The impact factor and indexed journal paper writing

Talk/Lecture
at Universiti Tun Hussein Onn Malaysia
5-6 Mar 2014

Invited Speaker: **Z.W. Zhong**
School of Mechanical & Aerospace Engineering
Nanyang Technological University, Singapore

Strategies for conference and journal papers and for book chapters and books

TABLE III. CORRELATION COEFFICIENTS BETWEEN FORCE FEATURES, AND SURFACE ROUGHNESS AS WELL AS TOOL WEAR

Force features	Correlation to surface roughness	Correlation to tool wear
Skewness	0.7601	0.7585
Kurtosis	-0.5578	-0.4588
Crest-factor	0.6171	0.4849
Peak	0.8008	0.8792
Peak to peak	0.7704	0.9028
Mean of RMS	0.8007	0.9309
Mean	0.7527	0.9563
Standard deviation	0.8032	0.9184
Mean of band power	0.8013	0.9337
Standard deviation of band power	0.8024	0.9161
Delta	0.2617	0.0732
Absolute deviation	0.8056	0.9468
Count	-0.6334	-0.8022
Rise time	-0.2927	-0.341
Area under curve	0.7343	0.8826
Duration	-0.3026	-0.3541

Z.W. Zhong, J.-H. Zhou, Ye Nyi Win Correlation Analysis of Cutting Force and Acoustic Emission Signals for Tool Condition Monitoring, 9th Asian Control Conference, Turkey, 2013.

TABLE IV. CORRELATION COEFFICIENTS BETWEEN AE FEATURES, AND SURFACE ROUGHNESS AS WELL AS TOOL WEAR

AE features	Correlation to surface roughness	Correlation to tool wear
Skewness	0.1359	-0.0271
Kurtosis	-0.6817	-0.9142
Crest-factor	-0.1602	-0.4632
Peak	0.5892	0.592
Peak to peak	0.6451	0.7764
Mean of RMS	0.6679	0.8355
Mean	0.1497	0.5643
Standard deviation	0.6671	0.8362
Mean of band power	0.6695	0.8398
Standard deviation of band power	0.6559	0.8195
Delta (change in signal)	-0.1774	-0.0801
Absolute deviation	0.6839	0.8553
Count	0.651	0.8039
Rise time	-0.1934	0.0975
Area under curve	0.5634	0.7931
Duration	-0.1933	0.0976

Z.W. Zhong, J.-H. Zhou, Ye Nyi Win Correlation Analysis of Cutting Force and Acoustic Emission Signals for Tool Condition Monitoring, 9th Asian Control Conference, Turkey, 2013.

TABLE V. TOOL WEAR ESTIMATION ACCURACY USING FORCE AND AE FEATURES

Tool wear estimation	Average relative error	MSE
Using 8 force features	2.024	0.0025
Using 8 AE features	2.648	0.0033

Z.W. Zhong, J.-H. Zhou, Ye Nyi Win Correlation Analysis of Cutting Force and Acoustic Emission Signals for Tool Condition Monitoring, 9th Asian Control Conference, Turkey, 2013.

TABLE VI. SURFACE ROUGHNESS ESTIMATION ACCURACY USING FORCE AND AE FEATURES

Surface roughness estimation	Average relative error	MSE
Using 8 force features	8.033	0.3518
Using 8 AE features	20.06	0.3579

Z.W. Zhong, J.-H. Zhou, Ye Nyi Win Correlation Analysis of Cutting Force and Acoustic Emission Signals for Tool Condition Monitoring, 9th Asian Control Conference, Turkey, 2013.

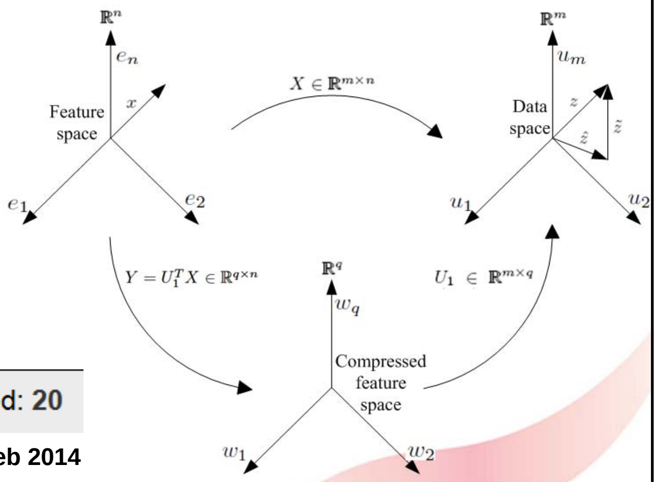
DFI - X as a Linear Transformation

Collected Data X

$$X = \begin{array}{c|cccc} & s_1 & s_2 & \cdots & s_n \\ \hline x_1 & \star & \star & \cdots & \star \\ x_2 & \star & \star & \cdots & \star \\ \vdots & \vdots & \vdots & \ddots & \star \\ x_m & \star & \star & \star & \star \end{array}$$

$X \in \mathbb{R}^{m \times n}$

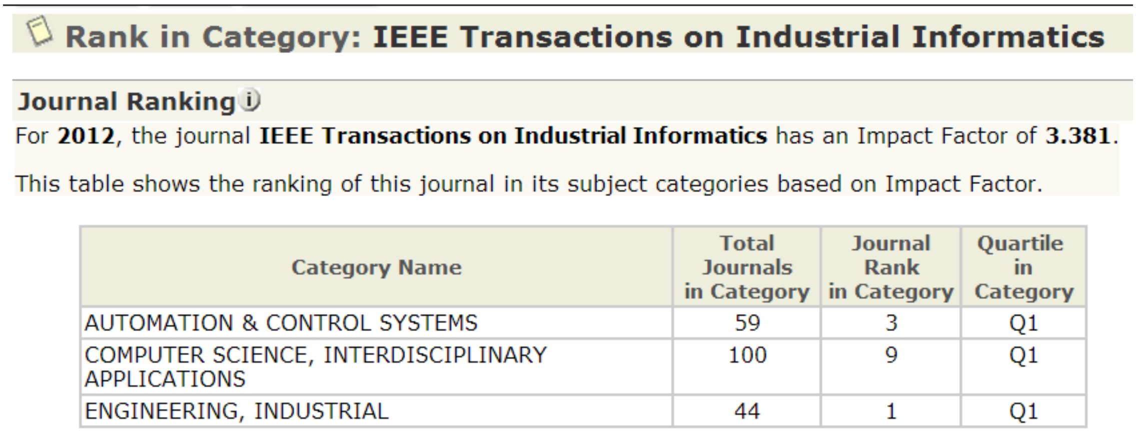
m >> n



J.H. Zhou, C.K. Pang, F.L. Lewis, **Z.W. Zhong,** Intelligent Diagnosis and Prognosis of Tool Wear Using Dominant Feature Identification, IEEE Transactions on Industrial Informatics, 5 (4) (2009) 454-464.

Times Cited: 20

On 26 Feb 2014



Rank in Category: IEEE Transactions on Industrial Informatics

Journal Ranking

For **2012**, the journal **IEEE Transactions on Industrial Informatics** has an Impact Factor of **3.381**.

This table shows the ranking of this journal in its subject categories based on Impact Factor.

Category Name	Total Journals in Category	Journal Rank in Category	Quartile in Category
AUTOMATION & CONTROL SYSTEMS	59	3	Q1
COMPUTER SCIENCE, INTERDISCIPLINARY APPLICATIONS	100	9	Q1
ENGINEERING, INDUSTRIAL	44	1	Q1

Source: Web of Science

DFI - Data Compression

Lemma 1: For any $y = U_1^T X x \in R^q$ vector $\hat{z} = U_1 y$ is the best least-square approximation to data vector $z \in R^m$

Singular Value Decomposition (SVD)

$$X = U \Sigma V^T$$

$$U \in \mathbb{R}^{m\times n} \quad \Sigma = \operatorname{diag}(\sigma_1, \sigma_2, \cdots, \sigma_n) \quad \sigma_1 \geq \sigma_2 \geq \cdots \geq \sigma_n > 0 \quad V \in \mathbb{R}^{n\times n}$$

$$\begin{aligned} X &= [\, U_1 \quad U_2 \,] \begin{bmatrix} \Sigma_1 & 0 \\ 0 & \Sigma_2 \end{bmatrix} \begin{bmatrix} V_1^T \\ V_2^T \end{bmatrix} \\ &= U_1 \Sigma_1 V_1^T + U_2 \Sigma_2 V_2^T \end{aligned}$$

$$q < m \quad n - q$$

$$\hat{X} = U_1 \Sigma_1 V_1^T$$

Data Compression

$$z = Xx = \underbrace{U_1 \Sigma_1 V_1^T x}_{\hat{z}} + \underbrace{U_2 \Sigma_2 V_2^T x}_{\tilde{z}}$$

$$Y = U_1^T X \in \mathbb{R}^{q\times n}$$

$$\begin{aligned} \hat{z}^T \tilde{z} &= (U_1 \Sigma_1 V_1^T x)^T U_2 \Sigma_2 V_2^T x \\ &= = x^T V_1 \Sigma_1 U_1^T U_2 \Sigma_2 V_2^T x = 0 \end{aligned}$$

- **Retained q SVs**
- **Optimal choice of R^q for least square errors of vectors in R^m**

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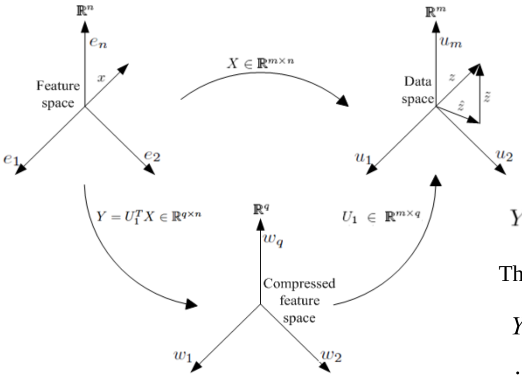
Times Cited: 20

J.H. Zhou, C.K. Pang, F.L. Lewis, **Z.W. Zhong,** Intelligent Diagnosis and Prognosis of Tool Wear Using Dominant Feature Identification, IEEE Transactions on Industrial Informatics, 5 (4) (2009) 454-464.

DFI - Selection of Dominant Features

Lemma 2: The i^{th} feature in feature space R^n maps into the reduced space R^q as the i^{th} column of matrix $\Sigma_1 V_1^T$



Three spaces Transfer

$$Y = U_1^T X = U_1^T (U_1 \Sigma_1 V_1^T + U_2 \Sigma_2 V_2^T) = \Sigma_1 V_1^T$$

The original feature vectors are in R^n denoted by $\{e_1, e_2, \cdots e_n,\}$

$$Y e_i = \Sigma_1 V_1^T e_i = [w_1 \quad w_2 \quad \cdots \quad w_n] e_i = w_i$$

i^{th} feature in R^n maps into the reduced space R^q as the i^{th} column of matrix $\Sigma_1 V_1^T$

Equivalent to select the best columns ω_i of $\Sigma_1 V_1^T \in R^q$

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J.H. Zhou, C.K. Pang, F.L. Lewis, **Z.W. Zhong,** Intelligent Diagnosis and Prognosis of Tool Wear Using Dominant Feature Identification, IEEE Transactions on Industrial Informatics, 5 (4) (2009) 454-464.

Case Study 1 – Tool Wear Prediction

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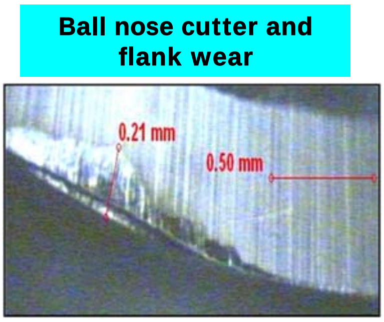
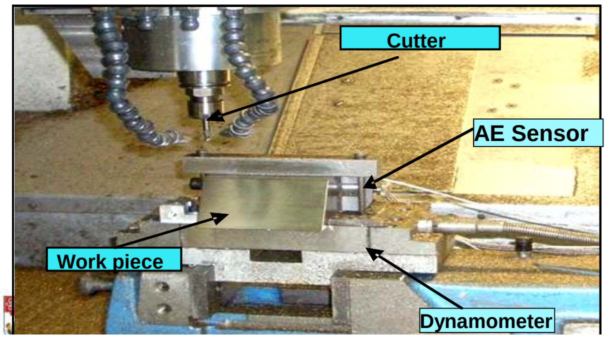
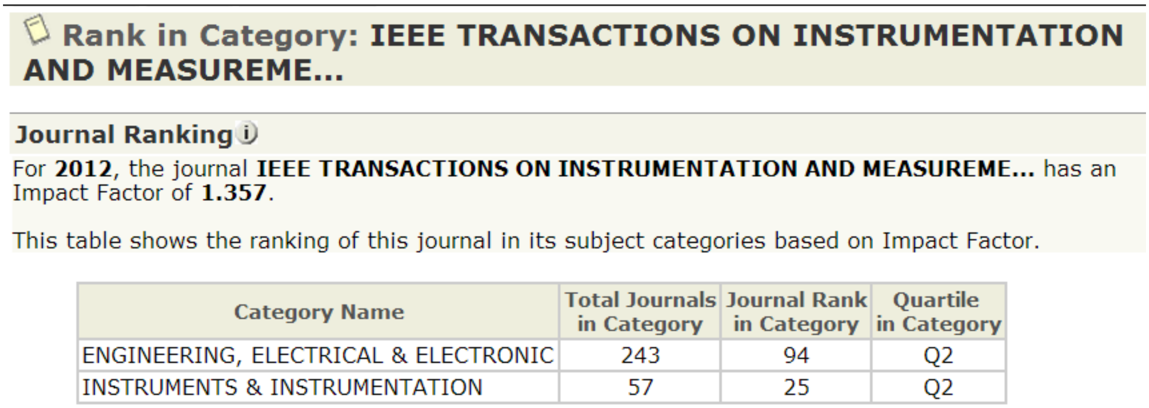




Components
Röders TEC vertical milling machine
6mm ball nose tungsten carbide cutters
Titanium Ti6Al4V workpiece
8152B211 Piezotron® AE sensor (Kistler)
Kistler 5127B11 multichannel charge amplifier
NI-DAQ PCI 6250 M series
LECIA MZ12.5
Computer

J.H. Zhou, C.K. Pang, **Z.W. Zhong**, F.L. Lewis, Tool Wear Monitoring Using Acoustic Emissions by Dominant-Feature Identification, IEEE Transactions on Instrumentation and Measurement 60 (2) (2011) 547-559.



Rank in Category: **IEEE TRANSACTIONS ON INSTRUMENTATION AND MEASUREME...**

Journal Ranking

For **2012**, the journal **IEEE TRANSACTIONS ON INSTRUMENTATION AND MEASUREME...** has an Impact Factor of **1.357**.

This table shows the ranking of this journal in its subject categories based on Impact Factor.

Category Name	Total Journals in Category	Journal Rank in Category	Quartile in Category
ENGINEERING, ELECTRICAL & ELECTRONIC	243	94	Q2
INSTRUMENTS & INSTRUMENTATION	57	25	Q2

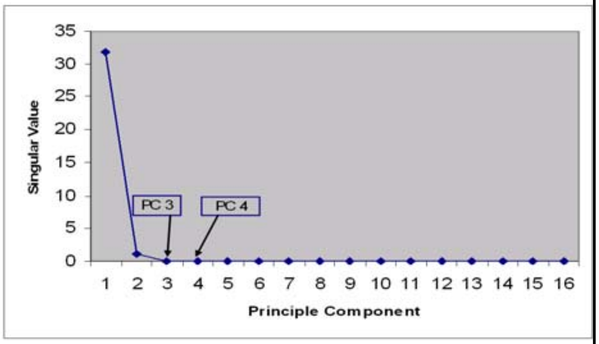
Source: Web of Science

Dominant Features and SVs

m=10,000 and n=16

No	Feature	Notation
1	Residual error	re
2	First order differencing	fod
3	Second order differencing	sod
4	Maximum force level	fm
5	Total amplitude of cutting force	fa
6	Combined incremental force changes	df
7	Amplitude ratio	ra
8	Standard deviation of force components in tool breakage zone	fstd
9	Sum of the squares of residual errors	sre
10	Peak rate of cutting forces	kpr
11	Total harmonic power	thp
12	Average force	fca
13	Variable force	vf
14	Standard deviation	std
15	Skew (3rd moment)	skew
16	Kurtosis (4th moment)	kts

Singular Values (SVs)



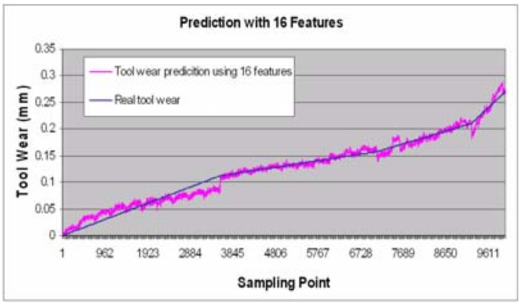
Identify dominant features using 3 or 4 retained SVs

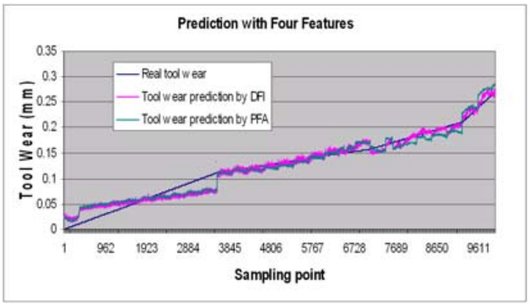
J.H. Zhou, C.K. Pang, **Z.W. Zhong**, F.L. Lewis, Tool Wear Monitoring Using Acoustic Emissions by Dominant-Feature Identification, IEEE Transactions on Instrumentation and Measurement 60 (2) (2011) 547-559

Times Cited: 8

On 26 Feb 2014

Prediction Results





Best possible prediction using 16 features with 8.8% mean relative error

Prediction using DFI selected 4 features with 11.61% mean relative error

Save up to 60% in computational time!

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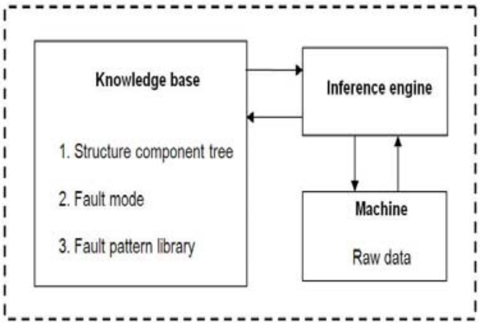
J.H. Zhou, C.K. Pang, F.L. Lewis, **Z.W. Zhong,** Intelligent Diagnosis and Prognosis of Tool Wear Using Dominant Feature Identification, IEEE Transactions on Industrial Informatics, 5 (4) (2009) 454-464.

Intelligent Fault Detection and Diagnosis of Rotating Machines

- We investigate different sensors, and different signal processing and feature extraction techniques.
- A hierarchical rule-based fault detection system which is comprised of a knowledge base coupled with an inference engine is proposed.
- The knowledge base that maps the fault mode to signal processing and defect detection methods is established.



The architecture of the rule-based diagnosis system

Z.W. Zhong, Y.T.L. Wee, J.H. Zhou, Intelligent Fault Detection and Diagnosis of Rotating Machines, International Conference on Intelligent Robotics and Applications, 2012, Canada.

Summary of the capabilities to detect the various machine faults using the current, torque and acceleration sensors and the signal processing methods investigated

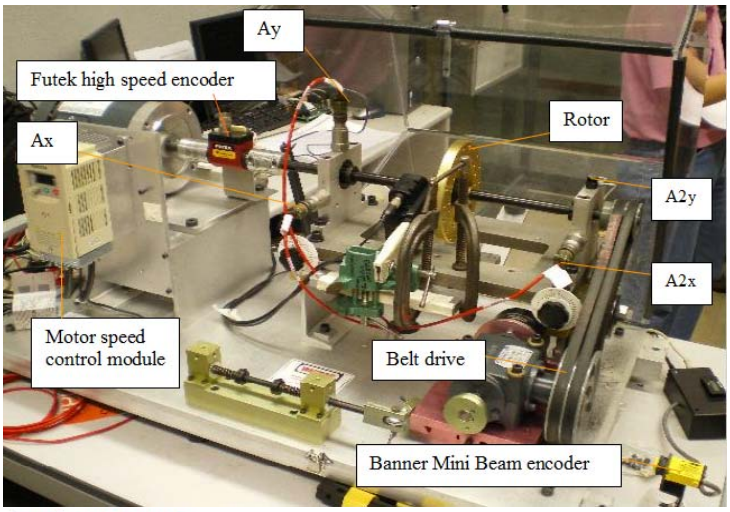
Fault Method		Loose belt	Machine unbalance	Bearing (Ball)	Bearing (Outer race)	Bearing (Multiple)	Rotor unbalance	Broken rotor bars	Faulty motor bearings
Root mean square	Current	√	X	X	X	X	Φ	Φ	X
	Torque	X	X	X	X	X	Φ	Φ	X
	Acceleration	X	X	Φ	Φ	Φ	X	X	X
Peak to peak	Current	√	X	X	X	X	Φ	Φ	X
	Torque	X	X	X	X	X	Φ	Φ	X
	Acceleration	X	X	Φ	Φ	Φ	X	X	X
Fast Fourier transform	Current	X	X	X	X	X	X	X	X
	Torque	X	X	X	X	X	X	X	X
	Acceleration	X	√	X	X	X	X	X	X
Hilbert transform	Current	X	X	X	X	X	Φ	Φ	√
	Torque	X	X	X	X	X	√	X	X
	Acceleration	√	X	√	√	X	X	X	X

Legends: √: Able to detect and distinguish; Φ: Able to detect but not able to distinguish; X: Unable to detect

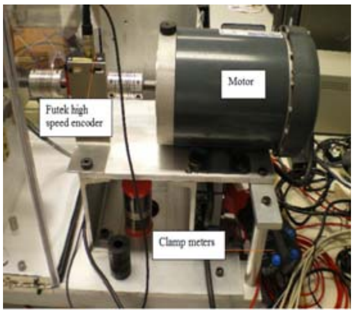
Z.W. Zhong, Y.T.L. Wee, J.H. Zhou, Intelligent Fault Detection and Diagnosis of Rotating Machines, International Conference on Intelligent Robotics and Applications, 2012, Canada.

Machine Faults Detection and Isolation

Fault Simulator Machine



Encoder and clamp meters



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J.H. Zhou, C.K. Pang, F.L. Lewis, **Z.W. Zhong**, Dominant Feature Identification for Industrial Fault Detection and Isolation Applications, Expert Systems With Applications 38 (8) (2011) 10676-10684.

http://www.ntu.edu.sg/home/mzwzhong

Feature Extraction

Features extracted

$$Min = \min(\{S_i\}_{i\in[a,b]})$$

$$Max = \max(\{S_i\}_{i\in[a,b]})$$

$$Averge(\mu) = \frac{\sum_{i\in[a,b]} x_i}{b-a}$$

$$\text{Root Mean Square(RMS)} = \sqrt{\frac{\sum_{i\in[a,b]}(\mathrm{x_i} - \bar{\mathrm{x}})^2}{b-a}}$$

$$\text{Standard deviation}(\sigma) = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i-\mu)^2}$$

$$\text{Skewness} = \frac{\mu_3}{\sigma^3} = \frac{E(x-\mu)^3}{E[(x-\mu)^2]^{3/2}}$$

$$\text{Kurtosis} = \frac{\mu_4}{\sigma^4}$$

$$\text{Crest factor} = \frac{|x|_{peak}}{x_{rms}}$$

Features extracted

$$f_{1st} = f_0$$

$$f_{2nd} = 2^* f_0$$

$$f_{3rd} = 3^* f_0$$

$$f_{BFF}(Hz) = \frac{PD}{BD} f_r \left[1 - \left(\frac{BD}{PD}\cos\beta\right)^2\right]$$

$$f_{1st\_BFF} = f_{BFF}(Hz)$$

$$f_{2nd\_BFF} = 2^* f_{BFF}(Hz)$$

$$f_{3rd\_BFF} = 3^* f_{BFF}(Hz),$$

$$f_{BPFO} = \frac{n}{2} f_r \left(1 - \frac{BD}{PD}\cos\beta\right)$$

$$f_{1st\_BPFO} = f_{BPFO}$$

$$f_{2nd\_BPFO} = 2^* f_{BPFO}\ .$$

$$f_{3rd\_BPFO} = 3^* f_{BPFO}$$

J.H. Zhou, C.K. Pang, F.L. Lewis, **Z.W. Zhong**, Dominant Feature Identification for Industrial Fault Detection and Isolation Applications, Expert Systems With Applications 38 (8) (2011) 10676-10684.
http://www.ntu.edu.sg/home/mzwzhong

All 8 sensors and 120 features

Fault identification accuracy

Machine status	Estimation	
	Correct	Wrong
Normal	100	0
Bearing ball fault	99	1
Imbalance	100	0
Loose belt	100	0
Bearing outer race fault	100	0

12 features from current, 12 features from torque,
18 feature from accelerometer

Total numbers of features: 12*3 +12 +18*4 = 120

J.H. Zhou, C.K. Pang, F.L. Lewis, **Z.W. Zhong**, Dominant Feature Identification for Industrial Fault Detection and Isolation Applications, Expert Systems With Applications 38 (8) (2011) 10676-10684.

Proposed 2-Stage Framework

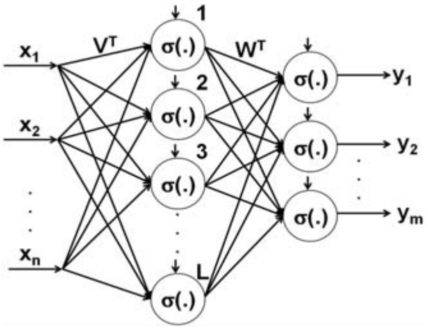
Decentralized DFI (DDFI)

$X_k \in R^{m \times n}$

Augmented DFI (ADFI)

$X = \left[X_1^T \; X_2^T \; \cdots \; X_K^T\right]^T$

Neural Network (NN)



1 hidden layer, 5 neurons, and radial basis functions

J.H. Zhou, C.K. Pang, F.L. Lewis, **Z.W. Zhong**, Dominant Feature Identification for Industrial Fault Detection and Isolation Applications, Expert Systems With Applications 38 (8) (2011) 10676-10684.

Decentralized DFI

Features Selected

Sensor	Features
C1	Mean
C1	Std
C1	Skew
C1	Crest
C1	First_harmonic
Torque	Min
Torque	Mean
Torque	Peak_peak
Torque	rRms
Torque	Crest
Torque	Skew
Ax1	Min
Ax1	Mean
Ax1	Crest
Ax1	Skew
Ax1	Outer_second_harmonic
Ax1	Outer_third_harmonic
Ax1	Cage_first_harmonic
Ax1	Cage_third_harmonic
Ay2	Min
Ay2	Mean
Ay2	Rms
Ay2	Std
Ay2	Skew
Ay2	Crest
Ay2	First_harmonic
Ay2	Second_harmonic
Ay2	Outer_third_harmonic

Prediction accuracy

Machine Status	Estimation	
	Correct	Wrong
Normal	95	5
Bearing ball fault	42	58
Imbalance	94	6
Loose belt	97	3
Bearing outer race fault	94	6

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J.H. Zhou, C.K. Pang, F.L. Lewis, **Z.W. Zhong**, Dominant Feature Identification for Industrial Fault Detection and Isolation Applications, Expert Systems With Applications 38 (8) (2011) 10676-10684.

120 features reduced to 28, 84.4% Accurate

Augmented DFI

Features Selected

Sensor	Features
C2	Average
C2	Maximum
C2	Crest factor
C2	Amplitude of 1*st* harmonic of rotational frequency
C2	Amplitude of 2*nd* harmonic of rotational frequency
Torque	Minimum
Torque	Standard deviation
Ax1	Minimum
Ax1	RMS
Ax1	Amplitude of 2*nd* harmonic of outer race frequency
Ax2	Maximum
Ax2	Minimum
Ax2	Amplitude of 2*nd* harmonic of cage frequency

Prediction accuracy

Machine Status	Estimation	
	Correct	Wrong
Normal	99	1
Bearing ball fault	99	1
Imbalance	100	0
Loose belt	100	0
Bearing outer race fault	99	1

120 features to 13, 8 sensors to 4! 99.4% Accurate

Computational Complexity

ADFI $O(mn^2)+O(n^3)=O(7.2\times10^6)+O(1.728\times10^6)$

DDFI $5\times(O(mn^2)+O(n^3))=5\times(O(1.44\times10^6)+O(1.728\times10^6))=O(7.2\times10^6)+O(8.64\times10^6)$

J.H. Zhou, C.K. Pang, F.L. Lewis, **Z.W. Zhong**, Dominant Feature Identification for Industrial Fault Detection and Isolation Applications, Expert Systems With Applications 38 (8) (2011) 10676-10684.

Books Chapters

- L. P. Khoo, **Zhong, Z.W.**, and H. Y. Lim, “Maintenance Planning Using Enterprise Data Mining,” *Recent Advances in Data Mining of Enterprise Data,* Edited by T.W. Liao and E. Triantaphyllou, World Scientific, Singapore, 2008, pp. 505-544.
- L. Wang, M. Xie, **Z.W. Zhong**, H.J. Yang and J. Li, 2008, “Design of Dexterous Arm-Hand for Human-Assisted Manipulation,” *Intelligent Robotics and Applications*, Edited by C. Xiong et al., Lecture Notes in Computer Science, Volume 5315, Springer, Berlin / Heidelberg, 2008, pp. 1233-1240.
- **Z.W. Zhong**, S.K. Nah and S.H. Tan, “Design and development of micro-gripping devices for manipulation of micro-parts,” *The Advances in Climbing and Walking Robots,* Edited by Xie M., Dubowsky S., Fontaine J. G., Tohki O. M. and Virk G., World Scientific, Singapore, 2007, pp. 599-606.
- L.P. Khoo, **Zhong, Z.**, and H.Y. Lim, “A Rough Set Based Tabu-Enhanced Genetic Algorithm Approach to Rule Induction,” *Evolutionary Algorithms and Intelligent Tools in Engineering Optimization*, Edited by W. Annicchiarico, J. Périaux, M. Cerrolaza and G. Winter, jointly published by CIMNE, Barcelona, Spain and WIT Press, Billerica, MA, 2005, pp. 141-166.
- Wang Z.F., Tan Y.H., Zirajutheen B. M. P., **Zhong Z.W.** “A Study of Chemical Mechanical Polishing Process for Polymeric Materials,” *Processing and Fabrication of Advanced Materials*, Edited by M Gupta, C Y H Lim, T S Srivatsan & R A Varin, World Scientific, Singapore, 2005, pp. 911-918.

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Books Chapters

- **Zhong Z.W.**, “Surface texture characterization using a Chroma Meter,” *Application of Photonic Technology 5,* Edited by Roger A. Lessard, George A. Lampropoulos, Gregory W. Schinn, SPIE Society of Photo-Optical Instrumentation Engineering, Bellingham, Washington, 2003, pp. 249-254.
- **Zhong Z.W.**, “Application of the moiré interferometry to thermal strain analysis for electronics packaging,” *Application of Photonic Technology 5,* Edited by Roger A. Lessard, George A. Lampropoulos, Gregory W. Schinn, SPIE Society of Photo-Optical Instrumentation Engineering, Bellingham, Washington, 2003, pp. 242-248.
- **Zhong Z.W.**, and Hung N.P., “Ultra-Precision Turning & Grinding of Metal Matrix Composites,” *Processing and Fabrication of Advanced Materials VIII*, Edited by K A Khor, M Wang, W Zhou, F Boey & T S Srivatsan, World Scientific, Singapore, 2001, pp. 913-920.
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- **Zhong, Z.**, "Image Scanners," *Wiley Encyclopedia of Electrical and Electronics Engineering*, Edited by J.G. Webster, John Wiley & Sons, USA, Vol. 9, 1999, pp. 634-642.
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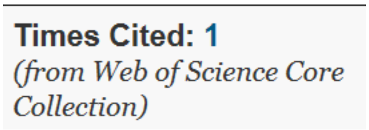

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On 26 Feb 2014

M.C.G. Lim, **Z.W. Zhong,** Dynamical behavior of copper atoms in a carbon nanotube channel, Carbon 49 (3) (2011) 996-1005.

