UC Irvine

UC Irvine Previously Published Works

Title

A solid-state bonding technique of large copper wires for high power devices operating at high temperature

Permalink

<https://escholarship.org/uc/item/8393r9pg>

Journal

Journal of Materials Science: Materials in Electronics, 26(6)

ISSN

0957-4522

Authors

Chen, YL
Wu, YY
Lee, CC

Publication Date

2015-03-04

DOI

10.1007/s10854-015-2864-z

Peer reviewed

A solid-state bonding technique of large copper wires for high power devices operating at high temperature

Yi-Ling Chen · Yuan-Yun Wu · Chin C. Lee

Received: 23 October 2014 / Accepted: 23 February 2015 / Published online: 4 March 2015
© Springer Science+Business Media New York 2015

Abstract Solid-state processes of bonding 1 mm copper (Cu) wires on Cu substrates and silicon (Si) chips, respectively, were developed. To overcome Cu oxidation issue, the bonding surface on the wire was plated a silver (Ag) layer. An annealing step followed to make the Ag layer much easier to deform and conform to the Cu or Si bonding surfaces. The bonding process was performed at 300 °C with 6.89 MPa. Wire-bond cross sections were studied using optical and electron microscopy, respectively. The images obtained exhibit nearly perfect Ag–Cu bonding interface. For wire-bonds made on Cu substrate, in-plane (shear) pull test measured a breaking of force 20.7–23.7 kg, comparable to the 22.5 kg breaking force of the Cu wire itself. Breaking forces on vertical (peel) pull test are about one-half of in-plane pull test results. For wire-bonds made on Si chip, breaking forces are about 80 % of those made on Cu substrate. Fracture modes were evaluated in details. 90 % of the wire-bonds broke with three modes mixed together: near Cu–Ag plating interface, inside Ag layer, and Ag–Cu bonding interface. Thus, the bonding interface is as strong as other regions of the wire-bond. This solid-state wire bonding process is expected to have valuable applications in high power and high temperature devices and modules where the wire-bonds have to stand alone without protection due to lack of high temperature molding compound and reinforcing materials.

1 Introduction

In the electronic industry, wire bonding is still the most popular interconnect method even though tape automated bonding (TAB) and flip-chip technology have gained application moment [1, 2]. At present, wire bonding is used in 75 % of discrete and integrated circuit (IC) devices due to its technology maturity, established equipment, flexibility, and reliability [3–5]. There are three basic wire bonding techniques: thermo-compression, ultrasonic, and thermosonic [6–8]. Popular wire materials have been aluminum (Al) and gold (Au) [9, 10]. Since Au is expensive and Al is not strong enough, copper (Cu) wire has recently been adapted. A major challenge for Cu wire is oxidation, making it difficult to bond to interconnect pads [11–13]. A great deal of research has been conducted to deal with Cu oxidation by coating Cu wires with noble metal such as palladium (Pd), Au, and Ag [14, 15]. The coating metals except Pd could cause problematic ball shapes, for example, a spearhead-like ball shape or a center-deviated ball shape [16]. Pd-coated Cu wires also pose challenges. Cu can form hard alloys with Pd that damages the bond pad. During the free-air ball forming process, Pd would dissolve into Cu instead of staying on the ball surface. During aging, Pd tends to diffuse and segregate to the bonding interface, which appears to degrade the bond strength [17, 18]. It seems that Cu wire bonding technique is still in the developing stage.

