Faculty of Industrial and Manufacturing Technology and Engineering

THERMOSONIC MICRO-INTERCONNECTIONS: INTERFACIAL Cu-Al INTERMETALLICS COMPOUND GROWTH STUDIES BASED ON STRESS MODELLING

Shariza Binti Sharir

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SHARIZA BINTI SHARIR

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

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DECLARATION

I declare that this thesis entitled "Thermosonic Micro-Interconnections: Interfacial Cu-Al Intermetallics Compound Growth Studies Based On Stress Modelling" is the results 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 : Shariza Binti Sharir

Date : 18 January 2024

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 : Professor Dr. Mohd Warikh Bin Abdul Rashid

Date : 18 January 2024

DEDICATION

To you, who puts me on top of the world.

and

To all of you, who cared and believed.

" Success is the sum of small efforts, repeated day in and day out."

Robert Collier

" The more that you read, the more things you will know,
the more that you learn, the more places you'll go."

Dr. Seuss

ABSTRACT

One of the most common wire bonding technology involving copper (Cu) wire interconnections is the thermosonic bonding technique. Still, the volumetric changes of intermetallic compounds (IMCs) formed at the bonding interface of Cu wire on Al bond pads induce voids formation in the Cu-Al IMC layer. This is much apparent especially after an annealing treatment of High Temperature Storage (HTS). Effects of Cu free air ball and bonding temperature with high temperature storage (HTS) treatment on Cu-Al bonding interface are unclear due to varying observations and inconsistencies in the bonding parameters. A quantitative stress analysis via statistical modelling was constructed to study the characteristic and formation of thermosonic Cu wire-Al bond pad system interfacial microstructure evolution. Objectives of this research are; (1) to study the characteristic and formation of Cu-Al IMC interfacial microstructure layer in thermosonic Cu wire-Al bond pad bonding process based on various bonding temperatures, Cu oxidation condition and HTS durations; (2) to study the influence of the Cu-Al IMC formation to the electrical contact resistance of the system. (3) to develop a theoretical model that describe the interfacial stress field of the Cu wire-Al bond pad system in terms of Cu-Al phase evolution. Microstructural characterizations were focused on Cu-Al IMC crystallographic system and compositional classification. Ball bond mechanical strength analysis were carried out to evaluate the bonding parameters with its strength. The bonding temperature was found to affect the thickness of the initial IMC layer formed at the bonding interface. The amount of the initial IMC formation in turn influences the saturation thickness of the IMC after HTS treatment. In the theoretical part, a stress model was proposed by coupling of both thermal misfit and diffusion induced stresses. It was found that the stress developed by interfacial Cu-Al IMC generally increased with the bonding temperature. The influence of forming gas supply was found to be less significant to affect the interfacial stress development, as the oxide layers did not hinder much the interdiffusion of Cu and Al atoms in the Cu-Al IMC formation. This report addressed the research gaps and presented a better understanding of the fundamental of interfacial Cu-Al IMC in thermosonic micro-interconnection. The results of the stress modelling could be a useful failure analysis technique for implementing Cu wire in the industry. In conclusion, the identified key parameters influencing Cu-Al IMC development and mechanical strength are in the following sequence: HTS duration > bonding temperature > forming gas supply as presented in the correlation matrix of various variables.

SALING SAMBUNGAN MIKRO TERMOSONIK : KAJIAN PERTUMBUHAN SEBATIAN ANTARA LOGAM ANTARA MUKA Cu-Al BERDASARKAN PEMODELAN TEGASAN

