Light Metals 2014
Edited by: John Grandfield
TMS (The Minerals, Metals & Materials Society), 2014

Light Metals 2014

ALUMINUM ALLOYS: DEVELOPMENT, CHARACTERIZATION AND APPLICATIONS

Corrosion and Fatigue

SESSION CHAIR
Tongguang Zhai
University of Kentucky
Lexington, KY, USA

Light Metals 2014
Edited by: John Grandfield
TMS (The Minerals, Metals & Materials Society), 2014

A NEW APPROACH FOR EVALUATION OF FATIGUE LIFE OF Al WIRE BONDS IN POWER ELECTRONICS

Golta Khatibi, Martin Lederer, Bernhard Czerny, Agnieszka Betzwar Kotas, Brigitte Weiss
Faculty of Physics, University of Vienna, Boltzmanngasse 5, A-1090 Wien, Austria

Keywords: Al Wire, Ultrasonic Bonding, Accelerated Testing, Fatigue, Reliability

Abstract

Ultrasonically bonded Al wire bonds on Al metallization pads are widely used in power semiconductors. The required long time reliability of the devices is highly dependent on the interfacial quality of Al wire and the bond pad. Reliability of wire bonds is commonly assessed by thermal and power cycling tests. Accelerated mechanical fatigue testing can be used as an alternative to these time consuming procedures. In the present study, lifetime of thick Al wedge bonds on Si substrates was investigated using a novel mechanical fatigue testing technique operating at high frequencies and elevated temperatures. The influence of microstructure, testing temperature and frequency on lifetime of Al wire bonds was investigated. Finite element analysis was applied to calculate the stress distribution at the interfacial region and to establish life time prediction curves. The results of mechanical isothermal fatigue curves were compared and correlated with thermal cycling data of Al wire bonds.

Introduction

Wire bonding is one of the most commonly used interconnection technologies in electronics due to its cost effectiveness and flexibility. Ultrasonic bonding is a solid state bonding process which is achieved by application of ultrasonic energy, pressure and time at low temperatures. A large variety of Al wires with different thickness and purity are used in semiconductor industry. Ultrasonic Al wedge bonds with diameters of 300 to maximum 500µm are commonly used in high power semiconductors to provide electrical connection between the silicon chip and the external leads of the devices [1]. An exemplary image of heavy Al wire bonds as used in power modules is shown in figure 1. It has been reported that wire bond-related failures count for more than 25 % of the total reliability problems of electronic devices during the manufacturing and testing conditions. Thus evaluation of the wire bond quality especially for high safety and long life applications is of extremely high importance. Failure of interconnects in microelectronics is mostly related to thermo-mechanical, vibrational and electrical loading during the fabrication and subsequent operational life. The main failure mechanism of wire bonded interconnects are wire bond lift-off and heel cracking. Lift-off failure type refers to separation of the wire from the bonding pad resulting in loss or degradation of electrical and mechanical connection and is mainly related to the thermal mismatch between the Al wire and silicon chip. During the operational life shear stresses are initiated in the bonding interface as a result of heating and cooling cycles which may lead to crack initiation, growth and final failure of the interconnect. Wire bond heel cracking refers to the breakage of the wire above the bonded area as a result of flexural fatigue due to repeated expansion and contraction of the wire loop during the temperature cycles [1].

A variety of established isothermal and thermal tests based on relevant standards are used for qualification of microelectronic components. These tests include simple shear or pull test for determination of wire bond strength and are extended to power or thermal cycling of devices. Since common thermal cycling procedures are extremely time consuming in many cases high temperature excursions and shorter dwell times are applied in order to reduce the testing duration [2]. For example a typical accelerated power cycling test can be conducted at a ΔT of up to 90°C and a heating /cooling cycles of about 60 seconds. However in many cases thermal acceleration might lead to faulty failure mechanisms which do not occur during the service life.

As an alternative to time consuming thermal and power cycling tests isothermal mechanical fatigue testing has been proposed as a method for rapid screening and qualification of interconnects in microelectronics [3]. This technique is based on using high frequency mechanical fatigue testing set-ups in order to induce stresses equivalent to those occurring during the thermal loading of a component in a significantly shorter testing time. Moreover the induced failure mechanisms resemble those occurring during thermal / power cycling procedures or service life. Lifetime prediction curves can be obtained by using analytical approaches and FEM simulations comparable with conventional power cycling reliability diagrams.

