Assistance to the Commission on Technological Socio-Economic and Cost-Benefit Assessment Related to Exemptions from the Substance Restrictions in Electrical and Electronic Equipment:

Study to assess renewal requests for 29 RoHS 2 Annex III exemptions [no. I(a to e -lighting purpose), no. I(f - special purpose), no. 2(a), no. 2(b)(3), no. 2(b)(4), no. 3, no. 4(a), no. 4(b), no. 4(c), no. 4(e), no. 4(f), no. 5(b), no. 6(a), no. 6(b), no. 6(c), no. 7(a), no. 7(c) - I, no. 7(c) - II, no. 7(c) - IV, no. 8(b), no. 9, no. 15, no. 18b, no. 21, no. 24, no. 29, no. 32, no. 34, no. 37]

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07 June 2016

Report for The European Commission

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Disclaimer:

Eunomia Research & Consulting, Oeko-Institut and Fraunhofer Institute IZM have taken due care in the preparation of this report to ensure that all facts and analysis presented are as accurate as possible within the scope of the project. However no guarantee is provided in respect of the information presented, and Eunomia Research & Consulting, Oeko-Institut and Fraunhofer Institute IZM are not responsible for decisions or actions taken on the basis of the content of this report.

21.0 Exemption 7a

Declaration

In the sections that precede the "Critical Review" the phrasings and wordings of stakeholders' explanations and arguments have been adopted from the documents provided by the stakeholders as far as required and reasonable in the context of the evaluation at hand. Formulations have been altered in cases where it was necessary to maintain the readability and comprehensibility of the text. These sections are based exclusively on information provided by applicants and stakeholders, unless otherwise stated.

Acronyms

CTE	Coefficient of thermal expansion; measure for the thermal mismatch between two materials bonded together
DA5	'Die Attach 5' – a partnership between Bosch, Infineon, Freescale, STM and NXP
DCB	Direct copper bonding
DBC	Direct-bonded copper, like DCB
EEE	Electrical and electronic equipment
HMP	High melting point
HMPS	high melting point solders
LHMPS	Lead-containing high melting point solders with at least 85 % of lead content
RoHS 1	Directive 2002/95/EC
RoHS (Directive)	Directive 2011/65/EU (recast RoHS Directive, RoHS 2) if not specified otherwise
SAC	Tin-silver-copper (solders)
SMT	Surface mount technology
TFCB	Thick film copper bonding
THT	Through hole technology

21.1 Description of the Requested Exemption

21.1.1 Overview of the Submitted Exemption Requests

Table 21-1 gives an overview of the various applications for the continuation of exemption 7(a).

IXYS apply for the continuation of exemption 7(a) with limited scope. This scope restrictionis related to the applicants' product portfolio and does not imply that IXYS have RoHS-compliant solutions for all other uses of lead-containing high melting point solders (LHMPS) in the scope of the current exemption 7(a). Bosch contributed to the stakeholder consultation in supporting the continuation of exemption 7(a) without changes, but alternatively proposed a specific exemption for their own specific use of LHMPS.

Table 21-1: Overview of applications and stakeholder inputs related to exemption 7(a)

Applicant	Requested Exemption	Requested Expiry Date/ Continuation	Remarks
Bourns[791]	Continuation of exemption without changes	5 years	-
Bosch[792]	Support for renewal without change, otherwise *"Lead in high melting temperature type solders used in high-power transducers (loudspeakers)"*	Not indicated	Submitted during public stakeholder consultation as answers to the consultation questionnaire
Chenmko	Unclear	Unclear	Application disqualified for formal reasons as lacking even most basic information
Formosa	Continuation of exemption without changes	5 years	Application disqualified for formal reasons as lacking even most basic information

791 Bourns Inc. 2015a "Exemption Request Exemption 7a: Document "7a_Exemption_extension_ap_7a.pdf"," Bourns Inc., http://rohs.exemptions.oeko.info/fileadmin/user_upload/RoHS_Pack_9/Exemption_7_a_/Bourns/7a_Exemption_extension_ap_7a.pdf

792 Bosch Security Systems GmbH 2015 "Document "Bosch-Stakeholder-contribution-Exemption-request-7a.pdf", submitted during the online stakeholder consultation," http://rohs.exemptions.oeko.info/fileadmin/user_upload/RoHS_Pack_9/Exemption_7_a_/Bosch-Stakeholder-contribution-Exemption-request-7a.pdf

Applicant	Requested Exemption	Requested Expiry Date/ Continuation	Remarks
Freescale et al.[793]	Continuation without change	Maximum validity period (5 years)	-
IXYS[794]	Lead in soft solder alloys used in power semiconductor devices containing more than 90 % lead	Maximum validity period (5 years)	Applicant mentions alternative technology (DCB, direct copper bonding)
Yea Shin Technology	Unclear	Unclear	Application disqualified for formal reasons as lacking even most basic information

21.1.2 Background and History of the Exemption

Exemption 7(a) "Lead in high melting temperature type solders (i.e. lead-based alloys containing 85 % by weight or more lead)" was already listed in the annex of Directive 2002/95/EC (RoHS 1)[795], when it was officially published in 2003. In 2008/2009, the exemption was reviewed for the first time.[796] The evaluators found that exemption 7(a) allowing the use of lead-containing high melting point solders (LHMPS) is still required. However, exemption 7(a) is material specific, while most other RoHS exemptions are application specific. LHMPS can therefore be used in each application as long as it contains at least 85 % of lead, even if lead-free alternatives are available. In the course of the exemption evaluation in 2008/2009, the reviewers stated that:

> *"[...]HMP solders are used where alternative solutions reducing the amounts of lead are available* [797]

