Bond tester study of CSP reliability through bump analysis

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Miniaturization, the drive to lead-free semiconductor products, combined with the increasingly harsh application environments impose stringent requirements on solder bump reliability in chip-scale packages (CSP). In addition to a clear quality specification, there is a need for comprehensive mechanical testing to ensure reliable solder connections over the projected lifetime of the device. Such tests must detect problems and nonconformances as early as possible in the production cycle. A systematic approach to predict product lifetime, monitor ongoing production, process control statistical methods, and failure analysis is needed in order to guarantee high-quality product.

While nondestructive tests like X-ray computer tomography are always desired, they cannot replace the information that can be deduced from standard mechanical bond test methods like shear and cold bump pull (CBP). This paper discusses CSP bump reliability in general, and various bond test methods in particular. A case study evaluating different solder compounds (Sn-0.7%Cu, Sn-3%Ag-0.5%Cu, Sn-3%Ag-0.7%Cu) is also presented in order to illustrate the methodology and discuss the challenges.

Discussion of bump failure modes in CSP packages

Open, intermittent contact in the final product is the major failure mode. This can be caused by delamination from excessive stress, coalescence of voids formed during assembly, undesirable intermetallic compounds (IMC) formed during reflow of the solder, or void formation through electromigration. Several root causes can also compound, e.g., when multiple IMCs with different electrical resistivity and/or voids cause current-crowding, thereby accelerating electromigration. These problems can be minimized by adequate process control, proper material choice, and design optimization to minimize stress from different coefficients of thermal expansion (CTE). It is important to note that even slight changes in alloy composition of the solder can have a large effect on its mechanical properties.

Shorts or leakage paths between bumps is another typical failure mode. Root causes for this are attributed to insufficient barrier by the underfill to whisker growth and surface contaminations leading to ionic or galvanic leakage paths. This mode is typically more related to underfill and cleaning than to bump composition and formation.

Process control

Once the solder composition, pad size and arrangement, and substrate material (under-bump metal choice and thickness) are finalized from finite element modeling (FEM), the assembly process, and its expected variation over substrate space and time has to be considered and examined. Common methods include DoE for process parameters and their variation, x-ray tomography and mechanical cross-sections (saw and polish or focused ion beam). These need to be performed on virgin devices and after accelerated life tests, such as thermal cycling and electromigration testing. The goal of this type of study is to understand the microstructure of the bump (including grain structure, precipitates, phase boundaries, IMC formation at under bump metallization (UBM), and occurrence of voids). In addition comparing samples with and without underfill will establish if the particular material used fulfills its task of stress attenuation and confinement of bumps to prevent premature delamination. These qualification tests should be regularly repeated as a monitoring program, e.g. on a quarterly basis.

In addition to this qualification and reliability monitoring program, a continuous process control system is needed and since no non-destructive tests exist, bump shear (BST) and bump pull test (BPT) before system assembly, as well as die shear (DST) and die pull testing (DPT) after assembly are wildly used. These tests are described in detail in various industry standards and publications. Brittle fail at the IMC interface, extensive voiding, pad lift, i.e., delamination of the metallization under the UBM, are all reject criteria commonly used by the industry. It is very important to test bump quality before and after CSP assembly. This double testing becomes instrumental when trying to distinguish between material defects and assembly-related weaknesses.

Bond tester techniques for evaluation of bump quality

The three most common techniques for evaluation of bump quality and integrity are bump shear (BST), cold bump pull (CBP) and hot bump pull (HBP). The HBP test was developed to study pad cratering failures as per IPC-9708 standard.

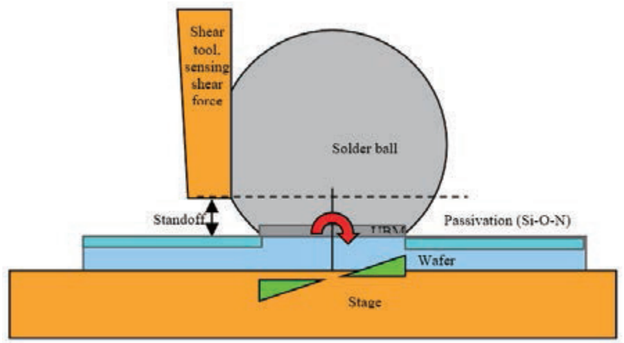

Figure 1: Schematic representation of shear test. The resulting momentum on the bump base is shown as a red arrow; green triangles represent the resulting tensile and compressive forces on the bump base.

The HBP test is performed by soldering a pin to the solder ball using a pre-defined temperature profile and then performing a pull test. The nature of the grip allows the pull force to be orientated with respect to the pad, simulating real life service conditions. Additional information can be obtained by cyclic loading.

It is well known that BST has complex force distribution (**Figure 1**). In addition, the shear tool imposes a rotational moment proportional to shear force and standoff (shear height), which in turn results in a lifting force at the leading edge of the UBM/bump system.

BPT (**Figure 2**), on the other hand, uniformly distributes the test force over the bump base. While BST imposes a significant pull stress only at the leading edge, CBP and HBP tests stress the whole UBM area, both at the IMC interface to the bump above and the pad structure below the UBM.

To summarize the above discussion, both shear and pull tests need to be considered and used when designing the test plan. The shear test is more straightforward and easy to perform and automate, however, in many cases, the pull test provides additional valuable information and failure modes that may not occur in a simple shear test.