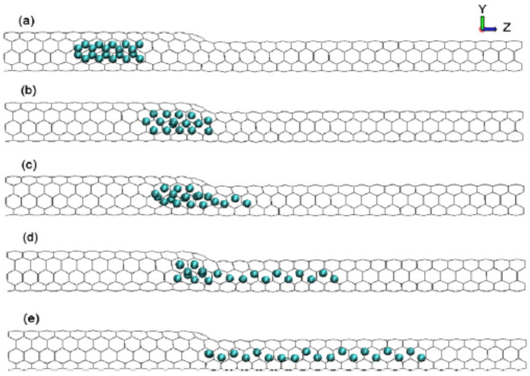
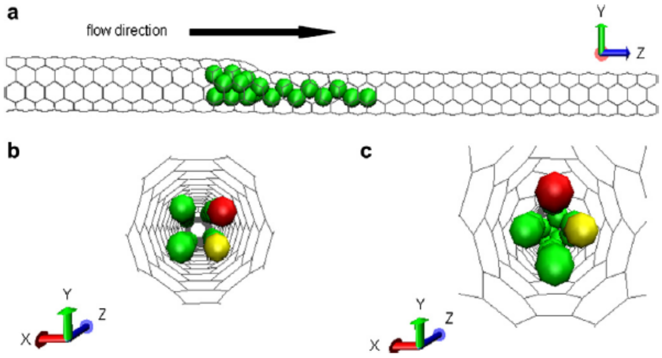
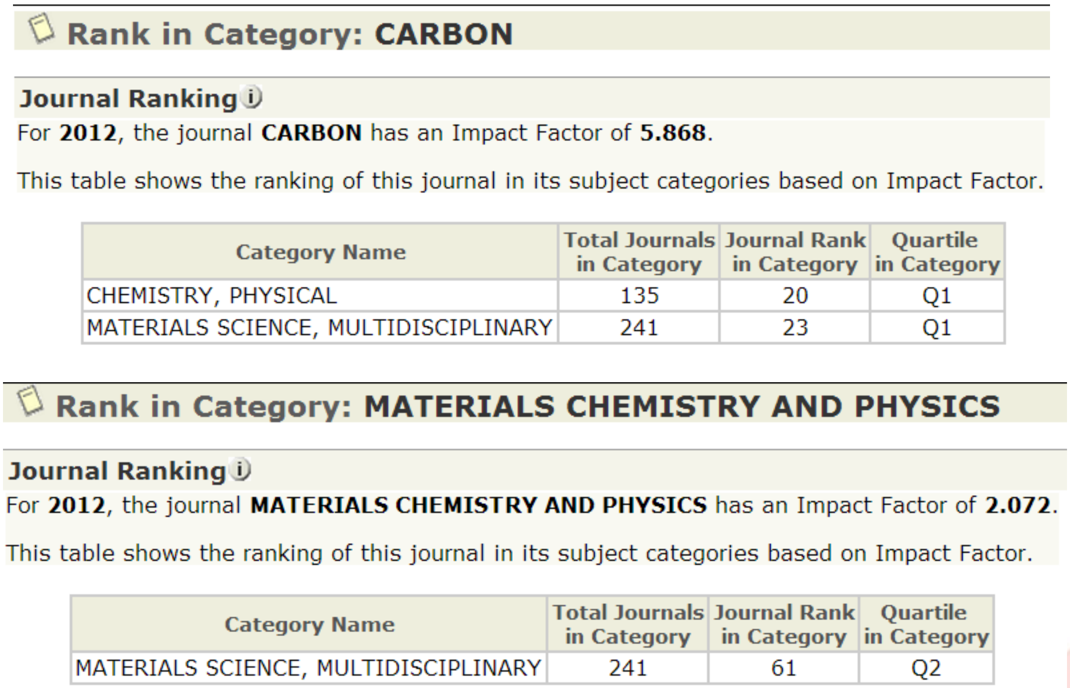


Fig. 1 – Transportation of copper along a (4,4)–(5,5) CNT channel with a 2 V bias voltage at 873 K. Snapshots were taken at (a) 1.6 ps, (b) 3.4 ps, (c) 4.4 ps, (d) 6.7 ps and (e) 9.0 ps, respectively.



Atomic arrangement of copper atoms in a carbon nanotube channel under electromigration conditions

Figure 1. Transportation of copper along a (5, 5)–(4, 4) CNT channel. (a) Side view of copper transport along a CNT channel. (b) Copper transport along the (5, 5) CNT. (c) Copper transport along the CNT junction.



Rank in Category: CARBON

Journal Ranking

For **2012**, the journal **CARBON** has an Impact Factor of **5.868**.

This table shows the ranking of this journal in its subject categories based on Impact Factor.

Category Name	Total Journals in Category	Journal Rank in Category	Quartile in Category
CHEMISTRY, PHYSICAL	135	20	Q1
MATERIALS SCIENCE, MULTIDISCIPLINARY	241	23	Q1

Rank in Category: MATERIALS CHEMISTRY AND PHYSICS

Journal Ranking

For **2012**, the journal **MATERIALS CHEMISTRY AND PHYSICS** has an Impact Factor of **2.072**.

This table shows the ranking of this journal in its subject categories based on Impact Factor.

Category Name	Total Journals in Category	Journal Rank in Category	Quartile in Category
MATERIALS SCIENCE, MULTIDISCIPLINARY	241	61	Q2

Source: Web of Science

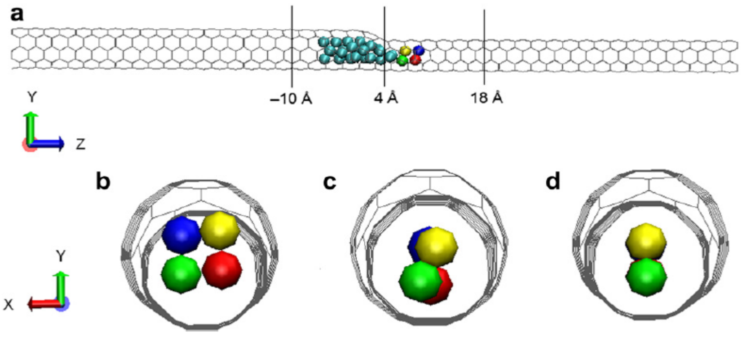
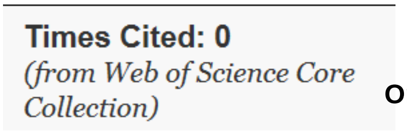


Fig. 1. (a) Transportation of copper along a (5,5)–(4,4) CNT channel with a 4 V bias voltage at 673 K. Snapshots were taken at (b) 5.4 ps, (c) 8.1 ps, (d) 15.1 ps respectively.

M.C.G. Lim, **Z.W. Zhong,** The effect of carbon nanotube chirality on the spiral flow of copper atoms in their cores, Materials Chemistry and Physics 137 (2) (2012) 519-531.



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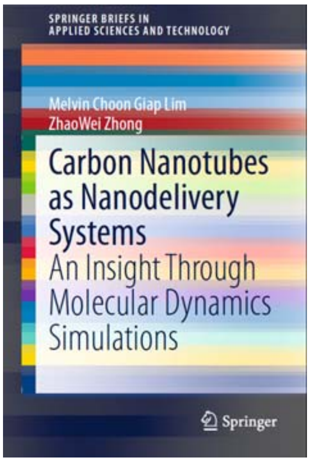
Books

- Melvin Choon Giap Lim, **ZhaoWei Zhong**, Carbon Nanotubes as Nanodelivery Systems - An Insight Through Molecular Dynamics Simulations, Springer, Singapore, 2013. ISBN 978-981-4451-38-3.
- Preeti S. Chauhan, Anupam Choubey, **ZhaoWei Zhong**, Michael G. Pecht, Copper Wire Bonding, Springer, USA, 2013. ISBN 978-1-4614-5760-2.



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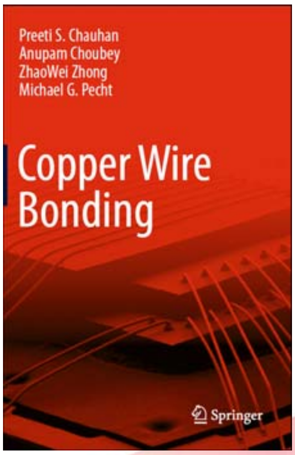

Preeti S. Chauhan
Anupam Choubey
ZhaoWei Zhong
Michael G. Pecht

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Journals that charge authors (and not for open access publication)

March 8, 2012

- Many journals charge authors even without making their articles freely available.
- Frequently these charges are to cover the cost of colour printing, which seems reasonable given that nowadays printed journal articles are a bonus not standard.
- Some journals have submission fees, others have page charges.
- If they go towards supporting a scientific society that you would like to donate to, for example, or if you feel that your paper will have its full impact only if printed in colour, you might be happy to pay.
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Colour charges

- In the past, print journals often charged authors for printing their article in colour, as colour printing was (and still is) more expensive than printing in black and white.
- With online publication there is no difference in cost, so it doesn't make sense for journals to charge authors for colour for the online version of an article. But some journals are still charging for colour printing.

A few examples (with links to the relevant page) are:

- The Journal of Neuroscience (Society for Neuroscience) charges US$1000 per colour figure, but offers free colour when it is judged essential by the editors **and** when the first and last authors are members of the society.
- J Biol Chem charges US$150 per colour figure (with discounts for society members).
- Evolution (Wiley-Blackwell) charges $500.00 per printed figure. FEMS Microbiology Letters (also Wiley-Blackwell) offers free colour provided that the colour is deemed essential for interpretation of the figure, whereas another Wiley-Blackwell journal, Proteomics, charges €500 for one colour figure up to €1664 for four.
- FASEB Journal charges US$350 per colour figure.
- BMJ Journals all seem to charge £250 per article for colour printing, but the BMJ itself (pdf) does not.

Source: http://sharmanedit.wordpress.com/2012/03/08/author-charges/

- Of Oxford University Press journals, Bioinformatics and Human Molecular Genetics charge £350/US$600/€525 per colour figure, whereas Journal of Experimental Botany charges £100/US$190/€150.
- Some Springer journals charge for colour printing.
- Similarly, some Nature Publishing Group journals charge for colour printing, but I wasn't able to find out which ones. As far as I can tell, Nature and its sister journals with the word 'Nature' in the title have no charges.
- Elsevier's author site seems to imply that all their journals have colour charges.
- Journals that do not charge for colour printing include:
- BMJ (pdf)
- Science
- Nature, Nature Genetics, EMBO Journal, EMBO Reports and some other Nature Publishing Group journals
- Development, Genes and Evolution (Springer), as proudly proclaimed on their home page
- Company of Biologists journals (such as Development and Journal of Cell Science)

Source: http://sharmanedit.wordpress.com/2012/03/08/author-charges/

Page charges

- Page charges seem to be almost as common as colour charges.
- One journal, Journal of Neuroscience, has publication fees per article (US$980, or US$490 for Brief Communications)

Others charge per page, sometimes over a certain limit. For example:

- FASEB Journal charges US$80 per printed page for the first 8 pages and $160 per page thereafter. Articles containing eight or more figures and/or tables cost an additional $150 per figure or table.
- J Biol Chem charges US$80 per page for the first nine pages and $160 per page thereafter (with discounts for society members).
- The charges don’t seem to be consistent within each publisher.
- Of Oxford University Press journals, Bioinformatics charges £100/US$190 per page over 7 pages (or over 4 or 2 pages for shorter article types). Journal of Experimental Botany and Human Molecular Genetics have no page charges.
- Of Wiley-Blackwell journals, Evolution charges US$55 per printed page (but society members can have 12 free pages a year). Proteomics charges €196 (US$261) per page over 7 pages (or over 4 pages for shorter article types). FEMS Microbiology Letters and Synapse have no page charges.

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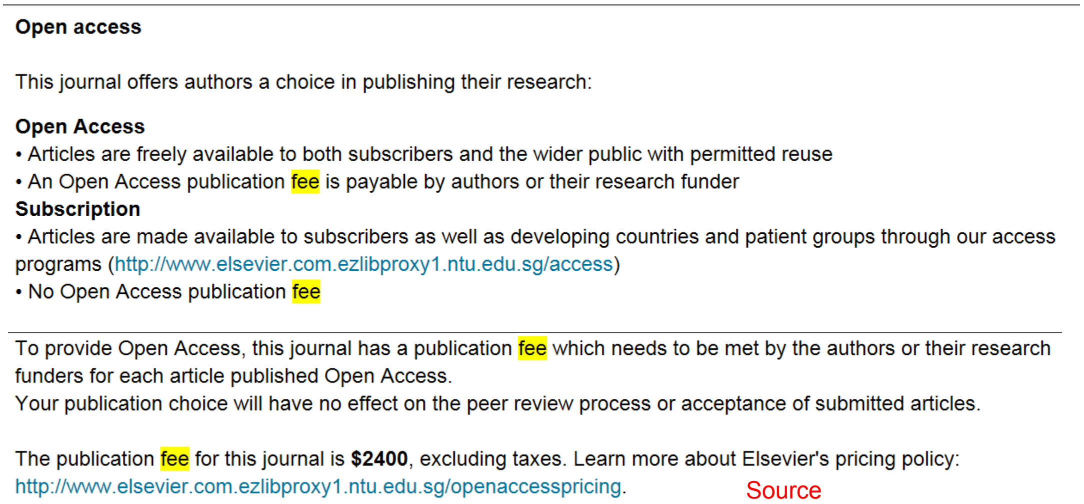
Page charges

- Some Elsevier journals have page charges.
- Journal of Structural Biology, Journal of Molecular Biology, Animal Behaviour and BBA Molecular Cell Research don’t have page charges.
- Nature and its sister journals with the word ‘Nature’ in the title have no charges.
- Some other journals published by Nature Publishing Group do have page charges, however. For example, EMBO Journal charges £158/US$242 per page (except pages containing only references).
- Obesity and Oncogene have no page charges.
- Some Springer journals charge for over-length articles.
- One publisher is consistent – none of the BMJ Journals or BMJ (pdf) have any page charges.

Fees for supplementary material

- FASEB Journal charges for supplemental ‘units’ (presumably files) at $160 each (up to four units are allowed).
- Proc Natl Acad Sci USA charges US$250 per article for up to five pages of SI (US$500 over six pages).



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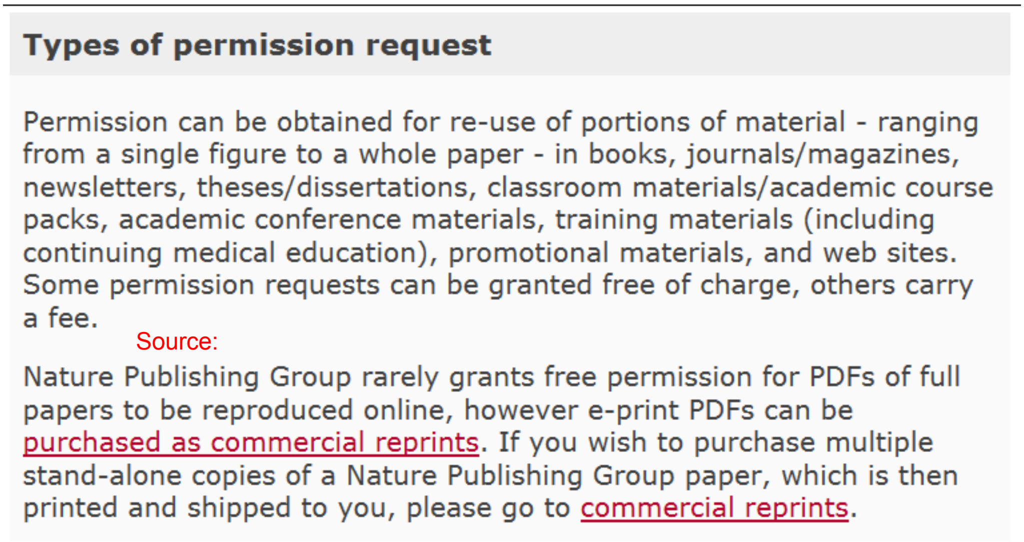

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Examples of research papers and review papers

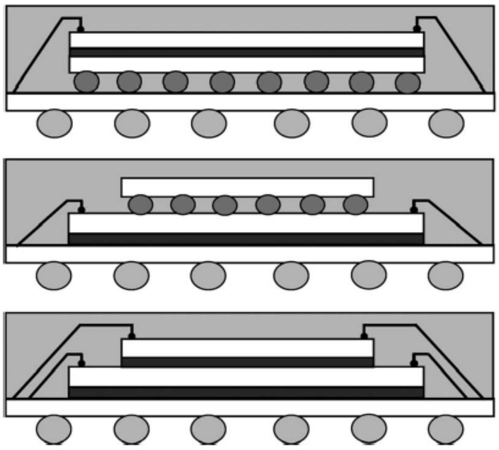
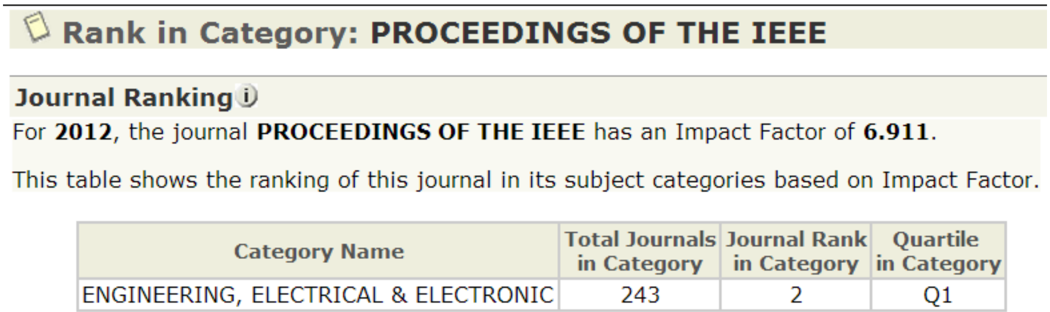


Fig. 1. Schematic diagrams of three interconnects for stacked die packages: (top) wire-bond/flip-chip, (middle) flip-chip/wire-bond, and (bottom) wire-bond/wire-bond [70], [75].

On 26 Feb 2014

Times Cited: 2
(from Web of Science Core Collection)

Z.W. Zhong, T.Y. Tee, Overview of Board-Level Solder Joint Reliability Modeling for Single Die and Stacked Die CSPs, Proceedings of the IEEE 97 (1) (2009) 175-183.



Rank in Category: PROCEEDINGS OF THE IEEE

Journal Ranking

For **2012**, the journal **PROCEEDINGS OF THE IEEE** has an Impact Factor of **6.911**.

This table shows the ranking of this journal in its subject categories based on Impact Factor.

Category Name	Total Journals in Category	Journal Rank in Category	Quartile in Category
ENGINEERING, ELECTRICAL & ELECTRONIC	243	2	Q1

Source: Web of Science

Capillary Design Considerations

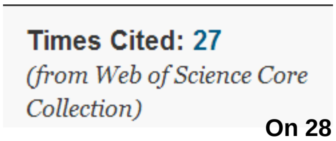
- Many companies were aggressively running evaluation and even making prototypes for 50-μm BPP applications.
- The anticipated problem with wire sweep during molding had forced many companies to revert back to larger wire size ranging from 23 μm to 25 μm.
- However, various problems arise on using a larger wire diameter on a smaller bond pad opening.
- For a wire diameter of 23 μm, the minimum capillary hole size needs to be at least 28 μm.
- Considering a tolerance of +2/-0 μm, the minimum chamfer diameter needs to be at least 34 μm for a reliable stitch bond.
- Such a chamfer diameter size would make it difficult to produce an average ball size of 38 μm for 50-μm BPP bonding.
- Considering that the smallest free air ball size at 1.4 times the wire diameter that the bonders can attain consistently, the deformed ball size cannot be further reduced.

Zhong, Z., and K. S. Goh, “Analysis and Experiments of Ball Deformation for Ultra-Fine-Pitch Wire Bonding,” Journal of Electronics Manufacturing, Vol. 10, No. 4, Dec. 2000, pp. 211-217.

Effect of capillary design

- Usually, small and large diameter wires produce small and large mashed ball diameters respectively.
- With the specially designed capillary configuration, a small mashed ball diameter can be produced using wire with a large diameter, which is a solution to avoid the anticipated problem with wire sweep.

Zhong, Z., and K. S. Goh, “Analysis and Experiments of Ball Deformation for Ultra-Fine-Pitch Wire Bonding,” Journal of Electronics Manufacturing, Vol. 10, No. 4, Dec. 2000, pp. 211-217.



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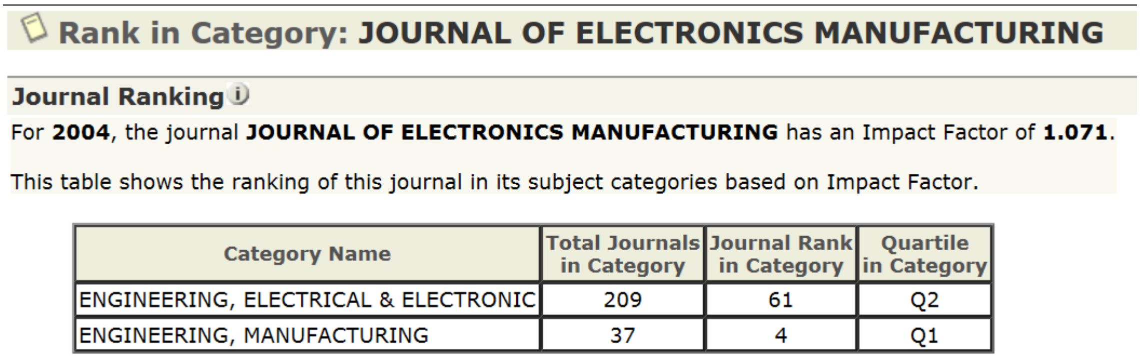


Rank in Category: JOURNAL OF ELECTRONICS MANUFACTURING

Journal Ranking

For **2004**, the journal **JOURNAL OF ELECTRONICS MANUFACTURING** has an Impact Factor of **1.071**.

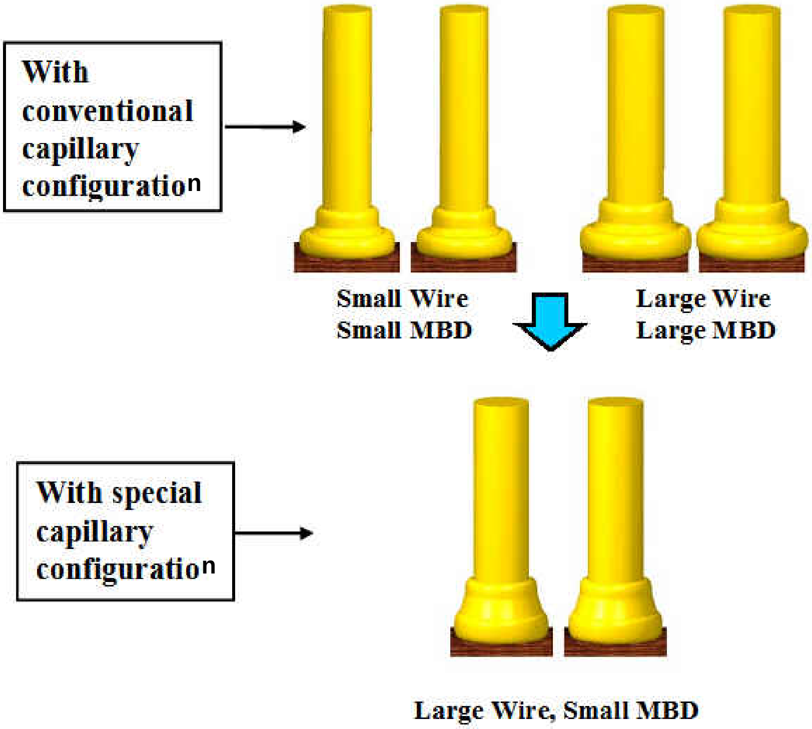
This table shows the ranking of this journal in its subject categories based on Impact Factor.

Category Name	Total Journals in Category	Journal Rank in Category	Quartile in Category
ENGINEERING, ELECTRICAL & ELECTRONIC	209	61	Q2
ENGINEERING, MANUFACTURING	37	4	Q1

Source: Web of Science

A special capillary configuration produces small mashed ball diameters (MBDs) with large wires

Source: Zhong, Z., and K. S. Goh, “Analysis and Experiments of Ball Deformation for Ultra-Fine-Pitch Wire Bonding,” Journal of Electronics Manufacturing, Vol. 10, No. 4, Dec. 2000, pp. 211-217.



With conventional capillary configuration

Small Wire
Small MBD

Large Wire
Large MBD

With special capillary configuration

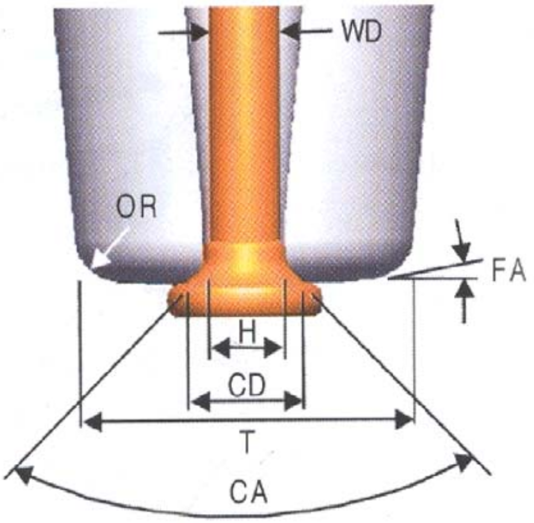
Large Wire, Small MBD

Considerations for Simulation and Experiments

- Unlike bonding on non-fine pitch devices, which can accommodate a wide range of ball size variation due to the large pad opening, bonding on ultra-fine-pitch devices requires the ball size to be controlled within a much tighter tolerance.
- The reduction in BPP requires the capillary tip dimensions to be reduced significantly to prevent the capillary from any interference with the adjacent wires during bonding.
- Optimal machine performance and capillary designs are necessary to achieve a reliable bond process control.
- In ultra-fine-pitch bonding, the most difficult task is to obtain small ball deformation consistency and reliable stitch formation.
- For a typical 50-μm BPP, the bond-pad opening is in the range of 40 μm to 44 μm.
- Considering the ball placement accuracy that bonders can attain, the eventual ball size needs to be controlled within an average of 38 μm to 40 μm.

Zhong, Z., and K. S. Goh, "Analysis and Experiments of Ball Deformation for Ultra-Fine-Pitch Wire Bonding," Journal of Electronics Manufacturing, Vol. 10, No. 4, Dec. 2000, pp. 211-217.

Critical dimensions of the bonding tool called the capillary



Source:

K.S. Goh, Z.W. Zhong, Two capillary solutions for ultra-fine-pitch wire bonding and insulated wire bonding, Microelectronic Engineering 84 (2) (2007) 362-367.

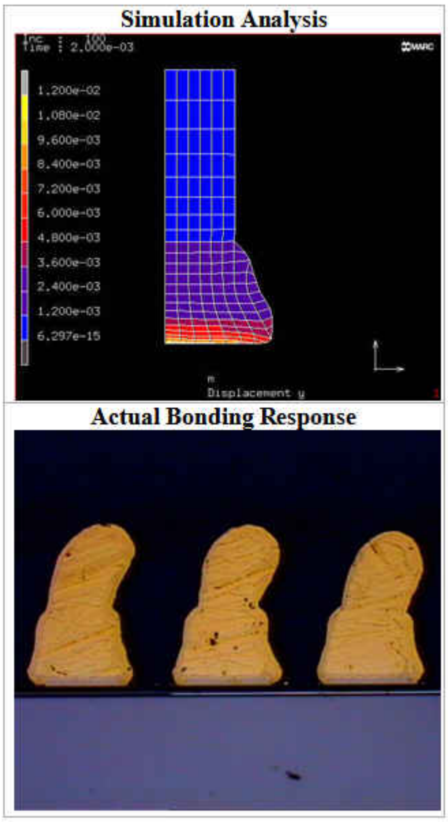
Small Precision Tools, Bonding Capillaries, 04/99-5, 1999.

Considerations for Simulation and Experiments

- We know the combination of various critical bonding parameters and capillary dimensions has significant effects on the ball deformation, but it was difficult to establish the individual effects of these parameters on the ball deformation.
- FEA with actual bonding experiments can help to overcome the difficulties and shorten the development time.
- The plastic deformation of a gold ball was simulated.
- The considerations include:
  - Wire and capillary (23-μm gold wire and a ceramic based zirconia composite capillary)
  - Critical machine setting (free air ball diameter, bonding force and time, bonding temperature, constant velocity from the search height)
  - The ultrasonic displacement waveform obtained from a laser vibrometer
  - Bond pad (an aluminum layer)
  - Critical capillary dimensions (hole diameter, chamfer diameter, chamfer angle, face angle, outside radius, and tip diameter)

Zhong, Z., and K. S. Goh, "Analysis and Experiments of Ball Deformation for Ultra-Fine-Pitch Wire Bonding," Journal of Electronics Manufacturing, Vol. 10, No. 4, Dec. 2000, pp. 211-217.

Examples of the simulation and actual bonding results



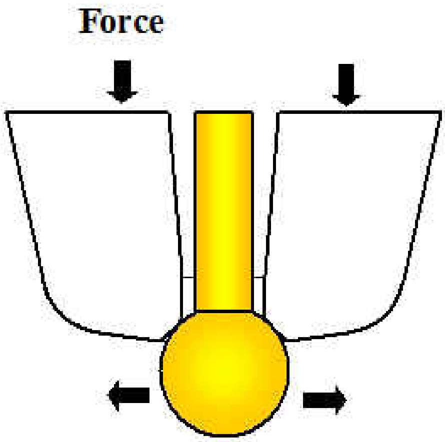
Source: Zhong, Z., and K. S. Goh, "Analysis and Experiments of Ball Deformation for Ultra-Fine-Pitch Wire Bonding," Journal of Electronics Manufacturing, Vol. 10, No. 4, Dec. 2000, pp. 211-217.

Critical dimensions and parameters

- The analysis revealed that the critical bonding tool dimensions and bonding process parameters such as free air ball consistency and bonding force played critical roles in reliable ball deformation.
- The chamfer angle and the chamfer diameter of the capillary have significant impacts on the ball deformation.
- The combined effect of the chamfer angle and the chamfer diameter can result in a smaller ball size by containing the amount of gold inside the capillary during impact and eventually restricting the gold squashed out during the bonding process.
- Although the hole size of the capillary can influence the final ball size, this is normally taken care of by using the smallest possible hole size for a particular wire diameter.
- In this case, it was decided that a wire diameter of 23 μm with a capillary hole size of 28 - 30 μm would be robust for a mass production environment.

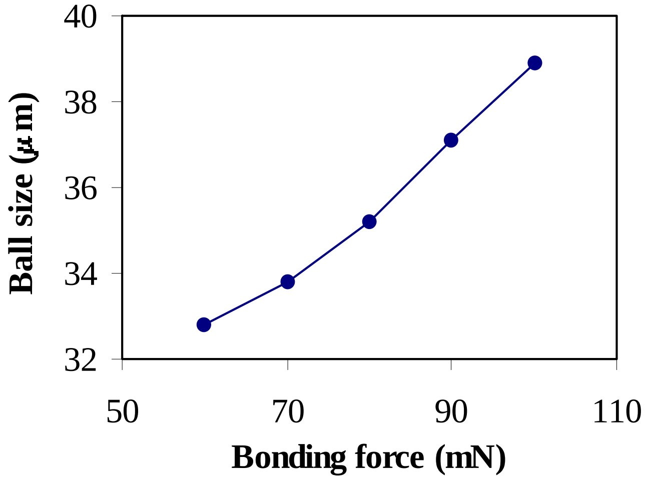
Zhong, Z., and K. S. Goh, "Analysis and Experiments of Ball Deformation for Ultra-Fine-Pitch Wire Bonding," Journal of Electronics Manufacturing, Vol. 10, No. 4, Dec. 2000, pp. 211-217.

A large free air ball can result in excessive gold squashed out during bonding



Source: Zhong, Z., and K. S. Goh, "Analysis and Experiments of Ball Deformation for Ultra-Fine-Pitch Wire Bonding," Journal of Electronics Manufacturing, Vol. 10, No. 4, Dec. 2000, pp. 211-217.

The relationship between ball size and bonding force obtained by the simulation. A lower bonding force results in a smaller ball size



Source: Zhong, Z., and K. S. Goh, “Analysis and Experiments of Ball Deformation for Ultra-Fine-Pitch Wire Bonding,” Journal of Electronics Manufacturing, Vol. 10, No. 4, Dec. 2000, pp. 211-217.

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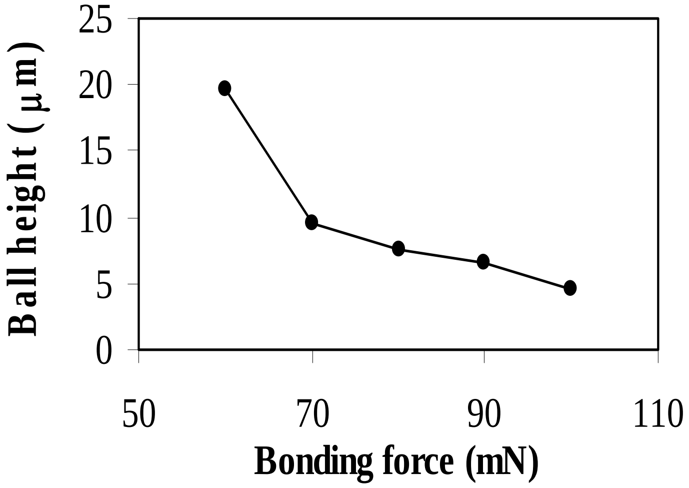
The relationship between ball height and bonding force obtained by the simulation. A lower bonding force produces a thicker ball height



Source: Zhong, Z., and K. S. Goh, “Analysis and Experiments of Ball Deformation for Ultra-Fine-Pitch Wire Bonding,” Journal of Electronics Manufacturing, Vol. 10, No. 4, Dec. 2000, pp. 211-217.