In the present study, lifetime of thick Al wedge bonds as used in commercial high power semiconductor modules (IGBTs) has been determined by using accelerated mechanical fatigue testing techniques. Two different types of experimental set-ups have been used in order to reproduce wire bond lift-off failure and heel cracking as typical failure modes in wire bonded interconnects. Finite element modelling was applied for calculation of stress/strain plots during fatigue loading and subsequent lifetime modelling.

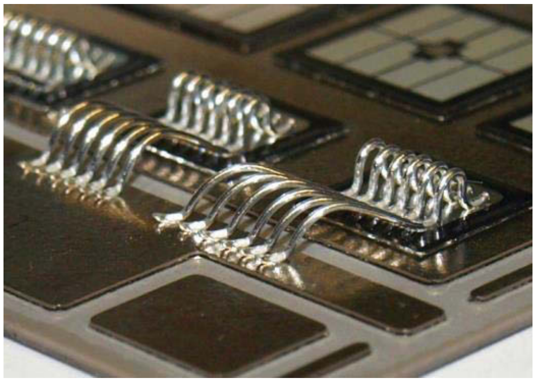


Figure 1: Image of Al wire bonds of a power semiconductor module

Experimental Details

Principles of Fatigue Testing Methods

The experimental set-ups used for fatigue testing of the wire bonds are shown in Fig 2a and 2b. A special set-up in combination with a vibrating system is used to induce forced cyclic vibrations in a microcomponent attached there on. The coupling between the micro-component and the sample holder is provided only by the interconnect area. Due to the inertia the component is accelerated relative to the sample holder resulting in generation of cyclic shear strain in the coupling (interconnect) area. The value of shear stress in the interconnect can be adjusted by selection of the displacement amplitude of the vibrating system. The average shear stress to fracture is related to the mass of the microcomponent and the fracture surface area. The vibration amplitudes and modes are determined by using a laser Doppler vibrometer. Isothermal fatigue testing can be conducted by using an infrared lamp or a hot air furnace up to about 150°C. The time to fracture was determined by using a microscopic camera. For more details on the principles of the testing method we refer to [3]. The micro-component used in the present study consisted of Al wire bonded chips as shown in figure 3a. For fatigue experiments the wire bond was glued to a specimen holder in a manner that the coupling of the chip to the holder was provided only by the wedge area (interface of the Al wire to the Si chip).

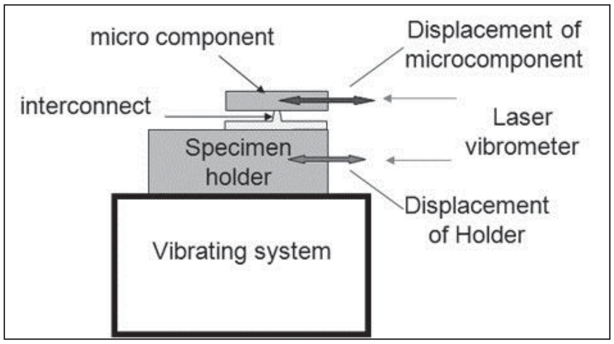


Figure 2a: Experimental set-up for accelerated shear fatigue testing of micro-components

A further setup used for fatigue testing of wire bonds is shown in figure 2b. The displacement controlled set-up which was originally proposed by [4] was used for evaluation and selection of optimized geometry of wire bond frame connections as used in power semiconductor modules. The set-up consists of a fixed and an oscillating part which can operate at excitation frequencies between few 100Hz up to 100 kHz depending on the required displacement. Using this set up the thermally induced expansion and contraction of a wire bond loop is simulated by adjustment of the cyclic displacement of the vibration system. Fatigue life curves are obtained in the low and high cycle regime with the failure mode being wire bond heel crack. The stress value in the heel region can be calculated by using FEM or an analytical model [5].