This research is focused on developing processes to bond large Cu wires to silicon (Si) chips and Cu substrates using solid-state bonding principle [19]. Some preliminary results were recently presented and published [20]. In this paper, complete and thorough evaluations, data, and results are reported. In recent development of automobile power modules, large wires are needed to carry high electrical

Y.-L. Chen (✉) · Y.-Y. Wu · C. C. Lee
Electrical Engineering and Computer Science, Materials and
Manufacturing Technology, University of California, Irvine,
Irvine, CA 92697-2660, USA
e-mail: yilingc2@uci.edu

current [21]. Furthermore, the advances of high power and high temperature AlGaIn and SiC semiconductor devices and resulting electronic modules have opened up the need of strong wire-bonds that can sustain high temperature. So far, high temperature molding compounds are still not available to reinforce the wire bonds and protect them against environment. Thus, in the foreseeable future, the wire-bonds probably have to stand alone without protection. In experiments, 1 mm diameter Cu wires are chosen for demonstration. Bare Cu wires have been used in nearly everywhere for centuries with high long-term reliability. Bare Cu wires can be protected further by plating with a layer of metals such as nickel (Ni) as needed. Among various bonding methods, the one that gives the wire-bond the highest melting temperature was chosen. That is to bond Cu wires directly to Si or Cu substrates without using any bonding medium. This is not an easy task because Cu oxidizes easily. To overcome this issue, a layer of Ag is plated over the bonding surface of Cu wires. Ball forming process used in the wire bonding processes in industries was not used. Ag has the highest electrical conductivity among metals. It is also ductile and can be bonded more easily using the solid-state bonding principle. The only compromise is the reduction of melting temperature from that of Cu, 1085 °C, to the eutectic temperature of the Cu–Ag binary system, 780 °C.

In what follows, the experimental designs and procedures are presented. Experimental results are reported and discussed. The solid-state bonding process requires only a single stage operation at 300 °C with 6.89 MPa pressure for 3 min. According to the cross sectional studies, the

bonding results are nearly perfect. No voids and cracks are observed on the bonding interface. The breaking force of the wire-bonds is evaluated by pull tests [22]. The wire-bonds are strong enough to be used as they are without protection. At the end of the paper, a short summary is given.

2 Experimental designs and procedures

To achieve maximum wire bond strength using solid-state bonding, the bonding surface must conform to the substrate to be bonded to. For flat substrates, the bonding surface on the wire must be flat too. So, the first step is to shape the bonding region of Cu wires to produce a flat surface. Since equipment is not available to produce flat surfaces on wires, a method was designed. The Cu wire was first wound on a cylindrical core made of insulating material. MACOR was chosen for the core material because it is a ceramic that can be machined easily [23]. Grooves are machined on the MACOR core to fix the Cu wire in position so that the Cu coil does not move during the process of machining the flat surface on the Cu coil. Figure 1 exhibits the major fabrication steps.

The MACOR core has a diameter of 12.7 mm (0.5 inch) and weighs only 0.02 kg. After winding the 1 mm Cu wire on the core to form a coil, the assembly is coated with lacquer. Flat surfaces on Cu coil are machined to a depth of 0.5 mm which is half of the wire diameter. Each elliptical flat surface has an area of 4.22 mm² (6.54×10^{-3} in²). The assembly is thoroughly washed and cleaned. The flat

Fig. 1 Fabrication steps to bond flat surfaces of a Cu coil on a Si chip or Cu substrate using solid-state bonding process: **a** 12.7 mm (0.5 inch) diameter MACOR core with groove, **b** winding 1 mm Cu wire on the groove and coating the assembly with lacquer, **c** machining the coil to produce flat surfaces on the wire, **d** electroplating 50 µm Ag on the flat surfaces of Cu wire, removing lacquer, and annealing at 350 °C for 5 h, **e** solid-state bonding at 300 °C with 6.89 MPa in 1.33×10^{-5} MPa vacuum for 3 min

surfaces are electroplated with 50 μm thick Ag. The plating solution contains 5–8 % potassium hydroxide and 2–3 % silver oxide. The lacquer that protects other areas from Ag plating is then removed by soaking in acetone bath at room temperature. The assembly is thoroughly cleaned again and annealed at 350 $^{\circ}\text{C}$ for 5 h to grow the Ag grains from 25 nm to a few microns, thus making it more ductile [24].

