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Lead-Free Solder Ball Fragility

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Government regulations for handling electronic waste materials are becoming more stringent. The European Union (EU) and China implemented regulations on the restriction of use of hazardous substances (RoHS) for electrical and electronic equipment on July 1, 2006 and March 1, 2007, respectively.

One of the intents embodied in these regulations is to ban the use of elemental lead (Pb), commonly used in the fabrication of BGA package solder balls. To comply with these regulations, BGA solder ball composition must be changed from eutectic solder (Sn_{63}/Pb_{37}) to Sn/Ag/Cu or Sn/Ag Pb-free solder. Xilinx is in compliance with these new regulations and provides Sn/Ag/Cu (SAC) solder balls on its FFG packages.

This white paper provides a brief overview of the ramifications of using Pb-free solder balls in BGA device packaging.

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Industry Status of Pb-Free Solder Applications

Since the introduction of the Pb-free initiatives, both industry and academia have extensively investigated solder ball composition and proposed the use of SAC305/405 solder alloys because of their high strength and reasonable melting point. Xilinx is following industry practice in using SAC305/405 solder in its Pb-free products.

Now that Pb-free device packages are in high-volume production, the industry is discovering that these alloys are more fragile than eutectic solders, producing high-ppm levels of inter-metallic compound (IMC) fractures when under high strain rates, such as during handling, shipping, and socketing.

Why Pb-Free Solder is More Fragile

Modulus Comparison between Sn/Pb and Pb-Free Solder

Table 1 and Figure 1 show the modulus of SAC405, SAC305, and Sn_{63}/Pb_{37} solders. It can be seen that the Pb-free solders have a higher modulus but less elongation when compared with eutectic Sn/Pb solder. A higher modulus and less elongation make Pb-free solders more fragile with poorer compliance.

Table 1: **Characteristics of Pb-Free and Eutectic Pb-Containing Solders**

Alloy	Modulus [GPa]	UTS [MPa]	Elongation [%]
$Sn_4/Ag_{0.5}/Cu$	53.3	52.4	35
$Sn_3/Ag_{0.5}/Cu$	51.0	53.3	46
Sn_{63}/Pb_{37}	40.2	57.3	50

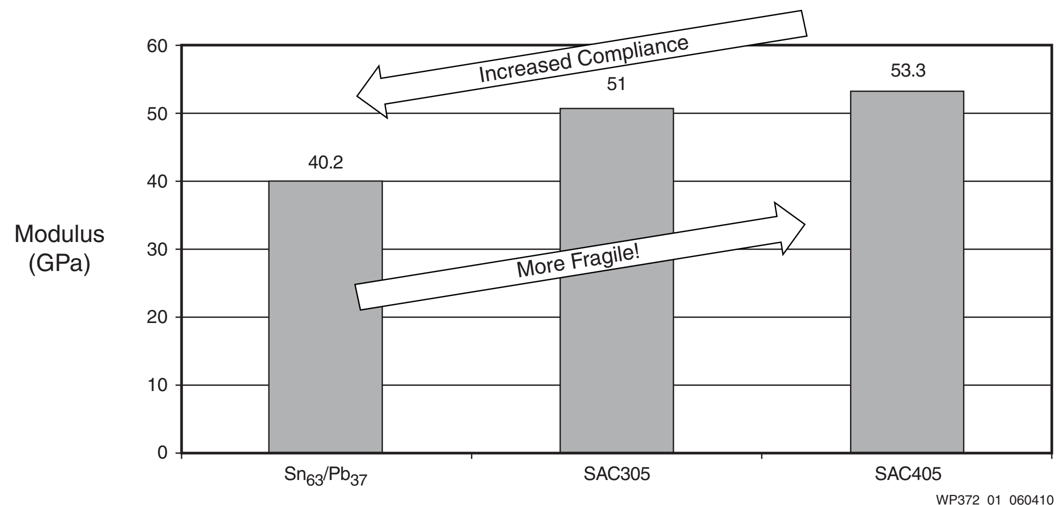

Figure 1: **Modulus Comparison between Sn/Pb and Pb-Free Solders**

IMC Brittle Fracture under High Strain Rate

Xilinx products use Electrolytic NiAu as a BGA pad surface finish. During the solder ball mount reflow process, Ag_3Sn, $(CuNi)_6Sn_5$, and $(CuNi)_3Sn$ IMCs are formed between the solder and the BGA pad. These IMCs comprise a brittle layer. If the solder joint is subjected to high strain rates of approximately 10^1–10^2/sec (dynamic to impact loading condition), IMC fractures can occur, as shown in Figure 2.

