Sensors & Transducers, Vol. 235, Issue 7, July 2019, pp. 37-42

Sensors & Transducers

Published by IFSA Publishing, S. L., 2019
http://www.sensorsportal.com

Cu/Al Clad and Ag-4Pd Ribbon Bonding for High Power IC Packages

[1, *] Chun-Hao CHEN, [2] Jan HOEFER, [3] Yen-Cheng LIN, [1] Chia-Ying LIN and [1] Tung-Han CHUANG

[1] Institute of Materials Science and Engineering, National Taiwan University, No. 1, Sec. 4, Roosevelt Rd., Taipei 10617, Taiwan

[2] Fraunhofer Institute for Reliability and Microintegration IZM, Gustav-Meyer-Allee 25, 13355 Berlin, Germany

[3] Wire Technology Co., LTD, No. 27, Aly. 56, Ln. 320, Sec. 1, Shatian Rd., Dadu Dist, Taichung 432, Taiwan

[*] Tel.: +886-2-3366-1326

[*] E-mail: d04527008@ntu.edu.tw

Received: 15 April 2019 /Accepted: 28 May 2019 /Published: 31 July 2019

Abstract: Ultrasonic Wire bonding is widely applied in the electronics industry, especially in the field of power integrated circuits (Power IC). In the present work, the bonding interface of Cu/Al clad and Ag-4Pd alloy 100 μm ultra-thin ribbons bonded on different DBC substrates metallized with Ni, Au and Pd were evaluated. The Cu/Al clad ribbons allowed a wider bonding parameter window, and both Cu/Al clad and Ag-4Pd ribbons showed a robust process and high yield rate (over 90 %) during bonding. Microscopic examination of the bonding interfaces showed no cracks or delamination of the metal layers on the substrates, and the interface of the Ag-4Pd ribbon on the DBC substrate remained the same after high temperature storage test (HTST) at 150 °C for 1000 h. The pull strengths of the Ag-4Pd ribbons on Cu/Ni substrate were higher, but the yield rate was poor (20 %). On the other hand, DBC substrates metallized with Ni/Pd, Ni/Au, and Ni/Pd/Au films showed superior bonding yield rates (over 90 %) with satisfactory pull strengths. The results indicated that Ag-alloy ribbons could be a great choice for Power IC packaging.

Keywords: Ultrasonic bonding, Ribbon Bonding, Cu/Al clad ribbon, Ag-alloy Ribbon, Power IC.

1. Introduction

Ultrasonic wire bonding is the most cost-effective way to provide interconnections in semiconductor devices. Recently, power integrated circuits (Power IC) have drawn increasing attention, especially in silicon-based Insulated Gate Bipolar Transistor (IGBT) modules. Automotive IGBT module packaging should meet the qualification standard of Automotive Electronics Council stress tests (AEC-Q101) [1], which requires dedicated quality control and high reliability. The key points in Power IC packaging are heat dissipation and tolerance of high current density. To accomplish the high current capability, heavy wire bonds are usually wedged in parallel on the junctions. Under relatively high current density, however, the narrow wedge spacing is prone to cause reliability issues such as electromigration and ion migration, leading to short circuits and module failure. Moreover, the wedge shape of the wire bonds implies smaller cross-sections, resulting in high resistance and inductance [2], so it is not favorable for power electronics. An alternative technology is ribbon bonding. Compared to conventional wire bonding, ultrasonic bonding of ribbon materials was considered to be a breakthrough in high power electronics because the larger cross-section area performed better in terms of lower impedance and inductance at high frequencies [3]. Traditionally, Al heavy wires and ribbons have been used for the interconnections between Power IC chips and Direct Bonded Copper (DBC) substrates [4-5]. Ribbon bonding of aluminum has been used in several applications, such as microwave electronics and DC–DC converters [2]. However, the relatively high resistivity and poor thermal stability of aluminum limits its usage, especially under high current density. Copper ribbon was considered as a substitutional material for Al and has a superior lifespan to that of Al products [6]. However, wedge bonding of Cu requires high ultrasonic power and bonding force, which is prone to cause damage to chips [7]. In addition, the hardness of copper ribbon results in a short lifetime of the bonding tool and incomplete cutting of the ribbon [8], neither of which is favorable in industrial production. The innovative alternatives of Cu/Al bimetal ribbon and Al-coated copper ribbon were proposed as feasible replacements for copper ribbon [9-10]. The clad ribbon allows a greater bonding parameter window due to the bimetal structure. The upper layer of copper provides better electrical properties and cost benefits, and the bottom layer of Al can be optimized as standard Al ribbon. Moreover, the bimetal Cu/Al clad ribbon can be easily produced by a cold-rolled process without further manufacturing processes. The main issue of such clad ribbons is reliability, for they usually fail in severe thermal cycle tests because the growth of intermetallic compounds between the Cu and Al causes heel cracks at the interface [11]. Other technologies such as copper clip bonding were also proposed to meet the requirements of high current density and better bonding quality [12-13]. However, clip bonding requires dedicated process control of the solder spraying and alignment of the joints, which is not favorable to industry due to cost concerns. The failures of copper and aluminum have presented the need for another substitutional material for bonding wire. One proposed material is Ag-alloy ribbon [14]. Having low electrical resistivity and great mechanical properties, Ag-alloy ribbon may be a good candidate for Power IC packaging solutions.

