FUNCTIONAL EVALUATION OF COPPER IN CONVENTIONAL WIRE BONDING AS COMPARED TO GOLD

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Abstract: *In the wire bonding process, the ever increasing gold (Au) price has created a necessity for looking at alternate materials viz., copper (Cu) for wire bonding, allowing Cu wire bonding to make a dramatic progress in recent years. The trend to shift towards Cu wire is expected to advance further in future, thus further improvement of bonding technique is indispensable as there are many challenges viz., handling of fragile pad structure, peeling, cracking below the bond pad, high oxidation rate, hardness and lower bondability of the wire bonds. In this paper, a series of experiments and characterizations (Mechanical, Electrical & SEM (Scanning Electron Microscope) has been conducted with 1mil Au and Cu wires to experimentally prove that Cu is a reliable replacement for Au in wire bonding process.*

Keywords: *Gold, Copper ball and wedge bonds, Bond parameters and Characterization*

1. INTRODUCTION

The wire bonding process plays major role in the MEMS (Micro Electro Mechanical Systems) packaging field. The wire bonding industry is undergoing a paradigm shift from Au to Cu wire bonding(1). This change to Cu wire bonding is driven mostly by economic considerations, and thus, the risks in the use of this technology must be carefully considered.

The ever increasing Au prices are created to look for alternative wire materials which can be used in this process. One of the main alternatives to Au wire is Cu wire due to its material properties. The industry is currently trying to implement these changes in wire bonding process.

Zhong (2009)[3] has conducted a detailed study on Cu wire bonding. Replacing Au wire with Cu wire in wire bonding process presents many challenges. Parameter optimization for ball bond formation, stitch bond formation, and looping profile are needed. Cu is harder than Au, and therefore bonding parameters, including bonding force, must be kept under tight control.

Since Cu wire is highly prone to oxidation, inert gas such as nitrogen or forming gas must be used during the bonding process. Cu wires have better thermal and electrical properties than Au wires. Cu is about 25 per cent more conductive than Au, accounting for better heat dissipation and increased power rating, a main factor to the development of high performance, high power and fine-pitch devices using smaller-diameter Cu wire to accommodate smaller pad sizes.

The main benefits of using Cu wire bonding over other bonding wires are lower material cost, higher electrical and thermal conductivity, high loop stability, better looping control etc. Cu wires have excellent ball neck strength after the ball formation process. The higher stiffness of Cu wires is more suitable for fine pitch bonding than that of Au wires. Cu wire can be directly bonded on bare Cu lead frames and PGA (Pin Grid Array) substrates, saving cost and time because of elimination of the plating process [3].

The objective of this research is to identify, evaluate and optimize the Cu wire bonding process to overcome the current challenges. Also to further conduct mechanical, electrical, SEM characterization and to compare the results with that obtained for Au to prove that the Cu is a reliable replacement for Au in wire bonding process.

2. EXPERIMENTATION

Various experiments on 1mil (25µm) diameter Au and Cu wires for ball and wedge bonding were conducted. Process optimization is essential for bonding process stability. The requirements for achieving high-quality first and second bonds are optimized process parameters, optimal bonding environment and a contamination free surface. Hence Plasma cleaning was used for surface activation of the samples which can help removing organic contaminants from the pad surface.

Although Au is a reliable material for the wire bonding and is directly referred by standards, the results greatly depend on the process working environment. Hence experiments of Au were also conducted with minimum optimization for verification of results alongside with that of the standards. These results were used as a comparative standard to optimize and evaluate Cu ball and wedge bonding processes. The parameters used here is considering the successful bonding of bonds on the package and quality of the wire used. The bonding parameters vary according to the bonding conditions and the application for which the interconnection is made. Initially, Cu bonds were not formed in both ball and wedge bonding processes. The wedge side (2nd bond) in both cases was not bonded properly and optimization of the wedge bond was conducted.

The bonding was conducted on different packages such as PCB sample, PGA (Pin Grid Array) & QFJ (Quad Flat J-leaded) packages which were having the Au pad material. The bonding process parameter adjustments for electric flame-off (EFO) current, Ultrasonic Power (USP), Bond Force (BF), Bond Time (BT) and Temperature have been optimized.

The 1 mil Au and Cu ball & wedge bonding has been conducted on a QFJ package. The optimized bond parameters for Au and Cu ball bonds are tabulated in table 1 and the wedge bonds are tabulated in table 2.

