Available online at www.sciencedirect.com
ScienceDirect
Microelectronic Engineering 84 (2007) 362–367
MICROELECTRONIC ENGINEERING
www.elsevier.com/locate/mee

Two capillary solutions for ultra-fine-pitch wire bonding and insulated wire bonding

K.S. Goh [a], Z.W. Zhong [b,*]

[a] SPT Asia Pte Ltd., 970 Toa Payoh North, #07-25/26, Singapore 318992, Singapore
[b] School of Mechanical and Aerospace Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798, Singapore

Received 10 August 2006; received in revised form 7 November 2006; accepted 14 November 2006
Available online 11 December 2006

Abstract

In this article, the new challenges and requirements in wire bonding are discussed, the problems in ultra-fine-pitch wire bonding and insulated wire bonding are analyzed, and then two capillary solutions to the problems are presented. Actual bonding experiments using the new capillaries were carried out and the results were satisfactory. Compared to the standard design, a new capillary design has a larger inner chamfer, a larger chamfer diameter and a smaller chamfer angle. This new capillary design has proved to improve the ball bondability and smaller ball size control for ultra-fine pitch wire bonding. A unique surface characteristic on the capillary tip surface has also been derived. The new finishing process developed creates a new surface morphology, which has relatively deep lines with no fixed directions. Compared to the standard capillary, this capillary has less slipping between the wire and the capillary tip surface in contact, and provides better coupling effect between them and better ultrasonic energy transfer. This capillary has been used to effectively improve the bondability of the stitch bonds for insulated wire bonding.

Keywords: Microelectronics packaging; Wire bonding; Capillary; Ultra-fine pitch; Insulated wire

1. Introduction

Integrated circuit (IC) chips are the key elements in microelectronic devices. However, they cannot work without power and signals. Therefore, microelectronic packaging is a must to supply power to IC chips and distribute signals among IC chips and microelectronic devices [1–4]. IC fabrication, microelectronic packaging and even machining of silicon substrate face more and more new challenges [5–9], as consumers of microelectronic devices, including the manufacturing engineers of microelectronic products, demand more and more, such as lower cost, better performance, smaller sizes and more functions.

Wire bonding is the most widely employed packaging technology in the semiconductor and microelectronics industries [10]. For peripheral array IC chips, wire bonding is cheaper than flip chip [11] if the IC chip size and the pad pitch are large [12]. The demands for wire bonding with high speed, accuracy and reliability are fulfilled by using advanced bonding machines equipped with modern cameras and intelligent algorithms [13].

More new technologies and materials are integrated to address scaling issues. Copper electroplating becomes a method to deposit on-chip interconnects. There are needs in IC chip making to have finer pitches and lines and integrate Cu with low-k and ultra-low-k materials [14].

The demands in electronics industry for smaller, lighter, faster and cheaper products have led to increased usage of advanced IC packages [15,16], and have sparked intensive interest in ultra-thin packages [17]. The wire loop height is one dominating element in reducing the thickness of IC packages [18].

A dielectric constant $k < 3$ is another challenging demand for dielectrics in multilevel metallization schemes of modern IC fabrication [19]. New IC devices based on

* Corresponding author. Tel.: +65 6790 5588; fax: +65 6791 1859.
E-mail address: mzwzhong@ntu.edu.sg (Z.W. Zhong).

0167-9317/$ - see front matter
doi:10.1016/j.mee.2006.11.002

the structure of low-k material/Cu are proposed [20]. The future high-end CMOS (complimentary metal-oxide semiconductor) logic technologies depend on ultra-low-k materials ($k \sim 2.3$ or lower) [21]. However, a polymer-induced bonding problem may exist when the bond pad is small, and sinking or cupping [22] can damage low-k diffusion barriers and cause failures.

In wire bonding, gold wires are the most widely used, but Al–Si wires [23] and copper wires are also employed for interconnection in microelectronics devices. A transition from Al to Cu metallization is taking place to improve the performance of advanced ICs [24]. Despite its many advantages, copper bonding wire has not been widely used because of its poor bondability for stitch bonds due to surface oxidation [25,26].

In ultrasonic bonding, ultrasounds allow metals to be cold-welded [27]. The wire metal is first softened by the ultrasonic energy. Then, the bonding force deforms the softened ball against the softened bond pad [28]. The ultrasonic energy and the force produce metallurgical interaction causing the atoms of the wire to diffuse into the bond pad [29].