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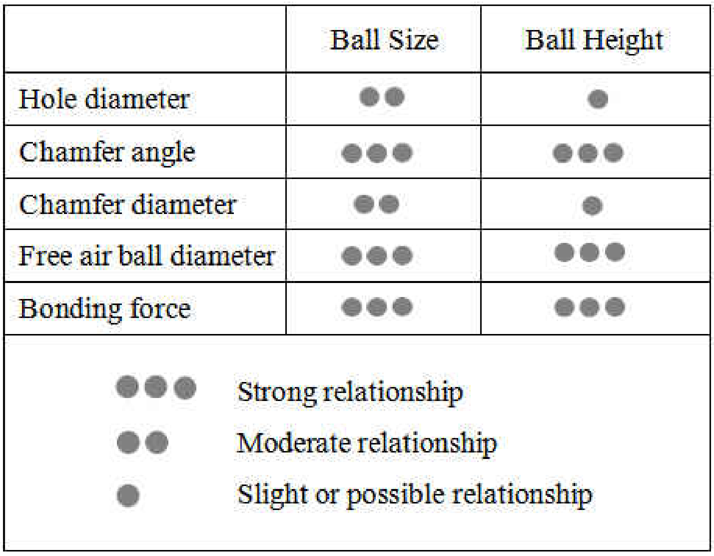
Critical dimensions and parameters

- For ultra-fine-pitch bonding, the free air ball diameter plays a critical role in the deformed ball size, ball height, and the bond quality.
- Too large a free air ball can result in excessive gold squashed out during bonding instead of containing the ball inside the capillary.
- A thicker ball height can affect the ultrasonic energy transfer from the capillary to the bond surface resulting in less intermetallic diffusion.
- A diameter of 32 - 33 µm is recommended as the average size of the free air balls for 50-µm BPP bonding using 23-µm gold wire.
- Besides those factors, machine parameters such as bonding force and search speed can influence the final geometry of the ball size.
- A lower bonding force results in a smaller ball size, which is a critical requirement for ultra-fine-pitch bonding, but produces a thicker ball height.
- The ideal situation would be to have as low a bonding force as possible to ensure that the ball is not over deformed.

Zhong, Z., and K. S. Goh, “Analysis and Experiments of Ball Deformation for Ultra-Fine-Pitch Wire Bonding,” Journal of Electronics Manufacturing, Vol. 10, No. 4, Dec. 2000, pp. 211-217.

Relationships of capillary dimensions, free air ball, and ball deformation

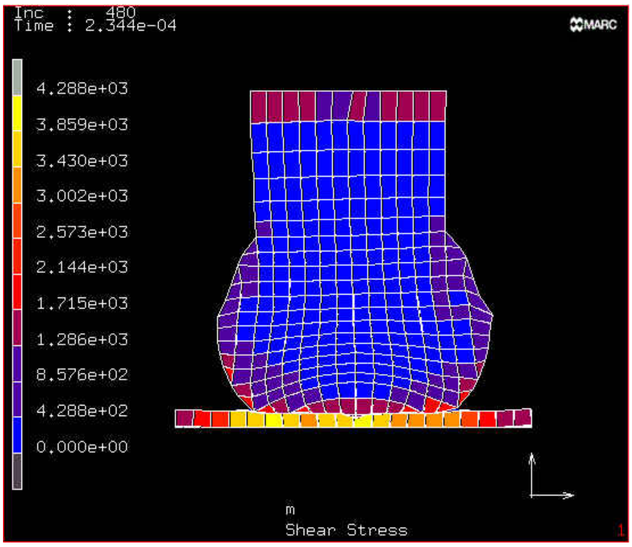


	Ball Size	Ball Height
Hole diameter	●●	●
Chamfer angle	●●●	●●●
Chamfer diameter	●●	●
Free air ball diameter	●●●	●●●
Bonding force	●●●	●●●

●●● Strong relationship
●● Moderate relationship
● Slight or possible relationship

Source: Zhong, Z., and K. S. Goh, “Analysis and Experiments of Ball Deformation for Ultra-Fine-Pitch Wire Bonding,” Journal of Electronics Manufacturing, Vol. 10, No. 4, Dec. 2000, pp. 211-217.

Stress distribution with the new capillary design



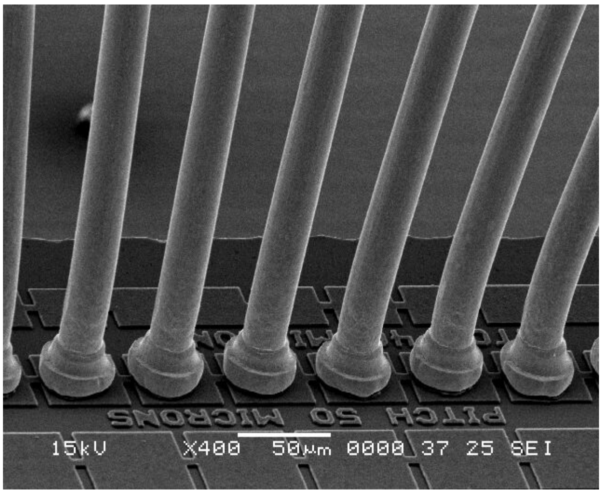
Source: Zhong, Z., and K. S. Goh, "Analysis and Experiments of Ball Deformation for Ultra-Fine-Pitch Wire Bonding," Journal of Electronics Manufacturing, Vol. 10, No. 4, Dec. 2000, pp. 211-217.

Critical dimensions and parameters

- The effects of the various capillary dimensions and free air ball variation on the ball deformation for ultra-fine-pitch bonding using the new capillary design can be summarized in the table.
- Stress analysis was also conducted to evaluate the stress level on the metallization between a standard capillary design and the new design.
- No significant difference was observed through the simulation.
- This observation was further verified with the cratering test with no sign of craters or oxide cracks during the visual inspection.

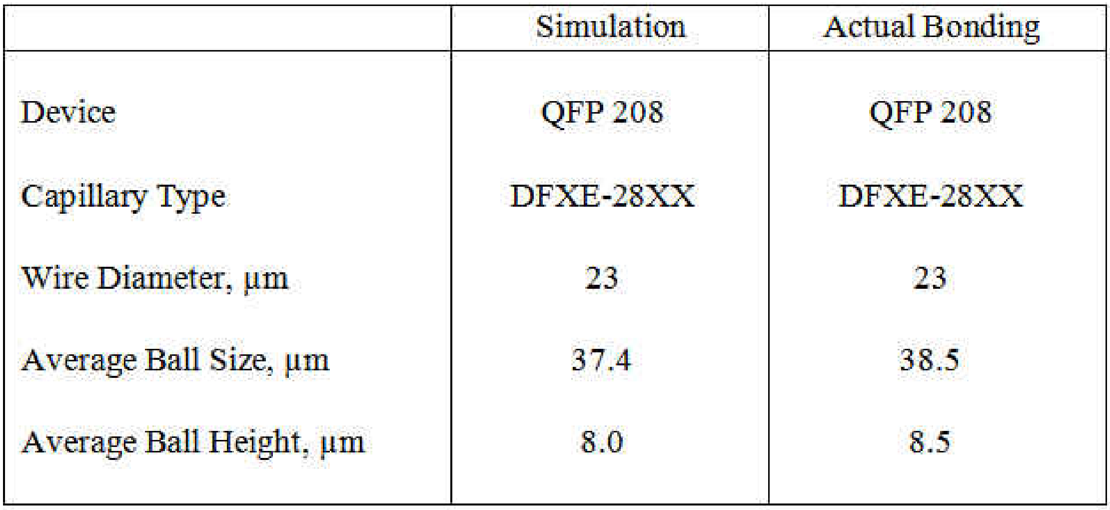
Zhong, Z., and K. S. Goh, "Analysis and Experiments of Ball Deformation for Ultra-Fine-Pitch Wire Bonding," Journal of Electronics Manufacturing, Vol. 10, No. 4, Dec. 2000, pp. 211-217.

An example of actual bonding responses of ultra-fine-pitch bonding on a 50-µm bond-pad-pitch platform using 23-µm gold wire



Source: Zhong, Z., and K. S. Goh, "Analysis and Experiments of Ball Deformation for Ultra-Fine-Pitch Wire Bonding," Journal of Electronics Manufacturing, Vol. 10, No. 4, Dec. 2000, pp. 211-217.

Comparison of simulation and actual bonding responses



	Simulation	Actual Bonding
Device	QFP 208	QFP 208
Capillary Type	DFXE-28XX	DFXE-28XX
Wire Diameter, µm	23	23
Average Ball Size, µm	37.4	38.5
Average Ball Height, µm	8.0	8.5

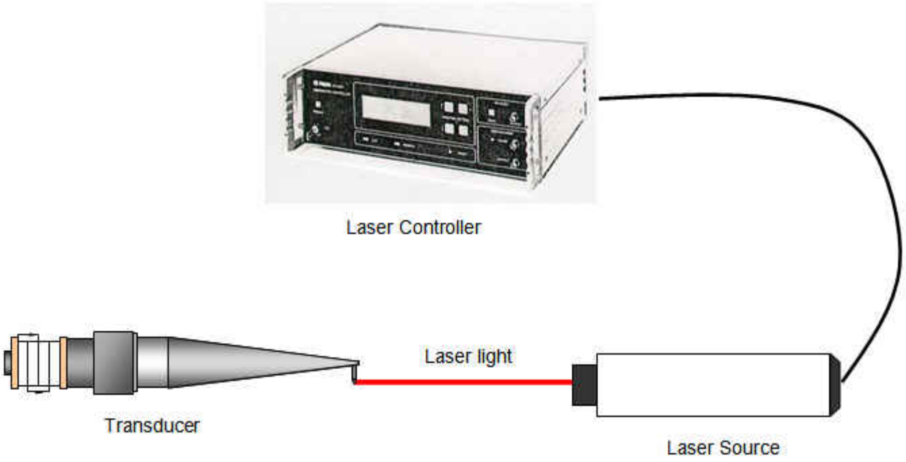
Source: Zhong, Z., and K. S. Goh, "Analysis and Experiments of Ball Deformation for Ultra-Fine-Pitch Wire Bonding," Journal of Electronics Manufacturing, Vol. 10, No. 4, Dec. 2000, pp. 211-217.

Experimental verification

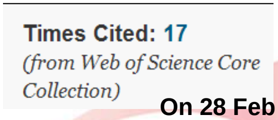
- Experimental verification on the analysis results was carried out on an ESEC 3008 wire bonder, software version 53.0 using a QFP (quad flat pack) 208 copper lead frame with silver coating and using a 23-μm wire size.
- Comparison of the simulation results with the experimental data indicated that the actual ball size (38.5 μm) was approximately 3% larger than that (37.4 μm) obtained from the simulation.
- This deviation could be due to the free air ball deviation, bonding force variation, tolerances of the capillary and the frequency of the transducer, which were not taken into consideration during the simulation.

Zhong, Z., and K. S. Goh, “Analysis and Experiments of Ball Deformation for Ultra-Fine-Pitch Wire Bonding,” Journal of Electronics Manufacturing, Vol. 10, No. 4, Dec. 2000, pp. 211-217.

Measurement of ultrasonic vibration of a capillary using a laser interferometer



Source: Zhong Z.W., and K.S. Goh, “Investigation of ultrasonic vibrations of wire-bonding capillaries,” Microelectronics Journal, Vol. 37, No. 2, 2006, pp. 107-113.


Times Cited: 17
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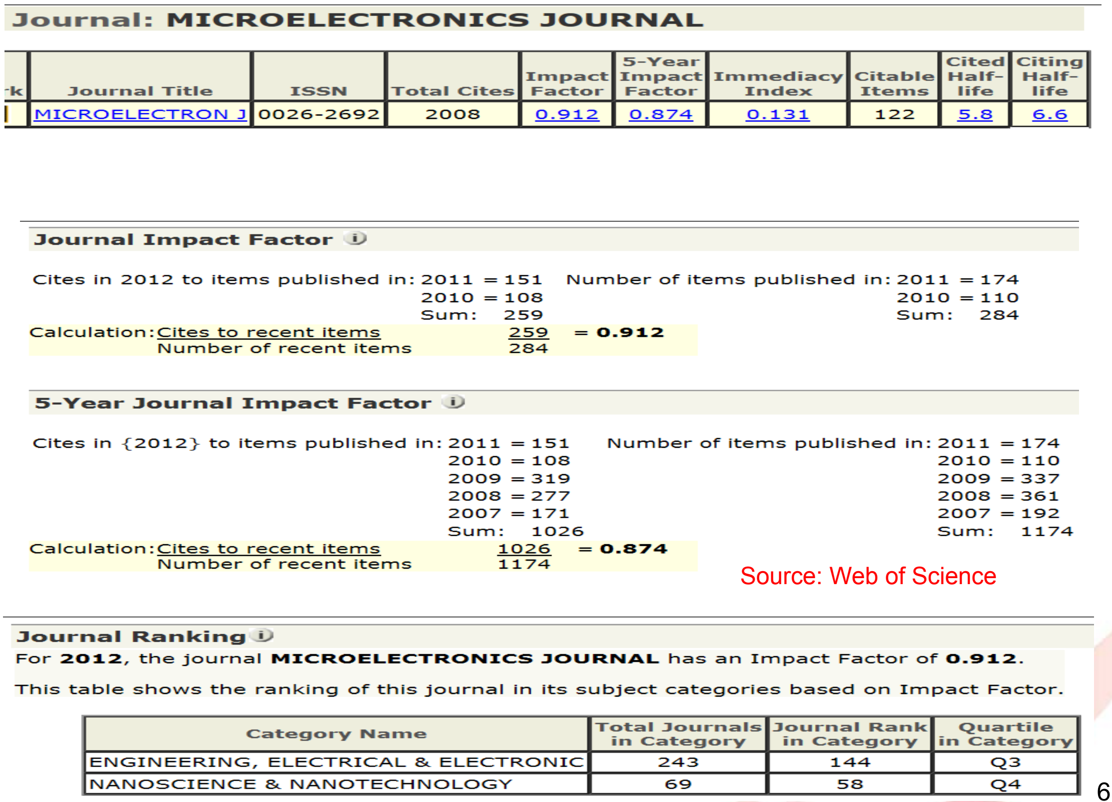
On 28 Feb 2014



Journal: **MICROELECTRONICS JOURNAL**

k	Journal Title	ISSN	Total Cites	Impact Factor	5-Year Impact Factor	Immediacy Index	Citable Items	Cited Half-life	Citing Half-life
	MICROELECTRON J	0026-2692	2008	0.912	0.874	0.131	122	5.8	6.6

Journal Impact Factor

Cites in 2012 to items published in: 2011 = 151
2010 = 108
Sum: 259

Number of items published in: 2011 = 174
2010 = 110
Sum: 284

Calculation: Cites to recent items / Number of recent items = 259 / 284 = **0.912**

5-Year Journal Impact Factor

Cites in {2012} to items published in: 2011 = 151
2010 = 108
2009 = 319
2008 = 277
2007 = 171
Sum: 1026

Number of items published in: 2011 = 174
2010 = 110
2009 = 337
2008 = 361
2007 = 192
Sum: 1174

Calculation: Cites to recent items / Number of recent items = 1026 / 1174 = **0.874**

Source: Web of Science

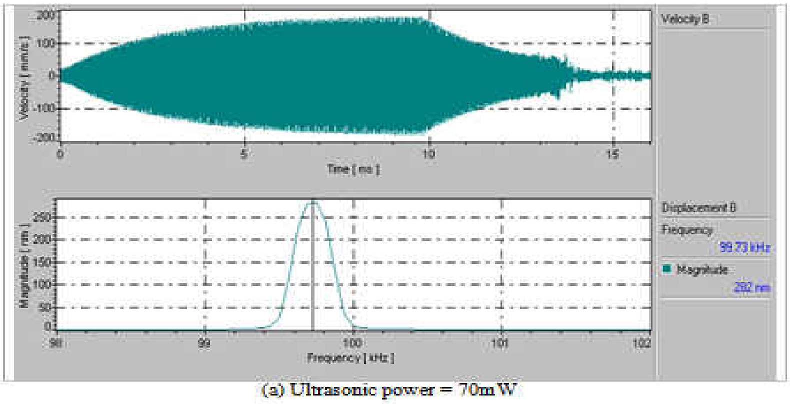
Journal Ranking

For **2012**, the journal **MICROELECTRONICS JOURNAL** has an Impact Factor of **0.912**.

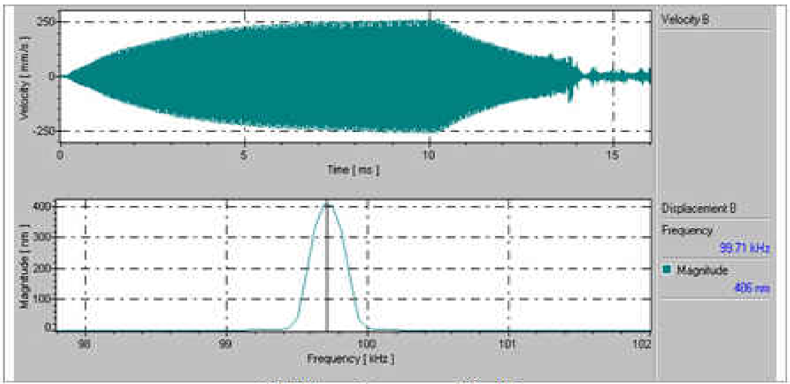
This table shows the ranking of this journal in its subject categories based on Impact Factor.

Category Name	Total Journals in Category	Journal Rank in Category	Quartile in Category
ENGINEERING, ELECTRICAL & ELECTRONIC	243	144	Q3
NANOSCIENCE & NANOTECHNOLOGY	69	58	Q4

Measured ultrasonic vibration waveforms of a capillary using (a) low and (b) high ultrasonic power settings



(a) Ultrasonic power = 70mW



(b) Ultrasonic power = 90mW

Source: Zhong Z.W., and K.S. Goh, "Investigation of ultrasonic vibrations of wire-bonding capillaries," Microelectronics Journal, Vol. 37, No. 2, 2006, pp. 107-113.

NANYANG TECHNOLOGICAL UNIVERSITY

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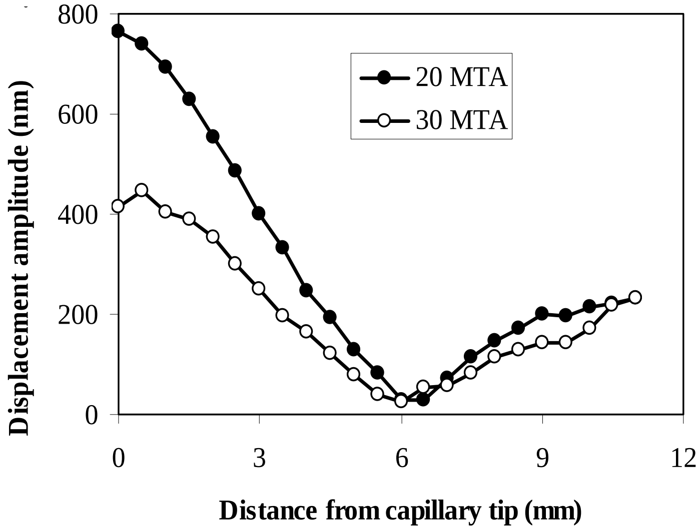
Transverse vibrations of two capillaries



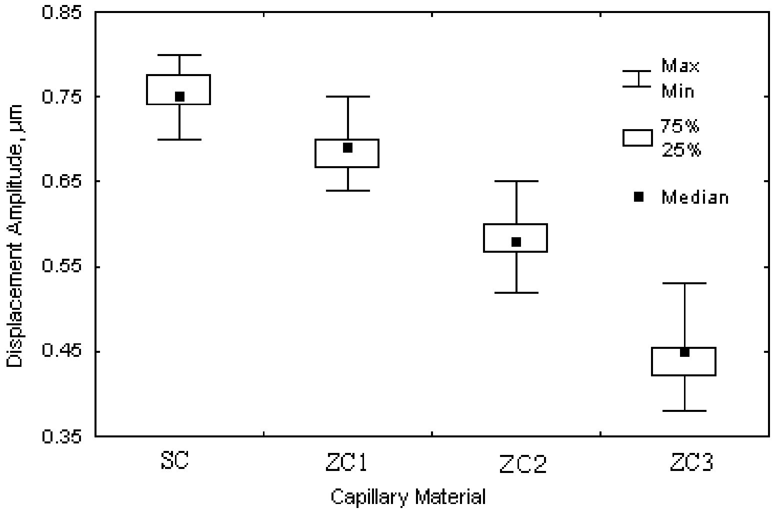
Source: Zhong Z.W., and K.S. Goh, "Investigation of ultrasonic vibrations of wire-bonding capillaries," Microelectronics Journal, Vol. 37, No. 2, 2006, pp. 107-113.

Amplitude of oscillation for different capillary diameter, bond power and force combinations

Tip Diameter (µm)	Bond Force (mN)	Bond Power (%)	Amplitude of Oscillation (nm)		
			Min.	Max.	Ave.
100	500	18	480	520	500
	300	12	440	460	447
	300	18	640	660	647
80	180	10	520	540	527
	100	5	280	320	300

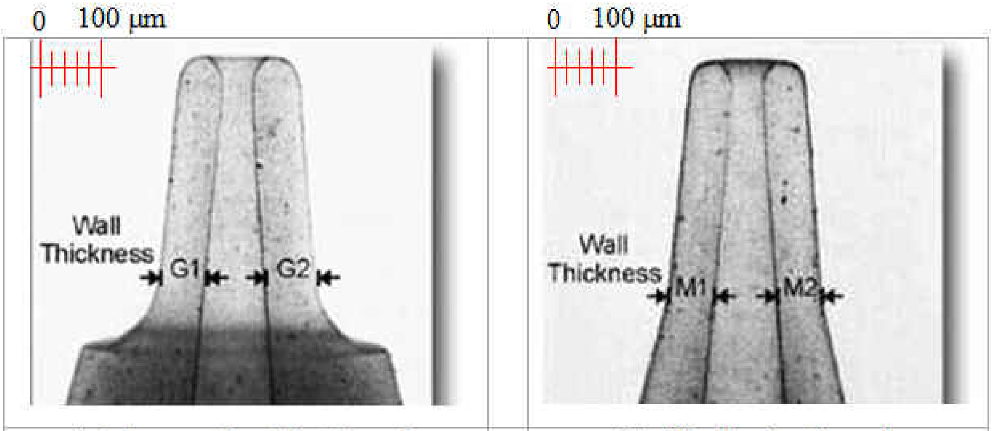
Source: Zhong Z.W., and K.S. Goh, "Investigation of ultrasonic vibrations of wire-bonding capillaries," Microelectronics Journal, Vol. 37, No. 2, 2006, pp. 107-113.

The vibrational displacement amplitude decreased as the amount of zirconia composition increased



Source: Zhong Z.W., and K.S. Goh, “Investigation of ultrasonic vibrations of wire-bonding capillaries,” Microelectronics Journal, Vol. 37, No. 2, 2006, pp. 107-113.

The conventional and slimline bottleneck capillaries

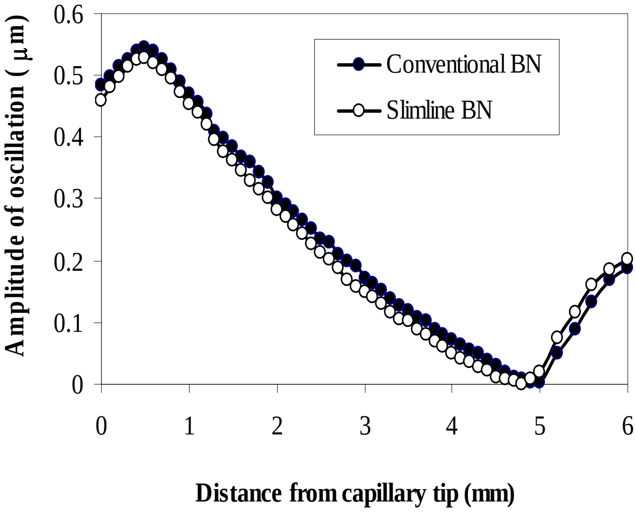


(a) Conventional bottleneck

(b) Slimline bottleneck

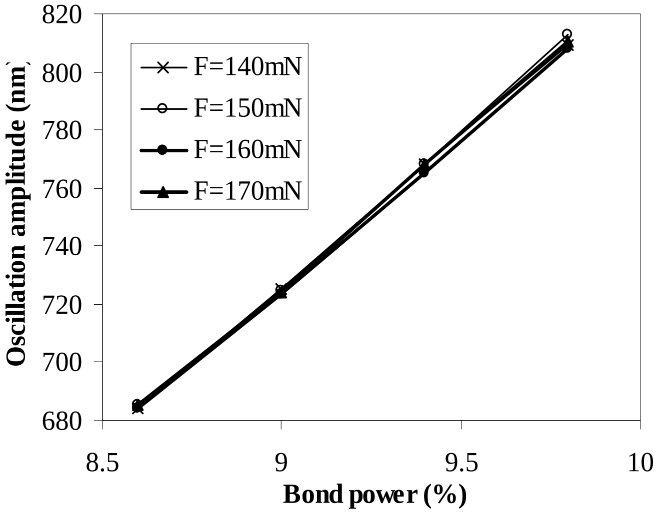
Source: Zhong Z.W., and K.S. Goh, “Investigation of ultrasonic vibrations of wire-bonding capillaries,” Microelectronics Journal, Vol. 37, No. 2, 2006, pp. 107-113.

Measured vibrational displacement amplitude of the conventional bottleneck (BN) and slimline BN capillaries



Source: Zhong Z.W., and K.S. Goh, “Investigation of ultrasonic vibrations of wire-bonding capillaries,” Microelectronics Journal, Vol. 37, No. 2, 2006, pp. 107-113.

Oscillation amplitude of the capillary for different bond power and bond force (*F*) combinations



Source: Zhong Z.W., and K.S. Goh, “Investigation of ultrasonic vibrations of wire-bonding capillaries,” Microelectronics Journal, Vol. 37, No. 2, 2006, pp. 107-113.

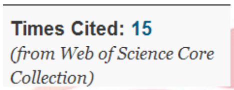
Fine and ultra-fine pitch wire bonding

- Advantages
- **Challenges/problems**
- Solutions/findings

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).
- The bonding capillary must have a smaller tip diameter for bonding devices with bond pad pitches (BPPs) below 50 um, a smaller hole size for bonding with a wire size as small as 10 um, better ultrasonic energy transfer, customized design for complex applications such as multi-tier bonding, stacked-dies wire bonding and insulated wire bonding.

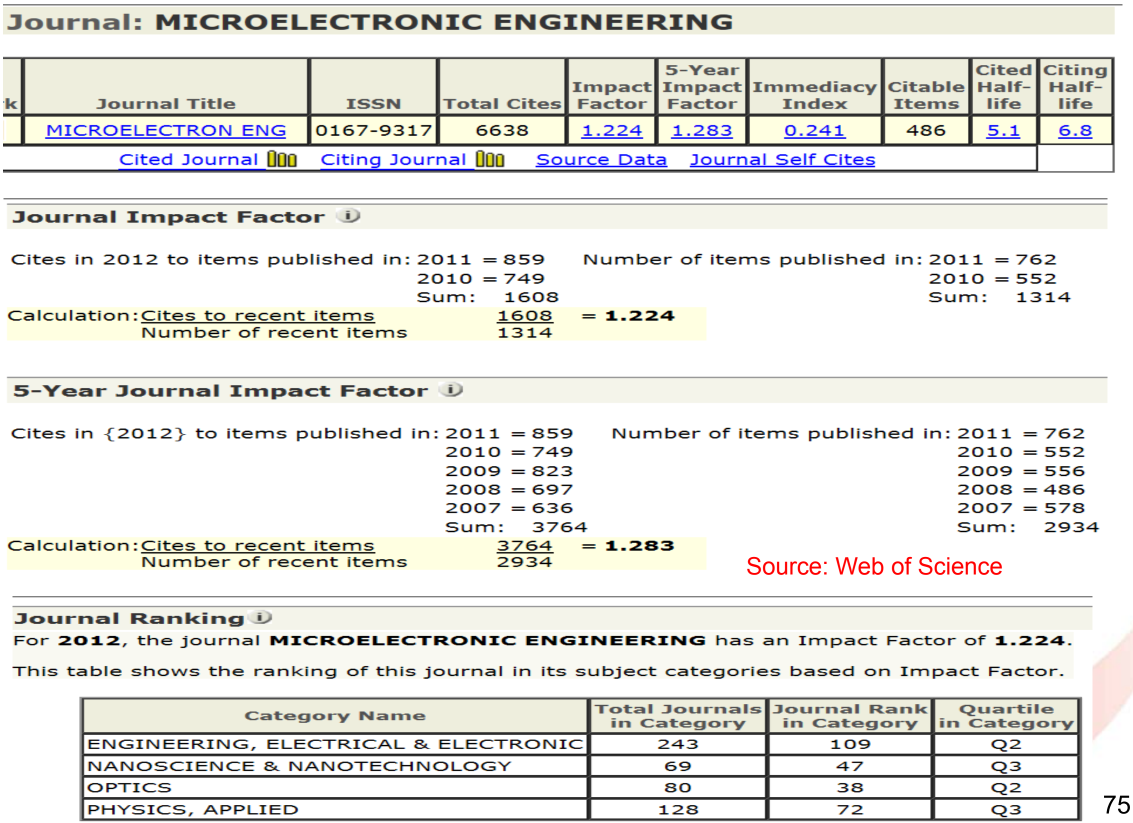
K.S. Goh, Z.W. Zhong, Two capillary solutions for ultra-fine-pitch wire bonding and insulated wire bonding, Microelectronic Engineering 84 (2) (2007) 362-367.



Times Cited: 15

(from Web of Science Core Collection)

On 28 Feb 2014



Journal: MICROELECTRONIC ENGINEERING

k	Journal Title	ISSN	Total Cites	Impact Factor	5-Year Impact Factor	Immediacy Index	Citable Items	Cited Half-life	Citing Half-life
	MICROELECTRON ENG	0167-9317	6638	1.224	1.283	0.241	486	5.1	6.8

Cited Journal Citing Journal Source Data Journal Self Cites

Journal Impact Factor

Cites in 2012 to items published in: 2011 = 859
2010 = 749
Sum: 1608

Number of items published in: 2011 = 762
2010 = 552
Sum: 1314

Calculation: $\frac{\text{Cites to recent items}}{\text{Number of recent items}} = \frac{1608}{1314} = \mathbf{1.224}$

5-Year Journal Impact Factor

Cites in {2012} to items published in: 2011 = 859
2010 = 749
2009 = 823
2008 = 697
2007 = 636
Sum: 3764

Number of items published in: 2011 = 762
2010 = 552
2009 = 556
2008 = 486
2007 = 578
Sum: 2934

Calculation: $\frac{\text{Cites to recent items}}{\text{Number of recent items}} = \frac{3764}{2934} = \mathbf{1.283}$

Source: Web of Science

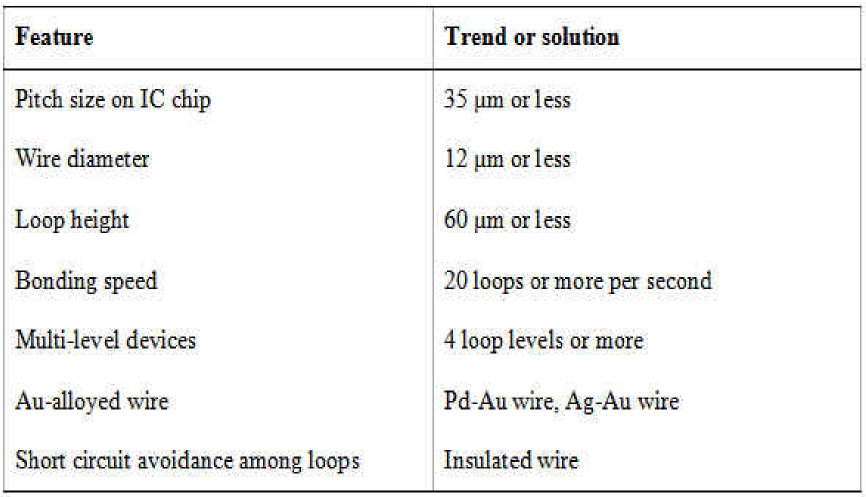
Journal Ranking

For **2012**, the journal **MICROELECTRONIC ENGINEERING** has an Impact Factor of **1.224**.

This table shows the ranking of this journal in its subject categories based on Impact Factor.