[793] Freescale Semiconductors/NXP et al. 2015a "Request for Continuation of Exemption 7a, document "Ex_7a_Freescale_Ex_Renewal_Dossier_2015_0723_v20_revised.pdf": Exemption request form," http://rohs.exemptions.oeko.info/fileadmin/user_upload/RoHS_Pack_9/Exemption_7_a_/Freescale_Semiconductor/Ex_7a_Freescale_Ex_Renewal_Dossier_2015_0723_v20_revised.pdf
[794] IXYS Semiconductor GmbH 2015a "Request for continuation of exemption 7a with limited scope, document "7a_IXYS_RoHS_V_Application_Form.pdf": Exemption request form," http://rohs.exemptions.oeko.info/fileadmin/user_upload/RoHS_Pack_9/Exemption_7_a_/IXYS/7a_IXYS_RoHS_V_Application_Form.pdf
[795] Directive 2002/95/EC of the European Parliament and of the Council of 27 January 2003 on the restriction of the use of certain hazardous substances in electrical and electronic equipment, RoHS 1, European Union (13 February 2003)
[796] Gensch, Carl-Otto, Oeko-Institut e. V., et al. 20 February 2009 Adaptation to scientific and technical progress under Directive 2002/95/EC: Final Report, with the assistance of Stéphanie Zangl, Rita Groß, Anna Weber, Oeko-Institut e. V., and Otmar Deubzer, Fraunhofer IZM, http://ec.europa.eu/environment/waste/weee/pdf/final_reportl_rohs1_en.pdf
[797] Ibid., page 86

1) The current general exemption for lead in HMP solders offers a loophole to bypass the use of lead-free solders or to avoid searching for other RoHS-compliant solutions that do not require the use of lead. Manufacturers use leaded HMP solders in applications, for which others offer lead-free solutions.[798]

2) The current general exemption unnecessarily increases the use of lead in applications, where lead-free solutions are technically impracticable and an exemption for the use of lower lead content solders would be possible or is already in place."[799]
A component manufacturer stated that "It has become more apparent that some of our customers are tending towards using higher lead alloys (typically 95 % lead rather than 50 % lead) '....]". [we] have actively encouraged switching to the lower lead content In/Pb solder alloys allowed by exemption 24."
Instead of using available or applying for a new exemption for the use of lead in low lead-content solders like e.g. the tin-lead solder with 37 % lead (SnPb37), manufacturers may shift to HMP solders with high lead contents of 85 % and more.[800]*"*

In 2009, the reviewers therefore recommended transferring exemption 7(a) into an application specific exemption:

"[...] in line with the latest Commission decisions on exemptions which are application and technology oriented and thus are use specific. [...] It cannot be assumed that [the] stakeholder comments cover all uses, in which the use of lead in HMP solders needs to be exempted [...]. Parts of the electronics industry thus might suddenly see themselves producing non-RoHS-compliant products if the general exemption would be changed into an application specific based on the available information from the stakeholder consultation for this review process. A new stakeholder consultation is required to give industry worldwide the opportunity to apply for the necessary application and technology specific exemptions. [...]

The reviewers propose leaving the exemption unchanged for now, but giving it an expiry date, which allows industry a reasonable time frame to apply for specific exemptions for the use of lead in HMP solders, where they are justifiable by the requirements set out in Art. 5(1)(b). [...] The consultants propose 30 June 2013 as the expiry date for exemption 7(a)."[801]

[798] Ibid., page 86
[799] Ibid., page 86
[800] Ibid., page 86
[801] Ibid., page 87

The Commission did not set an expiry date. In 2011, exemption 7(a) was transferred to Annex III of the recast directive 2011/65/EU[802] (RoHS 2) without changes, and the maximum period to the next review or the expiry of the exemption was respectively extended from July 2014 under RoHS 1 to July 2016 under RoHS 2 for use in all electrical and electronic equipment (EEE) in the scope of the RoHS Directive other than EEE in categories 8 and 9.

As the RoHS Directive requires that *"Exemptions from the restriction for certain specific materials or components should be limited in their scope [...]"*, and in order to avoid abuse of exemption 7(a), the scope specification of exemption 7(a) is in the focus of the present review as far as such exemptions would be in line with the conditions for exemptions laid down in Art. 5(1)(b).

21.1.3 Technical Description of the Requested Exemption

The technical background of exemption 7(a) was described in detail in the report of the last review of this exemption in 2009.[803] This chapter therefore only presents the most relevant technical facts and information that is of relevance for this review.

The technical background of the Bourns[804] and IXYS[805] exemption requests are technically equivalent to the technical description submitted by Freescale/NXP et al.[806] They are therefore not specifically explained in this chapter.

According to Freescale et al.[807] the most important property for lead (Pb) HMP solders (LHMPS) is the high melting point, which is solely managed by the lead composition. Other practical properties, such as electrical conductivity, thermal conductivity, ductility, corrosion-resistivity, appropriate oxidation nature, and wettability are also inherent in lead. Lead is the only known element which gives all these properties. Table 21-2 sums up the properties of lead required in LHMPS.

21.1.3.1 Specific Properties of Lead in LHMPS

In Table 21-2 and in the subsequent figures, Freescale et al.[808] present the required properties of lead in HMPS. It is the physical and chemical properties of the alloys that are important. Some combinations of elements (e.g. AuSn) will meet some criteria, but the essential requirement is the unique combination of essential properties of HMP solders with lead, not any single property.

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[802] Recital 19 of the Directive 2011/65/EU of the European Parliament and of the Council of 8 June 2011 on the restriction of the use of certain hazardous substances in electrical and electronic equipment (recast), RoHS 2, European Union (1 July 2011)

[803] Op. cit. Gensch, Carl-Otto, Oeko-Institut e. V., et al. 20 February 2009, p. 76 et seqq.

[804] dddOp. cit. Bourns Inc. 2015a

[805] Op. cit. IXYS Semiconductor GmbH 2015a

[806] Op. cit. Freescale Semiconductors/NXP et al. 2015a

[807] Ibid.

[808] Ibid.