Both Cu substrates and Si chips are chosen for the wire bonding experiments. The Si chip emulates a semiconductor device. The Cu substrate represents Cu pads on a package, a module, or a circuit board. Cu substrates of 20 mm $\times$ 25 mm are cut from 99.9 % pure 0.8 mm thick Cu sheet. The Si chips are scribed from 50.8 mm (2 inch) wafers that are deposited 30 nm chromium (Cr) and 100 nm Au by e-beam evaporation system at 3.99×10^{-11} MPa vacuum. The Cr layer is the adhesion layer and the Au layer protects Cr from oxidation. The flat Ag surfaces of the Cu coil on the MACOR core are bonded to a Cu substrate or a Si chip, respectively. The assembly is mounted on the graphite platform and applied with 6.89 MPa pressure in a vacuum bonding chamber that is pumped to 1.33×10^{-5} MPa vacuum [25] and heated to 300 $^{\circ}\text{C}$ with a dwell time of 3 min. The 6.89 MPa is determined by the applied force divided by the actual bonding area. For 1 mm $\times$ 3 mm bonding area, the corresponding force is only 2.13 kg. The applied force includes the weight of MACRO core. The 6.89 MPa pressure is 10 times lower than what has been used in industrial thermo-compression bonding processes [26, 27]. The assembly is taken out of the bonding chamber after natural cooling in 1.33×10^{-5} MPa vacuum. It takes about 120 min to cool down to room temperature. Each turn of the Cu coil on the MACOR core is cut open and the core is removed. Figure 2 is the sample after this step. For cross sectional evaluations, samples are mounted in epoxy-resin, cut in halves, and polished. SEM and energy dispersive X-ray spectroscopy (EDX) are used to examine the bonding quality,

Fig. 2 The Cu coils bonded on Cu substrate after each turn was cut open and the MACOR winding core was removed

compositions and the microstructure. In-plane pull test and vertical pull test are performed to measure the breaking force of the wire bonds. The fracture modes and surfaces are studied using optical microscope, SEM, and EDX.

3 Experimental results and discussion

Prior to bonding, the Cu wires plated with Ag on the flat surface were annealed at 400 $^{\circ}\text{C}$ for 5 h. Figure 3 displays the optical microscopy images of the cross section of the wire-bond on Cu substrate. The bonding interface appears to be of high quality without voids or cracks. However, a dark line in the Ag layer near the electroplating interface shows up. In Fig. 4 and Table 1, EDX study reveals it to be Cu diffusion band. A concern is that the strength of the Cu diffusion band is unknown. Thus, the annealing temperature was reduced to 350 $^{\circ}\text{C}$. Figure 5a shows the new result of the entire bonding area. There is no black Cu diffusion band inside the Ag layer. It is also seen that the

Fig. 3 Optical microscopy images of an Ag-plated Cu wire annealed at 400 $^{\circ}\text{C}$ for 5 h and then bonded to Cu substrate at 300 $^{\circ}\text{C}$ with 6.89 MPa pressure

Fig. 4 The SEM image includes a black band inside the Ag layer and EDX data demonstrate that it is a Cu diffusion band inside the Ag layer

Table 1 EDX data on Fig. 4 showing the Cu diffusion into Ag

Location	Compositions (at.%)	
	Cu	Ag
①	100.0	0.0
②	74.6	25.4
③	69.1	30.9
④	0.0	100.0

Cu wire is well bonded to the Cu substrate. Figure 5b shows clearly both the plating Cu–Ag interface and bonding Ag–Cu interface. No voids, gaps, or cracks are observed.