A decisive factor affecting the properties of the wire bonds is the vibration behavior of the bonding tool called the capillary [30,31]. The bonding quality can be distinguished by observing the change of the vibration amplitude [32]. Ultra-fine-pitch wire bonding and copper wire bonding require high stability and robustness of the ultrasonic vibration [33]. The parameter settings including the ultrasonic generator power and bonding force require expert knowledge to optimize the bonding process [34].

In next sections, based on our understanding for wire bonding and our research and developmental activities, the new challenges and requirements in wire bonding are discussed, the problems in ultra-fine-pitch wire bonding and insulated wire bonding are analyzed, and then two capillary solutions to the problems are presented. Actual bonding experiments using the new capillaries were carried out and the results are reported.

2. Challenges and requirements

Today's challenges in wire bonding are reduction in bond pad pitch, reduction in wire size, high pin-count devices with more than 1500 wires, emergence of advanced packages, emergence of alloyed and copper wires, cost reduction, and enhanced manufacturability of capillaries for ultra-fine-pitch wire bonding.

Today's requirements for microelectronics products are increased consumer demands, portable and miniaturized sizes, high speed, increased functionality, low-k devices, lighter, smaller and thinner devices (die size reduction, micro-pitch bonding), and reduced packaging cost (cheaper substrate, longer bonding-tool life, smaller wire size).

Table 1 lists future wire bonding trends in order to meet the new challenges and requirements. The bonding capillary must have a smaller tip diameter for bonding devices with bond pad pitches (BPPs) below 50 μm, a smaller hole size for bonding with a wire size as small as 10 μm, better ultrasonic energy transfer, customized design for complex applications such as multi-tier bonding, stacked-dies wire bonding and insulated wire bonding.

Table 1
Future wire-bonding trends

Feature	Trend or solution
Pitch size on IC chip	35 μm or less
Wire diameter	12 μm or less
Loop height	60 μm or less
Bonding speed	20 loops or more per second
Multi-level devices	4 loop levels or more
Au-alloyed wire	Pd–Au wire, Ag–Au wire
Short circuit avoidance among loops	Insulated wire

The bonding wire must have a smaller wire size (10–12 μm), high tensile strength, and a short heat affected zone for low loop requirements. The wire diameter reduction also leads to cost saving. There are demands for insulated wire to prevent wire shorts, as well as alloyed gold wire and copper wire.

The quality of the lead frame or substrate may have to be improved. The surface roughness and the hardness of the lead or substrate become important in advanced wire bonding processes. Stitch and tail bonds on tiny bumps will cause non-sticking on lead.

Wire bonders must have sufficient bonding speed, Z-resolution, bond placement accuracy, free air ball (FAB) forming consistency, and looping algorithms. For example, the wire bonders for bonding 30-μm BPP devices should have bond placement accuracy of ± 1.5 μm for 3σ accuracy, advanced Z-axis control with contact detection resolution of 0.4 μm, a dual-frequency ultrasonic transducer for optimal bonding performance, and optimal transducer and bonding-tool geometry. The dual-frequency transducer provides a high frequency for forming ball bonds (first bonds) and a low frequency for forming stitch bonds (second bonds).

3. Ultra-fine-pitch wire bonding

Manufacturing of microelectronic devices with higher circuitry integration of IC chips and finer pitch interconnections is the current trend in the industry. These devices require higher numbers of input/output (I/O) for thermal, power and signal management. To increase I/O numbers, the BPPs have to be reduced significantly, which causes many problems in wire bonding for volume production of such devices.

Fig. 1 shows the wire bonding problems caused by reduction in bond pad pitch. When band pad pitch decreases, smaller ball size control becomes an issue. The process for low-k device bonding is also very sensitive for ultra-fine pitch bonding, during which relatively high reject rates caused by metal pad peeling are often observed. One solution to the problem is parameter optimization and

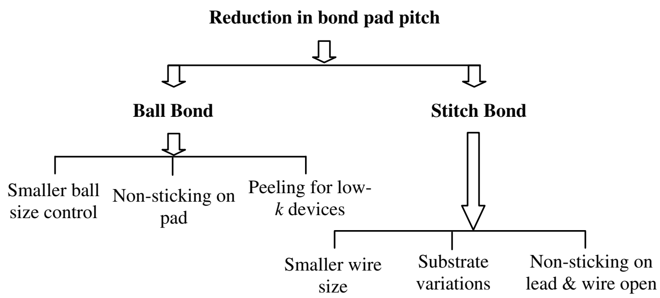

Fig. 1. Problems caused by reduction in bond pad pitch.

