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Advanced Thermal Management Materials

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ISBN 978-1-4614-1962-4 ISBN 978-1-4614-1963-1 (eBook)
DOI 10.1007/978-1-4614-1963-1
Springer New York Heidelberg Dordrecht London

Library of Congress Control Number: 2012944176

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Preface

Microelectronics packaging was born out of necessity when the integrated circuit (IC) was invented in 1947. Microelectronics packaging is interdisciplinary in nature and involves physics, chemistry, materials science, mechanical engineering, electrical engineering, and more. Microelectronics packaging refers to the enclosure of electronic devices or ICs according to the requirements of each component to achieve a reasonable layout, assembly, bonding, and connection. It is important since it protects devices from moisture, heat, mechanical stresses, mechanical shock, thermal shock, and chemical erosion/corrosion.

Nowadays the trends in electronics are toward a small footprint, light weight, low cost, high performance, and high reliability. All of these trends have led to highly integrated ICs and sophisticated packaging schemes. When the chip power density increases, it is critically important to dissipate the extra heat efficiently. If the heat is not managed properly, the chip's working environment is worsened, leading to higher chip operating temperatures and unstable device performance. In extreme cases, the chips burn out, resulting in fire and safety hazards. Statistically speaking for semiconductors, for every 18 °C operating temperature increase, chip reliability is reduced by two to three times. Therefore, it is very important to manage the waste heat properly.

Different thermal management materials are used in microelectronics packaging. They typically possess a high thermal conductivity (TC) and a low coefficient of thermal expansion (CTE) and are used mainly to dissipate heat and to provide structural support. Traditionally they are also called heat sink materials.

There are many ways to manage waste heat, such as cryogenic coolers, active chilled water pipes, and cooling fans. Most of these methods focus on external heat management, i.e., on how to dissipate waste heat from the environment. There is another fundamental challenge, which is how to dissipate the heat from the IC active layer itself. This is typically done by conduction using heat sink materials.

Lately there has been a great deal of active research on thermal management materials, especially on dielectrics, metals, and metal matrix composites. Results of current research are typically dispersed in various technical journals and conference proceedings. Thermal management engineers have been hard pressed to find a comprehensive and practical book to cover both the fundamentals of thermal management and selection guidelines, an issue this book hopes to address.

The main objective of this book is to introduce various thermal management materials and their fabrication methods. Most of the materials covered are based on our 10+ years of direct R&D and manufacturing experience. We hope to provide an effective reference book for thermal management engineers and packaging engineers.

The book is divided into ten chapters. Chapters 1, 2, and 3 cover the basics of thermal management and traditional thermal management materials. Chapters 4, 5, 6, 7, and 8 cover copper- and aluminum-based thermal management materials. Finally, Chaps. 9 and 10 discuss the application of these materials in laser diodes and future development trends.

It is our goal to introduce the reader to thermal management basics, theory, and application. At the same time, we strive to reference as many of the latest research papers as possible so that readers can attain a comprehensive understanding of the current status and future trends of the field. As stated previously, thermal management materials are being actively studied worldwide. We cannot possibly cover all the latest developments and welcome feedback from readers like you.

During the writing of this book, we received generous support from Prof. Renzheng Tang, Prof. Zhifa Wang, and Dr. Yi Gu and from graduate students Hong Wu, Dexin Chen, Jun Zhou, Qiwang Zhang, and Xing Yu from Central South University. Without their support and guidance, this book could not have been written. In addition, we would like to extend our appreciation to Ganesh Hariharan and Michael Shaw from Torrey Hills Technologies, LLC, and Adam Ding from the University of Southern California. They rendered valuable assistance in providing materials for several chapters.