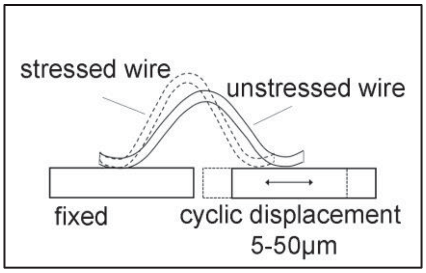
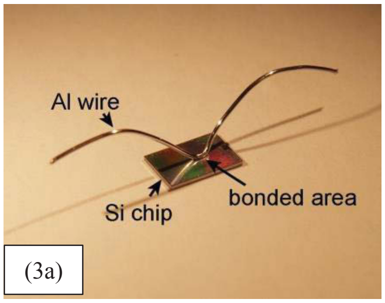


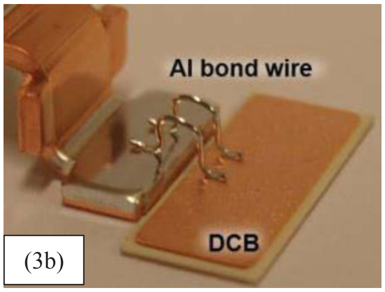
Figure 2b: Displacement controlled mechanical fatigue set-up for wire bond frame connections

Specimen geometry and characterization

Two different types of wire bonded specimens were prepared for fatigue life investigations (Fig. 3a and 3b). The samples shown in figures 3a were used for determination of fatigue strength with respect to the bonding interface (lift-off failure). For this purpose Al wires with a thickness of 400µm were ultrasonically bonded to a thin layer of Al metallization on the Si chips. The samples were subsequently heat treated at 120°C for 200h in order to obtain a microstructure similar to the wire bonds subjected to long time power cycling tests (e.g. $\Delta T = 80°C$, $T_{max} = 120°C$ and about $N = 20000$ cycles). A standard shear testing device was used to measure the interfacial shear strength. Tensile tests of Al wires were conducted to determine the stress-strain curves required for FEM. The second type of model specimens consisted of 400µm Al wire loops which were ultrasonically wedge bonded onto direct bonded copper (DBC) substrates from one side and Ni coated Cu terminals from the other side. The latter side was clamped to a xyz stage and the former side was attached to the vibrating system in order to induce heel crack failure in the wire loops subjected to displacement controlled cyclic loading. Fatigue tests were conducted at two different frequencies: 500 Hz by using an electromagnetic shaker and 20 kHz by application of ultrasonic resonance fatigue testing system [5]. The velocity of vibration (displacement) was measured by a laser Doppler vibrometer (Polytec PSV-400).



(3a)



(3b)

Figure 3a, b: Wire bond specimen geometries for mechanical fatigue testing

SEM micrographs of the cross sections of as- bonded and aged wire bonds are presented in figures 4a and 4b. The microstructure of the original Al wire can be deduced from the free end the bonding area showing a rather homogeneous structure with an average grain size of about 20µm. The wedge area reveals a highly distorted and fine microstructure due to the ultrasonic bonding process (Fig. 4a). A number of large recrystallized grains can be observed in the wedge area after aging at 120°C /200h (marked with an arrow) (Fig. 4b).

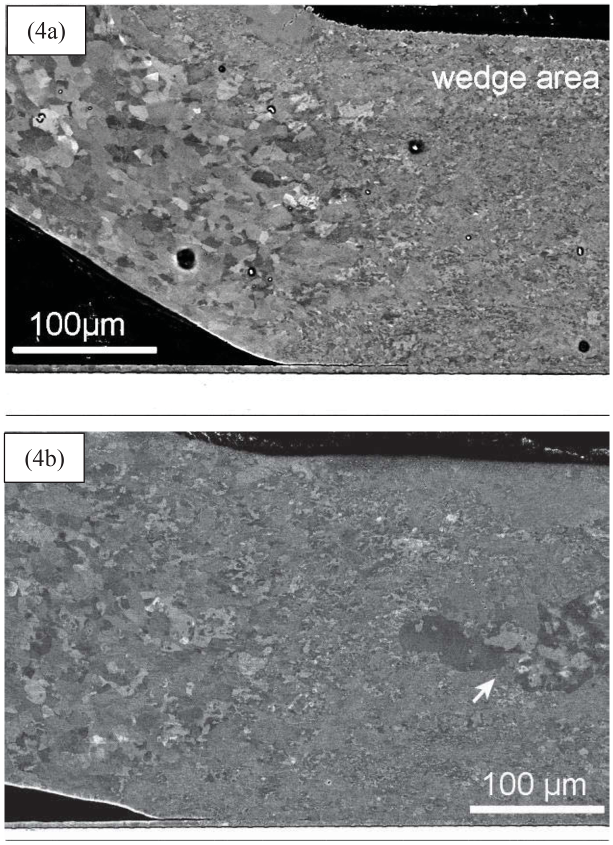


Figure 4 a, b: Grain size distribution in an Al wedge bonds in (a) as-bonded condition and (b) heat treatment at 120°C-200h (SEM –BSE images)

