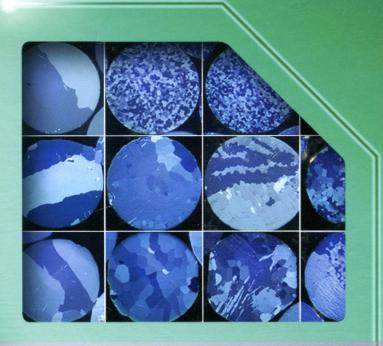
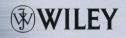
Edited by K. N. Subramanian

Lead-free Solders

Materials Reliability for Electronics





Wiley Series in Materials for Electronic & Optoelectronic Applications

Lead-free Solders: Materials Reliability for Electronics

Edited by

K. N. SUBRAMANIAN

Department of Chemical Engineering and Materials Science, Michigan State University, Michigan, USA



This edition first published 2012 © 2012 John Wiley and Sons Ltd

Registered office

John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, United Kingdom

For details of our global editorial offices, for customer services and for information about how to apply for permission to reuse the copyright material in this book please see our website at www.wiley.com.

The right of the author to be identified as the author of this work has been asserted in accordance with the Copyright, Designs and Patents Act 1988.

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, except as permitted by the UK Copyright, Designs and Patents Act 1988, without the prior permission of the publisher.

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic books.

Designations used by companies to distinguish their products are often claimed as trademarks. All brand names and product names used in this book are trade names, service marks, trademarks or registered trademarks of their respective owners. The publisher is not associated with any product or vendor mentioned in this book. This publication is designed to provide accurate and authoritative information in regard to the subject matter covered. It is sold on the understanding that the publisher is not engaged in rendering professional services. If professional advice or other expert assistance is required, the services of a competent professional should be sought.

The publisher and the author make no representations or warranties with respect to the accuracy or completeness of the contents of this work and specifically disclaim all warranties, including without limitation any implied warranties of fitness for a particular purpose. This work is sold with the understanding that the publisher is not engaged in rendering professional services. The advice and strategies contained herein may not be suitable for every situation. In view of ongoing research, equipment modifications, changes in governmental regulations, and the constant flow of information relating to the use of experimental reagents, equipment, and devices, the reader is urged to review and evaluate the information provided in the package insert or instructions for each chemical, piece of equipment, reagent, or device for, among other things, any changes in the instructions or indication of usage and for added warnings and precautions. The fact that an organization or Website is referred to in this work as a citation and/or a potential source of further information does not mean that the author or the publisher endorses the information the organization or Website may provide or recommendations it may make. Further, readers should be aware that Internet Websites listed in this work may have changed or disappeared between when this work was written and when it is read. No warranty may be created or extended by any promotional statements for this work. Neither the publisher nor the author shall be liable for any damages arising herefrom.

Library of Congress Cataloging-in-Publication Data

Subramanian, K. N., Ph. D.

Lead-free solders: materials reliability for electronics / edited by K.N. Subramanian. p. cm.

Includes bibliographical references and index.

ISBN 978-0-470-97182-6 (cloth)

1. Lead-free electronics manufacturing processes. 2. Solder and soldering. I. Title.

TK7836.S825 2012

621.381-dc23

2011038790

A catalogue record for this book is available from the British Library.

Print ISBN: 9780470971826

Set in 10/12pt Times by Thomson Digital, Noida, India

Printed in Malaysia by Ho Printing (M) Sdn Bhd

Contents

Pre	Series Preface Preface List of Contributors Thematic Area I: Introduction			xv xvii xix
The				1
1	Rol		of Lead-Free Electronic Solder Interconnects: aterial and Service Parameters manian	3
	1.1 1.2	Impose	al Design for Reliable Lead-Free Electronic Solders Joints and Fields and the Solder Joint Responses that Affect	3
			Reliability	5
	1.3		nical Integrity	5
	1.4		omechanical Fatigue (TMF)	6
	1.5		er Growth	7 7
	1.6 1.7		omigration (EM) omigration (TM)	8
	1.8		Potential Issues	8
The	emati	c Area l	II: Phase Diagrams and Alloying Concepts	11
2		_	rams and Their Applications in Pb-Free Soldering	13
	Sini	ı-wen Cl	hen, Wojciech Gierlotka, Hsin-jay Wu, and Shih-kang Lin	
	2.1	Introdu	action	14
	2.2	Phase I	Diagrams of Pb-Free Solder Systems	14
	2.3		le of Applications	23
		2.3.1	General Applications (Melting, Solidification,	
			Interfacial Reactions)	23
		2.3.2	Effective Undercooling Reduction (Co Addition)	28
		2.3.3		
			Interfacial Reactions)	32
		2.3.4	the second secon	32
		2.3.5	1 2	34
		2.3.6	Up-Hill Diffusion (Sn-Cu/Ni)	36 30
		1 4 /	LIMITED SH SUPPLY LANZSHIE III	34