Table 21-2: Required performance of HMPS solder and specific properties of lead

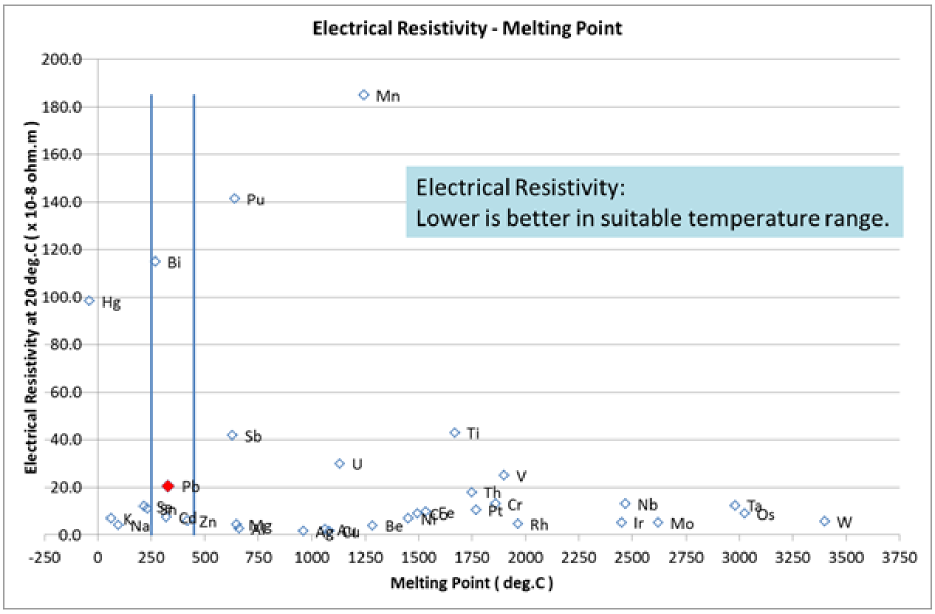
Performance requirements	Reasons for the requirements	Function of lead	Data
High melting points	Not to be melted during secondary assembly steps including soldering. Functionality of electrical parts not to deteriorate.	While HMPS applications require minimum melting points above 250°C, solder processes have an upper limit defined as 450 °C. Few elements have melting points in this range. 250°C is a critical limit, and in reality for most applications the melting point for the HMPS in specific applications is higher. Lead is the least hazardous among these elements such as tellurium, cadmium or thallium.	Melting points, cf. Figure 21-1 to Figure 21-11 below
Electrical connection	Electrical functionality	Lead is the unique element which has practical qualities of melting point, electrical conductivity, thermal conductivity, mechanical reliability and chemical stability with an ideal balance.	Electrical resistivity, cf. Figure 21-1 and Figure 21-2 below
Thermal conduction	To ensure the reliability of electronic components due to the heat dissipation		Thermal conductivity, cf. Figure 21-3and Figure 21-4 below
Ductility	To join the materials having the different coefficients of expansion together (To ensure mechanical reliability)		Young's modulus, cf. Figure 21-5 and Figure 21-6 below
Corrosion-resistivity	To ensure the reliability		Ionization tendency (very low next to hydrogen, it means difficult to oxidize), cf. Figure 21-7 and Figure 21-8 below
Oxidation nature	To prevent oxidation at the secondary mounting; To ensure the reliability		Standard electrode potential, cf. Figure 21-9 and Figure 21-10 below

Source: Freescale et al.[809]

[809] Ibid.

The below figures illustrate the properties of lead for wide and narrow temperature ranges respectively. Freescale et al.[810] plotted as many different metallic elements as possible in the ‘wide temperature’ range figures to show that elements present in the high melting point solder domain are extremely limited. The ‘narrow temperature range’ graphs are presented by enlarging the illustrations in order to make it easier to understand the properties of lead in the melting domain of high melting point solders. The narrow temperature range is necessary from the processability and usability points of view.

Figure 21-1: Electrical resistivity and melting points of elements (wide temperature range)

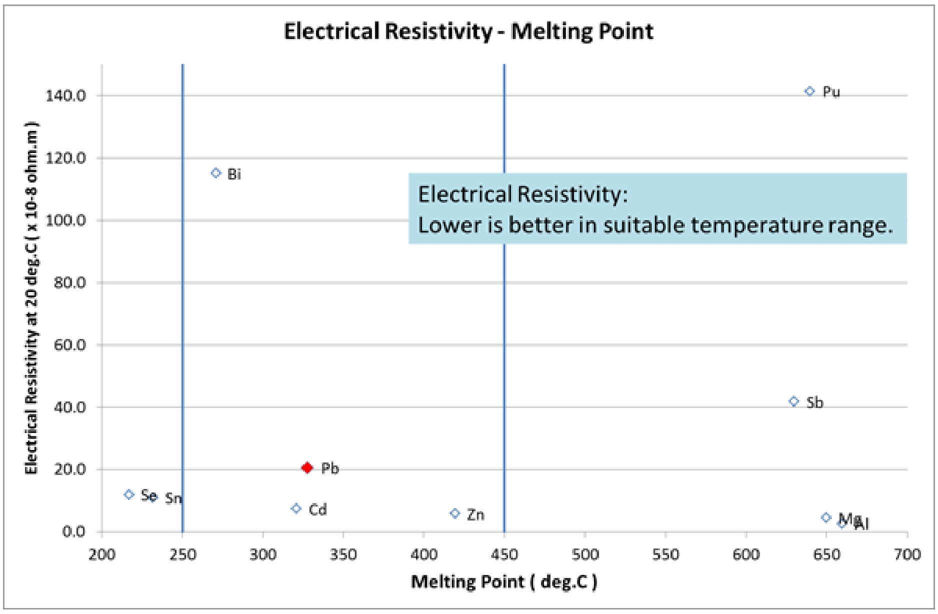


Source: Freescale et al.[811]

[810] Freescale Semiconductors/NXP et al. 2016a: “Answers to second questionnaire, document "Exe_7a_Questionnaire-2_Freescale_Response_2016-01-28.pdf", received via e-mail by Dr. Otmar Deubzer, Fraunhofer IZM, from Griffin Teggeman, Freescale (NXP) et al., on 28 January 2016” unpublished manuscript,

