The International Journal of Advanced Manufacturing Technology (2018) 96:299–306
https://doi.org/10.1007/s00170-018-1596-7

ORIGINAL ARTICLE

Effect of heat input on failure mode and connection mechanism of parallel micro-gap resistance welding for copper wire

S. Cong [1] · W. W. Zhang [1] · Y. S. Wang [1] · Z. J. Wen [1] · Y. H. Tian [2]

Received: 3 May 2017 / Accepted: 10 January 2018 / Published online: 20 January 2018

Abstract

In order to confirm the failure mode and connection mechanism of parallel micro-gap resistance welding with 40 μm copper wire on 300 nm gold plated quartz substrate, the effect of heat input was discussed on bonding interface evolution. Wire bonding processes and their mechanical tests (tensile test and shear test) were carried out to analyze the failure modes. It is shown that the failure modes are bulk separation, partial separation, and melting at middle of interface, which deeply depend on the heat input. Too large a heat input can cause the copper wire and gold layer melt, while too small a heat input can not fully promote element diffusion of the bonding interface and lead to an unreliable connection. Simulation on wire bonding processes was carried out to propose the shape variation of copper wire and temperature distribution of bonding interface. With the increase of heat input, the bonding interface area increases significantly, and the thickness sharply decreases. The connection mechanism of bonding interface is changing from local plastic deformation, subsequent electro-migration to final melting. Meanwhile, the temperature at the bonding interface is exponentially increased, which is deeply related with the generation of intermediate phase. The micro-structure of bonding interface was observed to point out the reaction products. It is shown that the intermediate phases Au_3Cu and AuCu are sequentially formed with the increase of temperature; however, the intermediate phase AuCu is corresponded with better connection performance.

Keywords Micron copper wire · Nanometer gold layer · Failure mode · Bonding · Intermediate phase

1 Introduction

Compared with the gold wire, copper wire has the advantage of low cost, high electrical resistivity and thermal conductivity, which can gradually replace the gold wire bonds in the majority of commercial semiconductor devices and precision electromechanical products [1, 2].

In the electronic packaging industry, copper wires have excellent ball neck strength, which is more suitable to fine pitch bonding than that of gold wires [3]. Meanwhile, Cu-Al system alloy has the advantage of lower IMC layer growing speed compared with that of Au-Al system alloy [4]. Ultrasonic ball or wedge bonding is widely used to realize copper diffusion bonding at elevated temperature in integrated circuit packaging. An achievement of ultrasonic wedge bonding with sub-micron copper wire on Au/Ni plated Cu substrate at ambient temperature was presented, and a detailed investigation from the aspects of process optimization and reliability effects on micro-structure of the bonding materials were performed [5, 6]. It is shown that it is possible to produce strong copper wire wedge bonds at room temperature, and the thinning of the Au layer was found directly below the center of the bonding tool with the bonding power increasing. A comparative study on the difference in interfacial behavior of thermally aged Cu wire bonding with Al and Au pads was conducted using transmission electron microscopy [7]. A variety of coherent orientation relationships have been identified between the grains of the Cu bonding wire and the IMCs in the present Cu bonds with Al and Au pads. Copper wire

✉ W. W. Zhang
zhangweiwei0509103@163.com

S. Cong
congsen305@163.com

[1] Institute of Electronic Engineering, China Academy of Engineering Physics, Mianyang 621900, China

[2] State Key Laboratory of Advanced Welding and Jointing, Harbin Institute of Technology, Harbin 150090, China

bonding on Au-plated substrate was proposed, and the influence of pedestal temperature on the characteristics and shear strength of wire bonds was investigated [8]. Higher pedestal temperatures are benefit for thinning of the copper ball bond, which lead to higher ball shear strength while producing no pad damages.

In the electromechanics, copper wire can be bonded on sheets (e.g., aluminum thin sheet and bronze thin sheet) to realize electromechanical transduction by variable processes such as resistance micro-welding, resistance spot welding, and laser micro-welding [9–11]. In order to maintain working stability, the effects of process parameter are always deeply discussed on micro-structure and tensile force to obtain high bonding performance. Compared with ultrasonic welding used for electronic packaging, parallel micro-gap resistance welding is more suitable for single wire bonding process in precision electromechanical products replaced of manual soldering process with the advantage of good stability and high reliability. Research on orthogonal design of experiment was carried out for parallel micro-gap resistance welding with 40 μm copper wire on 300 nm Au-plated quartz substrate, and the effect of process parameters was discussed on the shape of bonding interface, tensile force, and shear force [12]. A group of optimized process parameters is obtained.

According to previous references, the mechanical performance and reliability of copper wire bonding are well discussed. However, their failure mode and connection mechanism are less recommended. In this paper, parallel micro-gap resistance welding process of 40 μm copper wire on 300 nm Au-plated substrate has been presented. The effect of heat input is discussed on the failure modes and micro-structure evolution by experiments, while the effect of heat input is discussed on the shape variation of copper wire, temperature distribution of gold layer and connection mechanism by simulation. Finally, a good joint with better performance is given.

