UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Faculty of Manufacturing Engineering

THE MICRO-STRUCTURAL CHARACTERIZATION OF THERMOSONIC Cu-Al INTERMETALLIC COMPOUNDS AND MODELLING OF ITS INTERFACE STRESS

Chua Kok Yau

Doctor of Philosophy

2015

© Universiti Teknikal Malaysia Melaka

THE MICRO-STRUCTURAL CHARACTERIZATION OF THERMOSONIC Cu-Al INTERMETALLIC COMPOUNDS AND MODELLING OF ITS INTERFACE STRESS

CHUA KOK YAU

A thesis submitted
in fulfillment of the requirements for the degree of Doctor of Philosophy

Faculty of Manufacturing Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2015

© Universiti Teknikal Malaysia Melaka

DECLARATION

I declare that this thesis entitled “The Micro-Structural Characterization of Thermosonic Cu-Al Intermetallic Compounds and Modelling of Its Interface Stress” is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature : ....

Name : ....

Date : ....

© Universiti Teknikal Malaysia Melaka

APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Doctor of Philosophy.

Signature :……………..

Supervisor Name :……………………….....................................

Date :……………………...

© Universiti Teknikal Malaysia Melaka

DEDICATION

To my beloved parents, wife and children.

© Universiti Teknikal Malaysia Melaka

ABSTRACT

Thermosonic bonding of the Cu wire on Al bond pad is a common technology used in semiconductor industry. However, recent research show voids formation at this bonding interface on micro-chip, after an annealing treatment of High Temperature Storage (HTS). This voids formation is believed due to the volumetric changes of intermetallic compounds (IMCs) formed at the bonding interface. In previous research, effects of Cu free-air-ball and bonding temperature with high temperature storage (HTS) treatment on Cu-Al bonding interface are unclear. Besides, previous research provides inconclusive knowledge in the evolution of Cu-Al bonding interface due to inconsistent observations and variations in the bonding parameters. Research with statistical approach could be useful to address this limitation, however, it is yet to be established for Thermosonic Cu-Al interconnection. Besides, the void formation due to volumetric changes of IMC is discussed only qualitatively. A quantitative stress analysis could close the gap of research. Objectives of this research are (1) to analyse the correlation of wire bonding parameters, the interfacial micro-structure change and mechanical strength of the synthesized Cu-Al bonding interface, (2) to propose a theoretical model that describe quantitatively the stress due to volumetric changes originated from Cu-Al phase evolution, (3) to evaluate the stress generated by Cu-Al phase evolution at the bonding interface and its correlation to the void formation. Micro-structural characterizations were focused on crystallographic, compositional and mechanical analyses. It was found that bonding temperature resulted in an exponential increment for initial overall IMC thickness and average Cu content of the phases formed at the bonding interface. Moreover, HTS increase the overall IMC thickness by volume diffusion mechanism. The relationship between parameters, mechanical ball shear strength and IMC thickness were obtained statistically. A mathematical stress model based on assumptions of isotropic and elastic binary solid-solution was proposed. This model enabled an estimation of interfacial stresses from compositional measurements. It was found that the stress developed by interfacial Cu-Al IMC generally increased with the bonding temperature. Besides, forming gas supply was found to be less significant to affect the stress development, due to the oxide layers did not hinder much the interdiffusion of Cu and Al atoms. However, with HTS, the growth of Cu rich IMC increased the stress and caused gap within copper oxide layer. This work addressed the research gaps and offered a better understanding of the fundamental of Thermosonic Cu-Al interconnection. The results of the stress modelling could be a useful failure analysis technique for implementing Cu wire in the industry.