vi Contents

	2.4 Conclusions Acknowledgments References				
3	Phase Diagrams and Alloy Development Alan Dinsdale, Andy Watson, Ales Kroupa, Jan Vrestal, Adela Zemanova, and Pavel Broz			45	
	3.1	Introdu	action	45	
	3.2	Compu 3.2.1	tational Thermodynamics as a Research Tool Concept of the Calculation of Phase Diagrams for	48	
			Multicomponent Systems	48	
		3.2.2	Modelling of the Gibbs Energy of the System	50	
	3.3		Critical Assessment of Thermodynamic Properties odynamic Databases – the Underlying Basis of the ling of Phase Diagrams and Thermodynamic Properties,	51	
			ses for Lead-Free Solders	51	
			Creation of the Thermodynamic Databases	52	
			Three Conditions of Consistency	52	
		3.3.3	Specialized Databases for the Modelling of Thermodynamic		
			Properties of Systems Relevant for Lead-Free Solders	54	
	3.4	Application 3.4.1	ation of the SOLDERS Database to Alloy Development Modelling of Phase Diagrams and	57	
			Thermodynamic Properties	58	
		3.4.2	Modelling of Other Properties	65	
	3.5	Conclu	sions	68	
	Refe	erences		68	
4			of Sn-based Solders with Ni(P) Substrates:		
			libria and Thermochemistry	71	
	Cle	mens Sci	hmetterer, Rajesh Ganesan, and Herbert Ipser		
	4.1	Introdu	action	72	
	4.2	Binary	Phase Equilibria	73	
		4.2.1	Literature Overview	73	
		4.2.2	New Experimental Results	77	
	4.3	Ternary	y Phase Equilibria Ni-P-Sn	85	
		4.3.1	Literature Overview	85	
		4.3.2	Experimental Results	86	
	4.4	Therm	ochemical Data	94	
		4.4.1	Literature Overview	95	
		4.4.2	New Experimental Results	99	
	4.5		nce of the Results and Conclusion	111	
		nowledg	ments	113	
	Refe	erences		113	

			Coments	V 41
ľhe	emati	c Area III: Microalloying to Improve Reliability		119
5	Reli	ects of Minor Alloying Additions on the Properties and ability of Pb-Free Solders and Joints'		121
	5.1	Introduction		122
	5.2	Controlling Ag ₃ Sn Plate Formation		125
	5.3	Controlling the Undercooling of Sn Solidification		132
	5.4	Controlling Interfacial Reactions		136
		5.4.1 Dissolution of UBM and Surface Finishes		137
		5.4.2 Cu-Sn Intermetallic Formation		138
		5.4.3 Interfacial Void Formation		143
		5.4.4 Spalling of Ni-Sn Intermetallics		144
	5.5			145
	5.6	Improving Mechanical Properties		149
		5.6.1 Strength and Hardness		149
		5.6.2 Drop Impact Resistance		150
		5.6.3 Thermal Fatigue Resistance		150
	5.7			151
	5.8	Summary		153
	Refe	erences		154
6		relopment and Characterization of Nano-composite Solder		161
	Jon	an Liu, Si Chen, and Lilei Ye		
	6.1	Introduction		162
	6.2	Nano-composite Solder Fabrication Process		162
		6.2.1 Nano-particle Fabrication		162
		6.2.2 Nano-composite Solder Fabrication		163
	6.3	Microstructure		166
		6.3.1 Grain Size		166
		6.3.2 IMC Layer		167
	6.4	and the second contract of the second contrac		167
		6.4.1 Viscosity		167
		6.4.2 Melting Point		168
		6.4.3 Wettability		168
		6.4.4 CTE		168
		6.4.5 Density and Young's Modulus		169
	6.5	Mechanical Properties		169
		6.5.1 Microhardness		169
		6.5.2 Creep Resistance		170
		6.5.3 Mechanical Strength		170
	66	6.5.4 Ductility Challenges and Solutions		170 171
	6.6	Challenges and Solutions		174
	6.7	Summary		1/4