Category Name	Total Journals in Category	Journal Rank in Category	Quartile in Category
ENGINEERING, ELECTRICAL & ELECTRONIC	243	109	Q2
NANOSCIENCE & NANOTECHNOLOGY	69	47	Q3
OPTICS	80	38	Q2
PHYSICS, APPLIED	128	72	Q3

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

Source: K.S. Goh, Z.W. Zhong, Two capillary solutions for ultra-fine-pitch wire bonding and insulated wire bonding, Microelectronic Engineering 84 (2) (2007) 362-367.

Challenges and requirements

- The bonding wire must have a small wire size, 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.

K.S. Goh, Z.W. Zhong, Two capillary solutions for ultra-fine-pitch wire bonding and insulated wire bonding, Microelectronic Engineering 84 (2) (2007) 362-367.

Challenges and requirements

- 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-um BPP devices should have bond placement accuracy of ±1.5 um for 3σ accuracy, advanced *Z*-axis control with contact detection resolution of 0.4 um, 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).

K.S. Goh, Z.W. Zhong, Two capillary solutions for ultra-fine-pitch wire bonding and insulated wire bonding, Microelectronic Engineering 84 (2) (2007) 362-367.

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.
- 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 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.

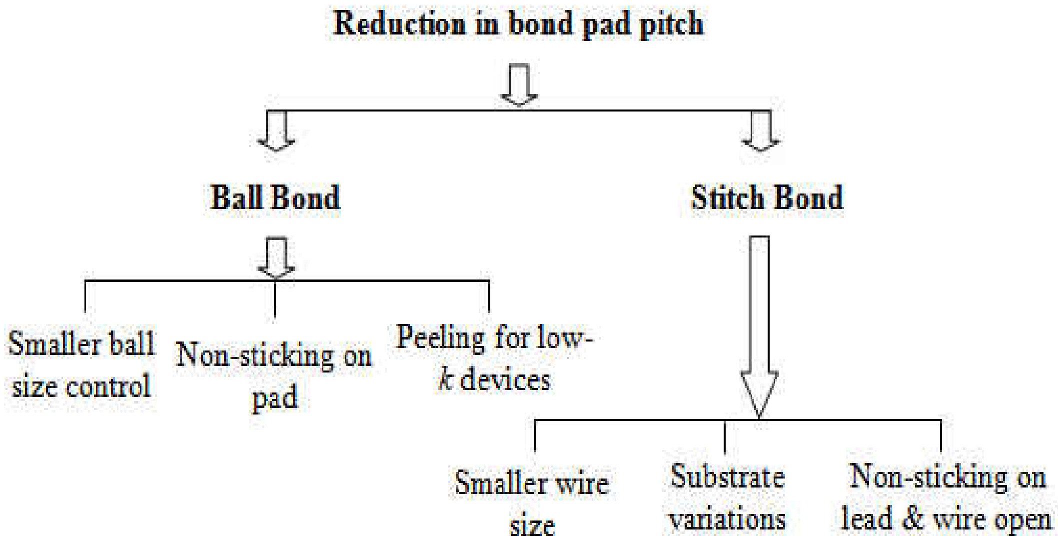
K.S. Goh, Z.W. Zhong, Two capillary solutions for ultra-fine-pitch wire bonding and insulated wire bonding, Microelectronic Engineering 84 (2) (2007) 362-367.

Ultra-fine-pitch wire bonding

- On the other hand, smaller wire sizes must be used for ultra-fine-pitch wire bonding, and this also causes stitch bond problems.
- 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.

K.S. Goh, Z.W. Zhong, Two capillary solutions for ultra-fine-pitch wire bonding and insulated wire bonding, Microelectronic Engineering 84 (2) (2007) 362-367.

Problems caused by reduction in bond pad pitch



Reduction in bond pad pitch

Ball Bond

Smaller ball size control

Non-sticking on pad

Peeling for low-*k* devices

Stitch Bond

Smaller wire size

Substrate variations

Non-sticking on lead & wire open

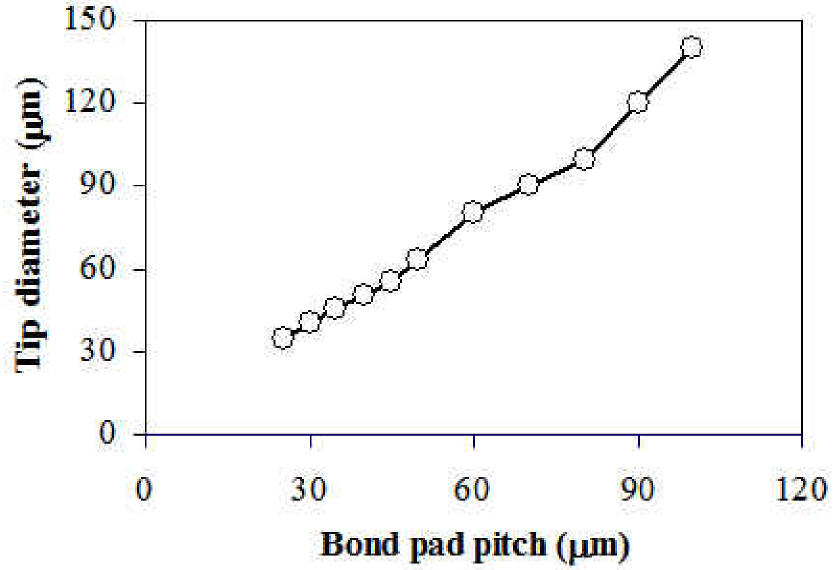
Source: K.S. Goh, Z.W. Zhong, Two capillary solutions for ultra-fine-pitch wire bonding and insulated wire bonding, Microelectronic Engineering 84 (2) (2007) 362-367.

Ultra-fine-pitch wire bonding

- The BPP in volume production was 44 um with wire bonding using ϕ20-um (0.8-mil) wire, although research and development in laboratories can achieve ultra-fine-pitch wire bonding for a much smaller BPP.
- 40-um BPP wire bonding is feasible using ϕ18-um (0.7-mil) wire with good reliability, while using ϕ20-um wire would 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 BPP requires the capillary tip diameter to be reduced significantly.
- The smaller tip diameter of a capillary for a smaller BPP is inevitable to prevent the capillary from any interference with the adjacent wires during wire bonding.

K.S. Goh, Z.W. Zhong, Two capillary solutions for ultra-fine-pitch wire bonding and insulated wire bonding, Microelectronic Engineering 84 (2) (2007) 362-367.

Tip diameters of capillaries versus bond pad pitches



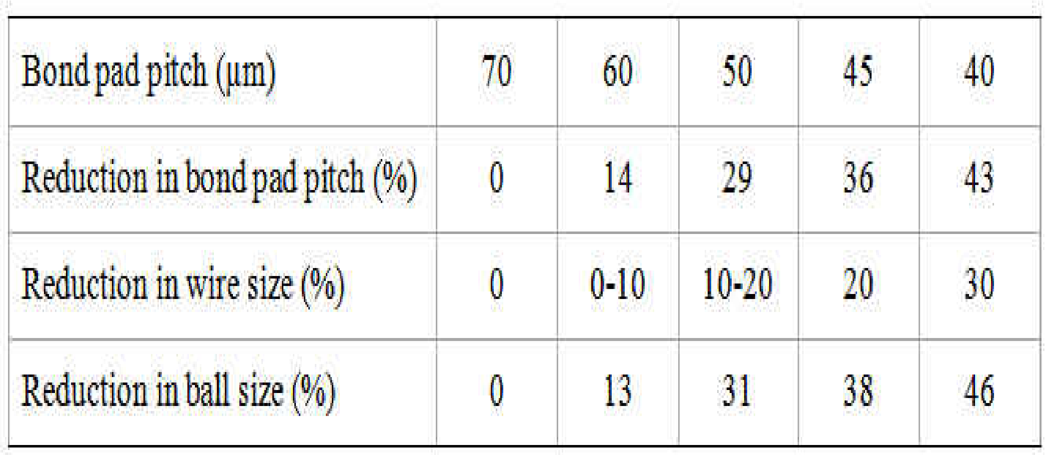
Source: K.S. Goh, Z.W. Zhong, Two capillary solutions for ultra-fine-pitch wire bonding and insulated wire bonding, Microelectronic Engineering 84 (2) (2007) 362-367.

Ultra-fine-pitch 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.
- With a decreased BPP, the wire size, ball size and ball shear decrease, and therefore there are more ball lifts during wire pull tests after aging tests.
- The reduced bondability is a problem.
- The bonding process is sensitive to bonding parameters.
- Non-sticking-on-pad problems may occur very often.

K.S. Goh, Z.W. Zhong, Two capillary solutions for ultra-fine-pitch wire bonding and insulated wire bonding, Microelectronic Engineering 84 (2) (2007) 362-367.

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

Source: K.S. Goh, Z.W. Zhong, Two capillary solutions for ultra-fine-pitch wire bonding and insulated wire bonding, Microelectronic Engineering 84 (2) (2007) 362-367.

Fine and ultra-fine pitch wire bonding

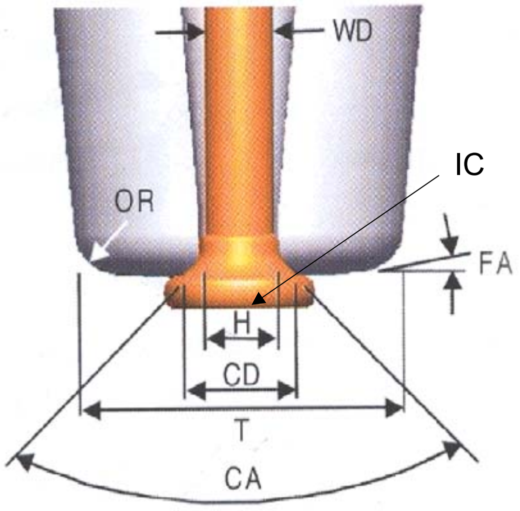
- Advantages
- Challenges/problems
- **Solutions/findings**

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).

K.S. Goh, Z.W. Zhong, Two capillary solutions for ultra-fine-pitch wire bonding and insulated wire bonding, Microelectronic Engineering 84 (2) (2007) 362-367.

Critical dimensions of the bonding tool called the capillary



Source:

K.S. Goh, Z.W. Zhong, Two capillary solutions for ultra-fine-pitch wire bonding and insulated wire bonding, Microelectronic Engineering 84 (2) (2007) 362-367.

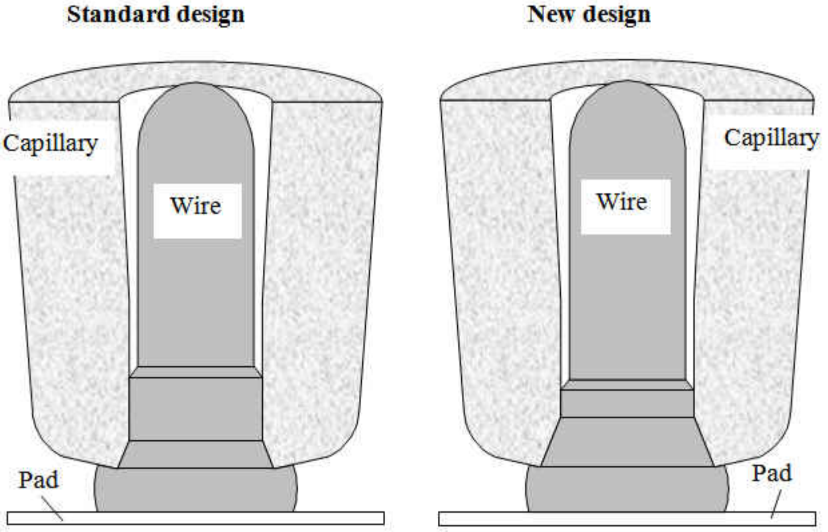
Small Precision Tools, Bonding Capillaries, 04/99-5, 1999.

New capillary design

- 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.
- 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.

K.S. Goh, Z.W. Zhong, Two capillary solutions for ultra-fine-pitch wire bonding and insulated wire bonding, Microelectronic Engineering 84 (2) (2007) 362-367.

Schematic diagrams of standard and new designs of capillaries



Source: K.S. Goh, Z.W. Zhong, Two capillary solutions for ultra-fine-pitch wire bonding and insulated wire bonding, Microelectronic Engineering 84 (2) (2007) 362-367.

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

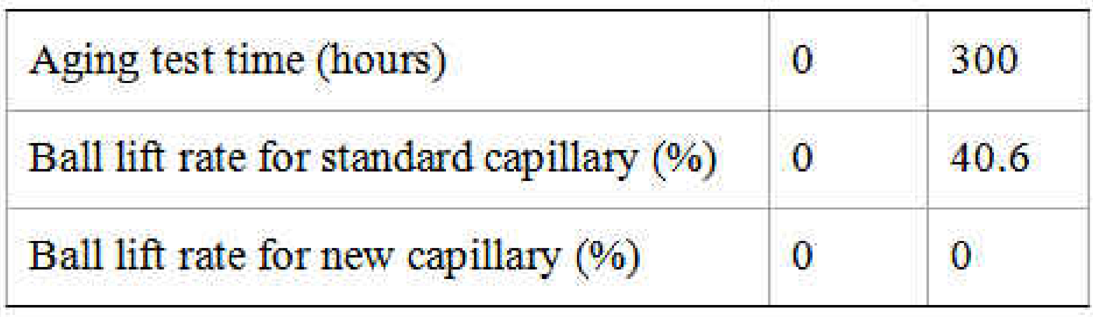
Source: K.S. Goh, Z.W. Zhong, Two capillary solutions for ultra-fine-pitch wire bonding and insulated wire bonding, Microelectronic Engineering 84 (2) (2007) 362-367.

Bonding experiments

- 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-um 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.
- Both the standard and the new capillaries could produce good ball bonds that resulted in 0% ball lift failure before the aging test.
- 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.

K.S. Goh, Z.W. Zhong, Two capillary solutions for ultra-fine-pitch wire bonding and insulated wire bonding, Microelectronic Engineering 84 (2) (2007) 362-367.

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

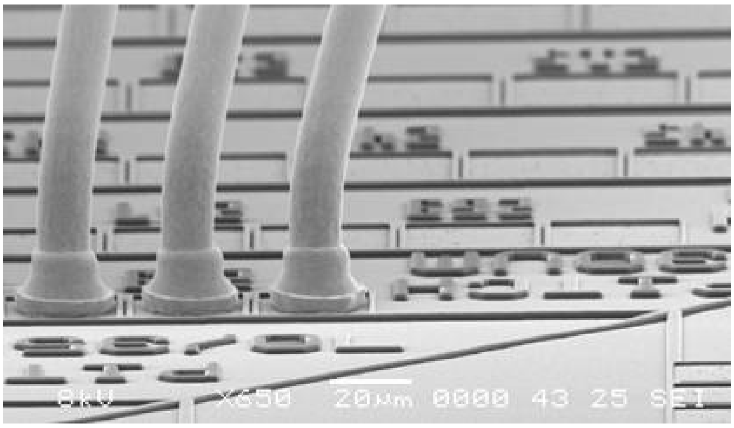


Aging test time (hours)	0	300
Ball lift rate for standard capillary (%)	0	40.6
Ball lift rate for new capillary (%)	0	0

- 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.

Source: K.S. Goh, Z.W. Zhong, Two capillary solutions for ultra-fine-pitch wire bonding and insulated wire bonding, Microelectronic Engineering 84 (2) (2007) 362-367.

Balls bonded using the new capillary, an ASM Eagle wire bonder, ϕ13 μm (0.5 mil) 3N gold wire and BGA devices with a 30-μm BPP



Source: K.S. Goh, Z.W. Zhong, Two capillary solutions for ultra-fine-pitch wire bonding and insulated wire bonding, Microelectronic Engineering 84 (2) (2007) 362-367.

Bonding resuls (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

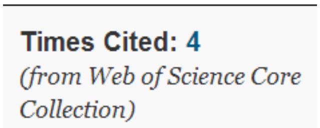
The bonding results meet the standard requirements, which are minimum ball shear = 4.2 gf, minimum ball shear per unit area (shear stress) = 6.0 g/mil^2, and minimum wire pull = 1.6 gf (Mil-Std-883E).

Source: K.S. Goh, Z.W. Zhong, Two capillary solutions for ultra-fine-pitch wire bonding and insulated wire bonding, Microelectronic Engineering 84 (2) (2007) 362-367.

Wire bonding of low-*k* devices

- **Advantages**
- Challenges/problems
- Solutions/findings

Z.W. Zhong, Wire bonding of low-*k* devices, Microelectronics International 25 (3) (2008) 19-25.



Times Cited: 4
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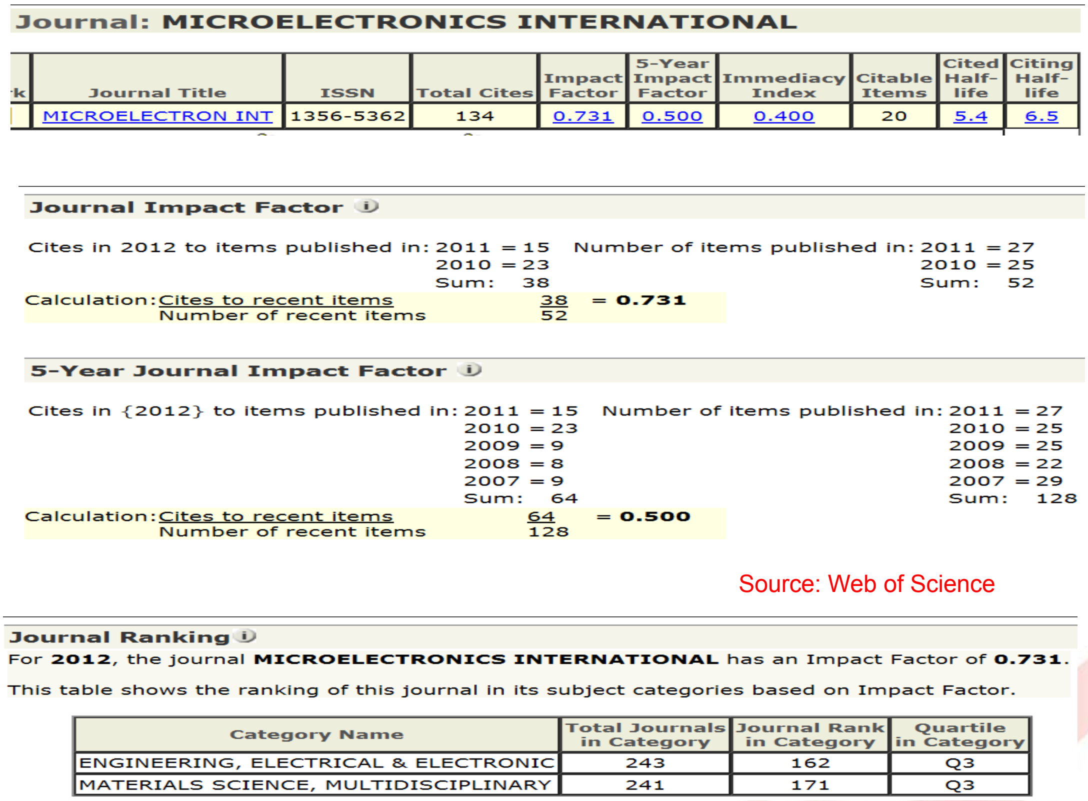
On 28 Feb 2014



Journal: MICROELECTRONICS INTERNATIONAL

k	Journal Title	ISSN	Total Cites	Impact Factor	5-Year Impact Factor	Immediacy Index	Citable Items	Cited Half-life	Citing Half-life
	MICROELECTRON INT	1356-5362	134	0.731	0.500	0.400	20	5.4	6.5

Journal Impact Factor

Cites in 2012 to items published in: 2011 = 15 2010 = 23 Sum: 38

Number of items published in: 2011 = 27 2010 = 25 Sum: 52

Calculation: Cites to recent items / Number of recent items = 38 / 52 = **0.731**

5-Year Journal Impact Factor

Cites in {2012} to items published in: 2011 = 15 2010 = 23 2009 = 9 2008 = 8 2007 = 9 Sum: 64

Number of items published in: 2011 = 27 2010 = 25 2009 = 25 2008 = 22 2007 = 29 Sum: 128

Calculation: Cites to recent items / Number of recent items = 64 / 128 = **0.500**

Source: Web of Science

Journal Ranking

For **2012**, the journal **MICROELECTRONICS INTERNATIONAL** has an Impact Factor of **0.731**.

This table shows the ranking of this journal in its subject categories based on Impact Factor.

Category Name	Total Journals in Category	Journal Rank in Category	Quartile in Category
ENGINEERING, ELECTRICAL & ELECTRONIC	243	162	Q3
MATERIALS SCIENCE, MULTIDISCIPLINARY	241	171	Q3

Advantages of low-*k* devices

- IC chips and microelectronics systems benefit from the size reduction, very often leading to increased functionality at lower costs.
- However, with the further shrinkages of the critical dimensions and the interconnection width, interconnection delay becomes a new bottleneck.
- The permittivity of interconnection insulators has to be reduced to have good circuit performance and limit parasitic coupling effects.

Keser, B. (2007), "Redistributed chip packaging", *Semiconductor International*, Vol. 30 No. 4, pp. SP-3-SP-10.

Vitiello, J., Ducote, V., Farcy, A., Gosset, L.G., Le-Friec, Y., Hopstaken, M., Jullian, S., Cordeau, M., Ailhas, C., Chapelon, L.L. (2006), "New techniques to characterize properties of advanced dielectric barriers for sub-65 nm technology node", *Microelectronic Engineering*, Vol. 83 No. 11-12, pp. 2130-5.

Wang, Z., Du, C., Han, M.C. (2005), "BGA 44um fine pitch low K wire bonding process development", *2005 Conference on High Density Microsystem Design and Packaging and Component Failure Analysis, HDP'05, art. no. 4017420*, pp. 1-6.

Advantages of low-*k* devices

- To meet the demand of lower interconnection delay, porous low-*k* materials are required.
- To reduce the resistance-capacitance delay in very large integrated interconnections, the industry has replaced SiO_2 with a low-*k* dielectric and the Al conductor with Cu.

Hoofman, R.J.O.M., Verheijden, G.J.A.M., Michelon, J., Iacopi, F., Travaly, Y., Baklanov, M.R., Tokei, Z., Beyer, G.P. (2005), "Challenges in the implementation of low-k dielectrics in the back-end of line", *Microelectronic Engineering*, Vol. 80 No., pp. 337-44.

Hsia, C.C. (2006), "The quest of porous ELK materials for high performance logic technologies", *Microelectronic Engineering*, Vol. 83 No. 11-12, pp. 2055-8.

Advantages of low-*k* devices

- The main advantages of using Cu/low-*k* materials are increased chip speed, thinner wires, higher density of the circuitry, better anti-migration performance, fewer wafer-fab-process steps, lower manufacturing cost and improved chip performance.
- Low-*k* liquid crystal polymer substrate also emerges to be a promising material for RF, microwave and millimetre-wave packaging. Its coefficient of thermal expansion can match that of low-*k* chips, which enhances packaging reliability.

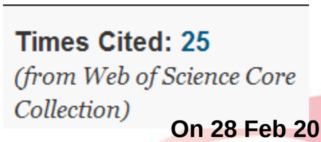
Wang, Z., Du, C., Han, M.C. (2005), "BGA 44um fine pitch low K wire bonding process development", *2005 Conference on High Density Microsystem Design and Packaging and Component Failure Analysis, HDP'05, art. no. 4017420*, pp. 1-6.

Yazdani, F. (2006), "Signal integrity characterization of microwave XFP ASIC BGA package realized on low-K liquid crystal polymer (LCP) substrate", *IEEE Transactions on Advanced Packaging*, Vol. 29 No. 2, pp. 359-63.

Findings from experimental investigations

- A 60-µm BPP wire-bonding process was developed using test chips with a SiO_2 dielectric layer under Al pads, and was then fine-tuned for a low-*k* device.
- It was found that the setting of the variable FAB (free air ball) size for the 2N (99% purity) Au wire should be a lower value than that for the 4N (99.99% purity) Au wires due to its lower melting temperature.
- Compared to the SiO_2 material, the low-*k* material needed longer bond time to overcome the energy loss because of the compliance of the low-*k* material.
- Stiffer wires required higher USG (ultrasonic-generator) power than a softer wire to deform the ball and achieve equivalent ball sizes and ball shear responses.
- The soft 4N wire needed lower USG power to achieve the bonding specification, and was suitable for wire bonding of the low-*k* device.

Tan, J., Zhong, Z.W., Ho, H.M. (2005), "Wire-bonding process development for low-k materials", *Microelectronic Engineering*, Vol. 81 No. 1, pp. 75-82.


Times Cited: 25
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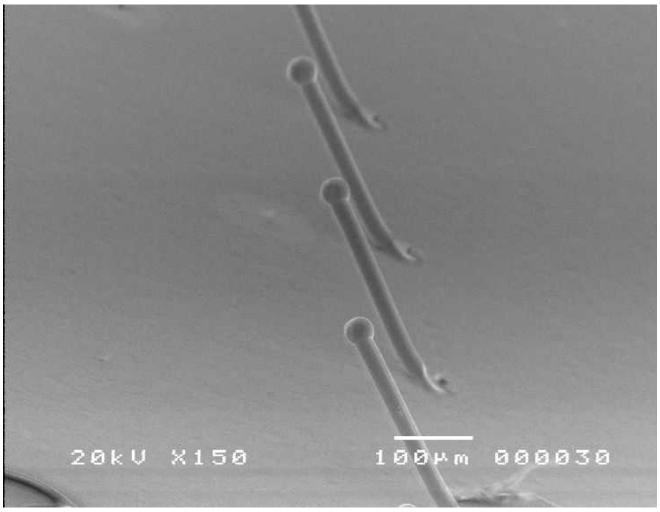
On 28 Feb 2014

Wire-bonding process development for low-k materials

- Free air balls (FABs) were formed using a special process, which allows FABs to be ‘flipped’ over after they were formed at the electronic-flame-off (EFO) cycle and bonded on the pads of leadframes without deforming FABs.
- The bonding was also known as cherry pit bonding.
- The standing FABs formed without any wire interfering with the circumference allowed the magnified image to be measured using an optical microscope equipped with customised vision software.
- The objective of the experiment was to confirm that FABs produced using different wire types were identical before actual process optimisation took place.

Tan, J., Zhong, Z.W., Ho, H.M. (2005), "Wire-bonding process development for low-k materials", *Microelectronic Engineering*, Vol. 81 No. 1, pp. 75-82.

SEM picture of cherry pit bonding



Source: Tan, J., Zhong, Z.W., Ho, H.M. (2005), "Wire-bonding process development for low-k materials", *Microelectronic Engineering*, Vol. 81 No. 1, pp. 75-82.

Wire-bonding process development for low-k materials

- The next experiment involved the 60-μm-BPP process optimisation using test dies with SiO_2. A stiff wire (4N, type 3) was selected for the baseline experiment, as it was the wire used in most fine-pitch applications.
- The objective of the experiment was to identify a set of baseline parameters that could be used for bonding the low-*k* device.
- An experimental matrix was generated for four variables selected.
- The experiment was designed and optimised using a response surface with a quadratic function.
- Finally, the low-*k* device was bonded on 35×35-mm 450-I/O PBGA substrates.
- The low-*k* material with $k = 2.7$ is a thin layer deposited by a chemical vapour deposition process under the aluminium pad.
- The experiment started with type-3 wire (stiff, 4N), followed by types 1 (2N) and 2 (4N).
- The bonding parameters established using type-3 wire were used as a starting point.

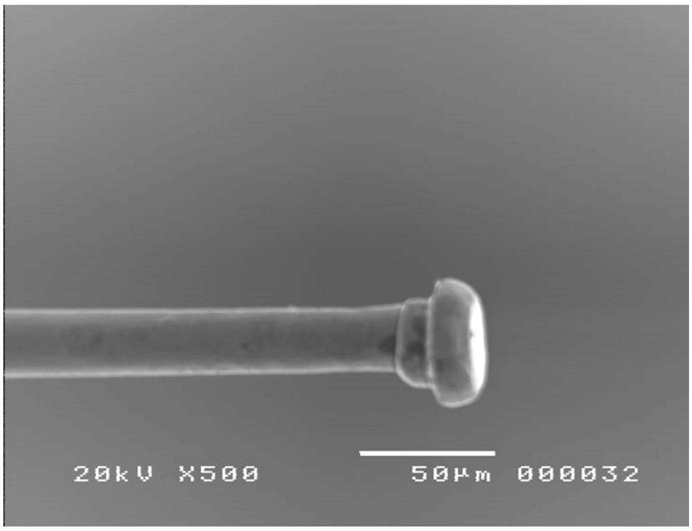
Tan, J., Zhong, Z.W., Ho, H.M. (2005), "Wire-bonding process development for low-k materials", *Microelectronic Engineering*, Vol. 81 No. 1, pp. 75-82.

Wire-bonding process development for low-k materials

- The main objective was first to achieve the ball size and ball shear readings within the specified ranges.
- If the results were not attained, the parameters would be adjusted accordingly. Inter-layer damage would be checked when the above criteria were met.
- The response of inter-layer damage would be studied for the three types of wire.
- FABs were squashed onto bond pads with a capillary to characterise the hardness property of wires.
- To eliminate effects of ultrasonic-generator (USG) power and sticking of smashed balls onto pads, USG parameters and bond force were set to zero and the bonding temperature was set at 100 °C.
- A force of 11.6 g was used to squash FABs, which was the same as the impact force used in bonding of the devices.
- To further emulate the ‘hardness test’ of single impact, the feature “Bump Bond Loop” was used.
- This would prevent the machine from squashing the balls a second time at the second bond location.
- This is because bump bonds are essentially a single bond process.
- Smashed ball diameters were then measured, and equivalent bulk hardness *Hv* was calculated using equations adopted from Vickers hardness test.

Tan, J., Zhong, Z.W., Ho, H.M. (2005), "Wire-bonding process development for low-k materials", *Microelectronic Engineering*, Vol. 81 No. 1, pp. 75-82.

SEM picture of a squashed FAB



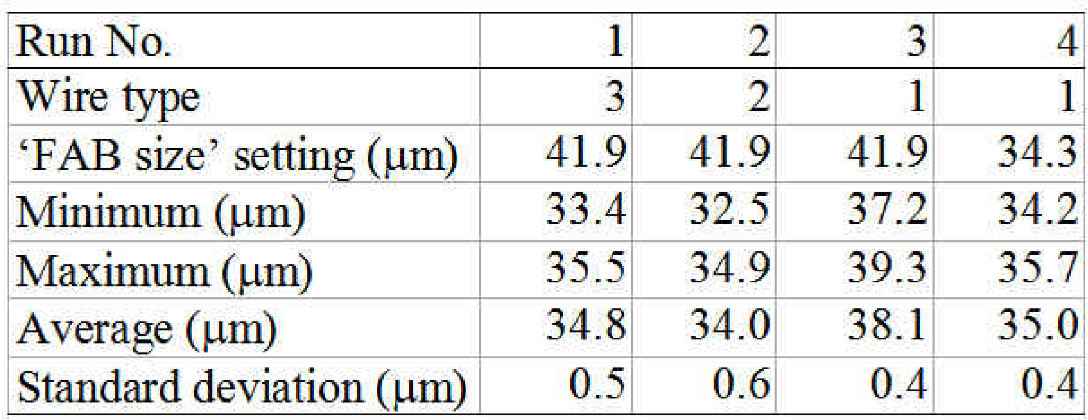
Source: Tan, J., Zhong, Z.W., Ho, H.M. (2005), "Wire-bonding process development for low-k materials", *Microelectronic Engineering*, Vol. 81 No. 1, pp. 75-82.

Wire-bonding process development for low-k materials

- According to a previous study, a heat-affected zone (HAZ) is a product of the plasma heat input during the EFO firing.
- There is a one-to-one monotonic functional relationship between the heat input and the EFO current.
- When the wire is heated by the plasma from the EFO discharge, the free air ball will re-crystallise.
- The hardness of the wire is thus proportional to the inverse of the square root of the grain size.
- The HAZ length is proportional to the temperature during heating, which is related to the EFO current.
- EFO current was kept constant at 30 mA in this experiment.

Tan, J., Zhong, Z.W., Ho, H.M. (2005), "Wire-bonding process development for low-k materials", *Microelectronic Engineering*, Vol. 81 No. 1, pp. 75-82.

Results of FAB measurements



Run No.	1	2	3	4
Wire type	3	2	1	1
'FAB size' setting (μm)	41.9	41.9	41.9	34.3
Minimum (μm)	33.4	32.5	37.2	34.2
Maximum (μm)	35.5	34.9	39.3	35.7
Average (μm)	34.8	34.0	38.1	35.0
Standard deviation (μm)	0.5	0.6	0.4	0.4

Type 1 (2N), Type 2 (4N), Type 3 (stiff, 4N)

Source: Tan, J., Zhong, Z.W., Ho, H.M. (2005), "Wire-bonding process development for low-k materials", *Microelectronic Engineering*, Vol. 81 No. 1, pp. 75-82.

