Ročník 2013 electroscope Číslo V

Wire-bonds Durability in High-temperature Applications

M. Klíma, B. Psota, I. Szendiuch

Department of Microelectronics, Faculty of Electrical Engineering and Communication, Brno University of Technology, Technická 3058/10, Brno, Czech Republic
E-mail : xklima01@stud.feec.vutbr.cz, xpsota031@stud.feec.vutbr.cz, szend@feec.vutbr.cz

Abstract:
This work aims to determine the suitability of use of low-temperature co-fired ceramics (LTCC) and thick film technology in applications with semiconductors based on SiC and GaN, which have high operating temperature. Especially, Heraeus HeraLock 2000 substrate is investigated. The paper is mainly focused on the behaviour and reliability of wire-bonds, which are used for connection of the above-mentioned semiconducting devices with a circuit or a package. A test sample was designed for this purpose, which was subjected to thermal load. Subsequently, changes in the bonds resistivity were studied, together with their strength and any defects caused by the thermal load. Other properties, such as termomechanical stress of the material for different temperature profiles were simulated in the ANSYS software. Created mathematical model simulated and compared differences between gold and aluminium wire-bond.

INTRODUCTION

Nowadays, the interest in high-temperature applications on low-temperature co-fired ceramic rises. It is caused by a new direction in semiconductor technology, especially by introduction of SiC and GaN semiconductors conditioned for power, high-frequency or sensoric applications.

Operating temperature of these devices ranges from 250 to 500 °C (theoretically up to 850 °C) [1], which is beyond feasibility of commonly used materials in consumer electronics. It is ceramic substrates in connection with thick-film technology particularly, that can broaden the usage of these semiconductors. Creation of chip-carrier or complete package is possible. High-Temperature Co-Fired Ceramic (HTCC) or LTCC is useable. For this research, LTCC was chosen, because of its simple processing and wide possibilities of modification. Its operating temperature depends on its type; it reaches up to 600 °C for most of available types. Additionally, LTCC allows fabrication of multilayer circuit boards and 3-dimensional structures. This fact can be utilized in design of cooling elements or cooling by a fluid [2]. Because LTCC allows also creation of conductive motive and passive circuit elements (R, C, L), formation of complete temperature resistive circuit in one package is possible. Of course, LTCC can be used in many other applications with high operating temperature, such as sensors, automotive, aerospace or cosmic applications.

Maximal operating temperature for used LTCC type Heraeus HeraLock 2000 (HL2000) is not known yet. It is presupposed that it is also up to 600 °C as for other LTCC substrates. The main advantage of HL2000 is its nearly zero-shrinkage during LTCC firing. Therefore, design of a package is easier.

One of the most important things, which must be solved ahead of commencing further experiments, is the connection between semiconductor chip and the electric circuit [3]. There are more possible solutions, but because of its availability, attention will be focused only on wire-bonding using gold microwire to create a conductive junction between the substrate and the chip (bare die). Aluminium microwire is also investigated, even though it is not so thermally stable, in comparison with gold one.

DESIGN OF TEST SAMPLE

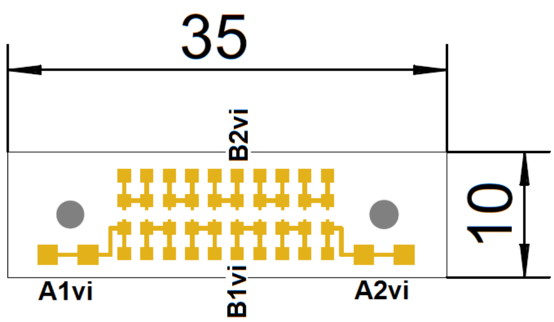

Fig. 1: Design of test sample

A test sample was designed for this purpose as seen in Fig. 1. For enhancement of strength and securing the planarity, the substrate is built up by three layers of HL2000, while each layer with size of 10 x 35 mm is provided with two pin-holes (2 mm in diameter) for matching during the lamination process. Thickness of fired substrate is about 300 µm and thermal conductivity 3 W·mK^{-1}, so the substrate is not a significant obstacle to heat distribution. Axial press was used for lamination.

