UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Faculty of Manufacturing Engineering

MODELLING OF WIRE BONDING CU-AL INTERMETALLIC FORMATION GROWTH TOWARDS INTERFACIAL STRESS

Lee Cher Chia

Master of Manufacturing Engineering
(Manufacturing System Engineering)

2017

MODELLING OF WIRE BONDING CU-AL INTERMETALLIC FORMATION GROWTH TOWARDS INTERFACIAL STRESS

LEE CHER CHIA

A thesis submitted
in fulfillment of the requirements for the degree of Master of
Manufacturing Engineering (Manufacturing System Engineering)

Faculty of Manufacturing Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2017

DECLARATION

I declare that this thesis entitle "Modelling of wire bonding Cu-Al intermetallic formation growth towards interfacial 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 : Lee Cher Chia
Date : 8/8/2017

APPROVAL

I hereby declare that I have read this dissertation/report and in my opinion this dissertation/report is sufficient in terms of scope and quality as a partial fulfillment of Master of Manufacturing Engineering (Manufacturing System Engineering).

Signature :

Supervisor Name : **DR. MOHAMAD RIDZUAN BIN JAMLI**
Senior Lecturer
Faculty of Manufacturing Engineering
Universiti Teknikal Malaysia Melaka

Date : 8/8/2017

DEDICATION

To my beloved wife, 3 lovely kids, mother and all family members. You are always my motivation to be where I am today. To my late father, hope you can also share my joy.

ABSTRACT

Quality requirement in the semiconductor industry is getting more stringent due to the application of semiconductor components that are widely used in automotive. Furthermore different materials combination is being introduced to semiconductor packages to improve their package performance and reduce cost. The new materials combination can increase the packages functionality adversely mismatch of different materials properties induced higher interconnection and package stress. With such scenario, quality of interconnects in the semiconductor products need more robust in order to withstand more severe condition and longer life. In this study the interfacial stress of Copper (Cu) Aluminium (Al) intermetallic compound (IMC) structure during high thermal stress condition is focused. Cu wire has been widely accepted as a main-stream interconnects to replace Au wire. Whereas Al bond pad is always the mostly used material for silicon semiconductor bond pad. According to Arrhenius equation, intermetallic growth is proportional to temperature. The Cu-Al IMC is complex due to the nanoscale and multiple phases exist. The Cu-Al IMC layer formed are normally in nanometer thickness, whereas Au-Al IMC is more thicker in micrometer. Analysis performed on Cu-Al IMC required more sophisticated and advanced tools. This is a big challenge for Cu-Al IMC studies. Thus the formation homogenous of Cu-Al IMC is more difficult to form compare to gold (Au) and Al IMC. Therefore using finite elements analysis (FEA) simulations of 3D models of various Cu-Al IMC compounds with different thickness is conducted to understand the stress and strain distribution at IMC layer. The numerical simulation is linear in nature and is based on linear isotropic material properties. Hence the equivalent stress is linear against increment of temperature. The modelling is using thermal-mechanical structure as the loading system. The effect of different IMC compound material properties is examined. From the numerical analysis once the IMC formed between Cu-Al interconnect the interfacial stress increased 22%. The stress reduced ~3% when IMC growth thicker. The equivalent stress saturated when IMC growth more than 50% of the total Al bond pad thickness. Comparing different Cu-Al IMC compound Cu_9Al_4 showed the most dominant impact towards the interfacial stress. Max equivalent stress and max elastic strain point occurred at the edge of Cu bond ball.

