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In situ fixture for multi-modal characterization during electromigration and thermal testing of wire-like microscale specimens

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ABSTRACT

A fixture has been designed and fabricated to facilitate accelerated electromigration (EM) testing with in situ imaging capability of wire-like specimens. This fixture design has enabled microstructural evolution studies in microscale (100 μm–500 μm in dimension) solder volumes. The fixture allows application of thermal and electrical stimulus to wire-like solders in situ during multi-modal characterization. The design is compatible with surface (2D) characterization techniques including optical microscopy (OM) and scanning electron microscopy (SEM) based analyses. SEM characterization using the fixture has also been coupled with electron back-scatter diffraction (EBSD). Grain orientation image maps (OIMs) were obtained for in situ crystallographic microstructural analysis of the test volumes. The fixture is also compatible with X-ray computed tomography (non-destructive and 3D), or XCT, analysis of microstructure volume. To apply 2D techniques, a facet has been polished into the solder volumes prior to mounting within the fixture, though this surfacing requirement is not required for XCT characterization. A demonstration of the fixture's successful EM testing function is provided. The compatibility of the fixture with these characterization tools is also demonstrated. Both functional thrusts of the new in situ fixture's design have been accomplished through the fixture's form which is provided in reproducible detail.

1. Introduction

In microelectronic packages, an array of interconnects which are both electrical and mechanical have been used between the die and the package substrate as well as between the package substrate and a printed circuit board (PCB) to which the package is mounted [1]. In flip-chip architectures, solder volumes with individual diameters of approximately 50 μm have been used to mount a die to a substrate [2]. In mounting a package to a PCB, a ball-grid-array (BGA) of solder volumes, with individual diameters of approximately 500 μm, has been used [3]. One significant long-term reliability concern with micro-scale solder volumes involves electromigration induced damage of the solder interconnects, established, in part, by the small conductor cross section that is realized with these architectures. Electromigration (EM) is the phenomenon of material migration under an applied electric field [4]. The dominant electrical carrier is electrons which move from the cathode toward the anode and cause a momentum exchange with thermally activated metal ions toward the anode yielding an 'electron wind' force [5]. It has been observed that at high current densities the electron wind force is substantially greater than, and opposite to, the electrostatic force, and thus is the dominating force on metal ions in the conductor [6].

A relatively small cross section implies high current density for a particular applied current magnitude. This effect is enhanced by current crowding [7], thermomigration [8], the high concentration of vacancies in the low-melting temperature solder systems leading to concerns over self diffusion induced voiding [9], the rapid diffusion of, for example, copper (a common substrate metal) through the solder by interstitial mechanisms even at low temperature [10], and current induced Joule-heating [11] which may cause aging effects on the solder grain structure and the formation of substrate-solder intermetallic compounds both at

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the interface and in the solder interior [12]. Due to the highly anisotropic nature of tin, the crystallographic influence at small volumes is enhanced as the number of grains is reduced. It has been observed that solder interconnects with the c-axis parallel to the electron flow experience a much higher consumption rate of the under-bump-metallization (UBM) and reduced life [13,14]. With these effects in mind, failure at the solder level within real packages is extremely complex. The microstructural evolution in an individual solder volume operating in an industrial package will conceivably depend on the electrical interconnectivity of the solder interconnects, the temperature and thermal gradient in the package, evolution in neighboring solders, the solder size and composition used, the substrate chemistry, and the thermal processing and heat treatment of the package and/or solder. Although previous research on electromigration induced material evolution in solders has been performed on actual packages or package-like testing structures [7,15–18], tests have also been conducted with individual solder volumes [19–22]. Testing of individual solder volumes has the advantage of effectively reducing peripheral influences in the test and isolating material and environment effects. However, a practical draw-back of the free-standing butt-joint comes from the frailness of the single micro-joint, making it extremely challenging to perform characterization, imaging, and testing from an experimental standpoint. This work demonstrates a new solution to this problem.

