

## Degradation of Al-1%Si Wires Bonded onto Copper Pads

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### Abstract:

The current load and its influence on degradation of Al-1%Si wires bonded onto copper pads is presented in this paper. The current load was chosen to occur the electromigration phenomenon during ageing. Our attention was paid to the direction of current from Cu pad to Al wire, and as well as reversed from Al wire to Cu pad. The dependencies of electrical resistance ( $\Delta R/R_0$ ) relative change vs time as well as dependencies of mechanical strength vs time for different types of current stresses (direct current  $I_{DC}$  and pulse current  $I_{PULSE}$ ) were obtained and evaluated. The results were evaluated in relation to all above mentioned conditions moreover thermal ageing at  $100^\circ\text{C}/1000$  h was applied and evaluated too.

### INTRODUCTION

Wire bonding is one of the most used method for first-level interconnection in low power microelectronic packaging as well as in power electronic. The alloys of Al and Au are the most commonly used materials for bonding wires. Currently, it is possible to notice rapid growth in using of Cu bonding, due to higher tensile strength, better elongation, electrical and thermal conductivities comparing to Au wires. The Cu wire bonding is cheaper in comparison to Au wire bonding. The electromigration is one of the phenomenon that occurs at high current densities and contributes to the degradation of bonded joints. The electromigration occurs at current density around  $10^4 \text{ A}\cdot\text{cm}^{-2}$  and more. High current density also supports the growth of intermetallic compounds (IMCs) due to localized Joule heating [1], [2], [3], [9].

Al/Cu interface is common in power electronic (Al wires bonded on DBC substrate) as well as in low power electronic (Al wire bonding, or modern Cu wire bonding process) and typical feature of this interface is creation and growth of IMC layer at Al/Cu. The phase diagram of Al/Cu interface pointing out on 5 phases:  $\gamma_2$  phase ( $\text{Cu}_9\text{Al}_4$ ),  $\delta$  phase ( $\text{Cu}_3\text{Al}_2$ ),  $\zeta_2$  phase ( $\text{Cu}_4\text{Al}_3$ ),  $\eta_2$  phase ( $\text{CuAl}$ ) and  $\Theta$  phase ( $\text{CuAl}_2$ ). Study of degradation of wire bonds and growth of IMC is realized by thermal ageing (with or without humidity) [4], [5], [6], [7], [8]. The effect of current density and electromigration in electronic devices are important in terms of reliability and durability of electronic components too [9], [10], [11].

The influence of electrical current on IMC growth at Al/Cu interface was studied in previous research on bimetallic samples [12]. The electromigration phenomenon of wire bonds on different systems are very actual because of miniaturization. The same electrical current in modern circuits but with finer

wires and finer bond pad pitch is applied [13], [14]. That is why deep analyze of this problem is needed. This paper is oriented to analyze of ageing wire bonds due to the electromigration of Al-1%Si wires bonded onto copper pads.

### EXPERIMENTAL SETUP AND RESULTS

#### Samples preparation and experimental arrangement

The standard Al-1%Si wire with  $25 \mu\text{m}$  in diameter bonded onto copper surface of standard PCB substrates was used for all experiments. The quality of wire bonds for samples were evaluated by visual inspection (MIL-STD 883 method 2017.7) as well as by wire bonder equipment set up according results from pull tests so the high strength with lowest variance was acquired. The minimum bond pull limit according MIL-STD-883 2011.9 was acquired for all bonds.

The sample layout is showed in Fig. 1. The stitch bond was bonded onto A, B and C pads (see Fig. 1b) by K&S wedge bonder 4129. The topology of sample was chosen so that only one part (the segment between A and B pads) of stitch bond was under current stress. The second segment of stitch bond (between B and C pads) was used for pull tests. The pull tests was realized by DAGE-4000 pull/shear bondtester. The resistance was measured by 4-wire method, the current part of circuit is between pads No. 1 and No. 2 and the voltage part of circuit was between pads No. 3 and No. 4 (Fig. 1b). The segment of stitch bonds between B and C pads was used as “leadwire” in voltage circuit, and stitch bonds between A and B pads was used as “leadwire” in current circuit. The electrical resistance of small piece of stitch bond which was bonded on B pad was measured in this configuration. One sample (Fig. 1a) consists of 15 wire bonds connected in serial circuit.