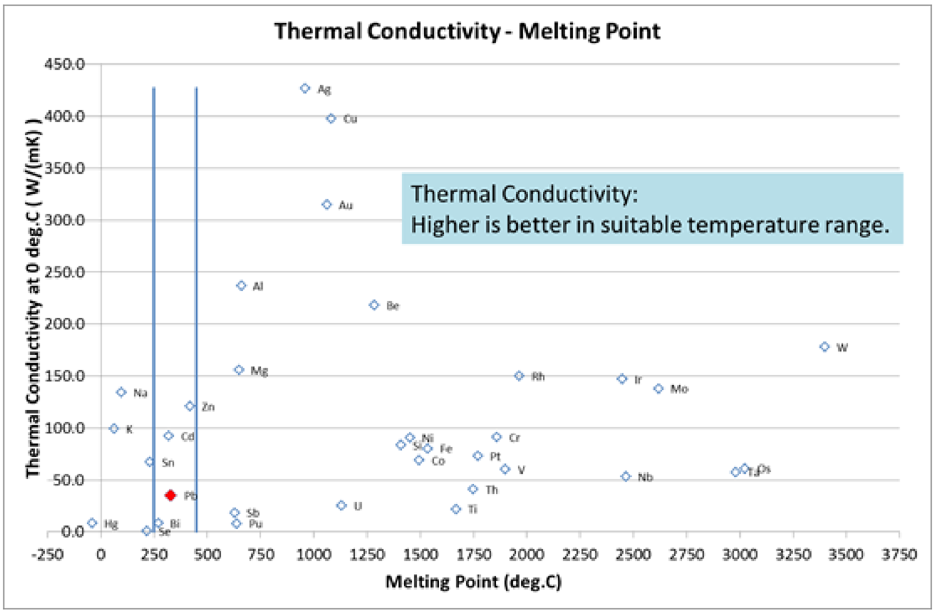
[811] Op. cit. Freescale Semiconductors/NXP et al. 2015a

Figure 21-2: Electrical resistivity and melting points by element (narrow temperature range)



Source: Freescale et al.[812]

Figure 21-3: Thermal conductivity and melting points by element (wide temperature range)



Source: Freescale et al.[813]

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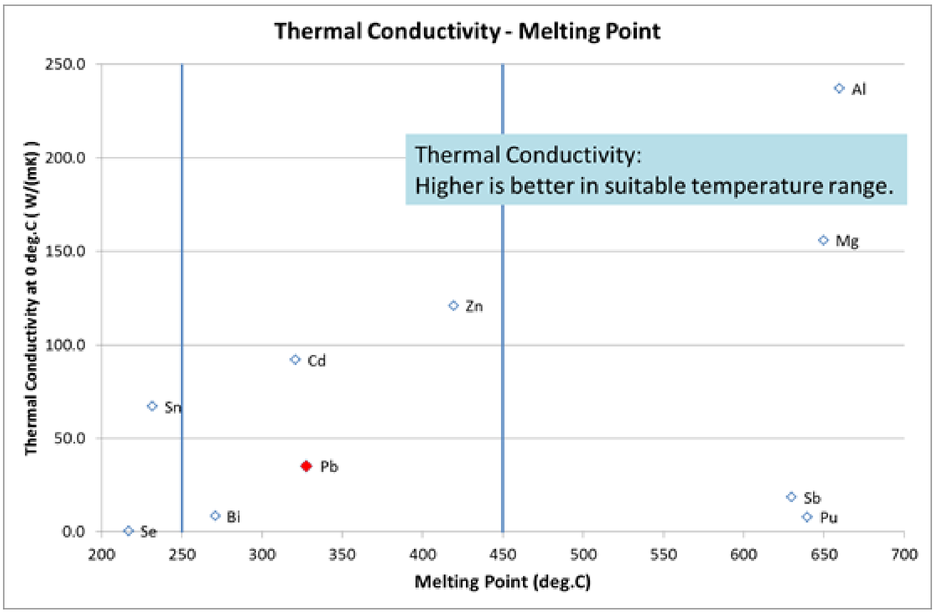
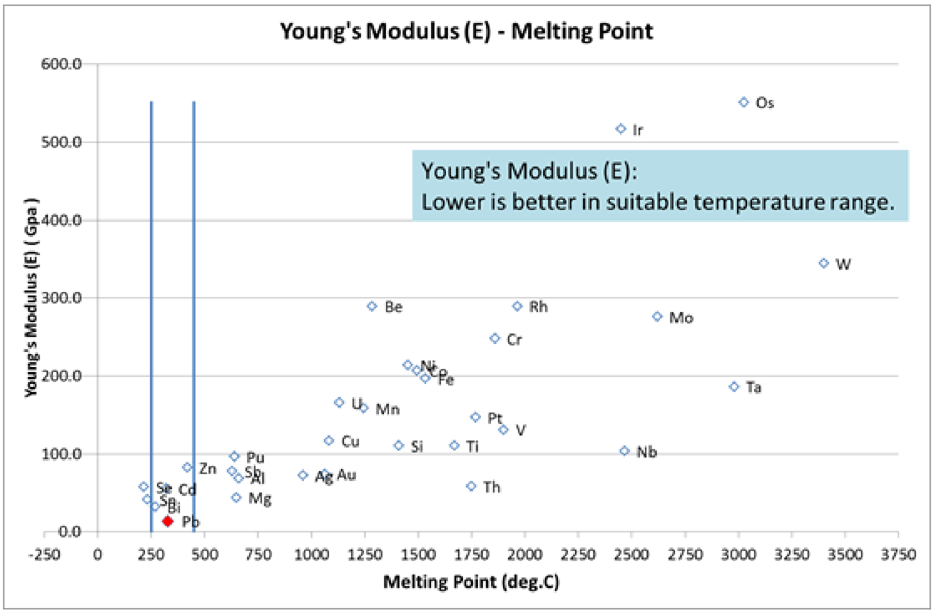
[812] Ibid.