Results and Discussion

Fatigue life of Al wire bonds with a lift-off-failure mode

Fatigue life curves of the Al wire bonds in as-bonded and aged conditions as a function of shear stress up to 1E9 loading cycles are presented in figure 5a. Isothermal mechanical fatigue tests on aged samples with a modified microstructure were conducted in order to simulate conditions similar to those accruing during the operational life or power cycling tests in an accelerated manner. For this purpose the aged samples were pre-heated at 80 °C for about 30 minutes and subsequently subjected to fatigue loading until failure. The testing temperature was chosen based on an average between 40°C and 120 °C as min. and max values typically used in active thermal cycling tests. In comparison with the results obtained for as-bonded wires (RT), isothermal fatigue curve of aged samples shows a rather slight shift of lifetime to lower values.

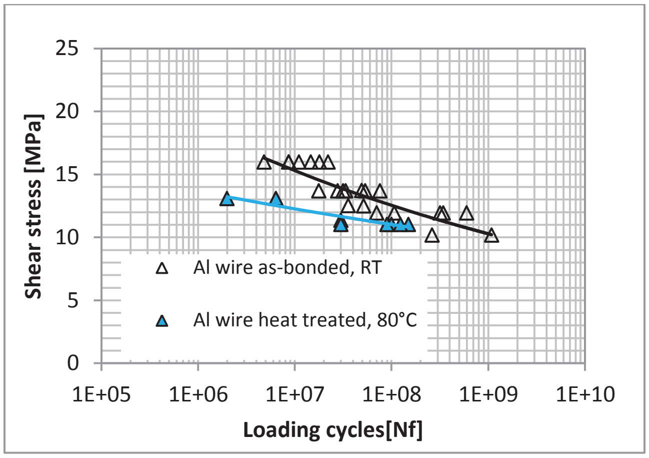


Figure 5a: Fatigue life of 400µm Al wedge bonds in as-bonded and aged conditions at RT and 80°C, test frequency 20 kHz

Our previous microstructural investigations of Al wire bonds at various conditions may be an explanation for the obtained results [6]. It was found that though thermal exposure and/or power cycling result in recrystallization and grain growth of Al wire but the extremely fine grained microstructure of the bonding interface is thermally stable and remain almost unchanged. Thus the reliability of Al wire-bonded interconnects is primarily influenced by the strength of the bonding interface in as-bonded condition. The somewhat lower fatigue life of the aged wires is due to deflection of crack path into the softer wire above the interface.

Based on the thermal coefficient mismatch between Al and Si ($\Delta\alpha$) and by using the equation $\Delta\varepsilon \sim (\alpha_{Al} - \alpha_{Si}).\Delta T$ the experimentally determined shear stress or strain values ($\Delta\varepsilon$) for Al bonds can be converted to an equivalent temperature difference (ΔT). Thus the experimental results can be compared with power cycling reliability curves as shown in figure 5b. Comparison of the thermal and isothermal-mechanical lifetime curves shows a good correlation between the obtained results at low cycle and high cycle fatigue regions. Further isothermal fatigue tests with a more homogeneous microstructure are in progress. Considering that power cycling tests require several months to obtain reliability curves in the range of one million cycles the given diagram shows that high frequency mechanical fatigue testing provides a reliable method for lifetime determination and rapid qualification of Al wedge bonds in a very short period of time.