2. Experiments

In the present study, cold-rolled Cu/Al clad ribbons and Ag-4Pd ribbons of 100 μm thickness were used. Tests were performed on the F&K DELVOTEC 5600 ultrasonic bonders with a typical ribbon wedge bond head, as shown in Fig. 1. Commercialized DBC substrates metallized with Ni, Pd and Au were used (Fig. 2). The ultrasonic transducer was set to 58.4 kHz and the ribbon span was optimized to 8 mm. The wire-pull tests were performed on a DAGE 4000Plus pull-shear tester to analyze the bond strength. The quality of the bonds was evaluated by cross-section polishing of the bond interface and investigated by optical microscopy (OM) and scanning electron microscopy (SEM). Moreover, the bonded Ag-4Pd ribbon modules were subjected to High Temperature Storage Test (HTST) at 150 °C for 1000 h. The polished cross-sections were also examined after the tests.

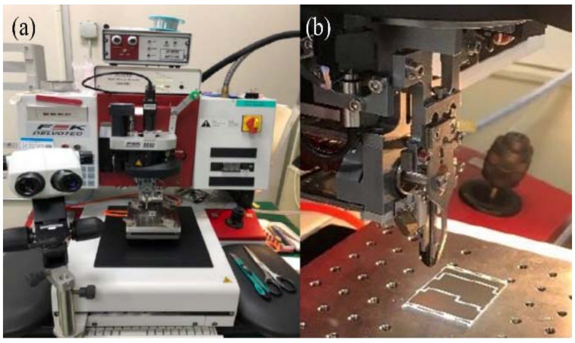

Fig. 1. (a) F&K DELVOTEC 5600 ultrasonic bonder, (b) ribbon bond head.

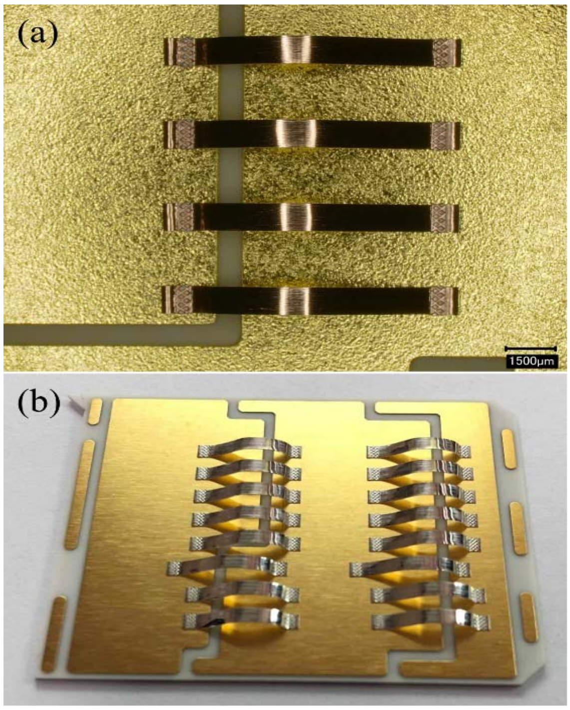

Fig. 2. (a) 100 μm thick Cu/Al clad ribbons bonded on NiPdAu DBC substrate, (b) 100 μm thick Ag-4Pd ribbons bonded on NiPdAu DBC substrate.

