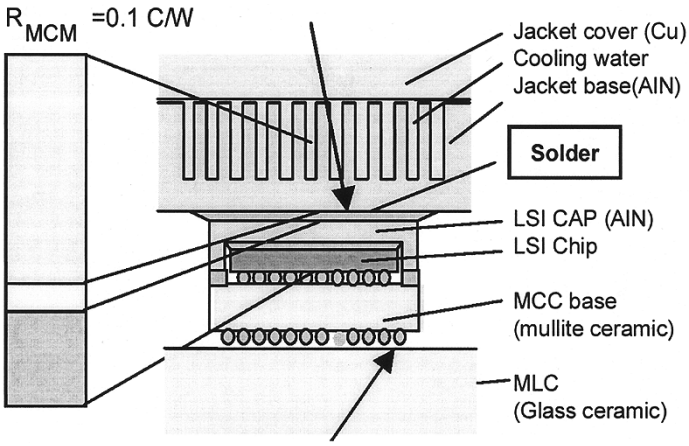

Fig. 1. Advanced package with microchannel technology.

1) inappropriate grain orientation, further complicated by the bipolar to CMOS transition (several past experiments have been conducted under ideal orientation situations);
2) the inevitable streamwise gradient, possibly mitigated by clever manifold design;
3) flow maldistribution, particularly where two-phase flow is involved, aggravated by nonuniform spatial and temporal heating.

Despite the slow adoption of microchannels into main-stream electronic packages, improvements in interface resistance have resulted in greater acceptance for advanced packages, such as the Hitachi DiSAC (Fig. 1). Examples of these improvements include soldering the microchannel heat exchanger to the chip and coupling these devices with other schemes, such as the use of aluminum nitride heat spreaders and solid/liquid phase change materials. One application area that may, however, provide the push for implementation of microchannel technology is the cooling of laser diode arrays, with its requirement for very high power and the critical need for extremely uniform temperatures.

Other studies of microscale heat transfer were also discussed. In design and optimization of various microscale devices, good success has been achieved in modeling microchannel heat sinks using a porous medium approach, which could simplify the necessary design tools.

Micro heat pipes of curved triangular and curved rectangular cross section have also been fabricated and studied, as have micro-jet impingement heat sinks. A novel concept involved a micro fin array where heat transfer enhancement was achieved by flow induced oscillation of the fins (Fig. 2). An array of microsensors, each with characteristic dimension of less than 100 μm, has also been developed to assist in temperature measurement of microscale devices. While a better understanding of the underlying physics has been obtained, and the ability to resolve microscale sensor data developed, barriers that remain include the availability of fabrication methods and the limited space for ultimate heat sinking in future devices.

Another challenge identified for future microscale systems is the development of engineering analysis tools to link the molecular dynamic simulation models to macroscale models, and enable analysis of multiscale systems. This requires modeling of nonequilibrium conditions, molecular transport, and complex boundary conditions. It was emphasized that a better understanding of the multiphase thermal physics in microscale systems is needed, such as nonequilibrium and noncontinuum effects, interfacial tension and wetting, complex geometry interactions of liquid and vapor flow, onset of nucleation, effect of wall roughness, wall conduction effects and dryout conditions in micro-evaporators.

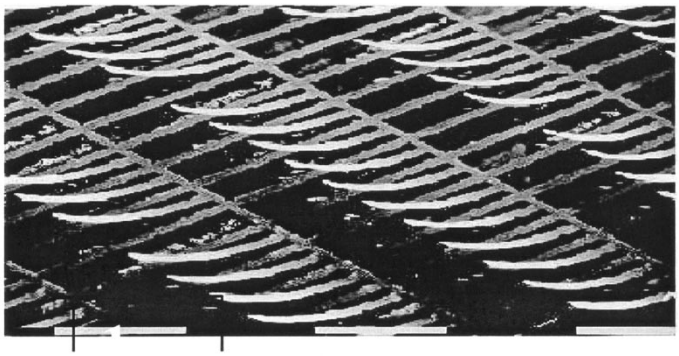

Fig. 2. Microfin array.

