Thematic Area I

Introduction

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Reliability of Lead-Free Electronic Solder Interconnects: Roles of Material and Service Parameters

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Abstract

This chapter is meant to provide a general overview of the issues affecting the reliability of lead-free electronic solder joints subjected to service environments. It is meant to be an introduction to the various thematic areas that are covered in this book. Hence no attempt to provide references to any of the topics mentioned in this chapter is given at the end of this chapter. Extensive references for each of these topics are cited by the authorities contributing various chapters to this book.

1.1 Material Design for Reliable Lead-Free Electronic Solders Joints

It is important to point out that solder joint is a multicomponent system. Solders used in electronic interconnects are in the joint geometry and its overall response to environmental and in-service parameters are influenced by the constraints present in that configuration. Such a joint has substrates, interface intermetallic compound layers that are necessary

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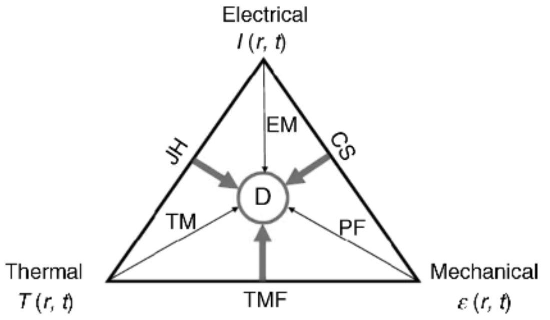
to form the necessary bonding, solder matrix with its own individual phases and intermetallic compounds (IMCs). In addition to geometrical issues, processing method used for fabrication of joints and the resultant microstructural features, service parameters encountered, and the response of the solder material to external influences, play significant roles in determining the reliability of the electronic solder joints. The service environments encountered are becoming more severe and the continuous rapid advances in microminiaturization of the electronic packages impose ever-increasing demands on such solder joints. Since solder joints present in modern microelectronics operate at very high homologous temperatures significant microstructural changes such as coarsening of the features present in the joint occur affecting their reliability. Because of the changes in the joint geometry to accomplish the microminiaturization such joints are expected to provide structural integrity in addition to providing electrical pathways. They are also expected to be mechanically compliant to dissipate the stresses that develop during service but be dimensionally stable.

Most of the lead-free solder alloys that are in current use contain significant amounts of tin. Such alloys have the suitable melting temperatures and wetting characteristics for utilization in consumer electronics. Among these, Sn-Ag-Cu alloys have been widely adopted. In order to minimize the deleterious effects of thermally induced coarsening of the phases present within the solder matrix and at the solder/substrate interfaces, and to improve the mechanical properties, several detailed studies on phase stability along with resultant developments have taken place. They have provided strategies involving minor amounts of additional alloying additions, as well as reinforcements to produce composite solders. Some of these approaches also help to improve the reliability of the lead-free solder joints. Since solders have to bond with substrates, the substrate materials and its finish will interact with the solder during the reflow process and during service. Several studies aim at combating reliability issues arising from the coarsening of these reaction products, which are quite often brittle.

The improvements to address problems listed in the last few paragraphs are the main contributions from those studying phase diagrams to develop suitable lead-free solder alloys, alloy additions to improve their service reliability, and composite solders. Such judicial material design to improve the service reliability invariably can take place only with the clear understanding of the service environments in which the electronic packages will be placed and the material response and resultant behaviors that affect their reliability. Joint geometry is an added contributing factor that can aggravate the influence of the service environment. However, such joint design is outside the realm of the material development to meet the challenges. If material design can either alleviate the material processes that affect the joint reliability either completely (or most of it), joint geometry hopefully will have minimal influence on the joint reliability.

The following sections address the material processes that influence the service reliability of lead-free solder joints. Detailed discussions on the developments in these avenues are brought out by world-renowned researchers in these fields in the chapters presented in various thematic areas.