In applications, the most important performance parameter is the breaking force of the wire-bond. Two pull tests were performed, in-plane and vertical. The pull test settings are based on military standards MIL-STD-883J method 2011.9 to measure the bond strengths [28]. The in-plane pull test applies the pulling force in a direction on the plane of the bonding interface, as depicted in Fig. 6a. For in-plane pull test, the wire connecting to the Cu substrate is cut to provide two ends accessible with the Cu substrate is clamped firmly. The vertical pull test applies force in a direction perpendicular to the plane of the bonding interface, as portrayed in Fig. 6b. The pull is applied by inserting a hook under the Cu wire with Cu substrate clamped firmly. Table 2 presents the pull test results of five typical wire-bonds made on Cu substrates. Three samples were pulled in-plane and two were pulled in vertical direction. The breaking force of in-plane pull test ranges from 20.7 to 23.7 kg, which is comparable to the breaking force of 1 mm Cu wire (22.5 kg) [29]. These values should be good enough to survive abuse in real applications. The corresponding shear strength ranges from 48 to 55 MPa. The breaking force of samples 4 and 5 on vertical pull test is 8.7 and 12.2 kg, respectively. The corresponding peel strength is 20.2 and 28.3 MPa. This is also called peel

Fig. 6 Two pull tests: **a** in-plane pull test and **b** vertical pull test**Table 2** Pull test breaking forces of Cu wire bonds made on Cu substrates

Sample	Breaking force (kg)	Pull force direction	Shear or peel strength (MPa)
1	20.7	In-plane	48.1 (shear)
2	23.7	In-plane	55.0 (shear)
3	23.3	In-plane	54.1 (shear)
4	12.2	Vertical	28.3 (peel)
5	8.7	Vertical	20.2 (peel)

Table 3 Pull test breaking forces of Cu wire bonds made on Si chips

Sample	Breaking force (kg)	Pull force direction	Shear or peel strength (MPa)
6	15.8	In-plane	36.7 (shear)
7	17.8	In-plane	41.3 (shear)
8	15.1	In-plane	35.1 (shear)
9	8.0	Vertical	18.6 (peel)
10	8.5	Vertical	19.7 (peel)

strength because the force is in the peel direction. It seems that the peel strength is about one-half of the shear strength. The breaking force of five wire bonds made on Si

Fig. 5 Cross-section SEM images of a typical wire bond annealed at 350 °C for 5 h and then bonded at 300 °C with 6.89 MPa pressure: **a** low magnification ($\times 200$), **b** high magnification ($\times 1000$)

chips is shown in Table 3. Overall, the breaking forces are about 80 % of those of wire bonds made on Cu substrates.

We then studied the fracture modes and fracture interfaces. Sample no. 2 broke at two interfaces: near Cu–Ag electroplating interface and Ag–Cu bonding interface. This is the only sample for which Cu wire broke first. Otherwise, the wire-bond is stronger than the Cu wire. All other samples broke at three interfaces: (A) near Cu–Ag electroplating interface, (B) inside Ag layer, and (C) Ag–Cu bonding interface, as illustrated in Fig. 7. Figure 8a is the SEM image of the Cu wire of sample 3 in Table 2 after being pulled off the Cu substrate. It broke at three interfaces with percentages below: mode A—40 %, mode B—25 %, and mode C—35 %. Figure 8b–d are the high magnification images of fracture modes A, B, and C, respectively. To identify accurately where mode A fracture

is, EDX analysis on Fig. 8b was performed and the data were presented in Table 4. It is seen that significant amount of Ag was detected. This indicates that the fracture occurs not exactly on the Cu–Ag plating interface, but rather inside the Ag and near the plating interface. EDX data on Fig. 8d are provided in Table 5. The small amount of Cu detected is within measurement error. Thus, it can be said that the mode C fractures at the Ag–Cu bonding interface. Some regions on Fig. 8d (mode C) are flat because Ag is ductile and deforms when the bonding force is applied.

