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Solutions for Certain Thermal Problems of Microelectronics

Ph.D. thesis

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Introduction

On the surface of integrated circuits the number of the integrated components and the operating frequency are continuously increasing. In the modern processors the dissipated power per unit area is reaching the 100W/cm^2 value. The stacked dies and 3D packaging possibilities as well result in elevated temperature of packaged devices. The generated heat must be conducted across the shortest and lowest thermal resistance way, accordingly the active or passive cooling of these devices are prominently important. The major cause of electronic failures is the elevated temperature; more than 55% of failures were caused by this phenomenon in the electronic systems. These reasons motivated my research work.

Aims of the research work

The elevated temperature encountered in different packaged electronic devices demands the application of careful temperature-aware design methodologies and electro-thermal simulations of the entire system. The results of various electro-thermal simulations and models in most of the cases yield good approximations. However, the simulation may take a long time, and after any changes in the system or in any parameters of the surroundings, the simulation should be executed again. Different measurement methods disturb the operation of the entire system, accordingly the original operation and temperature distribution cannot be investigated (e.g. a computer case must be opened for measuring by a thermo vision camera, which cannot fit into two PCI cards).

The aim of my research work was to develop a new tool with which the actual temperature distribution of an electronic system can be characterized. Using a contactless temperature measurement procedure the temperature distribution and the places of high dissipation elements on an operating assembled PWB (Printed Wired Board) (e.g.: PCI or AGP cards) can be measured and localized in a dense rack system, where only a thin measuring board could be inserted between the operating cards.

In other applications, the uniform heat distribution may be the most important issue during operation. This is the case e.g. at a high temperature test chamber, where the evolving homogenous temperature distribution – within the close proximity of the heating filaments – is elementary. This is needed to maintain that during accelerated fatigue testing every part of the device under test is heated up to the same temperature. In the case of a test chamber only a contactless temperature measuring method can be used in order to measure the evolving heat distribution. By using the new contactless method for determining the temperature distribution the possible inequality of the heat distribution and the places of the high dissipation elements or different hot-spots in an operating high temperature test chamber can be measured and localized.

In recent years the reliability of Micro Electro Mechanical Systems (MEMS) and integrated circuits became a very important issue. The reliability of these devices strongly depends on the quality of the heat removal path from their packages. If the heat dissipated within the package can not leave the package seamlessly, the temperature of the chip or of the MEMS element within the package increases, and in worst cases may cause damages on the entire device. In order to avoid this, checking the quality of the heat flow path of the package is a very important step. A frequently encountered problem of the packaging technology is the testing of the die attach quality, as the die attach is usually the weakest element of the heat flow path. Any void or delamination in the die-attach results in increased thermal resistance which cause elevated chip temperature.

To avoid packaging of the badly attached devices, the right place of the die attach qualification are in a much earlier phase of the manufacturing, before the bonding and encapsulating process begin, immediately after the die attaching. In this case only non-electric methods can be considered for measuring the heating or cooling curve.

For this reason the further aim of my research work was to develop a new measurement methodology, for qualifying the die attach quality of semiconductor devices by sensing the thermal dilation of the measured devices. It has a great importance in the packaging of high power devices. By using this methodology it could be possible to avoid packaging of badly attached devices in a much earlier phase of the manufacturing, before the bonding and encapsulating. This method could be convenient for determining the thermal expansion map on the surface of different packages, structures.

The rapid advances in transistor density and switching frequency of VLSI circuits as encountered in microprocessors have induced dramatic increases in die heat flux and power consumption. Conventional air-cooling systems are reaching their limits, thus, new designs are investigated in order to be able to cope with increased heat flux and keeping junction temperatures tolerable. An urgent demand for more efficient cooling has risen, which resulted in micro-scale thermal management solutions. Other approaches include application of integrated micro-refrigerators attached close to the hot-spot locations. For example in these applications high heat-flux (up to 300W/cm^2) are achieved with localized cooling.

The further aim of my research work was to develop a new thermal characterization method of micro-scale cooling assemblies, like a micro-channel cooling plate based on thermal transient testing methodology.