2 Structure and process

2.1 Research procedure

Figure 1 shows the bonding specimen used in precision electromechanical products. A pure copper wire with the diameter of 40 μm is bonding on the gold layer with the thickness of 300 nm by parallel micro-gap resistance welding process. An easy operated SW P300 type welding machine with the power of 220 V/50HZ and electrode pressure of 0.1 ~ 2.9 N was used to achieve the bonding process.

According to Joule law, the heat input is consisted of the bonding voltage and bonding time. Hence, for the parallel micro-gap resistance welding, the bonding voltage and bonding time have an interactive effect on connection morphology, namely the increase of both bonding voltage and bonding time can improve the bonding performance. Three factors with five levels orthogonal experiment design has been conducted in the previous reference [12], and the optimal process parameters are given. Table 1 shows the four groups of experiment design. From the viewpoint of total energy, different combination of bonding voltage and bonding time may represent the same heat input. Hence, to make the variables simple and direct-viewing, only bonding time was used to represent the heat input changing.

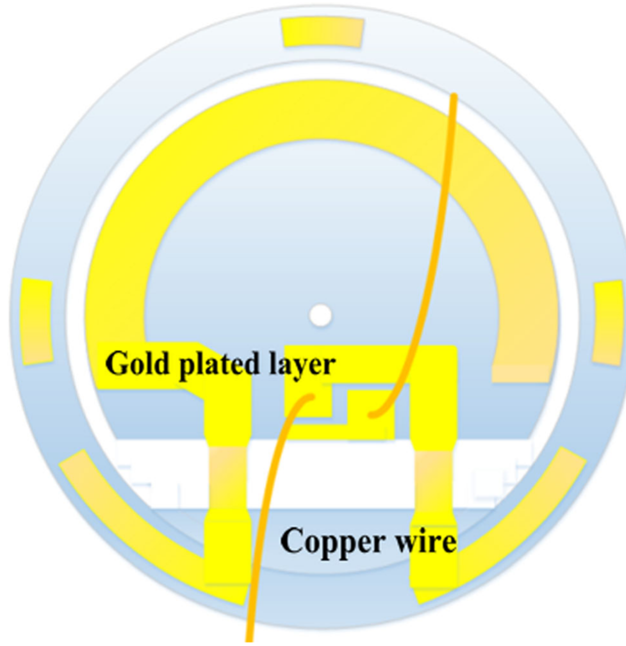


Fig. 1 Schematic drawing on bonding process of micron copper wire and nanometer gold layer

2.2 Finite element model

Reaction products at the bonding interface depend on the temperature distribution during welding process. In order to point out the shape variation of copper wire, the temperature distribution of gold layer and the connection mechanism, the

Table 1 Process parameters

Serial no.	Pressure/N	Voltage/V	Time/ms
1	0.8	0.5	8
2	0.8	0.5	14
3	0.8	0.5	17
4	0.8	0.5	20

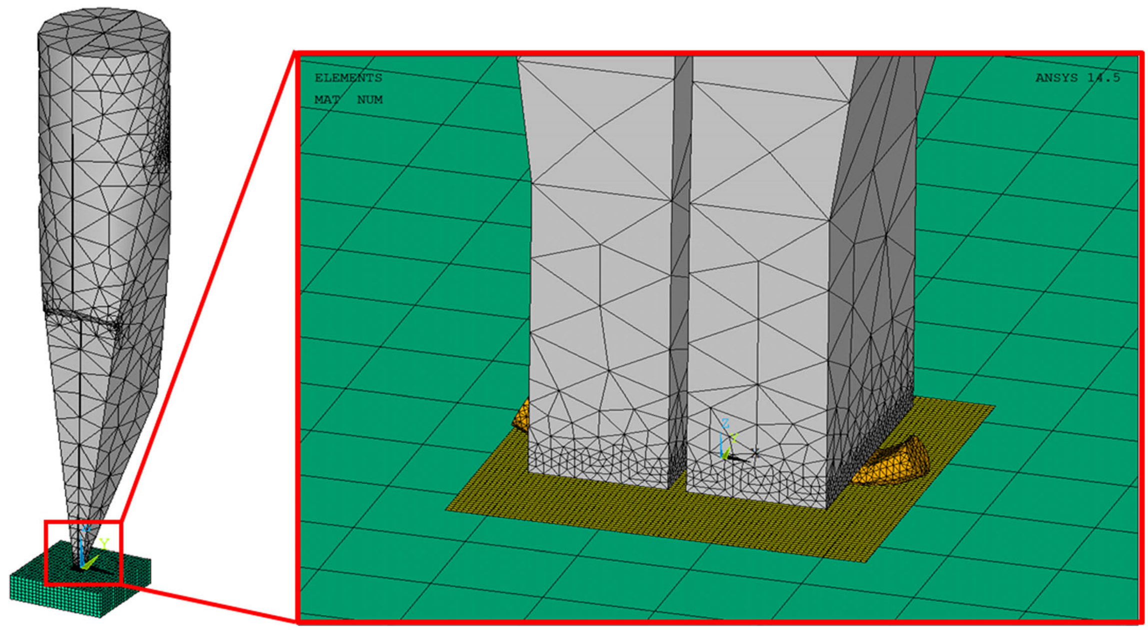


Fig. 2 Finite element model

parallel micro-gap resistance welding process was analyzed by numerical simulation with software ANASYS.