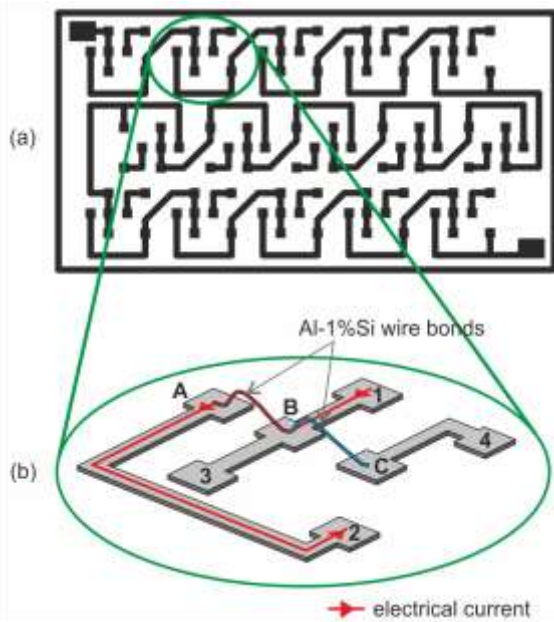


Fig. 1: Sample layout (a) and stitch wire bond stressed by electrical current (b)

Wire bonds were exposed to current stress (direct current  $I_{DC}$  and pulse current  $I_{PULSE}$ ) at room temperature and to thermal ageing at  $100^{\circ}\text{C}$  with no current from 0 hour to 750 hours. The contact resistance of bonds and bond strength by destructive pull test were measured during tests. Degradation of Al-1%Si wires bonded onto copper pads is relating to both changes: in contact resistance as well as in bond strength. Experiment was realized in such way that

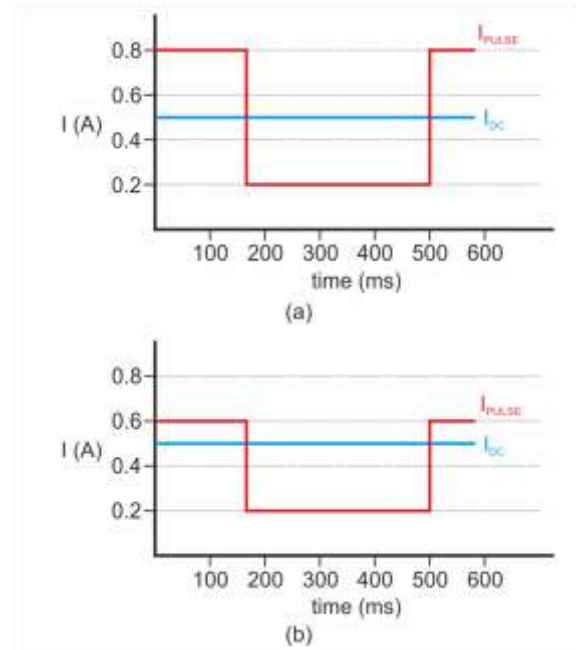


Fig. 2: Shape of direct current ( $I_{DC}$ ) and pulse current ( $I_{PULSE}$ ) until (a) and after (b) first 100 hours

the current flows through Al/Cu interface from Cu pad into Al wire (this current flow is showed in Fig.

1b) as well as reversed (from Al wire into Cu pad) during ageing. This should ensure failure kinetics as a function of polarity of current flow and helps to identify the failure caused by electromigration mechanism.

The direct current  $I_{DC}$  was chosen so that the current density overcome  $10^4 \text{ A.cm}^{-2}$  in order to ensure sufficient current density for electromigration. The root mean square (RMS) of pulse current  $I_{PULSE}$  has been chosen to match with direct current  $I_{DC}$  level. This ensure equal Joule heating for both, direct current  $I_{DC}$  stress as well as pulse current  $I_{PULSE}$  stress and the peak of pulse current  $I_{PULSE}$  helps increase the current density in short time (Fig. 2a). The current peak for  $I_{PULSE}$  reduced (Fig. 2b) after 100 hours of ageing due to excessive failures of wire ponds in case of pulse current. Differences between measured resistances and bond strengths for direct current  $I_{DC}$  and pulse current  $I_{PULSE}$  under these conditions can indicate on electromigration phenomenon.