New scientific results

1st thesis

I developed a new contactless methodology for temperature mapping of circuits and boards in dense rack system or computer cases during operation and for characterizing the evolved temperature distribution in a high temperature test chamber. With the proposed method the IR radiation-distribution of the measured surfaces from a close proximity of the sensor card can be monitored, enabling in situ IR measurement.

The new sensor card was realized on a PWB board. On the surface 4×4 number square shape (1cm×1cm) copper areas were placed in a matrix arrangement. On these copper plates thermal test dies were attached for sensing the temperature changes. The surface of the sensor card was black painted in order to achieve the highest absorption of IR radiation. The frequency of the output signal of the thermal test dies is proportional to the sensed temperature.

The measured results were verified by thermal simulations and hand calculation.

1.1. I proved that the new contactless characterization methodology is applicable for localizing the places of the hot-spot and for determining the temperature distribution in a dense system.

1.2. I proved that the proposed methodology enables in situ heat distribution measurement inside a high temperature test chamber during operation, with the detection of potentially uneven heat distribution. I proved that the homogenous temperature distribution has evolved at a distance of 1cm from the heating filaments.

2nd thesis

I developed a new methodology for testing the die attach quality by sensing the thermal dilation of the measured devices. A frequently encountered problem of the packaging technology is the testing of the die attach quality, as the die attach is usually the weakest element of the heat flow path. Any void or delamination in the die-attach results in increased thermal resistance which cause elevated chip temperature and failures.

By applying the new measurement methodology the difference between the thermal dilatations of different quality die attached samples can be detected. The Talystep stylus system was used to measure the thermal dilatation. I checked the die attach quality of the samples by using X-Ray system. I verified the measurement results by simulations, hand calculations and another sort of measuring method (laser interferometer measuring system).

By using this methodology it could be possible to avoid packaging badly attached devices in a much earlier phase of the manufacturing, before the bonding and encapsulating take place.

2.1 I proved that the inhomogeneous thermal dilatation of the surface of packaged electronic devices – caused by the inhomogeneous heat distribution – can be measured by applying the new measurement methodology. Both of the contactless laser interferometer or contact type Talystep stylus measurement method can be applied. By using the laser interferometer measurement system the inhomogeneous thermal dilatation of the semiconductor surface can be measured.

2.2 I proved that the different quality of die attaches causes different thermal dilatation, and the new methodology is appropriate for detecting this difference. Between the good (maximum 10% voids) and the bad (attached only on one corner or edge of the semiconductor) samples 1μm dilatation difference can be measured.

3rd thesis

I developed a new methodology for thermal characterization of micro-scaled cooling assemblies based on thermal transient testing and I obtained a new model to define the thermal behavior of these devices.

The measurement sample was attached to a power transistor which was used as a dissipator and a temperature sensor as well. The thermal transient response to a dissipation step of the transistor was recorded. The measured transients (cooling curves) were transformed into structure functions from which the partial thermal resistance corresponding to the cooling assembly was identified. I measured and demonstrated the gas flow rate vs. partial thermal resistance function and create a second order model for modeling the thermal conductance at different gas flow rate.

Additionally I completed the measurement setup by a heat-flux sensor in between the dissipator and the micro-cooler to be able to verify the measurement results. Good matching of the heat transfer coefficient values resulting from the two different methods was found and it proves the applicability of the new method.

3.1 Carrying out the identification procedure at different flow rates the thermal characteristics of the micro-cooler were obtained. I determined the thermal conductance vs. gas flow rate function of the „I” channel geometry micro-cooler assembly.

3.2 Based on the measurement results I created a second order model for modeling the thermal conductance changing vs. different gas flow (φ) rate:

$$G_{th} = a \cdot \varphi^2 + b \cdot \varphi + c$$

3.3. Based on the measurement results I proved that between the 45μm and 70μm channel depth „I” channel geometry micro-cooler devices the difference between the HTC (heat transfer coefficient) values is not significant (under 10% difference).

3.4. I proved that the HTC of the new „Y” channel geometry micro-cooler device is bigger than the HTC of the „I” channel geometry device with the same channel depth. The difference is 40%, 24% at different gas flow rates, and smaller at bigger flow rates.

Own publications related to the thesis

Publications related to the 1st thesis

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