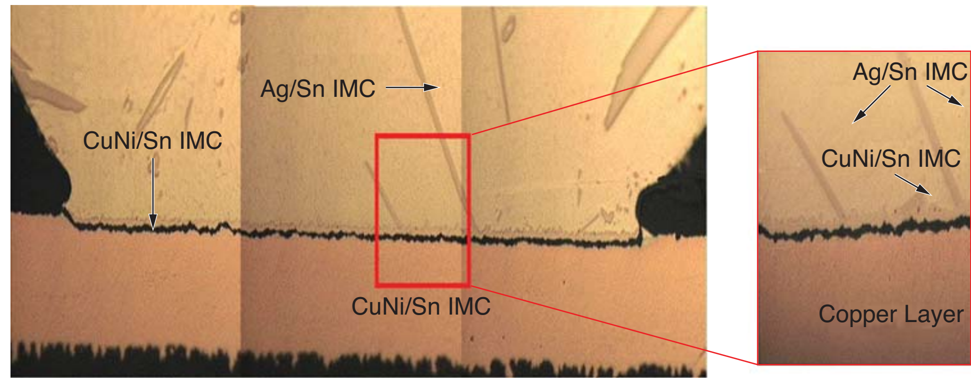

Figure 2: **Pb-Free Solder IMC Fracture under High Strain Rate**

Figure 3 illustrates that if the same strain is applied quasi-statically, Pb-free solders go into a plastic deformation phase without catastrophic failure. If impact loading is applied, however, stress increases dramatically. This phenomenon shows that proper handling is essential for devices using Pb-free solders.

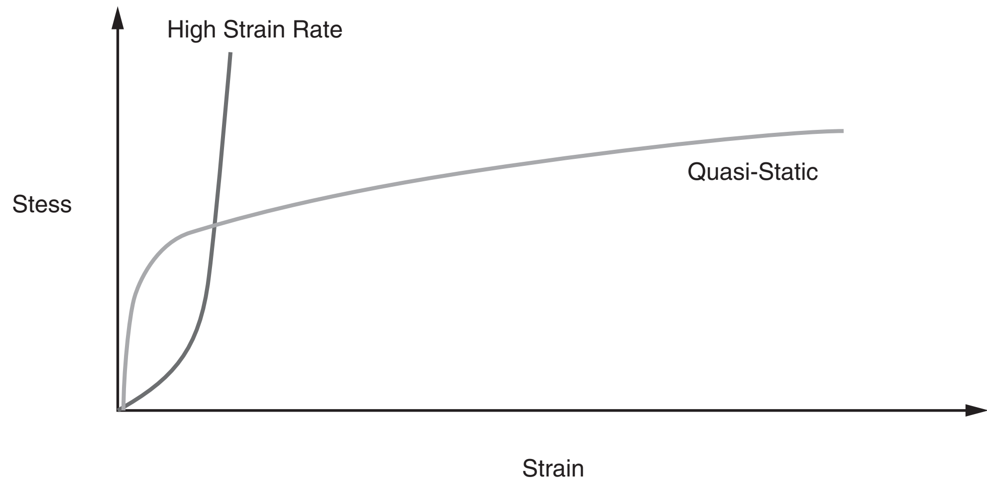

Figure 3: **Pb-Free Solder Response under Different Strain Rates**

Summary and Recommendations

- The industry-wide replacement of eutectic Sn/Pb solders by Pb-free solders is for environmental and regulatory reasons, not for reasons of technical improvement. SAC305 and SAC405 are the mainstream formulation choices for Pb-free solder.
- Pb-free solders are more fragile and have worse compliance compared to Sn/Pb solders. A brittle IMC layer is formed between solder and BGA pad. For Xilinx products, this IMC layer is $(CuNi)_6Sn_5$ and $(CuNi)_3Sn$.
- High strain rate loading of Pb-free solder balls can cause the brittle IMC layer to fracture. Moderate loading, on the other hand, causes plastic deformation of the solder ball and prevents brittle fracturing.
- Proper handling of Pb-free BGA packages during shipping and board mounting is required to avoid high strain rates.

Revision History

The following table shows the revision history for this document:

Date	Version	Description of Revisions
06/28/10	1.0	Initial Xilinx release.

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