3. Results and Discussions

The Cu/Al clad and Ag-4Pd ribbons were bonded with DBC substrates electroplated with surface metallization layers of thickness 70–80 μm. To evaluate the quality of the bonds, the as-bonded cross-sections of the Ag-4Pd and Cu/Al ribbons were imaged and are shown in Fig. 3. The deformation of the ribbons was obvious in both cases, but that of the Cu/Al clad ribbon was more severe. The results indicated that although the bottom aluminum layer of the clad ribbon provides a wide window of bonding parameters, the hardness of the top Cu layer requires higher bond strength, which results in ribbon deformation (white circle in Fig. 3(b)).

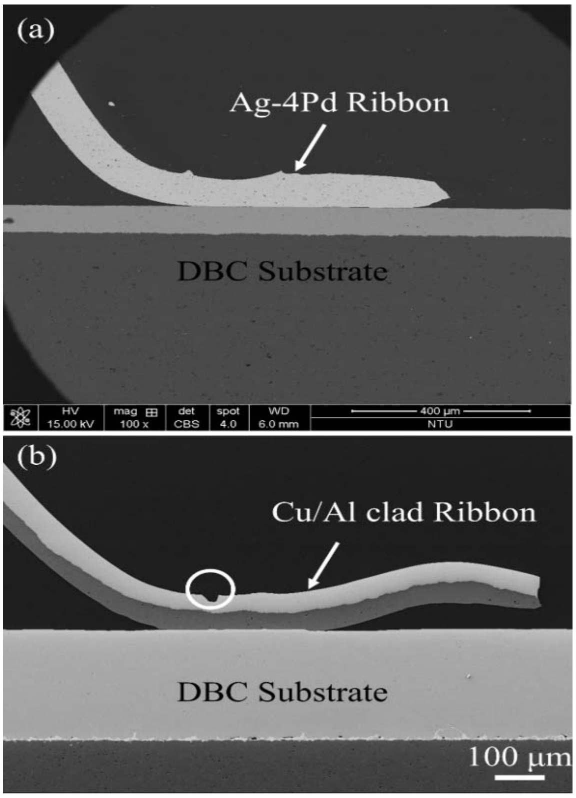

Fig. 3. Cross-sectional SEM images of (a) Ag-4Pd alloy ribbon, (b) Cu/Al clad ribbon as-bonded on DBC substrates.

Although the yield rate of the process could reach almost 95 %, the deformation-caused shrinkage of the cross-sectional area could be expected to lead to reliability issues such as stress concentration, lower pull strength and higher current density in the localized area. It was previously reported that crack propagation during the power cycle tests were determined by the deformation of the Al layer [9]; our result showed a drastic increase in the pull strength in less-deformed ribbons with optimized bonding parameters (Fig. 4). The pull strengths of the severely deformed clad ribbons on Cu/Ni/Au and Cu/Ni/Pd/Au DBC substrates were 1052.4 gf and 1084.0 gf, with the result code of neck/wedge break. With the optimized bonding parameters, however, those of the clad ribbons on Cu/Ni/Au and Cu/Ni/Pd/Au DBC substrates reached 1287.6 gf and 1551.8 gf, with the result code of mid-span (Fig. 5). On the other hand, the Ag-4Pd ribbon also showed a great yield rate (over 90 %) without sophisticated adjustment of the bonding parameters, and the deformation of the structures was not obvious. Finally, it was previously reported that copper ribbon had a cutting issue after the second bond, leading to tail-up and pull off the interface and subsequently weakened bonds [8]. However, both the Cu/Al clad and Ag-4Pd ribbons showed great cutting and no damage to the substrate during the process, indicating that the working properties of both ribbons were superior to that of Cu ribbon.