Wire-bonding process development for low-k materials

- The results indicated that the same parameters could not be used for the 2N wire.
- This is because while the 4N wires (types 2 and 3) produced compatible FAB sizes, a larger FAB was formed for the 2N wire.
- This was attributed to its alloy constituents, which lowered the melting temperature that caused more volume of the wire to be melted during the EFO discharge, forming a larger FAB.
- A lower setting value of ‘FAB size’ was used to achieve comparable FAB sizes.
- This variable controls the EFO firing time during the FAB formation of the wire bond cycle.
- Run No. 4 for type-1 wire is the result achieved by using a smaller ‘FAB size’ setting.

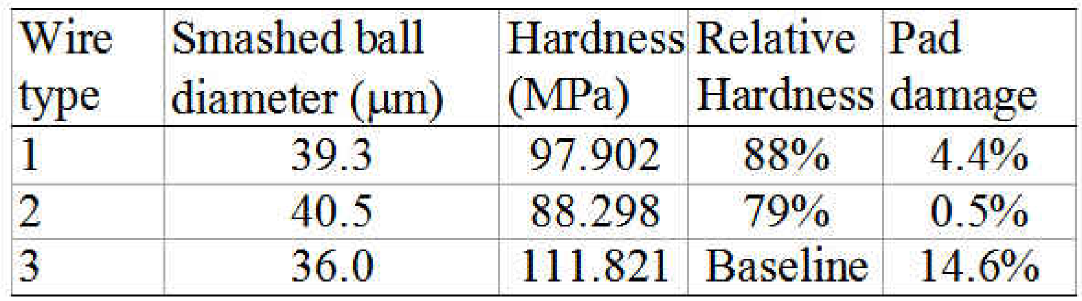
Tan, J., Zhong, Z.W., Ho, H.M. (2005), "Wire-bonding process development for low-k materials", *Microelectronic Engineering*, Vol. 81 No. 1, pp. 75-82.

Wire-bonding process development for low-k materials

- This phenomenon is not typical for all 2N alloys but only for the alloy used in this experiment.
- The alloy compositions of 2N wires strongly influence thermal and mechanical properties of the resultant wires.
- Using DOE with ECHIP® software, the significant variables to the responses were identified.
- Bond force, USG power and bond time were found to be significant in the experiment.
- A set of optimised parameters that best meet the requirements was also found.
- Zero pad-inter-layer damage/peeling had been achieved by the 60-μm-BPP wire bonding process for the device with SiO_2.
- Squashed ball diameters of gold wires were measured.
- Equivalent bulk wire hardness was then calculated.

Tan, J., Zhong, Z.W., Ho, H.M. (2005), "Wire-bonding process development for low-k materials", *Microelectronic Engineering*, Vol. 81 No. 1, pp. 75-82.

Bulk wire hardness and pad damage



Wire type	Smashed ball diameter (μm)	Hardness (MPa)	Relative Hardness	Pad damage
1	39.3	97.902	88%	4.4%
2	40.5	88.298	79%	0.5%
3	36.0	111.821	Baseline	14.6%

Type-3 wire has the highest bulk material hardness while type-2 wire has the lowest among the three wire types.

Source: Tan, J., Zhong, Z.W., Ho, H.M. (2005), "Wire-bonding process development for low-k materials", *Microelectronic Engineering*, Vol. 81 No. 1, pp. 75-82.

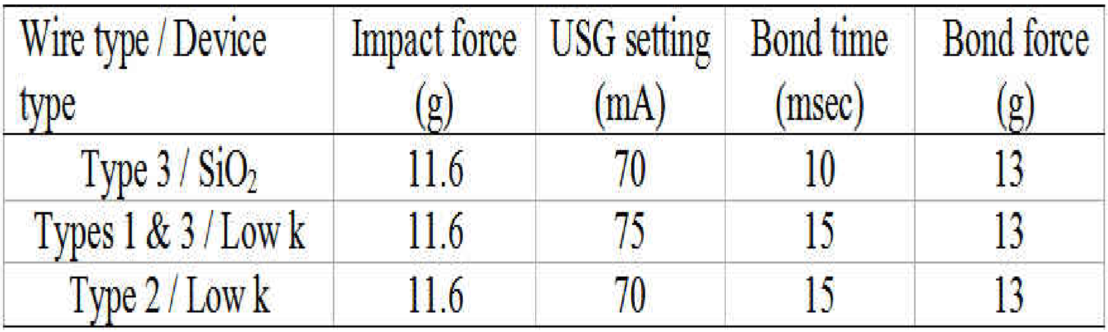
Wire-bonding process development for low-k materials

- The bonding results of the low-*k* device showed that longer bond time was required for all three types of wires than the SiO_2 base-lined device.
- This was due to the low-*k* material being relatively more compliant than SiO_2.
- Longer bond time was needed to overcome the loss of energy to achieve the same bonding quality for the SiO_2 material.
- Type-1 and type-3 wires also required higher USG power to achieve equivalent response to the SiO_2 based device.
- They had higher bulk material hardness than type-2 wire.
- With higher bulk material hardness, higher USG energy was needed.

Type 1 (2N), Type 2 (4N), Type 3 (stiff, 4N)

Tan, J., Zhong, Z.W., Ho, H.M. (2005), "Wire-bonding process development for low-k materials", *Microelectronic Engineering*, Vol. 81 No. 1, pp. 75-82.

Summary of parameter settings used in the DOE tests for devices with the low-*k* material or SiO_2

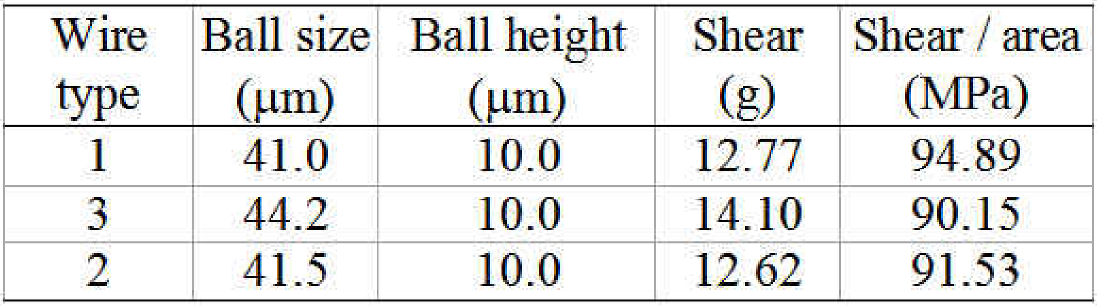


Wire type / Device type	Impact force (g)	USG setting (mA)	Bond time (msec)	Bond force (g)
Type 3 / SiO_2	11.6	70	10	13
Types 1 & 3 / Low k	11.6	75	15	13
Type 2 / Low k	11.6	70	15	13

Type 1 (2N), Type 2 (4N), Type 3 (stiff, 4N)

Source: Tan, J., Zhong, Z.W., Ho, H.M. (2005), "Wire-bonding process development for low-k materials", *Microelectronic Engineering*, Vol. 81 No. 1, pp. 75-82.

Bonding responses



Wire type	Ball size (µm)	Ball height (µm)	Shear (g)	Shear / area (MPa)
1	41.0	10.0	12.77	94.89
3	44.2	10.0	14.10	90.15
2	41.5	10.0	12.62	91.53

Type 1 (2N), Type 2 (4N), Type 3 (stiff, 4N)

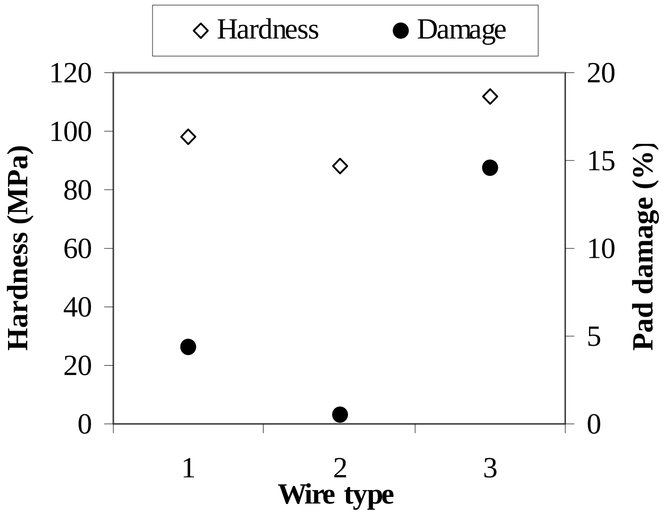
Source: Tan, J., Zhong, Z.W., Ho, H.M. (2005), "Wire-bonding process development for low-k materials", *Microelectronic Engineering*, Vol. 81 No. 1, pp. 75-82.

Wire-bonding process development for low-k materials

- Next, to assess the pad structure, a cratering inspection test was performed.
- The bonded devices were etched with KOH solution for 20 minutes.
- The solution dissolved Al pads allowing bonded balls to be removed without disturbing the dielectric layers.
- 450 bonded pads were checked for any damage using an optical microscope.
- A graph was also plotted to relate bulk wire hardness to inter-layer damage.
- The results revealed that type-2 wire caused negligible damage to the layer under the Al pad.

Tan, J., Zhong, Z.W., Ho, H.M. (2005), "Wire-bonding process development for low-k materials", *Microelectronic Engineering*, Vol. 81 No. 1, pp. 75-82.

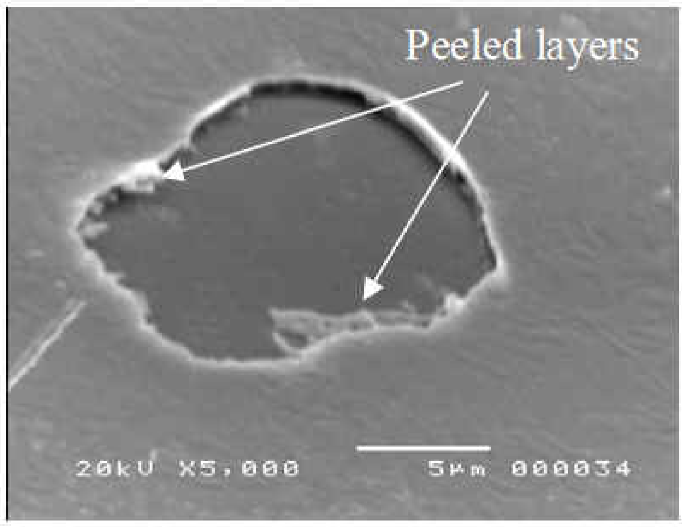
Bulk hardness and pad damage in percentage



Type 1 (2N), Type 2 (4N), Type 3 (stiff, 4N)

Source: Tan, J., Zhong, Z.W., Ho, H.M. (2005), "Wire-bonding process development for low-k materials", *Microelectronic Engineering*, Vol. 81 No. 1, pp. 75-82.

Etched bond pads on the low-*k* device bonded with type-1 wire

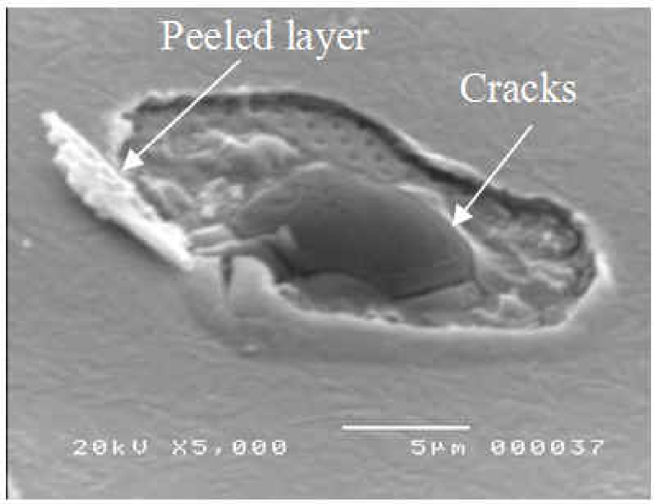


- There was peeling of inter-layers under the Al pad for samples bonded with type-1 wire.
- Two layers of the material peeled off after KOH etching.

Type 1 (2N)

Source: Tan, J., Zhong, Z.W., Ho, H.M. (2005), "Wire-bonding process development for low-k materials", *Microelectronic Engineering*, Vol. 81 No. 1, pp. 75-82.

Etched bond pads on the low-*k* device bonded with type-3 wire

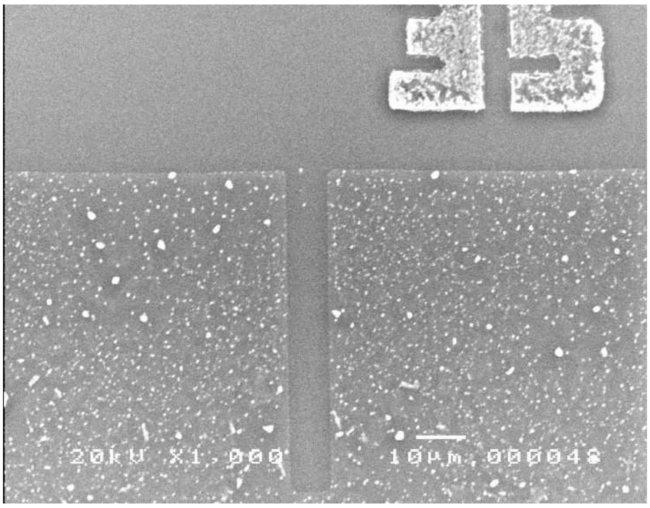


- It illustrates damage of inter-layers for a sample bonded with type-3 wire.
- Its failure mode was different from that observed in the previous figure.
- Cracks were observed beneath the peeled material.

Type 3 (stiff, 4N)

Source: Tan, J., Zhong, Z.W., Ho, H.M. (2005), "Wire-bonding process development for low-k materials", *Microelectronic Engineering*, Vol. 81 No. 1, pp. 75-82.

Etched bond pads on the base-lined SiO_2 device bonded with type-3 wire

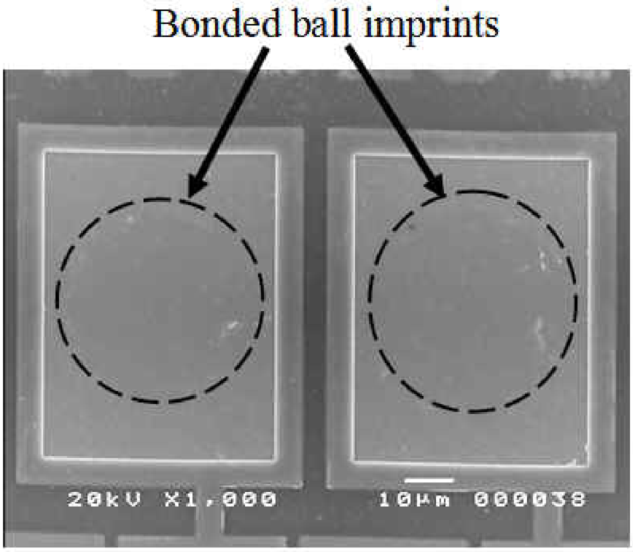


Type 3 (stiff, 4N)

- •A reference is shown with KOH solution etching of the base-lined SiO_2 device bonded with type-3 wire.
- •Compared to the low-*k* device, the USG energy needed to achieve the required responses for the baseline SiO_2 material was also lower.

Source: Tan, J., Zhong, Z.W., Ho, H.M. (2005), "Wire-bonding process development for low-k materials", *Microelectronic Engineering*, Vol. 81 No. 1, pp. 75-82.

Etched bond pads on the low-*k* device bonded with type-2 wire



- •There were only light imprints on the etched surfaces, which indicated that the pads had been bonded.
- •No cracks or delamination of inter-layers were observed on the pads.

Type 2 (4N)

Source: Tan, J., Zhong, Z.W., Ho, H.M. (2005), "Wire-bonding process development for low-k materials", *Microelectronic Engineering*, Vol. 81 No. 1, pp. 75-82.

Wire-bonding process development for low-k materials

- From these findings, pad damage on the low-*k* device was proportional to bulk material hardness of the wire used.
- According to a finite element analysis, stress concentration was found near the perimeters of bonded balls.
- Hence, the material failed at the area with the highest stress concentration.

Tan, J., Zhong, Z.W., Ho, H.M. (2005), "Wire-bonding process development for low-k materials", *Microelectronic Engineering*, Vol. 81 No. 1, pp. 75-82.

Wire-bonding process development for low-k materials

- Bonding on low-*k* devices was investigated with 3 types of gold wires with different mechanical properties.
- Type 3 wire was the hardest among the 3 types of wires, about 21% harder than type 2 wire.
- The setting of the variable 'FAB size' for the 2N wire should be a lower value than the 4N wires due to its lower melting temperature.
- Stiffer wires needed higher USG power than a softer wire to deform the ball after impact and achieve equivalent ball size and ball shear responses.
- Longer bond time was also needed for the low-*k* material compared to the SiO_2 material, to overcome the energy loss due to the compliance of the low-*k* material.
- Pad damage on the low-*k* device was proportional to bulk material hardness.
- The soft 4N wire required lower USG power to achieve the bonding specification, and was the most suitable wire to be used for wire bonding of the low-*k* device.

Type 1 (2N), Type 2 (4N), Type 3 (stiff, 4N)

Tan, J., Zhong, Z.W., Ho, H.M. (2005), "Wire-bonding process development for low-k materials", *Microelectronic Engineering*, Vol. 81 No. 1, pp. 75-82.

Solutions

- Although wire bonding has been a well-established technology for many years, the bonding tool design becomes more complex and the process is very sensitive for wire bonding of low-*k* ultra-fine-pitch devices.
- Two different types of external transition profile were considered in order to use lower ultrasonic-generator power for preventing pad damage.
- The ultrasonic vibration displacements of the capillaries were measured using a laser interferometer.
- To solve the ball lift (non-sticking) problem for wire bonding of low-*k* ultra-fine-pitch devices, optimization of the capillary internal profile was attempted to improve bondability and increase the percentage of the intermetallic compound in the bond interface.
- Actual wire bonding experiments were also conducted to test the capillary designs.

K.S. Goh, and Zhong Z.W., "Development of capillaries for wire bonding of low-*k* ultra-fine-pitch devices," Microelectronic Engineering, Vol. 83, No. 10, 2006, pp. 2009-2014.

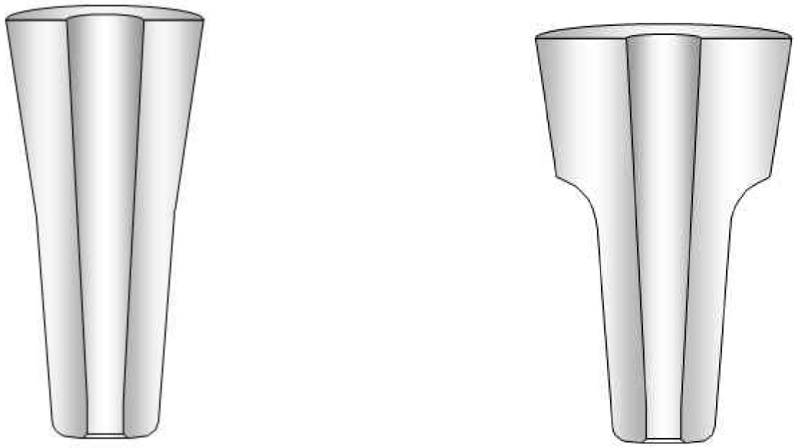
Times Cited: 9
(from Web of Science Core Collection) **On 28 Feb 2014**

Solutions

- For wire bonding of low-*k* ultra-fine-pitch devices, lower ultrasonic-generator power is needed to prevent pad damage.
- Optimization of the external profile of a capillary can make the capillary more efficient to transfer ultrasonic vibrations in the preferred direction with lower ultrasonic-generator power.
- A capillary is a tiny hollow tube used to guide the wire and create ball and stitch bonds.
- Capillaries with "bottlenecks" are used in fine and ultra-fine pitch bonding because their slim profile near the tip prevents contact with adjacent wires. The overall cone angle is referred to as the main taper angle.
- The minimum bottleneck angle is set to avoid contact with adjacent wires.
- Two different types of transition profile were considered.
- The difference between the two capillaries is the transition between the bottleneck angle and the main taper angle.
- All other dimensions of Capillaries A and B are the same except for the transition.
- Capillary A has a sharp transition between the main taper angle and the bottleneck angle, while Capillary B has a small radius transition.

K.S. Goh, and Zhong Z.W., "Development of capillaries for wire bonding of low-*k* ultra-fine-pitch devices," Microelectronic Engineering, Vol. 83, No. 10, 2006, pp. 2009-2014.

A sharp transition vs. B small radius transition



Source: K.S. Goh, and Zhong Z.W., “Development of capillaries for wire bonding of low-*k* ultra-fine-pitch devices,” Microelectronic Engineering, Vol. 83, No. 10, 2006, pp. 2009-2014.

Study the ultrasonic displacement of the capillary

- A robust wire-bond process with a defined operating window is important.
- The only way to observe this was inspecting and testing after wire bonding.
- This situation can be improved by incorporating a laser vibrometer as a monitoring system to study the ultrasonic displacement of the capillary during wire bonding.
- Laser interferometry was used to measure the vibration amplitude at the capillary tips and investigate the vibration characteristics of each design.
- A laser Doppler vibrometer is an optical instrument that employs laser interferometric principles to measure velocity and displacement of points on a vibrating structure.
- The mobile unit of the laser vibrometer, which included a camera, a scanning unit, and an optical sensor head, was mounted onto a tripod.
- The laser beam from the optical sensor head was directed perpendicularly to a vibrating capillary.
- With the reflection from the vibrating capillary, the laser beam travelled back towards the mobile unit and was detected by the sensor head.
- An electronic signal processor in the vibrometer then demodulated the signal.
- Using an FFT algorithm, the vibrometer software converted the velocity of the transverse vibration to displacement amplitude.

K.S. Goh, and Zhong Z.W., “Development of capillaries for wire bonding of low-*k* ultra-fine-pitch devices,” Microelectronic Engineering, Vol. 83, No. 10, 2006, pp. 2009-2014.

Vibration behaviour of the capillary

- A decisive factor for the electrical and mechanical properties of the wire bond is the vibration behaviour of the capillary, which transmits the ultrasonic energy from the transducer to the interface of the bonding media.
- The ultrasonic displacement causes the capillary to vibrate in a back and forth manner or sinusoidal motion.
- Using the laser vibrometer to investigate the vibration characteristics of capillaries has provided valuable information in understanding and improving the performance of capillaries.
- Comparative analysis was conducted to investigate the ultrasonic energy transfer performance of Capillaries A and B.
- Design optimization of Capillary B was performed based on the vibration measurement results followed by wire bonding tests.
- The main objective of such design optimization was to provide consistent and efficient ultrasonic energy transfer to the tip of the capillary in the preferred direction.

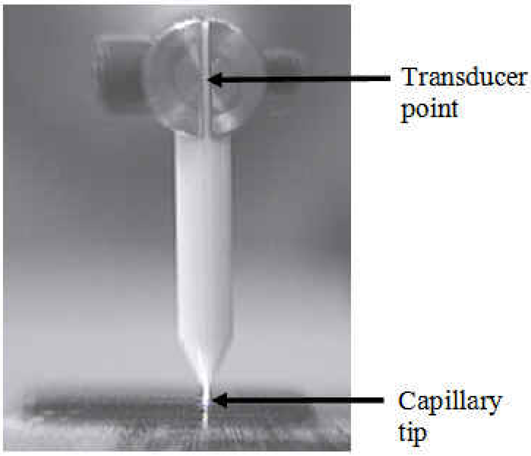
K.S. Goh, and Zhong Z.W., “Development of capillaries for wire bonding of low-*k* ultra-fine-pitch devices,” Microelectronic Engineering, Vol. 83, No. 10, 2006, pp. 2009-2014.

Ultrasonic vibration performance of Capillaries A and B

Capillary	Displacement at transducer point (nm)	Displacement at capillary tip (nm)	Amplification factor
A	183	353	1.93
B	186	491	2.64

- The amplification factor (the ratio of the vibration displacement at the capillary tip to that at the transducer point) of Capillary B is 37% higher than that of Capillary A.
- This is because the specially designed external profile of Capillary B amplifies more amount of ultrasonic vibration to its tip than the slim-line bottleneck Capillary A.

Source: K.S. Goh, and Zhong Z.W., “Development of capillaries for wire bonding of low-*k* ultra-fine-pitch devices,” Microelectronic Engineering, Vol. 83, No. 10, 2006, pp. 2009-2014.



Actual bonding responses

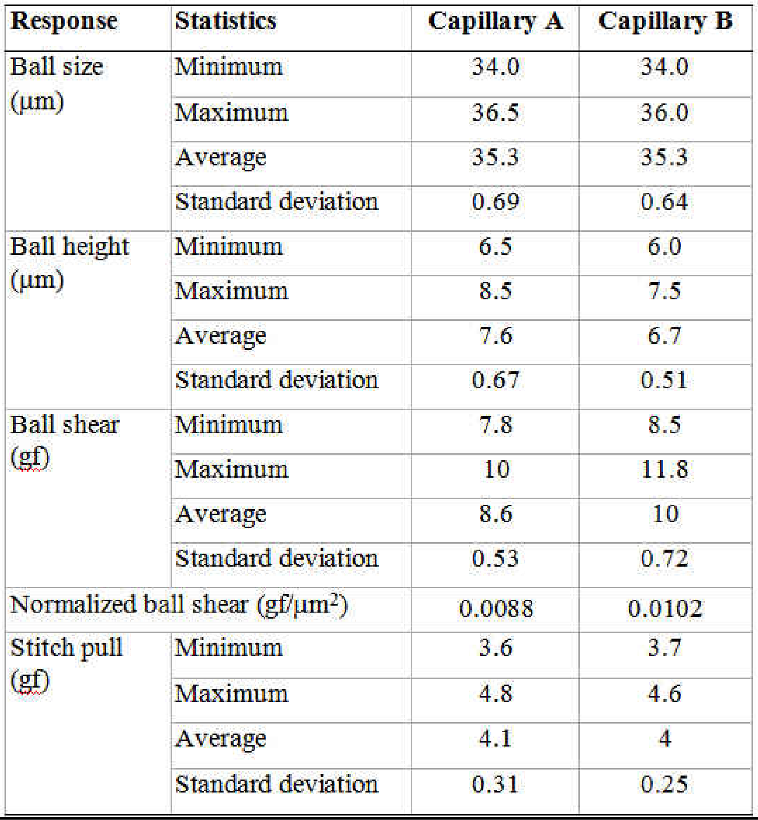
- Actual bonding responses were tested using 45-um BPP BGA devices, 20-um gold wire, and an ASM Eagle 60 wire bonder with ultrasonic-generator power = 52 mW and 115 mW for Capillary A, and 39 mW and 90 mW for Capillary B for first and send bonds, respectively.
- Ball shear strength and stitch pull tests were performed after wire bonding.
- The normalized ball shear strength, which is the ball shear per unit area of the ball size, is computed.

K.S. Goh, and Zhong Z.W., "Development of capillaries for wire bonding of low-*k* ultra-fine-pitch devices," Microelectronic Engineering, Vol. 83, No. 10, 2006, pp. 2009-2014.

Comparison of actual bonding responses for Capillaries A and B

- Capillary B produced satisfactory results in terms of all four measures (ball size, ball height, ball shear and stitch pull).
- In contrast, Capillary A would require more ultrasonic power (52 mW for Capillary A compared to 39 mW for Capillary B) to achieve the same first bond integrity.

Source: K.S. Goh, and Zhong Z.W., "Development of capillaries for wire bonding of low-*k* ultra-fine-pitch devices," Microelectronic Engineering, Vol. 83, No. 10, 2006, pp. 2009-2014.



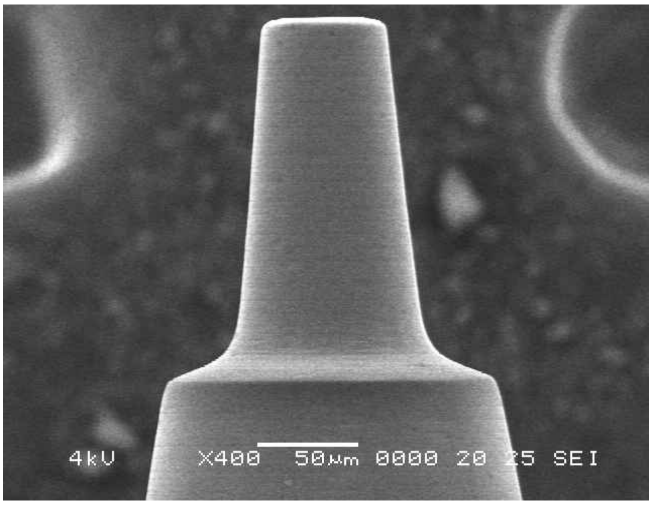
Response	Statistics	Capillary A	Capillary B
Ball size (µm)	Minimum	34.0	34.0
	Maximum	36.5	36.0
	Average	35.3	35.3
	Standard deviation	0.69	0.64
Ball height (µm)	Minimum	6.5	6.0
	Maximum	8.5	7.5
	Average	7.6	6.7
	Standard deviation	0.67	0.51
Ball shear (gf)	Minimum	7.8	8.5
	Maximum	10	11.8
	Average	8.6	10
	Standard deviation	0.53	0.72
Normalized ball shear (gf/μm^2)		0.0088	0.0102
Stitch pull (gf)	Minimum	3.6	3.7
	Maximum	4.8	4.6
	Average	4.1	4
	Standard deviation	0.31	0.25

Bottlenecks

- Currently, most of the capillaries used in the microelectronics industry are ground to shape.
- This grinding process, however, limits the repeatability, accuracy and wall thickness consistency of the capillary taper, resulting in a weakened bottleneck taper.
- It generates stresses in the ceramic material and creates initial micro-fractures that proliferate during wire bonding.
- ThUS, the ceramic injection molding technology has been utilized to mold the capillaries, which provides stronger bottlenecks because no grinding stresses are generated.
- Capillary B was manufactured by injection molding followed by a special ultra-precision finishing process.

K.S. Goh, and Zhong Z.W., "Development of capillaries for wire bonding of low-*k* ultra-fine-pitch devices," Microelectronic Engineering, Vol. 83, No. 10, 2006, pp. 2009-2014.

Capillary B manufactured by injection molding followed by a special ultra-precision finishing process



Source: K.S. Goh, and Zhong Z.W., "Development of capillaries for wire bonding of low-*k* ultra-fine-pitch devices," Microelectronic Engineering, Vol. 83, No. 10, 2006, pp. 2009-2014.

Optimization of the capillary internal profile

- To solve the ball lift problem for wire bonding of low-*k* ultra-fine-pitch devices, optimization of the capillary internal profile was tried to improve bondability and increase the percentage of the intermetallic compound in the bond interface.
- Besides wire diameter (WD), free air ball (FAB), bonding force, and ultrasonic vibration amplitude, critical capillary dimensions can also affect the wire-bond formation.
- The critical dimensions include hole diameter (H), chamfer diameter (CD), chamfer angle (CA), face angle (FA), inner chamfer (IC), outer radius (OR), and tip diameter (T).

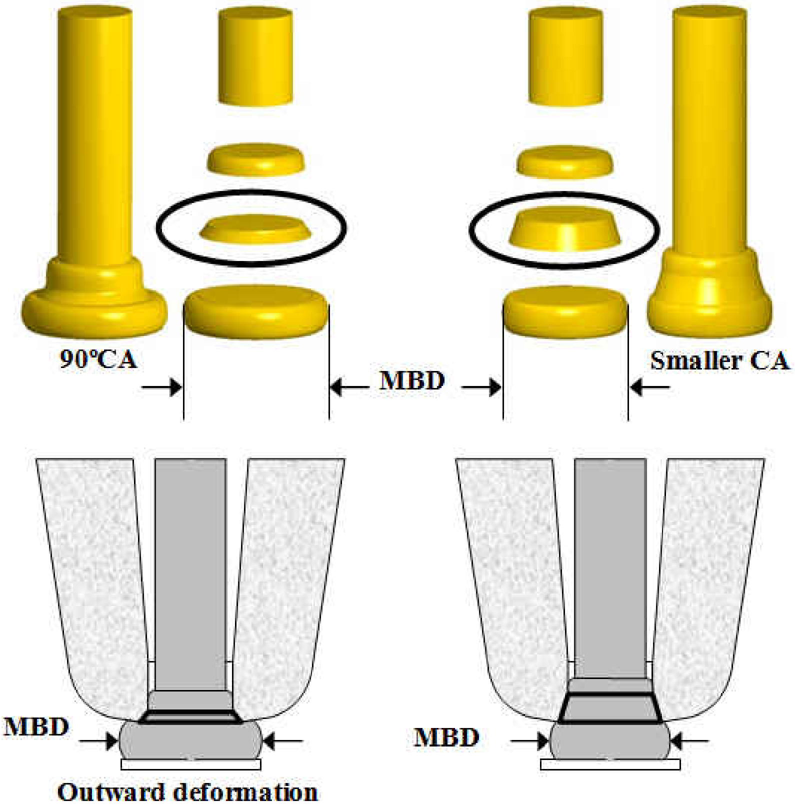
K.S. Goh, and Zhong Z.W., “Development of capillaries for wire bonding of low-*k* ultra-fine-pitch devices,” Microelectronic Engineering, Vol. 83, No. 10, 2006, pp. 2009-2014.