Changes of wire-bonds quality after application of thermal load were assessed by resistivity measurement and tensile strength pull-test. Elements needed for measurement were included in the design. A conductive motive was formed by a chain of conductive pads for connection of ten bonds, because of increasing resistivity change. Four-point method was chosen for more precise measurement of resistivity. Conductive pads were placed into design – pairs of pads A1vi and A2vi are used to measure the total chain resistivity, type of pads B1vi and B2vi is used to measure resistivity of each bond.

Manufacturing of the test sample

The conductive motive was printed with a gold-based thick-film paste Heraeus TC8101. This paste is bondable. Resistance to oxidation at high temperatures is supposed. Screen-printing was used for paste deposition. The sample was fired on standard temperature profile according to manufacturer's recommendation. The test sample prepared for wire-bonding is shown on figure 2.

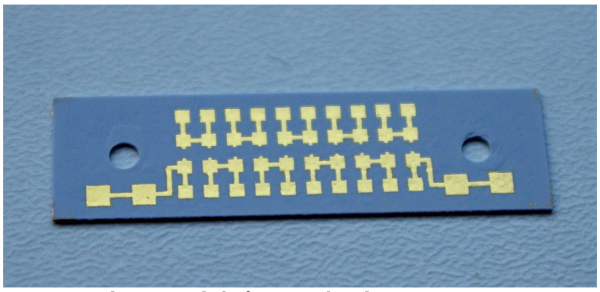

Fig. 2: Fired test sample before wire-bonding

The gold wire was chosen, because of material compatibility with used paste, which is highly resistant to corrosion, migration and has good conductivity [4] [5] [6]. The gold wire-bonds (25 µm in diameter) were made by ultrasonic wire-bonder. Used parameters are presented in table below.

Settings of wire-bonding parameters

	First weld	Second weld
Power	270 mW	290 mW
Force	300 mN	320 mN
Time	320 ms	250 ms
Temperature	50 °C	50 °C

VERIFICATION OF MATEMATICAL MODEL

Overview

The structure mentioned above was modelled in simulation software ANSYS Workbench. Thanks to the virtual model we have obtained first insight into the wire-bond behaviour in the high temperature environment in a short time. Moreover, we have located the most temperature stressed places as well as the temperature distribution in the system.

Settings

The virtual model is symmetrical along the X axis. This fact was used within the model creation, where we have made only half of the system. Half-model simulation allows usage of finer mesh, which brings better results. This method saves computing time. Final model can be seen in the Fig. 3.

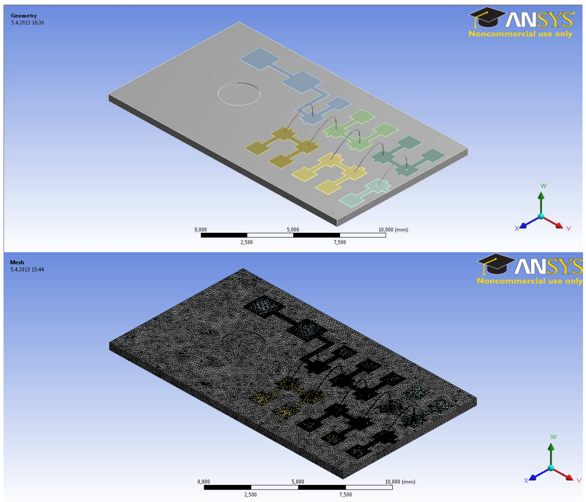

Fig. 3: Virtual model (top) and the meshed structure (bottom)

In the simulation process, combination of the thermal and mechanical analysis was used. In the first step, the virtual structure was thermally loaded and afterwards the equivalent stress for the wire-bonds was calculated. The boundary conditions were set according to the temperature profile, shown in Fig. 4, with maxima at 400°C and 300°C.

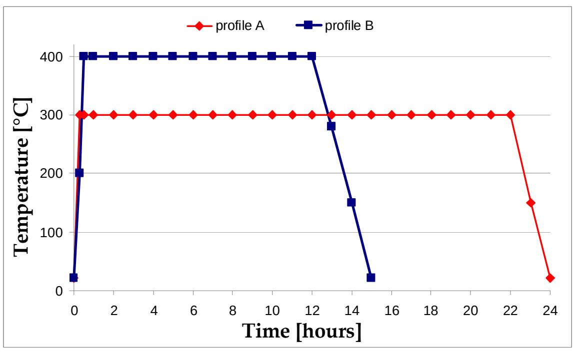

Fig. 4: Temperature profiles for input data

In the simulations, two basic materials for wire-bonding were used - gold and aluminium. Both materials were chosen because of their availability. Materials were compared and more suitable material for usage at high temperature was determined. Required material data for thermo-mechanical simulations are Young´s Modulus, Poisson´s ratio, coefficient of thermal expansions, thermal conductivity, specific heat and density; these are summarized in table below.