	Acknowledgments	175		
	References	176		
The	ematic Area IV: Chemical Issues Affecting Reliability	179		
7	Chemical Changes for Lead-Free Soldering and Their Effect			
	on Reliability	181		
	Laura J. Turbini			
	7.1 Introduction	181		
	7.2 Soldering Fluxes and Pastes	181		
	7.3 Cleaning	185		
	7.4 Laminates	185		
	7.5 Halogen-Free Laminates	186		
	7.5.1 Z-axis CTE	187		
	7.5.2 Interconnect Stress Test (IST)	187		
	7.5.3 Time to Delamination	187		
	7.5.4 Temperature to Decomposition	188		
	7.6 Conductive Anodic Filament (CAF) Formation	189		
	7.7 Summary References	193 193		
	References	193		
The	ematic Area V: Mechanical Issues Affecting Reliability	195		
8	Influence of Microstructure on Creep and High Strain Rate			
	Fracture of Sn-Ag-Based Solder Joints	197		
	P. Kumar, Z. Huang, I. Dutta, G. Subbarayan, and R. Mahajan			
	8.1 Introduction	198		
	8.2 Coarsening Kinetics: Quantitative Analysis of Microstructural Evolution	199		
	8.2.1 Experimental Procedure	199		
	8.2.2 Results and Discussion	200		
	8.3 Creep Behavior of Sn-Ag-Based Solders and the Effect of Aging	206		
	8.3.1 Experimental Procedure	206		
	8.3.2 Results and Discussion	207		
	8.4 Role of Microstructure on High Strain Rate Fracture	219		
	8.4.1 Experimental and Analytical Procedure	220 222		
	8.4.2 Results and Discussion8.5 Summary and Conclusions	227		
	Acknowledgments	227		
	References	228		
9	Microstructure and Thermomechanical Behavior Pb-Free Solders D.R. Frear	233		
	9.1 Introduction	233		
	9.2 Sn-Pb Solder	234		

			Contents	ix
	0.2	DI. F.	Callera	237
	9.3		Solders	
				238
			Interfacial Intermetallic Formation of Pb-Free Solders	240
			Mechanical Metallurgy of Pb-Free Solder Alloys	243
		9.3.4	Thermomechanical Fatigue Behavior of Pb-Free Solder Alloys	245
		Summa	ry	248
	Refere	ences		249
10	Elec	ctromec	chanical Coupling in Sn-Rich Solder Interconnects	251
	Q.S.	Zhu, H	Y.Y. Liu, L. Zhang, Q.L. Zeng, Z.G. Wang, and J.K. Shang	
	10.1	Introdu	uction	252
	10.2	Experi	mental	253
	10.3	Result		255
		10.3.1	Surface Morphology of Sn-3.5Ag-0.7Cu Interconnects	
			after Electromigration	255
		10.3.2	Surface Morphology of Pure Sn Interconnect after	
			Electromigration	256
		10.3.3	· ·	
			after Electromigration	257
		10.3.4		
			Electromigration	258
		10.3.5		
		10.5.5	Electromigration	260
	10.4	Discus		264
	10.1	10.4.1	Stress Induced by Vacancy Concentration at the	
		10.4.1	Grain Boundary	264
		10.4.2	•	20.
		10.4.2	Formation on the Surface	265
		10.4.3	and development and development to the second secon	266
		10.4.3		267
			- · · · · · · · · · · · · · · · · · · ·	201
		10.4.5	Stress-Relaxation Rate	268
	10.5	G 1		
		Concl		269 270
		owledgi	ments	_
	Refer	ences		270
11	Effe	ect of T	emperature-Dependent Deformation Characteristics on	
			echanical Fatigue Reliability of Eutectic Sn-Ag Solder Joints	273
			Deep Choudhuri, and K.N. Subramanian	
	11.1	Introd	uction	274
	11.2	Exper	imental Details	275
	1000 35	11.2.1		275
		11.2.2		275
		11.2.3	· -	276
			Mechanical Testing	276

