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Xingcun Colin Tong

Advanced Materials for Thermal Management of Electronic Packaging

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This book is dedicated to my wife Dali, our daughter Lingbo, and our sons William and Alan. Their love fully filled my heart during the long hours of work on this book

Preface

The need for advanced thermal management materials in electronic packaging has been widely recognized as thermal challenges became barriers to the electronic industry's ability to provide continued improvements in device and system performance. With increased performance requirements for smaller, more capable, and more efficient electronic power devices, systems ranging from active electronically scanned radar arrays to web servers all require components that can dissipate heat efficiently. This requires that the materials have a high capability for dissipating heat and maintaining compatibility with the die and electronic packaging. In response to these critical needs, revolutionary advances in thermal management materials and technologies for active and passive cooling now promise integrable and cost-effective thermal management solutions. As a result, a large number of papers, articles, and presentations have been published on the development of high-performance materials to solve the vexing problem of device and package-level cooling and thermal management. However, no comprehensive and accessible book has been available on this topic for students, materials scientists, and electronics engineers.

To meet this need, *Advanced Materials for Thermal Management of Electronics Packaging* takes a systems approach ranging from thermal management fundamentals to a balance between cost and performance in materials selection and assessment. Chapter 1 begins with an outline of heat transfer theory and discusses thermal management solutions, materials selection, and component design guidelines. Chapter 2 provides an extensive review of assessment techniques and characterization methodologies for advanced thermal management materials and components. Chapter 3 provides an overview of the state of the art of high-performance advanced electronic packaging materials and their thermal management functions, including properties of key materials, state of maturity, applications, processing, and future directions. Chapters 4 through 8 provide an in-depth introduction to the large and increasing number of advanced thermal management materials, including carbonaceous materials and carbon matrix materials, thermally conductive polymer matrix composites, high thermal conductivity metal matrix composites, ceramic composites, and emerging thermal interface materials. Chapters 9 through 11 discuss advanced materials and design for heat spreaders, air cooling heat sinks, liquid

cooling, and thermoelectric cooling devices. Finally, Chapter 12 presents a development roadmap with applications, trends, and perspectives on the future.

It is a great pleasure to acknowledge the help and support I have received from my colleagues who have provided me with various supports and contributed to my understanding of thermal management materials and approaches in electronic packaging. I would like to express my sincere gratitude to my editors, Dr. David Packer and all other editing staff who worked very hard to give the text its final polish.

Schaumburg, IL Xingcun Colin Tong

Contents

Abbreviations

ABGA	Advanced ball grid array
ABS	Acrylonitrile-butadiene-styrene
ACPI	Advanced configuration and power interface
AES	Auger electron spectroscope
AFM	Atomic force microscopy
AMC	Aluminum matrix composite, or airborne molecular contamination
APG	Annealed pyrolytic graphite
ASTM	American Society for Testing and Materials
BGA	Ball grid array
BIOS	Basic input/output system
BIST	Built-in self-test
BLT	Bond line thickness
BSE	Back scattered electrons
BTE	Boltzmann particle transport equation
CAD	Computer aided design
CBGA	Ceramic ball grid array
CCC	Carbon/carbon composite
CCD	Charge coupled device
CCFL	Cold cathode fluorescent lamp
CFCC	Continuous fiber ceramic composite
CFD	Computational fluid dynamics
CHF	Critical heat flux
CMC	Ceramic matrix composite
CMOS	Complementary metal oxide semiconductor
CNF	Carbon nanofiber
CNT	Carbon nanotube
COB	Chip on board
COP	Coefficient of performance
CPU	Central processing unit
C-SAM	C-mode scanning acoustic microscope
CSF	Combination of solar and fuel cells
CTE	Coefficient of thermal expansion
CTI	Computer telephony integration

CVD	Chemical vapor deposition
CVI	Chemical vapor infiltration
CW	Continuous wave
dB	Decibel
DCB/DAB	Direct copper/aluminum bonded ceramic substrate
DF	Density factor
DFT	Density functional theory, or discrete Fourier transform
DIP	Dual-in-line package
DLC	Diamond like carbon
DNA	Deoxyribonucleic acid
DS	Decision support
DSP	Digital signal processing
DTM	Dynamic thermal management
ECU	Electronics cooling unit
EDA	Electronic design automation, or electronic document access
EDIFICE	Embedded droplet impingement for integrated cooling of electronics
EDM	Electrodischarge machining
EDS	Energy dispersive spectroscopy of X-rays
EELS	Electron energy loss spectrum
EG	Electron gas
EIA	Environmental impact assessment
EMA	Effective medium approximation
EMC	Electromagnetic compatibility
EMI	Electromagnetic interference
EMS	Electronic music studios
EPDM	Ethylenepropylene diene monomer
ESD	Electromagnetic discharge
ESPI	Electronic speckle pattern interferometry
EV	Electric vehicle
FCBGA	Flip chip ball grid array
FEA	Finite element analysis
FET	Field effect transistors
FIT	Failure in time
FLG	Few layer graphene
FMEA	Failure mode and effect analysis
FPBGA	Flip chip plastic ball grid array
GAEC	Gas-assisted evaporative cooling
GGI	Gold–gold interconnection
GLP	Graphite loaded polymer
HAST	Highly accelerated stress test
HEV	Hybrid electric vehicle
HFE	Hydroflouroether
HIP	Hot isostatic press
HOPG	Highly oriented pyrolytic graphite

HPHT	High pressure and high temperature
HRTEM	High resolution transmission electron microscopy
HVAC	Heating, ventilating, and air conditioning
HVOS	High-velocity oxyfuel spraying
Hz	Hertz
IACS	International annealed copper standard
IC	Integrated circuit
ICA	Isotropic conductive adhesive
ID	Inside diameter
IGBT	Insulated-gate bipolar transistor
IMS	Insulated metal substrate, metal core board
IPEM	Integrated power electronics module
IR	Infrared
JCPDS	Joint committee on powder diffraction standards
JTRS	Joint tactical system
LCD	Liquid crystal display
LCP	Liquid crystal polymer
LD	Laser diode
LDA	Laser diode array
LED	Light-emitting diode
LEM	Lunar excursion module
LMA	Low melting alloy
LRU	Line replaceable unit
MBLT	Minimum bond line thickness
MCAD	Mechanical computer-aided design
MEMS	microelectromechanical system
MH	Metal hydride
MIL	Military
MLC	Multilayer ceramic
MMC	Metal matrix composite
MPU	Memory protection unit
MRU	Modular refrigeration unit
MSRS	Miniature scale refrigeration system
MTBF	Mean time between failure
MTTF	Mean time to failure
MWNT	Multi-walled carbon nanotube
NEMS	Nanoelectromechanical systems
NMP	Net material product, or *N*-methylpyrrolidone
OD	Outside diameter
OEE	Overall equipment effectiveness
OEM	Original equipment manufacturer
OPC	Object linking and embedding for process control
OTD	On time delivery
PAA	Polyacrylic acid
PAI	Polyamideimide