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Microstructural and mechanical analysis of Cu and Au interconnect on various bond pads

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ABSTRACT

Effects of High Temperature Storage (HTS) and bonding toward microstructure change of intermetallic compound (IMC) at the wire bonding interface of 3 types of bond pad (Al, AlSiCu and NiPdAu) were presented in this paper. Optical and electron microscope analyses revealed that the IMC growth rate of samples under 175 and 200 °C HTS increased in the order of Al > AlSiCu > NiPdAu. Besides, higher HTS and bonding temperatures also promoted higher IMC thickness. The compositional study showed that higher HTS and bonding temperature developed rapid interdiffusion in bonding interface. In the mechanical ball shear test, a decrease of the shear force of Al and AlSiCu bond pads after 500 h HTS was believed due to poorly developed IMC at bonding interface. On the other hand, shear force degradation at 1000 h was due to excessive growth of IMC that in turn causes the formation of defects. For NiPdAu bond pad, increasing trend of shear force with HTS duration at 175 °C implied a good reliability of the Cu wire bonding. The rapid microscopic inspection on Cu wired Al bond pad under HTS 175 °C showed the IMC development from the periphery to the center of the ball bond. However, after 500 h voids started to develop until the crack was observed at 1000 h.

1. Introduction

Thermosonic wire bonding has been extensively developed and applied in semiconductor industry productions including Integrated Circuit (IC) and optoelectronics [1,2]. This technique utilizes both thermal and ultrasonic energies to achieve solid state welding between the wire material and bond pads on a microchip [2]. Welded wire connects the microchip and external circuit ensuring functionality of the microchip. Thermosonic wire bonding mechanism is explained as follows: first, the formation of the free air ball (FAB) by melting the wire tip by using electrical sparkling, so-called "Electro Flame Off" (EFO) process. Then compression of FAB by capillary against the bond pad with a pre-set force together with ultrasonic vibration in lateral direction. Ultrasonic vibration softens the FAB and results in plastic deformation. Afterward, scrubbing of FAB relative to the bond pad due to ultrasonic vibration removes surface contamination and oxides. This in turn results in formation of new intermetallic phase at the bonding interface. The new intermetallic phase anchors the FAB and bond pad promoting bonding between them [2]. Wire bonding process is completed by wire looping and stitch bonding on a substrate finger pad.

The conventional wire bonding employed Au wires as interconnection materials [3]. Au wire has the advantage of oxidation free in the ambient environment, good corrosion resistance and electrical conductivity. However, the explosive growth of Au commodity price leads to a scenario that an alternative cheaper wire material need to be developed [4]. Cu wire material has been extensively developed in industry as a replacement of costly Au wire [4,5]. Relative to Au, Cu material has better physical properties [6] which are appropriate for interconnection purpose. Table 1 lists some of these properties. Lower electrical and thermal conductivity of Cu material allow interconnect application in high power and speed chip functionality [7]. Moreover, higher modulus of elasticity of Cu material implies higher wire stiffness which is suitable for fine pitch bonding application [8]. Besides, higher stiffness and in turn higher loop reliability of Cu wire result in better wire sweep resistance in fine pitch devices during molding or encapsulation process [9].

High temperature storage (HTS) has been a common industrial standard isothermal annealing/aging process. It is suitable for

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Table 1
Material properties comparison between Cu and Au.

Material properties	Cu	Au
Modulus of elasticity (GPa)	110	77
Electrical conductivity (10^7 Ω^{-1} m^{-1})	6.0	4.3
Thermal conductivity (W m^{-1} K^{-1})	398	315
Linear coefficient of thermal expansion (10^{-6} K^{-1})	17.0	14.2
Specific heat, c_p (J kg^{-1} K^{-1})	386	128

assessing microstructures development of the intermetallic compound (IMC) formed at the wire–bond pad interface. The microstructural evolution of IMC has been an area of interest for research as it is believed that the formation and growth of IMC at the bonding interface after HTS is affecting the reliability and performance of the device. Common HTS duration reported are 0, 168, 500, 1000 [10,11] and some even >2000 h [12,13]. Little information is available for HTS duration that is within the increment of finer durations. The bond pad is a metallization deposited on the circuit of a microchip and to be bonded by wires. It serves as input/output (I/O) terminal that connect external circuits via bonded wires. There are a few common bond pad materials used in the industry that are ready for Cu wire bonding, i.e. pure metal of Al [14], alloyed metallization of Al/Cu [15] and Al/Si/Cu [16] and layered metallization of Ni/Pd/Au [12]. Al deposition on Si substrate offers a good adhesion between them because Al reduces native SiO_2 that exist on the Si surface to Si [17]. For Al/Cu bond pad system, Cu with concentration between 0.5 and 5 wt% is added into Al to prevent electro migration [18]. The electro migration is originated from momentum transfer between electrons and metal atoms. Under high current density, the electro migration results in cracks in the bond pad due to dragging of Al atoms by electron through grain boundary diffusion. The cracks that exist within the bond pad may result in open a circuit failure.