11.2.4 Mechanical Testing

x Contents

	11.3	Results and Discussion	276
		11.3.1 Effects of Temperature	277
		11.3.2 Effects of Strain Rate	283
		11.3.3 Influence of Temperature Regime of TMF on the	
		Residual Mechanical Properties	286
		11.3.4 Effect of Temperature Regime of TMF on Surface-Damage	
		Accumulation	289
		11.3.5 Evolution of Microstructural Damages during	
		Low-Temperature Regime TMF	291
	11.4		294
	Refer	•	295
The	matic	Area VI: Whisker Growth Issues Affecting Reliability	297
12		Whiskers: Causes, Mechanisms and Mitigation Strategies	299
	Niti	n Jadhav and Eric Chason	
	12.1	Introduction	299
	12.2	Features of Whisker Formation	303
	12.3	Understanding the Relationship between IMC Growth,	
		Stress and Whisker Formation	308
	12.4	Summary Picture of Whisker Formation	314
	12.5	Strategies to Mitigate Whisker Formation	316
	12.6	Conclusion	318
	Ackn	owledgments	318
	Refer	ences	318
13	Tin	Whiskers	323
	Kat.	suaki Suganuma	
	13.1	Low Melting Point Metals and Whisker Formation	323
	13.2	Room-Temperature Tin Whiskers on Copper Substrate	325
	13.3	Thermal-Cycling Whiskers on 42 Alloy/Ceramics	326
	13.4		329
	13.5		330
	13.6	•	331
	13.7		332
	13.8	Future Work	334
	Refer	ences	334
The	ematic	Area VII: Electromigration Issues Affecting Reliability	337
14		ctromigration Reliability of Pb-Free Solder Joints ng-Hyun Chae, Yiwei Wang, and Paul S. Ho	339
	14.1	Introduction	339
	14.2	Failure Mechanisms of Solder Joints by Forced Atomic Migration	342

			Content	s xi
		14.2.1	EM	342
		14.2.1		347
	14.3	IMC G		351
	17.5		Under Thermal Aging	351
			Under Current Stressing	358
	144		of Sn Grain Structure on EM Reliability	363
	14.5		· · · · · · · · · · · · · · · · · · ·	366
		wledgm		369
	Refere			369
15	Chih	Chen, S.	ration in Pb-Free Solder Joints in Electronic Packaging hih-Wei Liang, Yuan-Wei Chang, Hsiang-Yao Hsiao, n, and K.N. Tu	375
	15.1	Introdu		376
	15.1		Features for EM in Flip-Chip Pb-Free Solder Joints	376
	13.2	15.2.1		377
		15.2.1		311
		13.2.2	During EM	378
		15.2.3		0,0
		10.2.0	EM Failure	382
		15.2.4		385
	15.3		es of Physical Properties of Solder Bumps During EM	386
		15.3.1		386
		15.3.2	Temperature Redistribution	390
		15.3.3	Mechanical Properties: Electromigration-Induced Brittleness	
			in Solder Joints	391
	15.4	Challer	nges for Understanding EM in Pb-Free Solder Microbumps	393
		15.4.1	Fast Dissolution of Cu and Ni under EM	393
		15.4.2	2	393
		15.4.3	ANADOROGEN AND SECTION OF THE CONTRACT	393
	15.5		omigration of Cu and Ni in Pb-Free Solder Microbumps	394
	15.6	Summa	•	394
		owledgm	nents	395
	Refere	ences		395
16	Sinn		Electromigration on Electronic Solder Joints hen, Chih-ming Chen, Chao-hong Wang,	401
			~	
	16.1	Introdu		401
	16.2		of Electromigration on Solders	402
		16.2.1 16.2.2	Solder Joints with Primarily Only One Moving Species Solder Joints with Significant Hillock	403
			and Void Formation	404
		16.2.3	Solder Joints with Phase Segregation	405