Figure 21-4: Thermal conductivity and melting points by element (narrow temperature range)



Source: Freescale et al.[814]

Figure 21-5: Young's modulus (E) by melting points (wide temperature range)



Source: Freescale et al.[815]

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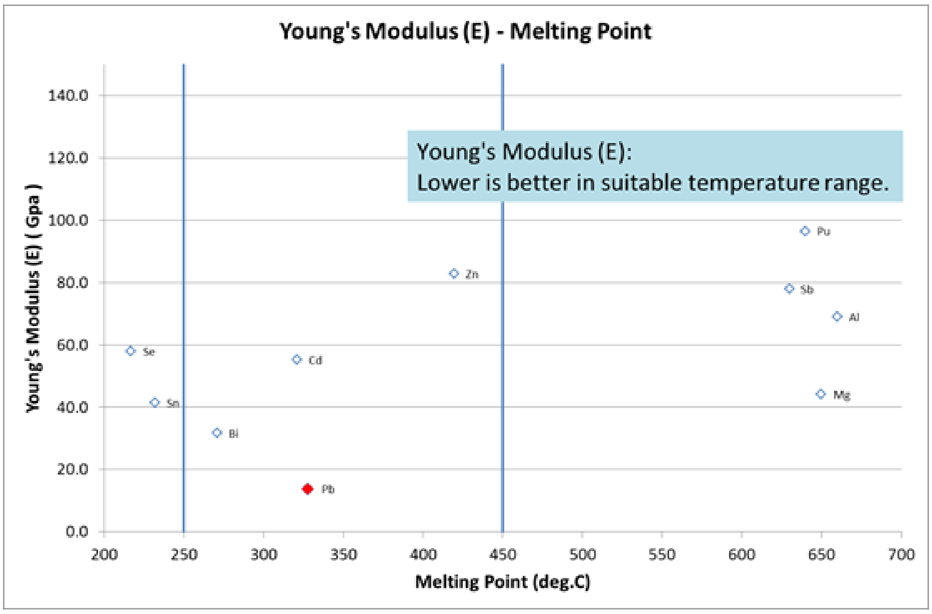
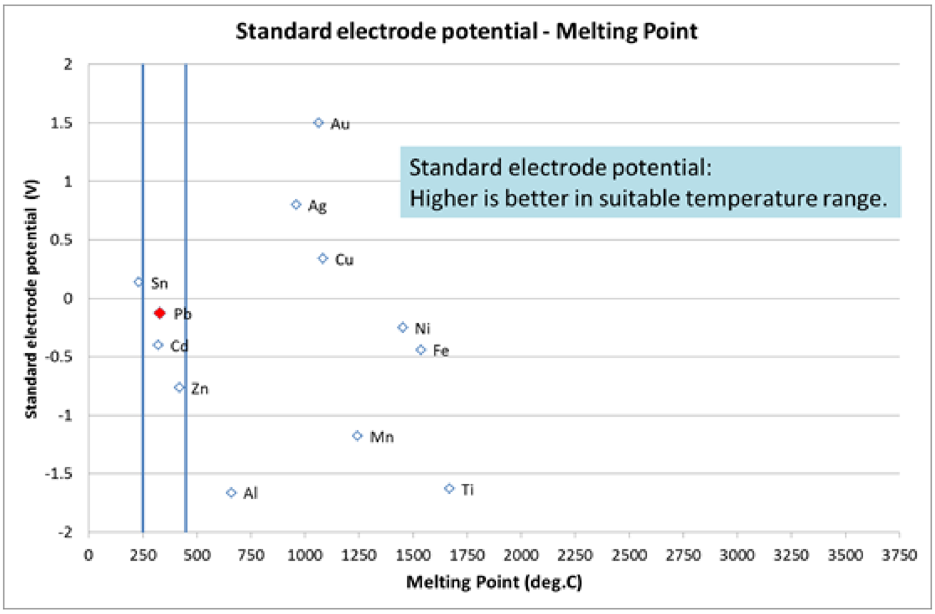
[813] Ibid.
[814] Ibid.

Figure 21-6: Young's modulus (E) by melting points (narrow temperature range)



Source: Freescale et al.[816]

Figure 21-7: Standard electrode and melting points of elements (wide temperature range)



Source: Freescale et al.[817]

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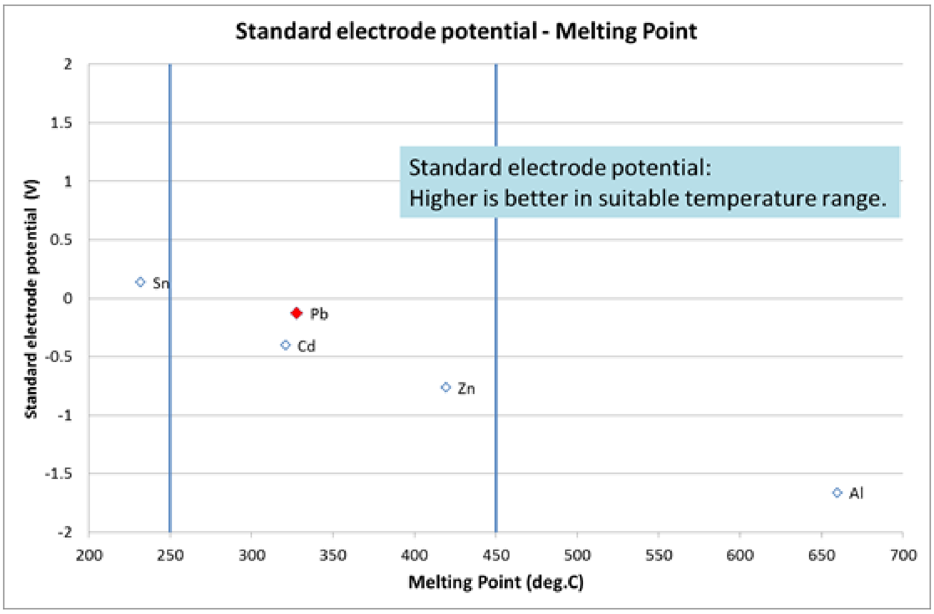
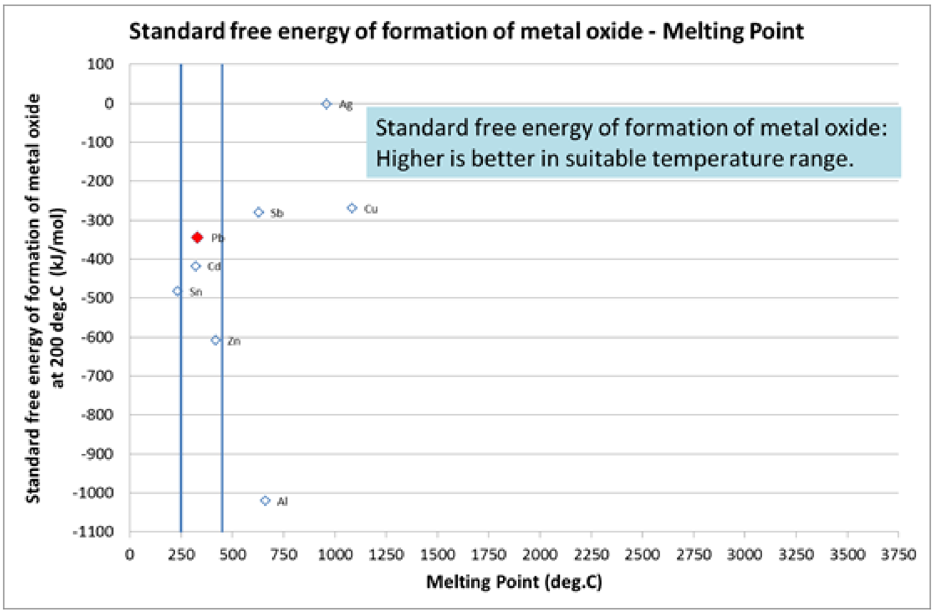
[815] Ibid.
[816] Ibid.