Addition of Cu element into Al bond pad improves its electro migration resistance as Cu atoms occupy vacancies in grain boundary which reduces grain boundary diffusion of Al and thus electro migration [19]. Al/Si/Cu bond pad typically contains 1 wt% Si and 0.5 wt% Cu in the Al metallization [20,21]. Addition of small amounts of Si in Al helps in preventing the rapid diffusion of the underlying Si into Al, which cause the formation of pits in the Si bulk. The formation of pits in Si is critical when Al diffuses into it creating Al conductive spikes that may damage the functionality of device [18]. The role of Cu in Al/Si/Cu bond pad is similar to that of Al/Cu, i.e. to improve the electro migration resistance. It is well known that mechanical pressure and ultrasonic vibration on the harder Cu wire (relative to Au) results in issues during wire bonding on Al based bond pads, e.g. excessive Al bond pad deformation (Al splash) and damage of the structure under bond pad [2,22]. Ni/Pd/Au bond pad is claimed to have advantages in Cu wire bonding over Al based bond pad [22]. In this bond pad system, Ni with hardness a few times greater than Al and Cu replaces Al. However, hard oxides on Ni surface cause infeasible bondability. The bondability issue has been eliminated by Pd deposition on Ni. Thin Au plating is generally for protecting Pd from oxidation. There are several reports with comprehensive structural studies at the bonding interfaces of various bond pad types with HTS annealing [5,8,22]; however, none of them compare different types of bond pads using physical samples which are produced using identical equipment, bonding parameters and period of time.

Effects of the wire bonding parameters toward the development of IMC at the bonding interface has been another area of interest for researchers. Xu et al. [23] studied the influence of bonding duration and temperature toward IMC crystallography and mechanical strength of the Cu wire–Al bond pad interface. Their works report that the increase of the bonding duration strengthen the bonding as it improves alumina fragmentation and result in the formation of continuous Cu–Al alloy. Moreover, a higher bonding temperature assists in the rupture of alumina and stimulates the interdiffusion at the bonding interface. This promotes the IMC formation and thus enhancing the bonding strength. However, the bonding temperature assessed in their work is up to 300 °C. The microstructure evolution of the bonding interface when higher bonding temperature is applied is unknown. In this paper, effects of high bonding temperatures and HTS conditions (temperature and duration) toward the microstructure change of IMC at the wire bonding interface of various bond pads, i.e. Al, AlSiCu and NiPdAu are focused. Optical microscopes (OM), scanning electron microscope (SEM) with energy dispersive X-ray (EDX) and transmission electron microscope (TEM) with EDX were used to characterize the microstructure of the bonding interfaces. Besides, a chemical etching method was employed for enhancing the IMC thickness measurement at the bonding interface.

2. Experimental procedure

2.1. Samples synthesis

Die bonding process that transfer diode micro-chip from wafer form to leadframe was carried out using TOSOK DBD1000 die bonder. Sample synthesis procedure, equipment, process parameters and materials used to synthesize the samples in this experiment were similar to that of [24], except that multiple bond pad types and 2 wire bonding temperatures were assessed. Diode micro-chips with Al, AlSiCu and NiPdAu were involved in the experiment. Moreover, wire bonded samples were further continued with molding, galvanic plating, trim and form and finally tested to obtain finished product of diode components. Tested samples that are in functional condition were sent for HTS annealing.

2.2. Sample preparation for analysis

The cold mounting of annealed sample was performed by encapsulating a specimen from each group of sample synthesized. After that, the mechanical grinding and polishing along the direction perpendicular to that of ultrasonic vibration was carried out. The grinding and polishing were continued until center of the bonding interface which consists of the ball bond, bond pad and Si substrate was exposed. For TEM analysis, the sample preparation approach as explained in Ref. [24] was used to extract a lamella from the selected cross-sectioned sample. The transfer of the lamella to TEM grid was carried out by ex-situ lift-out method.

2.3. Microstructural study

Microstructural studies were performed using Zeiss Axioskop 2 MAT optical microscope (OM) and JEOL-LV/EDX SEM with EDX feature were performed on selected samples. Furthermore, some samples were collected after the wire bonding process for the mechanical ball shear test using Dage series 4000 ball shear tester. This is to study the correlation of the microstructure and mechanical strength of the ball bond. Table 2 shows the sample matrix which records the configuration of the bond pad type-bonding temperature-HTS condition of the sample fabricated in this study. The validation of phase identification by SEM-EDX was performed by TEM-EDX analysis on a selected sample. The TEM analysis and phase validation was carried out by FEI CM200 TITAN with EDX capability.