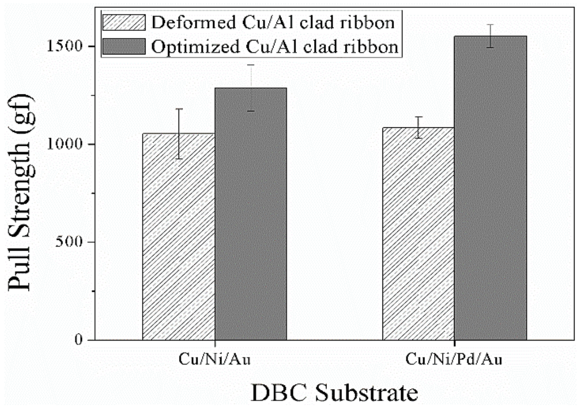

Fig. 4. Pull strength of Cu/Al clad ribbon on Cu/Ni/Au and Cu/Ni/Pd/Au DBC substrates.

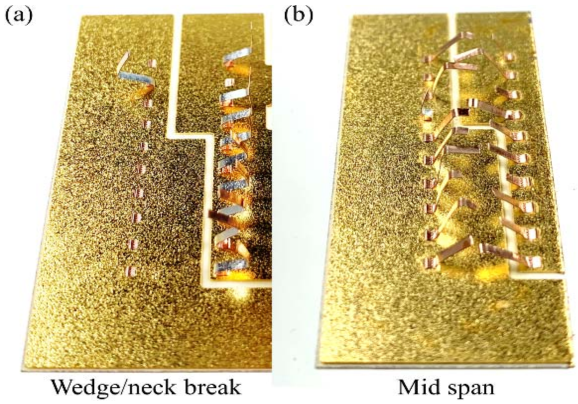

Fig. 5. Pull test result codes of Cu/Al clad ribbon on DBC substrates: (a) deformed ribbon; (b) optimized ribbon.

The quality of the bonds was examined in polished cross-section samples, which gave clear indications of chip damage or deformation in the metallization layers during the bonding process. It has been reported that the Cu/Al clad ribbon usually exhibits uneven deformation because of the difference in the moduli of the two metals [7, 9]. The aluminum layer was expected to have most of the deformation during the bonding process, and Al-splash at the front/tail side resulted in fatigue cracking and delamination of the metal layer in the subsequent reliability tests [9]. In the present study, the SEM cross-sectional images of the bond interfaces of Cu/Al clad ribbon and Ag-alloy ribbon on Cu/Ni/Au and Cu/Ni/Pd/Au DBC substrates in the as-bonded conditions, shown in Fig. 6, Fig. 7 and Fig. 8, respectively, indicated that both the Cu/Al clad ribbon and Ag-4Pd ribbon had a continuous bonding interface without cracking or splashing of the metallization layer on each substrate. Therefore, no damage was caused to the substrates during the bonding process.

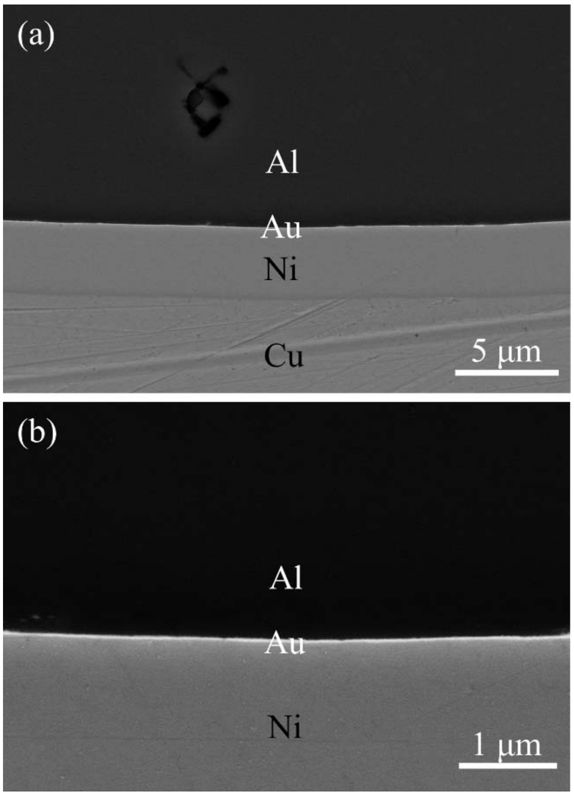

Fig. 6. Interfacial image of (a) Cu/Al alloy ribbon as-bonded on Cu/Ni/Au DBC substrate, (b) high magnification of interface.

