APPLICATION NOTE

Mechanical Characterization of Pb-Free Solder Bumps

Nanoindentation Measurement of Hardness & Modulus as a Function of Time & Temperature

Introduction

As microelectronics manufacturers work to reduce or eliminate Pb from their device packages, characterization of the mechanical properties of various Pb-free solder alloys has become an important industry challenge. The changes in temperature and stress experienced by a solder connection over various time scales during application, processing, and use will greatly influence the resulting microstructure of the material, in large part determining its mechanical properties. Since the volume of a solder bump on a microcircuit is extremely small, nanoindentation is the appropriate technique for direct measurement of the solder's mechanical response. Nanoindentation provides a means to quantitatively measure the hardness, modulus, and creep behavior as a function of temperature.

Nanoindentation Creep Testing

In a traditional (quasi-static) indentation test, a load is applied to force an indenter into the surface of a material, the load is held constant for some time, and then the load is withdrawn. With knowledge of the probe shape, applied force, indenter penetration depth, and unloading stiffness, the material's hardness and modulus can be calculated. Force and displacement are measured continuously, producing a Force vs. Displacement curve, the slope of which at the initial unloading point gives the contact stiffness. A single quasi-static test therefore produces a single measurement of hardness and modulus at the maximum penetration depth of the test.

In a dynamic indentation test, a relatively small sinusoidal oscillation is superimposed onto the quasi-static loading profile. Load amplitude, displacement amplitude, and the phase lag between them are used to calculate the contact stiffness continuously throughout the test. Since stiffness is known at all times in a dynamic test, hardness and modulus can also be measured continuously.

Many materials exhibit some degree of creep while the quasi-static indenter load is held constant, but characterization of the creep behavior has traditionally been difficult. Displacement error from thermal drift, while usually minor at short times, becomes prohibitively large after several minutes or hours. Hysitron's **nanoDMA® III** reference creep testing technique overcomes this limitation by applying a dynamic force throughout the test, allowing contact stiffness to be continuously measured. The modulus of the material (the reference modulus) is calculated early in the test, while error from thermal drift is negligible. For the remainder of the test, as the quasi-static load is held constant, continuous measurement of contact stiffness along with knowledge of the modulus allows contact area (and therefore, contact depth and hardness) to be calculated without any reliance on the quasi-static displacement measurement, making background thermal drift irrelevant. By performing creep tests in such a manner, tests as long as several hours can be reliably performed.

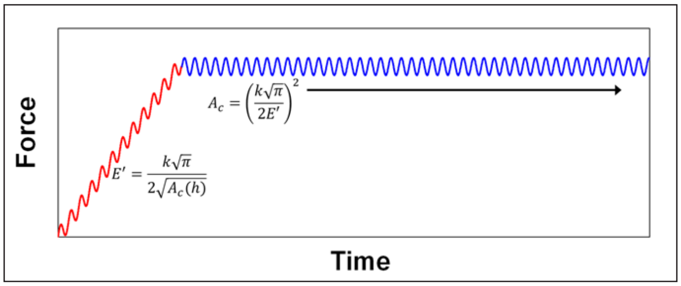

Figure 1: Schematic representation of a **nanoDMA III** creep test.

Mechanical Characterization of Pb-Free Solder Bumps

Solder bumps composed of 3% Ag and 97% Sn were prepared on top of Cu pillars patterned onto a Si wafer. Figure 2 gives an optical micrograph of the structure. The solder caps were roughly 20 µm wide and were domed on top. A Hysitron **TI 950 TriboIndenter®** equipped with **nanoDMA III** and a **xSol High Temperature Stage** was used to perform creep measurements

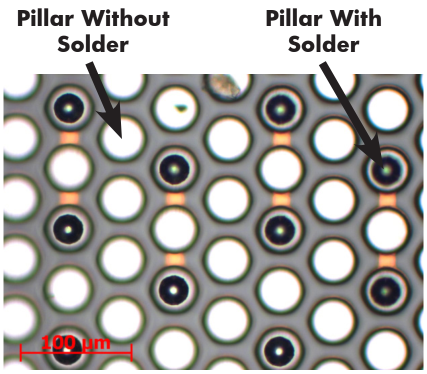

Figure 2: Optical micrograph of the silicon, copper, solder structure. Sample provided by Jürgen Grafe, FHG-IZM-ASSID, Dresden, Germany, and Kong-Boon Yeap, FHG-IFZP, Dresden, Germany.