Figures 6a, b and c show the lift-off fracture surface of Al wire bonds (foot prints) subsequent to fatigue failure. The images show that fatigue cracks are initiated at the terminations and periphery of the wire bonds and grow into the bonding interface. Final fracture occurs in the Al wire above the interface due to fatigue. A higher amount of aluminium remnants is observed on the fracture surface of aged wires which can be related to the presence of larger grains in the wedge area. The increased surface roughness of the Al metallization layer around the bond foot print as observed in figure 6a is due to thermal fatigue of the Al film during the current loading. The similarity of the wire bond failure modes of thermally and mechanically cycled wedge bonds is a further significant support for applicability of accelerated mechanical fatigue testing for reliability assessment of wire bonded interconnects.

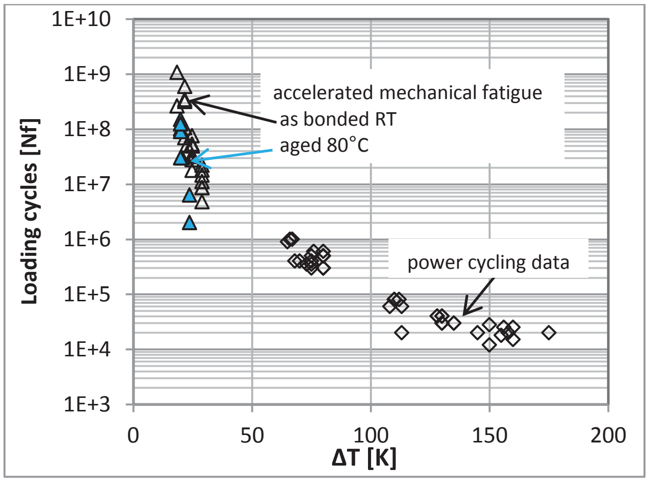


Figure 5b: Comparison of lifetime of Al wirebonds obtained by power cycling [7] and mechanical shear fatigue testing

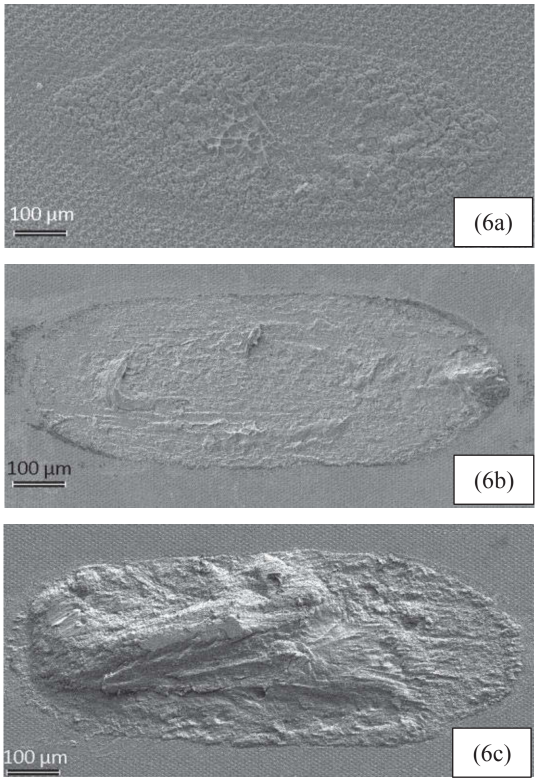


Figure 6: Fracture surfaces of Al wedge bonds after (a) power cycling test, (b) mechanical shear fatigue at RT and (c) 80°C

Fatigue life of Al wire bonds with heel crack-failure mode

Figure 7 shows the fatigue life curves of three different series of wire bond loops as a function of stress at the heel region plotted against loading cycles to failure. Fatigue tests were conducted by using two different loading frequencies of 500 Hz and 20 kHz (open and closed symbols respectively) in the range of 1E5 up to 1E9. The cyclic displacement amplitudes were adjusted in the range of 5 to 20 µm and were chosen to simulate the thermal expansion of the frame bonds during the operation. The heel stress was calculated based on the respective displacement amplitude and the loop geometry by using an analytical model as proposed in [6]. Depending on the loop height, offset and distance between the two wedges stress concentration at the wire bond heel region varies during the cyclic loading resulting in different lifetime of Al frame connections. Detailed investigation on the influence of specimen geometry on fatigue life of wire bonds is given in [6].