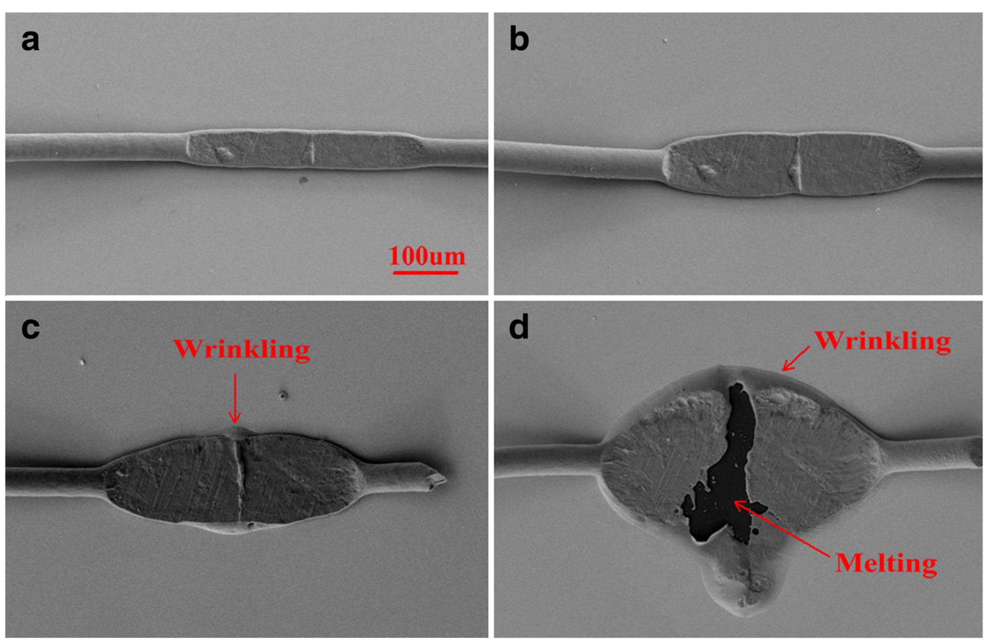
Finite element model is shown in Fig. 2. To improve the calculation accuracy, direct coupling method including temperature field, electric field, and stress field was proposed, and the temperature and stress distribution were given. Besides, the size effect of the model was considered in the process of bonding. Solid227 coupling unit was selected for electrode and copper wire, Solid226 coupling element was selected for gold layer and quartz substrate, and Contact174 element and Target170 element were used for characterizing the bonding contact or bonding disconnection. In the process of bonding, the mechanical properties and physical parameters were provided with the variation of temperature.

3 Bonding interface morphology and failure mode analysis

3.1 Variation of bonding interface morphology

When the bonding time is 8 ms, as shown in Fig. 3a, it is in a critical state of connection, and the bonding quality is

Fig. 3 Bonding interface morphology. **a** 8 ms. **b** 14 ms. **c** 17 ms. **d** 20 ms



