Adaptation to scientific and technological progress under Directive 2002/95/EC

Joint response from EICTA, AeA Europe, EECA ESIA and ZVEI to the general and specific questionnaires relating to exemption 7a

31-March-08

Content

General questionnaire

1. For which substance(s) or compound(s) should the requested exemption be valid?	Lead in high melting temperature type solders (i.e. lead-based alloys containing 85% by weight or more lead)
2. What is the application in which the substance/compound is used for and what is its specific technical function?	1) High lead solders are used to form high reliability electrical connections [Annex 1, Annex 3, Annex 4] 2) High Pb solders are also used to form a high conductivity thermal interface to the back of a semiconductor device, also known as die attach. The use of high melting temperature solders is required in power devices and discrete semiconductors. These typically are used in high reliability applications, such as automotive and server applications. 3) High melting temperature solder used as a sealing substance between tubular plugs and metal cases - Crystal resonators, crystal oscillators. These applications can be found in many products, including PCs, cellular phones, and other home appliances. 4) High melting solders are used for a reliable internal connection in passive components, to withstand soldering processes, especially those using lead-free solder.
3. What is the specific (technical) function of the substance/compound in this application?	1) In soldered electrical connections, high lead solders have unique material properties that enable solder joints to withstand a high number of thermal fatigue cycles and resist electromigration failure. [See Annex 1 , Annex 3 and Annex 4]. Examples of applications include large BGA or Solder column packages, as well as some discrete devices in high reliability electronics. 2) In soldered thermal interfaces to semiconductor devices, high lead solders enable high conductivity interfaces between the die and the leadframe/heat spreader that are capable of meeting hierarchical* reflow temperature requirements for components to be soldered to the board, while also having sufficient mechanical compliance required to prevent device damage during manufacture and operation. The melting point of these solders should be higher than the reflow temperature that is used for board assembly. The latter temperature has gone up to 260 °C due to Pb-free assembly. No suitable Pb-free solder has been found with a melting temperature as high as solders containing >85% Pb. 3) For crystal resonators that are made by mounting a quartz vibrating reed onto a tubular plug and sealing them into a metal case, high melting temperature solder is used as a sealant for the plug

	and metal case. Also, there are many crystal oscillators that are crystal resonators molded in plastic. The reason that high temperature solder is used as a sealant for plugs and metal cases is that air impairs vibration of the reed and the crystal resonator will not oscillate. Therefore a vacuum must be maintained inside the case. Solder is used as a sealant between the plug and metal case to protect the vacuum. A Pb-free substitute for high melting temperature solder doesn't exist as a sealant. 4.) Passive components containing internal solder joints have to withstand peak soldering temperatures of 250° - 260°C and the higher heat transfers of lead free soldering process during the production of EEE. For that reason, high temperature solders with a lead content of more than 85% are used. *Note: In a hierarchical reflow process, the initial semiconductor die must be attached to the package with a thermal interface that does not reflow during subsequent manufacturing processes.
4. Please justify why this application falls under the scope of the RoHS Directive (e.g. is it a finished product?	All of the devices under discussion in exemption 7a are components that are then assembled into a finished EEE system.
- Is it a fixed installation?	No. While some of these devices are used in fixed systems, many of them may also be used in non-fixed installations.
- What category of the WEEE Directive does it belong to?).	It is expected that devices using this exemption have potential applications in categories 1 through 10.
5. What is the amount (in absolute number and in percentage by weight) of the substance/compound in:	
i) the homogeneous material[1]	1) In the case of high-lead solder connection for electrical interconnect, the percentage of lead used in the solder prior to the component attach is typically in the range of 90-97% by weight. In the case of BGA or Solder Column packages, the soldering process will result in some blending of the original solder alloy with the solder alloy used for component attach, resulting in regions of alloy that could fall below 85% lead content. 2) In the case of thermal interface materials, the percentage of lead is typically 90-95% by weight. 3) In the case of crystal resonators and oscillators, and passive components, the percentage of lead in the homogenous material is greater than 85% by weight.
ii) the application, and	Under this exemption, the amount of lead used in each application is estimated as follows: Server equipment : 3-45 grams per server Telecommunications and switching: 2-25 grams/system

	Thermal interface/die attach: 0.001g to 0.075g per device, average .047g Crystal resonators: 0.7mg/pcs to 1.4mg/pcs of lead per device Internal connection of passive components : 30 mg/pcs to 60 mg/pcs
iii) total EU annually for RoHS relevant applications?	Under this exemption, the amount of lead entering the EU annually is estimated to be approximately 47 tonnes. This estimate is based upon industry approximations, as well as calculations from DG ENV. Study Contract N 07010401/2006/449269/MAR/G4 "The Producer Responsibility Principle of the WEE Directive", August 19, 2007.
6. Please check and justify why the application you request an exemption for does not overlap with already existing exemptions respectively does not overlap with exemption requests covered by previous consultations.	*Not applicable – this is only for new exemption requests*
7. Please provide an unambiguous wording for the (requested) exemption.	Lead in high melting temperature type solders (i.e. lead-based alloys containing 85% by weight or more lead). 'Solder' is defined as "alloys used to create metallurgical bonds between two or more metal surfaces to achieve an electrical and/or physical connection". In this context, the term 'solder' also includes all materials that become part of the final solder joint, including solder finishes on components or printed circuit boards.
8. Please justify your contribution according to Article 5 (1) (b) RoHS Directive whereas:	
o Substitution of concerned hazardous substances via materials and components not containing these is technically or scientifically either practicable or impracticable;	1) Electrical Interconnect: Please see Annex 1 , Annex 3, Annex 4, and Annex 5 for details on the technical impracticability of alternative solders. While alternative alloys exist, they do not meet reliability requirements. High lead solders contain a unique combination of ductility and reflow temperature hierarchy required for high reliability applications. At this moment there is no commercially available Pb-free material as a substitute that has the necessary electrical and / or thermal conductivity as well as the right material properties (such as coefficient of thermal expansion (CTE), ductility etc.) to maintain high reliability 2) Thermal Interface Die Attach applications: Pb-based die attach materials have a combination of good thermal performance, electrical performance and can deform in thermal cycling without cracking or causing joined components to crack. There are no known suitable Pb-free replacements. The high melting temperature alloys like AuSn are hard and brittle. Pb-free solutions perform poorly in thermal cycling reliability tests, typically cracking in either the solder or in the joints. Conductive adhesive materials do not yet have suitable thermal conductivity. These adhesives also have inconsistent results on joint quality. Development is underway, but could take many years to approach the capability of high Pb solder.