From the perspective of reliability, a severe heel crack was reported in the Cu/Al clad ribbon bonded on MOSFET standard Al metallization after a certain number of power cycle tests because of the weakened aluminum [9]. Besides, the aluminum and gold interface system entails issues such as overgrowth of intermetallic compounds, which can cause delamination and crack propagation [15-16]. Although the wide window of the bonding parameters and outstanding yield rate of Cu/Al clad ribbon would be favorable to industry, the reliability issue of Cu/Al clad ribbon still needs to be addressed in the future. On the other hand, the sound interfaces of the Ag-4Pd ribbon modules were subjected to high temperature storage test (HTST) at 150 °C for 1000 h. The high temperature storage test can cause the degradation and failure of packaging modules, leading to detachment of the wire joints. However, the bonding interface of Ag-alloy ribbon on DBC substrate remained almost unchanged after the HTST, as shown in Fig. 9. No intermetallic compounds were found at the interface because the surface metallization layers (Au/Pd) were solid solutions to Ag-alloy ribbons. This result provides clear evidence that Ag-alloy ribbons can be expected to have outstanding properties with DBC substrates due to the ribbon material itself.

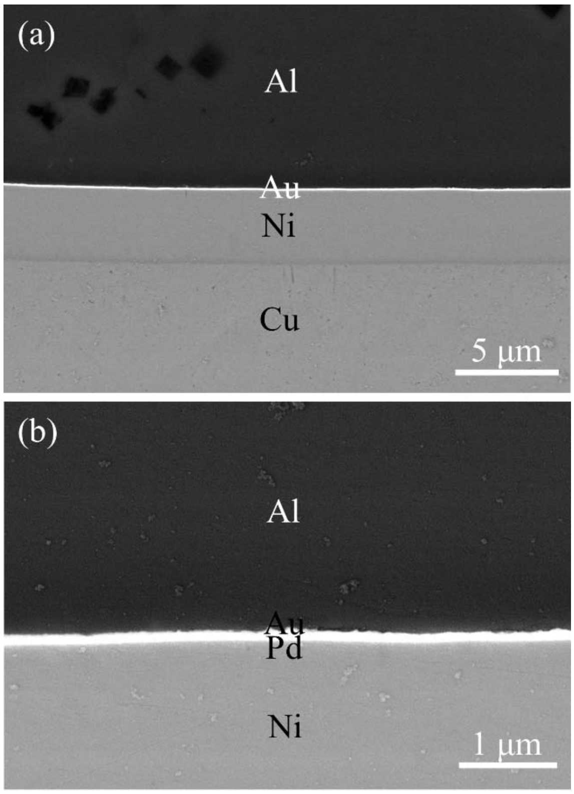

Fig. 7. Interfacial image of (a) Cu/Al alloy ribbon as-bonded on Cu/Ni/Pd/Au DBC substrate, (b) high magnification of interface.