Effect of chamfer shape

- Analysis has revealed that chamfer angle, inner chamfer and chamfer diameter of a capillary have significant effects on the ball deformation.
- A smaller chamfer angle and a larger inner chamfer could reduce the meshed ball diameter (MBD) by 12%.
- The combined effect of a smaller chamfer angle, a larger inner chamfer and a larger chamfer diameter could result in a smaller ball size by containing the amount of gold inside the capillary during impact and eventually restricting the gold squashed out during the bonding process, which was proved by actual bonding results.
- About 40% of the free air ball was contained within the inner chamfer.

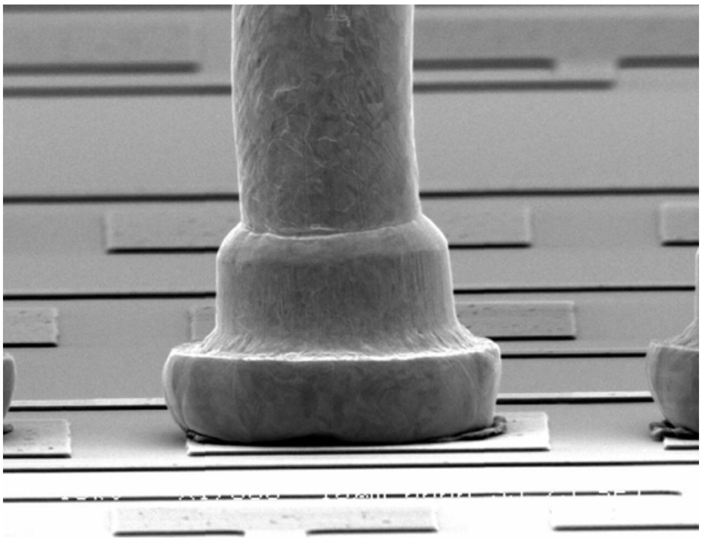
K.S. Goh, and Zhong Z.W., “Development of capillaries for wire bonding of low-*k* ultra-fine-pitch devices,” Microelectronic Engineering, Vol. 83, No. 10, 2006, pp. 2009-2014.

Effects of smaller chamfer angle (CA) and larger inner chamfer (IC) with the same chamfer diameter, hole diameter, wire diameter and free air ball



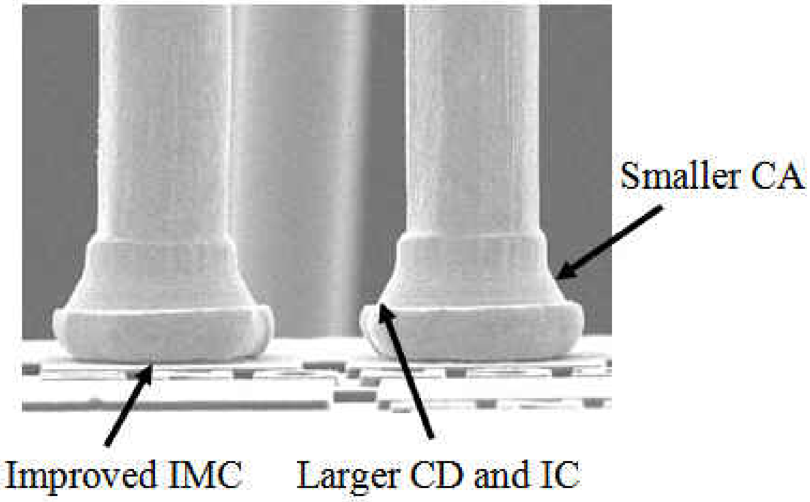
Source: K.S. Goh, and Zhong Z.W., "Development of capillaries for wire bonding of low-*k* ultra-fine-pitch devices," Microelectronic Engineering, Vol. 83, No. 10, 2006, pp. 2009-2014.

SEM picture of a reference ball bond produced using a standard capillary



Source: K.S. Goh, and Zhong Z.W., "Development of capillaries for wire bonding of low-*k* ultra-fine-pitch devices," Microelectronic Engineering, Vol. 83, No. 10, 2006, pp. 2009-2014.

SEM picture of two ball bonds produced using a capillary with a smaller chamfer angle, a larger inner chamfer and a larger chamfer diameter



Source: K.S. Goh, and Zhong Z.W., "Development of capillaries for wire bonding of low-*k* ultra-fine-pitch devices," Microelectronic Engineering, Vol. 83, No. 10, 2006, pp. 2009-2014.

Bonding responses

- Actual bonding responses were tested using 45-um BPP BGA devices, 20-um gold wire with ultrasonic-generator power = 85 mW for first bonds.
- Capillaries C and D were tested and the differences between the two capillaries were the internal profile dimensions.
- The second-bond power setting was 100mW for using both Capillaries C and D because they had the same external profile, which was not the same as that of Capillary B.
- Capillary C had chamfer diameter = 28 um, a standard chamfer angle, and inner chamfer = 2 um, while Capillary D had chamfer diameter = 30 um, a smaller chamfer angle, and inner chamfer = 3 um.

K.S. Goh, and Zhong Z.W., "Development of capillaries for wire bonding of low-*k* ultra-fine-pitch devices," Microelectronic Engineering, Vol. 83, No. 10, 2006, pp. 2009-2014.

Comparison of actual bonding responses obtained using Capillaries C and D

Capillary D produced better or at least equivalent results on all four measures (ball size, ball height, ball shear and wire pull).

Source: K.S. Goh, and Zhong Z.W., “Development of capillaries for wire bonding of low-*k* ultra-fine-pitch devices,” Microelectronic Engineering, Vol. 83, No. 10, 2006, pp. 2009-2014.

Response	Statistics	Capillary C	Capillary D
Ball size (µm) Sample size: 20 Specification: 35±2	Minimum	34.6	34.5
	Maximum	36.8	35.6
	Average	35.8	34.9
Ball height (µm) Sample size: 10 Specification: 7-11 µm	Minimum	7.5	8.5
	Maximum	8.9	10.6
	Average	8.2	9.3
Ball shear (gf) Sample size: 45 Specification: Min. 9 gf	Minimum	10.1	10.4
	Maximum	11.6	12.6
	Average	10.9	11.5
Normalized ball shear (gf/µm^2)		0.0108	0.0120
Stitch pull (gf) Sample size: 45 Specification: Min. 3 gf	Minimum	6.0	6.2
	Maximum	7.2	7.1
	Average	6.4	6.5

Aging test

- An aging test was performed to evaluate the bonding reliability.
- The aging-test conditions were 175°C with responses taken at 0, 24 and 96 hours.
- No metal pad peeling was observed.
- No ball lift was observed for the wire bonds produced by Capillary D, while there was one ball lift failure for the wire bonds produced by Capillary C after 96 h of the aging test.

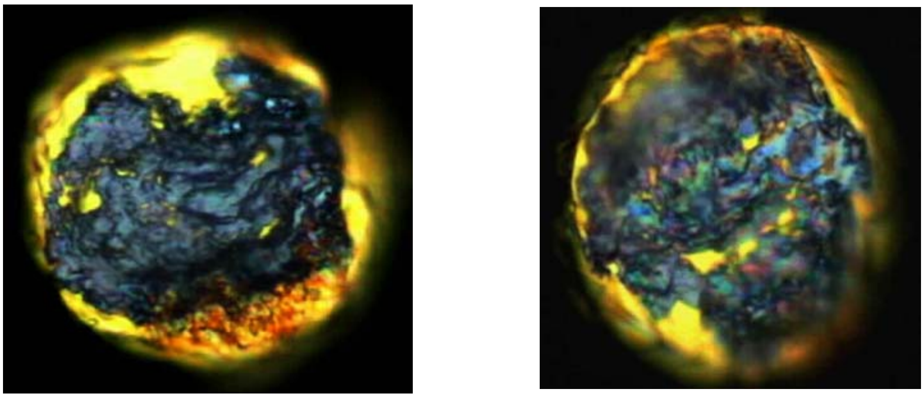
K.S. Goh, and Zhong Z.W., “Development of capillaries for wire bonding of low-*k* ultra-fine-pitch devices,” Microelectronic Engineering, Vol. 83, No. 10, 2006, pp. 2009-2014.

Comparison of aging test results of the wire bonds produced by Capillaries C and D

Aging test time (h)	Failure count for Capillary C	Failure count for Capillary D
0	0/24	0/24
24	0/24	0/24
96	1/24 (Ball lift)	0/24

Source: K.S. Goh, and Zhong Z.W., “Development of capillaries for wire bonding of low-*k* ultra-fine-pitch devices,” Microelectronic Engineering, Vol. 83, No. 10, 2006, pp. 2009-2014.

Intermetalic compounds produced using Capillaries C (a) and D (b)



(a) (b)

Source: K.S. Goh, and Zhong Z.W., “Development of capillaries for wire bonding of low-*k* ultra-fine-pitch devices,” Microelectronic Engineering, Vol. 83, No. 10, 2006, pp. 2009-2014.

Intermetallic compounds

- It can be seen that Capillary D resulted in a larger percentage of the intermetallic compound than Capillary C.
- This percentage difference of the intermetallic compounds explains why there was one ball lift failure for the wire bonds produced by Capillary C but not by Capillary D after 96 h of the aging test.
- The design has proven to improve the ball bondability and achieve small-ball-size control for low-*k* ultra-fine-pitch bonding.

K.S. Goh, and Zhong Z.W., “Development of capillaries for wire bonding of low-*k* ultra-fine-pitch devices,” Microelectronic Engineering, Vol. 83, No. 10, 2006, pp. 2009-2014.

Findings from experimental investigations

- External transition profiles were investigated for using lower USG power to prevent low-*k* pad damage.
- The results revealed that the ratio of the vibration displacement at the capillary tip to that at the transducer point of a capillary with a small radius transition between the main taper and bottleneck angles was 37% higher than that of a capillary with a sharp transition.
- This resulted in satisfactory results in terms of ball shear, ball size, ball height, and stitch pull.

Goh, K.S., Zhong, Z.W. (2006), "Development of capillaries for wire bonding of low-k ultra-fine-pitch devices", *Microelectronic Engineering*, Vol. 83 No. 10, pp. 2009-14.

Findings from experimental investigations

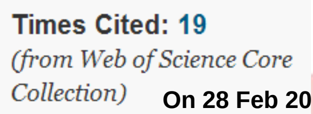
- To solve the ball lift problem for wire bonding of low-*k* ultra-fine-pitch devices, optimization of the capillary internal profile was also attempted to improve bondability.
- Compared to a standard design, a capillary with a smaller chamfer angle, a larger inner chamfer and a larger chamfer diameter could increase the percentage of the intermetallic compound in the bond interface.
- As a result, metal pad peeling and ball lift failures were not observed for the bonded low-*k* ultra-fine-pitch devices after an aging test.

Goh, K.S., Zhong, Z.W. (2006), "Development of capillaries for wire bonding of low-k ultra-fine-pitch devices", *Microelectronic Engineering*, Vol. 83 No. 10, pp. 2009-14.

Copper wire bonding

- – **Advantages**
- – Challenges/problems
- – Solutions/findings

Z.W. Zhong, Wire bonding using copper wire, Microelectronics International 26 (1) (2009) 10-16.



Times Cited: 19

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On 28 Feb 2014

Advantages of wire bonding using copper wire

- Gold wire has been the most widely used wire in wire bonding.
- In recent years the price of Au has greatly increased, fueling the demand for high-volume wire bonding using Cu wire, which can lead to significant cost savings due to lower raw material cost.
- Copper is not subject to sudden price fluctuations in the market.
- The price of copper wire is 10-40% of that of gold wire.

Chen, H., Lee, S.W.R., Ding, Y. (2006), "Evaluation of bondability and reliability of single crystal copper wire bonding", *2005 Conference on High Density Microsystem Design and Packaging and Component Failure Analysis, HDP'05*.

England, L., Jiang, T. (2007), "Reliability of Cu wire bonding to Al metallization", *Proceedings - Electronic Components and Technology Conference*, pp. 1604-13.

Hong, S., Hang, C., Wang, C. (2005), "Experimental research of copper wire ball bonding", *2005 6th International Conference on Electronics Packaging Technology*.

Tian, Y.H., Lum, I., Won, S.J., Park, S.H., Jung, J.P., Mayer, M., Zhou, Y. (2005), "Experimental study of ultrasonic wedge bonding with copper wire", *2005 6th International Conference on Electronics Packaging Technology*.

Advantages of wire bonding using copper wire

- Copper wires have better thermal and electrical properties than gold wires.
- Copper is about 25% more conductive than gold, 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 copper wire to accommodate smaller pad sizes.
- Higher electrical conductivity leads to less heat generation and a higher speed.

Chen, H., Lee, S.W.R., Ding, Y. (2006), "Evaluation of bondability and reliability of single crystal copper wire bonding", *2005 Conference on High Density Microsystem Design and Packaging and Component Failure Analysis, HDP'05*.

England, L., Jiang, T. (2007), "Reliability of Cu wire bonding to Al metallization", *Proceedings - Electronic Components and Technology Conference*, pp. 1604-13.

Ratchev, P., Stoukatch, S., Swinnen, B. (2006), "Mechanical reliability of Au and Cu wire bonds to Al, Ni/Au and Ni/Pd/Au capped Cu bond pads", *Microelectronics Reliability*, Vol. 46 No. 8, pp. 1315-25.

Tian, Y.H., Lum, I., Won, S.J., Park, S.H., Jung, J.P., Mayer, M., Zhou, Y. (2005), "Experimental study of ultrasonic wedge bonding with copper wire", *2005 6th International Conference on Electronics Packaging Technology*.

Advantages of wire bonding using copper wire

- Copper wires have excellent ball neck strength after the ball formation process.
- The higher stiffness of copper wires is more suitable to fine pitch bonding than that of gold wires.
- Copper wire can be directly bonded on bare Cu lead frames and BGA substrates, saving cost and time because of elimination of the plating process.

Chen, H., Lee, S.W.R., Ding, Y. (2006), "Evaluation of bondability and reliability of single crystal copper wire bonding", *2005 Conference on High Density Microsystem Design and Packaging and Component Failure Analysis, HDP'05*.

Goh, K.S., Zhong, Z.W. (2007), "A new bonding-tool solution to improve stitch bondability", *Microelectronic Engineering*, Vol. 84 No. 1, pp. 173-9.

Hong, S., Hang, C., Wang, C. (2005), "Experimental research of copper wire ball bonding", *2005 6th International Conference on Electronics Packaging Technology*.

Tian, Y.H., Lum, I., Won, S.J., Park, S.H., Jung, J.P., Mayer, M., Zhou, Y. (2005), "Experimental study of ultrasonic wedge bonding with copper wire", *2005 6th International Conference on Electronics Packaging Technology*.

Advantages of wire bonding using copper wire

- High stiffness and high loop stability of Cu wire result in better wire sweep performance during molding or encapsulation for fine pitch devices, and can help to achieve longer/lower loop profiles.
- Copper has higher stiffness than gold, leading to better looping control and less wire sagging for fine pitch and ultra-fine pitch wire bonding.
- Using Cu wire for wire bonding can be a solution to the wire short problem caused by small wire sizes, besides other solutions such as using insulated wire and having varying loop heights.

Chen, H., Lee, S.W.R., Ding, Y. (2006), "Evaluation of bondability and reliability of single crystal copper wire bonding", *2005 Conference on High Density Microsystem Design and Packaging and Component Failure Analysis, HDP'05*.

England, L., Jiang, T. (2007), "Reliability of Cu wire bonding to Al metallization", *Proceedings - Electronic Components and Technology Conference*, pp. 1604-13.

Goh, K.S., Zhong, Z.W. (2007), "A new bonding-tool solution to improve stitch bondability", *Microelectronic Engineering*, Vol. 84 No. 1, pp. 173-9.

Ratchev, P., Stoukatch, S., Swinnen, B. (2006), "Mechanical reliability of Au and Cu wire bonds to Al, Ni/Au and Ni/Pd/Au capped Cu bond pads", *Microelectronics Reliability*, Vol. 46 No. 8, pp. 1315-25.

Zhong, Z.W. (2008), "Wire bonding using insulated wire and new challenges in wire bonding", *Microelectronics International* Vol. 25 No. 2, pp. 9-14.

Zhong, Z.W., Tee, T.Y., Luan, J.-E. (2007), "Recent advances in wire bonding, flip chip and lead-free solder for advanced microelectronics packaging", *Microelectronics International*, Vol. 24 No. 3, pp. 18-26.

Advantages of wire bonding using copper wire

- There is also very little void formation in the Al-Cu system compared with the Al-Au system.
- The growing speed of the intermetallic compound (IMC) between Cu and Al is much lower than that between Au and Al, resulting in less heat generation, lower electrical contact resistance, better reliability and better device performance compared to Au/Al bonds.

Chen, H., Lee, S.W.R., Ding, Y. (2006), "Evaluation of bondability and reliability of single crystal copper wire bonding", *2005 Conference on High Density Microsystem Design and Packaging and Component Failure Analysis, HDP'05*.

England, L., Jiang, T. (2007), "Reliability of Cu wire bonding to Al metallization", *Proceedings - Electronic Components and Technology Conference*, pp. 1604-13.

Hong, S., Hang, C., Wang, C. (2005), "Experimental research of copper wire ball bonding", *2005 6th International Conference on Electronics Packaging Technology*.

Tian, Y.H., Lum, I., Won, S.J., Park, S.H., Jung, J.P., Mayer, M., Zhou, Y. (2005), "Experimental study of ultrasonic wedge bonding with copper wire", *2005 6th International Conference on Electronics Packaging Technology*.

Copper wire bonding

- Advantages
- **Challenges/problems**
- Solutions/findings

Z.W. Zhong, Wire bonding using copper wire, Microelectronics International 26 (1) (2009) 10-16.

Challenges in wire bonding using copper wire

- Copper is easy to be oxidized in air, and thus copper wire bonders must have additional tools to prevent copper oxidation.
- Additional bonding parameters for using forming inert gas need to be optimised, and additional cost of forming gas must be considered.
- Although N_2 gas can be a suitable option, a forming gas mixture of 95%N_2/5%H_2 has been shown to be the best choice.

Chen, H., Lee, S.W.R., Ding, Y. (2006), "Evaluation of bondability and reliability of single crystal copper wire bonding", *2005 Conference on High Density Microsystem Design and Packaging and Component Failure Analysis, HDP'05*.

England, L., Jiang, T. (2007), "Reliability of Cu wire bonding to Al metallization", *Proceedings - Electronic Components and Technology Conference*, pp. 1604-13.

Goh, K.S., Zhong, Z.W. (2007), "A new bonding-tool solution to improve stitch bondability", *Microelectronic Engineering*, Vol. 84 No. 1, pp. 173-9.

Hong, S., Hang, C., Wang, C. (2005), "Experimental research of copper wire ball bonding", *2005 6th International Conference on Electronics Packaging Technology*.

Challenges in wire bonding using copper wire

- Copper wires have much higher hardness and stiffness than gold wires.
- Copper wire bonding needs more ultrasonic energy and higher bonding force, which can damage the Si substrate, form die cratering and induce cracking and peeling of the bonding pad.
- A stage temperature of 150-200°C is also needed for bonding copper wire.
- As-drawn copper wire possesses higher strength and hardness, but its lower ductility reduces the reliability of bonding.
- The lower strength of the annealed wire results in breakage.
- There is also a need to investigate the effects of the process parameters on the hardness of Cu FABs, because Cu exhibits a larger strain-hardening effect at a higher strain rate.

Bhattacharyya, A., Rittel, D., Ravichandran, G. (2005), "Effect of strain rate on deformation texture in OFHC copper", *Scripta Materialia*, Vol. 52 No. 7, pp. 657-61.

Chen, H., Lee, S.W.R., Ding, Y. (2006), "Evaluation of bondability and reliability of single crystal copper wire bonding", *2005 Conference on High Density Microsystem Design and Packaging and Component Failure Analysis, HDP'05*.

Hong, S., Hang, C., Wang, C. (2005), "Experimental research of copper wire ball bonding", *2005 6th International Conference on Electronics Packaging Technology*.

Hung, F.Y., Wang, Y.T., Chen, L.H., Lui, T.S. (2006), "Recrystallization effect and electric flame-off characteristic of thin copper wire", *Materials Transactions*, Vol. 47 No. 7, pp. 1776-81.

Tian, Y.H., Lum, I., Won, S.J., Park, S.H., Jung, J.P., Mayer, M., Zhou, Y. (2005), "Experimental study of ultrasonic wedge bonding with copper wire", *2005 6th International Conference on Electronics Packaging Technology*.

Zhong, Z.W., Ho, H.M., Tan, Y.C., Tan, W.C., Goh, H.M., Toh, B.H., Tan, J. (2007), "Study of factors affecting the hardness of ball bonds in copper wire bonding", *Microelectronic Engineering* Vol. 84 No. 2, pp. 368-74.

Challenges in wire bonding using copper wire

- Because copper wire is harder than gold wire, to improve stitch bondability, higher parameter settings have to be used, causing heavy cap marks and potential short tails or wire open.
- Cu/Au stitch bonds are weak, and thus copper wire bonding has wire open and short tail defects, poor process control, and low stitch pull readings.
- Oxidation of Cu wire leads to poor bondability for stitch bonds, which can result in increased non-sticking rates.
- Although many wire suppliers add dopants and anneal Cu wire to lower the hardness, softer Cu wire may help to magnify the tendency of work hardening and cause large variations in stitch pull strength.

England, L., Jiang, T. (2007), "Reliability of Cu wire bonding to Al metallization", *Proceedings - Electronic Components and Technology Conference*, pp. 1604-13.

Goh, K.S., Zhong, Z.W. (2007), "A new bonding-tool solution to improve stitch bondability", *Microelectronic Engineering*, Vol. 84 No. 1, pp. 173-9.

Kaimori, S., Nonaka, T., Mizoguchi, A. (2006), "The development of Cu bonding wire with oxidation-resistant metal coating", *IEEE Transactions on Advanced Packaging*, Vol. 29 No. 2, pp. 227-31.

Challenges in wire bonding using copper wire

- During wedge bonding of copper wire, two failure modes occur, lifting off of the wedge bond and uncontrolled breakage of copper wire during tail formation, if the wire is not deformed enough during bonding.
- Thick oxide can prevent a good wedge bond, which becomes critical when a spool of Cu wire is on the bonding machine for long time periods.
- The longer it has been removed from its package, the thicker the oxide becomes.
- A Cu ball is too strong (compared to an Au ball) to be sheared in half after it work-hardens during ball bonding.
- The Cu-Al interface is the weakest link in the system, and thus the ball lifts during the shear test.

England, L., Jiang, T. (2007), "Reliability of Cu wire bonding to Al metallization", *Proceedings - Electronic Components and Technology Conference*, pp. 1604-13.

Tian, Y.H., Lum, I., Won, S.J., Park, S.H., Jung, J.P., Mayer, M., Zhou, Y. (2005), "Experimental study of ultrasonic wedge bonding with copper wire", *2005 6th International Conference on Electronics Packaging Technology*.

Challenges in wire bonding using copper wire

- During Cu wire bonding, high pressure is put on bond pad structures, which can contain low-*k* materials having very low stiffness ranging 1-10 GPa, depending on the porosity in low-*k* materials.
- This means future wire bonding will be performed using stiffer wire on a weaker support structure.

Degryse, D., Vandevelde, B., Beyne, E. (2005), "Cu bonding to Cu low K wafers: a systematic study of the mechanical bonding process", *Proceedings of the 6th International Conference on Thermal, Mechanical and Multi-Physics Simulation and Experiments in Micro-Electronics and Micro-Systems*, pp. 41-8.

Copper wire bonding

- Advantages
- Challenges/problems
- **Solutions/findings**

Z.W. Zhong, Wire bonding using copper wire, Microelectronics International 26 (1) (2009) 10-16.

Findings & solutions for Cu wire bonding

- Investigation of copper wire ball bonding on an Al-metallised silicon substrate found that the solidification proceeded from the ball towards the wire and the orientation of the cell-type fine substructures was irregular due to a rapid solidification of Cu during the electric sparking.
- Slip was the major mechanism involved in the overall deformation of polycrystalline copper, although twinning was also found in very limited bonds.
- The shear force of the ball bonds did not degenerate after 1500 hours at 200°C, and it had some extension of increasing, due to the interface diffusion of the bonds.

Hong, S., Hang, C., Wang, C. (2005), "Experimental research of copper wire ball bonding", *2005 6th International Conference on Electronics Packaging Technology*.

Findings & solutions for Cu wire bonding

- Cross section analysis after ultrasonic wedge bonding using copper wire at ambient temperature on Au/Ni/Cu metallization of a PCB finds a continuous interconnection between copper wire and Au/Ni/Cu metallization.
- Three common failure modes found are bond break when the bond is deformed excessively, bond lifting off from the metallization surface, and wire break at the bond neck, which is the preferred mode indicating good bonding.
- Strong copper wire wedge bonds on an Au/Ni plated Cu substrate are obtained by ultrasonic bonding at room temperature, achieved by wear action induced by ultrasonic vibration.
- The ultrasonic power enhances deformation of the copper wire because of the ultrasonic softening effect followed by the strain hardening of the copper bond.
- Higher bonding force and power are needed for the second bond than the first bond to have strong pull force.

Tian, Y., Wang, C., Lum, I., Mayer, M., Jung, J.P., Zhou, Y. (2008), "Investigation of ultrasonic copper wire wedge bonding on Au/Ni plated Cu substrates at ambient temperature", *Journal of Materials Processing Technology*, Vol. In Press, Corrected Proof No.

Tian, Y.H., Lum, I., Won, S.J., Park, S.H., Jung, J.P., Mayer, M., Zhou, Y. (2005), "Experimental study of ultrasonic wedge bonding with copper wire", *2005 6th International Conference on Electronics Packaging Technology*.

Findings & solutions for Cu wire bonding

- Investigation of the annealing effect (at 150-250°C for 1 hour) on the mechanical properties of copper wire revealed that with annealing temperatures > 200°C, copper wire possessed a fully annealed structure, its hardness and tensile strength decreased, and its elongation was raised significantly.
- By re-crystallisation, the matrix structure transferred from thin, long grains to equiaxed grains and a few annealed twins.
- The FAB microstructures of the annealing wire after EFO (electronic-flame-off) were column-like grains, which grew from the heat-affected zone (HAZ) to the Cu ball, and the preferred orientation was (100).
- Due to the thermal effect of EFO, the necks of Cu balls underwent re-crystallisation and grain growth was induced.
- Decreased hardness and strength of the HAZ led to breakage sites of the wires to be in the HAZ near Cu balls.

Hung, F.Y., Wang, Y.T., Chen, L.H., Lui, T.S. (2006), "Recrystallization effect and electric flame-off characteristic of thin copper wire", *Materials Transactions*, Vol. 47 No. 7, pp. 1776-81.

Findings & solutions for Cu wire bonding

- After annealing, single crystal copper wires were bonded on Au (1-2 µm thick) and Al (2 µm thick) surfaces without gas protection.
- Cu_3Au and AuCu IMCs were found at the Cu/Au interface while $CuAl_2$ was found at the Cu/Al interface.
- After thermal aging, Kirkendall voids were discovered at the Cu/Au interface.
- Annealed Cu wires exhibited tensile strength and elongation characteristics comparable to those of Au wires.

Chen, H., Lee, S.W.R., Ding, Y. (2006), "Evaluation of bondability and reliability of single crystal copper wire bonding", *2005 Conference on High Density Microsystem Design and Packaging and Component Failure Analysis, HDP'05*.

Findings & solutions for Cu wire bonding

- Studies of the IMC growth in wire bonds and the Cu-to-Si diffusion behaviour reveal that Au-Al IMC grows much faster than Cu-Al IMC.
- Cu-to-Si diffusion is faster than Au-to-Si diffusion under the same annealing condition.
- With a TiW barrier layer adopted, Cu or Au diffusion to Si is decreased.
- Al pad deformation induces more Cu-to-Si diffusion.
- Cu-Al IMC is thinner than Au-Al IMC at the bonding interface, which results in better bond strength and smaller electrical resistance.

Zhang, S., Chen, C., Lee, R., Lau, A.K.M., Tsang, P.P.H., Mohamed, L., Chan, C.Y., Dirkzwager, M. (2006), "Characterization of intermetallic compound formation and copper diffusion of copper wire bonding", *Proceedings - Electronic Components and Technology Conference*, pp. 1821-6.

Zhang, S., Chen, C., Lee, R., Lau, A.K.M., Tsang, P.P.H., Mohamed, L., Chan, C.Y., Dirkzwager, M. (2007), "Effects of Al pad deformation and TiW barrier layer on copper-to-silicon diffusion and intermetallic compound formation in copper wire bonding", *Proceedings of the International Symposium and Exhibition on Advanced Packaging Materials Processes, Properties and Interfaces*, pp. 189-95.

Findings & solutions for Cu wire bonding

- As one solution to the poor bondability problem due to surface oxidation, electroplating of an oxidation-resistant metal on Cu wire was conceived to prevent surface oxidation.
- Experiments using ϕ25-μm wires with a 0.1-μm-thick oxidation-resistant metal revealed that electroplating of Ag, Au, Ni or Pd on Cu wire increased bond strengths but produced problematic ball shapes except the Pd-plated Cu wire, which could produce the same ball shape as that of Au wire.
- Pressure cooker, temperature humidity bias and temperature cycling tests confirmed that the Pd-plated Cu wire had excellent reliability and bondability.

Kaimori, S., Nonaka, T., Mizoguchi, A. (2006a), "Development of "Hybrid Bonding Wire"", *SEI Technical Review*, No. 63, pp. 14-8.

Kaimori, S., Nonaka, T., Mizoguchi, A. (2006b), "The development of Cu bonding wire with oxidation-resistant metal coating", *IEEE Transactions on Advanced Packaging*, Vol. 29 No. 2, pp. 227-31.

Findings & solutions for Cu wire bonding

- Through bond integrity testing, it was found that increasing the temperature could enlarge the bondability window and less bonding force could be used.
- Lower ultrasonic power and bonding force could help minimise pad cratering.
- Cu ball bonds performed better than Au ball bonds in wire pull and ball shear tests.
- Ball lifts were the shear failure modes, while neck breaks and pad lifts were the wire pull failure modes.
- The pads occasionally lifted, but this was not detrimental because the pull strength values were not smaller than the neck break values.
- Mechanical properties of the Cu bonds were superior to those of Au bonds.

England, L., Jiang, T. (2007), "Reliability of Cu wire bonding to Al metallization", *Proceedings - Electronic Components and Technology Conference*, pp. 1604-13.

Findings & solutions for Cu wire bonding

- A weak tail bond can result in non-uniform tail length and FAB formation.
- The bonder stops before flaming off the tail, reducing the production throughput, if the tail bond is weak enough to loose before the clamp can close, resulting in the wire being blown out from the capillary.
- The cleanliness of bonding pads is important for using Cu wire.
- Plasma cleaning of the lead-frame before bonding increases the tail breaking stability significantly, and an average Cu tail breaking force > 50 mN is obtained, comparable to that obtained using Au wire.
- The standard deviation of the Cu tail breaking force is about two times that obtained using Au wire.

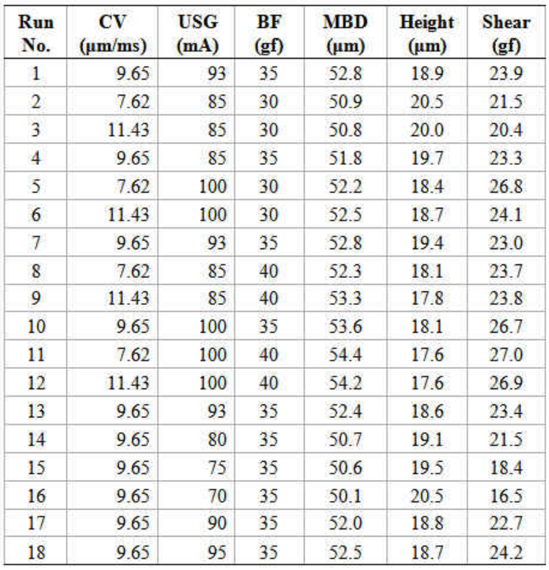
Lee, J., Mayer, M., Zhou, Y., Hong, S.J. (2007), "Iterative optimization of tail breaking force of 1 mil wire thermosonic ball bonding processes and the influence of plasma cleaning", *Microelectronics Journal*, Vol. 38 No. 8-9, pp. 842-7.

Findings & solutions for Cu wire bonding

- Investigations of Cu wire bonding on metallised and plated materials such as Al, Cu, Ag, Au and Pd find that asperity deformation is the most significant factor for good bonding.
- Ultrasonic energy breaks the oxide film and deforms asperities, while the bonding force increases the asperity proximity.
- The copper bonds are harder than the wire, exhibiting work hardening.
- Soft Al with lower asperity deformation is easier to be wire bonded than harder surfaces (Ni, W, Mo, Cr, Co, Ta).
- Good adhesion can be achieved on bare and plated surfaces with surface roughness (Ra) of 0.01-0.15 µm and 0.02-0.6 µm, respectively.