	The high lead solder has a high melting point as well as good thermal conductivity. The high melting point (> 260 °C) is necessary because if the die attach material melts during board assembly there is a high chance of failures inside the package due to movement of the die (bond wire crossing). Although the die attach is high in Pb content the total volume is very limited due to the fact that this solder is only applied within the package in small amounts. **3) Oscillators:** After the crystal resonator and crystal oscillator are delivered to the device manufacturer, the manufacturer solders them onto printed circuit boards. Recently this solder is often Sn-Ag-Cu solder because of the lead-free trend. The temperature used for this soldering is 250° - 260°C. Sn-Ag-Cu solder melts at a temperature lower than 250°C (close to 217°C). However, crystal resonators and crystal oscillators that are joined by solder internally have to be able to withstand soldering temperatures of 250° - 260°C at the device manufacturer. For that reason, high temperature solder of more than 85% lead content is used to seal the interior of the crystal resonator or crystal oscillator to get the melting properties needed so the solder does not melt completely even at 250° - 260°C.
o Elimination or substitution of concerned hazardous substances via design changes is technically or scientifically either practicable or impracticable;	**1) Electrical Interconnects:** For long life reliability, no other material has been found with the unique combination of ductility, hierarchical reflow temperature and electrical properties of high lead alloys. The replacement of high lead solder alloys in electrical interconnect will require a dramatic reduction in the solder joint stresses to enable the use of any of the known lead-free alloys. Lower solder joint stresses can only be achieved through the use of new electronic packaging materials. Selection of new packaging materials requires extensive electrical and mechanical characterization to assure long term reliability. An example of an alternative material that can reduce solder joint stress is replacement of ceramic ball grid array packages with organic laminate ball grid array packages. While these technologies have been shown suitable for many consumer applications, they have not yet been demonstrated to have adequate reliability for complex electronics interconnect, such as found in servers, networking equipment and high end gaming equipment. In addition, new Pb-free alloys will be needed to reduce electromigration (EM) failures to acceptable levels, as described in Annex 4. Greater integration and higher power density of continually evolving electronic devices / systems will only exacerbate these factors. New Pb-free materials will need to handle future as well as existing conditions. **2) TIM applications:** Elimination of Pb content in the high Pb die attach material is not possible by design changes. Only materials with acceptable reflow temperatures, ductility, and thermal conductivity can provide an acceptable substitute. **3) Crystal oscillator:** As a sealant, there are organic adhesives, but these cannot withstand vacuums (because they are moisture-permeable). Therefore there are no substitute measures for

	high temperature solder.
o Negative environmental, health and/or consumer safety impacts caused by substitution are either likely or unlikely to outweigh environmental, health and/or consumer safety benefits thereof (If existing, please refer to relevant studies on negative or positive impacts caused by substitution).	In all of the applications under discussion, the use of lead-free alloys would result in significant reduction in the reliability of a wide range of products. In the best case, decreased reliability would result in increased electronic waste due to premature device failure and reduced manufacturing yield. In the worst case, unexpected failures could cause consumer safety concerns. Many of the high performance / high reliability applications that use high-Pb solders require exacting performance characteristics because there is significant risk to human life / safety, including air traffic control, other transportation systems control and governmental security or defense systems. Low reliability substitutions in these systems would result in considerable human mortality / suffering. For the die attach application, due to low volume and the fact that high-lead solders are only used inside the packages the environmental/health impact is low, especially comparing this to the fact that these are often used in application where high reliability and safety is a major concern, such as in automotive power devices. Au (gold) based solders show decreased product reliability. Environmental impact of Au mining and processing outweigh the environmental risk of existing high temp Pb soldering system.
9. Please provide sound data/evidence on why substitution / elimination is either practicable or impracticable (e.g. what research has been done, what was the outcome, is there a timeline for possible substitutes, why is the substance and its function in the application indispensable or not, is there available economic data on the possible substitutes, where relevant, etc.).	1) Electrical Interconnect: Please see Annex 1 , ANNEX 3 and Annex 4 for details on the technical impracticability of alternative solders. While alternative alloys exist, they do not meet reliability requirements for all applications. A specific example shown in Figure 2 demonstrates a qualification effort to replace a high-lead BGA with a SAC alloy BGA. It was found that while lead-free solutions are available, they do not meet the required reliability goal. While work on lead-free alternatives is continuing, it is apparent that significant invention and/or major system redesigns will be required. It is difficult to predict when this invention will be successful. 2) TIM: ANNEX 2 contains technical details on the thermal interface application. At this time, no acceptable alternatives have been found. 3) Crystal oscillator: A number of materials could conceivably be used as substitutes; however, there are the following concerns. a. There is SnAu80, which gives high temperature melting properties, but it has inferior malleability and is brittle and therefore cannot be used. b. There is also SnCu, but this has a low melting point and cannot withstand soldering temperatures of 250° - 260°C. c. There is also AgCu, but its melting temperature is too high to be used (700° - 900°C). d. As a sealant, there are organic adhesives, but these cannot withstand vacuums (because they are moisture-permeable).