16.	.3 Effects 16.3.1	s of Electromigration on Interfacial Reactions Asymmetric IMC Layer Growth (Electron from Solder to	408
		Substrate: Enhancement, Electron from Substrate to Solder:	400
	1622	Suppression)	408
	16.3.2	Asymmetric IMC Layer Growth (Electron from Solder to	
		Substrate: Suppression, Electron from Substrate to Solder: Enhancement): Peltier Effect	409
	16.3.3	Symmetric IMC Layer Growth (Cathode and Anode:	409
	10.5.5	Enhancement or Suppression)	411
	16.3.4	No Effect with Passage of Electric Current	411
	16.3.5	Effects of Electromigration on Reaction Phases: Evolution of	411
	10.5.5	Reaction Phase and Alternating Layer Formation	411
	16.3.6		
16.		Microstructural Changes Caused by Electromigration	412
10.	Growtl	ing Description of Effects of Electromigration on IMC	414
	16.4.1	The Atomic Flux Summation Model	414
	16.4.2	The Atomic Flux Summation Wodel The Atomic Flux Summation with Stress Modification	414
	10.4.2	Model	415
	16.4.3	Generalized Modeling for Growth of IMC Layer	
16.			416
	knowledgn		418
	knowledgii ferences	nents	418
NC.	lefelices		418
Thema	tic Area V	III: Thermomigration Issues Affecting Reliability	423
17 T	hermomig	TII: Thermomigration Issues Affecting Reliability gration in SnPb and Pb-Free Flip-Chip Solder Joints K.N. Tu, Hsiao-Yun Chen, Hsiang-Yao Hsiao, and Chih Chen	423 425
17 T	Shermomig Sian Tian, K	gration in SnPb and Pb-Free Flip-Chip Solder Joints X.N. Tu, Hsiao-Yun Chen, Hsiang-Yao Hsiao, and Chih Chen	
17 T	Thermomigian Tian, M I Introdu 2 Therm	gration in SnPb and Pb-Free Flip-Chip Solder Joints K.N. Tu, Hsiao-Yun Chen, Hsiang-Yao Hsiao, and Chih Chen action omigration in SnPb Flip-Chip Solder Joints	425
17 T	T hermomig ian Tian, K	gration in SnPb and Pb-Free Flip-Chip Solder Joints K.N. Tu, Hsiao-Yun Chen, Hsiang-Yao Hsiao, and Chih Chen uction omigration in SnPb Flip-Chip Solder Joints Thermomigration in Unpowered Composite SnPb	425
17 T	Thermomigian Tian, M I Introdu 2 Therm	gration in SnPb and Pb-Free Flip-Chip Solder Joints K.N. Tu, Hsiao-Yun Chen, Hsiang-Yao Hsiao, and Chih Chen uction omigration in SnPb Flip-Chip Solder Joints Thermomigration in Unpowered Composite SnPb Solder Joints	425
17 T	Thermomigian Tian, M I Introdu 2 Therm	gration in SnPb and Pb-Free Flip-Chip Solder Joints K.N. Tu, Hsiao-Yun Chen, Hsiang-Yao Hsiao, and Chih Chen uction omigration in SnPb Flip-Chip Solder Joints Thermomigration in Unpowered Composite SnPb	425 425 427
17 T	Thermomigian Tian, K 1 Introdu 2 Therm 17.2.1	gration in SnPb and Pb-Free Flip-Chip Solder Joints K.N. Tu, Hsiao-Yun Chen, Hsiang-Yao Hsiao, and Chih Chen action omigration in SnPb Flip-Chip Solder Joints Thermomigration in Unpowered Composite SnPb Solder Joints In-Situ Observation of Thermomigration in Composite SnPb Solder Joints	425 425 427
17 T	Thermomigian Tian, K 1 Introdu 2 Therm 17.2.1	gration in SnPb and Pb-Free Flip-Chip Solder Joints K.N. Tu, Hsiao-Yun Chen, Hsiang-Yao Hsiao, and Chih Chen uction omigration in SnPb Flip-Chip Solder Joints Thermomigration in Unpowered Composite SnPb Solder Joints In-Situ Observation of Thermomigration in Composite	425 425 427