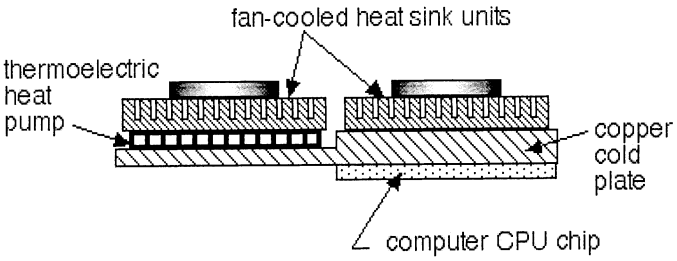

Fig. 3. Active on-board cooling system.

A promising project that is currently under investigation is an embedded processor-based adaptive control cooling system. It features a thermoelectric heat pump and fan-cooled heat sink directly mounted on the CPU (Fig. 3) and an on-board digital microprocessor that controls sensor inputs and outputs, as well as performs computational analysis for optimal control.

B. Discussion

Participants were interested in the active on-board cooling system, and its readiness for implementation. It was pointed out that more work is required on performance assessment and fault detection before it can be deployed in actual systems. Analysis tools are also being developed to show that the adaptive control system will accurately model actual thermal processes. In spite of the success of the porous medium approach to modeling microchannels, it was pointed out that the underlying phenomena in microchannel transport for specific cooling applications still needed investigation. Among the challenges, participants expressed concerns on the persistence of high temperature gradients in microchannel arrays and the uncertainties, especially where two-phase flow is involved. Panel members reiterated that work is currently underway to address the issue of temperature nonuniformity.

C. Critical Issues and Research Needs

While considerable research on microscale cooling has been carried out in the past two decades, there has been limited evidence of successful implementation of the technology in commercial systems. It is critical that research be coupled more

closely with industry input, including issues of reliability, manufacturing difficulties and cost. While a bulk of the past studies have focused on enhancing the ability of microscale devices to remove large amounts of heat at a high heat flux level, and understanding the underlying phenomena, it was suggested that attention be directed also at other components of a complete microsystem cooling design. For example, in a closed-loop liquid cooling system, heat rejection between the liquid and the ultimate sink (ambient air), as well as the circulation of the fluid in the loop within often confined spaces, need to be investigated. To be able to develop fully integrated systems, research teams need to be familiar with electrical/electronic design, micron and sub-micron level thermal transport, microscale fabrication techniques, and materials processing (especially bonding technology), in addition to the heat transfer mechanisms in the cooling system.

III. Panel 3: Component Through System Level Numerical Modeling – Requirements, Reality and Future

(M. Baelmans, Katholieke University, Leuven, Belgium, J. Lohan, Galway-Mayo Institute of Technology, Galway, Ireland, C. Patel, Hewlett Packard, USA, and P. Rodgers, Electronics Thermal Management, Westport, Ireland)

As computing power and its availability increase, electronic system thermal designers are afforded an opportunity to numerically model more complex geometries and thermofluids problems in the search for effective cooling solutions in short periods of time. In doing so, it is possible to converge quickly on the best thermal design, thereby reducing both product design cycle times and development costs by avoiding time-consuming and expensive experimentation. However, despite many advances, very few design teams have developed the confidence in numerical modeling to abandon the experimental prototype phase.

Since it is predicted that the thermal management community will continue to depend heavily on direct air-cooling [2], this panel session therefore sought to:

1) review recent advances in computational fluid dynamics (CFD) based numerical modeling techniques and contrast these against designers' expectations for easy-to-use modeling tools that produce accurate results in the shortest time;
2) highlight the need for realistic benchmark data at component, printed circuit board (PCB) and system levels, to assist the development of more accurate codes and modeling techniques;
3) preview future numerical tools, their anticipated capabilities and forecast their availability.

A. Summary of Presentations

It was proposed that CFD software should become fully integrated within existing product design tools and offer a template for successful thermal design. This design feature should be backward-compatible, providing guidance or advisory functions to nonthermal designers early in the product design cycle. Examples at the PCB level might include the need to highlight optimum component placement strategy from the thermal management perspective, to an electronic engineer at the PCB layout stage, or indeed automatic consultation with an in-built library of package thermal performance data might suggest the most appropriate package design for certain power dissipation levels at the package selection stage. Similar suggestions might be made to mechanical or industrial designers at the system level, regarding system orientation, fan placement or requirements for venting.