	Therefore there are no substitute measures for high temperature solder.
10. Please also indicate if feasible substitutes currently exist in an industrial and/or commercial scale for similar use.	While lead-free alternatives have been developed for some uses, it is clear that these alternatives are not a feasible replacement for all high-lead solder applications. Current lead-free solders exist based on the SnAgCu system, however, their melting points are similar to the solders used in board assembly. If these solutions were used, then the die attach would become liquid, resulting in a reliability hazard. Other alternatives like SnAgSb suffer from the same low temperature reflow temperature, as well as the uncertainty of the environmental impact of Sb. SnAu80 is a commercially available Pb-free die attach with a high melting temperature, however several concerns exist for this system. The interconnect is brittle, CTE mismatch between die and solder prevent use on larger die, negative environmental impact of Au. SnCu: melting point below 250° - 260°C, not a viable alternative AgCu: because of a too high melting temperature at 700° - 900°, not a viable alternative
11. Please indicate the possibilities and/or the status for the development of substitutes and indicate if these substitutes were available by 1 July 2006 or at a later stage.	Invention of new Pb-free solders with appropriate melting ranges and with the necessary mechanical properties for sufficient reliability is still required in all three application areas. Acceptable substitutes were not available by 1 July 2006. Since no candidates have yet been discovered, it is unlikely that such invention and subsequent reduction to practice can occur within the next four years.
12. Please indicate if any current restrictions apply to such substitutes. If yes, please quote the exact title of the appropriate legislation/regulation.	Since there are no suitable substitutes, this question is not applicable.
13. Please indicate benefits / advantages and disadvantages of such substitutes.	As previously discussed, any of the known lead free substitutes will reduce the component reliability to an unacceptable level. Epoxy based die attach are used in applications that are used in where lower reliability and/or low thermal conductivity is required. In the cases where the exemption exist these substitutes can't be applied due to reliability demands or thermal demand.
14. Please state whether there are overlapping issues with other relevant legislation such as e.g. the ELV Directive that should be taken into account.	While there may be overlap in the use in lead in solder the conditions under which a product needs to operate (temperature, humidity) may differ significantly. We are not aware of any conflicting legal requirements. Based on the current state of electronic packaging technology, it is anticipated that high-Pb solders will be needed beyond 2010.

15. If a transition period between the publication of an amended Annex is needed or seems appropriate, please state how long this period should be for the specific application concerned.	Since there is not a practicable alternative to the high lead solders, a transition period is not applicable. The industry is making every effort to design away from high lead solders where feasible. While it is expected that there will be a continued reduction in the requirement for this exemption, significant invention that has not yet occurred will be required before the exemption can be eliminated for all applications. If such invention were to occur, it is expected that at least three years would be required to transition to the new technology. It is also expected that existing equipment would be allowed continued use of this exemption for upgrades and service requirements
16. Additional comments	

Specific questionnaire

1. Which types of solders (composition and melting points) are currently used in applications falling under this exemption? Specify what type of applications these solders are used in.	Alloy compositions typically are in the range of 90-97% lead by weight. Compositions by application are outlined in question 5 of the general questionnaire. It is possible that these solders can be found in a wide range of products, encompassing WEEE categories 1 through 10. Specific applications were outlined in question 2 of the general questionnaire.
2. Is the exemption still required for all of these applications? In which applications can the use of these leaded solders not yet be avoided? Please present a roadmap or similar evidence for the elimination of lead. If possible, please provide a roadmap with activities, milestones and timelines towards the replacement of lead in High Melting Point (HMP) solders used in these applications.	There is currently no known solution that would enable all of the listed applications to completely remove this exemption. General question 8 listed the specific measures that have been taken to develop alternatives. At the current time there is no alternative material that has the required physical properties. In the case where Pb-free alternatives are available, they do not fulfill the requirements. The industry is researching alternatives but suitable materials have not been discovered. Replacement of high lead solders will involve significant invention that is not yet complete, making it impossible to predict a phase out date that would meet the needs of all applications. Annex 1 demonstrates a qualification effort to replace a high-lead BGA with a SAC alloy BGA. This example illustrates that while lead-free solutions are available, they do not meet the required reliability goal. NXP and other petitioners for this exemption are also involved in the EU sponsored COST MP0602 program which intends to investigate Pb-free alternatives for the high temperature high Pb solders. Feedback is given to the participating institutes about the requirements for die attach solders.
3. What is the amount of lead per application, the lead content in the homogeneous material, the annual production volume as well as the number of applications related to exemption 7(a) put on the EU market annually.	Please refer to question 5 in the general questionnaire.
4. What has changed compared to the last evaluation in 2004?	Since 2004, there have not been successful new material inventions that would enable the replacement of all high-lead alloys. The industry continues to search out and test new materials as replacements for high-lead solders.

Annex 1 - Electrical Interconnects Technical Details

Very dense interconnect requirements often dictate much larger IC packages than are typically found in consumer products. In many cases, these packages require the use of high-lead solders (containing more than 85% or more lead) in a variety of BGA (Ball Grid Array) and CGA (Column Grid Array) packages. The high lead solder forms highly reliable solder connections due to unique physical properties that are not possible with lead-free alternatives.

The high-lead content of these alloys prevent them from melting during the SMT assembly process; maintaining a fixed stand-off height between the ceramic package body and the PCB. Combined with ductile material properties, this standoff height creates mechanical compliance that allows the solder joint to withstand prolonged thermal and mechanical fatigue cycles, as well as excellent resistance to mechanical shock failures.

HP has done considerable reliability testing of lead-free alternatives. Figure 1 shows a cross section of two versions of the same high-CTE ceramic package. One version uses high lead solder balls, while the other version used lead-free tin-silver-copper (Sn-Ag-Cu, or SAC) alloy balls. As can be seen, the distance between the package and the PCB is reduced considerably with the lead-free version. This is because the lead-free solder ball melts during the assembly process, and collapses under the weight of the package. This reduced stand-off height significantly increases the solder joint strain for a given thermal cycle range.