ultra-fine height control of the wire-bonding machine to reduce the damage to the underneath layers during impact. When bond pad pitch decreases, ball bond becomes a major issue as we are operating within the range of non-sticking on pad and peeling, i.e. lower parameter settings result in non-sticking and higher parameter settings cause metal pad peeling. The process window is narrow.

On the other hand, smaller wire sizes must be used for ultra-fine-pitch wire bonding as discussed in the previous section, and this also causes stitch bond problems. During the stitch bond formation, the least scrubbing action is encountered at the tail bond location. For wire bonding on poor bondability lead frames, the tail bond can be easily detached away from the stitch bond during the wire termination process, causing non-sticking on lead or wire open. Stitch bond problems also result from inconsistent lead frame/substrate quality such as variations in plating thickness, surface roughness and hardness. These variations often result in non-sticking on lead or low stitch pull readings.

The smallest BPP currently in volume production is 44 μm with wire bonding using ϕ20-μm (0.8-mil) wire, although research and development in laboratories can achieve ultra-fine-pitch wire bonding for a much smaller BPP. Products with a 44-μm BPP have been in volume production for more than one year. Products with a 40-μm BPP are expected to be in volume production by 2007, depending on the development activities of the users of wire bonding. Based on current technology advances, 40-μm BPP wire bonding is feasible using ϕ18-μm (0.7-mil) wire with good reliability, while using ϕ20-μm wire will be a challenge.

Wire bonding on ultra-fine-pitch devices requires the bonded ball size to be controlled within a very tight tolerance. The reduction in the bond pad pitch requires the capillary tip diameter to be reduced significantly. Fig. 2 shows tip diameters of capillaries versus bond pad pitches. The smaller tip diameter of a capillary for a smaller bond pad pitch is inevitable in order to prevent the capillary from any interference with the adjacent wires during wire bonding.

Given such tight wire bonding requirements, optimal bonding machine performance and capillary designs are necessary to achieve a reliable bonding process control. Advanced equipment is needed to handle small capillary tip manufacturing. Ultra-precision finishing processes are also required to avoid weakened bottlenecks.

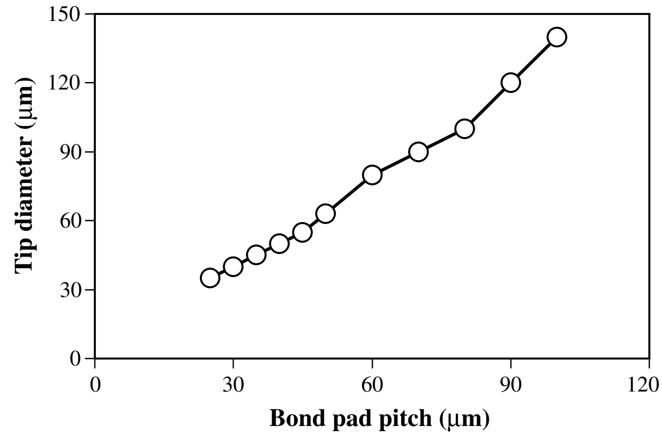

Fig. 2. Tip diameters of capillaries versus bond pad pitches.

Table 2
The reductions in bond pad pitch, wire size, and ball size

Bond pad pitch (μm)	70	60	50	45	40
Reduction in bond pad pitch (%)	0	14	29	36	43
Reduction in wire size (%)	0	0–10	10–20	20	30
Reduction in ball size (%)	0	13	31	38	46

With a decreased bond pad pitch, the wire size, ball size and ball shear decrease, and therefore there are more ball lifts during wire pull tests after aging tests. The wire size reduction is not proportional to the reduction in the ball size and bond pad pitch, as shown in Table 2. The reduced bondability is a problem. The bonding process is sensitive to bonding parameters. Non-sticking-on-pad problems may occur very often.