Figure 21-8: Standard electrode and melting points of elements (narrow temperature range)



Source: Freescale et al.[818]

Figure 21-9: Standard free energy of metal oxide formation and melting points of elements (wide temperature range)



Source: Freescale et al.[819]

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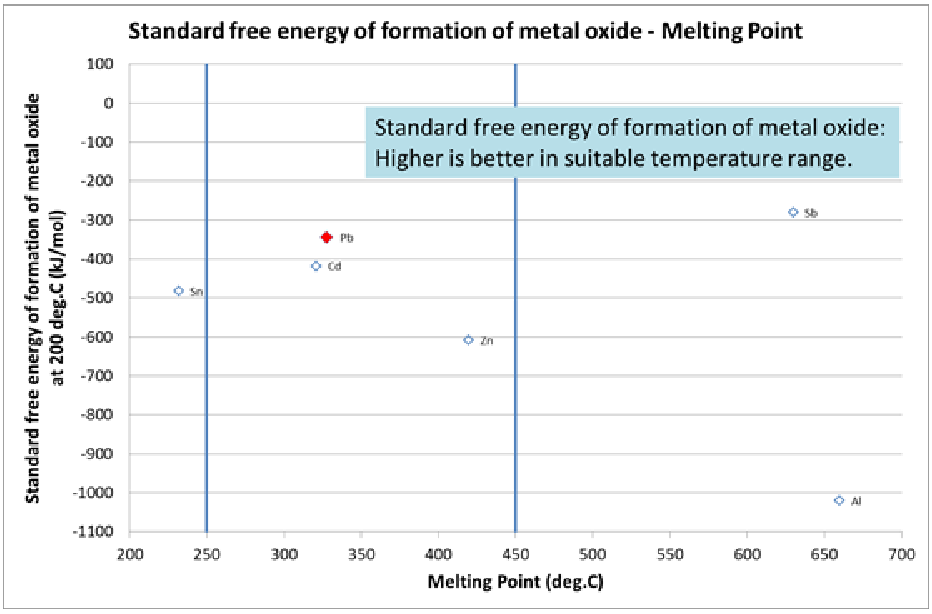
[817] Ibid.
[818] Ibid.

Figure 21-10: Standard free energy of metal oxide formation and melting points of elements (narrow temperature range)

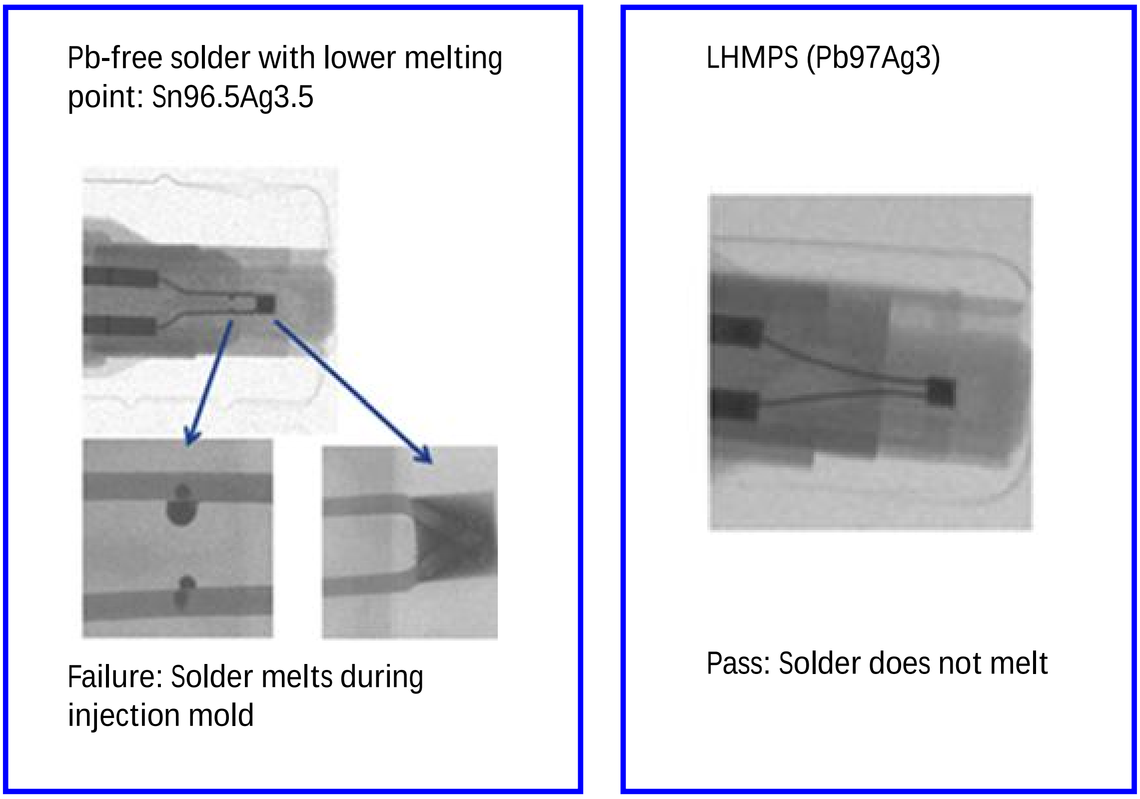


Source: Freescale et al.[820]

With Figure 21-11, Freescale et al.[821] explain why a thermistor requires high HMPS. Thermistor devices are used in high temperature / harsh environment applications. This requires plastic over-moulding with materials having a working temperature of ~ 260 ^{o}C. High temperature solder is required to avoid any reflows which weaken the connecting lead[822]-to-thermistor adhesion. The left picture in Figure 21-11 details the solder reflow from plastic over-moulding with lead-free type solders. The picture on the right depicts high temperature lead-based solder in the same over-moulding operation.