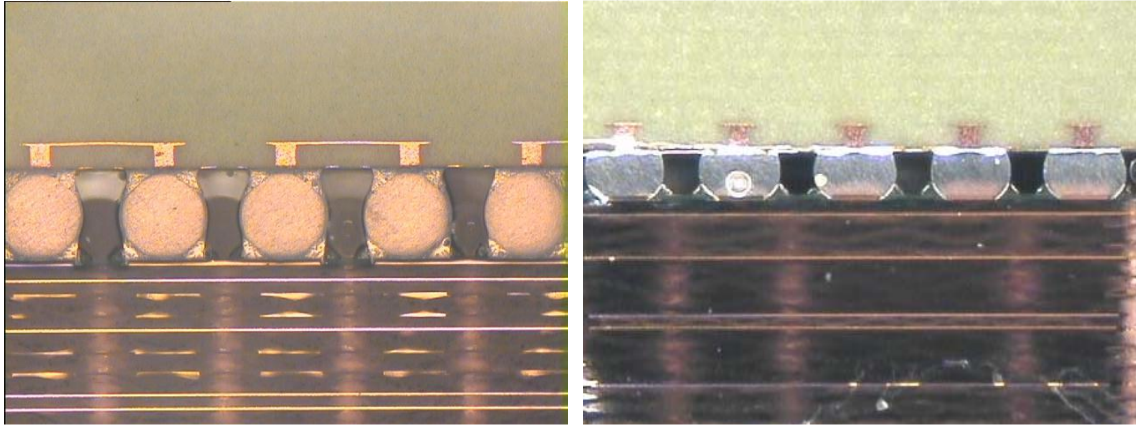


Figure 1 High lead BGA (left) vs. lead-free BGA (right) (Courtesy of HP)

Thus, when the same package was tested in high lead and lead-free versions, there was a significant difference in solder joint fatigue life. Figure 2 shows the life predictions of various leaded and lead-free solder joints for this device, based on the experimental data. While this testing was performed on high-CTE ceramic, we would expect even shorter life of solder joints on packages that use alumina ceramic. Of the interconnect choices, only high lead solder columns or high lead solder balls met the product life requirement at the specified operating conditions. To date, there are no lead-free alternatives to high-lead interconnects that will give adequate fatigue life with large ceramic packages.

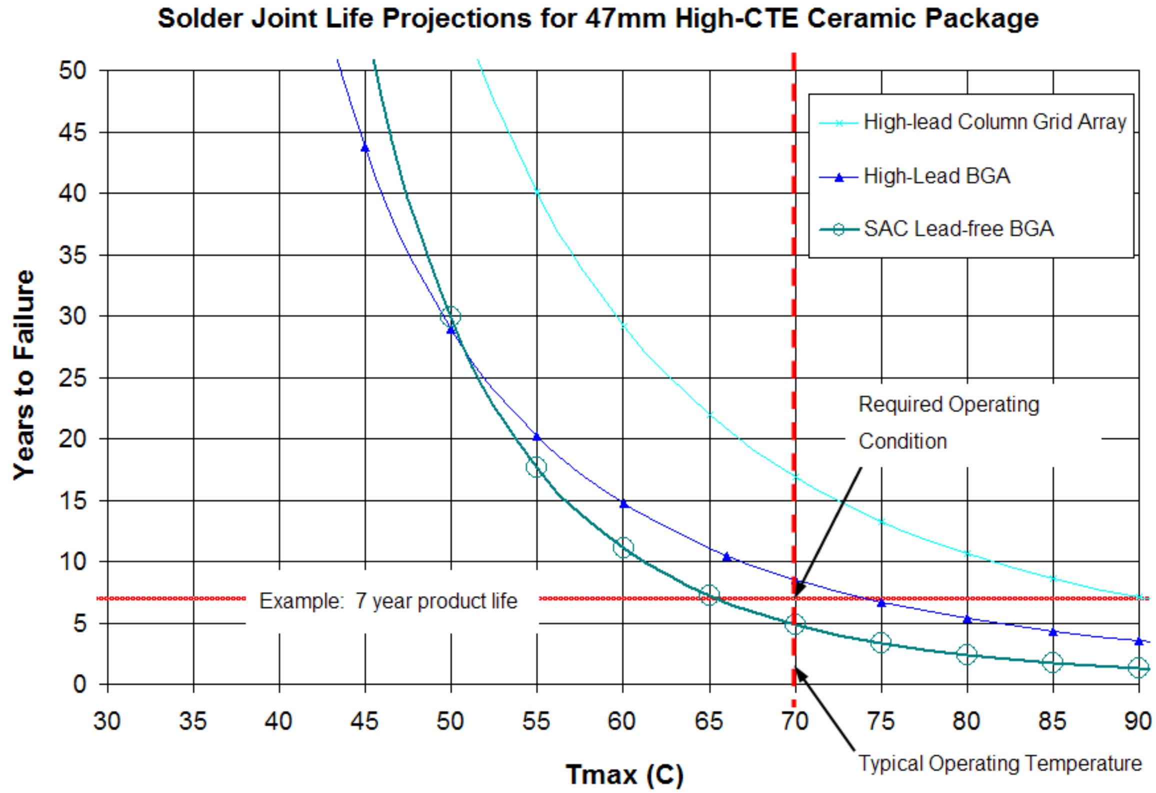
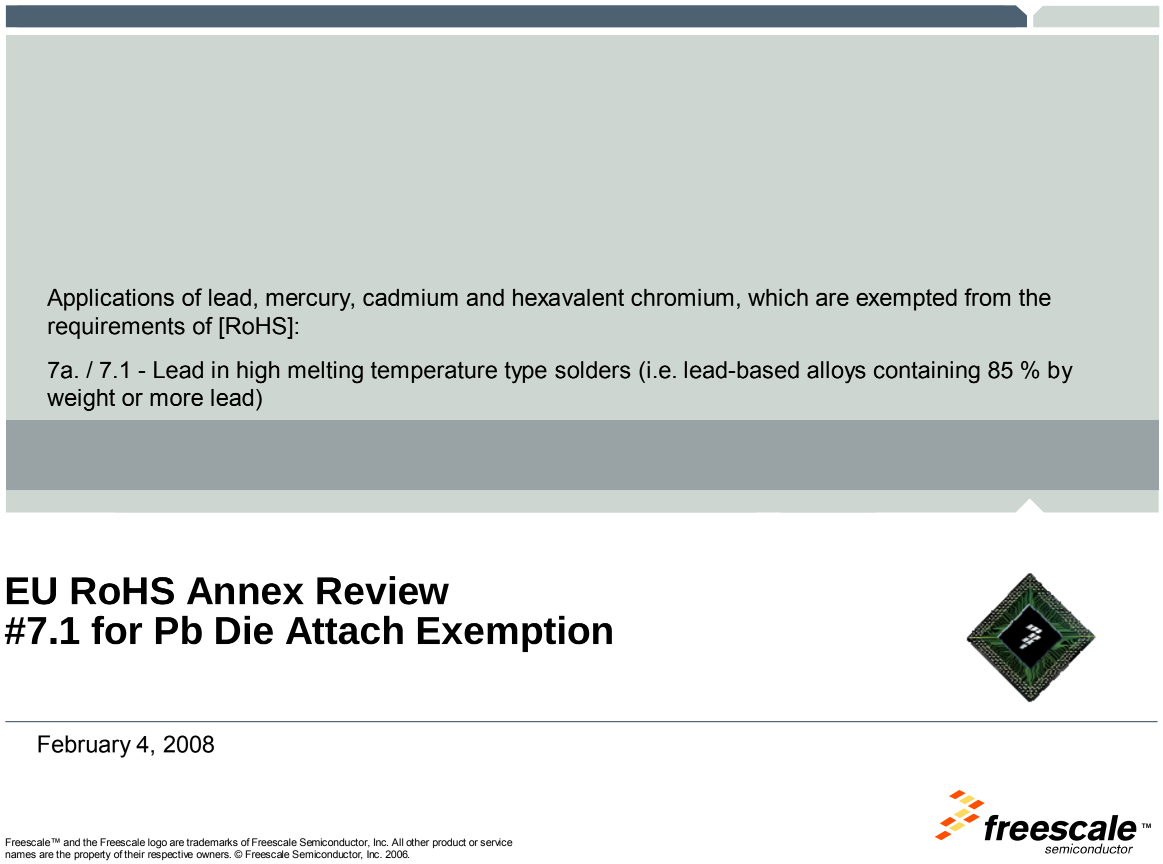