© Universiti Teknikal Malaysia Melaka

ABSTRAK

Ikatan wayar kuprum (Cu) pada pad aluminium (Al) secara Thermosonic adalah teknologi biasa digunakan dalam industri semikonduktor. Tetapi, kajian baru-baru ini mendapati bahawa pembentukan ruang kosong di antaramuka ikatan, selepas penyepuhlindapan penyimpanan suhu tinggi (PST). Pembentukan ruang kosong ini dipercayai disebabkan tekanan terjana daripada perubahan isipadu sebatian antara logam (SAL) yang terbentuk di antaramuka ikatan. Berdasarkan kajian sebelum ini, kesan-kesan 'bebola-udara-bebas' wayar kuprum, suhu ikatan dengan PST pada antaramuka ikatan Cu-Al adalah tidak jelas. Selain itu, kajian sebelum ini tidak memberikan pengetahuan berkesimpulan tentang revolusi antaramuka ikatang Cu-Al. Ini disebabkan pemerhatian-pemerhatian yang tidak selaras and parameter-parameter ikatan yang bervariasi. Penyelidikan berdasarkan statistic adalah berguna untuk menangani batasan ini. Walaubagaimanapun, cara ini belum ditubuhkan untuk system Cu-Al Thermosonic. Selain itu, pembentukan ruang kosong disebabkan perubahan isipada SAL telah dibincang secara kualitatif sahaja. Analisis tekanan secara kuantitatif amat diperlukan. Objektif kajian ini termasuk: (1) untuk menganalisis korelasi antara pelbagai parameter tersebut, perubahan struktur mikro and kekuatan mekanik antaramuka Cu-Al disintesis, (2) untuk mencadangkan model teori yang menghuraikan tekanan disebabkan perubahan isipadu fasa Cu-Al, (3) untuk menilai tekanan terjana di antaramuka ikatan Cu-Al and hubungannya dengan pembentukan ruang kosong di situ. Pemcirian struktur dari segi kristalografi, komposisi and mekanik diberi tumpuan dalam kerja penyelidikan ini. Suhu ikatan didapati membawa kesan kepada peningkatan tebal SAL awal (secara eksponen) and kandungan Cu dalam SAL ini di antaramuka ikatan. Lagipun, PST didapati meningkatkan ketebalan keseluruhan SAL dengan mekanisme peresapan kekisi. Hubungan antara parameter, kekuatan mekanik and ketebalan SAL diperolehi scara statistik. Model matematik berdasarkan andaian system logam binari isotropic dan elastik dicadangkan. Model ini membolehkan penganggaran tekanan antaramuka daripada ukuran komposisi. Tekanan terjana oleh SAL Cu-Al secara umumnya meningkat dengan suhu ikatan. Bekalan 'forming gas' didapati kurang penting untuk memberi kesan dalam pengembangan tekanan. Ini disebabkan oleh lapisan oksida berada di antaramuka ikatan tidak menghalang peresapan atom-atom Cu dan Al. Tetapi, dengan PST, pertumbuhan SAL yang kaya dalam kandungan Cu meningkatkan magnitud tekanan dan menyebabkan pembentukan jurang dalam lapisan kuprum oxida. Kerja ini membolehkan pemahaman asas yang lebih baik dalam bidang ikatan Cu-Al Thermosonic. Keputusan model tekanan berguna sebagai teknik analisis kegagalan untuk pelaksanaan wayar Cu dalam industry semikonduktor.

© Universiti Teknikal Malaysia Melaka

ACKNOWLEDGEMENTS

First and foremost, I would like to take this opportunity to express my sincere appreciation to my main supervisor, Associate Professor Dr. T. Joseph Sahaya Anand, and co-supervisor, Associate Professor Dr. Mohd Warikh Bin Abd Rashid, from the Faculty of Manufacturing Engineering Universiti Teknikal Malaysia Melaka (UTeM) for their essential supervision, continuous support and encouragement towards the completion of this thesis. I would also like to thank my external co-supervisor, Associate Professor Dr. Azman Jalar, the deputy director of Institute of Microengineering and Nanoelectronics (IMEN) from Universiti Kebangsaan Malaysia (UKM), for his insightful advice and continuous support for this work.

Particularly, I would like to thank Ms. Hng May Ting, Ms. Ng Mei Chin, Dr. Lim Boon Huat, Mr. See Beng Keng, Mr. Ong Meng Tong, Mr. Lee Cher Chia for contributing materials and processings from industry. Also, supports from Mr. Yong Foo Khong for scanning transmission electron microscope (STEM) analysis are highly appreciated. This research could hardly be completed without your supports.

I would also like to express my deepest gratitude to Mr. Azhar Shan Bin Abu Hassan and Mr. Hairulhisham Bin Rosnan, from material laboratory, Faculty of Manufacturing Engineering, for their supports and efforts in laboratorial works.

Special thanks to all my parents, wife, and friends for their moral supports along the journey to complete this research. Last but not least, many thanks to everyone who had been contributed directly or indirectly to the success of this research.

© Universiti Teknikal Malaysia Melaka

TABLE OF CONTENTS

Page

DECLARATION
DEDICATION
ABSTRACT **i**
ABSTRAK **ii**
ACKNOWLEDGEMENT **iii**
TABLE OF CONTENTS **iv**
LIST OF TABLES **viii**
LIST OF FIGURES **xi**
LIST OF APPENDICES **xviii**
LIST OF ABBREVIATIONS **xix**
LIST OF SYMBOLS **xxi**
LIST OF PUBLICATIONS **xxiii**

CHAPTER
1 INTRODUCTION **1**
- 1.1. Background 1
- 1.2. Problem Statement 4
- 1.3. Objective 5
- 1.4. Scope 5
- 1.5. Chapter Outline 6