4. Results and discussion

4.1. A capillary solution for reduction in BPP

Besides bonding force, ultrasonic vibration amplitude, wire diameter (WD), and free air ball, critical capillary dimensions can also affect the wire-bond formation. The critical dimensions include tip diameter (T), hole diameter (H), face angle (FA), chamfer angle (CA), chamfer diameter (CD), inner chamfer (IC), and outer radius (OR), as shown in Fig. 3.

Intensive research has revealed that chamfer diameter, inner chamfer and chamfer angle have significant effects on the ball deformation. Optimization of these three key dimensions can improve ball bondability.

As shown in Fig. 4 and Table 3, compared to the standard design, a new capillary design has a larger inner chamfer, a larger chamfer diameter and a smaller chamfer angle, which lead to a smaller bonded ball size by containing the amount of the wire material inside the capillary during impact and restricting the softened wire material being squashed out during wire bonding.

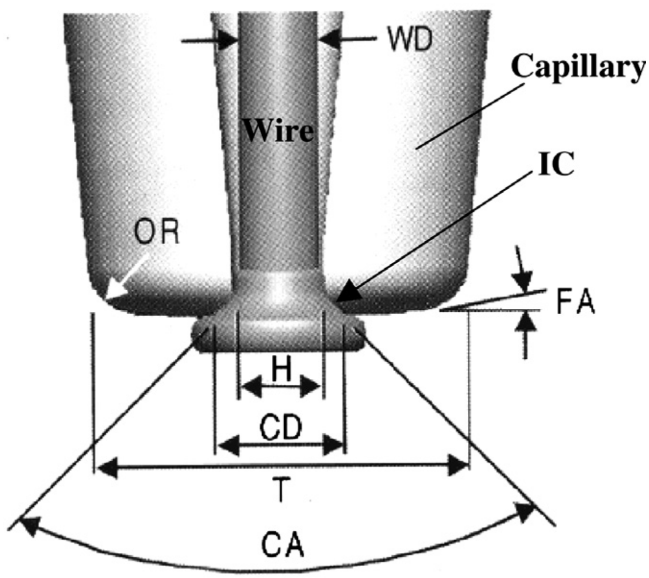

Fig. 3. Critical dimensions of the bonding tool called the capillary [35].

The new capillary design has proved to improve the ball bondability and small ball size control for ultra-fine-pitch wire bonding. About 40% of the free air ball is contained within the inner chamfer.

Actual bonding experiments were conducted using an ASM Eagle wire bonder, 40-μm bond-pad-pitch devices and ϕ18-μm (0.7-mil) gold wire. An aging test (baking at 175 °C) was carried out after bonding. Then, wire pull tests were performed to evaluate the wire-bond reliability. Table 4 compares the ball lift rates of the ball bonds produced using a standard capillary and the new capillary. Both the standard and the new capillaries could produce good ball bonds that resulted in 0% ball lift failure before the aging test.

However, after 300 h of the aging test, the ball lift rates of the ball bonds produced using the standard capillary and the new capillary were 40.6% and 0%, respectively. Further investigation revealed that the new capillary produced a larger percentage of the intermetallic compound than the standard capillary. The percentage difference of the intermetallic compounds explains why there were 40.6% ball lift failures for the wire bonds produced by the standard capillary but not by the new capillary after 300 h of the aging test.

Fig. 5 shows examples of the balls bonded using the new capillary, an ASM Eagle wire bonder, ϕ13 μm (0.5 mil) 3 N gold wire and BGA devices with a 30-μm bond pad pitch, and Table 5 shows the bonding results. The bonding results meet the standard requirements, which are minimum ball shear = 4.2 gf, minimum ball shear per unit area (shear stress) = 6.0 g/mil^2, and minimum wire pull = 1.6 gf (Mil-Std-883E) [36].