ABSTRAK

Keperluan kualiti yang semakin tinggi dalam industri semikonduktor disebabkan oleh penggunaan komponen semikonduktor yang digunakan secara meluas dalam sektor automotif. Tambahan pula kombinasi bahan-bahan yang berbeza diperkenalkan kepada pakej semikonduktor untuk meningkatkan prestasi pakej dan sementara mengurangkan kos. Gabungan bahan-bahan baru boleh meningkatkan fungsi pakej tetapi menyebabkan ketidakpadanan yang buruk. Bahan-bahan yang berbeza ciri-ciri mengakibatkan sambungan yang lebih tinggi dan tegasan pakej. Dengan senario itu, kualiti 'interconnects' dalam produk semikonduktor perlu menjadi lebih mantap untuk menahan keadaan yang lebih teruk dan bertahan lebih lama. Dalam kajian ini, tumpuan diberikan kepada tegasan antara muka sebatian antara logam (IMC,) struktur Tembaga (Cu), dan Aluminium (Al) semasa dalam keadaan tegasan haba yang tinggi. Wayar Cu telah diterima secara meluas sebagai pilihan utama 'interconnects' untuk menggantikan wayar Au. Manakala Al sebagai bahan pad ikatan sentiasa digunakan untuk silikon semikonduktor. Mengikut persamaan Arrhenius, pertumbuhan antara logam adalah berkadar dengan suhu. Cu-Al IMC adalah kompleks kerana skala nano dan pelbagai fasa wujud. Lapisan Cu-Al IMC dibentuk biasanya dalam ketebalan nanometer, manakala Au-Al IMC adalah lebih tebal dalam mikrometer. Analisis dilakukan ke atas Cu-Al IMC diperlukan alat yang lebih canggih dan maju. Ini adalah satu cabaran besar bagi kajian Cu-Al IMC. Oleh itu pembentukan rata Cu-Al IMC adalah lebih sukar untuk membentuk bandingkan dengan emas (Au) dan Al IMC. Oleh itu dengan menggunakan analysis unsur terhingga (FEA), simulasi model 3D pelbagai sebatian Cu-Al IMC dengan ketebalan yang berbeza dijalankan untuk memahami agihan tegasan dan terikan pada lapisan IMC. Simulasi berangka adalah linear secara asas dan adalah berdasarkan kepada sifat bahan linear isotropik. Oleh itu tegasan yang setara adalah linear terhadap kenaikan suhu. Model tersebut menggunakan struktur haba mekanikal sebagai sistem pembebanan. Kesan sifat bahan sebatian yang berbeza ketebalan IMC diperiksa. Dari analisis berangka apabila IMC dibentuk di antara sambungan Cu-Al, tegasan antara muka meningkat 22%. Tegasan mengurang ~ 3% apabila IMC menebal. Tegasan setara tidak berubah apabila pertumbuhan IMC lebih dari 50% daripada jumlah ketebalan Al pad ikatan. Perbandingan yang berbeza kompaun Cu-Al IMC Cu_9Al_4 menunjukkan kesan yang paling dominan terhadap tegasan antara muka. Tegasan setara maksimum dan titik terikan elastik maximum berlaku di pinggir ikatan Cu.

ACKNOWLEDGEMENTS

First and foremost, I would like to take this opportunity to express my sincere acknowledgement to my supervisor Dr. Mohamad Ridzuan Bin Jamli from the Faculty of Manufacturing Engineering, Universiti Teknikal Malaysia Melaka (UTeM) for his essential supervision, support and encouragement towards the completion of this thesis.

I would also like to express my greatest gratitude to Associate Professor Dr. T. Joseph Sahaya Anand Faculty of Manufacturing Engineering, co-supervisor of this project for his advice, suggestions and coordination of CREST R&D grant. Special thanks to Dr. Lim Boon Huat (project leader) and Dr. Chua Kok Yau (technical advisor), who proposed me to this research project.

Particularly, I would also like to express my deepest gratitude to Mr. Hairuldin, the technicians from mechanical design laboratory Faculty of Manufacturing Engineering, for the assistance in the lab.

I would also like to express my truthful gratitude to my superior, Mr. Pradeep, Mr. Seliyan, Mr. Suu MinFoh, Mr. Chong HanWoo for their support during the period of my Master courses.

Special thanks to all my peers, my beloved wife, kids, mother, siblings and late father for their moral support in completing this degree. Lastly, thank you to everyone who had been to the crucial parts of realization of this project.