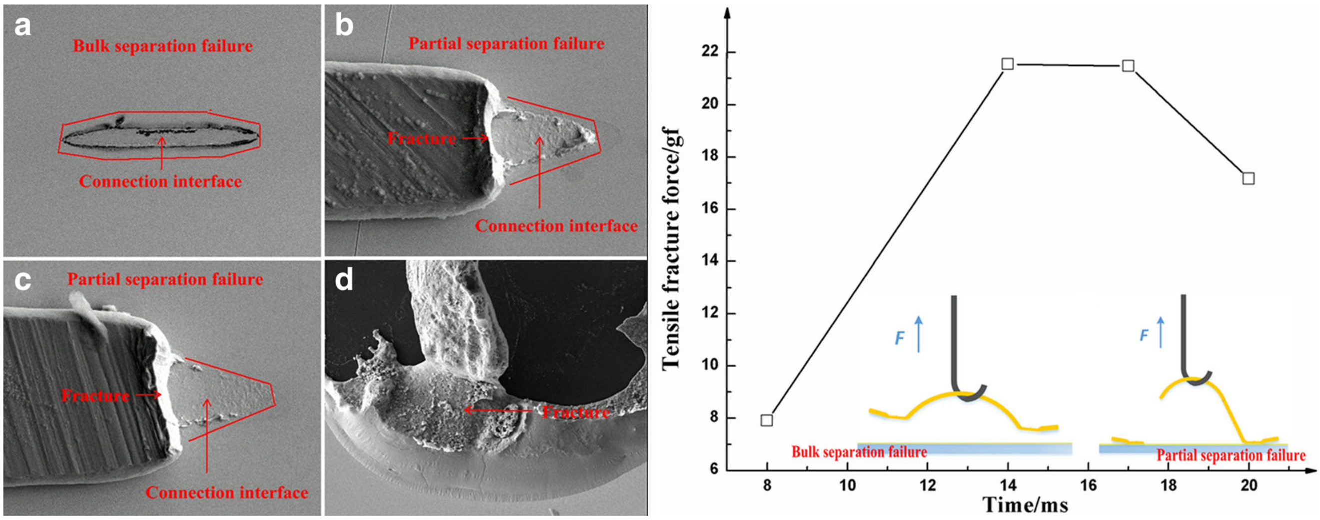


Fig. 4 Tensile failure mode and fracture force. **a** 8 ms. **b** 14 ms. **c** 17 ms. **d** 20 ms

not reliable. When the bonding time is 14 ms, as shown in Fig. 3b, the heat gathers at the center, and the bonding interface gradually becomes elliptic shape. The bonding quality is reliable. As the bonding time is increased to 17 ms, as shown in Fig. 3c, severe plastic deformation occurs on the connection position of the bonding interface, a slight wrinkling of gold layer appears around the bonding interface, but no defect happens. When the bonding time is 20 ms, as shown in Fig. 3d, due to high heat input, there is a melting phenomenon at the center of bonding interface. When it is stretched, fracture quickly appears on the melting position in the bonding process. It is experimentally proved that the connection style of bonding interface is changed from solid phase diffusion to fuse joining with the increase of bonding time.

3.2 Tensile failure mode analysis

According to tensile test, the fracture morphology and the corresponded fracture force are shown in Fig. 4. When the bonding time is 8 ms, as shown in Fig. 4a, bulk separation failure occurs on bonding interface and the tensile fracture force of bonding interface is only 7.9 gf. Some of bonding interface area forms effective connection, but the connection strength is not reliable. When the bonding time is 14 and 17 ms, respectively, as shown in Fig. 4b, c, the tensile fracture force is 21.5 and 21.4 gf, respectively. Plastic deformation occurs at connection position between bonding interface and copper wire until necking and subsequent fracture. The bonding interface is reliable. When the bonding time is 20 ms, as shown in Fig. 4d, due to the melting phenomenon at the

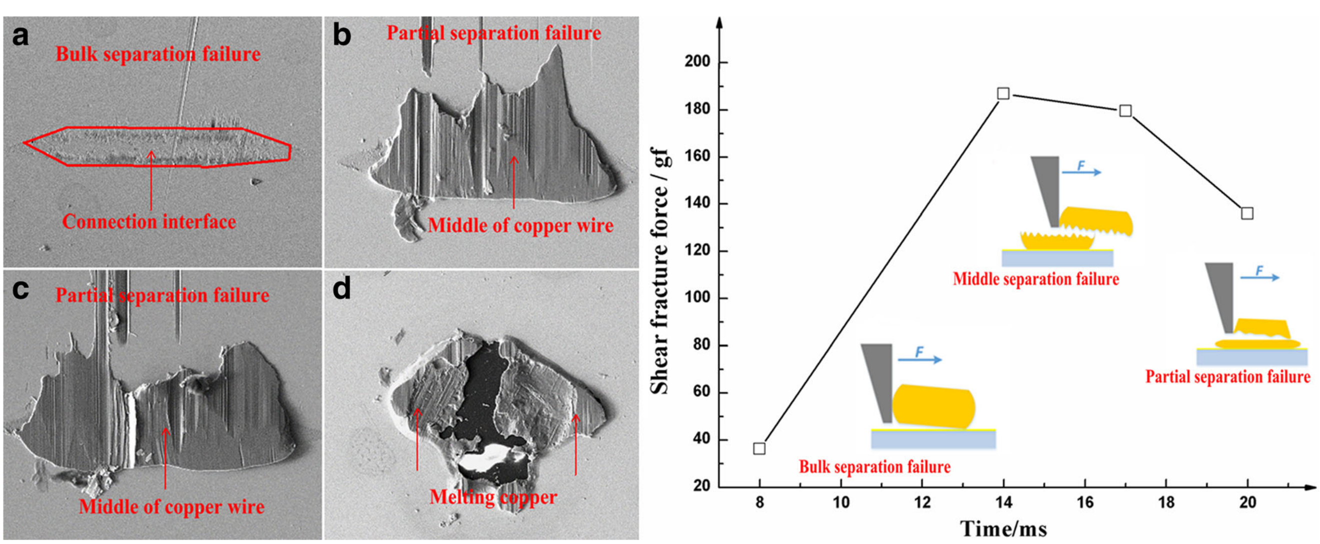


Fig. 5 Shear failure mode and fracture force. **a** 8 ms. **b** 14 ms. **c** 17 ms. **d** 20 ms