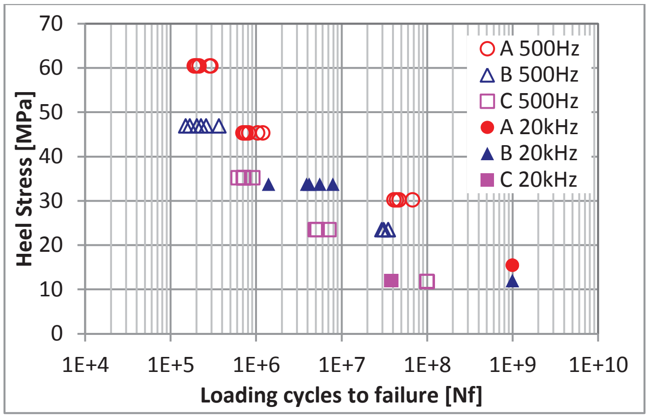


Figure 7: Fatigue lifetime of wire bond frame connections in dependency of the loop shape.

It is interesting to note that independent from the used set-up and testing frequency (open and closed symbols) the obtained fatigue data correspond very well in all stress levels. These results indicate no effect of testing frequency on fatigue response of Al wires. Earlier investigations on fatigue behaviour of the FCC materials at high frequencies have shown a negligible effect on their life time at low homologous temperatures especially in the range above 100 Hz and 20 kHz [8]. It can be concluded that independent of testing frequency, mechanical fatigue testing can be used for evaluation of fatigue life of Al wires covering a broad range of loading amplitudes in the low cycle and high cycles fatigue regimes.

Finite Element Analysis

In the present study Finite Element Analysis was focused on the lift-off failure mode of aluminium wire-bonds (Fig. 5a). For this purpose averaged values for the shear stress occurring at the interface of wire and chip were determined. The averaged shear stress was obtained from the inertia forces caused by the vibrations of the silicon chip divided by the contact area of bond-wire and chip (bond foot print). However, a more detailed analysis shows that the stresses are not equally distributed along the contact area of wire and chip and stress concentrations are observed at the periphery of the contact area. We consider the local maxima of the values for the von Mises stress as criterion for the initiation of fatigue cracks. This fracture criterion relates the purely mechanical loading modes of the accelerated testing method to the thermo-mechanical stresses observed in electronic parts under service conditions. The elasto-plastic behaviour of the aluminium wire is modeled according to the multi-linear kinematic hardening approach using experimental results from tensile tests of the wires as input for ANSYS material model. Mechanical loading of the ultrasonic testing setup was simulated according to a transient approach where the acceleration of the sample was induced by oscillation of the sample holder (Fig. 2a). From a total of 50 time steps for one period of oscillation the time step was selected at which the maximum of von Mises stress was observed in the aluminium wire as shown in Fig. 8a. This simulation was repeated for different amplitudes of oscillation.

In conclusion, the fatigue life of wire-bonds could be described using a Basquin relation

$$\sigma_{vM} = C \cdot N_f^{\,b}$$

where σ_{vM} is the maximum of von Mises stress appearing in the simulation of the bond-wire, and N_f is the experimentally determined number of loading cycles to failure. The coefficient C and the exponent b are obtained from a numerical fit of the model to experimental data of the accelerated test as shown in figure 5a. The results for the fit parameters were C = 35.002 MPa and b = 0.02. The parameters C and b may be further used to predict the lifetimes of wire-bonds under service conditions for which the thermo-mechanical stresses are evaluated by a transient coupled field analysis. Figure 8b shows FEM simulations of an IGBT module subjected to current loading of 4 A per wire with switching frequency of 5 Hz at a pulse frequency of 1.25 kHz [9]. These conditions are similar to those observed during the operation of power modules in frequency inverters with low ΔT and very high number of loading cycles. Though high stresses are also observed in the Si chip due to current loading, however lift-off failure always occurs in the aluminium wire-bonds. Thus lifetime predictions based on the Basquin relation in the high cycle regime can be made using experimental mechanical fatigue testing techniques.

Summary

A brief overview on the application of accelerated mechanical fatigue testing techniques for evaluation of Al wire bonded interconnects in microelectronics is presented. Using suitable experimental set-ups in the frequency range of 200-20 kHz fatigue life curves at room and elevated temperatures can be obtained and typical failure mechanisms can be reproduced. Finite Element Analysis was conducted for interpretation of the experiments, comparison of thermally and mechanically induced stresses and establishment of lifetime models. The proposed techniques can be used for rapid qualification and lifetime prediction during the design and fabrication of different types of interconnects.