[819] Ibid.
[820] Ibid.
[821] Ibid.
[822] not Pb

Figure 21-11: Thermistor requirement for LHMPS



Source: Freescale et al.[823]

Freescale et al.[824] explain that similar circumstances are relevant with current limiting thermistor products. Current limiting thermistors can reach temperatures up to 240 °C during normal operating conditions in the field. In order to stay above the plastic and solder melting point for this application, LHMPS are the only commercial solution available at this time.

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[823] Ibid.
[824] Ibid.

21.1.3.2 Uses of LHMPS

Table 21-3 lists the uses of LHMPS, which are illustrated with examples in the figures below the table.

Table 21-3: Uses of LHMPS

<table>
<tr><th>LHMP solder use</th><th>Examples of related products</th><th>Reasons for necessity</th></tr>
<tr><td>For combining elements integral to an electrical or electronic component:
- a functional element with a functional element; or,
- a functional element with wire/terminal/heat sink/substrate, etc.</td><td>· Resistors, capacitors, chip coil, resistor networks, capacitor networks, power semiconductors, discrete semiconductors, microcomputers, ICs, LSIs, chip EMI, chip beads, chip inductors, chip transformers, power transformers, lamps, etc.;
· see examples in Figure 21-12to Figure 21-17 below</td><td rowspan="3">· Stress relaxation characteristic with materials and metal materials at the time of assembly is needed.
· When it is incorporated in products, it needs heatproof characteristics to temperatures higher than 250 to 260°C.
· It is needed to achieve electrical characteristic and thermal characteristic during operation, due to electric conductivity, heat conductivity / high thermal dissipation, etc.
· It is needed to gain high reliability for temperature cycles, power cycles, etc.</td></tr>
<tr><td>For mounting electronic components onto sub-assembled modules or sub-circuit boards</td><td>· Hybrid IC, modules, optical modules, etc.
· See example in Figure 21-18 below</td></tr>
<tr><td>As a sealing material between a ceramic package or plug and a metal case</td><td>· SAW (Surface Acoustic Wave) filter, crystal resonators, crystal oscillators, crystal filters, etc.
· See example in Figure 21-19 below</td></tr>
</table>

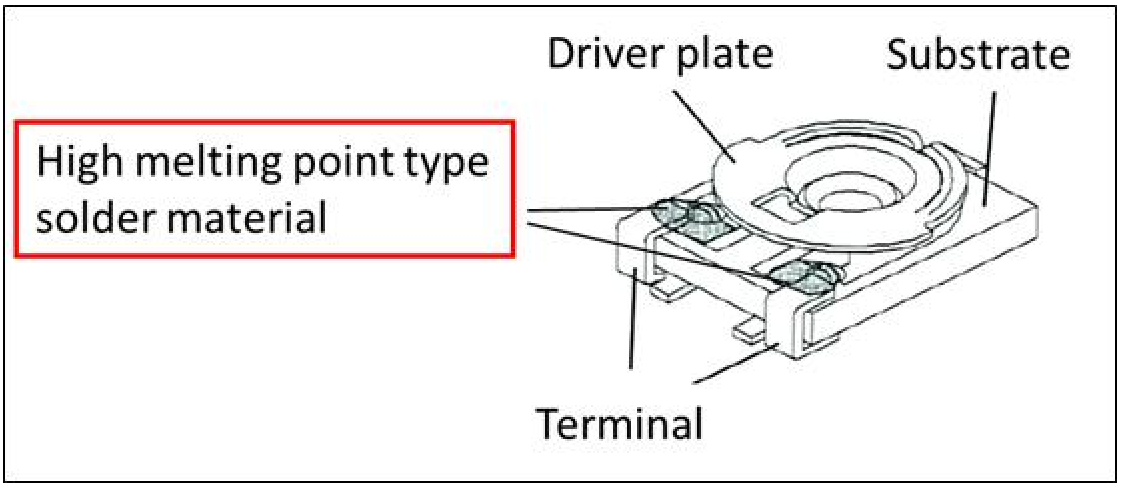
Source: Freescale et al.[825]

LHMPS uses for combining elements integral to an electrical or electronic component

Freescale et al.[826] provide five examples in the below figures for how LHMPS are used to combine elements integral to an electrical or electronic component – either a functional element with a functional element, or a functional element with wire/terminal/heat sink/substrate, etc.

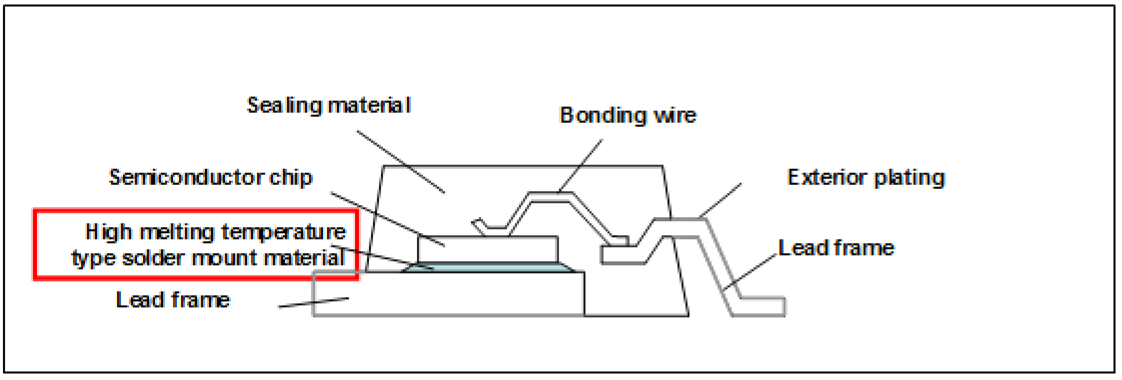
[825] Ibid.
[826] Ibid.