ABSTRAK

Salah satu teknologi ikatan dawai yang paling lazim yang melibatkan sambungan wayar logam kuprum, Cu ialah teknik ikatan termosonik. Namun, perubahan isipadu sebatian antara logam (SAL) yang terbentuk pada permukaan Cu dan tapak Al mendorong pembentukan ruang-ruang kosong dalam lapisan intermetalik Cu-Al. Ini amat ketara terutamanya selepas rawatan Penyimpanan Suhu Tinggi (PST). Kesan bebola udara bebas wayar Cu dan suhu sambungan dengan rawatan PST ke atas system intermetalik Cu-Al adalah tidak jelas disebabkan oleh pemerhatian yang berbeza-beza dan parameter sambungan wayar yang dikaji secara tidak konsisten. Pendekatan statistik dicadangkan adalah lebih berguna untuk menangani kekangan ini. Analisis tekanan kuantitatif melalui model statistik dipercayai boleh menutup jurang penyelidikan ini. Objektif penyelidikan ini adalah (1) untuk mengkaji ciri-ciri dan pembentukan struktur mikro antara ikatan dawai Cu pada permukaan pad Al, yang dijana melalui kaedah termosonik yang dimanipulasi berdasarkan pelbagai suhu ikatan, keadaan pengoksidaan Cu dan tempoh PST; (2) untuk mengkaji pengaruh pembentukan Cu-Al IMC kepada rintangan sentuhan dalam system elektrik unit tersebut; dan (3) untuk membangunkan model teori yang menerangkan medan tekanan antara muka sistem pad ikatan dawai-Al Cu dari segi evolusi fasa Cu-Al. Analisa mikrostruktur tertumpu pada sistem kristalografi intermetalik Cu-Al dan klasifikasi komposisi. Analisis kekuatan mekanikal ikatan bola dikaji untuk menyiasat kesan parameter ikatan dawai terhadap kekuatannya. Suhu ikatan didapati mempengaruhi ketebalan lapisan SAL awal yang terbentuk pada lapisan intermetalik Cu-Al. Kadar pembentukan SAL awal pula mempengaruhi ketebalan pembentukan SAL selepas rawatan PST. Dalam bahagian teori, model tekanan telah dicadangkan dengan gandingan kedua-dua ketidaksesuaian haba dan tekanan resapan dalam system intermetalik Cu-Al. Pemerhatian mendapati bahawa tekanan yang dibangunkan oleh lapisan SAL Cu-Al secara amnya meningkat dengan suhu proses ikatan dawai tersebut. Pengaruh pembentukan bekalan gas didapati kurang ketara dan tidak menjejaskan perkembangan tekanan antara muka yang jelas kerana lapisan oksida tidak banyak menghalang proses interdifusi antara atom-atom Cu dan Al dalam pembentukan lapisan SAL Cu-Al. Laporan ini menangani jurang penyelidikan dan membentangkan pemahaman yang lebih baik tentang asas pembentukan tekanan antara muka penyambungan Cu-Al termosonik. Keputusan pemodelan tegasan boleh menjadi suatu teknik analisis yang berguna untuk mengkaji penyambungan wayar Cu dalam industry secara lebih mendalam. Kesimpulannya, parameter utama yang dikenal pasti mempengaruhi perkembangan intermetalik Cu-Al adalah dalam tertib berikut: tempoh PST >suhu ikatan > bekalan gas pembentukan seperti yang dipersembahkan dalam matriks korelasi pelbagai pembolehubah.

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LIST OF ABBREVIATIONS

Al - Aluminum

Au - Aurum

BSE - Back Scattered Electron

BST - Ball Shear Test

CTE - Coefficient of Thermal Expansion

Cu - Copper

EDX - Energy Dispersive X-Ray

EFO - Electronic Flame Off

FAB - Free Air Ball

FCC - Face Centered Cubic

FESEM - Field Emission Scanning Electron Microscope

FG - Forming Gas

HTS - High Temperature Storage

IMC - Intermetallic Compound

IC - Integrated Circuit

JEDEC - Joint Electron Device Engineering Council

SEM - Scanning Electron Microscope

Pd - Palladium

SiC - Silicon Carbide

Si - Silicon

HAADF - High Angle Annular Dark Field

TEM - Transmission Electron Microscope

WPT - Wire Pull Test

TC - Temperature Cycling

PCT - Pressure Cooker Test

OM - Optical Microscope

XRD - X-Ray Diffraction

LIST OF SYMBOLS

ρ	- Radius Of Curvature
μ	- Shear Modulus
σ	- Stress
E	- Elastic Modulus
κ	- Bulk Modulus
α	- Coefficient of Thermal Expansion
T	- Temperature
s	- Substrate
i	- Layer-i
ε	- Normal Strain At x-axis
D	- Mass Density
$\overline{V}$	- Partial Molar Volume
A	- Atomic Weight
ΔV	- Volume Change
V	- Volume
R	- Atomic Radius
n	- Number of Mole
α-Al	- Al Phase
θ	- $CuAl_2$ Phase
η2	- CuAl Phase
ξ2	- Cu_4Al_3 Phase
δ	- Cu_3Al_2 Phase

$\gamma 1$	- Cu_9Al_4 Phase
$\alpha 2$	- Cu Phase
(Cu)	- Cu Rich Terminal Solid Solution
(Al)	- Al Rich Terminal Solid Solution
A	- Area
C	- Concentration of Solute
GPa	- Giga Pascal
Å	- Armstrong
nm	- nanometer
at%	- Atomic Percentage
wt%	- Weight Percentage
mole	- Mole
NA	- Avogrdro's Number
gcm^{-3}	- Gram per Centimeter Cube
°C	- Degree Celcius
kg/mole	- Kilogram per Mole
kg/m^3	- Kilogram per Meter Cube
$mole/m^3$	- Mole per Meter Cube
µm	- Micrometer
$\bar{x}$	- Mean Value
σ	- Standard Deviation Value

LIST OF PUBLICATIONS

Journals

Parts of this thesis have been published in:

Chua Kok Yau, T. Joseph Sahaya Anand, **S. Shariza,** Yong Foo Khong, Lee Cher Chia, Lim Boon Huat, Ranjit Singh and R.T. Rajendra Kumar, 2020. Statistical analysis on the mechanical and micro-structural characteristics of thermosonic Cu-Al interconnection. *Microelectronics Reliability*, 109, pp. 113664.

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T. Joseph Sahaya Anand, **S. Shariza,** Chua Kok Yau, A.R.M. Warikh, Kok-Tee Lau and Lim Boon Huat. Electrical studies of Cu wire interconnections in electronic packages upon high temperature storage. Presented at: *The 4th International Symposium in Research in Innovation and Sustainability (ISoRIS 2019)*, 28-29 August 2019, Penang, Malaysia.
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Won the Best Paper Award.