2 LITERATURE REVIEWS **8**
- 2.1. Wire Bonding Technology 8
- 2.2. Bond Tool and Geometry of The Bonded Wire 10
- 2.3. Wire Bonding Process 13
  - 2.3.1. Ultrasonic Wire Bonding 14
  - 2.3.2. Thermosonic Wire Bonding 16
- 2.4. Wire Materials 17
- 2.5. Bond Pad Materials 21
- 2.6. High Temperature Storage (HTS) Treatment 23
- 2.7. Thermosonic Cu-Al Bonding Technology and Its Limitations 24
  - 2.7.1. Cu-Al Intermetallic Compound 25
  - 2.7.2. Cu-Al Phase Diagram 26
  - 2.7.3. Bonding Temperature and Its Effects on The Growth of Interfacial Cu-Al IMC 31
  - 2.7.4. Forming Gas Supply 33
- 2.8. Common Analytical Tools For Assessing Cu-Al Bonding Interface 35
  - 2.8.1. Field Emission Scanning Electron Microscope 36
  - 2.8.2. Transmission Electron Microscope 40
  - 2.8.3. Energy Dispersive X-ray 43
  - 2.8.4. Nano Beam Diffraction 46
  - 2.8.5. X-ray Diffraction 47

© Universiti Teknikal Malaysia Melaka

2.8.6. Mechanical Ball Shear Test 50
2.9. Stress Analysis 51
2.10. Statistical Approach 55
2.10.1. Taguchi Method 55
2.10.2. Analysis of Variance 58
2.10.3. Regression analysis 61
2.11. Summary 63

3 METHODOLOGY 66
3.1. The Synthesis of Cu Wire-Al Bond Pad Samples 68
3.1.1. Design of Experiment 70
3.2. Sample Preparation 74
3.2.1. Mechanical Cross-Section for Microscopic Analysis 75
3.2.2. Focused Ion Beam (FIB) Milling for Lamella Extraction 77
3.2.3. Sample Collection of Cu Wire-Al Bond Pad for XRD Measurements 78
3.3. Characterizations of Cu-Al Samples 80
3.4. Modelling of Stress Developed at Cu-Al Bonding Interface 82
3.4.1. Equations for Thermal Misfit and Diffusion-Induced Stresses 83
3.4.2. Predictions of Material Properties of Solid Solution 87
3.4.3. Relationship between Concentrations (C_s, C_i and x) 89
3.4.4. Partial Molar Volume of Solid Solution 90
3.5. Summary 93

4 RESULTS 94
4.1. Effects of HTS Toward the Microstructures of Cu-Al Bonding Interface 94
4.1.1. Cu-Al Samples Synthesized At 100°C 95
4.1.1.1. Imaging Analysis of Cu-Al Bonding Interface by FESEM 95
4.1.1.2. Compositional Analysis of Cu-Al Bonding Interface by EDX 101
4.1.1.3. STEM, EDX and NBD Analyses on Selected Cu-Al Samples 106
4.1.1.4. Total IMC Thickness Measurement Analysis 113
4.1.1.5. Mechanical Ball Shear Test Analysis 114
4.1.2. Cu-Al Samples at Bonding Temperature of 280°C 115
4.1.2.1. FESEM Imaging Studies of Cu-Al Bonding Interface 115
4.1.2.2. EDX Compositional Studies of Cu-Al Bonding Interface 122
4.1.2.3. STEM and EDX Analyses on Samples Before and After 1000 hours of HTS Treatment 127
4.1.2.4. Total Cu-Al IMC Thickness Analysis 137
4.1.2.5. Mechanical Ball Shear Test Analysis 138
4.1.3. Cu-Al Samples Synthesized at Bonding Temperature of 400°C 139