Overview of realized test experiments including the number of tested samples for appropriate stress method are in the Tab. 1. The electrical resistivity of wire bonds were measured after 0, 20, 40, 60, 80, 100, 350, 500 and 750 hours of ageing, and relative resistance change ( $\Delta R/R_0$ ). Because the measurement of resistivity is nondestructive method, the number of samples was only 2 (one samples consists 15 bonds) for each type of stress. The destructive pull test was used for measuring of bond strength, so in this case the number of samples was 60 for each type of stress. The maximum load during pull test was measured after 0, 40, 80, 200, 500 and 750 hours of ageing, 2 samples (2 x 15 bonds) per stress method for each time. The relative change in maximum load during pull test ( $\Delta F/F_0$ ) was evaluated in final.

Tab. 1: Overview of realized test experiments including the number of tested samples

Stress method /evaluated quantity	Number of bonds ( $\Delta R/R_0$ )	Number of bonds ( $\Delta F/F_0$ )
$I_{DC}$ : Al $\rightarrow$ Cu	30	180
$I_{DC}$ : Cu $\rightarrow$ Al	30	180
$I_{PULSE}$ : Al $\rightarrow$ Cu	30	180
$I_{PULSE}$ : Cu $\rightarrow$ Al	30	180
Thermal ageing*	30	180

\*  $100^{\circ}\text{C}$  from 0 to 750 hrs / no current

### Experimental results and discussion

The dependencies of relative change in contact resistance ( $\Delta R/R_0$ ) vs time for different current stresses (direct current  $I_{DC}$  and pulse current  $I_{PULSE}$ ) are shown in Fig. 3. We can observe expected dependencies for different polarity of current flow (Cu $\rightarrow$ Al vs Al $\rightarrow$ Cu) as well as for type of current flow ( $I_{DC}$  vs.  $I_{PULSE}$ ). In the case of  $I_{DC}$ , the difference in  $\Delta R/R_0$  for current flow from Al wire to Cu pad and current flow from Cu pad to Al wire was about 17.5% after 750 hours. In case of  $I_{PULSE}$ , the difference is

about 12.0% after 750 hours. We can assume that higher growth of  $\Delta R/R_0$  for Al→Cu compared with Cu→Al for both  $I_{DC}$  and  $I_{PULSE}$  is influenced mainly by electromigration on Cu/Al interface. The growth of resistivity in all cases indicate the degradation of bonds, and it is more rapid in case of current flow from Al wire to Cu pad.

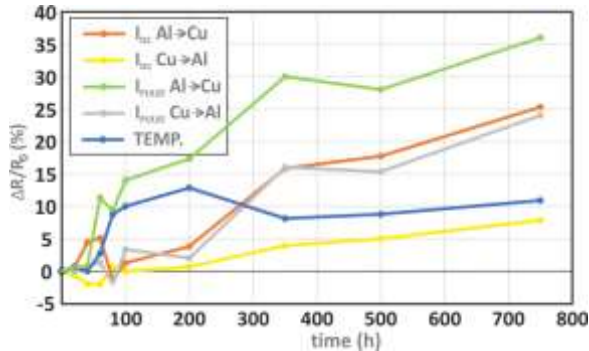


Fig. 3: Relative change in resistance ( $\Delta R/R_0$ ) vs time for different stresses (direct current:  $I_{DC}$  Cu→Al,  $I_{DC}$  Al→Cu, pulse current:  $I_{PULSE}$  Cu→Al,  $I_{PULSE}$  Al→Cu and thermal ageing)

The mechanical stress caused by Joule heating of wire bond during peak and its cooling during low current load have to take into account in the case of pulse current stress. We can observe the visible degradation of wire bond (Fig. 4) by thermal expansion during heating and thermal contraction during cooling what caused failure of bond in loop. Visible moving of wire was observed in current pulse load.

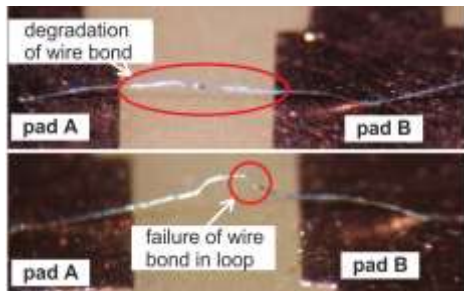


Fig. 4: Degradation of wire bond and failure of wire in loop after stress by pulse current