There is a clear need to test components, materials and bonds under controlled conditions that generate failure modes similar to those observed in service. In general, bond testing involves pulling or shearing at relatively low strain rates. Solder joints often fail by ductile fracture of the bulk solder and other parts of the joint do not experience the stress levels they would see if the loading on the joint had been more rapid. All joints can be thought of as a chain where the links of the chain represent the various materials that make up the joint. A simple solder joint on a PC board comprises a number of links: bulk solder, an intermetallic layer at the interface with the bond pad, the bond pad, an adhesive layer between the bond pad, and the organic substrate and the substrate itself. The joint is only as good as its weakest link and at low strain rates this is often the bulk solder. It is well known that solders exhibit time-dependent deformation and that their yield point increases dramatically with strain rate. The much higher strain rates associated with impact and board bending result in much higher forces on the bond pad, as for these cases there is less time for the material to flow. High strain rates produce larger bond pad forces. Soldered connections can fail in a brittle manner at high rates of strain. Low strain rate testing cannot pick up the microstructural changes that occur at the bond interface responsible for a brittle connection. Low strain rates cannot identify microstructural changes that lead to brittle fracture. Therefore, in order to study brittle fracture failures, we need to employ high strain rate testing in addition to the regular BST and CBP.

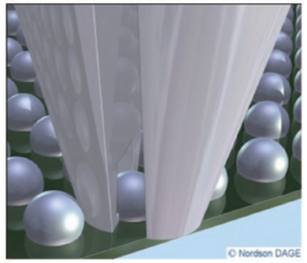

Figure 2: Illustration of a cold-bump pull (CBP) test. Force geometry is less complex than BST and a uniform tensile stress is projected over the bump base.

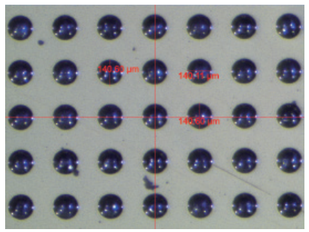

Figure 3: SAC305 solder bumps after first reflow as used in this study.

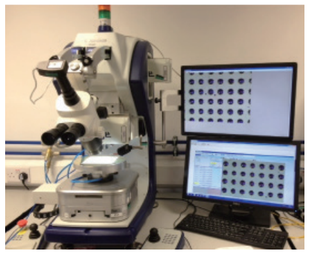

Figure 4: Test setup for BST testing. The wafer samples were secured using a vacuum wafer chuck.

Case study: low-speed shear test of various SAC alloys

In order to illustrate the above discussions, we performed a simple bond tester study of various SAC solder alloys. Lead-free solders around the Sn-Ag-Cu eutectic point offer many significantly stronger solder alloy. Thus, the Sn-Ag-Cu system can offer many interesting material property variations around its eutectic point (SAC, close to SAC378 or Sn-3.75%Ag-0.8%Cu). These can be effectively studied using the bond tester methods discussed above.

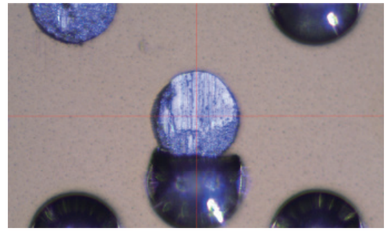

Figure 5: Ductile failure of an SAC305 bump. The test speed was 500µm/s with a 10µm shear height (standoff).

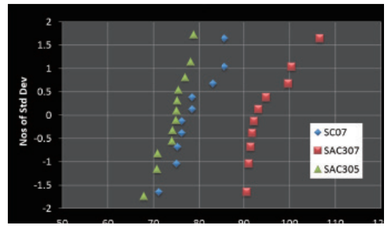

Figure 6: Cumulative distribution of a ball shear test for three lead-free solder compounds.

Summary

As a general conclusion, we want to reinforce that there is a clear need to test components, materials and bonds under controlled conditions that generate failure modes similar to those observed in real life. A simple solder joint can fail due to multiple factors and the weakest link could be in the bulk solder, the intermetallic layer at the interface with the bond pad, the bond pad itself, the adhesive layer between the bond pad, and the organic substrate and the substrate itself. This implies that a test methodology comprising standard BST and BPT, as well as high strain rate testing and HBP, provide a comprehensive set of test results that can be used to monitor quality and optimize design and materials. In addition, camera-assisted automation of the bond testing process permits large statistically significant data sets to be acquired in a short period of time, and minimizes operator dependency.

Biographies

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choices of parameters critical to assembly, such as melting point or range, thermal expansion coefficient, ductility or hardness. The specimen consisted of 125µm solder balls of SAC305 (Sn-3%Ag-0.5%Cu), SAC307 (Sn-3%Ag-0.7%Cu), SC07 (Sn-0.7%Cu) that were placed on pads of 120µm diameter. The under bump metal (UBM) consisted of 5µm-thick Ni coated with an Au anti-oxidation layer. After reflow, the solder balls formed 90µm-high bumps with a diameter of about 140µm (**Figure 3**), indicating a slight sag compared to a perfectly spherical bump (97µm-high, 134µm maximum diameter).

HBP tests showed exclusively solder failure, while CBP tests showed solder extrusion failures in some cases. We therefore concentrated on a simple shear testing experiment in order to evaluate the three different solder alloys. BST was performed using a 150µm-wide flat chisel at 500µm/s with a 10µm shear height (standoff). The wafers were secured using a vacuum wafer chuck. The test setup is shown in **Figure 4** and a typical ductile failure mode is shown in **Figure 5**.

Figure 6 shows the shear test results on a normalized distribution plot. The narrow distribution indicates a fairly well controlled process with random process variation. Based on this, it can be concluded that SAC 305 and SC07 perform in a very similar way. However, only slight variation in composition (increasing Cu content by 0.2% in SAC307) results in a