We next observed the wire bond residue on the Cu substrate after in-plane pull test. The Cu substrate on which Cu wire sample 3 was bonded also had three fracture modes. All three fracture modes on the Cu substrate are presented in Fig. 9, to show how they look. Figure 9b–d are symmetrical to Fig. 8b–d. For Fig. 9b, c, they are very

Fig. 7 A cross sectional sketch showing three fracture modes: A, B, and C. Mode A is not exactly on the Cu–Ag electroplating interface, but inside Ag and near the interface

Fig. 8 SEM images of the bonding region of sample 3 in Table 2 after Cu wire being pulled off the Cu substrate: **a** the entire bonding region, **b** mode A fracture near Cu–Ag electroplating interface, **c** mode

B fracture surface inside Ag layer, and **d** mode C fracture on Ag–Cu bonding interface

similar to Fig. 8b, c. Figure 9d it displays small amount of Ag traces on the Cu substrate. Thus, it still can be said that most of this region fractures at the Ag–Cu bonding interface. Figure 10 exhibits the wire-bond of sample 4 which is bonded to Cu substrate after vertical pull test. It

Table 4 EDX data on Fig. 8b showing mode A fracture surface of sample 3 after in-plane pull test

Location	Compositions (at.%)	
	Cu	Ag
①	81.5	18.5
②	52.0	48.0
③	95.1	4.9
④	68.4	31.6

Table 5 EDX data on Fig. 8d showing mode C fracture surface of sample 3 after in-plane pull test

Location	Compositions (at.%)	
	Cu	Ag
①	0.0	100
②	1.3	98.7
③	0.9	99.1

broke in three modes. Figure 11 presents the wire-bond of sample 7 which is bonded to Si chip after in-plane pull test. The wire-bond of sample 9 made on Si chip after vertical pull test is presented in Fig. 12. They also broke in three modes.

4 Summary and outlook

In this research, we developed solid-state bonding processes to bond 1 mm large Cu wires on Cu substrates and Si chips, respectively. To reduce the bonding pressure, the bonding surface on the Cu wire was plated with Ag and annealed to make it deform more easily. The bonding process was performed at 300 °C with 6.89 MPa for 3 min. This pressure is 10 times lower than what has been used in industrial thermo-compression processes. For 1 mm × 3 mm bonding surface, the force applied is only 2.13 kg. In-plane (shear) pull test measured a breaking of force 20.7 to 23.7 kg, comparable to the 22.5 kg breaking force of the Cu wire. With further improvement on bonding conditions, it is possible to make the wire-bond stronger than the Cu wire itself. There is also room to reduce the bonding temperature and pressure.

Fig. 9 SEM images of wire bond residue of sample 3 on Cu substrate after pull test: **a** the entire bonding region, **b** mode A fracture near Cu–Ag electroplating interface, **c** mode B fracture surface inside Ag layer, and **d** mode C fracture on Ag–Cu bonding interface

Fig. 10 SEM images of the Cu wire bond sample 4 which is bonded to Cu substrate after vertical pull test: **a** the entire bonding region, **b** *mode A* fracture near Cu–Ag electroplating interface, **c** *mode B* fracture surface inside Ag layer, and **d** *mode C* fracture on Ag–Cu bonding interface

Fig. 11 SEM images of the Cu wire bond sample 7 which is bonded to Si chip after in-plane pull test: **a** the entire bonding region, **b** *mode A* fracture near Cu–Ag electroplating interface, **c** *mode B* fracture surface inside Ag layer, and **d** *mode C* fracture on Ag–Si bonding interface

Fig. 12 SEM images of the Cu wire bond sample 9 which is bonded to Si chip after vertical pull test: **a** the entire bonding region, **b** mode A fracture near Cu-Ag electroplating interface, **c** mode B fracture surface inside Ag layer, and **d** mode C fracture on Ag-Si bonding interface

This research is a preliminary process development to demonstrate the feasibility of wire-bonds that are strong and can sustain continuous high operating temperature such as 350 °C. With the materials involved, the upper operating temperature limit is the eutectic temperature of the Cu-Ag binary system, 780 °C. Further experiments are required to access the lifetime of the wire-bonds at specific operating temperatures.