© Universiti Teknikal Malaysia Melaka

4.1.3.1. Morphological Studies of Cu-Al Bonding Interface by FESEM 139
4.1.3.2. Compositional Studies of Cu-Al Bonding Interface by EDX 145
4.1.3.3. STEM and EDX Analyses on Selected Cu-Al Samples Synthesized at 400°C 149
4.1.3.4. Total IMC Thickness Measurement Analysis 157
4.1.3.5. Mechanical Ball Shear Test Analysis 159
4.2. Effect of Forming Gas Supply Towards The Micro-Structure of Interfacial IMC 160
4.2.1. Cross-Sectional FESEM Imaging Analysis at Cu-Al Bonding Interface 160
4.2.2. STEM and EDX Analyses at Cu-Al Bonding Interface 162
4.2.3. Mechanical Studies of Ball Shear Test 174
4.3. Mechanical Ball Shear Performance Analysis by Taguchi approach 175
4.4. STEM and EDX Analyses at Cu-Al Bonding Interface for Taguchi Sample Matrix 179
4.4.1. Characterizations on Annealed Sample Synthesized at 100°C Without Forming Gas Supply 179
4.4.2. Characterizations on Annealed Sample Synthesized at 280°C With Forming Gas OFF 184
4.4.3. Characterizations on Annealed Sample Synthesized at 400°C Without Forming Gas Supply 187
4.5. XRD Characterization With Two Different Sample Preparation Techniques 191
4.5.1. By Mechanical Collection Technique 191
4.5.2. By Chemical Etching Technique 199
4.6. Theoretical Modelling 201
4.6.1. Prediction of Elastic Properties of Solid Solution 201
4.6.2. Prediction of Concentration of Solute and Partial Molar Volume of Solid Solution 205
4.6.3. Prediction of Stresses 207
4.6.4. Stress Analysis to Evaluate the Effect of Bonding Temperatures 208
4.6.5. Stress Analysis To Assess the Effect of HTS Treatment 211
4.6.5.1. For Cu-Al Samples Synthesized at 100°C 211
4.6.5.2. For Cu-Al Samples Synthesized at 280°C 212
4.6.6. Stress Analysis to Evaluate the Effect of Forming Gas Supply 214
4.6.7. Stress Analysis Based on Taguchi Orthogonal Matrix 216
4.7. Applications of Taguchi Method on The Stresses Generated at Cu-Al Bonding Interface 220
4.8. Summary 222

5 DISCUSSION 225
5.1. IMC Growth at The Bonding Interface and Its Correlation to The 225

© Universiti Teknikal Malaysia Melaka

Mechanical Bond Strength
5.2. Relationship Between Ball Shear Strength and Bonding Parameters 229
5.3. Chemical Composition Distribution Across The Bonding Interface 230
5.4. Grain Boundary Diffusion at Low Bonding Temperature 232
5.5. The Presence of Oxide Layers at Cu-Al Bonding Interface 233
5.6. Formation of Gap Within The Oxide Layer at Cu-Al Bonding Interface 237
5.7. Possible Mechanism of The Formation of Uncommon Features at Cu-Al Bonding Interface 240
5.8. Summary 245

6 CONCLUSION AND RECOMMENDATIONS FOR FUTURE STUDIES 247
6.1. Conclusion 247
6.2. Contributions To Knowledge 248
6.3. Recommendations For Future Studies 249

REFERENCES 251
APPENDICES 264

© Universiti Teknikal Malaysia Melaka

LIST OF TABLE

Table	Title	Page
2.1	Comparison between wire bonding technologies (Harman, 2010; Pan and Fraud, 2004; Charles, 2007; Lum et al., 2006; Xu et al., 2008)	11
2.2	Material properties comparison between Cu and Au (Calister, 2004).	20
2.3	Micro-structural and physical properties of Cu-Al phases (Xu, 2010).	28
2.4	Wire bonding parameters applied in some of the reports focus on Thermosonic Cu-Al system.	32
2.5	d_{hkl} for various crystal systems and their relationship with Miller indices.	49
2.6	Orthogonal array (L9) (Puh et al., 2012)	56
2.7	S/N equations for different quality characteristic (Nalbant et al., 2007)	57
2.8	Standard two way AVONA arrangement (Sahai and Ageel, 2000).	59
2.9	Examples of critical F values based on α=0.10 (Walck, 2007).	61
3.1	Optimized Thermosonic wire bonding parameters used to synthesize Cu-Al samples.	69
3.2	Full factorial sample matrix of Cu-Al samples.	71
3.3	Taguchi L9 Orthogonal Matrix used to synthesize Cu-Al samples.	72
3.4	Sample matrix of Cu-Al samples for direct comparisons.	73
3.5	Sample Matrix to evaluate the effect of HTS treatment on Cu-Al samples. Forming gas supplies were turned ON.	74

© Universiti Teknikal Malaysia Melaka

4.1 Summary of EDX measurements of sample synthesized at 100°C. 102

4.2 Summary of predicted Cu-Al phases from FESEM EDX for sample synthesized at 100°C. 104

4.3 Summary of compositional analysis on as-synthesized sample produced with 100°C. 109

4.4 Summary of compositional analyses on sample synthesized at 100°C after 1000 hours of HTS. 112

4.5 Summary of EDX measurements of sample synthesized at 280°C. 123

4.6 Summary of predicted phases for sample synthesized at 280°C. 124

4.7 Summary of compositional analysis of Cu-Al bonding interface interpreted from Figure 4.19. 130

4.8 Summary of compositional analysis of sample synthesized at 280°C after 1000 hours of HTS. 136

4.9 Summary of EDX measurements of sample synthesized at 400°C. 146

4.1 Summary of predicted phases for sample synthesized at 400°C. 147

4.11 Summary of compositional analysis of Cu-Al bonding interface of the sample synthesized at 400° before HTS treatment. 152