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CHAPTER 1

INTRODUCTION

1.1 Background

Semiconductor devices bring many advantages to mankind living. Semiconductors are present in most of the modern electronic devices in daily life. Therefore the requirements for electronic semiconductor devices are getting more stringent. Many breakthroughs in materials and processes were to enhance the semiconductor device application. Semiconductors are exactly what the name implies. They have the properties of a conductor, such as metal wiring, and the properties of an insulator in one substance. Having both conductor and insulator function under different condition, this property of making it possible to utilize them as a controllable switch. Essentially, this means that the engineer can utilize them to control the state of components within a system with a very small amount of voltage, resulting in a great deal more voltage or current being sent to another component. Put many of these devices together, which is possible because of modern manufacturing techniques and build an extremely complex system out of very small and durable components.

All these complex circuits are most commonly build on the pure silicon wafers. Then the silicon wafers will be sawn into small pieces. Each sawn pieces is known as a chips which is a complete electrical function. The fully function circuit silicon chip are then protected and packaged by the plastic or ceramic compound. Plastic or ceramic packaging involves mounting the die, connecting the die pads to the pins on the package, and sealing the die. Tiny wires are used to connect the electrical circuits pads to the pins on the package. This process is known as wire bonding process. The process is currently completed by automated machine, wire bonders.

Wire bonding process is an instantaneous welding process that joint electrical circuit on silicon chips to the fan out leadframe. The circuit that packaged on leadframe is finally solder to the PCB board to create a complete function system. Wire bonding process is performed on elevated temperature condition. Meanwhile when bonding free air ball (FAB) contact with bond pad ultrasonic power is applied to enhance the intermetallic compound (IMC) of the 2 metals joint. Therefore the wire bonding process is known as thermosonic bonding, as temperature and ultrasonic is applied during bonding process. Homogeneous IMC formation between Cu-Al enabled diffusion of 2 metals during application. The growth rate and IMC thickness was not easily detected by conventional method e.g. optical and scanning electron microscopes. The thin IMC formation at the thermosonic Cu-Al bonding interface is difficult be detected due to the nano structure. Insufficient of IMC between 2 metals joint will lead to separation under stress condition. A good metal joint is very crucial to ensure the electrical connection maintain the integrity throughout the product application life usage.

Most widely accepted in the market bonding padding pads are by Aluminium (Al) and bonding wires is Gold (Au). However due to the advances in technologies, Copper (Cu) wire bonding technology is now widely held in mass production of semiconductor industry for interconnection. The main benefit is cost advantage against Au wire and secondly enhances product performance and reliability. In recent decade Au price had surge tremendously whereas Cu price was increasing at a more stable pace. Furthermore Cu is also more superior in term of heat and electrical transfer compare to Au. More new products are design in with Cu wire bonding and new wire bonding machine also equipped with Cu wire bonding capability. The market trend shows acceptance of Cu wire bonding products increasing yearly. Thus, Cu wire become the most accepted interconnect material besides Au & Al wire.

However Cu wire property – hardness, is one of the key challenges for wire bonding process. This lead to a more narrow process window compare to Au wire and lead to more reliability risk. Many researches been carried out to overcome the Cu wire bonding challenges. From material aspect, softer Cu wire, robust bond pad, etc. are developed to enhance the process ability. From process aspect, multi-steps bonding is the preferred solution. Multi-steps bonding segmented bonding into impact stage and bonding stage. The impact stage is the first contact of the FAB to the bond pad, which is crucial to form the ball size, ball height and bond pad cratering defect. The bonding stage determines the integrity of bonding. Different impact force by varying the machine setting, the output response is the Al remnant thickness and cratering result. Recent researches showed reaction rate of Cu-Al IMC formation was obtained using the Arrhenius plot and therefore the theoretical IMC thickness can be calculated as a function of time and temperature (Yeoh, 2007 and Kim 2003). However Cu-Al IMC phases is very complex and under different temperature stress condition Cu-Al IMC is changing. Different IMC phase exhibited different properties which will cause the changes of interfacial stress. Due to the complex Cu-Al IMC formation Cu-Al bonding challenges is much more higher compare to Au-Al bonding. Through the numerical modelling a minimum Al remnant thickness and Cu-Al IMC phase at zero hour can be targeted in order for the Cu-Al interface to withstand the thermal reliability stress. As Cu-Al IMC formation is not easily detected using conventional analysis method, numerical modelling will be good tools to predict the correlation between Cu-Al IMC and the changes of interfacial stress. By utilizing numerical modelling characterization of Cu-Al can be more predictable and visualized. Ultimately, optimum setting for impact stage and bonding stage can be identified for a robust bonding.