Fundamental research on process development has always been some distance away from production. For the wire bonding process reported here, it is practically possible for the industry to turn it in production if the industry is willing to invest in and develop the equipment needed. The path to production is outlined below: (a) shape the end of Cu wires into the geometry needed, (b) plate the bonding surface of Cu wires with Ag and anneal the Cu wires, (c) design and build a machine with a bonding head that grabs the end of the Cu wires, heat it, and press it onto the bond pad is already preheated. In future high temperature electronics operating at 350 °C or above, the wire bonding method reported should be valuable to the electronic industry.

Acknowledgments This research was supported by the II-VI Foundation.

References

1. I.V. Kassamakov, H.O. Seppanen, M.J. Oinonen, E.O. Haegstrom, J.M. Osterberg, J.P. Aaltonen, H. Saarikko, Z.P. Radivojevic, Scanning white light interferometry in quality control of single-point tape automated bonding. *Microelectron. Eng.* **84**, 114–123 (2007)
2. K. Sun-Chul, K. Young-Ho, Flip chip bonding with anisotropic conductive film (ACF) and nonconductive adhesive (NCA). *Curr. Appl. Phys.* **13**, S14–S25 (2013)
3. H. Xu, V.L. Acuff, C. Liu, V.V. Silberschmidt, Z. Chen, Facilitating intermetallic formation in wire bonding by applying a pre-ultrasonic energy. *Microelectron. Eng.* **88**, 3155–3157 (2011)
4. Z.W. Zhong, Overview of wire bonding using copper wire or insulated wire. *Microelectron. Reliab.* **51**, 4–12 (2011)
5. G.G. Harman, Ultrasonic bonding systems and technologies, including a description of the ultrasonic wire bonding mechanism, in *Wire Bonding in Microelectronics*, 3rd ed. (McGraw-Hill, New York, 2010), ch. 2, sec. 6, pp. 33–38
6. J.B. Pan, P. Fraud, Wire bonding challenges in optoelectronics packaging, in *Proceedings of the 1st SME Annual Manufacturing Technology Summit*, pp. 1–7, Aug 2004
7. C.D. Breach, F.W. Wulff, A brief review of selected aspects of the materials science of ball bonding. *Microelectron. Reliab.* **50**, 1–20 (2010)
8. M. Mayer, O. Paul, D. Bolliger, H. Baltes, Integrated temperature microsensors for characterization and optimization of thermosonic ball bonding process. *IEEE Trans. Compon. Packag. Technol.* **23**, 393–398 (2000)