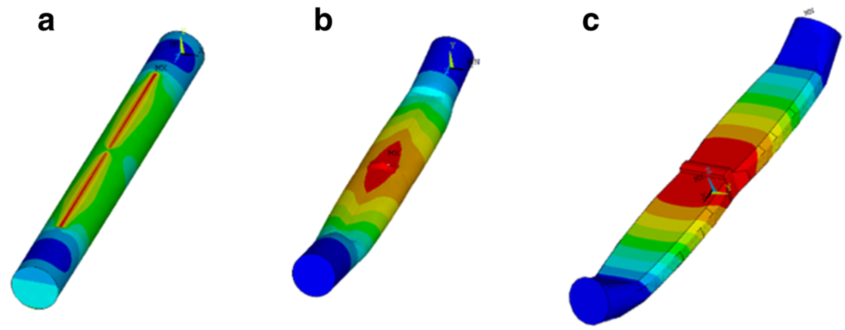


Fig. 6 Shape variation during bonding process. **a** 8 ms. **b** 14 ms. **c** 17 ms

middle of bonding interface, void occurs and fracture quickly appears on the melting position. Hence, the tensile fracture force is decreased to 17.2 gf. It is experimentally proved that there would be a better mechanical performance when the heat input is within a reasonable range.

3.3 Shear failure mode analysis

According to shear test, the fracture morphology and the corresponded fracture force are shown in Fig. 5. When the bonding time is 8 ms, as shown in Fig. 5a, it is in a critical state of connection, a bulk separation failure occurs when shear force is applied. The shear fracture force of bonding interface is only 36.2 gf. When the bonding time is 14 and 17 ms respectively, as shown in Fig. 5b, c, bonding interface connects firmly, and the shear fracture force is 187.0 and 179.6 gf, respectively. A partial failure occurs at the middle of deformed copper wire, and the bonding interface is reliable. When the bonding time is 20 ms, as shown in