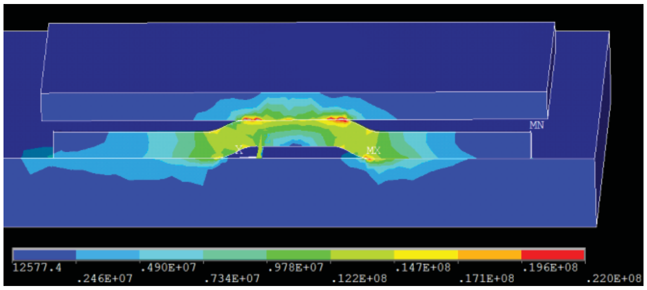


Figure 8a: Plot of the von Mises stress [Pa] for the time step where the von Mises stress in the bond-wire takes its maximum (accelerated mechanical fatigue testing).

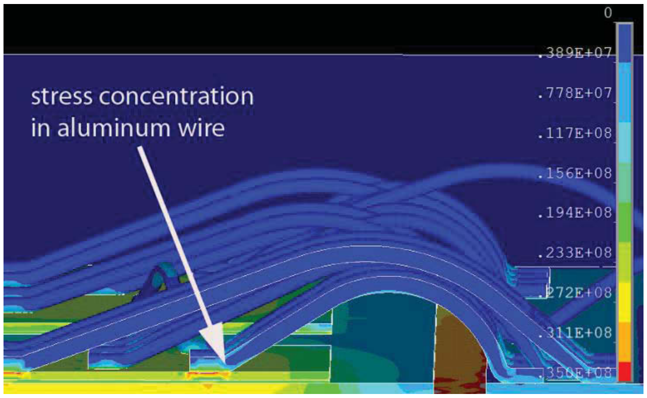


Figure 8b: Plot of the von Mises stress [Pa] for the wire-bond under service conditions. The results for the temperature distribution of a thermal analysis were used as input to the elasto-plastic mechanical simulation presented in the figure.

Acknowledgement

Financial support of Austrian Research Promotion Agency (FFG) and the City of Vienna (ZIT) in frame of Comet program (K-Project micromat) is highly acknowledged.

References

[1] G. Harman, Wire Bonding in Microelectronics: Materials, Processes, Reliability and Yield McGraw Hill, New York (1997)

[2] Mechanics of Microelectronics, G.Q. Zhang, W.D. van Driel, X.J. Fan, Springer, Dordrecht (2006)

[3] G. Khatibi, M. Lederer, B. Weiss, T. Licht, J. Bernardi, and H. Danninger; Accelerated Mechanical Fatigue Testing and Lifetime of Interconnects in Microelectronics; Procedia Engineering 2 (2010) 511 – 519

[4] S. Ramminger, N. Seliger, und G. Wachutka, Reliability Model for AI Wire Bonds subjected to Heel Crack Failures, Microelectronics Reliability, Vol. 40, 8–10, (2000) 1521–1525

[5] B. Czerny, A. Paul, G. Khatibi, M. Thoben, Influence of Wirebond Shape on its Lifetime With Application to Frame Connections", Proc. of EuroSimE 2013

[6] G. Khatibi, B. Weiss, J. Bernardi, S. Schwarz, Microstructural Investigation of Interfacial Features in Al Wire Bonds, Journal of Electronic Materials, Vol. 41, Issue 10 (2012), 3436 – 3446

[7] T. Herrmann, J. Lutz, Josef, M. Feller, R. Bayerer, T. Licht, Power Cycling Induced Failure Mechanisms in Solder Layers, Proc. EPE, Aalbourg, Denmark : IEEE (2007) 1 – 7

[8] J.K. Tien, Ultrasonic Fatigue, ed. Wells, Buck, Roth, Tien, Conf. Proc. AIME, 1982 pp. 1-14

[9] B. Czerny, M. Lederer, B. Nagl, A. Trnka, G. Khatibi, M. Thoben, Thermo-mechanical analysis of bonding wires in IGBT modules under operating conditions, Microelectronic Reliability, Vol. 52, Issues 9–10 (2012) 2353–2357