The similar process of expansion and contraction occurs on interface between Cu pads and Al wire. Higher growth of  $\Delta R/R_0$  for pulse current  $I_{PULSE}$  compared with direct current  $I_{DC}$  is therefore caused not only by electromigration but also by thermal/mechanical stress on bond interface between two materials (Cu pads and Al wire) with different coefficient of thermal expansion. The total number of failure was 51 (28 bonds for Al→Cu and 23 bonds for Cu→Al) for bonds stressed by pulse current vs zero for bonds stressed by direct current during the first 100 hours of ageing. The level of current peak in case of pulse current was reduced for this reason (Fig. 2b). Only 3 failure of bonds was observed after this

reduction from 100 hours to 750 hours of ageing in case of  $I_{PULSE}$ . The higher growth of  $\Delta R/R_0$  for Al→Cu compared with Cu→Al for both  $I_{DC}$  and  $I_{PULSE}$  was still observed despite the lower pulse current peak.

The second evaluation method of wire bond was realized by pull test of wire bonds. The relative change in maximum load during pull test ( $\Delta F/F_0$ ) vs time for different stresses are showed in Fig.5. The change in  $\Delta F/F_0$  did not prove the visible dependencies neither on the electrical current flow nor on electrical current type (direct current  $I_{DC}$  and pulse current  $I_{PULSE}$ ) and it is similar to thermal ageing at 100°C. This ambiguous dependence on the type of stress may be caused by error of pull tests. The result of pull test is dependent on hook placement under loop of measured bond and it is not always the same. This can cause unequal measurement conditions and “blur” the differences for different stress which would be otherwise visible. In addition, the pull tests were performed always on another new group of samples due to destructive character of test compared to resistivity measurement. The resistivity was measured on one group of samples (3 samples) for each kind of stress, but always on same group in different time. However, it can be concluded that the decreasing of bond strength for all type of stress (Fig. 5) is the most significant especially in the first 100 hours.

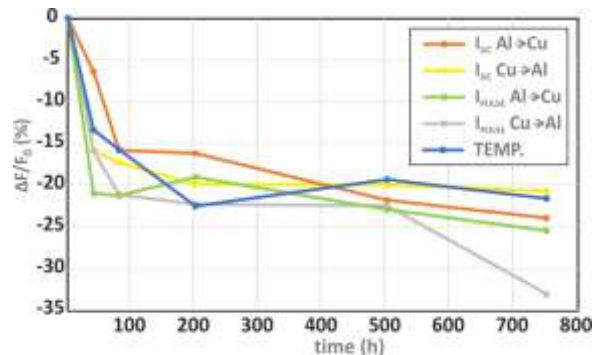


Fig. 5: Relative change in maximum load during pull test ( $\Delta F/F_0$ ) vs time for different stresses (direct current:  $I_{DC}$  Cu→Al,  $I_{DC}$  Al→Cu, pulse current:  $I_{PULSE}$  Cu→Al,  $I_{PULSE}$  Al→Cu and thermal ageing)

Degradation of Al-1%Si wires bonded onto copper pads is relating to change of contact resistance and bond strength. The comparison of both dependencies (Fig. 3 and Fig. 5) shows, that the degradation is more rapid after 40 hours of ageing. The dependence on direction of electrical current flow (Al→Cu vs Cu→Al) is significant after 100 hours of ageing and it is clearly identified only by resistivity measuring (Fig. 3). The growth in electrical resistance is caused by changes on interface and by growth of IMC. The main problem is thermal heating and cooling during cycling in the case of pulse current with high peak current density. This cycling cause also visible mechanical degradation. The high peak current

density was chosen to clearly exceed the activation energy of electromigration. This phenomenon is not so significant in case of low power electronic with lower current densities.

## CONCLUSIONS

The degradation of wire bonds under thermal and electrical stress was evaluated according measuring of relative change in electrical resistance on time and in maximum load during pull test on time. The high current density used in experiments was selected for exceed the activation energy of electromigration. The high current density brings additional problem with cyclic heating and cooling of wires and its thermal expansion/contraction in case of pulse current. This leads to failure and breaking wire in loop. Nevertheless, the results of experiments point on degradation dependence on current flow direction through Cu/Al interface and it is directionally depended. Directional dependency can be caused by electromigration phenomena and it is more rapid in case of current flow from Al-1%Si wire into Cu pad. The pulsed current stress lead to faster degradation of wire bonds.

It was proved in our experiments that for evaluation of the degradation level of Al-1%Si wires bonded onto copper pads that the growth of resistivity is more rapid in case of current flow from Al wire to Cu pad.

## ACKNOWLEDGMENTS

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