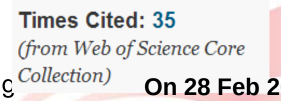
Murali, S., Srikanth, N., Wong, Y.M., Vath Iii, C.J. (2007), "Fundamentals of thermo-sonic copper wire bonding in microelectronics packaging", *Journal of Materials Science*, Vol. 42 No. 2, pp. 615-23.

Details of the ultrasonic generator (USG) current setting, contact velocity (CV) and bond force (BF), and the bonding responses (mashed ball diameter (MBD), ball height and ball shear)



Run No.	CV (µm/ms)	USG (mA)	BF (gf)	MBD (µm)	Height (µm)	Shear (gf)
1	9.65	93	35	52.8	18.9	23.9
2	7.62	85	30	50.9	20.5	21.5
3	11.43	85	30	50.8	20.0	20.4
4	9.65	85	35	51.8	19.7	23.3
5	7.62	100	30	52.2	18.4	26.8
6	11.43	100	30	52.5	18.7	24.1
7	9.65	93	35	52.8	19.4	23.0
8	7.62	85	40	52.3	18.1	23.7
9	11.43	85	40	53.3	17.8	23.8
10	9.65	100	35	53.6	18.1	26.7
11	7.62	100	40	54.4	17.6	27.0
12	11.43	100	40	54.2	17.6	26.9
13	9.65	93	35	52.4	18.6	23.4
14	9.65	80	35	50.7	19.1	21.5
15	9.65	75	35	50.6	19.5	18.4
16	9.65	70	35	50.1	20.5	16.5
17	9.65	90	35	52.0	18.8	22.7
18	9.65	95	35	52.5	18.7	24.2

Source: Zhong, Z.W., Ho, H.M., Tan, Y.C., Tan, W.C., Goh, H.M., Toh, B.H., Tan, J. (2007), "Study of factors affecting the hardness of ball bonds in copper wire bonding", *Microelectronic Engineering* Vol. 84 No. 2, pp. 368-74.



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On 28 Feb 2014

Factors affecting the hardness of ball bonds in copper wire bonding

- A cherry pit bonding process was used to ensure that the FABs obtained were only spherical balls.
- Forming gas (95% N_2 and 5% H_2) was used to prevent copper oxidation and to prevent oxygen from dissolving into the copper during melting, which might lead to hardening of the copper ball.
- The targeted FAB diameter was 46.5 μm.
- Optimum ball-bond parameters were obtained using the DOE to ensure that a bonding process window was established instead of a single point process.
- EFO current was 120 mA and EFO firing time was 206 μs.
- Ultrasonic generator (USG) current setting, contact velocity (CV) and bond force (BF) were the DOE factors and the bonded mashed ball diameter (MBD), ball height and ball shear were the bonding responses, where 1 gf = 9.8 mN.

Zhong, Z.W., Ho, H.M., Tan, Y.C., Tan, W.C., Goh, H.M., Toh, B.H., Tan, J. (2007), "Study of factors affecting the hardness of ball bonds in copper wire bonding", *Microelectronic Engineering* Vol. 84 No. 2, pp. 368-74.

Factors affecting the hardness of ball bonds in copper wire bonding

- Different combinations of EFO current and firing time settings were used to obtain the same FAB diameter of 46.5 μm.
- These FABs with the same size, obtained under different firing conditions with a range of low to high EFO current, were ball bonded with the same ball bond parameters.
- The bonded devices were then mounted in epoxy resin, cross-sectioned in the normal metallographic manner along the longitudinal direction, and polished with diamond suspensions of 6, 3 and 1 μm in size.
- The behaviour of a bonded gold ball and its heat affected zone depend very much on the characteristics of FAB formation, which is affected by the EFO parameter settings, mainly the EFO current level and its corresponding firing time.

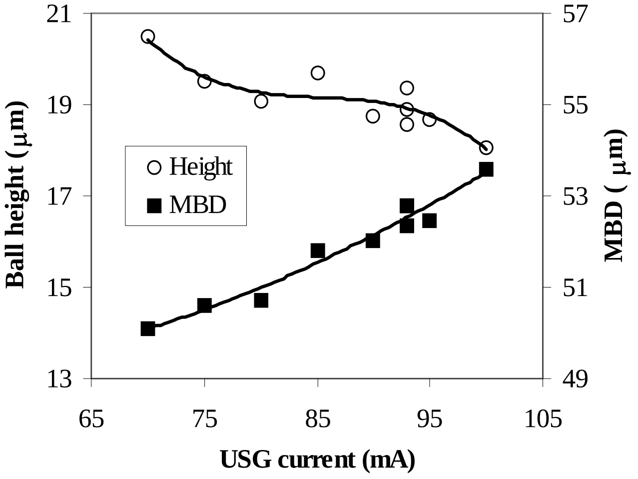
Zhong, Z.W., Ho, H.M., Tan, Y.C., Tan, W.C., Goh, H.M., Toh, B.H., Tan, J. (2007), "Study of factors affecting the hardness of ball bonds in copper wire bonding", *Microelectronic Engineering* Vol. 84 No. 2, pp. 368-74.

Factors affecting the hardness of ball bonds in copper wire bonding

- For copper wire bonding, there is a need to get the FAB properties to that of gold FABs as close as possible, because most bond-pad structures are developed to suit the nature of gold wire bonding
- Vickers hardness measurements were performed along the length of the polished cross-section of the bonded balls using a Fischerscope HP100C hardness tester with a Vickers indenter by applying a 10-mN load with a dwell time of 5 seconds.
- The test uses a pointed diamond indenter and presses it into the surface of the material to be tested.
- To ensure accurate measurement of the hardness, indentations were measured in a SEM.

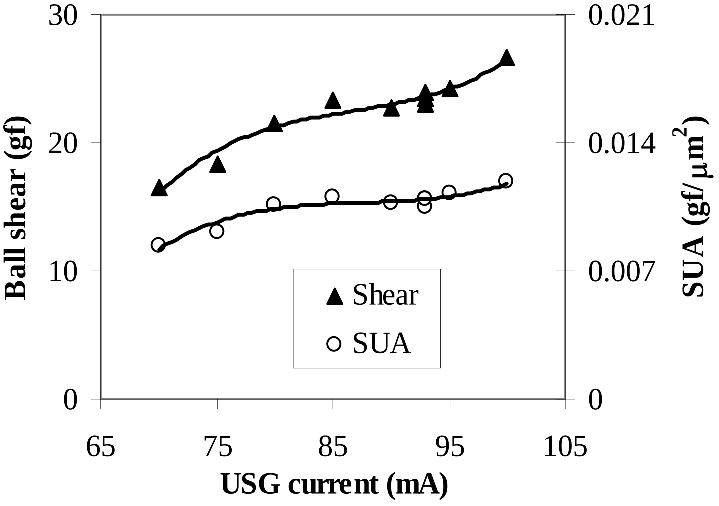
Zhong, Z.W., Ho, H.M., Tan, Y.C., Tan, W.C., Goh, H.M., Toh, B.H., Tan, J. (2007), "Study of factors affecting the hardness of ball bonds in copper wire bonding", *Microelectronic Engineering* Vol. 84 No. 2, pp. 368-74.

Effects of ultrasonic generator (USG) current on MBD and ball height



Source: Zhong, Z.W., Ho, H.M., Tan, Y.C., Tan, W.C., Goh, H.M., Toh, B.H., Tan, J. (2007), "Study of factors affecting the hardness of ball bonds in copper wire bonding", *Microelectronic Engineering* Vol. 84 No. 2, pp. 368-74.

Effects of ultrasonic generator (USG) current on ball shear and shear per unit area (SUA)



Source: Zhong, Z.W., Ho, H.M., Tan, Y.C., Tan, W.C., Goh, H.M., Toh, B.H., Tan, J. (2007), "Study of factors affecting the hardness of ball bonds in copper wire bonding", *Microelectronic Engineering* Vol. 84 No. 2, pp. 368-74.

Bonding responses & Effects of USG current

- Measurements with a sample size of 16 were done to obtain the average values of MBD, ball height and ball shear.
- The increase in ultrasonic generator current and bond force would result in increased MBD and decreased ball height, while contact velocity had little effect on these two responses.
- Increase in ultrasonic generator current would increase ball shear but increase in contact velocity would reduce this response.
- The experiments did not produce any NSOP (non-sticking on pad) defect with any of the parameter settings in the DOE table.
- A process window was formed with a contact velocity of 9.65 μm/ms and a bond force of 35 gf as the constant settings.

Zhong, Z.W., Ho, H.M., Tan, Y.C., Tan, W.C., Goh, H.M., Toh, B.H., Tan, J. (2007), "Study of factors affecting the hardness of ball bonds in copper wire bonding", *Microelectronic Engineering* Vol. 84 No. 2, pp. 368-74.

Factors affecting the hardness of ball bonds in copper wire bonding

- The shear per unit area represents how well the weld between the copper and its Al bond pad of an IC chip has been formed.
- There could be an optimum ultrasonic generator current setting in the region of saturation of shear per unit area.
- Higher shear per unit area could be achieved by using higher ultrasonic generator current, but this might cause cratering on the Al bond pad of the IC chip.
- Next table shows FAB sizes obtained using three EFO current and firing time settings.

Zhong, Z.W., Ho, H.M., Tan, Y.C., Tan, W.C., Goh, H.M., Toh, B.H., Tan, J. (2007), "Study of factors affecting the hardness of ball bonds in copper wire bonding", *Microelectronic Engineering* Vol. 84 No. 2, pp. 368-74.

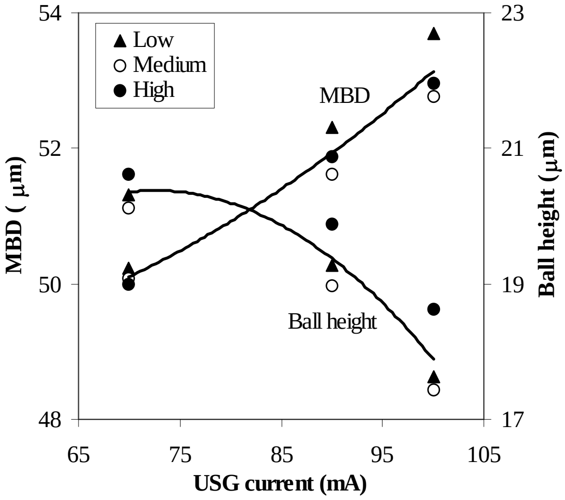
Average FAB sizes obtained using three EFO current and firing time settings

EFO ID	EFO current (mA)	Firing time (µs)	FAB size (µm)
High	105	243	46.73
Medium	60	476	46.54
Low	30	1248	46.55

The settings resulted in average FAB sizes that were close to the required FAB size of 46.5 µm.

Source: Zhong, Z.W., Ho, H.M., Tan, Y.C., Tan, W.C., Goh, H.M., Toh, B.H., Tan, J. (2007), "Study of factors affecting the hardness of ball bonds in copper wire bonding", *Microelectronic Engineering* Vol. 84 No. 2, pp. 368-74.

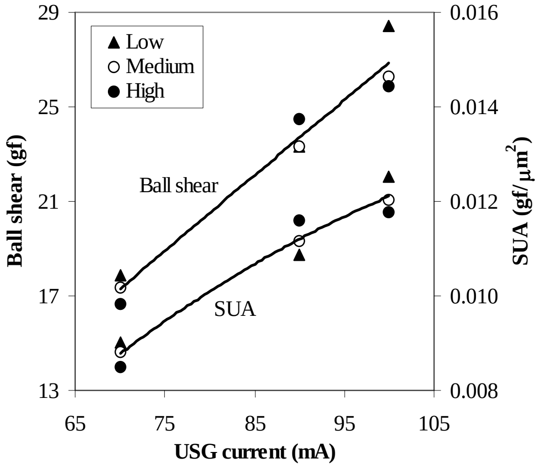
Bonded MBDs and bonded ball heights obtained using three ultrasonic generator (USG) current settings (70, 90 and 100 mA) and the FABs formed using the three (high, medium and low) EFO current settings



- At each USG current level for each response (size, height, shear or SUA), there are three data indicating the responses corresponding to the three EFO current settings.
- The three USG current settings (70, 90 and 100 mA) had more significant effects on the responses than the three (high, medium and low) EFO current settings.

Source: Zhong, Z.W., Ho, H.M., Tan, Y.C., Tan, W.C., Goh, H.M., Toh, B.H., Tan, J. (2007), "Study of factors affecting the hardness of ball bonds in copper wire bonding", *Microelectronic Engineering* Vol. 84 No. 2, pp. 368-74.

Ball shear and shear per unit area (SUA) of the ball bonds obtained using three ultrasonic generator (USG) current settings (70, 90 and 100 mA) and the FABs formed using the three (high, medium and low) EFO current settings



- At each USG current level for each response (size, height, shear or SUA), there are three data indicating the responses corresponding to the three EFO current settings.
- The three USG current settings (70, 90 and 100 mA) had more significant effects on the responses than the three (high, medium and low) EFO current settings.

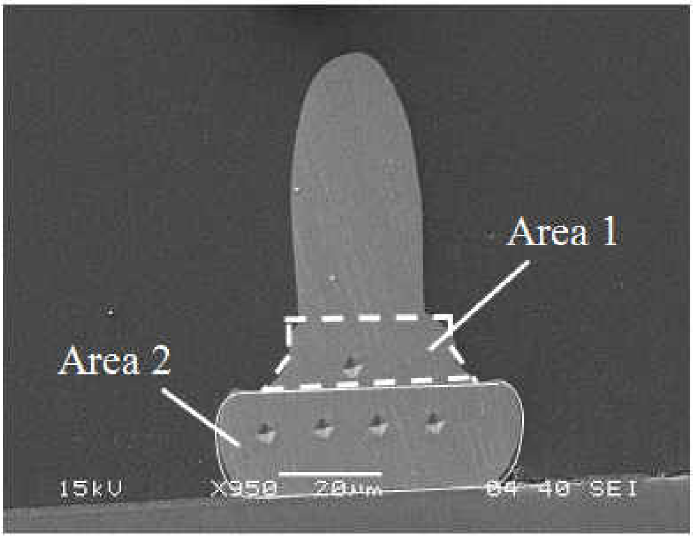
Source: Zhong, Z.W., Ho, H.M., Tan, Y.C., Tan, W.C., Goh, H.M., Toh, B.H., Tan, J. (2007), "Study of factors affecting the hardness of ball bonds in copper wire bonding", *Microelectronic Engineering* Vol. 84 No. 2, pp. 368-74.

Factors affecting the hardness of ball bonds in copper wire bonding

- Optical measurement of the ball bonds and the shear measurement method could only distinguish the differences made by the USG current settings but not that made by the three EFO current settings.
- There was a need to employ a measuring method with higher resolution to quantify the effects of different EFO current levels.
- This led to the use of Vickers hardness test.
- After the FAB has been squashed to the shape of the ball bond by the initial contact velocity, the weld is formed by application of ultrasonic and thermal energies together with bonding force.
- The ultrasonic energy reduces the yield stress of the copper ball and at the same time helps to form the weld at the interface.
- Once a good weld is formed, there should be no displacement at the interface, because it will degrade the weld.
- Higher ultrasonic generator current resulted in more deformed ball bonds and good welds with higher ball shear and shear per unit area, with the process parameter settings investigated.

Zhong, Z.W., Ho, H.M., Tan, Y.C., Tan, W.C., Goh, H.M., Toh, B.H., Tan, J. (2007), "Study of factors affecting the hardness of ball bonds in copper wire bonding", *Microelectronic Engineering* Vol. 84 No. 2, pp. 368-74.

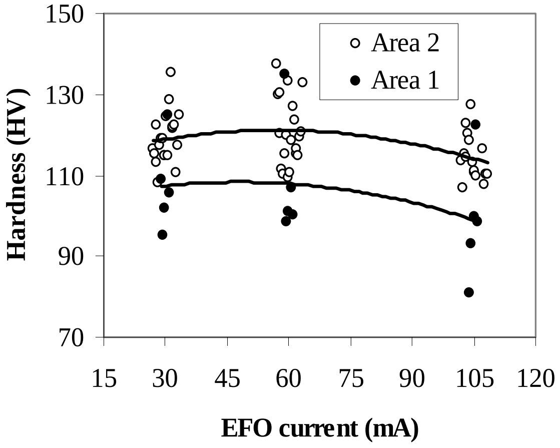
Indentation locations for microhardness tests



- Vickers hardness tests were conducted to quantify the effects of different EFO current levels on the microhardness of the ball bonds.
- This figure illustrates an example of indentations performed on the inner-chamfer area of the bonding tool (Area 1, outlined in white broken lines) and the smashed ball area (Area 2, outlined in white solid lines).

Source: Zhong, Z.W., Ho, H.M., Tan, Y.C., Tan, W.C., Goh, H.M., Toh, B.H., Tan, J. (2007), "Study of factors affecting the hardness of ball bonds in copper wire bonding", *Microelectronic Engineering* Vol. 84 No. 2, pp. 368-74.]

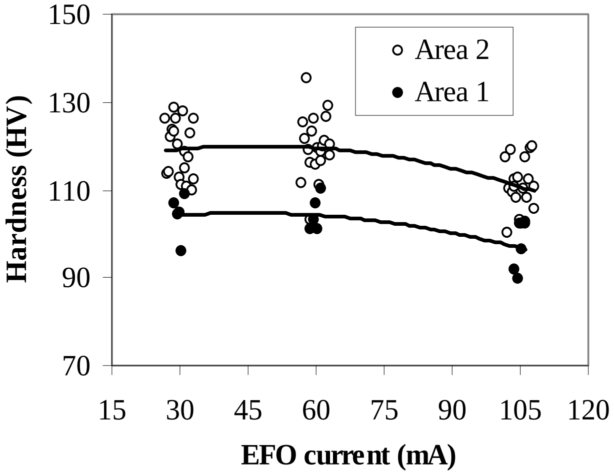
Vickers hardness numbers (HV) of the ball bonds obtained using ultrasonic generator current = 90 mA, contact velocity = 7.62 µm/ms and the FABs formed using the three (high, medium and low) EFO current settings shown in DOE Table



- The average numbers of the Vickers hardness of bonded balls formed at higher EFO current are lower than those formed at lower EFO current.
- The average Vickers hardness on the inner-chamfer area of the bonding tool (Area 1) is slightly lower than that of the smashed ball area (Area 2).

Source: Zhong, Z.W., Ho, H.M., Tan, Y.C., Tan, W.C., Goh, H.M., Toh, B.H., Tan, J. (2007), "Study of factors affecting the hardness of ball bonds in copper wire bonding", *Microelectronic Engineering* Vol. 84 No. 2, pp. 368-74.

Vickers hardness numbers (HV) of the ball bonds obtained using ultrasonic generator current = 90 mA, contact velocity = 11.43 µm/ms and the FABs formed using the three (high, medium and low) EFO current settings shown in DOE Table



- The average numbers of the Vickers hardness of bonded balls formed at higher EFO current are lower than those formed at lower EFO current.
- The average Vickers hardness on the inner-chamfer area of the bonding tool (Area 1) is slightly lower than that of the smashed ball area (Area 2).

Source: Zhong, Z.W., Ho, H.M., Tan, Y.C., Tan, W.C., Goh, H.M., Toh, B.H., Tan, J. (2007), "Study of factors affecting the hardness of ball bonds in copper wire bonding", *Microelectronic Engineering* Vol. 84 No. 2, pp. 368-74.

Factors affecting the hardness of ball bonds in copper wire bonding

- There were measurement errors, which were inherent to the hardness test and were included in the hardness values.
- Thus, two *t*-tests were applied to the results to statistically compare the hardness values of Area 2 obtained with high EFO current to those obtained with medium EFO current.
- There was a highly significant difference (*P*-value = 0.008) between the mean (114.26 HV) of the hardness values obtained with high EFO current and that (120.82 HV) obtained with medium EFO current. The estimated difference was 6.56 HV. (CV = 7.62 μm/ms)
- There was a very highly significant difference (*P*-value < 0.001) between the mean (110.55 HV) of the hardness values obtained with high EFO current and that (119.83 HV) obtained with medium EFO current. The estimated difference was 9.28 HV. (CV = 11.43 μm/ms)
- The processes with various EFO currents resulted in different mashed (deformed) ball dimensions, which resulted in different work-hardening levels and thus affected the Area-2 hardness values of the processes with various EFO currents.

Zhong, Z.W., Ho, H.M., Tan, Y.C., Tan, W.C., Goh, H.M., Toh, B.H., Tan, J. (2007), "Study of factors affecting the hardness of ball bonds in copper wire bonding", *Microelectronic Engineering* Vol. 84 No. 2, pp. 368-74.

Factors affecting the hardness of ball bonds in copper wire bonding

- The smashed ball area (Area 2) was expected to have higher hardness than the inner-chamfer area of the bonding tool (Area 1), because it experienced more strain hardening.
- The *t*-test confirmed that the Vickers hardness of the balls bonded using FABs formed at 105-mA EFO current was lower than that formed at 60-mA EFO current, with a difference of approximately 10 HV.
- Because all parameters were constant except for the EFO firing conditions, it is reasonable to deduce that the hardness decrease on the bonded balls is attributed to the higher EFO current setting.
- To visualize the effect of the 10-HV hardness difference, it is better to express it in terms of yield stress.

Zhong, Z.W., Ho, H.M., Tan, Y.C., Tan, W.C., Goh, H.M., Toh, B.H., Tan, J. (2007), "Study of factors affecting the hardness of ball bonds in copper wire bonding", *Microelectronic Engineering* Vol. 84 No. 2, pp. 368-74.

Factors affecting the hardness of ball bonds in copper wire bonding

- A semi-empirical relationship between HV and yield stress $\sigma_{0.2}$ was proposed by Saraswati et al. to be:

$$\sigma_{0.2} = 3.27HV(0.1)^n$$

Where, *n* is a strain-hardening index.

- This semi-empirical relationship indicates that the lower the hardness (HV), the lower will be the yield stress ($\sigma_{0.2}$).
- This relationship enables the estimation of the yield stress ratio by simply taking the ratio of hardness (HV) and assuming that n is a constant.
- The calculation using the ratio of hardness numbers for FABs formed at 60 mA and 105 mA revealed a 9% reduction in yield stress.
- This has the implication that the stress experienced on the bond pad is lower when it is bonded with the copper FAB formed at 105-mA EFO current compared with that formed at 60 mA.

Zhong, Z.W., Ho, H.M., Tan, Y.C., Tan, W.C., Goh, H.M., Toh, B.H., Tan, J. (2007), "Study of factors affecting the hardness of ball bonds in copper wire bonding", *Microelectronic Engineering* Vol. 84 No. 2, pp. 368-74.

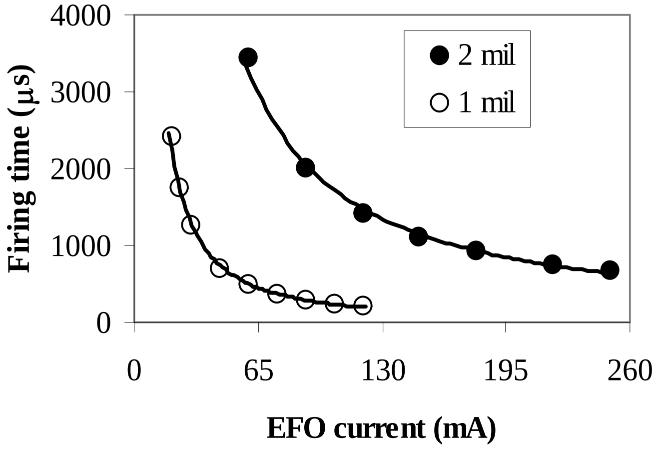
(Saraswati, E.P.P. Theint, D Stephan, H.M. Goh, E. Pasamanero, D.R.O. Calipto, F.W. Wulff, C.D. Breach, High Temperature Storage (HTS) Performance of Copper Ball Bonding Wires, Proceedings of the 7th Electronic Packaging Technology Conference, Singapore, 7-9 Dec, 2005, pp. 602–607.)

FABs formed by "high" EFO current

- The copper FAB formed by "high" EFO current is a relative term, because it also heavily depends on the copper wire diameter used.
- EFO current of 105 mA can be considered high for forming FABs using a copper wire diameter of 25.4 μm, but this could be low for forming FABs using a copper wire diameter of 50.8 μm.
- Thus, using EFO current as a standard index is not appropriate.
- 120 mA is "high" EFO current for 25.4-μm (1 mil) copper wire, but it is regarded as "low" for 50.8-μm (2 mil) copper wire.

Zhong, Z.W., Ho, H.M., Tan, Y.C., Tan, W.C., Goh, H.M., Toh, B.H., Tan, J. (2007), "Study of factors affecting the hardness of ball bonds in copper wire bonding", *Microelectronic Engineering* Vol. 84 No. 2, pp. 368-74.

EFO firing conditions for obtaining a FAB diameter of 46.5 μm with 25.4-μm (1 mil) wire and obtaining a FAB diameter of 93 μm with 50.8-μm (2 mil) wire



Source: Zhong, Z.W., Ho, H.M., Tan, Y.C., Tan, W.C., Goh, H.M., Toh, B.H., Tan, J. (2007), "Study of factors affecting the hardness of ball bonds in copper wire bonding", *Microelectronic Engineering* Vol. 84 No. 2, pp. 368-74.

Factors affecting the hardness of ball bonds in copper wire bonding

- For gold wire bonding, it was shown numerically that higher EFO current would result in higher maximum FAB temperature [1].
- It is deemed that the same mechanism works for copper FABs, and it is the higher temperature that contributes to the lower hardness, during FAB formation using higher EFO current.
- During copper FAB formation, if the inert-gas is insufficient to provide totally volumetric coverage, oxidation will take place during melting of the wire tail [2].
- This will result in a pointed FAB, because the surface tension will significantly decrease due to oxidation of the surface layer of the molten copper FAB [3].

Zhong, Z.W., Ho, H.M., Tan, Y.C., Tan, W.C., Goh, H.M., Toh, B.H., Tan, J. (2007), "Study of factors affecting the hardness of ball bonds in copper wire bonding", *Microelectronic Engineering* Vol. 84 No. 2, pp. 368-74.

[1] W. Qin, I.M. Cohen, P.S. Ayyaswamy, Ball Size and HAZ as functions of EFO Parameters for Gold Bonding Wire, Proceedings of the Pacific Rim / ASME International Intersociety Electronic and Photonic Packaging Conference, New York, 1997, pp. 391–398.

[2] H.M. Ho, J. Tan, Y.C. Tan, B.H. Toh, P. Xavier, Modelling Energy Transfer to Copper Wire for Bonding in an Inert Environment, Proceedings of the 7th Electronic Packaging Technology Conference, Singapore, 7-9 Dec. 2005, pp. 292–297.

[3] E. Ricci, R. Novakovic, Wetting and Surface Tension Measurements on Gold Alloys, Gold Bulletin 34 (2) (2001) 41–49.

Factors affecting the hardness of ball bonds in copper wire bonding

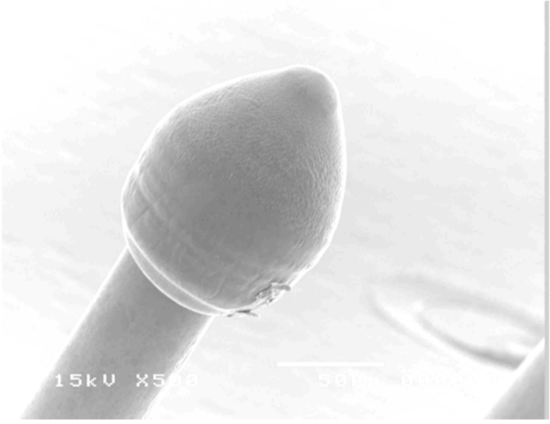
- An experiment using ϕ50.8-μm copper wire was performed to confirm that higher EFO current tends to result in a higher temperature during FAB formation.
- The experiment was the typical cherry pits bonding.
- Copper FABs having the same diameter were obtained using different combinations of EFO current and firing time settings at a low flow rate of forming gas.
- These FABs were then inspected using the SEM to investigate the roundness of the FABs.

Zhong, Z.W., Ho, H.M., Tan, Y.C., Tan, W.C., Goh, H.M., Toh, B.H., Tan, J. (2007), "Study of factors affecting the hardness of ball bonds in copper wire bonding", *Microelectronic Engineering* Vol. 84 No. 2, pp. 368-74.

SEM pictures of the cherry bond pits for the inspection of the FABs formed with 250-mA EFO current

Source: Zhong, Z.W., Ho, H.M., Tan, Y.C., Tan, W.C., Goh, H.M., Toh, B.H., Tan, J. (2007), "Study of factors affecting the hardness of ball bonds in copper wire bonding", *Microelectronic Engineering* Vol. 84 No. 2, pp. 368-74.

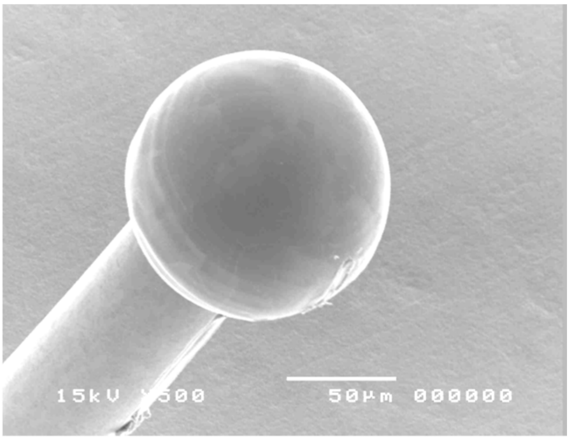
SEM picture of a pointed FAB with a scaling surface



- There was some level of scaling at the region of the pointed ball.
- The scaling was most likely due to oxidization of the surface layer of the molten copper FAB.

Source: Zhong, Z.W., Ho, H.M., Tan, Y.C., Tan, W.C., Goh, H.M., Toh, B.H., Tan, J. (2007), "Study of factors affecting the hardness of ball bonds in copper wire bonding", *Microelectronic Engineering* Vol. 84 No. 2, pp. 368-74.

SEM picture of a spherical FAB with a relatively smooth surface



The spherical ball had a relatively smooth surface.

Source: Zhong, Z.W., Ho, H.M., Tan, Y.C., Tan, W.C., Goh, H.M., Toh, B.H., Tan, J. (2007), "Study of factors affecting the hardness of ball bonds in copper wire bonding", *Microelectronic Engineering* Vol. 84 No. 2, pp. 368-74.

Numbers of round FABs formed using different EFO current and firing time settings

EFO current (mA)	Firing time (µs)	FAB diameter (µm)	No. of round FABs
250	700	94.99	80/100
220	820	97.79	98/100
180	1050	100.85	100/100
150	1200	97.92	100/100
120	1500	97.27	100/100
90	2250	100.42	100/100
60	3500	94.99	100/100

FABs formed at higher EFO current had occasional pointed balls.

Source: Zhong, Z.W., Ho, H.M., Tan, Y.C., Tan, W.C., Goh, H.M., Toh, B.H., Tan, J. (2007), "Study of factors affecting the hardness of ball bonds in copper wire bonding", *Microelectronic Engineering* Vol. 84 No. 2, pp. 368-74.

Factors affecting the hardness of ball bonds in copper wire bonding

- There were more non-spherical FABs formed by higher EFO current.
- This could be due to the following reason:
- During copper FAB formation, the maximum temperature of the copper ball can be very high.
- The sudden expanding in volume due to rise in temperature at the molten FAB vicinity can be several times that of the original volume.
- Therefore, if the flow rate is not sufficiently high to provide a complete inert gas envelope during the melting of the copper FAB, the oxygen in the surrounding air may come in and oxidization of the surface layer of the molten copper FAB takes place, resulting in a pointed FAB.
- FABs formed at higher EFO current had occasional pointed balls.

Zhong, Z.W., Ho, H.M., Tan, Y.C., Tan, W.C., Goh, H.M., Toh, B.H., Tan, J. (2007), "Study of factors affecting the hardness of ball bonds in copper wire bonding", *Microelectronic Engineering* Vol. 84 No. 2, pp. 368-74.

Factors affecting the hardness of ball bonds in copper wire bonding

- It is reasonable to assume that higher EFO current could result in higher temperature during the melting of FABs.
- This is further supported by the fact that all FABs with similar diameters formed at lower EFO current did not have pointed FABs.
- To have all FABs in the spherical form, to increase the flow rate of the forming gas can be another solution.
- This will provide volumetric coverage with sufficient inert gas during copper FAB formation.

Zhong, Z.W., Ho, H.M., Tan, Y.C., Tan, W.C., Goh, H.M., Toh, B.H., Tan, J. (2007), "Study of factors affecting the hardness of ball bonds in copper wire bonding", *Microelectronic Engineering* Vol. 84 No. 2, pp. 368-74.