Material data of gold and aluminium

Material property	Au	Al
Density [g.cm^{-3}]	19,3	2,77
TCE [ppm.C^{-1}]	14	23,1
Young´s Modulus [GPa]	79	71
Poisson´s Ratio [-]	0,42	0,33
Thermal Conductivity [W.m.K^{-1}]	318	148
Specific Heat [J.kg^{-1}.C^{-1}]	128	875

Results

The desired output from the simulations was the mechanical stress of the structure, which in our case is represented by the Equivalent (von Mises) stress. Total deformation of the structure is also mentioned.

The example of the system deformation is shown at the next picture (see Fig. 5). Result is dependent on the fix point, which is set. In this case, the deformation is related to the center of the model.

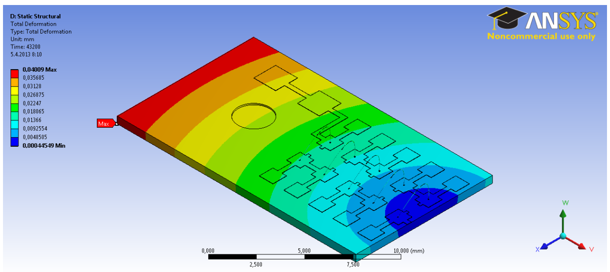

Fig. 5: Total deformation of the structure

The mechanical stress was lower for gold wire and also deformation of the structure reached lower values. This result was same in both profiles. However, the differences were not so big in the life-time cycle to form a significant reliability aspect.

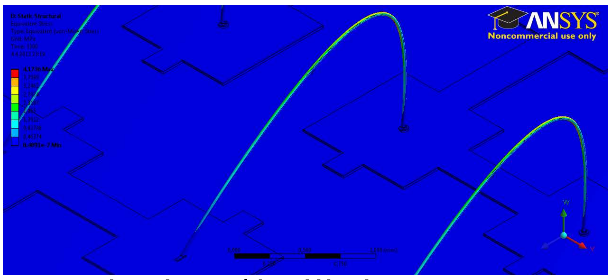

Fig. 6: Mechanical stress of the gold bond

Although, the stress was different for both materials, the point with the biggest stress value was the same for both configurations, as we can see in Fig. 6, and it appeared on the top of the bond. This could cause various troubles, because the highest temperature is also in this location. The most probable cause is worse heat sink from the top, because of long distance from substrate. Therefore, it will be necessary to protect the wire by some additional material, for example glass-based filler, which could decrease maximal temperature of the whole created structure, because of lower melting point or different coefficient of thermal expansion. The situation is shown in Fig. 7.

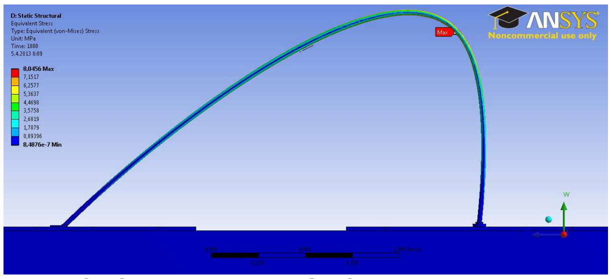

Fig. 7: The aluminium wire stress distribution

Performed simulations revealed that the gold wire material is better for high temperature application. Although stress level does not reach critical values it is prerequisite to protect the wire-bond. The temperature as well as mechanical stress would be much higher, if the current flow through the wire is included in the calculation.

MEASUREMENT

Thermal loading

After wire-bonding, groups of samples were put into a batch furnace, which was used similarly to a climatic chamber. Samples were subjected to constant temperatures in range of 300 – 850 °C for different count of twenty-four hours cycles. The 850 °C cycle was just informative and it took one hour. After each step, the resistivity of samples was measured and compared with default resistivity. Pull test on a Dage PC2400 device followed on to determine the mechanical strength of the bonds. Changes in the quality of the bonds were evaluated optically.