1.2 Imposed Fields and the Solder Joint Responses that Affect Their Reliability



This schematic illustrates damage resulting from multiple fields and their complex interactions. Processes identified in this schematic are EM – electromigration, TM – thermal migration, PF – plastic flow and fracture, JH – Joule heating, CS – current stressing, TMF – thermomechanical fatigue. The scenario presented in this schematic illustrates the complex state of damage accumulation resulting from various fields encountered during service (direct effects: EM, TM, PF), and their mutual interactions (coupled effects: TMF, JH, CS), that affect the reliability of lead-free electronic solder joints.

Even during service these fields are time and position dependent. For example, temperature depends on the environment and Joule heating from the current density that can vary with hills and valleys that form due to electromigration. Similarly, the mechanical stress state will depend on the stresses that develop due to coefficient of thermal expansion (CTE) mismatches between the entities present in the joint, stresses that develop due to atom/ion migration caused by electron wind forces, and externally imposed loads. Among those listed the major damage contributors that affect the reliability of the lead-free electronic solders are (i) mechanical integrity, (ii) thermomechanical fatigue, (iii) whisker growth, (iv) electromigration, and (v) thermomigration. It should be pointed out that this is not an ordered list, and that there are significant mutual interactions between them. Such mutual interactions will become progressively more important with the continued efforts towards microminiaturization of electronic packages. Among the five processes listed above, whisker growth, electromigration, and thermomigration have become reliability concerns mainly due to such miniaturization.

1.3 Mechanical Integrity

An electronic package contains several solder joints and their reliability is what needs to be understood. However, reliability studies carried directly with such complex packages quite often cannot provide the means to evaluate the actual material-related issues that cause the failure, a critical piece of information warranted for material developments. On the other hand, if model system studies are carried out, the model geometries used should be representative of those actually encountered in the electronic packaging. Carrying out studies on bulk solder specimens, without any of the constraints encountered in the joint configuration, will not be of any relevance to what happens in the joints.

Depending on the application the solder joints present in electronic packages may be experiencing different ranges of temperatures. In addition to the heating that results from passage of electric current, ambient conditions encountered during service can play significant roles. The deformation mode of Sn-based solders is highly sensitive to temperature and strain rate. Any reliability modeling should take this issue into account, along with issues of constraints and joint geometry.

Reliability under impact loading is a very important consideration not only for shipping considerations, but also for accidental dropping of a device. Industrial drop tests are carried out to check for the impact reliability during shipping. Charpy-type impact tests where the impact load is delivered to the individual solder ball attached to the substrate are also employed. In a realistic electronic package the impact delivered to some other location is realized by the solder. Hence, such tests cannot provide the necessary information about the detailed stress states, modes of fracture, and so on, that are critical for material design. In addition, there are several scenarios, like in automotive and aerospace applications, where random bumping can cause repeated impact loading.

1.4 Thermomechanical Fatigue (TMF)

Thermal excursions encountered in service cause significant damage to solder joints affecting their service reliability. Several material-related processes occur during heating, cooling, and dwell at temperature extremes. For example, the heating and cooling rates, temperature regime (high/low), temperature difference, dwell times at high- and low-temperature extremes, do significantly affect the integrity of the solder joints. These studies have shown that heating rate is an important contributor affecting the joint reliability. Damage accumulation in solder joints subjected to TMF results from a highly inhomogeneous stress distribution. Such stresses arise from CTE mismatches between various entities present in the joint. Anisotropy of tin could be a major contributing factor for such damage accumulation since the CTE difference between *a*- and *c*-directions of body-centered tetragonal β-Sn is almost twice that of the CTE difference between polycrystalline copper and polycrystalline Sn. Manifestation of the damage from TMF occurs only after several hundred TMF cycles, although the residual mechanical and electrical properties deteriorate significantly from the very early stages of TMF. Grain-boundary sliding and decohesion are the predominant damage modes that result from TMF. Although such events occur throughout the solder present in the joint, the predominant surface manifestation of the same is highly localized to the solder regions adjacent to solder/substrate IMC layer. Constraints imposed by the substrate appear to cause strain localization to such regions. During the later stages of TMF, when the residual properties tend to stabilize, the surface damage progresses by joining of the individual distributed cracks and cause the catastrophic failure.