17 T	Thermomigian Tian, K. 1 Introdu 2 Therm 17.2.1 17.2.2	gration in SnPb and Pb-Free Flip-Chip Solder Joints K.N. Tu, Hsiao-Yun Chen, Hsiang-Yao Hsiao, and Chih Chen action omigration in SnPb Flip-Chip Solder Joints Thermomigration in Unpowered Composite SnPb Solder Joints In-Situ Observation of Thermomigration in Composite SnPb Solder Joints	425 425 427 427 429
17 T 7. 17. 17.	Thermomigian Tian, K. 1 Introdu 2 Therm 17.2.1 17.2.2	gration in SnPb and Pb-Free Flip-Chip Solder Joints K.N. Tu, Hsiao-Yun Chen, Hsiang-Yao Hsiao, and Chih Chen action omigration in SnPb Flip-Chip Solder Joints Thermomigration in Unpowered Composite SnPb Solder Joints In-Situ Observation of Thermomigration in Composite SnPb Solder Joints Thermomigration in Unpowered Eutectic SnPb Solder Joints	425 425 427 427 429 431
17 T 7. 17. 17.	Thermomigian Tian, K Introdu Therm 17.2.1 17.2.2 17.2.3 Therm	gration in SnPb and Pb-Free Flip-Chip Solder Joints K.N. Tu, Hsiao-Yun Chen, Hsiang-Yao Hsiao, and Chih Chen action omigration in SnPb Flip-Chip Solder Joints Thermomigration in Unpowered Composite SnPb Solder Joints In-Situ Observation of Thermomigration in Composite SnPb Solder Joints Thermomigration in Unpowered Eutectic SnPb Solder Joints omigration in Pb-Free Flip-Chip Solder Joints	425 425 427 427 429 431
17 T 7. 17. 17.	Thermomigian Tian, K Introdu Therm 17.2.1 17.2.2 17.2.3 Therm 17.3.1	gration in SnPb and Pb-Free Flip-Chip Solder Joints K.N. Tu, Hsiao-Yun Chen, Hsiang-Yao Hsiao, and Chih Chen uction omigration in SnPb Flip-Chip Solder Joints Thermomigration in Unpowered Composite SnPb Solder Joints In-Situ Observation of Thermomigration in Composite SnPb Solder Joints Thermomigration in Unpowered Eutectic SnPb Solder Joints omigration in Pb-Free Flip-Chip Solder Joints Thermomigration of Cu and Ni in Pb-Free Flip-Chip	425 427 427 429 431 432
17 T 17. 17.	Thermomigian Tian, K Introdu Therm 17.2.1 17.2.2 17.2.3 Therm 17.3.1	gration in SnPb and Pb-Free Flip-Chip Solder Joints K.N. Tu, Hsiao-Yun Chen, Hsiang-Yao Hsiao, and Chih Chen uction omigration in SnPb Flip-Chip Solder Joints Thermomigration in Unpowered Composite SnPb Solder Joints In-Situ Observation of Thermomigration in Composite SnPb Solder Joints Thermomigration in Unpowered Eutectic SnPb Solder Joints omigration in Pb-Free Flip-Chip Solder Joints Thermomigration of Cu and Ni in Pb-Free Flip-Chip Solder Joints	425 427 427 427 429 431 432 435
17 T 17. 17.	Thermomigian Tian, K Introdu Therm 17.2.1 17.2.2 17.2.3 Therm 17.3.1 4 Driving 17.4.1	gration in SnPb and Pb-Free Flip-Chip Solder Joints K.N. Tu, Hsiao-Yun Chen, Hsiang-Yao Hsiao, and Chih Chen uction omigration in SnPb Flip-Chip Solder Joints Thermomigration in Unpowered Composite SnPb Solder Joints In-Situ Observation of Thermomigration in Composite SnPb Solder Joints Thermomigration in Unpowered Eutectic SnPb Solder Joints omigration in Pb-Free Flip-Chip Solder Joints Thermomigration of Cu and Ni in Pb-Free Flip-Chip Solder Joints g Force of Thermomigration	425 427 427 427 429 431 432 435 435
