DEFORMATION OF SOLDER JOINTS UNDER CURRENT STRESSING: EXPERIMENTAL MEASUREMENT AND NUMERICAL SIMULATION

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Summary The in-situ displacements evolutions of lead-free solder joints under electric current stressing are measured with Moiré Interferometry technique. Large deformations due to electromigration were observed in solder joint under high density current stressing. An electromigration constitutive model is applied to simulate deformations of the lead-free solder joints under current stressing. The simulations predict reasonably close displacement results to Moiré Interferometry experimental results in both spatial distributions and time history evolutions.

INTRODUCTION

Electromigration in solder joints under high direct current density is known as a reliability concern for the future high density microelectronic packaging and power electronic packaging. The trend in flip-chip and Ball Grid Array (BGA) packaging to increase I/O count drives the interconnecting solder joints to be smaller in size and, thus, carry higher current density. A physical limit to increasing current density in both microelectronics and power electronics is electromigration in solder joints. In this paper, the deformation of lead-free solder joint under high density current stressing is measured with Moiré Interferometry technique. The lead-free solder alloy used in the Moiré Interferometry experiment is Sn95.5/Ag4/Cu0.5. With improved thermal management in the experiments, high current density ($10^4 A/cm^2$) was applied to the solder joint without much heat generation. An electromigration constitutive model is presented and applied to simulate the deformation evolution in lead-free solder joints under electromigration. The simulation results are compared with the experimental results.

EXPERIMENTAL

Figure 1 shows the scheme of the test BGA module and the test fixture. The fabrication of BGA module follows the same procedure described in a previous paper [1]. Copper plates are used to clamp the test module in order to provide electrical contacts. The set-up of the stressing circuitry and a description of Moiré Interferometry technique used in the experiment can be found in our previous paper [1]. The height of the solder joint is 1.5*mm* and the width is reduced to 1*mm*. The thickness of the solder joint is polished down to about 0.25mm. When 30 *Amps* of current is applied, a current density above 10^4 A/cm^2 can be achieved in the solder joint. The temperature on the sample was measured (with thermal couples) to be uniformly distributed in the test module and was kept almost constant (around 30ºC) during the entire period of current stressing (up to 1000 hours).

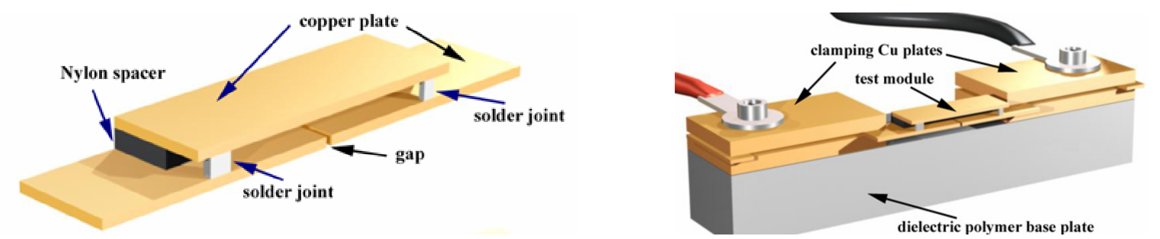


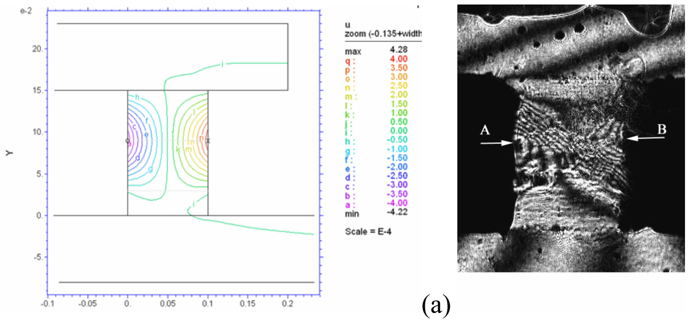
Figure 1 Scheme of the test module and the test fixture

Both U and V fields developed a lot of Moiré fringes during the course of current stressing (Figure 2b and Figure 3b). The U field fringes were predominantly in the vertical direction and the V field fringes were predominantly in the horizontal direction, indicating that normal deformations were predominant during stressing. The evolutions of Moiré fringes in both fields were observed to become steady after 1000 hours of current stressing, indicating that the deformation of solder joint under electric current stressing reaches steady state after 1000 hours of stressing. The measured deformations are mostly due to current stressing in that: first, thermal deformation in the solder joint would be mainly shear deformation in such test structure. However, the measured deformations were mainly normal deformations. Second, the temperature increase due to joule heating was only several degrees. Therefore, thermal deformation should be negligible. Third, temperature was kept almost constant during stressing. Thermal deformation should become steady within a short period of time. However, the observed deformation took hundreds of hours to reach steady state. Fourth, a supportive experiment indicates that no deformation would be measured if no current is applied to the test vehicle.