The purpose of this work is using finite element analysis (FEA) modelling to study the effect Cu-Al IMC compound and thickness towards the interfacial stress. Cu-Al IMC layer is crucial for the reliability of the bonding yet very complex. Recent researches were focus on the characterization of Cu-Al IMC using sophisticated equipment eg. Transmission Electron Microscope (TEM) and X-ray Diffraction (XRD). FEA were widely used for wire bonding force and ultrasonic impact during bonding process and semiconductor package stress analysis. Numerical modelling of Cu-Al IMC and interfacial stress at Cu-Al IMC was not much reported. Insufficient IMC formation will cause premature failure. Understanding the Cu-Al IMC characteristic will be advantage to improve the product performance and broaden the applications.

1.2 Problem Statement

Despite Cu wire can yield a significant cost saving potential for semiconductor packaging industries, its implementation is still limited, especially, for automotive applications. In part due to experience of premature reliability failure and inconsistent manufacturing stability in mass production environment. This unwanted behavior or characteristic is resulted from lack of details and in depth understanding of Cu wire bonding process & bond pad metallization intermetallic formation. Therefore more research is focusing on the Cu bonding technology. Cu bonding is believed to replace Au wire bonding in the near future.

Even though there are many intensive research and development on application of cu wire to replace gold since 80s, the limitation is still not addressed. Also, recent researches showed long duration of high temperature storage (HTS) leads to void formation at Cu wire –Al bond pad (Cu-Al) interface. This can increase the separation gap between IMC and Cu ball, also the electrical resistance of the component. However, the mechanism of the void formation and its influence to electrical failure remain unknown. Besides, effect of wire bonding process parameters towards the interfacial micro-structure and its correlation to void formation at the bonding interface are not well understood. This leads to difficulty for Cu wire implementation in industry.

The Cu-Al intermetallic (IMC) layer formed are normally in nanometer thickness, whereas comparatively Au-Al intermetallic is more thicker in micrometer(Xu et al. 2011b)(Xu et al. 2011b). Researches and analysis performed on Cu-Al IMC required much more sophisticated and advance tools. This was a big challenge for Cu-Al IMC studies. By using software simulation tools the characteristics of Cu-Al IMC can better be understood and quantified.

Researches in the field of thermosonic Cu-Al interconnection lacks of a quantitative description of stress generation originated from phase formation of transformation at the bonding interface. The Cu-Al IMC layer is generally complex as multiple phases of IMC can be found and exist parallel. The Cu-Al IMC can be either Cu rich or Al rich. Different IMC phase will create different interfacial stress within the layer but the quantify stress is not fully identified (Pelzer et al. 2012)(Pelzer et al. 2012).

There is limited simulation done base on the Cu-Al intermetallic layer. Majority Cu-Al thermo sonic bonding simulation researches is on bonding force impact towards bonding reliability. The stress in between IMC layer and among different IMC formation is not widely reported.

1.3 Objectives of the Study

The main objectives of this research study are show as follow :

i. To construct a finite element model of **Al-Cu Intermetallic phase** properties mismatch towards interfacial stress.

ii. To characterize stress distribution at bonding interface base on experimental and modelling results.

1.4 Scope of the Study

This research study will be only focus on the first bond. The numerical modelling of first bond of Cu-Al IMC after completed wire bonding cycle. Material use in this research will be limited by using the pure copper wire and copper base lead frame. Chip bond pad metallization will be focus on aluminium bond pad.