Table 1: Optimized Bond Parameters of Au & Cu Ball Bonds

Bond Parameters	Au Ball bonds		Cu Ball bonds	
	1st bond	2nd bond	1st bond	2nd bond
Bond Time (ms)	30	30	30	24
Ultrasonic Power (Digit)	90	90	100	125
Bond Force (gf)	34	34	34	28

Table 2: Optimized Bond Parameters of Au & Cu Wedge Bonds

Bond Parameters	Au Wedge bonds		Cu Wedge bonds	
	1st bond	2nd bond	1st bond	2nd bond
Bond Time (ms)	24	24	22	22
Ultrasonic Power (Digits)	125	125	100	120
Bond Force (gf)	30	34	24	24

The work stage temperature used for Au & Cu was 90°C and 120°C respectively. The inert gas used for Cu ball formation is Nitrogen with the flow rate of 0.8 Nl/min. The bonding process was optimized finally by careful variation of the bond and loop parameters based on the characterization results.

3. CHARACTERIZATION RESULTS & DISCUSSIONS

The different type of characterizations for evaluating the wire bond such as Mechanical, Electrical and SEM were conducted on each experiment of Au and Cu ball and wedge bonds. The characterization results are discussed in detail below.

3.1 Mechanical

Mechanical tests to evaluate the quality and robustness of wire bonds include shear and pull tests. The bond pull test is the most widely used technique for the evaluation and control of wire bond quality. The procedure for wire pull test is positioning a hook underneath the wire and pulling in the vertical direction either until the bond breaks (destructive testing) or until a predefined force is reached (non-destructive testing).

Generally the MIL-STD-883G (8) standard is taken as the reference for evaluating the mechanical bond strength of wire bonding. As per the standard, the target result range for 1mil (25µm) wire bonding is as shown in the table 3.

Table 3: 1Mil Wire Bond Optimum Range Values as per MIL-STD-883G

Pull Test Value (Mechanical Characterization)	
Ball-Wedge Bonds	3gf
Wedge-Wedge Bonds	

The destructive bond pull test was conducted on several experiments of Au & Cu ball bonds and the best pull test results obtained with respective optimized bond parameters are tabulated in table 4.

Table 4: Destructive Bond Pull Test for Au & Cu Ball Bonds

Wire Material	BT (ms)	USP (Digits)	BF (gf)	Pull test value (gf)	Failure Mode
Au	30/ 30	90/ 90	34/ 34	12.30	Ball-neck break
Cu	30/ 24	100/ 125	34/ 28	11.24	1st bond heel break

Where BT-Bond Time, USP-Ultrasonic Power, BF-Bond Force

As per the MIL-STD-883G [(8)] values shown in the table 3 the Cu bonds have successfully passed the minimum required criteria and are well above the prescribed range. The destructive pull test value of 11.24 gf was obtained for Cu ball bonds. This is an excellent result as the maximum breaking load given by the manufacturer (HERAEUS) for 1 mil Cu wire is 12.24 gf.

The graph shown in figure 1 indicates the consistency of mechanical pull test value of Cu ball bonds with force greater than 3 gf. Detailed study of each experiment was conducted and the bond parameters were optimized to improve the characterization results.

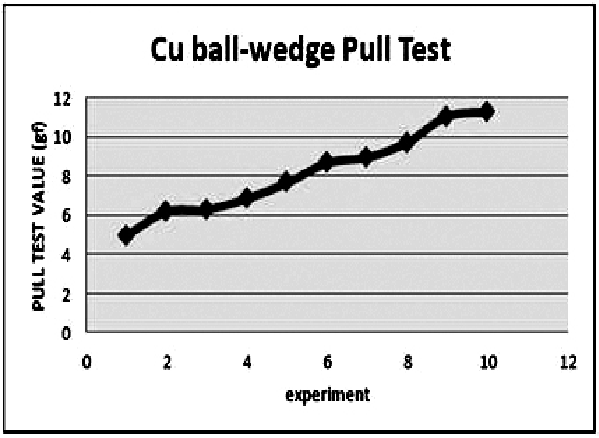


Fig 1. Graph of Cu Ball Bonds Pull Test vs. No of Experiments

Similarly, the destructive bond pull test was conducted on several experiments of Au & Cu wedge bonds and the best pull test results obtained with respective optimized bond parameters are tabulated in table 5.

Table 5: Destructive bond pull test for Au & Cu Wedge bonds

Wire Material	BT (ms)	USP (Digits)	BF (gf)	Pull test value (gf)	Failure Mode
Au	24/ 24	125/ 125	30/ 34	13.60	Ball-neck break
Cu	22/ 22	100/ 120	24/ 24	11.60	1st bond heel break

Where BT-Bond Time, USP-Ultrasonic Power, BF-Bond Force

The destructive pull test value for Cu wedge bonds is 11.60 gf. As explained in the results of Cu ball bonds, in this case also the results obtained are excellent and are meeting the minimum required value of MIL-STD-883G [(8)].