17 T T 17.	Thermomigian Tian, K 1 Introdu 2 Therm 17.2.1 17.2.2 17.2.3 3 Therm 17.3.1 4 Drivin 17.4.1 5 Coupli	gration in SnPb and Pb-Free Flip-Chip Solder Joints K.N. Tu, Hsiao-Yun Chen, Hsiang-Yao Hsiao, and Chih Chen Inction Inction Inction Incidentation in SnPb Flip-Chip Solder Joints Thermomigration in Unpowered Composite SnPb Solder Joints In-Situ Observation of Thermomigration in Composite SnPb Solder Joints Thermomigration in Unpowered Eutectic SnPb Solder Joints Omigration in Pb-Free Flip-Chip Solder Joints Thermomigration of Cu and Ni in Pb-Free Flip-Chip Solder Joints g Force of Thermomigration Irreversible Processes of Thermomigration	425 427 427 427 429 431 432 435 435 438
17 T. 17. 17. 17. 17.	Thermomia ian Tian, K Introdu Therm 17.2.1 17.2.2 17.2.3 Therm 17.3.1 Driving 17.4.1 Coupli Coupli	gration in SnPb and Pb-Free Flip-Chip Solder Joints K.N. Tu, Hsiao-Yun Chen, Hsiang-Yao Hsiao, and Chih Chen Inction Omigration in SnPb Flip-Chip Solder Joints Thermomigration in Unpowered Composite SnPb Solder Joints In-Situ Observation of Thermomigration in Composite SnPb Solder Joints Thermomigration in Unpowered Eutectic SnPb Solder Joints Thermomigration in Pb-Free Flip-Chip Solder Joints Thermomigration of Cu and Ni in Pb-Free Flip-Chip Solder Joints g Force of Thermomigration Irreversible Processes of Thermomigration ng between Thermomigration and Creep	425 427 427 427 429 431 432 435 435 438
17 T. 17. 17. 17. 17.	Thermomia ian Tian, K 1 Introdu 2 Therm 17.2.1 17.2.2 17.2.3 3 Therm 17.3.1 4 Driving 17.4.1 5 Coupli 6 Coupli Therm	gration in SnPb and Pb-Free Flip-Chip Solder Joints K.N. Tu, Hsiao-Yun Chen, Hsiang-Yao Hsiao, and Chih Chen Inction Inction Inction Inction Inction Incomposite SnPb Incomposite SnPb	425 427 427 429 431 432 435 438 439
17 T 17. 17. 17. 17. 17. 17. 17. Aci	Thermomia ian Tian, K 1 Introdu 2 Therm 17.2.1 17.2.2 17.2.3 3 Therm 17.3.1 4 Driving 17.4.1 5 Coupli 6 Coupli Therm	gration in SnPb and Pb-Free Flip-Chip Solder Joints X.N. Tu, Hsiao-Yun Chen, Hsiang-Yao Hsiao, and Chih Chen detion omigration in SnPb Flip-Chip Solder Joints Thermomigration in Unpowered Composite SnPb Solder Joints In-Situ Observation of Thermomigration in Composite SnPb Solder Joints Thermomigration in Unpowered Eutectic SnPb Solder Joints omigration in Pb-Free Flip-Chip Solder Joints Thermomigration of Cu and Ni in Pb-Free Flip-Chip Solder Joints g Force of Thermomigration Irreversible Processes of Thermomigration ng between Thermomigration and Creep ng between Thermomigration and Electromigration: oelectric Effect on Electromigration ary	425 427 427 427 429 431 432 435 435 439

	Contents	xiii
Thematic Area IX: Miniaturization Issues Affecting Reliability		443
18 Influence of Miniaturization on Mechanical Reliability of Lead-Free Solder Interconnects Golta Khatibi, Herbert Ipser, Martin Lederer, and Brigitte Weiss		445
18.1 Introduction		445
18.2 Effect of Miniaturization on Static Properties of Solder Joints		
(Tensile and Shear)		448
18.2.1 Constraint and Geometry Effects in Model Joints		448
18.2.2 Constraining Effects in Actual Joints		466
18.2.3 Fracture Mechanics Considerations of Solder Joints		473
18.3 Creep and Relaxation of Solder Joints		475
18.4 Summary and Conclusions		478
References		482
Index		487