The following are the scopes defined in this project :

1. The numerical modelling of Cu-Al IMC is an axis symmetry model. As Cu ball after bonding process was a cylinder with diameter of 70μm and height of 15μm. The IMC can only formed underneath the Cu ball area.
2. Pure Al and Cu material properties were used for the modelling. Intermetallic formation was also based on pure Al and Cu. The intermetallic phase is static at the point of modelling. The changes and growth of Cu-Al IMC phase was subjected to high temperature storage (HTS) condition.
3. Material constitutive model constructed, including pure metals and their solid solution, was linear elastic and isotropic.
4. Boundary condition : Cu-Al displacement and under thermal stress condition. Temperature was constant during the interdiffusion of materials, and interdiffusion of

materials resulted in solid solution only. No external vibration or stress to enhance the IMC growth.

Theoretical models that described the stress field and interfacial electrical resistance will be developed based on micro-structural characteristics of the Cu-Al interface and experimental parameters. These models that describe tendency of void formation and resistance change in metal-metal couple are the new knowledge in the field. Combination of these models and Finite Element Analysis software enables detail analysis. This research enables generation of useful knowledge for manufacturing robust Cu-Al couple and thus reliable Cu wired micro-electronic components.

1.5 Gantt Chart

Time line for the overall project is shown in Gantt Chart in Appendix A.

CHAPTER 2

LITERATURE REVIEW

In this chapter, key results of the previous research were reviewed. The research gaps justified the direction of the research to be performed in this work. This chapter is organized into three subsections to cover different aspects of the research. It begins with the review of the bonding technology. Followed by the Cu-Al IMC growth and the factor influencing the growth. Then the key techniques for finite element analysis (FEA) modelling were reviewed and discussed.

2.1 Wire Bonding Technology

The advancement in micro-chip designs enables more functionality and capability of the electronic devices. However, these devices could not function without a proper interconnection between the micro-chip and external circuit. More than 90% of the interconnections are achieved by wire bonding technique (Harman 2010). Though there are alternative newer interconnection technologies, e.g. flip-chip assembly and tape automated packaging, however, wire bonding technique remains to be the preferred interconnection solution in semiconductor industry (Chauhan et al. 2013). The popularity of the wire bonding technology is due to its potential in cost, yield and reliability improvements (Breach & Wulff 2010).

Wire bonding technique is basically a solid state welding process that fuses two metals, to form a robust contact. First bond, the welding is between bonding wire and bond pad. Second bond the welding is between bonding wire and leadframe. The evolution of wire bond start with Thermo-Compression bonding to Ultrasonic bonding and Thermosonic bonding (Chauhan et al. 2013). Thermo-Compression bonding was first introduced in 50's. This technique uses mechanical force and high temperature (above 300°C) to perform bonding. However this technique required high impact on the bonding pad and need high heat which additionally stresses the electrical circuits.

In the 60's Ultrasonic bonding was introduced to the industry. Ultrasonic was applied to enhance the welding joint integrity and the compression force can reduce to decrease the impact on the bonding pad. This technique is carried out at room temperature with a combination of mechanical force and ultrasonic vibration. The ultrasonic vibration is generated by an oscillating feature, i.e. transducer. This transducer uses piezoelectric element to convert the electrical current with ultrasonic frequency (typically 100kHz) to mechanical vibrations (Harman 2010). This facilitates the bondability of the bonding. This Ultrasonic bonding is limitedly used in the bonding of Al wires with large diameters (75 to 500um) for high power, microwave and optoelectronics applications (Harman 2010). In semiconductor industry, Ultrasonic bonding is usually called wedge bonding as "wedge" is used as bonding tool (Lum et al., 2006).

Since 70's Thermosonic wire bonding technique was introduced and dominating the wire bonding industry. It combines thermal energy, ultrasonic vibrations and mechanical compression to achieve bonding between wire and bond pad materials (Anand et al. 2012). Another distinct feature of Thermosonic bonding is the electronic flame off (EFO) unit. Making used of the electrical potential difference to melt the bonding wire to create a free air ball (FAB). Compare to Thermo-Compression bonding technique, this technology required a lower temperature, typically between 125 to 240°C, to achieve bonding. This range of the operation temperature avoids the damage of the temperature