Figure 2 Solder Joint Life Prediction Based on Interconnect Selection (Courtesy of HP)



Applications of lead, mercury, cadmium and hexavalent chromium, which are exempted from the requirements of [RoHS]:

7a. / 7.1 - Lead in high melting temperature type solders (i.e. lead-based alloys containing 85 % by weight or more lead)

EU RoHS Annex Review
#7.1 for Pb Die Attach Exemption

February 4, 2008

Annex 3 IBM Position on RoHS exemption 7a - Lead (Pb) in High Melting Temperature Solders

Many applications require high reliability (≤ 10 ppm per module), high power / performance (≥ 300 watts per die) or both. Examples of applications that require high performance and / or high reliability are servers, high capacity / high speed memory units, surface and air transportation system controllers, energy system controllers, financial institution computers, government security and military systems, computers used in many fields of research and consumer electronics including high end electronics gaming systems. In these applications, the reliability of all components must be correspondingly high in order for entire systems to operate to committed expectations. The use of high melting temperature solders is required to assure highly reliable joints when attaching flip-chip die to carriers, wirebond die to carriers, and discrete components to modules. Discrete components include power devices, fuses, crystals / oscillators, filter networks, inductors, MOSFET's, varistors, voltage regulators and other high power devices. No suitable Pb-free solder has been found with a melting temperature as high as solders containing ≥85%Pb, or "high-Pb" solders, which is necessary for such applications.

In combination with eutectic SnPb, high-Pb solders provide for a "solder hierarchy." Melting temperatures of Pb-containing solders can be changed by making subtle changes in solder composition. Having multiple solders that melt at different temperatures facilitates manufacturing processes. An example is that a component fabricated early in the manufacture of a product can be joined using a high melting solder. Another component that is joined later in the process can be joined using a lower temperature solder without affecting the previously formed solder joint. In other situations, a high temperature solder structure may be created to define the separation, or gap, between components. Then the components can be actually joined using a lower melting solder, thus preserving the necessary gap. The fact that all PbSn solders are chemically and metallurgically compatible further enables this solder hierarchy. The advantages of this hierarchical relationship are exploited in many manufacturing processes for a multitude of components and systems. Such a solder hierarchy has yet to be developed relative to Pb-free solders.

In addition to enabling the development of a solder hierarchy, high-Pb solders are resistant to IMC (intermetallic compound) growth as compared to Pb-free solders. Suppression of IMC growth is essential to a robust solder joint. IMC's are brittle and non-adherent, so promote early joint fatigue failure. The rate of intermetallic formation is directly proportional to the time at elevated temperature relative to the melting temperature of the material. Present Pb-free solders include 95Sn5Ag (221 °C to 245 °C), SnCu eutectic (228 °C), SnAg eutectic (221 °C) and Sn3.5Ag0.7Cu eutectic (216 °C). (Where a melting range is given, it means that the alloy is non-eutectic, so melts over a range of temperatures rather than at a single melting point. Melting commences at the lower temperature and continues until the entire mass becomes liquid at the higher temperature.) By contrast, high-Pb solders include 97Pb3Sn (300 °C to 313 °C), 95Pb5Sn (308 °C to 312 °C) and 90Pb10Sn (275 °C to 302 °C). The lower melting temperatures of the Pb-free solders makes them significantly more prone to IMC formation, resulting in earlier and more joint-fracture failures, than corresponding high-Pb joints.

Mechanical properties of high-Pb solders are also critical to many applications. When solder joints are produced between dissimilar materials, Si die and organic die carriers for example, thermomechanical mismatches are created. As soon as the solder solidifies, differences in CTE (coefficient of thermal expansion) cause stress to accumulate in the various members of the assembly. When room temperature (or lower temperatures encountered in shipping and / or applications ambience) are reached, there can exist considerable stress between members of an electronic assembly. Due to its high ductility (propensity to "creep"), Pb in a solder joint significantly mitigates resulting stresses. By contrast, Pb-free solders are much more creep resistant, and transfer stresses directly to underlying structures in the components being joined. For example, in the case of flip-chip die attach, under-bump metallurgical (UBM) structures that are designed to withstand the lower stresses of high-Pb systems fail when subjected to higher stresses imparted by Pb-free solders. Indeed, in assessments of some large chip systems using Pb-free solders, failure has been observed before any life testing was initiated, so-called "time zero" fails.