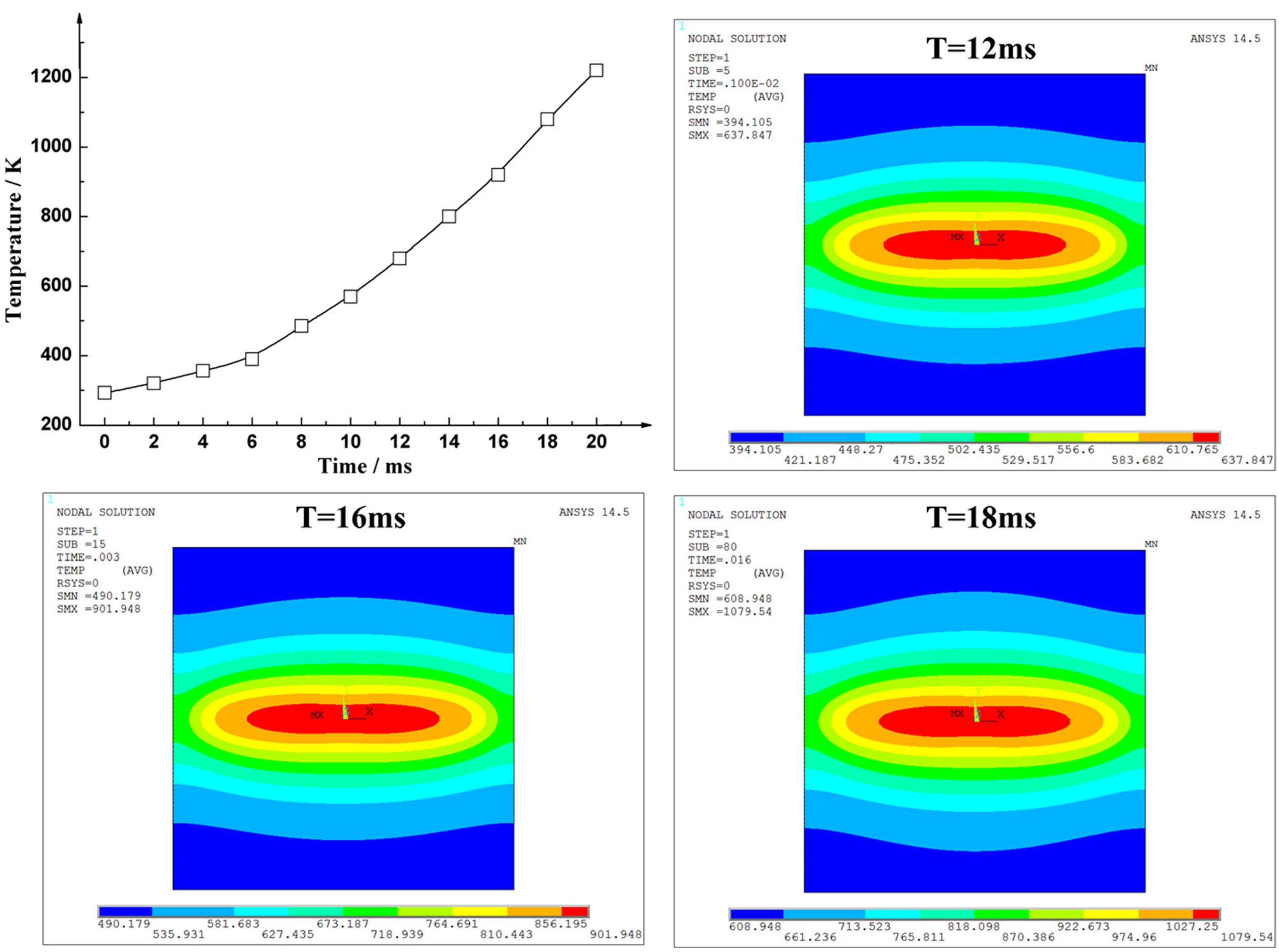


Fig. 7 Temperature variation at the solder joint center of gold layer

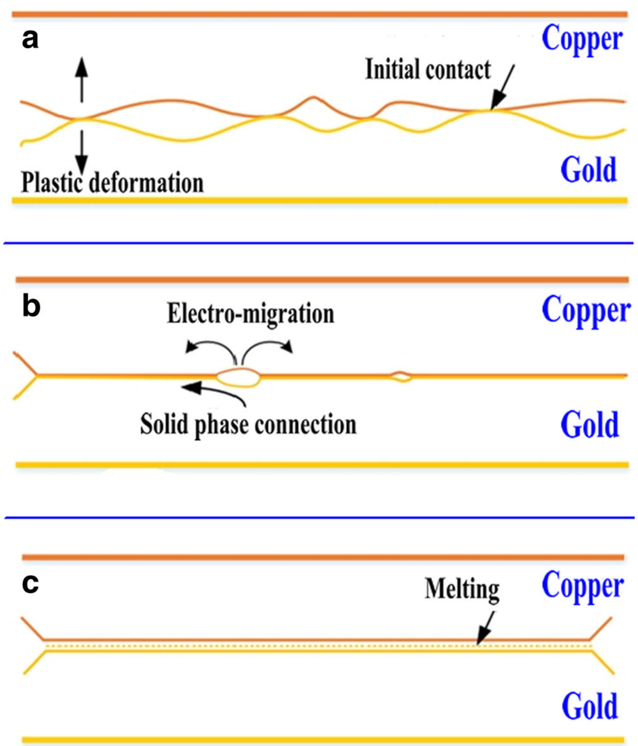


Fig. 8 Schematic diagram of connection mechanism. **a** 8 ms. **b** 14 ~ 17 ms. **c** 20 ms

Fig. 5d, bonding interface partially melts, and the tensile fracture force is decreased to 136.4 gf. It is experimentally proved that too large or too small a bonding time can lead to an unreliable connection interface.

4 Connection mechanism and micro-structure evolution

4.1 Connection mechanism

Figure 6 shows the variation of copper wire shape in the bonding process. At the beginning of the bonding, as shown in Fig. 6a, the copper wire has small deformation. When bonding time reaches 12 ms, obvious deformation appears on the copper wire. When bonding time is 14 ms, as shown in Fig. 10b, obvious deformation of the copper wire appears and up-warp phenomenon occurs on both ends of the copper wire. When the bonding time is 17 ms, as shown in Fig. 10c, the bonding interface area increases significantly, and the thickness decreases sharply.

The connection mechanism of wire bonding deeply depends on temperature of bonding interface. Figure 7 shows the temperature variation at the solder joint center of gold layer. When the bonding time is less than 8 ms, the temperature rises slowly. Owing to the bonding interface has low temperature, the atomic diffusion degree between copper and gold is not sufficient, and it cannot form effective connection interface. With the increase of bonding time, temperature fast rises. When the bonding time is greater than 12 ms and interface temperature is more than 700 K, gold and copper atoms diffuse and form a stable solid solution. When bonding time reaches 20 ms and interface temperature reaches 1200 k, diffusion interface generates low melting point alloy and melts; after interface center joule heat reaches parent metal melting point, copper and gold layer melt. At this time, the bonding mode is fusion welding.

Figure 8 is the variation of bonding interface with the increase of temperature. As shown in Fig. 8a, initial contact between copper wire and gold layer produces local plastic deformation. With the increase of electro-migration, as shown in Fig. 8b, the contact area gap disappears due to the rapid growth of diffusion, and the solid solution forms. If the temperature gradually increases, as shown in Fig. 8c, the interface center joule heat reaches parent metal melting point, and gold and copper layer both melt, which leads to failure of the interface at the moment. In the process of the actual connection, bonding interface with the solid phase connection has the optimal quality.