In this work, we wish to be able to study microstructural evolution and damage, during thermal excursions and electromigration, by a combination of several techniques such as X-ray microtomography (XCT) and electron backscattered diffraction (EBSD) in a scanning electron microscope (SEM). It has been previously demonstrated that multi-modal characterization is becoming increasingly important in materials science [23]. This is mainly due to the large range of feature/defect sizes present within a given material, for example, macroscopic voiding, microcracking, or grain structure. Different characterization techniques span limited length scales, and a single characterization technique does not, and cannot, provide all of the critical structural information [24]. In this paper, we describe a new fixture design which enables a wide range of in situ testing believed to be impossible, more challenging, or less versatile with the test vehicles implemented by previous researchers. The fixture's design enables the application of electrical current, temperature control through two modes, and minimal joule heating of the specimen during testing. Further, it is compatible with optical microscopy (OM), high resolution XCT imaging, and orientation image mapping (OIM) by EBSD in a SEM. Although these characterization and imaging modes are demonstrated with the fixture, other characterization techniques are possible with the fixture, for example, energy dispersive spectroscopy (EDS) or X-ray diffractometry (XRD). Although solder volume investigations were the motivation for the fixture design, the design described here is also applicable to any wire-line specimen, and has applications in not only electromigration studies but thermal studies as well.

2. Materials and methods

A design was conceived for inducing and monitoring accelerated EM damage in individual solder volumes of a butt-joint geometry and for performing in situ 2D and 3D characterization of damage and microstructure evolution. It is emphasized that although the fixture was conceived for the study of butt-joint solder micro-volumes, it may similarly be used for other joint geometries (with modification) or for any wire-like specimen (without modification). Fig. 1 provides a rendering of a 3D model of the fixture, and demonstrates key design features which were incorporated. The design provided critical functionality for both characterization and testing. Two key features of the fixture that enabled in situ testing include provision of mechanical support and release of free-standing joints during testing. These features also provided a means for destructive characterization post-test. Electromigration testing required application of an electrical current through the sample. The fixture provided this capability through a conductive sample grip which facilitated electrical connection to lead from a power supply. The grips were mechanically constrained to one another using a non-conductive member to limit the flow of current to that of the test volume itself while simultaneously inhibiting undesired mechanical forces from acting on the test volume. Accelerated electromigration required elevated test temperature conditions. The fixture has several desirable characteristics from a thermal standpoint. The electrically conductive sample grips are also highly thermally conductive, which was important for two reasons. First, the fixture was designed such that a conductive heater may be applied to the surface of the sample grips to achieve elevated temperature within the test volume. In this conductive heating configuration, a resistive heater was used, and temperature was controlled in the test volume through the applied power to the resistive heater. Convection heating has also been used by placing the test fixture within a convection furnace, although in this approach, the thermal conductivity of the fixture was less critical. Second, as the sample experienced current stressing, joule heating was expected to potentially occur within the joint and the relatively large highly thermally conductive grips/contacts were designed to act as an efficient heat sink. In electromigration, dissipation of joule-heating was sought to minimize deviations between the target and actual testing temperature to enable more accurate migration analysis and mechanistic insight. The fixture was also designed to study microstructure evolution through thermal aging in the individual solder volumes (without necessarily applying a current). To monitor the test volume temperature during EM testing, which may deviate from the applied temperature due to joule heating, the fixture was designed such that a thermocouple could be placed near the test volume within the fixture.

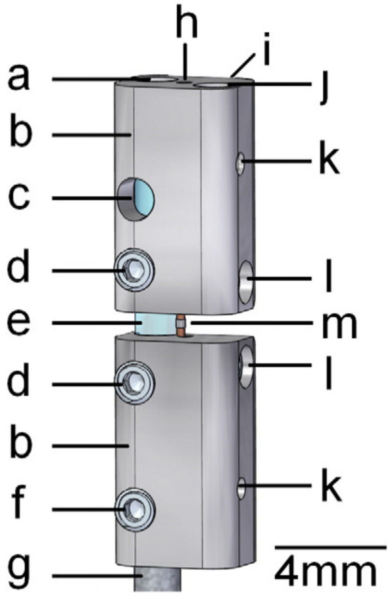

Fig. 1. A CAD model representation of the new in situ EM fixture, a) SUPPORT rod port, b) aluminum block, c) threaded heater constraint, d) support rod constraint, e) glass support rod, f) fixture support constraint, g) fixture support post within same port as support rod, h) sample port, i) electrical lead constraint (not visible), j) electrical lead port, k) gas vent, l) sample constraint, and m) sample test volume.

As seen in Fig. 1, the design consisted of two aluminum (2024 T351) blocks, into which each half of the sample's bases were constrained. In the design, a Zerodur® (SCHOTT North America, Inc.) glass rod mechanically constrained the aluminum blocks with respect to one another. Aluminum was chosen for the conductive blocks considering an ideal combination of stiffness, strength, and electrical/thermal conductivity. The design was such that a specimen may be placed into each block through cylinders in either end, which, in the prototype here provided, were fabricated using a 500 μm hole obtained by electrical discharge