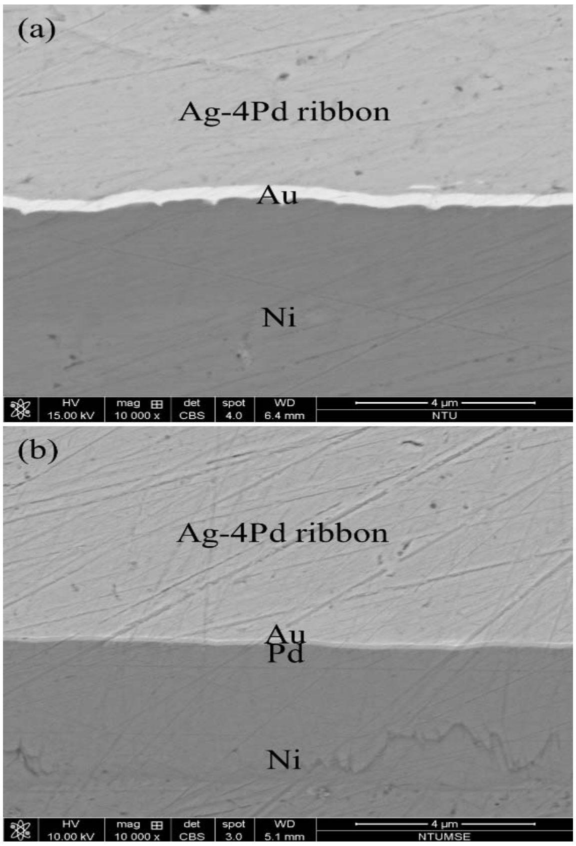

Fig. 8. Interfacial image of Ag-4Pd ribbon as-bonded on (a) Cu/Ni/Au, (b) Cu/Ni/Pd/Au DBC substrate.

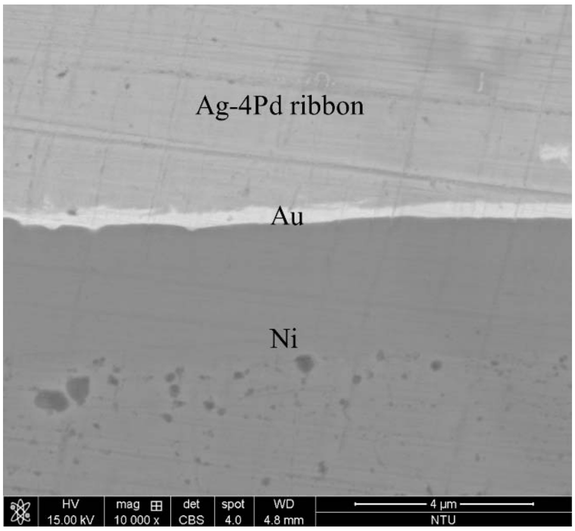

Fig. 9. Interfacial image of Ag-4Pd alloy ribbon on Cu/Ni/Au DBC substrate after HTST at 150 °C for 1000 h.

The pull strengths of the Cu/Al clad ribbon and Ag-4Pd ribbon on the DBC substrates were evaluated. Fig. 10 shows that the pull strength of the Cu/Al clad ribbon was superior to that of the Ag-4Pd ribbon in the initial as-bonded state. However, both ribbons showed sufficient pull strengths on the two types of DBC substrates: 1287.6 gf and 779.6 gf on Cu/Ni/Au DBC substrate, and 1551.8 gf and 796.2 gf on Cu/Ni/Pd/Au DBC substrate, respectively. The result code after pull tests of the Ag-4Pd ribbon was classified as wedge crater due to the strong tensile strength of the Ag-4Pd ribbon. In addition, the two types of ribbon both had great yield rates during bonding (over 90 %). Nevertheless, the bonding strength of the Ag-4Pd ribbon module after HTST was also examined, and it showed a slight increase in pull strength.

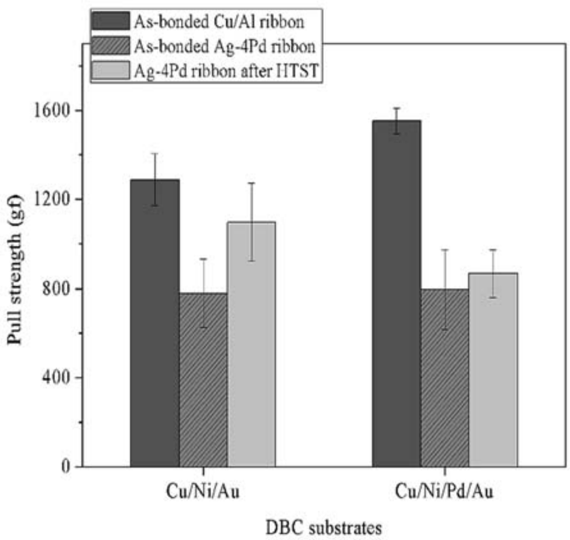

Fig. 10. Wire pull strengths of Cu/Al clad ribbon and Ag-4Pd alloy ribbon with different types of metallized DBC substrates.