Compact models of all system elements, including components, heat sinks, fans and vents should be available from libraries. These should include both thermal resistance and volume or flow resistance models, as their introduction would help reduce computational time and allow numerical model domains to be extended from component to system level. For system level simulations, compact modeling is also possible for flow features. These compact models are distinct from the one for conduction problems. Therefore conduction and convection problems should be distinguished.

In discussing challenges and issues for modeling board-mounted electronic component heat transfer, one panelist divided the thermal design cycle into different phases and outlined the predictive accuracy requirements of CFD analysis at the various phases. Using the metric of component junction temperature, these requirements range from $\pm 10\,^{\circ}\mathrm{C}$ or $\pm 20\%$ of measurement in the early design phase. The goal is to select the thermal management strategy, to $\pm 3\,^{\circ}\mathrm{C}$ or $\pm 5\%$ in the final design phase, where this variable forms a critical boundary condition for component thermo-mechanical and electrical performance analyses, and reliability predictions.

Two independent case studies [3], [4] were presented to highlight the limitations of the turbulence modeling typically employed in CFD codes dedicated to the thermal analysis of electronic equipment. Both studies showed the following.

i) The temperature of all components, from leading to trailing edge, could not be accurately predicted using either the laminar or turbulent flow models employed, thereby highlighting the need for a flow model capable of modeling transition.
ii) Greatest prediction errors and discrepancies between flow models were found to occur in aerodynamically sensitive regions of the boards, where separating, re-attaching or unsteady flow features were identified by experimental flow visualization.
iii) Extremely dense grids are required to accurately predict populated PCB heat transfer. While the use of component compact thermal models (CTM) eliminates the detailed modeling of component internal architecture, the gridding requirements still remain in the fluid domain to resolve the flow detail and its impact on component heat transfer.

Another panelist discussed the future of CFD for electronics cooling, and predicted that the required improvements in prediction accuracy are likely to come from computational techniques that allow the Navier-Stokes equations to be solved for each instant in time. Such methods include either direct numerical simulations (DNS) that allow all flow features to be captured, or a less-demanding solution procedure based on removing the

TABLE I
ESTIMATED COMPUTATIONAL TIME FOR DNS BASED SIMULATIONS USING CURRENT COMPUTING POWER

Dimensions	30x30x70 mm^3	30x500x500 mm^3	2x2x2 m^3
Number of cells	2.10^6	$2.3\ 10^8$	$2.5\ 10^{11}$
Workstation	7 days	4 years	5,000 years
Top 10 Computer	2 min	6 h	8 months

smaller eddies known as large eddy simulation (LES) [5]. Both these approaches have been shown to capture all features of the flow. However, while these approaches have recently been introduced into commercial codes, their application has been limited by the computational power requirements, and their application to heat transfer is yet to be established. For example, Table I presents estimates of the computational time required to solve typical component, PCB and system level problems using DNS. This table [6] is based on turbulent properties of the wake. It is clear that the application of DNS techniques for routine design is at least five years away [7]. It should however be noted that various approaches such as VLES and DES, are currently available. These lie between DNS and RANS, and represent the first steps toward the application of DNS techniques as computing power increases.

B. Discussion

It was suggested that CFD is currently more suitable for the initial or early design phase, and not the final stages where more detail is necessary and the expectations on predictive accuracy are greater. As a result, it is quite often used to get a qualitative picture of the global flow field and approximate operating temperatures, rather than accurate component operating temperatures for reliability predictions.

While the prediction accuracy for the k-epsilon flow model is not likely to be great for component-PCB level problems, it is attractive based on ease of use and convergence time.

It was suggested that CFD tools need to be enhanced to enable modeling of phase-change. In the use of compact models, it was pointed out that the quality level of the model used should be specified.