Measurement of wire-bonds resistivity

Four-point method was used for measurement of bonds resistivity. After each cycle, two samples were put away and were not subjected to cycling. These were measured. Final value represents an average of twenty values of wire-bond resistivity (two samples). As you can see on fig. 8, there is a change of bonds resistivity after exposition to high temperature. Measurement of the chain shows very similar results and measured resistivity (after cycling) was always lower then default. Unfortunately, it is not possible to conclude any rule due to the measurement error.

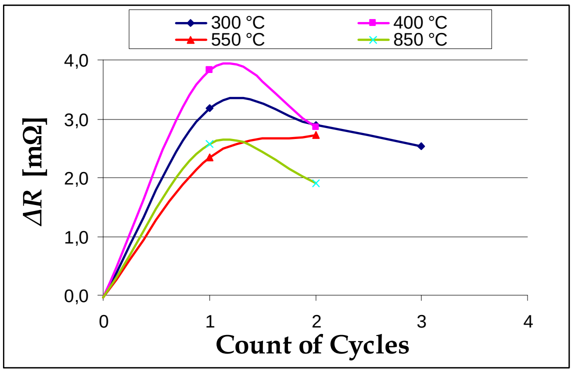

Fig. 8: Change of wire-bonds resistivity during temperature cycling

Measurement of tensile strength

Bonding of thick-film layers is accompanied with huge range of bonds' tensile strength. It is caused by relatively big and patchy roughness of a surface, which is typical for thick-film layers. On this layer, it is usually possible to create bond with tensile strength from 6 to 14 g. Results of the pull-test showed standard tensile strength of bonds which were not cycled. As it is shown in fig. 10, tensile strength is decreasing with thermal load. As in previous case, only trend of tensile strength decrease can be determined, but it is probable that higher thermal load will cause bigger decrease. An interesting finding is that the bonds cycled at lower temperature were torn in the substrate, unlike the bonds cycled at higher temperature which were torn in the middle. That could correspond with simulation result, that the most stressed point of wire-bond is the top.

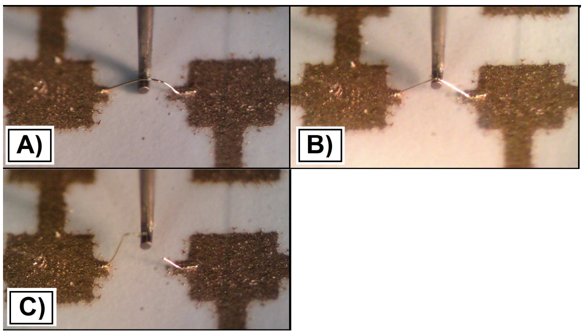

Fig. 9: Progression of the pull-test: A) Tool placing; B) Increasing of force; C) Tearing of the wire

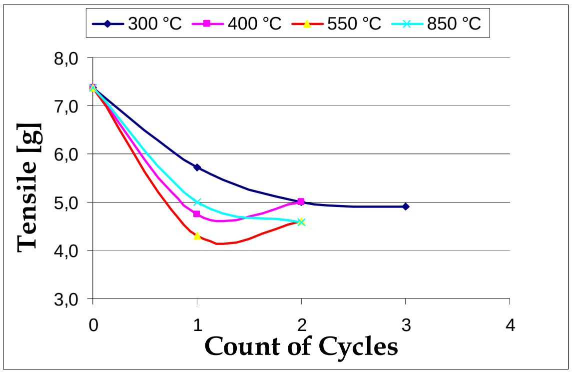

Fig. 10: Change of wire-bonds strength during temperature cycling

For pull-test, Dage PC2400 *Micro* Bond Tester was used.

SUMMARY

The main goal of this research was to specify reliability of gold wire-bonds on LTCC substrate at high operating temperature. The gold wire was chosen for its oxidation resistance and availability. A test sample was designed for this purpose. The sample was also simulated in ANSYS software. Aluminium wire was also included for simulations for its availability too, however, significant degradation at high temperatures is expected.