4.12 Summary of compositional analysis of Cu-Al bonding interface of the sample synthesized at 400° after 500 hours HTS treatment. 157

4.13 Summary of compositional analysis of the Cu-Al sample synthesized at 280°C and without forming gas supply. 173

4.14 Results of ball shear measurements of the Cu-Al samples and their S/N ratio. 176

4.15 Response Table for S/N ratio. 176

4.16 Comparison between the predicted and measured S/N ratio and shear strength of the Cu-Al samples. 177

4.17 ANOVA of ball shear strengths of the Cu-Al samples. 178

4.18 Summary of the compositional analysis on sample S4 183

4.19 Summary of the compositional studies on sample S5. 187

4.20 Summary of the compositional analysis of sample S9. 190

4.21 Summary of crystallographic detail of phase detected. 197

© Universiti Teknikal Malaysia Melaka

4.22 Material related constants used in the analysis (Calister, 2004). 202

4.23 Results of the predicted stress and their S/N ratio 220

4.24 Response table for the S/N ratio of the stresses predicted. 221

5.1 Features and stresses of various locations at Cu-Al bonding interface of S1. 239

© Universiti Teknikal Malaysia Melaka

LIST OF FIGURE

Figure	Title	Page
2.1	Illustrations of (a) ceramic capillary, (b) cross-sectional view of the tapered tip of (a). Modified from (CoorsTek, 2014)	12
2.2	Illustrations of (a) ball bond and (b) wedge bond. Modified from (Charles, 2009)	13
2.3	The illustrations for the process flow of Ultrasonic wedge bonding. Modified from (Harman, 2010).	15
2.4	The illustration for the process flow of Thermosonic ball bonding. Modified from (Harman, 2010).	18
2.5	Four tiered ball bond management in a micro-chip for graphic processing applications (Singh et al., 2005).	20
2.6	The appearance of IMC layer in sample synthesized at 280°C after 500 hours of HTS 175°C.	26
2.7	Binary Cu-Al thermal equilibrium phase diagram (ASM, 1992).	28
2.8	Comparison of FESEM micrograph of Cu FABs synthesized with (a) forming gas ON, (b) forming gas OFF (Lee et al., 2010).	34
2.9	The design of a common copper kit. (Breach, 2010).	34
2.10	The construction of a conventional SEM equipment (Zhou et al., 2007).	37
2.11	SEM micrographs show the structures of (a) thermionic and (b) field effect electron sources (Spectral solutions, 2014).	38
2.12	Illustration of signal generations resulted from interactions between incident electron and the surface of a sample (Fultz and Howe, 2013).	40
2.13	Construction of TEM equipment (Fultz and Howe, 2013).	41
2.14	Schematic of an annular detector in a STEM. Modified from (Fultz and Howe, 2013).	43
2.15	The broadening of energetic electron beam in (a) bulk sample, and (b) in thin lamella. Adapted from (Fultz and Howe, 2013).	45

© Universiti Teknikal Malaysia Melaka

2.16 Illustration of EDX measurements taken at Cu, IMC and Al. Overlapping of the interaction volume and Cu bulk results occurs when EDX measurement is taken close to the Cu-IMC interface. 45
2.17 An indexed XRD diffractogram of Al thin film (Birkholz, 2006). Inset shows the similar diffractogram with y-axiz in square-root of count rate. 48
2.18 Mechanical ball shear test configuration (Harman, 2010). 51

3.1 Flow chart of the processes of the experiment. 67

3.2 The illustration of the structure of the synthesized Thermosonic Cu-Al sample. 69

3.3 OM images of cross-sectioned samples with (a) a smooth polished bonding interface, and (b) a damaged bonding interface. 77
3.4 The geometrical considerations of the multi-layer structure. 85

3.5 The illustration of the process flow of the stress calculation. (a) The composition measurements, (b) the calculated x_{Cu} profile from (a), (c) the converted C profile, (d) Predicted elastic material properties, (e) predicted stresses profile. 92
4.1 FESEM micrographs of the cross-sectional Cu-Al bonding interface synthesized at 100°C before HTS treatment. 96
4.2 FESEM micrographs of cross-sectional Cu-Al bonding interface synthesized at 100°C after 200 hours of HTS treatment. 97
4.3 FESEM micrographs of cross-sectional Cu-Al bonding interface synthesized at 100°C after 500 hours of HTS treatment. 98
4.4 FESEM micrographs of cross-sectional Cu-Al bonding interface synthesized at 100°C after 700 hours of HTS treatment. 99
4.5 FESEM micrographs of cross-sectional Cu-Al bonding interface synthesized at 100°C after 1000 hours of HTS treatment. 100
4.6 (a) STEM overview of the lamella of sample synthesized at 100°C before HTS treatment. The magnified micrographs at selected regions are shown in inset (b) to (d). 108
4.7 (a) to (d) line scan EDX profiles (i) to (iv) as defined in Figure 4.6, respectively. 108
4.8 NBD pattern taken from the IMC grain. 109