C. Critical Issues and Research Needs

1) Need to introduce easy-to-use CFD tools into standard design tools.
2) Improved, but easy to use, turbulence models are required to enhance prediction accuracy.
3) Introduction of two-phase models in electronics cooling oriented CFD is also required.
4) Libraries of compact models should be introduced for the main elements of electronic systems.
5) Indication of the quality of the compact models through experimental validation is needed.

With the absence of sufficient computing power to run DNS and LES based numerical codes, the CFD vendors and research community need to allocate more resources toward the development or inclusion of more sophisticated flow models capable of simultaneously modeling laminar, transition, and turbulent flows as well as turbulent wakes. These models also need to be incorporated into a CFD software that is easy to use and can be seamlessly imbedded in standard product design tools.

The following was recommended.

1) CFD software needs to be integrated into the product design process so that thermal design issues are addressed at the early design phase.
2) Greater efforts should be placed on improving the numerics and fluid flow modeling of CFD codes dedicated to the thermal analysis of electronic systems. This will only be achieved if the electronics industry allows code vendors to re-deploy some of their resources, often focused on developing pre- and post processing capabilities, or component compact thermal modeling methodologies, to improve predictive accuracy.
3) Until improvements in predictive accuracy are realized, flow visualization should be undertaken on mock-up prototypes in the early design phase, to identify aerodynamically sensitive regions on the board, where temperature predictions should be treated with caution.
4) Significant expertise is required for the analysis of board-mounted electronics, to build the numerical models, define the grid and obtain fully converged grid-independent solutions. Therefore, the use of CFD demands significant resources in terms of manpower and solution time, which can extend to days. This is at odds with the current design requirements of fast and efficient analysis, with the premise that the analysis is also accurate.

IV. PANEL 4: TRANSPORT ISSUES IN THE MANUFACTURING OF ELECTRONIC PACKAGES

(B. Sammakia, State University of New York at Binghamton, F. Andros, State University of New York at Binghamton, D. Copeland, Fujitsu Laboratories of America, B. Guenin, Sun Microsystems, J.Y. Murthy, Purdue University, and J. Zuo, Thermacore International)

There are numerous significant transport issues that arise in the development, assembly, qualification and manufacturing of organic packages. These issues include such diverse areas as the chemical processing of cards and boards during etching, plating and rinsing, lamination of cores, drilling of plated through-holes, profiling (the separation of individual chip carriers or boards from a large panel) and adhesive curing, all of which occur during the manufacturing of the boards and chip carriers.

During assembly and re-work there are significant issues that arise in solder re-flow during module attach and re-work, adhesive cure during heat-sink attach, under-fill application process in flip chip carriers, and under-fill cure. In test and burn-in there are concerns with solder and adhesive creep due to the high temperature and mechanical load on the chip carrier. During reliability stress testing there are concerns during all of the thermal stress tests regarding the establishment of appropriate stress acceleration factors that relate the laboratory tests to actual field conditions. During shipping and handling,

similar concerns arise in simulating potential temperature excursions that may occur.

In addition to these thermal issues that arise in manufacturing, additional ones arise in the thermal management of packages due to manufacturing processes and limitations. These include interfacial de-lamination due to surface conditions, residual stresses in the package that impact the thermal performance of the package and manufacturing tolerances that inherently affect the thermal performance.

The panel provided a brief overview of many of these issues, and went into a detailed discussion of key research topics of general interest to the electronics packaging community.

A. Summary of Presentations

Current issues related to the thermal analysis of electronics packaging were discussed. It was pointed out that most analyzes and experimental studies are focused on thermal management of packages, while considerably less attention is paid to thermal issues in the manufacturing and qualification stages of the development cycles. Issues such as the difference between the strain and damage incurred to a package in isothermal cycling versus power cycling and the implications to the reliability projections were discussed in some detail. An overview of heat sink manufacturing issues, limitations and applications was presented. The effects of cost, fan performance, form factor and miniaturization were presented.

An outline of issues related to micro packaging was offered, with emphasis on the importance of interfacial materials that are part of the thermal path. These interfaces are often composed of thermal grease or thermal adhesives, and any damage to them may be critical to the performance and reliability of the package. Tools available for measuring these interfaces such as acoustic microscopy do not provide interface thickness data, which is critical.