4.2. A capillary solution for insulated wire bonding

The primary objective of using insulated wire for wire bonding is to prevent wire shorting. Insulated wire bonding

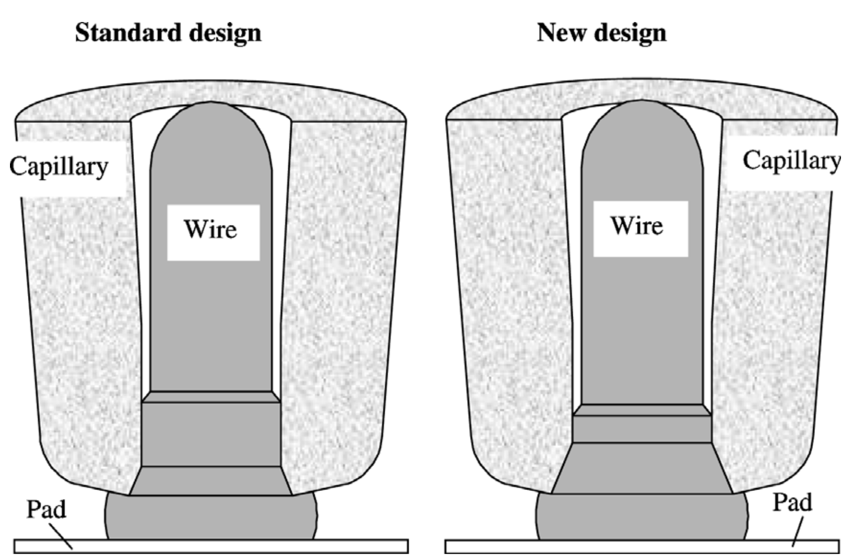

Fig. 4. Schematic diagrams of standard and new designs of capillaries.

Table 3
Key dimensions of standard and new designs of capillaries

Dimension	Standard capillary	New capillary 1
Chamfer angle	90°	A smaller angle
Chamfer diameter	Smaller (minimum 8 μm smaller than the ball size)	Larger (minimum 5 μm smaller than the ball size)
Inner chamfer	2 μm	More than 2.5 μm

Table 4
Ball lift rates of the ball bonds produced using a standard capillary and the new capillary

Aging test time (h)	0	300
Ball lift rate for standard capillary (%)	0	40.6
Ball lift rate for new capillary (%)	0	0

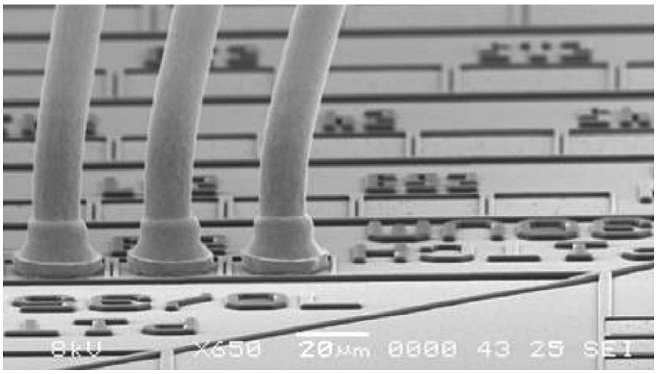

Fig. 5. Examples of the balls bonded using the new capillary, ϕ13 µm (0.5 mil) 3 N gold wire and BGA devices with a 30-µm bond pad pitch.

Table 5
Bonding results (30-µm bond pad pitch)

Response	Minimum	Maximum	Average
Ball size (µm)	23.0	25.0	23.8
Ball height (µm)	5.0	7.0	6.0
Ball shear (gf)	5.17	6.85	5.99
Shear stress (g/mil^2)	7.36	10.1	8.73
Wire pull (gf)	2.15	3.98	2.63

was developed more than 10 years ago. Due to the high processing cost and lack of market demands, insulated wire bonding was not popular.

As packages become more complicated, insulated wire has market demands because it is one of the solutions to prevent wire short, which becomes a problem due to the reduction in bond pad pitches and wire sizes, etc. Today, the gold wire is coated with an insulation layer of approximately 0.8-µm thick. This insulation layer will evaporate at a temperature of 300 °C.

There is no concern with ball bonds because the firing of the electronic-flame-off (EFO) to form a free air ball will melt the insulation layer on the wire. However, to obtain reliable stitch bonds between the insulated wire and lead/substrate plating is a challenge. Non-sticking on lead (NSOL) is the major problem with the stitch bonds due to the presence of the insulation coating.