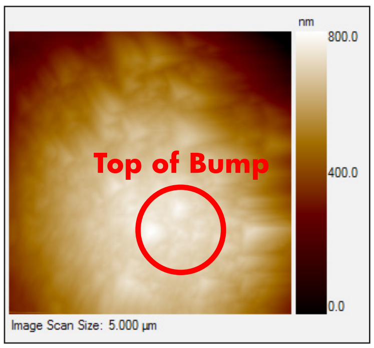

Figure 3: Topographical SPM image of a solder bump prior to testing with the target test location indicated by the circle.

at 25, 50, 100, 150, and 175 °C using a diamond Berkovich probe. Prior to each measurement, the instrument's *in-situ* SPM imaging capability was used to image the topography of the sample surface and position each test precisely on the top of the dome, where the surface was nearly flat and perpendicular to the probe. For each test, the force was ramped quickly to peak force and then held constant for 1000 seconds while the stiffness was continuously measured by a 220 Hz oscillation. As the load was held, the contact stiffness increased with the increasing penetration depth of the probe.

The quasi-static force for each test was chosen such that the initial depth of the indent would be approximately 500 nm, and the dynamic force was selected to give a displacement amplitude of roughly 1 nm. The target depth was chosen as a balance of two considerations. For a very small indent, surface roughness could affect the accuracy of the measurement, but if the indent was too large, the free edges around the perimeter of the solder bump could have an effect.

Figures 4-5 show contact depth and hardness as they changed over time, and Figure 6 shows modulus as a function of temperature. From 25 to 150 °C, the creep curves had similar shapes, but there was a clear difference at 175 °C. The creep rates at 175 °C were much higher, and the hardness decayed by 70% over the course of the 1000 second hold. The transition in creep behavior suggests a change in the deformation mechanism between 150 and 175 °C, and the results made clear that the mechanical properties of the solder bumps deteriorate rapidly above 150 °C.

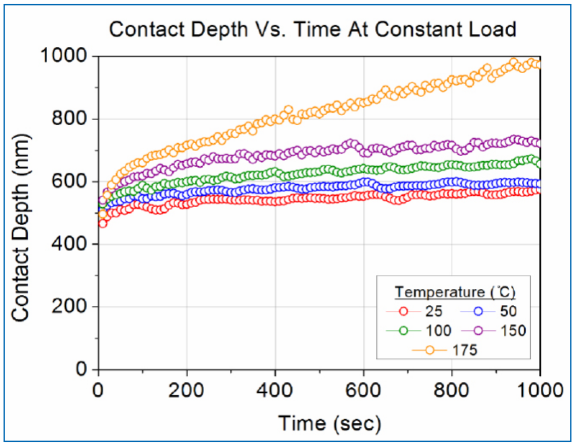

Figure 4: Depth vs. time at each temperature.

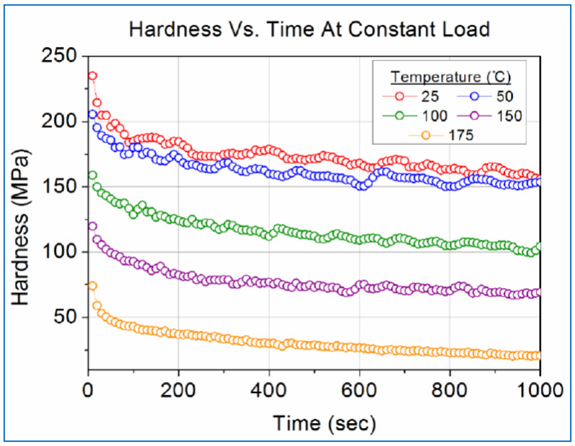

Figure 5: Hardness vs. time at each temperature.

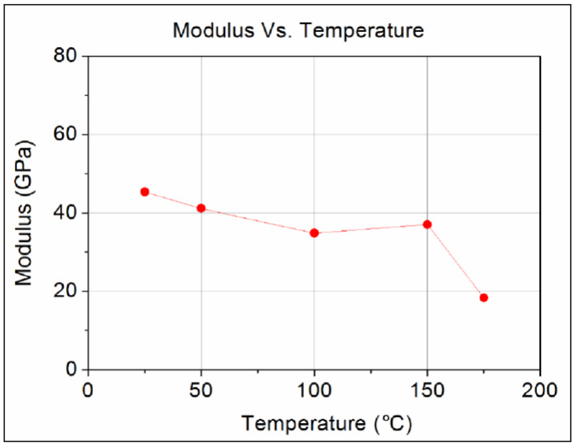

Figure 6: Modulus measured at each temperature.

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