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Chapter 1
Introduction to Thermal Management in Microelectronics Packaging

Abstract Heat generated by electronic devices and circuitry must be dissipated to improve reliability and prevent premature failure. Thermal management goes hand in hand with microelectronics packaging. In this chapter, we will present the motivations and the basic concepts of thermal management by heat sink materials, such as heat flux, thermal resistance, and thermal circuits. Next we will introduce the levels and classifications of packaging and the functions of microelectronics packaging. Finally, we will introduce the development stages of thermal management materials.

1.1 Basics of Thermal Management in Microelectronics Packaging

In extreme environments, temperatures can reach up to 1,000°C and higher. The power density in some computer servers can reach up to 5 W/cm^2. The junction temperature is the highest temperature of the semiconductor in an electronic device. It is generally accepted that the maximum junction temperature is about 150°C for silicon devices. It is desirable to keep it below 85°C. The maximum junction temperatures allowed for SiC and GaN materials are approximately 750 and 350°C, respectively. Statistically, the reliability of integrated circuit (IC) chips is reduced by two to three times for every 18°C increase in chip temperature.

There are many ways to reduce the IC chip operating temperature, e.g., cryogenic coolers, active chilled water pipes, cooling fans, and heat sinks. The cooling of optics and detectors to reduce signal noise is one of the important applications of cryogenic cooling technologies both today and for the near future.

One of the most important functions of thermal management materials in microelectronic packaging is the efficient transfer of heat from the semiconductor junction to the ambient environment. This process can be separated into three phases:

- Heat transfer within the semiconductor component package;
- Heat transfer from the package to a heat dissipater;
- Heat transfer from the heat dissipater to the ambient environment.

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DOI 10.1007/978-1-4614-1963-1_1,

1.1.1 Heat Flux

Radiation, conduction, and convection are three ways to dissipate heat from a device. The rate at which heat is conducted through a material is proportional to the area normal to the heat flow and to the temperature gradient along the heat flow path. For a 1D, steady-state heat flow the rate is expressed by Fourier's equation:

$$\frac{Q}{A} = k\frac{\Delta T}{d}$$

where:

k = thermal conductivity, W/m-K,
Q = rate of heat flow, W,
A = contact area,
d = distance of heat flow,
ΔT = temperature difference.

1.1.2 Thermal Resistance

Thermal resistance is the measure of a substance's ability to dissipate heat, or the efficiency of heat transfer across the boundary between different media. A heat sink with a large surface area and good air circulation (airflow) gives the best heat dissipation:

$$R = A\frac{\Delta T}{Q} = \frac{d}{k}$$

For homogeneous materials, thermal resistance is directly proportional to thickness. For nonhomogeneous materials, the resistance generally increases with thickness, but the relationship may not be linear.

The thermal impedance, Θ, of a material is defined as the sum of its thermal resistance and any contact resistance between it and the contacting surfaces:

$$\Theta = R_{material} + R_{contact} = R_{material} + \left(T_a - T_b\right)/Q,$$

where T_a and T_b are temperatures at the interfacing boundaries.

Surface flatness, surface roughness, clamping pressure, material thickness, and compressive modulus have a significant effect on contact resistance. Because these surface conditions can vary from application to application, the thermal impedance of a material will also be application dependent.

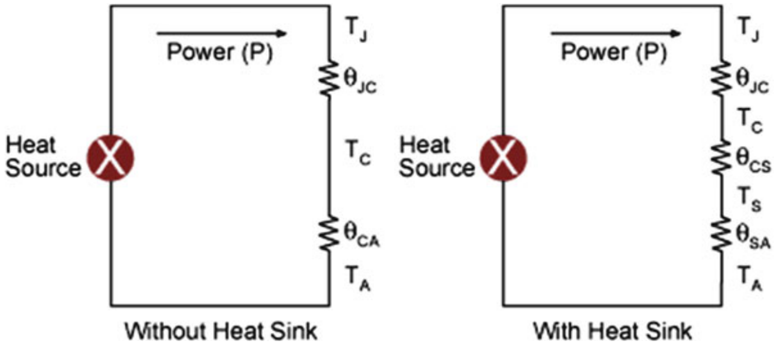

Fig. 1.1 Thermal circuit models [1]