It is possible that the surface metallization layers (Au/Pd) slightly underwent a diffusion path at the interface with the Ag-4Pd ribbon during the HTST. Thus, the broadened diffusion coupling of the Au/Pd and Ag-4Pd ribbon interfaces provides a stronger bonding strength at the interface.

Last, in order to examine the bondability of the Ag-4Pd ribbon on different types of DBC, the Ag-4Pd ribbon was bonded on Cu/Ni, Cu/Ni/Pd, Cu/Ni/Pd/Au, and Cu/Ni/Au substrates. The results showed that Cu/Ni had the highest pull strength of 956.7 gf (Fig. 11), but the yield rate on such substrate was poor (20 %). On the other hand, the DBC substrate metallized with Ni/Pd, Ni/Au, and Ni/Pd/Au films showed great bonding yield rates (over 90 %) and satisfactory pull strengths of 619.3, 779.6 gf, and 796.2 gf. The failure mode after wire-pull was classified as wedge crater due to the strong tensile strength of the Ag-4Pd ribbon. The results illustrated that Ag-alloy ribbon has great properties and is a promising candidate for ultrasonic wire bonding in Power IC packaging.

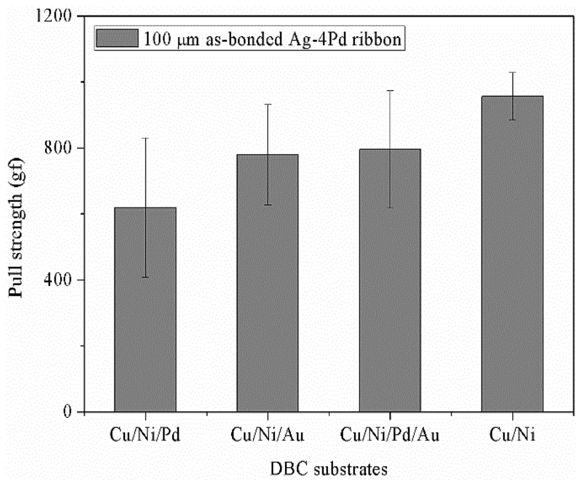

Fig. 11. Wire pull strengths of Ag-4Pd alloy ribbon with different types of metallized DBC substrates.

4. Conclusions

1. The bondability of the Cu/Al clad and Ag-4Pd ribbons on various DBC substrates was evaluated. With optimized parameters, the Cu/Al clad ribbon had robust pull forces of 1287.6 gf and 1551.8 gf on Cu/Ni/Au and Cu/Ni/Pd/Au DBC substrate. The Ag-4Pd ribbon had less deformation, but both ribbons showed a robust process with a high yield rate (over 90 %) during bonding.

2. The bonding interface showed no cracking or delamination of metal layers on the substrates. Although the bond strength of the as-bonded Cu/Al clad ribbon was 40 to 50 % higher, the interface of the Ag-4Pd ribbon on DBC substrates remained the same after high temperature storage test (HTST) at 150 °C for 1000 h, indicating that Ag-4Pd ribbon could be an attractive solution in terms of reliability.

3. The pull strength of the Ag-4Pd ribbon on different types of DBC was 956.7 gf on the Cu/Ni substrate, but the yield rate was poor (20 %). On the other hand, DBC substrate metallized with Ni/Pd, Ni/Au, and Ni/Pd/Au films showed great bonding yield rates (over 90 %) and satisfactory pull strengths of 619.3 gf, 779.6 gf and 796.2 gf. The results indicated that Ag-alloy ribbon would be a better choice for Power IC packaging in terms of reliability.

Acknowledgements

This study was sponsored by the industrial and academic cooperation programs of Wire Technology Co. LTD. and the Ministry of Science and Technology, Taiwan, under Grant No. MOST-107-2622-E-002-019-CC2 and the Doctoral Student Study Abroad Program 2019, under grant No. 108-2917-I-002-023.