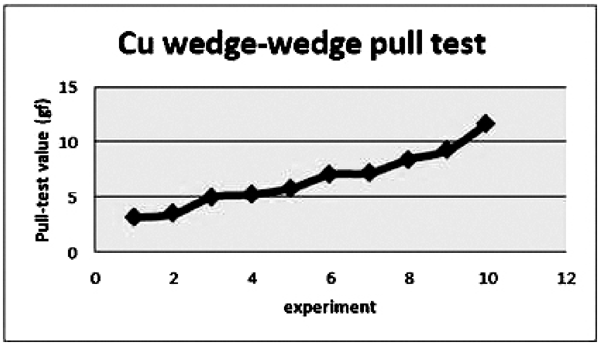


Fig 2. Graph of Cu Wedge Pull Test vs. No of Experiments

The graph showed in figure 2 indicates the repeatability of mechanical pull test values in Cu wedge bonds with pull force greater than 3 gf. Detailed study of each experiment was conducted and the bond parameters were optimized to improve the characterization results, similar to the Cu ball bonds.

3.2 Electrical

The Electrical tests have been conducted to check the functionality of the bonds non-destructively. A non-sticking bond will result in an electrical open, while two adjacent bonds in contact will result in an electrical short. The electrical resistance increases as the amount of inter-metallic compound increases. And an open circuit failure is an indication of extensive voiding at the interface. There are no standard references available for carrying out electrical characterization of wire bonds.

The electrical characterization was conducted on each set (10 bonds) of Au & Cu ball and wedge bonds. The bond length of 1 mm bonds were bonded on QFJ package for electrical test and the obtained results are shown in the Figure 3.

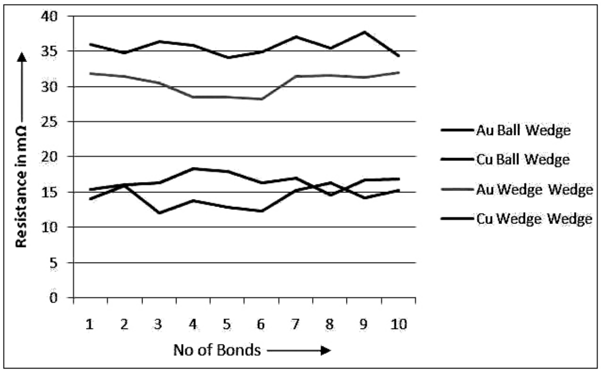


Fig 3. Graph of Electrical Resistance vs. No. of Bonds (Au & Cu Ball and Wedge)

The graph in figure 3 shows the electrical resistance measured for Au & Cu ball and wedge bonds. The electrical characterization was conducted to check the wire open & short defects. A batch of 10 bonds was tested and no such defects were found. The mean resistance value of 16.54 mΩ and 14.20 mΩ were obtained for Cu ball and wedge bonds respectively which are tabulated in table 6. These bonds had approximately 50% less resistance than the Au ball & wedge bonds. This implies that Cu bonds have better conductivity than Au bonds so by using Cu wire we can reduce the length and thickness of the wire bonds to obtain similar results. Also the standard deviation and range were calculated for each set which are tabulated in table 6.

Table 6: Calculated Parameters of Electrical Characterization for Au & Cu Bonds

Wire Material	Gold		Copper	
Type of bonding	B-W	W-W	B-W	W-W
Mean Resistance (mΩ)	35.61	30.50	16.54	14.20
Standard Deviation (SD)	1.12	1.35	1.02	1.42
Range	3.69	3.73	3.64	3.92

Where B-W is Ball-Wedge and W-W is Wedge-Wedge

3.3 SEM Characterization

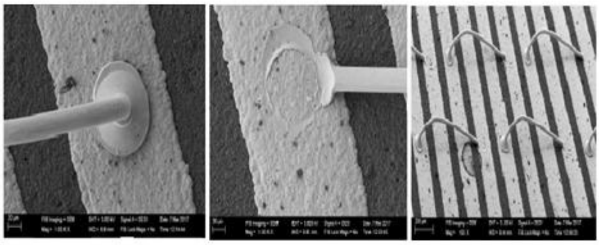
The bonds have been compared with a known standard through SEM means to detect pad splashing, bond dimensions, and bond deformation. Several other techniques, such as electron dispersive spectroscopy (EDS), and X-ray imaging, may also be used. Due to the decreasing size of bonding wires and high density wire bonding, advanced methods such as SEM are popular.

Generally the MIL-STD-883G (8) standard is taken as the reference for inspecting the wire bonds. As per the standard, the target result range for 1mil (25µm) wire bonding are as shown in the table 7.