1.1.3 Thermal Management Examples with a Heat Sink and Without a Heat Sink

To simplify the thermal transport concept, we use the thermal circuit model, which is similar to the electric circuit model. The through circuit element is the power, and the potential element is the temperature. The circuits shown in Fig. 1.1 represent two cases (Table 1.1):

- *Case 1*: the bare die is connected to the case and the case is exposed to the environment;
- *Case 2*: the bare die is connected to the case, then to a heat sink, and the case is exposed to the environment.
- Junction temperature without a heat sink:

$$T_J = T_a + Q \times \theta_{JA} = 50 + 20 \times 4.7 = 148^{\circ}\mathrm{C}$$

- Junction temperature with heat sink and its heat resistance equals 1.35°C/W and has an interface material with a heat resistance of 0.13°C/W.

$$T_J = T_a + Q \times (\theta_{JC} + \theta_{CS} + \theta_{SA}) = 50 + 20(0.13 + 0.1 + 1.35) = 81.6^{\circ}\mathrm{C}.$$

From the two simple cases we understand that a well-chosen heat sink material could lower the junction temperature and significantly improve the reliability of the device performance because the junction temperature is controlled under 85°C.

1.2 Heat Generation and the Purpose of Thermal Management in Microelectronics Packaging

Since the inception of semiconductor devices in 1948, the miniaturization of electronic components, microminiaturization, and the integration of technology, especially the emergence of new chip materials (such as SiC and GaN) and their

Table 1.1 Thermal circuit parameters [1]

Parameters	Name	Unit	Description	Example
Θ_{JA}	Θ from junction to ambient	°C/W	Specified in data sheet	4.7°C/W
Θ_{JC}	Θ from junction to case	°C/W	Specified in data sheet	
Θ_{CS}	Θ from case to heat sink	°C/W	Thermal interface material thermal resistance	
Θ_{CA}	Θ from case to ambient	°C/W		
Θ_{SA}	Θ from heat sink to ambient	°C/W	Specified by heat sink manufacturer	0.13°C/W
T_J	Junction temperature	°C	Junction temperature as specified under recommended operating conditions for device	
T_{JMAX}	Maximum junction temperature	°C	Maximum junction temperature as specified under recommended operating conditions for device	85°C
T_A	Ambient temperature	°C	Temperature of local ambient air near component	
T_{Amax}	Maximum ambient temperature	°C	Maximum temperature of local ambient air near component	50°C
T_S	Heat sink temperature	°C		
T_C	Device case temperature	°C		
Q	Power	W	Total power from operating device; use estimated value for selecting a heat sink	20 W

applications, have led to an increase in electronic equipment power density and required greater heat dissipation in high-power FR, microwave, and millimeter-wave devices and on-board and satellite electronic equipment. As the temperature of semiconductor devices increases by 10°C, their reliability is reduced by 50 %. In 2000, the heat flux of large computer chips has exceeded 100 W/cm^2. At present, it reaches a level of 300 W/cm^2. The main methods for cooling electronic equipment include natural cooling, forced air/liquid cooling, cold plate, phase-change cooling, heat pipes, and so on.

Electronic packaging refers to the enclosure of electronic devices or ICs according to the requirements of each component to achieve a reasonable layout, assembly, bonding, connecting, and operating environment. It also includes process isolation and protection to prevent the buildup of moisture, dust, and harmful gases on electronic devices or ICs, to prevent external damage, and to stabilize component parameters. Thermal management of electronic packaging concerns the temperature control of heat-consumption electronic devices, unit systems, or whole systems by reasonable cooling, heat-dissipation, and structural-design optimization to ensure normal and reliable operations. Thermal management materials function as the substrate, or base, of electronic components; they cool and support electronic components.