Conclusions

- Ultrasonic generator current is the most significant factor to increase the bonded MBD, ball shear and shear per unit area and to decrease the ball height.
- The microhardness of bonded copper balls is related to the EFO parameters, with FABs obtained by higher EFO current being softer.
- The lower Vickers hardness is attributed to the higher maximum temperature during the FAB melting state.
- Higher EFO current results in a higher maximum temperature of the copper FAB.
- Because EFO current and firing time are closely related, it is more appropriate to use firing time as an index.
- This would make it less dependent on the diameter of the wire.
- For copper wire bonding, to achieve a softer FAB so as to minimize the stress induced during ball bond impact, it is recommended to have shorter firing time during FAB formation, use a lower contact velocity to minimize the impact stress, and use a higher gas flow rate to provide sufficient inert-gas coverage in order to avoid pointed FABs.

Zhong, Z.W., Ho, H.M., Tan, Y.C., Tan, W.C., Goh, H.M., Toh, B.H., Tan, J. (2007), "Study of factors affecting the hardness of ball bonds in copper wire bonding", *Microelectronic Engineering* Vol. 84 No. 2, pp. 368-74.

Findings & solutions for Cu wire bonding

- Aging at 250°C is performed to study the Cu/Al IMC growth in Cu ball bonds.
- It is found that Cu/Al IMCs are mainly Cu_9Al_4 and $CuAl_2$, with CuAl present in smaller amounts.
- Cu/Al IMCs form at the bond periphery and extend towards the bond centre.
- Cavities also start to grow from the ball periphery towards the bond centre, and finally form a complete fracture between the upper IMC layer and the ball bottom surface.
- The IMC growth rate decreases gradually with the increasing aging time and stops when the fracture completes.

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Findings & solutions for Cu wire bonding

- Many factors affect the quality of copper wire bonds.
- Experimental and numerical approaches are mainly adopted to investigate wire bonding using copper wire.
- Experimental investigations are the basis for technology development and science discovery.
- Thus, bonding and testing experiments are typically conducted to evaluate the performance of wire-bonded devices.
- Optimal parameters result from proper selection and suitable design of experiments at the earliest stage of process development cycles.

Z.W. Zhong, Wire bonding using copper wire, Microelectronics International 26 (1) (2009) 10-16.

Alagumurthi, N., Palaniradja, K., Soundararajan, V. (2006), "Optimization of grinding process through design of experiment (DOE) - A comparative study", *Materials and Manufacturing Processes*, Vol. 21 No. 1, pp. 19-21.

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Findings & solutions for Cu wire bonding

- On the other hand, numerical investigations are also widely conducted because this approach can save cost, time and manpower for time-consuming experiments and tests.
- FEA is useful to discover facts or investigate processes in a way that no other tool can accomplish.
- There is increasing research on applying FEA to wire-bonded packages, although articles reporting FEA of Cu-wire-bonded packages are still scarce.

Z.W. Zhong, Wire bonding using copper wire, Microelectronics International 26 (1) (2009) 10-16.

Chen, K.M., Tang, K.H., Liu, J.S. (2008), "Reliability evaluation of BOAC and normal pad stacked-chip packaging using low-K wafers", *Microelectronics Reliability*, Vol. 48 No. 3, pp. 408-15.

Chen, K.M., Wu, B.C., Tang, K.H., Cheng, F.Y., Kao, N.H., Lai, J.Y. (2006), "An investigation into the effects of probing and wire bonding stress on the reliability of BOAC", *Microelectronics Reliability*, Vol. 46 No. 2-4, pp. 335-42.

Fiori, V., Beng, L.T., Downey, S., Gallois-Garreignot, S., Orain, S. (2007a), "3D multi scale modeling of wire bonding induced peeling in Cu/low-k interconnects: Application of an energy based criteria and correlations with experiments", *Proceedings - Electronic Components and Technology Conference*, pp. 256-63.

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Ishiko, M., Usui, M., Ohuchi, T., Shirai, M. (2006), "Design concept for wire-bonding reliability improvement by optimizing position in power devices", *Microelectronics Journal*, Vol. 37 No. 3, pp. 262-8.

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Tee, T.Y., Zhong, Z. (2004a), "Board level solder joint reliability analysis and optimization of pyramidal stacked die BGA packages", *Microelectronics Reliability*, Vol. 44 No. 12, pp. 1957-65.

Tee, T.Y., Zhong, Z. (2004b), "Integrated vapor pressure, hygroswelling, and thermo-mechanical stress modeling of QFN package during reflow with interfacial fracture mechanics analysis", *Microelectronics Reliability*, Vol. 44 No. 1, pp. 105-14.

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Findings & solutions for Cu wire bonding

- FEA of a Cu-to-Cu wire-bond forming process reveals that the bonding position significantly affects the local stress near the bond, and the wire should be bonded at the pad center.
- The stress is large if the pad size is close to the wire ball size.
- The bonding temperature also largely affects the stress.
- Raman spectroscopy combined with FEA is a helpful tool to investigate bonding stresses and optimize bonding parameters.

Chen, J., Degryse, D., Ratchev, P., De Wolf, I. (2004), "Mechanical issues of Cu-to-Cu wire bonding", *IEEE Transactions on Components and Packaging Technologies*, Vol. 27 No. 3, pp. 539-45.

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Findings & solutions for Cu wire bonding

- The traditional configuration with SiO_2 dielectric and Al interconnection layers is being replaced with low-*k* dielectrics and Cu interconnection layers.
- Numerical investigations reveal that the yield stress of the wire bond determines the pressure on the pad structure.
- A stiffer and thicker capping lowers local stresses under the bond edge.
- Cu and Au bond wires have a work-hardening effect.
- Higher forces are needed to form a Cu bond, leading to higher stresses in the pad structure.
- A stiffer capping redistributes the deformation over a larger area, resulting in a smaller local deformation in the metal layer at the bond edge, and the stress peak decreases.

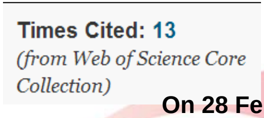
Degryse, D., Vandevelde, B., Beyne, E. (2004), "Mechanical FEM simulation of bonding process on Cu LowK wafers", *IEEE Transactions on Components and Packaging Technologies*, Vol. 27 No. 4, pp. 643-50.

Degryse, D., Vandevelde, B., Beyne, E. (2005), "Cu bonding to Cu low K wafers: a systematic study of the mechanical bonding process", *Proceedings of the 6th International Conference on Thermal, Mechanical and Multi-Physics Simulation and Experiments in Micro-Electronics and Micro-Systems*, pp. 41-8.

How to improve stitch bondability

- As the material of the bonding wire, 2N gold-alloyed wire, copper wire, insulated wire, etc. can be selected.
- Insulated wires are coated with a layer of insulation polymer of approximately 0.8-um thickness all round.
- In this study, the so-called 2N gold-alloyed wire used has a size of 25 um, and compositions of 99% gold and 1% palladium from Tanaka Denshi Kogyo K.K.
- The hardness of copper wire is approximately 25% higher than gold wire.
- The copper wire used in this study has a wire size of 25 um and 99.99% Cu from Tanaka Denshi Kogyo K.K.
- These wires are generally harder than 4N gold wire and are more difficult to bond especially for lead frame devices.
- Common stitch bond problems are wire open and non-sticking on lead.
- The challenge is how to improve the stitch bondability using these types of wires.

Goh, K.S., Zhong, Z.W. (2007), "A new bonding-tool solution to improve stitch bondability", *Microelectronic Engineering*, Vol. 84 No. 1, pp. 173-9.



Times Cited: 13
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On 28 Feb 2014

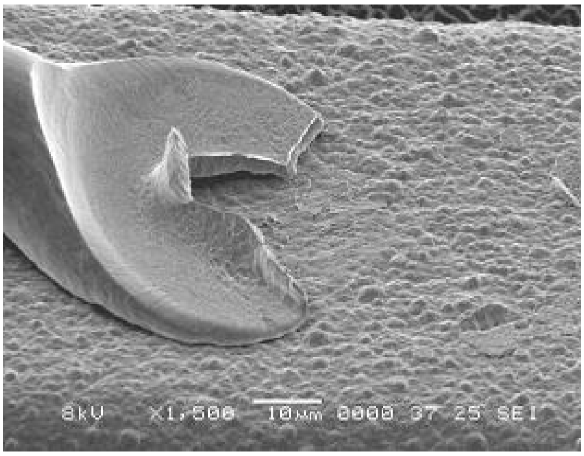
How to improve stitch bondability

- On the other hand, 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.
- Most of the times, the problems are only known after die attach and during wire bonding.
- The challenge is how to improve the stitch bondability using these types of lead frames/substrates.

Goh, K.S., Zhong, Z.W. (2007), "A new bonding-tool solution to improve stitch bondability", *Microelectronic Engineering*, Vol. 84 No. 1, pp. 173-9.

Bonding on a poor bondability lead frame

- 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.
- This is an indication of non-sticking on lead (NSOL).



Source: Goh, K.S., Zhong, Z.W. (2007), "A new bonding-tool solution to improve stitch bondability", *Microelectronic Engineering*, Vol. 84 No. 1, pp. 173-9.

A new bonding solution

- In wire bonding, the bonding tool is the capillary, which is a tiny hollow tube used to guide the wire and create ball and stitch bonds.
- The necessary bonding force and ultrasonic energy are transmitted/transferred to the wire and the bonding pad/substrate by the capillary to form the bonds.
- Besides wire diameter, free air ball, bonding force and ultrasonic vibration amplitude, critical capillary dimensions can also significantly affect the wire-bond formation.
- The critical dimensions include hole diameter, chamfer diameter, chamfer angle, face angle, inner chamfer, outer radius, and tip diameter.

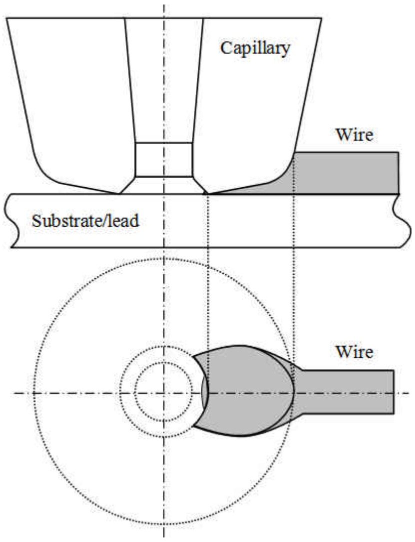
Goh, K.S., Zhong, Z.W. (2007), "A new bonding-tool solution to improve stitch bondability", *Microelectronic Engineering*, Vol. 84 No. 1, pp. 173-9.

A new bonding solution

- From the view of capillary design and manufacturing, possible solutions to the problems are optimization of tip diameter, face angle and outer radius, and new surface finishing of capillaries.
- There are limitations to the optimization of tip diameter, face angle and outer radius.
- The tip diameter is limited by the BPP of the devices.
- For example, for a BPP of 50 um, the maximum tip diameter is 63 um.
- Compared to the standard capillary design, a smaller face angle (8° compared to 11°) improves stitch bondability, but this leads to lower stitch pull readings.
- A smaller outer radius (5 um compared to 8 um) also improves stitch bondability, but this can cause heel crack.
- Thus, a new surface-finishing process for manufacturing of capillaries was developed as a new bonding tool solution to the problems addressed in this case study.

Goh, K.S., Zhong, Z.W. (2007), "A new bonding-tool solution to improve stitch bondability", *Microelectronic Engineering*, Vol. 84 No. 1, pp. 173-9.

Schematic diagram of stitch bond formation



- The behavior of wire is based on inter-diffusion of atoms across the mating interface.
- This causes the bonding wire and the bond surface to soften.
- A very small amount of heat is created in the bond from the ultrasonic energy transferred through the capillary.

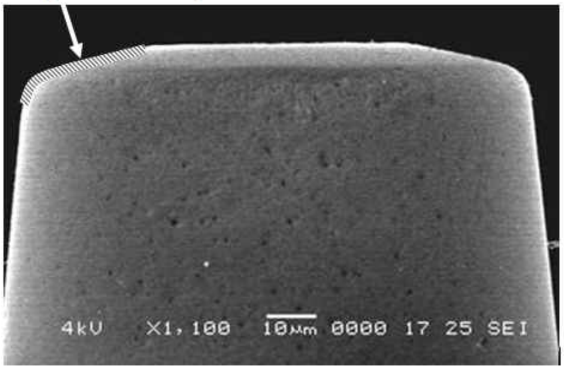
Source: Goh, K.S., Zhong, Z.W. (2007), "A new bonding-tool solution to improve stitch bondability", *Microelectronic Engineering*, Vol. 84 No. 1, pp. 173-9.

The portion of a capillary tip shown by a curved line has a direct impact on the stitch formation

- The portion of a capillary tip shown by a curved line has a direct impact on the stitch formation.
- To achieve good bondability for the stitch bond, the coupling effect between the capillary and the wire must be improved.
- This can be achieved by enhancing the morphology or texture of the capillary tip surface.

Source: Goh, K.S., Zhong, Z.W. (2007), "A new bonding-tool solution to improve stitch bondability", *Microelectronic Engineering*, Vol. 84 No. 1, pp. 173-9.

This portion shown by a curved line



A new bonding solution

- Roughness was used as the basis for the surface morphology control by most of the capillary manufacturers.
- Roughness is of significant interest because it determines the friction of the capillary tip surface in contact with the wire surface.
- This affects the bondability and the load-up rate.
- As the BPP becomes smaller, the effect of the capillary-tip surface roughness on improvement of bondability has become less significant.
- Given the current situation with the batch-to-batch variations of the substrate materials, a new capillary-tip surface morphology needs to be developed.

Goh, K.S., Zhong, Z.W. (2007), "A new bonding-tool solution to improve stitch bondability", *Microelectronic Engineering*, Vol. 84 No. 1, pp. 173-9.

A new bonding solution

- In terms of the new capillary-tip surface morphology, we look at the surface texture instead of roughness.
- Surface texture is the combination of roughness, waviness and lay (lay refers to the direction of the surface texture).
- Through extensive studies and optimizations, a unique surface characteristic on the capillary tip surface has been derived.
- Reported with detailed experimental results, this feature has proven to improve the stitch bondability for a wide variety of wire-bonding applications using various wires and lead frames.
- Compared to the standard capillary, the new 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.
- The deep lines also serve as reservoirs for small particles to escape, which may come from the out-gassing or the lead frame/substrate.

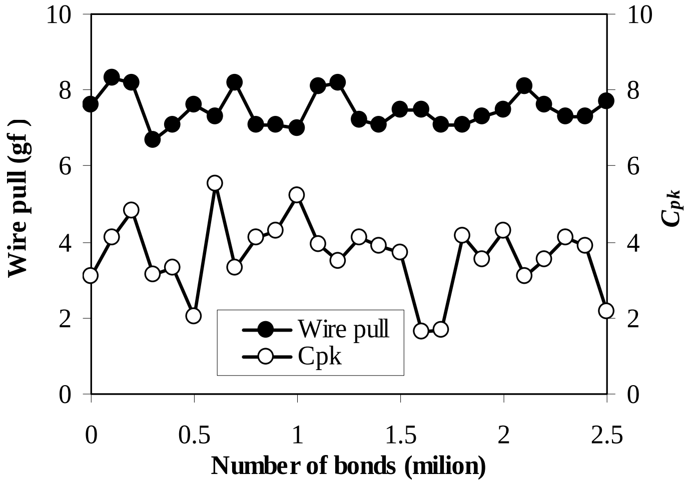
Goh, K.S., Zhong, Z.W. (2007), "A new bonding-tool solution to improve stitch bondability", *Microelectronic Engineering*, Vol. 84 No. 1, pp. 173-9.

Bonding on unstable lead frames/substrates

- Some low-cost lead frames/substrates with large batch-to-batch variations are unstable lead frames/substrates.
- Typical problems in wire bonding on such lead frame/substrates are non-sticking on lead and short tail, which lead to increased machine-down time.
- To overcome such problems, the capillary must be more robust to handle the variations.
- The use of the new capillary has proven to minimize the occurrence of non-sticking on lead and short tail defects during wire bonding.
- Bonding experiments were carried out using 60-um BPP devices with such lead frames, the new capillary, and 25-um gold wire.
- Ball shear and wire pull tests were performed after wire bonding. The bonding criterion was minimum 3 gf wire pull.

Goh, K.S., Zhong, Z.W. (2007), "A new bonding-tool solution to improve stitch bondability", *Microelectronic Engineering*, Vol. 84 No. 1, pp. 173-9.

Wire pull readings and C_{pk} values versus the number of bonds

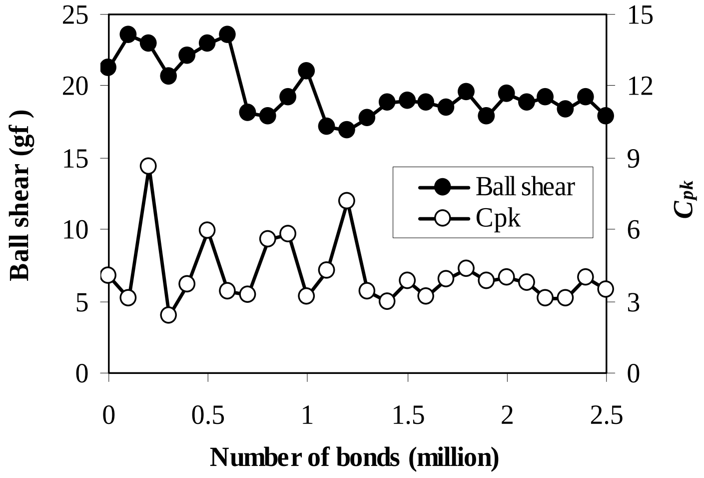


C_{pk} = (Average reading – Minimum specification limit)/(3σ)

σ is the standard deviation

Source: Goh, K.S., Zhong, Z.W. (2007), "A new bonding-tool solution to improve stitch bondability", *Microelectronic Engineering*, Vol. 84 No. 1, pp. 173-9.

Ball shear readings and C_{pk} values versus the number of bonds



Source: Goh, K.S., Zhong, Z.W. (2007), "A new bonding-tool solution to improve stitch bondability", *Microelectronic Engineering*, Vol. 84 No. 1, pp. 173-9.

Machine statistics: numbers of bond count, non-sticking on lead (NSOL), wire open and short tail defects

No. of bond counts	No. of setting	No. of NSOL	No. of wire open defects	No. of short tails
0K	100K	0	0	0
1000K	1100K	2	0	0
2400K	2500K	6	0	5

Source: Goh, K.S., Zhong, Z.W. (2007), "A new bonding-tool solution to improve stitch bondability", *Microelectronic Engineering*, Vol. 84 No. 1, pp. 173-9.

Bonding on unstable lead frames/substrates

- The bonding performance of the new capillary and a standard capillary was also compared.
- The defect rate produced using the new capillary was 4,500 PPM (parts per million), only 28% of the defect rate (15,936 PPM) produced using the standard capillary.
- The defect rate reduction was 72%.
- The stitch defect rate due to non-sticking on lead, wire open and short tail problems produced using a standard capillary could be significantly reduced by using the new capillary.

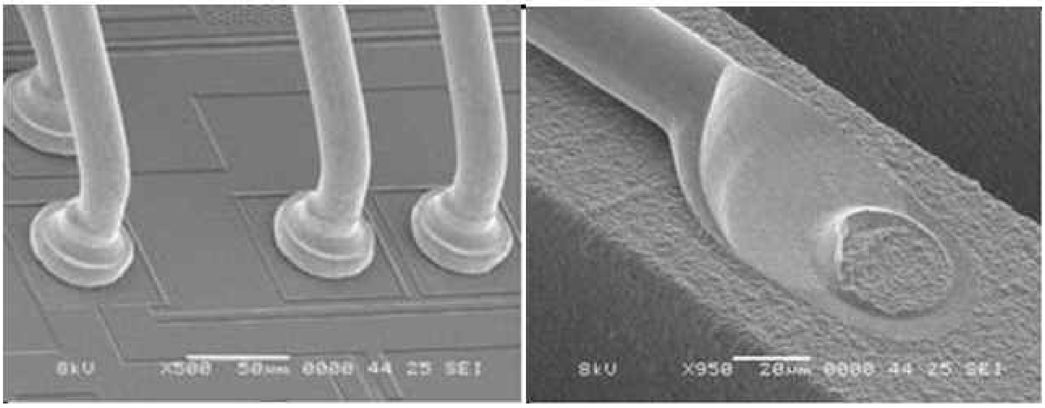
Goh, K.S., Zhong, Z.W. (2007), "A new bonding-tool solution to improve stitch bondability", *Microelectronic Engineering*, Vol. 84 No. 1, pp. 173-9.

Bonding using 2N gold wire

- 2N gold wire with 99% purity typically consists of 1% palladium.
- The wire is harder than gold wire due to the addition of 1% palladium to the gold wire.
- A typical problem for bonding on QFP devices using harder wire is that the operating window is very narrow due to non-sticking on lead or wire open.
- The main challenge in such wire bonding is to be able to bond continuously without stoppages.
- The new capillary has proven to improve the bondability of the stitch bond with the enhanced coupling effect.
- Bonding experiments were performed using 70-um BPP QFP devices, the new capillary, 25-um 2N wire, and an ASM Eagle 60 wire bonder.

Goh, K.S., Zhong, Z.W. (2007), "A new bonding-tool solution to improve stitch bondability", *Microelectronic Engineering*, Vol. 84 No. 1, pp. 173-9.

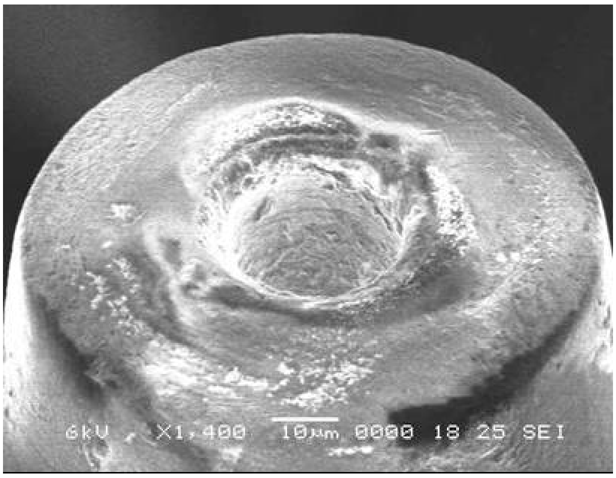
Samples of ball and stitch bonds of the 2N wire



The new capillary helps to enhance the capillary coupling effect on the wire during bonding, hence improving the bondability of the stitch bond.

Source: Goh, K.S., Zhong, Z.W. (2007), "A new bonding-tool solution to improve stitch bondability", *Microelectronic Engineering*, Vol. 84 No. 1, pp. 173-9.

Capillary tip condition at 600,000 bonds



At 600,000 bonds, the load-up on the capillary is also satisfactory with no excessive loading (The standard tool life is set at 500,000 bonds).

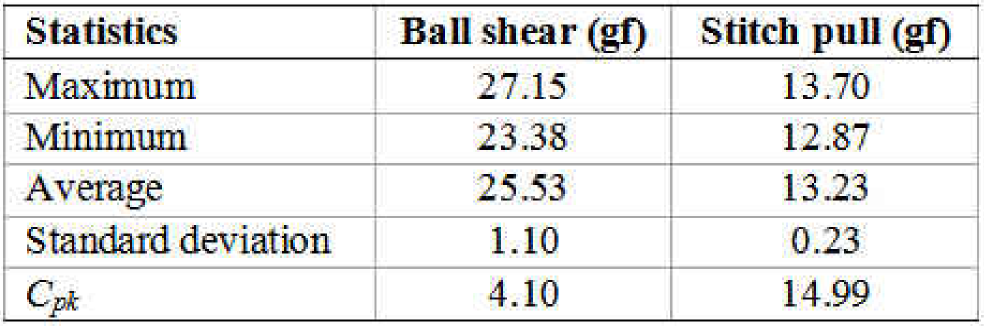
Source: Goh, K.S., Zhong, Z.W. (2007), "A new bonding-tool solution to improve stitch bondability", *Microelectronic Engineering*, Vol. 84 No. 1, pp. 173-9.

Bonding using copper wire

- Because copper wire is generally harder, to improve stitch bondability, higher parameter settings were used, causing heavy cap marks and potential short tails or wire open.
- Cu/Au stitch bonds are weak.
- Thus, copper wire bonding has wire open and short tail defects, poor process control, and low stitch pull readings.
- Examples of stitch pull readings of copper wire bonds produced using a standard capillary are minimum reading = 4.7 gf, maximum reading = 9.0 gf, average reading = 6.3 gf, standard deviation = 1.8 gf, and C_{pK} = 0.61 gf.

Goh, K.S., Zhong, Z.W. (2007), "A new bonding-tool solution to improve stitch bondability", *Microelectronic Engineering*, Vol. 84 No. 1, pp. 173-9.

Ball shear and stitch pull test results (copper wire bonding using the new capillary and 70-um BPP BGA devices)

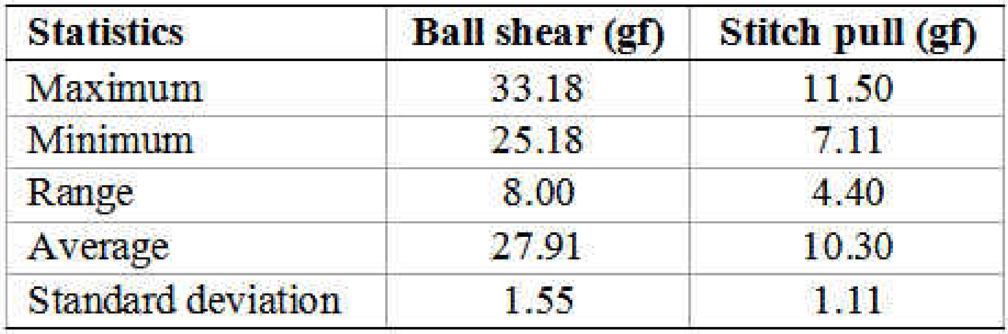


Statistics	Ball shear (gf)	Stitch pull (gf)
Maximum	27.15	13.70
Minimum	23.38	12.87
Average	25.53	13.23
Standard deviation	1.10	0.23
C_{pk}	4.10	14.99

- Bonding experiments using the new capillary were conducted with 70-um bond-pad-pitch BGA devices and 25-um copper wire.
- Ball shear strength and stitch pull tests were performed after wire bonding.
- The table shows satisfactory results confirmed by the ball shear and stitch pull tests.

Source: Goh, K.S., Zhong, Z.W. (2007), "A new bonding-tool solution to improve stitch bondability", *Microelectronic Engineering*, Vol. 84 No. 1, pp. 173-9.

Ball shear and stitch pull test results (copper wire bonding using the new capillary)

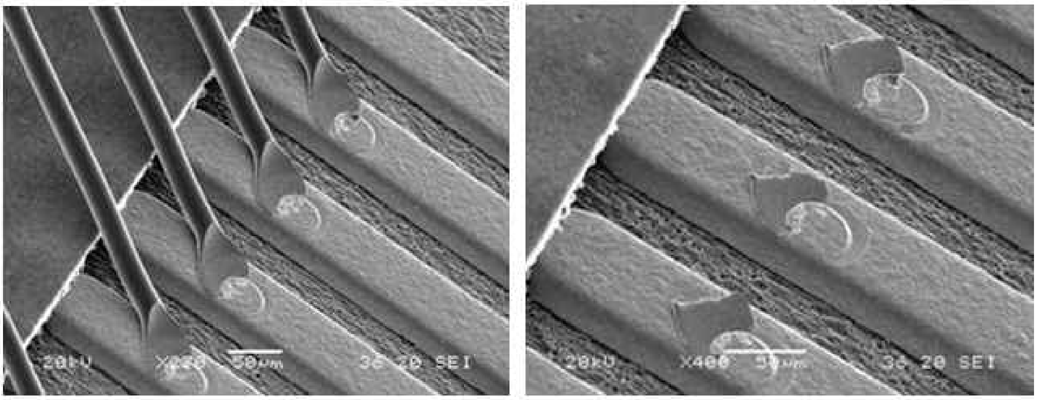


Statistics	Ball shear (gf)	Stitch pull (gf)
Maximum	33.18	11.50
Minimum	25.18	7.11
Range	8.00	4.40
Average	27.91	10.30
Standard deviation	1.55	1.11

- Bonding experiments using the new capillary were also performed with 100-um BPP BGA devices and 25-um copper wire, and ball shear strength and stitch pull tests were conducted after wire bonding.

Source: Goh, K.S., Zhong, Z.W. (2007), "A new bonding-tool solution to improve stitch bondability", *Microelectronic Engineering*, Vol. 84 No. 1, pp. 173-9.

SEM pictures of copper stitch bonds before and after the stitch pull test



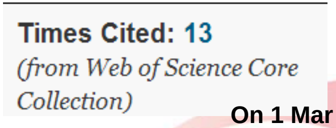
Bonding experiments using the new capillary were performed with 100-um bond-pad-pitch BGA devices and 25-um copper wire.

Source: Goh, K.S., Zhong, Z.W. (2007), "A new bonding-tool solution to improve stitch bondability", *Microelectronic Engineering*, Vol. 84 No. 1, pp. 173-9.

Wire bonding using insulated wire

- **Advantages**
- Challenges/problems
- Solutions/findings

Z.W. Zhong, Wire bonding using insulated wire and new challenges in wire bonding, Microelectronics International 25 (2) (2008) 9-14.


Times Cited: 13
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On 1 Mar 2014

Advantages of insulated wire

- A problem using small wire sizes in a microelectronics package is that a wire may short to another conductive structure due to sweeping, which may occur during encapsulation when the liquid encapsulant moves the soft wire towards another conductive structure.
- Smaller diameter wires tend to have higher wire sweeping and shorting rejects.
- Besides using copper wire, using insulated wire can be one of the solutions to the wire shorting problem.

Downey, S.H., Harper, P.R. (2006), "Packaged IC using insulated wire", *US Patent 7138328*.

Harun, F., Chan, C.M., Tan, L.C., Beng, L.T., Tiu, K.B., Yong, S.S. (2007), "Wirebonding insulated wire and capillary therefor", *US Patent 7261230*.

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 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 BPPs 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.

Goh, K.S., Zhong, Z.W. (2007), "Two capillary solutions for ultra-fine-pitch wire bonding and insulated wire bonding", *Microelectronic Engineering*, Vol. 84 No. 2, pp. 362-7.

Times Cited: 15
(from Web of Science Core Collection)

On 28 Feb 2014

A capillary solution for insulated wire bonding

- 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.
- A standard finishing for a capillary tip surface was matt finishing.
- Through extensive studies and optimizations, a unique surface characteristic on the capillary tip surface has been derived.
- The new finishing process developed creates a new surface morphology, which has relatively deep lines with no fixed directions.

Goh, K.S., Zhong, Z.W. (2007), "Two capillary solutions for ultra-fine-pitch wire bonding and insulated wire bonding", *Microelectronic Engineering*, Vol. 84 No. 2, pp. 362-7.

Times Cited: 15
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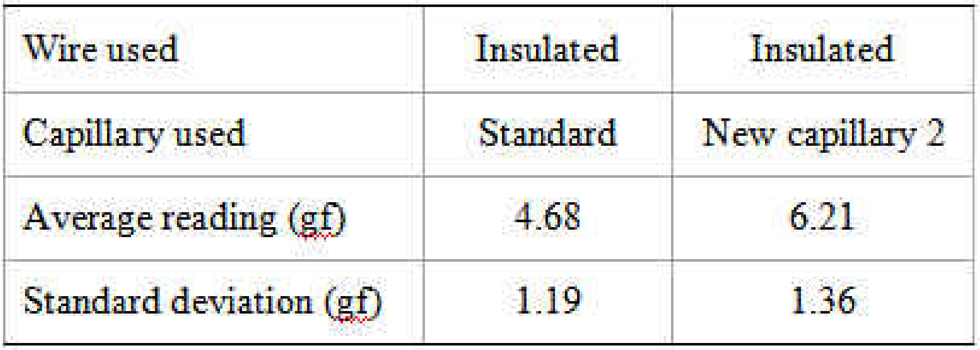
On 28 Feb 2014

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

Source: Goh, K.S., Zhong, Z.W. (2007), "Two capillary solutions for ultra-fine-pitch wire bonding and insulated wire bonding", *Microelectronic Engineering*, Vol. 84 No. 2, pp. 362-7.

A capillary solution for insulated wire bonding

- Bonding experiments were carried out using an ASM Eagle wire bonder, PBGA devices with a 65-μm BPP, ϕ25-μm insulated wire, and a standard capillary and this new capillary.
- Stitch pull test were then conducted.
- 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 the new capillary 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.
- 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.
- Compared to the standard capillary, the new capillary 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.
- Thus, this new capillary has been used to effectively improve the bondability of the stitch bonds for insulated wire bonding.

Goh, K.S., Zhong, Z.W. (2007), "Two capillary solutions for ultra-fine-pitch wire bonding and insulated wire bonding", *Microelectronic Engineering*, Vol. 84 No. 2, pp. 362-7.