High-Pb solders have melting temperatures ≥ 294 °C (Celsius). Since current carrying capability is roughly a function of melting point for many solders, these high melting points correlate to the ability to carry the high electrical currents required for high power / performance applications. The metallurgical / electrical properties of Pb-free solders have been found to be in inferior to Pb-free solders, being a significant limitation in their use in high performance applications. A primary failure mechanism for electrical carrying solder joints is EM (electromigration). In electromigration, applied electrical fields and currents result in atomic mobility throughout a structure. As atoms are displaced, vacancies remain. These vacancies coalesce into voids, typically along a grain boundary or material interface. As voids form, current carrying cross sectional area decreases, current density increases, thus accelerating void formation and growth. Eventually, the entire interface can fail. Although influences by many factors including melting temperature, relative diffusion rates of different species, grain orientation and current density, presently available Pb-free solders are more prone to EM failure than hi-Pb solders.

In high power wire-bond components, besides providing a reliable electrical connection, the solder die attach joint is often utilized to dissipate high thermal loads at elevated operating temperatures. No suitable Pb-free material has been found that can meet the electrical conductivity, thermal conductivity and operating temperature requirements of these components.

High reliability / high performance modules are typically used in applications that have significant risk to human life, injury or substantial property loss such as national security, air traffic control, telecommunications, network infrastructure, power grid distribution and financial management systems. In such critical applications, to replace high performance/ high reliability modules with lower performance / lower reliability substitutes would pose significant risk to human life and personal injury.

Due to the low melting initiation (<230 °C) of commercially available Pb-free solders, none is suitable for joining discrete components to modules in applications that require a solder hierarchy. In the case of high power wirebond die attach and other internal component soldering, presently available Pb-free solder alloys are not adequate to dissipate the thermal load generated. Lead-free solders are now used in lower performance applications where reliability and power / thermal requirements are less stringent. For example some PowerPC systems and consumer products have been converted totally from PbSn to SAC solder. Investigation of reliability failure mechanisms and search for appropriate Pb-free solder alloys with appropriate melting ranges and with the necessary thermo-mechanical properties is required for high performance / high reliability applications continues unabated.

Annex 4. Avago Technologies Electromigration Study (additional document)

Avago -
Electromigration.pdf

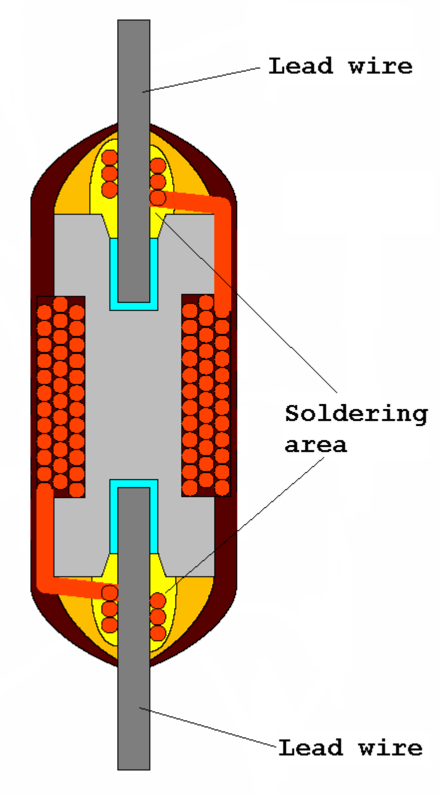
Annex 5 EPCOS Example for passive components

1. Substance/Usage/Difficulty level

Substance	Related Usage	Reduction difficulty level
Lead in high melting temperature type (HT) solders (i.e. tin-lead solder alloys containing more than 85% lead)	RF axial chokes, but in principle all arguments given herein stand also for the use of HT Solders with ceramic components, and other inductive components, than this example	Impossible to be substituted by 2010

2. Reason for Usage

Place of usage (Sketch)	Reason for usage (technical importance)

	The reasons that high temperature solder is used by RF axial: ① To keep the requirements for lead out of 2002/95/EC, lead free solders are used for the production of equipped electronic boards of various EEE. For this soldering process Sn-Ag-Cu is a commonly used material. With peak process temperatures of 250° - 260°C and timely extended preheat zones with maximum temperatures up to 220°C and more, the process energy is about 30% higher compared to a leaded soldering processes. Therefore and because of an extended heat transfer the internal temperatures in the component are raised above the melting point of e.g. Sn-Ag-Cu solder which melts at a temperature lower than 250°C (close to 217°C). As in the example on the left, RF axial chokes and inductors, ceramic components with internal solder joints have to withstand peak soldering temperatures of 250° - 260°C. For that reason, high temperature solders with a lead content of more than 85% are used ② The plating material of the lead wire is melt is in general pure tin.

3. Availability of substitution technology at commercial/industrial scale

Principle substitutes available are SnCu / AgCu or SnAu

4. Technical reasons why substitution is not possible

A number of materials could conceivably be used as substitutes; however, there are the following concerns.

- There is SnAu, which gives high temperature melting properties, but it has inferior malleability and is brittle and therefore cannot be used.
- SnCu, melting point below 250° - 260°C, no alternative
- AgCu, because of a too high melting temperature at 700° - 900°, no alternative

5. Further comments (Öko-Institute Freiburg)

See page 55 of Adaptation to Scientific and Technical Progress of Annex II Directive 2000/53/EC Contract N°07010401/2007/470145/ATA/G4 Final Report Freiburg, 16 January 2008 published by **Öko-Institut e.V.** Dr. Joachim Lohse, Stéphanie Zangl, Rita Groß, Carl-Otto Gensch and **Fraunhofer IZM** Dr. Otmar Deubzer

“..... The high melting point solders with more than 85% by weight would, however, be allowed, **as alternatives are currently not yet available**......” This statement of the Öko-Institute stands for passive components used automotive applications as well as for EEE products.