4.9 (a) STEM overview of the lamella of sample synthesized at 100°Cafter 1000 hours of HTS treatment. (b) to (d) show the magnified micrograph at selected regions. 111
4.10 (a) to (c) were results of line scan EDX (i) to (iii) as defined in Figure 4.9, respectively. 111
4.11 (a) The plot of total IMC thickness versus HTS durations for sample synthesized at 100°C, (b) Results of linear regression analysis. 114

© Universiti Teknikal Malaysia Melaka

4.12 Box plot of ball shear strength versus HTS durations for samples synthesized at the bonding temperature of 100°C. 115

4.13 FESEM micrographs of the cross-sectional Cu-Al bonding interface synthesized at 280°C before HTS treatment. 117

4.14 FESEM micrographs of the cross-sectional Cu-Al bonding interface synthesized at 280°C after 200 hours of HTS treatment. 118

4.15 FESEM micrographs of the cross-sectional Cu-Al bonding interface synthesized at 280°C after 500 hours of HTS treatment. 119

4.16 FESEM micrographs of the cross-sectional Cu-Al bonding interface synthesized at 280°C after 700 hours of HTS treatment. 120

4.17 FESEM micrographs of the cross-sectional Cu-Al bonding interface synthesized at 280°C after 1000 hours of HTS treatment. 121

4.18 (a) STEM overview of the lamella of the Cu-Al bonding interface synthesized at 280°C before HTS treatment. (b) to (c) show the magnified micrographs at selected regions. 128

4.19 (a) to (c) were line scan EDX Cu-Al profiles of measurements (i) to (iii) as defined in Figure 4.18, respectively. 128

4.20 (a) STEM overview of the lamella of sample synthesized at 280°C after 1000 hours of HTS treatment. (b) to (d) show the magnified micrograph at selected regions. 131

4.21 Magnified STEM micrograph revealed the existence of the particles and stripes features in the IMC with darker. Synthesized conditions: bonding temperature 280C and after 1000 hours of HTS treatment. 132

4.22 (a) to (f) were line scan EDX profiles (i) to (vi) as defined in Figure 4.20, respectively. 133

4.23 NBD diffraction pattern that matched the diffration from zone axis [-1 -2 0] of θ phase. 133

4.24 (a) The plot of total IMC thickness versus HTS durations for the Cu-Al samples synthesized at 280°C, (b) Results of the corresponding linear regression analysis. 137

4.25 Box plot of ball shear strength versus HTS durations for the Cu-Al samples synthesized at the bonding temperature of 280°C. 138

4.26 FESEM micrographs of the cross-sectional Cu-Al bonding interface synthesized at 400°C before HTS treatment. 140

4.27 FESEM micrographs of the cross-sectional Cu-Al bonding interface synthesized at 400°C after HTS 200 hours. 141

4.28 FESEM micrographs of the cross-sectional Cu-Al bonding interface synthesized at 400°C after HTS 500 hours. 142

4.29 FESEM micrographs of the cross-sectional Cu-Al bonding interface synthesized at 400°C after HTS 700 hours. 143

4.30 FESEM micrographs of the cross-sectional bonding interface synthesized at 400°C after HTS 1000 hours. 144

© Universiti Teknikal Malaysia Melaka

4.31 (a) STEM overview of the lamella of sample synthesized at 400°C before HTS treatment. (b) to (d) show the magnified micrograph at selected regions. 151

4.32 (a) to (c) show line scan EDX profiles of measurements (i) to (iii) as defined in Figure 4.31, respectively. 151

4.33 (a) STEM overview of the lamella of sample synthesized at 400°C after 500 hours of HTS treatment. (b) to (d) show the magnified micrograph of the selected regions around the bonding interface. 153

4.34 Results of EDX line scan measurements as defined by arrow (i) to (v) in Figure 4.33. 153

4.35 (a) The plot of total IMC thickness versus HTS durations for Cu-Al sample synthesized at 400°C, (b) the results of the corresponding linear regression analysis. 158

4.36 Box plot of ball shear strength versus HTS durations for Cu-Al samples synthesized at the bonding temperature of 400°C. 159

4.37 FESEM micrographs of the cross-sectioned of the as-synthesized Cu-Al sample produced at 280°C and without the forming gas supply. 161