To achieve good bondability for the stitch bonds, the coating of the insulated wire needs to be removed to expose the gold wire. Currently, a standard finishing for a capillary tip surface is matt finishing. Through intensive studies and optimizations, a unique surface characteristic on the capillary tip surface has been derived. The new finishing process

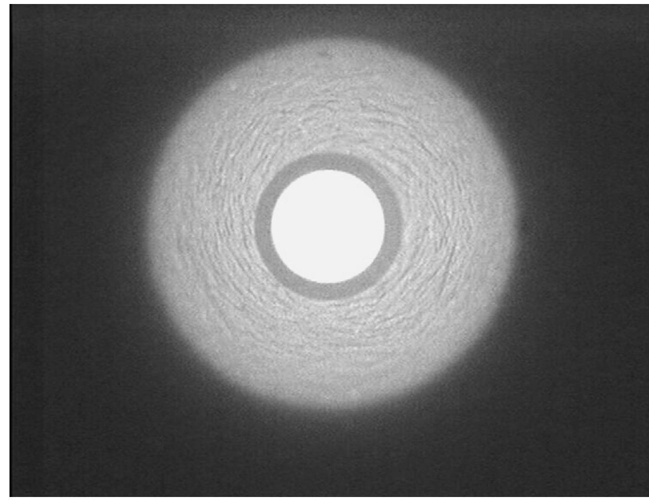

Fig. 6. The top-view picture of a new capillary tip-surface with relatively deep lines.

developed creates a new surface morphology, which has relatively deep lines with no fixed directions as shown in Fig. 6.

Bonding experiments were carried out using an ASM Eagle wire bonder, PBGA devices with a 65-µm BPP, ϕ 25-µm insulated wire, and a standard capillary and this new capillary. Stitch pull tests were then conducted and Table 6 summarizes the stitch pull readings of the stitch bonds.

As shown in Table 6, when a standard capillary was used for bonding the insulated wire, the average stitch pull reading of the stitch bonds was 4.68 gf. The average stitch pull reading of the stitch bonds obtained using new capillary 2 was 6.21 gf, 33% higher than that obtained using the standard capillary. This was due to the new surface morphology of the tip surface shown in Fig. 6. The relatively deep lines with no fixed directions transfer ultrasonic energy more efficiently during ultrasonic vibrations and break the thin insulation layer of the insulated wire effectively. In other words, compared to the standard capillary, new capillary 2 manufactured using the new finishing process has less slipping between the wire and the capillary tip surface in contact, and provides better coupling effect between them and better ultrasonic energy transfer. Therefore, this new capillary has been used to effectively improve the bondability of the stitch bonds for insulated wire bonding.

Table 6
Stitch pull readings of the stitch bonds produced using an ASM Eagle wire bonder, PBGA devices with a 65-µm BPP, ϕ25-µm insulated wire, and a standard capillary or new capillary 2

Wire used	Insulated	Insulated
Capillary used	Standard	New capillary 2
Average reading (gf)	4.68	6.21
Standard deviation (gf)	1.19	1.36

5. Conclusions

The new challenges and requirements in wire bonding are discussed, the problems in ultra-fine-pitch wire bonding and insulated wire bonding are analyzed, and then two capillary solutions to the problems are presented. Actual bonding experiments using the new capillaries were carried out and the results were promising. Compared to the standard design, a new capillary design has a larger inner chamfer, a larger chamfer diameter and a smaller chamfer angle. This new capillary design has proved to improve the ball bondability and smaller ball size control for ultra-fine pitch wire bonding. It produced a larger percentage of the intermetallic compound than the standard capillary, and this resulted in 0% ball lift failure after 300 h of an aging test. A unique surface characteristic on the capillary tip surface has also been derived. The new finishing process developed creates a new surface morphology, which has relatively deep lines with no fixed directions. Compared to the standard capillary, this capillary has less slipping between the wire and the capillary tip surface in contact, and provides better coupling effect between them and better ultrasonic energy transfer. This capillary has been used to effectively improve the bondability of the stitch bonds for insulated wire bonding.