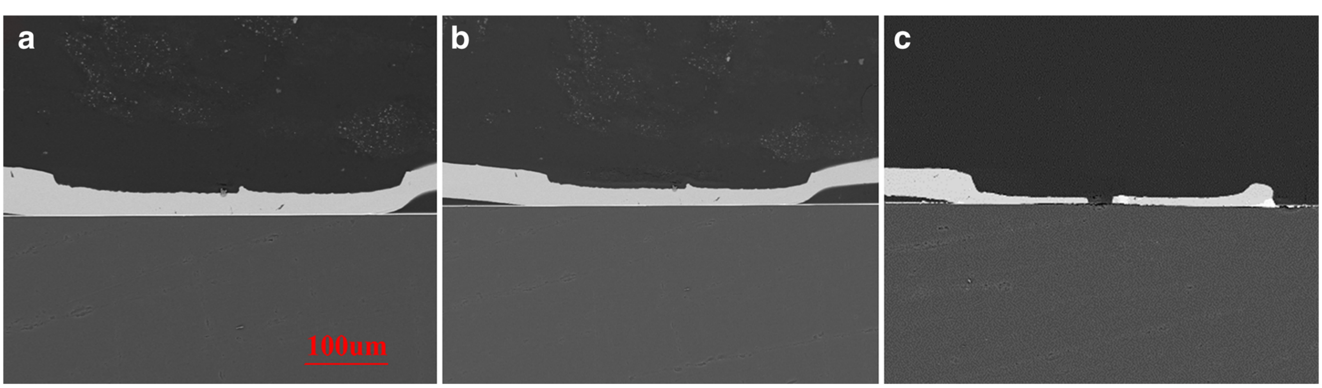


Fig. 9 Sectional profiles of bonding interface. **a** 14 ms. **b** 17 ms. **c** 20 ms

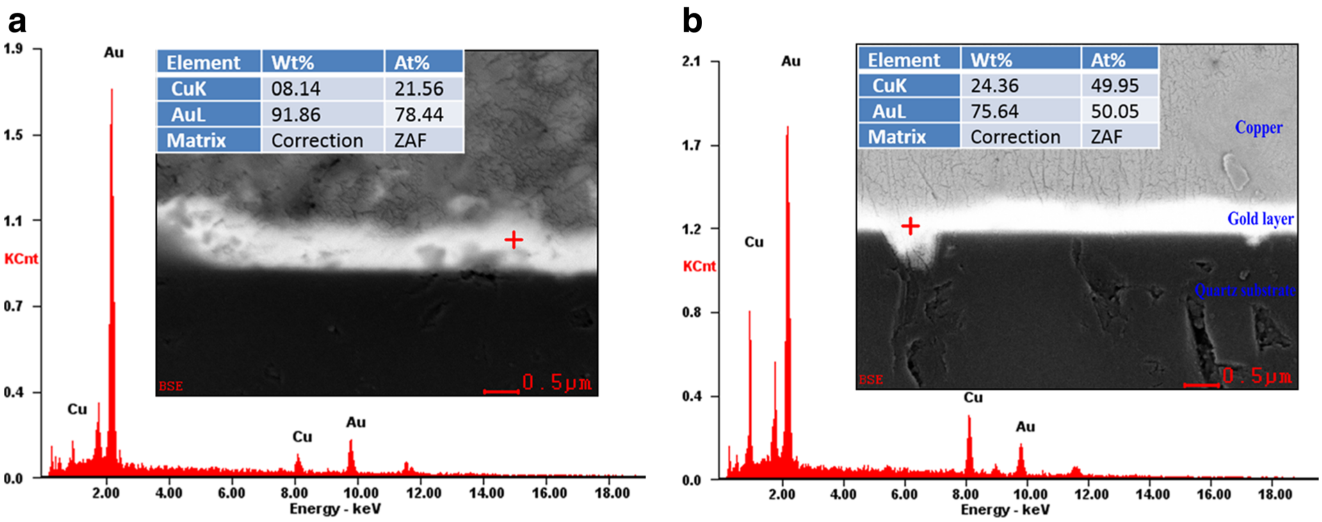


Fig. 10 Energy spectrum analysis at two points of the bonding interface. **a** 8 ms. **b** 17 ms

4.2 Micro-structure evolution

Under the condition of different process parameters, the sectional profiles of bonding interface analyzed by SEM are shown in Fig. 9. As bonding time increases, the height of bonding interface declines gradually, and the area of bonding interface increases. When bonding time is too long, interface center is burnt through, and the gold layer is squeezed to both sides of the section. After continuing to increase the bonding time, holes expand to both ends, and the whole interface is eventually severely damaged.

According to the Au-Cu system [13], solid solution (Au, Cu) forms at the elevated temperature, and then the solid solution transforms into three kinds of intermediate phases, namely Au_3Cu, AuCu, and $AuCu_3$, which are decided by ratio of Cu to Au. Bonding interface temperature plays an important role for the gold atoms diffusion into copper and form variable kinds of intermediate phases. Figure 10 shows the interface connection layer and the energy spectrum analysis with different bonding times. The connection layer includes three parts: copper wire at the top, connection layer and gold layer at the middle, and the substrate at the bottom. When the bonding time is 8 ms, the percentage of Cu and Au is about 1:3 at the bonding interface, where generates the intermediate phase Au_3Cu. When the bonding time is 17 ms, the interface has reliable connection quality and no holes and other defects are found. The percentage of Cu and Au is about 1:1 at the bonding interface, where generates the intermediate phase AuCu.