4.38 Bright field TEM micrograph of the Cu-Al sample synthesized at 280°C and without forming gas supply. (a) to (d) are magnified micrographs that revealed voids and IMC features. Inset (e) shows a magnified STEM micrograph that better visualize the present of IMC. 163

4.39 OM images of (a) a symmetrical non-oxidized ball bond and (b) an asymmetrical and off-centred oxidized ball bond. 165

4.40 Bright field TEM micrographs of Cu-Al bonding interface synthesized at 280°C and with forming gas supply ON. (a) to (d) are magnified micrographs that revealed voids and IMC features at the bonding interface. (c) is a dark field image. 167

4.41 IMC thickness comparison between sample with and without forming gas supply. 168

4.42 Line scan EDX results across an IMC layer of (a) sample with forming gas ON, (b) sample with forming gas OFF. 169

4.43 STEM micrographs of the as-synthesized sample bonded with bonding temperature 280°C and forming gas OFF. (a) represents the overview micrograph of the lamella. (b) to (d) are magnified micrographs at selected region of the lamella. 171

4.44 Composition profiles across the Cu-Al bonding interface as defined by arrows (i) to (vi) in Figure 4.43. 171

4.45 (a) and (b) are the FESEM micrographs for the Cu-Al bonding interface synthesized with forming gas supply OFF and ON, respectively. Insets show magnified micrograph in high stress regions for IMC thickness measurements. 174

4.46 The response graph of S/N ratio of ball shear strength with different factors and levels. 177

4.47 STEM micrographs of the sample S4 synthesized with bonding temperature 100°C, forming gas OFF and after 500 hours of HTS treatment. (a) shows the overview micrograph of the lamella. (b) to (d) are magnified micrographs at 181

© Universiti Teknikal Malaysia Melaka

some selected regions around the bonding interface.

4.48 (a) to (d) show the line scan EDX results measured along arrow (i) to (iv) defined in Figure 4.47. 181

4.49 NBD diffraction patterns obtained from the IMC. The indexing of the diffraction patterns matched (a) [1 -1 0] from θ, and (b) [-9 -7 6] from η_2 phases. 182

4.50 STEM micrographs of the sample S5 synthesized at 280°C with forming gas OFF and after 500 hours of HTS treatment. (a) shows the overview micrograph of the lamella. (b) and (c) are magnified micrographs at selected regions at the bonding interface. 186

4.51 (a) to (c) show the line scan EDX results measured along arrow (i) to (iv) as defined in Figure 4.50. 186

4.52 STEM images of sample S5 that was synthesized at 400°C without forming gas supply and after HTS 1000hours. (a) was the overview micrograph, (b) to (d) were the magnified micrographs at the selected RoIs. 188

4.53 Compositional studies on sample S9. (a) to (d) were the measurements' results taken along arrow (i) to (iv) as defined in Figure 4.52. 188

4.54 (a) The optical image of the wire bonded specimen in leadframe form. (b) The schematic demonstrating the material configurations of a unit of specimen. 192

4.55 OM image of crushed specimen prepared by the manual collection of the wires and micro-chips. 193

4.56 (a) FESEM of the crushed Cu-Al specimen, (b) corresponding EDX results 193

4.57 (a) Optical micrograph of a bundle of the specimen consisted of Cu wires and Al bond pads. (b) magnified optical micrograph showing the existence of Al under Cu ball bond. 194

4.58 EDX analysis on the bottom side of the ball bond. Al was detected. 195

4.59 XRD diffractograms for the specimens prepared with three different methods. 196

4.60 (a) The diffractogram from XRD measurement using Noiseless sample holder. (b) A duplicate of diffractogram from Figure 4.59(b). 198

4.61 SEM EDX validation on the elimination of Cu-Al IMC after etching with KOH 50%. 200

4.62 Diffractograms after KOH etching with different concentrations. 201

4.63 (a) The reference model of Cu-Al metal couple with a layer of solid solution sandwiched between the pure metals. (b) The plot of Cu concentration versus the thickness of the solid solution. 202