On the base of simulation results, the gold bond showed better results, as supposed, especially due to lower deformation. The simulation also showed the most stressed point of bond on the top of its loop. It could explain why more thermally loaded bonds were torn in the middle during the pull-test. Worse heat sink from that area could be an explanation. Addition of glass-based filler could solve this problem. Nonetheless, this solution decreasing maximal operating temperature, because of its lower melting point, and its coefficient of thermal expansion (TCE) has to be the same as TCE of wire-bond. Simulation of aluminium wire showed also satisfying results, but worse stability at high temperature is supposed.

Measuring of resistivity change caused by thermal load did not show any significant trends. Four-point method was used. Each value represents average of twenty measured wire-bond resistivities (two measured samples). After cycling above 300 °C, the resistivity is decreased in most cases by a few mΩ, which is negligible. Measurement of whole wire-bond chain had very similar results and also trend. Results do not depend on count of cycles significantly.

Results of pull-test confirm an available tensile strength of bond on LTCC substrate (F = 7 g). Decrease of tensile strength due to thermal loading is apparent; it decreases approximately by 2 g, which can be insufficient for some application. Interesting finding is that the bonds cycled at lower temperature were torn in the substrate, unlike the bonds cycled at higher temperature, which were torn in the middle. This corresponds with the simulations and it shows the most stressed point of wire-bond after application of thermal load.

Based on the found information, we can say that the usage of gold wire-bonds on LTCC substrate at high operating temperature is possible for civil applications [7].

ACKNOWLEDGEMENT

Funding for this research was supported through grant project of the Czech Ministry of Education for Brno University of Technology FEKT-S-11-5/96 “Research of excellent technologies for 3D packaging and interconnection”. Financial support from CEITEC (Central European Institute of Technology Centre) CZ.1.05/1.1.00/02.0068 project is also highly acknowledged.

[1] Bienert, C., Roosen, A. Characterization and improvement of LTCC composite materials for application at elevated temperatures. *Journal of the European Ceramic Society*. 2010, vol. 30, no. 2, pp. 369-374. ISSN 09552219. DOI: 10.1016/j.jeurceramsoc.2009.05.023. Available from WWW: <http://linkinghub.elsevier.com/retrieve/pii/S0955221909002568>.

[2] Nowak, D., Dziedzic, A. LTCC package for high temperature applications. *Microelectronics Reliability*. 2011, vol. 51, no. 7, pp. 1241-1244. ISSN 00262714. DOI: 10.1016/j.microrel.2011.02.018. Available from WWW: < http://linkinghub.elsevier.com/retrieve/pii/S0026271411000692>.

[3] Johannessen, R., Oldervoll, F., Strisland, F. High temperature reliability of aluminium wire-bonds to thin film, thick film and low temperature co-fired ceramic (LTCC) substrate metallization. *Microelectronics Reliability*. 2008, vol. 48, no. 10, pp. 1711-1719. DOI: 10.1016/j.microrel.2008.06.008. Available from WWW: <http://www.sciencedirect.com/science/article/ pii/S0026271408001637#>.

[4] Lopez, C., Chai, L., Shaikh, A., Stygar, V. Wire bonding characteristics of gold conductors for low temperature co-fired ceramic applications. *Microelectronics Reliability*. 2004, vol. 44, no. 2, pp. 287-294. ISSN 00262714. DOI: 10.1016/S0026-2714(03)00195-1. Available from WWW: <http://linkinghub.elsevier.com/retrieve/pii/S0026271403001951>.

[5] Kosina, P., Hejatkova, E., Sandera, J. Vapour deposition on LTCC for 3D structure. *Electronics*. 2008, vol. 2008, no. 1, pp. 115 - 120. ISSN 1313-1842. Available from WWW: <http://ecad.tu-sofia.bg/et/2008/ET2008_Book4/Technologies%20in%20Electronics/115-Paper-P_Kosina2.pdf>.

[6] HERAEUS. *Advanced material TC8010* [Co-Fired Gold Conductor]. 2013 [cit. 7.4.2013]. Available from WWW: <http://heraeus-thickfilm.com/media/webmedia_local/media/datasheets/ltccmaterials/TC8101.pdf>.

[7] Klima, M., Pstota, B., SzendiuchH, I. Wire-Bonds Durability in High- Temperature Applications. In *Electronic Devices and Systems - IMAPS CS International Conference 2013*. first. Brno: VUT, 2013. pp. 38-43. ISBN: 978-80-214-4754- 7.