References

[1]. AEC-Q101-REV–C Standard, STRESS TEST QUALIFICATION FOR AUTOMOTIVE GRADE DISCRETE SEMICONDUCTORS, *Automotive Electronics Council*, June 29, 2005.

[2]. S. Jacques, R. Leroy, M. Lethiecq, Impact of aluminum wire and ribbon bonding technologies on D2PAK package reliability during thermal cycling applications, *Microelectronics Reliability*, Vol. 55, Issue 9-10, Aug. 2015, pp. 1821-1825.

[3]. B. K. Benton, Benefits of Automated Ribbon Bonding for Microwave Applications, *Palomar Technologies Inc.*, Vista, CA, 2000.

[4]. I. W. Qin, P. Reid, R. E. Werner, D. Doerr, Automatic Wedge Bonding with Ribbon Wire for High Frequency Applications, in *Proceedings of the 27th Annual IEEE/SEMI International Electronics Manufacturing Technology Symposium,* 2002, pp. 97-103.

[5]. G. G. Harman, L. W. Charles, Materials Problems Affecting Reliability and Yield of Wire Bonding in VLSI Devices, in *MRS Proceedings*, *Cambridge University Press*, Vol. 154, 1989, pp. 401-413.

[6]. J. Ling, T. Xu, C. Luechinger, Large Cu Wire Wedge Bonding Process for Power Devices, in *Proceedings of the IEEE 13th Electronics Packaging Technology Conference*, 2011, pp. 1-5.

[7]. J. Ling, T. Xu, R. Chen, O. Valentin, C. Luechinger, Cu and Al-Cu Composite-Material Interconnects for Power Devices, in *Proceedings of the IEEE 62nd Electronic Components and Technology Conference (ECTC'2012)*, 2012, pp. 1905-1911.

[8]. N. Marenco, M. Kontek, W. Reinert, J. Lingner, M.-H. Poech, Copper Ribbon Bonding for Power Electronics Applications, in *Proceedings of the IEEE European Microelectronics Packaging Conference (EMPC'2013)*, Grenoble, France, 9-12 Sep. 2013.

[9]. C. Luechinger, R. Chen, J. Fu, B. Poncelet, O. Valentin, T. J. Walker, T. Xu, Aluminum-Copper Ribbon Interconnects for Power Devices, *IEEE Transactions on Components, Packaging and Manufacturing Technology*, Vol. 7, Issue 9, Sep. 2017, pp. 1567-1577.

[10]. US Patent No. 4,355,082, Ultra Thin Wire for Semiconductor, 1981.

[11]. S. Park, S. Nagao, T. Sugahara, K. Suganuma, Heel crack propagation mechanism of cold-rolled Cu/Al clad ribbon bonding in harsh environment, *J Mater Sci: Mater Electron*, Vol. 26, 2015, pp. 7277-7289.

[12]. Y. Zhu, H. Chen, K. Xue, M. Li, J. Wu, Thermal and Reliability Analysis of Clip Bonding Package Using High Thermal Conductivity Adhesive, in *Proceedings of the IEEE 15th Electronics Packaging Technology Conference (EPTC'2013)*, Singapore, 11-13 Dec. 2013, pp. 259-263.

[13]. K. K. Lwin, C. E. Tubillo, T. Panumard, J. Dimaano, N. Suthiwongsunthorn, S. Sirinorakul, Copper Clip Package for high performance MOSFETs and its optimization, in *Proceedings of the IEEE 18th Electronics Packaging Technology Conference (EPTC'2016)*, Singapore, 30 Nov. – 3 Dec. 2016, pp. 259-263.

[14]. C. H. Che, Y. C. Lin, T. H. Chuang, Ultrasonic Bonding of Ag-4Pd Alloy Ribbon for High Power IC Packages, in *Proceedings of the 2nd International Conference on Microelectronic Devices and Technologies (MicDAT'2019)*, Amsterdam, The Netherlands, 22-24 May 2019, pp. 51-54.

[15]. 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, *Microelectronics Reliability*, Vol. 46, 2006, pp. 1315-1325.

[16]. Xu H., *et al.*, Intermetallic phase transformations in Au-Al wire bonds, *Intermetallic*, Vol. 19, Issue 12, 2011, pp. 1808-1816.