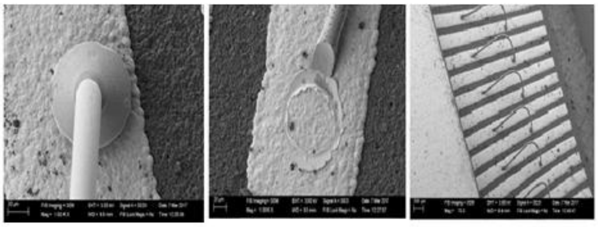
Table 7: 1mil Wire Bond Optimum Range Values as per MIL-STD-883G

Bond Dimensions (SEM Characterization)	
Ball diameter	50 µm -125 µm
Wedge width	30 µm -150 µm

The SEM characterization was conducted on Au & Cu ball bonds to study the bond dimensions, deformation and bond splash. The characterized SEM images of Au and Cu ball bonds are shown in the figure 4.



a. Au Ball bond b. Au wedge bond c. Au ball-wedge bonds



d. Cu Ball bond e. Cu wedge bond f. Cu ball-wedge bonds

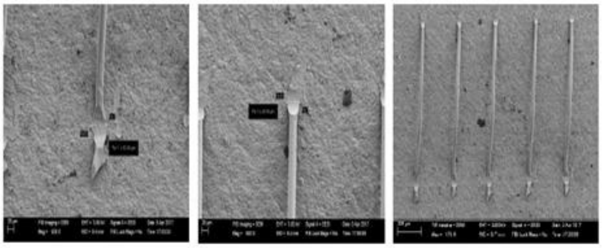
Fig 4. SEM Images of a, b, c: Au Ball Bonds and d, e, f: Cu Ball Bonds

The figure 4a, b, c shows the SEM images of Au ball bonds and figure 4d, e, f shows the Cu ball bonds and the measured dimensions are tabulated in table 8.

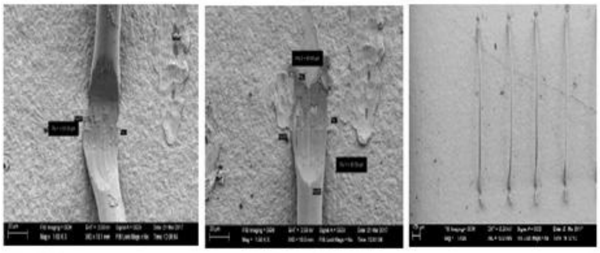
Table 8: Bond Dimensions of Au & Cu Ball Bonds

Dimensions	Au ball bonds	Cu ball bonds
Ball bond diameter (1st bond)	79.57 µm	79.86 µm
Wedge bond width (2nd bond)	39.67 µm	34.40 µm

Similarly, the SEM characterization was conducted on the Au & Cu wedge bonds to study the bond dimensions, deformation and the bond splash. And the characterized SEM images of Au and Cu wedge bonds are shown in figure 5.



a. Au 1st wedge b. Au 2nd wedge c. Au wedge-wedge bonds



d. Cu 1st wedge e. Cu 2nd wedge f. Cu wedge-wedge bonds

Fig 5. SEM Images of a, b, c: Au Wedge Bonds and d, e, f: Cu Wedge Bonds

The figure 5a, b, c shows the SEM images of Au wedge bonds and figure 5d, e, f shows the Cu wedge bonds and the measured dimensions are tabulated in table 9.

Table 9: Bond Dimensions of Au & Cu Wedge Bonds

Dimensions	Au wedge bonds	Cu wedge bonds
1st wedge bond width	50.88 µm	33.08 µm
2nd wedge bond width	34.40 µm	38.59 µm

The SEM results shown that the Cu bond dimensions are well within the prescribed range as per MIL-STD-883G (8) (ref. Table 7.) no deformation and bond splash were found.

4. CONCLUSION

The Cu ball bonds were successfully bonded. The mechanical destructive pull test result obtained was 91.83% of the breaking load of the wire whereas in case of Au it was only 86.13%. The electrical resistance measured for the Cu ball bonds is approximately 50% less than that measured for the Au ball bonds. The SEM characterization results were also in accordance with the standard referred.

Similarly, Cu wedge bonding was also successfully bonded and the mechanical destructive pull test result was 94.77% of the breaking load of the wire. It was 95.23% in case of Au. The electrical resistance measured for the Cu wedge bonds are also approximately 50% less than that measured for the Au wedge bonds. The bond dimensions are in par with the standard.

These characterization results obtained shows that Cu can be certainly used as a reliable replacement in conventional wire bonding process.

5. ACKNOWLEDGEMENT

The authors express their thanks to Director, CMTI, Ms. Usha.S, Joint Director, CMTI and Shanmugaraj V, HOD (SVT), CMTI for providing opportunity and support to carry out the above research work. The authors would also like to thank NMTC department of CMTI for providing assistance in characterization.

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