Based on TMF evaluation with realistic temperature profiles, and findings from actual electronic packages placed in service, several new solder compositions with various minor alloying additions to Sn-Ag-Cu (SAC) alloy have been developed. A major hurdle encountered in this approach is the coarsening of the intermetallic compounds that form during service affecting the joint reliability. Studies dealing with dwell-time issues indicate presence of small amounts of Ni in addition to Cu in the solder significantly improves the reliability of the solder joint under situations with longer dwell at the high-temperature extreme. Inert particle reinforcements have not been effective since they do not bond with the solder matrix. An alternate approach to improve service reliability of solder joints is to incorporate compatible nanostructured reinforcements with surface-active radicals to promote bonding with metal, following which they become inert. Such strongly bonded inert reinforcements that do not coarsen during service improve the reliability of lead-free solder joints subjected to TMF during service.

1.5 Whisker Growth

It has long been known that Sn exhibits whisker growth. However, such events did not receive any attention in electronic interconnects till recently. Microminiaturization of electronic components has resulted in close spacing of current carrying lines. Quite often the spacing is of the order of about 100 μm. If whiskers grow to a length of about 50 μm in adjacent lines shorting can occur resulting in electrical failure. Although several models have been proposed for whisker growth from solid substrate, none of them have been proved to be satisfactory. Compressive stresses are believed to make whiskers grow from their base. In Sn-based solder joints such compressive stresses that can arise from the formation of Cu-Sn IMC at Sn grain boundaries present in the solder are believed to cause such whisker growth. Such IMC formation can be facilitated by Cu diffusion from the substrate. For continuous growth of whiskers from the base such compressive stresses need to be present on a continuous basis, and such stresses should not be relaxed. Hence, stresses that are externally applied, or resulting from volume changes involved in formation of IMCs, and those that develop during electromigration, can facilitate whisker growth. There are conflicting views on whisker growth directions and locations from which whiskers grow. If the whisker growth is caused by Cu diffusion from the substrate followed by IMC growth, one should be able to arrive at a solution to this problem. However, no known reliable solution to this problem exists at present. Some of the difficulties in whisker growth investigations are encountered due to uncertainties about when and where will whiskers form and grow. As a consequence evaluation of the effectiveness of attempted mitigation strategies to prevent whisker growth becomes difficult.

1.6 Electromigration (EM)

EM in electronic solders has become an important concern in recent years. Ion migration in the presence of high current density has long been known in computer industry where incorporation of copper atoms at grain boundaries present in aluminum current-carrying lines has provided a solution to such a problem. In electronic interconnects the presence of high current density has not been a significant concern until miniaturization of electronic components and higher service temperatures has caused EM to become a potential reliability issue in electronic interconnects. Although events contributing to this mass movement are due to material-related issues, it can be further aggravated by geometry in which the material is employed. The latter can impose current crowding and associated localized Joule heating, resulting in enhanced mass movement in localized regions. Based on the intended roles, several alloys used in electronics and energy-related applications are multiphase materials. In these alloys the electromigration-induced changes will depend strongly on the atomic species present, solid solubility, morphological features of the microstructural constituents, and phase stability.

Localized Joule heating and current crowding, have been of great concern. Grain growth and reorientation of grains, phase segregation, and interfacial events; contribute to damage accumulation by electromigration, in addition to hill and valley formation. Unlike the case of aluminum lines in computers, solders present in the electronic interconnects operate at very high homologous temperatures. As a consequence lattice diffusion, in addition to grain-boundary diffusion becomes an important consideration