It is experimentally proved that the failure mode depends on the diffusion of Cu into Au layer, and the intermediate phase AuCu at bonding interface has a good mechanical performance.

5 Conclusion

Bonding process of 40 μm copper wire on 300 nm Au-plated substrate has been presented. The effect of heat input is discussed on the failure modes and micro-structure evolution by experiments, while the effect of bonding time is discussed on the shape variation of copper wire, temperature distribution of gold layer and connection mechanism by simulation. The main conclusions are listed at below:

1) As the bonding time increases, bonding interface area and bonding strength gradually increase. However, too large a bonding time can cause the gold layer wrinkle or fuse, and bonding interface mechanics performance to fall sharply.
2) When the bonding time is too small, the failure mode is bulk separation, which is not reliable. As the bonding time increases, the failure mode is partial separation. The bonding interface has good connection performance, and fracture occurs on the interface neck (tensile failure mode) or middle of deformed copper wire (shear failure mode), where suffers from severe plastic deformation. When the bonding time is too large, void occurs at middle of interface and fracture quickly appears on the melting position owing to the melting phenomenon.
3) With the increase of bonding time, the temperature variation at the solder joint center of gold layer in the process of bonding is exponentially increased, which decides the generation type of reaction production. With the increase of electro-migration and joule heat, the contact area gap disappears due to the rapid growth of diffusion, and the tightly-connected solid bonding interface is formed. When interface center joule heat reaches parent metal melting point, gold and copper layer both melt, which leads to failure of the bonding interface.

Funding information This paper was financially supported by *NSAF Funding (No.U1730107)*. The authors would like to take this opportunity to express their sincere appreciation.

Compliance with ethical standards

Conflict of interest The authors declare that they have no competing interests.

References

1. Zhong ZW (2009) Wire bonding using copper wire. Microelectron Int 26(1):10–16
2. Chauhan P, Zhong ZW, Pecht M (2013) Copper wire bonding concerns and best practices. J Electron Mater 42(8):2415–2433
3. Tian YH, Lum I,Won SJ, Park SH, Jung JP, Mayer M, Zhou Y (2005) Experimental study of ultrasonic wedge bonding with copper wire. In: proceeding of 6th International Conference on Electronics Packaging Technology, pp 389–393
4. Hong S, Hang C, Wang C (2005) Experimental research of copper wire ball bonding. In: Proceeding of 6th International Conference on Electronics Packaging Technology, pp 441–445
5. Tian YH, Wang CQ, Lum I, Mayer M, Jung JP, Zhou Y (2008) Investigation of ultrasonic copper wire wedge bonding on Au/Ni plated Cu substrates at ambient temperature. J Mater Process Technol 208(1):179–186. https://doi.org/10.1016/j.jmatprotec.2007.12.134
6. Tian YH, Wang CQ, Zhou Y (2008) Bonding mechanism of ultrasonic wedge bonding of copper wire on Au/Ni/Cu substrate. Trans Nonferrous Metals Soc China 18(1):132–137
7. Kim HG, Kim SM, Lee JY (2014) Microstructural evaluation of interfacial intermetallic compounds in Cu wire bonding with Al and Au pads. Acta Mater 64:356–366
8. Singh G, Haseeb ASMA (2016) Effect of pedestal temperature on bonding strength and deformation characteristics for 5N copper wire bonding. J Electron Mater 45(6):3244–3248. https://doi.org/10.1007/s11664-016-4403-y
9. Mo B, Guo Z, Li Y (2011) Mechanism of resistance microwelding of insulated copper wire to phosphor bronze sheet. Mater Trans 52(6):1252–1258
10. Shi W, Wang W, Huang Y (2016) Laser micro-welding of Cu-Al dissimilar metals. Int J Adv Manuf Technol 85(1–4):185–189. https://doi.org/10.1007/s00170-015-7925-1
11. Wan XD, Wang YX, Zhao DW (2016) Quality monitoring based on dynamic resistance and principal component analysis in small scale resistance spot welding process. Int J Adv Manuf Technol 86(9–12):3443–3451
12. Zhang WW, Cong S, Wen ZJ, Liu Y, Wang YS, Tian YH (2017) Experiments and reliability research on bonding process of micron copper wire and nanometer gold layer. Int J Adv Manuf Technol 92(9–12):4073–4080
13. Okamoto H, Chakrabarti DJ, Laughlin DE, Massalski TB (1987) The Au-Cu (gold-copper) system. J Phase Equilib 8(5):454–474. https://doi.org/10.1007/BF02893155