References

[1] P. Palm, J. Maattanen, A. Picault, Y. De Maquille, Microelectronics International 18 (3) (2001) 27–31.
[2] T.Y. Tee, H.S. Ng, D. Yap, X. Baraton, Z. Zhong, Microelectronics Reliability 43 (7) (2003) 1117–1123.
[3] M. Petzold, L. Berthold, D. Katzer, H. Knoll, D. Memhard, P. Meier, K.-D. Lang, Microelectronics Reliability 40 (8–10) (2000) 1515–1520.
[4] C.P. Wong, S. Luo, Z. Zhang, Science 290 (5500) (2000) 2269–2270.
[5] Y.G. Lu, Z.W. Zhong, J. Yu, H.M. Xie, B.K.A. Ngoi, J.B. Chai, A. Asundi, Review of Scientific Instruments 72 (4) (2001) 2180–2185.
[6] A. Hamidi, N. Beck, K. Thomas, E. Herr, Microelectronics Reliability 39 (6–7) (1999) 1153–1158.
[7] C.D. Breach, F. Wulff, Microelectronics Reliability 44 (6) (2004) 973–981.
[8] Z. Zhong, W.Y. Lee, Materials and Manufacturing Processes 16 (4) (2001) 471–482.
[9] F. Oldervoll, F. Strisland, Microelectronics Reliability 44 (6) (2004) 1009–1015.
[10] C.-T. Su, T.-L. Chiang, IEEE Transactions on Electronics Packaging Manufacturing 25 (1) (2002) 13–18.
[11] Z. Zhong, Soldering and Surface Mount Technology 13 (2) (2001) 35–38.
[12] J.H. Lau, IEEE Transactions on Electronics Packaging Manufacturing 23 (1) (2000) 4–11.
[13] H. Burkhalter, Microelectronics Journal 28 (2) (1997) xviii–xxiv.
[14] V.M. Dubin, Microelectronic Engineering 70 (2–4) (2003) 461–469.
[15] Z. Zhong, Microelectronics International 16 (3) (1999) 6–14.
[16] D. Manessis, R. Patzelt, A. Ostmann, R. Aschenbrenner, H. Reichl, Microelectronics Reliability 44 (5) (2004) 797–803.
[17] K. Gurnett, Microelectronics Journal 26 (7) (1994) xxiii–xxvi.
[18] K. Gurnett, Microelectronics Journal 26 (7) (1995) i–v.
[19] E. Hartmannsgruber, G. Zwicker, K. Beekmann, Microelectronic Engineering 50 (1–4) (2000) 53–58.
[20] W.-C. Chen, S.-C. Lin, B.-T. Dai, M.-S. Tsai, Journal of the Electrochemical Society 146 (8) (1999) 3004–3008.
[21] K. Mosig, T. Jacobs, K. Brennan, M. Rasco, J. Wolf, R. Augur, Microelectronic Engineering 64 (1–4) (2002) 11–24.
[22] G.G. Harman, C.E. Johnson, IEEE Transactions on Components and Packaging Technologies 25 (4) (2002) 677–683.
[23] W. Qin, R. Doyle, T. Scharr, M. Shah, M. Kottke, G. Chen, D. Theodore, Microelectronic Engineering 75 (1) (2004) 111–116.
[24] C.M. Whelan, M. Kinsella, L. Carbonell, H.M. Ho, K. Maex, Microelectronic Engineering 70 (2–4) (2003) 551–557.
[25] S. Kaimori, T. Nonaka, A. Mizoguchi, IEEE Transactions on Advanced Packaging 29 (2) (2006) 227–231.
[26] P. Ratchev, S. Stoukatch, B. Swinnen, Microelectronics Reliability 46 (2006) 1315–1325.
[27] L. Parrini, IEEE Transactions on Electronics Packaging Manufacturing 26 (1) (2003) 37–45.
[28] G.G. Harman, Wire Bonding in Microelectronics: Materials, Processes, Reliability, and Yield, McGraw Hill, NY, 1997.
[29] S. Kim, N. Hemati, EEP-Structural Analysis in Microelectronics and Fiber Optics 8 (1994) 31–40.
[30] Z. Zhong, K.S. Goh, Journal of Electronics Manufacturing 10 (4) (2000) 211–217.
[31] U. Draugelates, K.-H. Konig, Vibrations Measurements 2358 (1994) 506–520.
[32] P.W.-P. Chu, C.-P. Chong, H.L.-W. Chan, K.M.-W. Ng, P.C.-K. Liu, Microelectronic Engineering 66 (1–4) (2003) 750–759.
[33] L. Parrini, IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control 48 (6) (2001) 1632–1639.
[34] C.D. Kinnaird, A. Khotanzad, IEEE Transactions on Electronics Packaging Manufacturing 22 (3) (1999) 233–243.
[35] Small Precision Tools, Bonding Capillaries, 04/99-5, 1999.
[36] Department of Defense, USA, Test Method Standard, Microcircuits, Mil-Std-883E, 1996.