9. A. Shah, H. Gaul, M. Schneider-Ramelow, H. Reichl, M. Mayer, Y. Zhou, Ultrasonic friction power during Al wire wedge-wedge bonding. *J. Appl. Phys.* **106**, 013503 1–013503 8 (2009)
10. S. Murali, N. Srikanth, C.J. Vath, An analysis of intermetallics formation of gold and copper ball bonding on thermal aging. *Mater. Res. Bull.* **38**, 637–646 (2003)
11. P. Liu, L. Tong, J. Wang, L. Shi, H. Tang, Challenges and developments of copper wire bonding technology. *Microelectron. Reliab.* **52**, 1092–1098 (2012)
12. P. Ratchev, S. Stoukatch, B. Swinnen, Mechanical reliability of Au and Cu wire bonds to Al, Ni/Au and Ni/Pd/Au capped Cu bond pads. *Microelectron. Reliab.* **46**, 1315–1325 (2006)
13. B.K. Appelt, A. Tseng, C.H. Chen, Y.S. Lai, Fine pitch copper wire bonding in high volume production. *Microelectron. Reliab.* **51**, 13–20 (2011)
14. J. Yeung, X. Hui, E. Chew, Effect of palladium on copper aluminate intermetallic growth in palladium copper bonding wire, in *Proceedings of the 13th International Conference on Electronic Packaging Technology & High Density Packaging (ICEPT-HDP)*, pp. 346–351, Aug 2012
15. I. Singh, I. Qin, H. Xu, H. Cuong, S. Low, H. Clauberg, B. Chylak, V. Acoff, Pd-coated Cu wire bonding technology: chip design, process optimization, production qualification and reliability test for high reliability semiconductor devices, in *IEEE 62nd Electronic Components and Technology Conference (ECTC)*, pp. 1089–1096, May 2012
16. S. Kaimori, T. Nonaka, A. Mizoguchi, The development of Cu bonding wire with oxidation-resistant metal coating. *IEEE Trans. Adv. Packag.* **29**, 227–231 (2006)
17. I. Qin, H. Xu, H. Clauberg, R. Cathcart, V. L. Acoff, B. Chylak, C. Huynh, Wire bonding of Cu and Pd coated Cu wire: bondability, reliability, and IMC formation, in *IEEE 61st Electronic Components and Technology Conference (ECTC)*, pp. 1489–1495, May 2011
18. H. Clauberg, B. Chylak, N. Wong, J. Yeung, E. Milke, Wire bonding with Pd-coated copper wire, in *IEEE CPMT Symposium Japan (Formerly VLSI Packaging Workshop of Japan)*, pp. 1–4, Aug 2010
19. C.C. Lee, L. Chang, The quantum theory of solid state atomic bonding, in *IEEE 64th Electronic Components and Technology Conference (ECTC)*, pp. 1335–1341, May 2014
20. Y.L. Chen, Y.Y. Wu, C.C. Lee, Silver-assisted copper wire bonding using solid-state processes, in *IEEE 64th Electronic Components and Technology Conference (ECTC)*, pp. 1529–1532, May 2014
21. J. Reiner, O. Vermesan, R. Bayerer, High temperature power electronics IGBT modules for electrical and hybrid vehicles, in *Proceedings of IMAPS International Conference on High Temperature Electronics Network (HiTEN)*, pp. 199–204, Sept 2009
22. G.G. Harman, C.A. Cannon, Micro-electronic wire bond pull test—how to use it, how to abuse it. *IEEE Trans. Compon. Hybrids Manuf. Technol.* **1**, 203–210 (1978)
23. D.A. Zych, Thermal-conductivity of a machinable glass ceramic below 1 K. *Cryogenics* **29**, 758–759 (1989)
24. W.P. Lin, C.H. Sha, P.J. Wang, C.C. Lee, Microstructures of silver films plated on different substrates and annealed at different conditions, in *IEEE 61st Electronic Components and Technology Conference (ECTC)*, pp. 1782–1786, May 2011
25. C.C. Lee, D.T. Wang, W.S. Choi, Design and construction of a compact vacuum furnace for scientific research. *Rev. Sci. Instrum.* **77**, 125104-1–125104-5 (2006)
26. C.H. Sha, P.J. Wang, W.P. Lin, C.C. Lee, Solid state bonding of silver foils to metalized alumina substrates at 260 degrees C. *J. Electron. Packag.* **133**, 041007-1–041007-3 (2011)
27. S. Das, A.N. Tiwari, A.R. Kulkarni, Thermo-compression bonding of alumina ceramics to metal. *J. Mater. Sci.* **39**, 3345–3355 (2004)
28. Department of Defense Test Method Standard, Bond Strength (Destructive Bond Pull Test), MIL-STD-883J Method 2011.9 (online). <http://www.landandmaritime.dla.mil/Downloads/MilSpec/Docs/MIL-STD-883/std883.pdf>. Accessed July 2014
29. USMILCOM Inc., Tensile strength of Cu wire (online). http://www.usmilcom.com/Basic_Electricity_Principles/TensileStrength.htm. Accessed Jan 2007