Comparison of Electromigration Performance of Sn/Ag Pb-free and Sn/Pb eutectic solder bumps on Substrates with ENIG Metallization

Dennis Eaton
Avago Technologies

Introduction

At present there exist exemptions to RoHS requirements for Pb in solders. These apply to flip-chip products used in server, storage, and storage array applications and in network infrastructure equipment for switching, signaling transmission, and network management for telecommunication. Many of these products use solder bumps (first level interconnect) made of Sn/Pb eutectic solder (63%Sn/37%Pb) or bumps with a higher Pb content. Some of the exemptions to Pb in solders are set to expire in the year 2010.

One of the consideration in choosing solder bump composition is the resistance of the bump material to electromigration (EM)—failure under conditions of high current and high temperature. Sn/Pb bumps with a high Pb content (90-97% Pb) have long been known to have excellent electromigration resistance. Sn/Pb eutectic bumps, while having lower electromigration resistance than high Pb bumps, still are sufficiently immune to electromigration that they can be used in many high-current, high-temperature applications. There are reports that Pb-free bumps have equal or better EM performance than Sn/Pb eutectic bumps. However, there is also evidence that Pb-free bumps can have worse EM performance in combination with certain substrate metallizations [1].

A study is in progress comparing the EM performance of Sn/Ag Pb-free solder bumps and Sn/Pb eutectic solder bumps. The results to date are presented here.

Experiment

Test structure

The test structure consists of silicon die containing series chain of 12 bumps in two rows of six bumps each. Six of the bumps have electrons flowing out of the silicon and six have electrons flowing into the silicon. The metallization on the silicon die is copper and connection to the bumps is made from all sides of the bump pad and on two metal levels. The metal lines are specifically designed to withstand the highest temperature and current used in the bump EM testing without the lines themselves undergoing resistance increase due to electromigration. The underbump metallization (UBM) is Ti/Cu/Ni. Midway between the two rows is a copper resistor which acts as a temperature sensor. The resistance of the test structure is recorded hourly using a 4-point measurement, where the 4-point connections are made at the ends of the chain, just where the bumps connect the die to the substrate. The initial resistance of the chain (at the stress temperature) is approximately 0.24 ohm. The substrate is a 24 pin DIP package. The substrate is high coefficient of thermal expansion ceramic (HITCE^{TM}). The substrate metallization is Electroless Nickel, Immersion Gold (ENIG).

Two types of bumps were used in this test: Sn/Pb eutectic solder and Sn/Ag solder. Both types of bumps were plated. The bump composition is the only variable in the test.

Experimental conditions

The samples were stressed at constant current and constant temperature in a large oven. Samples of each solder type were distributed evenly throughout the oven to mitigate any temperature differences across the oven. The uniformity of the oven temperature was $\pm 0.6^{o}$C. As of the present time, the stress has been applied for 2,566 hours.

Results

A bump chain is considered to have failed when the resistance increases by 0.03 ohm from its original value. (This value was chosen so that there would be a significant number of failures in the Sn/Pb group. If a higher resistance increase were chosen, the conclusions would remain the same.) Failure analysis in this and previous EM tests has found that one of the bumps in the chain typically increases in resistance while the resistance of the others stays relatively constant. Furthermore, the failures were found to occur at the silicon side of the bump for bumps that have electron flow out of the silicon. Therefore, each chain of 12 bumps has 6 opportunities for failure. When one bump in a chain fails, the other five active bumps are automatically suspended at the time the first bump fails. The data analysis is done using this censoring convention.

As of 2,566 hours, there have been 27 failures out of 27 parts for the Sn/Ag Pb-free bumps and 16 failures out of 27 parts for the Sn/Pb eutectic bumps. A lognormal plot of the failure data using Rank Regression on X (RRX) is shown in Figure 1 [2]. The plots clearly show the superiority in electromigration resistance of Sn/Pb eutectic bumps over Pb-free bumps on this substrate metallization.

Analysis

Solder bump electromigration test data, such as is shown here, is used to establish the maximum allowable bump current at a given bump temperature. The model used is Black's equation, which relates time to failure (TTF) with the temperature and current density.

$$TTF \propto J^{-n} \exp\left(\frac{E_a}{kT}\right)$$

For solder bumps, it is convenient to substitute the applied current, I, for the current density J, which is possible when the bumps have a common geometry [3].

Although proprietary considerations prevent revealing the stress current and temperature for the test, we can indicate the relative maximum currents predicted by the results presented here.