NUMERICAL SIMULATION OF DEFORMATIONS OF SOLDER JOINTS UNDER CURRENT STRESSING

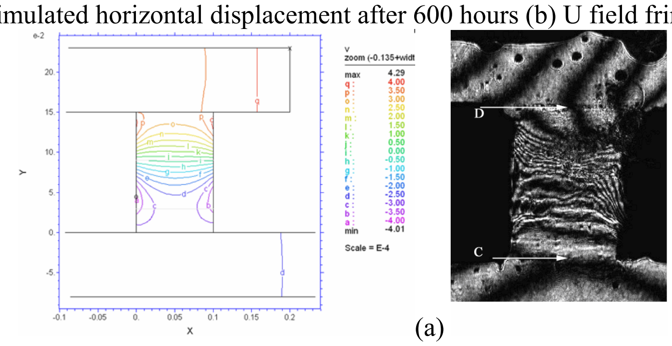
The electromigration in solder joints is viewed as a coupled diffusion-mechanical process in the modeling. The electron flow assisted vacancy diffusion process gives rise to volumetric strain in the conducting solder alloy. This volumetric strain is superimposed into the strain due to mechanical loading (analogous to thermal strain) as proposed by Sarychev

[2].Under the mechanical boundary constrains, the volumetric strain due to diffusion results in stress build-up within the structure. If the hydrostatic stress state within the conducting solder is changed or there is hydrostatic stress gradient created, the stress state will in turn affect the vacancy flux or vacancy generation rate in the diffusion process. The deformations within the solder joints can be determined by solving the coupled diffusion and mechanical equilibrium partial differential equations. The detailed formulation of the electromigration model is reported in a previous paper [3]. In this paper, we extend this constitutive model to simulate the electromigration of lead-free solder alloy. We performed 2-D FEM simulations, in which the plane stress assumption is applied to solder joints and plane strain assumption is applied to cupper substrates.



(a) (b)

Figure 2 (a) Simulated horizontal displacement after 600 hours (b) U field fringe after 605 hours



(a) (b)

Figure 3 (a) Simulated vertical displacement after 600 hours (b) V field fringe after 605 hours

Figures 2-3 show the comparisons between the numerical simulation and Moiré Interferometry results. The simulated distributions of both horizontal and vertical displacements resemble the distributions measured by experiment: there are large normal deformation developed in the horizontal direction but the horizontal normal deformations are not uniform along the both edges of the solder joint; there are also large normal deformation developed in the vertical direction. The simulation results are not exactly the same as the experiment measurements. But considering all the assumptions that were taken and many simplifications of the simulation model, the simulation results are quit reasonable. Comparisons of time history evolutions of displacements between the simulation and the experimental results also show close agreements. This indicates that this electromigration model is reasonably good at predicting the mechanical behavior of lead-free solder alloy under electric current stressing. In the experiments, the thicknesses of the solder joints were not uniform. In the simulation, this non-uniformity is taken into account by means of applying non-uniformly distributed current density. Solder joints with different current density level were tested and numerically simulated. Both the experimental results and simulations suggest that, in addition to the current density level, current density distribution within the solder joint has a great effect on the displacement development in the solder joint under current stressing. Specifically, greater non-uniformity in current density leads to greater normal deformations within the solder joint.

CONCLUSIONS

In this paper, the in-situ displacements evolutions of lead-free solder joints under electric current stressing are measured with Moiré Interferometry technique. Large deformation was observed in solder joint under high density current stressing. The deformations are due to electromigration in the solder joints. An electromigration constitutive model is applied to simulate deformations of the lead-free solder joints under current stressing. The simulations predict reasonably close displacement results to Moiré Interferometry experimental results in both spatial distributions and time history evolutions. This indicates that this electromigration model is reasonably good at predicting the mechanical behavior of lead-free solder alloy under electric current stressing. Both the experimental observations and finite element simulation results indicate that, in addition to the current density level, the current density distribution within the solder joint has a great effect on the displacement development in the solder joint under current stressing.

References

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