1.7 Thermomigration (TM)

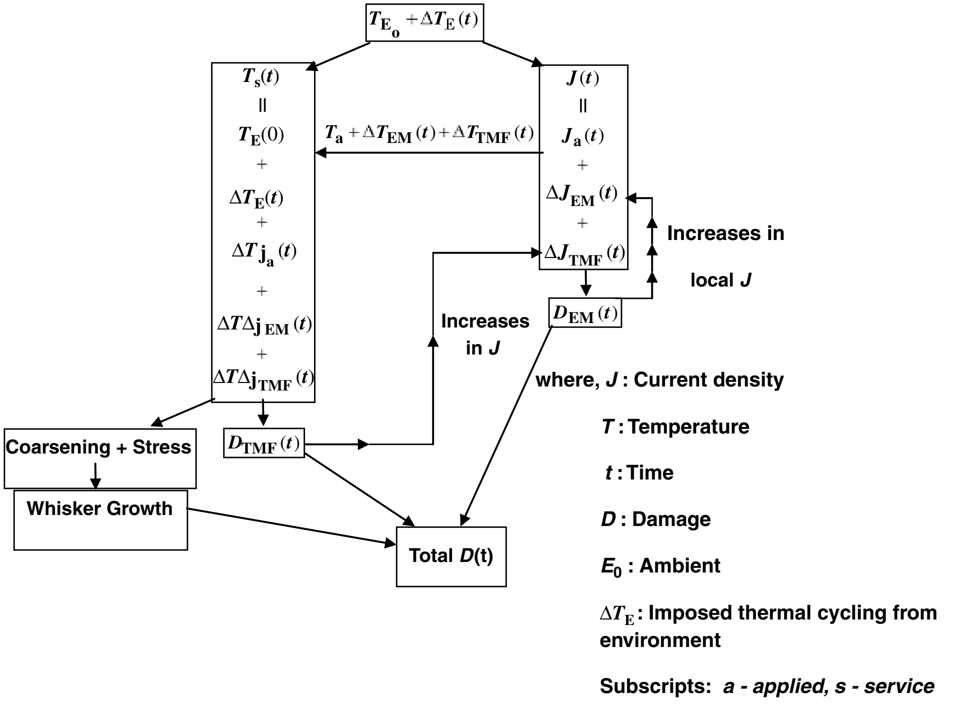
Microstructural coarsening in solder joints can occur due to the high temperatures encountered during service. Segregation and coarsening of the phases can occur due to electromigration. In addition to these effects, small temperature differences in adjacent regions can result from joint geometry and localized Joule heating during electromigration. Even though such temperature differences can be small, they can result in very significant temperature gradients in the miniaturized electronic solder joints. These large temperature gradients can give rise to additional microstructural evolution and damage. This reliability issue has gained attention in recent years.

1.8 Other Potential Issues

Sn exhibits polymorphism. At temperatures above 13 ^{o}C the stable form of Sn has body-centered tetragonal structure (β-Sn) and below this temperature the stable crystalline form is diamond cubic (α-Sn). Transformation form one form to the other is extremely sluggish and is very sensitive to the purity of the metal. Hence, Sn present in solder joints under environments encountered in service exists in body-centered tetragonal structure. However, if the solder joints are exposed to extremely low temperatures for significant lengths of time in future applications, β to α phase transformation can occur resulting in a significant volume increase of about 27%. Since α-phase is extremely brittle, such increase in volume causes extensive cracking and spalling. Such an event, known as 'tin pest' could potentially become a reliability concern for microelectronics, in applications such as aerospace, and extremely cold locations like in Polar regions.

Synergistic aspects of the various issues that affect the reliability of the solder joint need to be addressed in its entirety. Segmentation to address the individual issues can quite often provide a solution to a particular concern, while totally destroying the integrity of the entity by affecting the other issues. In the current scenario TMF is not the only issue that affects the reliability of a solder joint. EM and whisker growth have become important due to the microminiaturization of the electronic components. Among these TMF is concerned with flow and adaptation of material to stresses that develop from thermal excursion encountered. However, the other two involve atom/ion migration. EM is concerned with formation of valleys and hillocks. Such events can attribute to significant additional Joule heating that once again should affect the conditions encountered during TMF. Such *self-perpetuating coupled events* cannot be considered as simple additive effects to TMF.

The following block diagram illustrates some such synergistic issues that need to be considered to evaluate the total damage affecting the reliability of lead-free electronic solder joints.



Another major concern is long-term reliability of microelectronic interconnects. Consumer electronics have relatively short life, and reliability evaluation can be carried out with realistic service parameters. In applications like in space or military, lifetime of an electronic component, the expected lifetime could be several decades. Suitable accelerated test methodologies are still to be developed to guarantee reliability for such applications.