Major manufacturing issues that arise in two-phase systems, such as fluid selection, were discussed. It was pointed out that the most desirable material is water, but issues with freezing exist. A discussion of heat pipe fabrication and integration into a system was also presented.

A summary of computational issues related to manufacturing was presented. One of the key issues identified is the need to develop multi-physics modeling particularly for emerging technology areas and emerging manufacturing techniques. The other key is to develop tools that may be integrated into the manufacturing process that would enable the prediction of critical items like manufacturing process capabilities and tolerance distributions.

Finally, an overview of heat sink manufacturing issues, limitations and applications was provided. Heat sinks can be manufactured by subtractive (machining), additive (brazing, soldering and swaging) or net-shape (micro forging, casting, extruding) processes, or a combination of these (for example, crosscut extrusions). Each of these processes has limits on the achievable dimensions, in turn limiting their performance. This results in each manufacturing technology having its own place on a cost-performance curve. In general, a minimization of system cost is the desired goal. A less expensive heat sink may require a stronger (higher RPM) fan. For a given fan size, this is usually achievable at the same cost. For a given noise level, a common constraint in desktop systems, this can only be achieved with a larger, and more expensive, fan. This is the simplest example of cost tradeoffs between heat sinks and other hardware. A more complicated situation is minimization of lifetime cost or energy of the system.

B. Discussion

Additional issues were raised in the discussion. The use of under-fills is quite pervasive in flip chip technology. Under fills that are reworkable are needed and although there are research and development activities in that area, there has not been (to the panel's knowledge) any product shipped with a rework-able under-fill. The use of modeling tools for under-fill flows varies depending upon the process. There are some processes that are very well suited for modeling, and are therefore well understood. On the other hand most manufacturing processes are complex and involve multi-physics phenomena. In addition to the complexity, manufacturing needs usually include very accurate predictions of specific outputs, as opposed to a relative or qualitative prediction. As a consequence, many manufacturing processes are modeled using semi empirical or empirical correlations that may not be generalized.

The issue of high forces (for example in extrusion) during heat sink manufacturing and their impact on the thermal performance of the heat sink, and the thermal conductivity or the surface roughness was raised. The panelists believed that typical manufacturing processes do not impact heat sink performance, particularly extruded aluminum heat sinks.

With reference to the wick types used most commonly in heat pipes, it was noted that avionics applications generally use grooved structures, while on-ground systems use sintered powder or mesh screens.

C. Critical Issues and Research Needs

1) There is a need for new numerical analysis tools that can be used to model multi-physics based phenomena. Examples are manufacturing processes that include photo exposure, manufacturing of MEMS devices, wet chemical etching/plating, and many others. Another key area is the modeling of manufacturing process distributions, defects and tolerances, so that modeling may be used as an integral part of the manufacturing process.
2) There is a need for a way to transfer designs from EDA tools directly into modeling tools without the need for extensive editing and modification. Some progress has been made with regard to electrical analysis.
3) There is a lack of detailed understanding of two-phase flows in general, and in heat pipes in particular.
4) Engineers in industry and researchers in academia have a need to access materials databases that can enable faster and more accurate analyzes.

Thermal, mechanical and reliability issues are closely tied to manufacturing, assembly and qualification of electronic packages. Modeling of these processes is complex and currently available commercial tools and algorithms can only perform parts of the modeling tasks and must be complemented by empirical measurements. Furthermore, as new emerging technologies such as MEMS, photonics, biotechnology and nanostruc-

tures make it to the manufacturing line, the problems will be exacerbated. There is therefore an obvious and urgent need for advanced modeling tools that are capable of modeling multi-physics based phenomena. There is also a need for an extensive properties database for engineering materials used in electronics packaging that is accessible to the modeling community in industry and academia.

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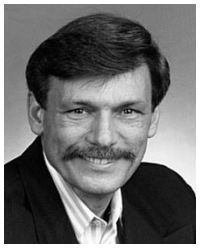

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K. C. Toh, photograph and biography not available at the time of publication.

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