4.64 The comparison of reported and predicted values of (a) shear, (b) bulk and (c) Young's moduli. 204

© Universiti Teknikal Malaysia Melaka

4.65	The plot of the predicted solute concentration, C versus fractional concentration of Cu, x_{Cu}.	206
4.66	The plot of the calculated partial molar volume of the solid solution, $\tilde{V}$ versus x_{Cu}.	206
4.67	The calculated distribution of three components of the diffusion induced stress.	207
4.68	(a) STEM images on the IMC formation at the bonding interface. (b) The corresponding x_{Cu} profile. (c) The corresponding predicted stresses. (i) to (iii) represent the results of the samples synthesized at 100, 280 and 400°C.	209
4.69	(a) STEM image of S7 synthesized at 100°C after 1000 hours of HTS treatment. (b) x_{Cu} profile obtained from the EDX measurement defined in (a). (c) The predicted stress profile along the EDX line across the bonding interface.	212
4.70	(a) STEM image of the bonding interface of S8 synthesized at 280°C after 1000 hours of HTS treatment. (b) x_{Cu} profile calculated from the EDX measurement defined in (a). (c) The predicted stress profile from x_{Cu} profile.	213
4.71	(a) STEM image of the bonding interface of S1 synthesized at 280°C before HTS treatment. (b) x_{Cu} profile calculated from the line scan EDX measurement defined in (a). (c) The predicted stress profile from x_{Cu} profile.	215
4.72	(a) STEM micrograph of sample S4 synthesized at 100°C without forming gas supply and after 500 hours of HTS treatment. (b) The calculated x_{Cu} profile from EDX measurement defined in (a). (c) The predicted stress distribution.	216
4.73	(a) STEM micrograph of sample S5 synthesized at 280°C without forming gas supply and after 500 hours of HTS treatment. (b) The x_{Cu} profile from the EDX measurement defined in (a). (c) The calculated stress distribution.	218
4.74	STEM micrograph of sample S6 synthesized at 400°C with forming gas ON and after 500 hours of HTS treatment. (b) the x_{Cu} profile from the EDX measurement specified in (a). (c) The predicted stress distribution.	218
4.75	STEM micrograph of sample S9 synthesized at 400°C with forming gas OFF and after 1000 hours of HTS treatment. (b) the x_{Cu} profile from the EDX measurement specified in (a). (c) The predicted stress distribution.	219
5.1	IMC thickness versus HTS durations for the bonding temperatures of (a) 100, (b) 280 and (c) 400°C.	226
5.2	Histogram of the ball shear strength distribution of samples prepared with different temperatures and HTS durations.	228
5.3	The plot of ball shear strength versus total IMC thickness.	228
5.4	The chemical composition distribution at both central and peripheral RoIs.	232
5.5	Chemical compositional distribution at Cu-Al bonding interfaces of (a) S10, (b) S8 and (c) S6.	234
5.6	(a) to (d) show the composition profiles of the bonding interface of samples S1, S4, S5 and S9, respectively.	236

© Universiti Teknikal Malaysia Melaka

5.7 The compiled composition profiles and their respective stress profiles of sample S1. 239

5.8 STEM micrograph of sample synthesized at 280°C with forming gas supply. (a) and (b) were that before and after 1000 hours of HTS treatment, respectively. Insets in (b) show the magnified micrographs that reveals the presence of rod and stripe-like features. 241

5.9 STEM micrograph shows the appearance of stripes and rods-like feature present at Cu-Al bonding interface. 243

5.10 Schematics of proposed mechanism of formations of uncommon features. (a) the initial thin IMC formation, (b) with prolonged HTS, volume and lateral diffusions of Cu atoms occurred simultaneously, (c) Upon consumption of the bond pad, the diffused Cu atoms partially penetrated into Si together with inversed diffusion to thicken a new IMC layer with higher Cu content, (d) the formations of stripes, rods-like features and periodic Cu composition were observed. 244

5.11 STEM micrograph of sample S6. The structure of the IMC formed was apparently rods-like. 244

© Universiti Teknikal Malaysia Melaka

LIST OF APPENDICES

APPENDIX	TITLE	PAGE
A	Derivations of ε_{t0}, ρ_t, ε_{c0} And ρ_c	264
B	Derivations of Conversion Equations	269
C	Derivation of The Number of Mole of Solute Atoms per unit Volume, *C*	272

© Universiti Teknikal Malaysia Melaka

LIST OF ABBREVIATIONS

Al	-	Aluminum
ASM	-	American Society for Metals
Au	-	Gold
BGA	-	Ball Grid Array
BST		Ball Shear Test
CTE	-	Coefficient of Thermal Expansion
Cu	-	Copper
EDX	-	Energy Dispersive X-Ray
EFO	-	Electro-Flame-Off
FAB	-	Free-Air-Ball
FESEM	-	Field Emission Scanning Electron Microscope
GB	-	Grain Boundary
HTS	-	High Temperature Storage
IMC	-	Intermetallic Compound
JEDEC	-	Joint Electronic Device Engineering Council
Ni	-	Nickel
SEM		Scanning Electron Microscope
Si	-	Silicon
STEM	-	Scanning Transmission Electron Microscope
W	-	Tungstun
XRD	-	X-Ray Diffraction

© Universiti Teknikal Malaysia Melaka