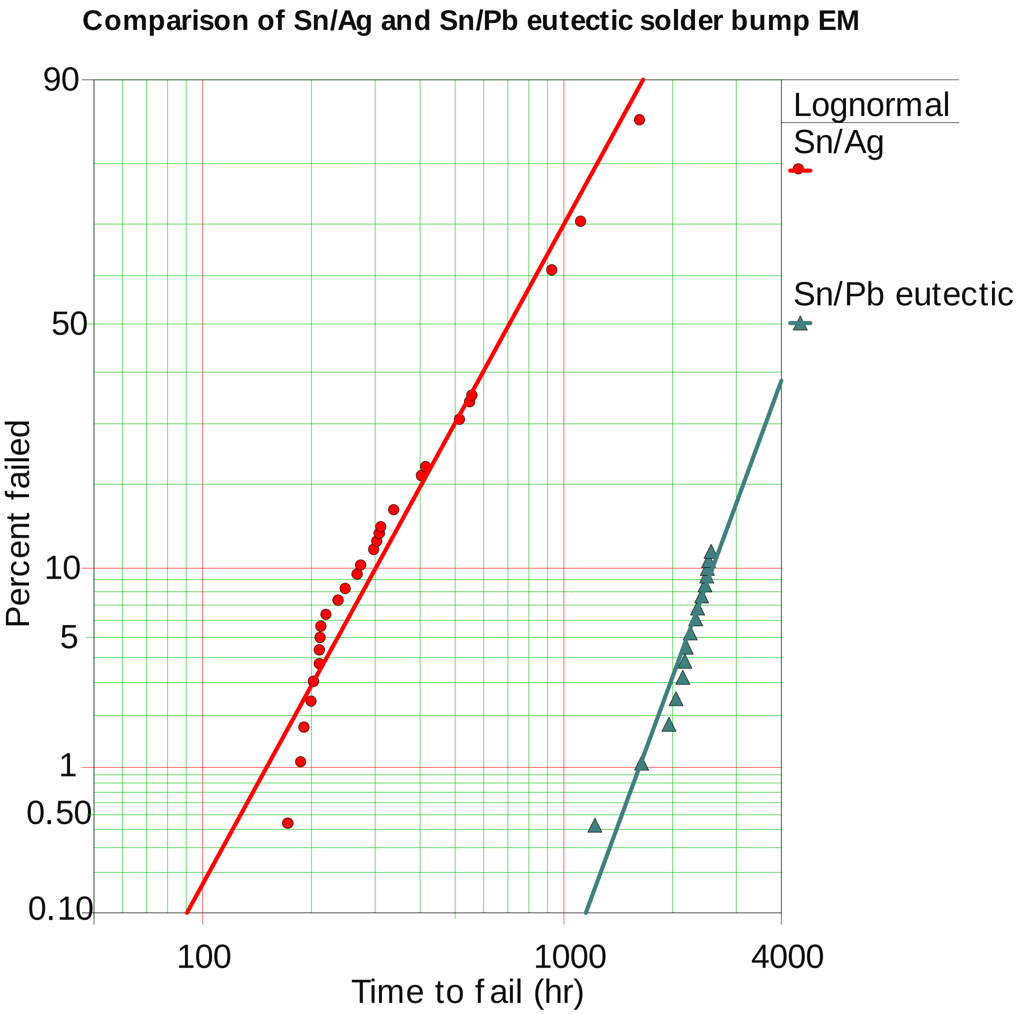


Figure 1. Lognormal failure plots of solder bump electromigration data.

In order to assure long-term reliability, a typical electromigration specification often states that the cumulative distribution function (CDF) of failed bumps be no more than x% (where x is a very small number) at the maximum junction temperature and maximum specified current (I_{spec}) for a lifetime of 100,000 hours (11.416 years). Electromigration data, such as those shown in Figure 1, are obtained at accelerated conditions of temperature and current. Then Black’s equation is solved for I_{max}, which is the maximum allowable bump current at the maximum use temperature, T_{use} [3].

$$I_{\max} = I_{acc} \cdot \left[\frac{t_{x\%}(I_{acc}, T_{acc})}{t_{x\%}(I_{\max}, T_{use})} \cdot e^{\frac{E_a}{k} \cdot \left(\frac{1}{T_{use}} - \frac{1}{T_{acc}}\right)} \right]^{\frac{1}{n}}$$

In this equation, I_{acc} and T_{acc} are the current and temperature respectively in the accelerated electromigration test. T_{use} is the maximum allowed temperature under use conditions. The time $t_{x\%}(I_{max},T_{use})$ is 100,000 hours. Values for E_a from the literature are typically 0.8 – 1.1 eV and values for n are typically 1.5 – 2.2.

For products using Sn/Pb solder bumps, the maximum specified current, I_{spec}, has been established to allow a safety margin. That is, I_{max}/I_{spec} must be greater than unity. The ratio of I_{max} to I_{spec} has been calculated for the data in Figure 1. The result is illustrated in Figure 2. It is seen that the Sn/Pb eutectic bump has margin, but the maximum allowable current for the Sn/Ag bump is far below the specification.

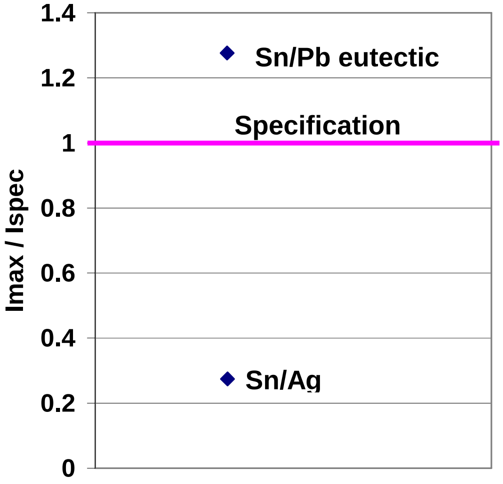


Figure 2. Illustration of the maximum bump currents allowed for Sn/Pb eutectic and for Sn/Ag solders compared to the maximum bump current specification

Conclusion

The results presented here, along with previously published results, clearly show that Sn/Ag Pb-free solder bumps do not meet the maximum bump current requirements of present flip-chip designs. So if Pb-free bumps were to be used, the number of bumps would need to be increased substantially, making the present high-performance chips impossible to fabricate. In the future, shrinking of bump size, increasing current requirements, and higher operating temperatures (particularly in servers, network infrastructure, and telecommunications) will require even higher bump currents. So it is quite possible that high Pb bumps, which have better EM performance than Sn/Pb eutectic bumps, will need to be used in those applications.

References

[1] Y.-S. Lai, C.-W. Lee, Y.-T. Chiu, Y.-H. Shao, “Electromigration of 96.5Sn-3Ag-0.5Cu Flip-chip Solder Bumps Bonded on Substrate Pads of Au/Ni/Cu or Cu Metallization,” *IEEE Electronic Components and Technology Conference*, 2006. pp. 641-645.

[2] Analysis was done using Reliasoft Weibull++ and the Reliasoft Rank Method. This rank method resulted in the best fit for the Sn/Ag curve. Analysis was also performed using RRX and the Standard Rank Method and using Maximum Likelihood Estimation (MLE). Both these alternate analysis methods gave worse (lower time to fail) results for the Sn/Ag bumps but better or equal results for the Sn/Pb bumps. Thus the analysis presented here gives the most optimistic result for Sn/Ag bumps.

[3] JEDEC PUBLICATION 154, “Guideline for Characterizing Solder Bump Electromigration under Constant Current and Temperature Stress,” January 2008.