Figure 21-12: Schematic view of potentiometer with HMP lead (Pb) solder visible from the outside



Source: Freescale et al.[827]

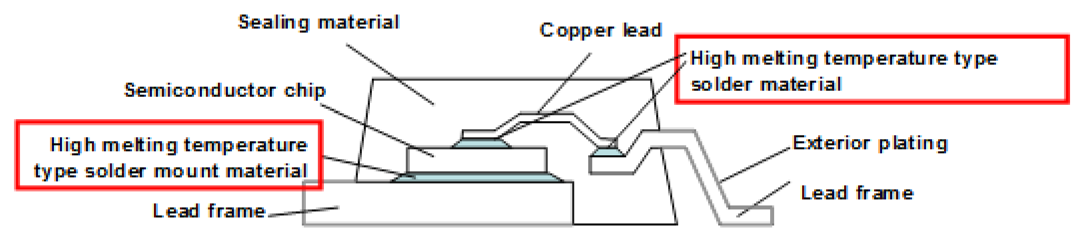
Figure 21-13: Schematic cross sectional view of a power semiconductor



Source: Freescale et al.[828]

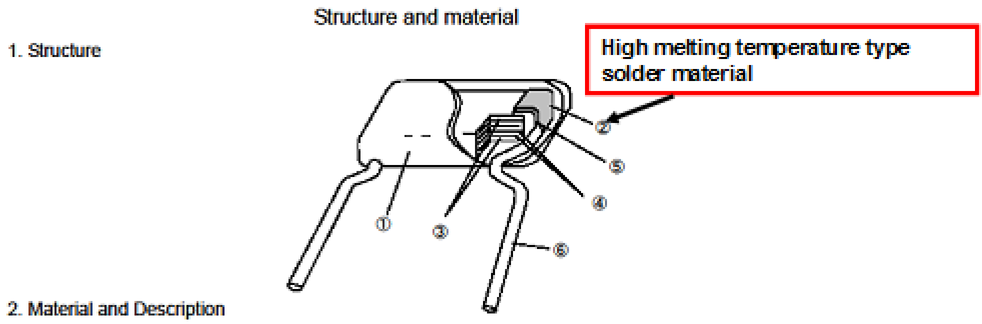
[827] Ibid.
[828] Ibid.

Figure 21-14: Schematic cross sectional view of internal connection of semiconductor



Source: Freescale et al.[829]

Figure 21-15: Schematic view of a capacitor with lead wire



2. Material and Description

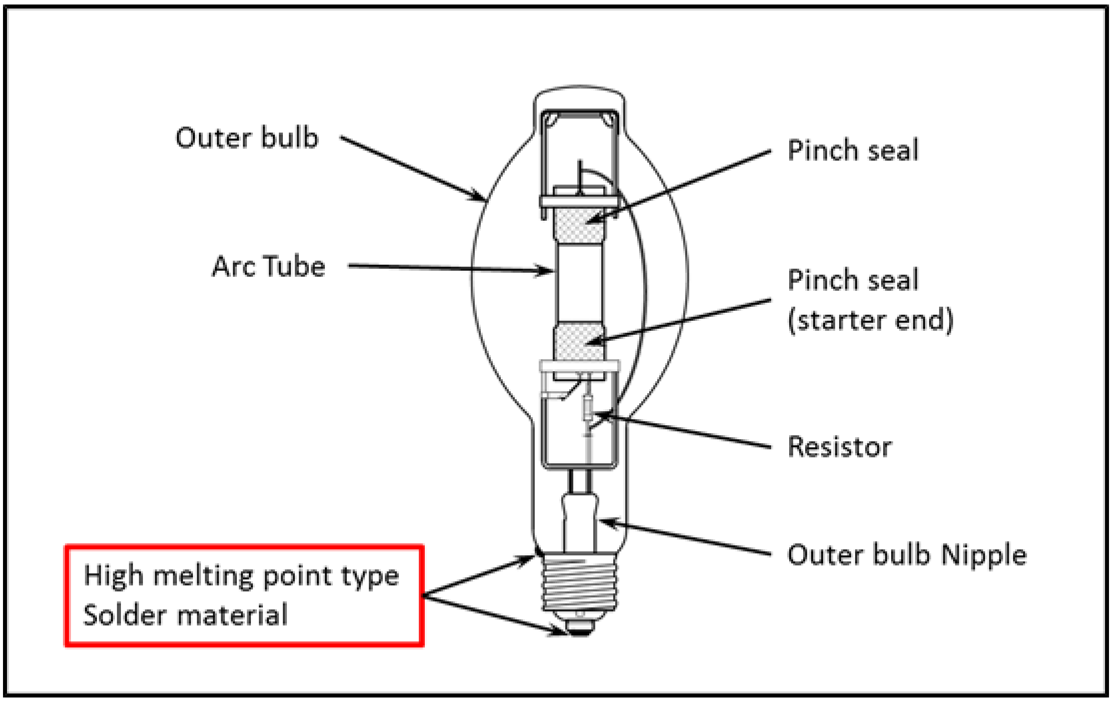
No.	Material	Description
①	Enclosure	Epoxy resin
②	Inner solder	Sn-Pb type solder *1
③	Dielectric	Ceramic
④	Inner electrode	Ni or Pd or Ag/Pd
⑤	Outer electrode	1)Ag/Pd or 2) Ag or Ag/Pd or Cu + Ni plating + Sn plating
⑥	Lead wire	Solder(Sn-2.5Cu) coated copper wire or Solder(Sn-2.5Cu) coated CP wire

*1 Lead in high melting temperature type solders (Pb:85% or more) are exempted from the requirements of RoHS.

Source: Freescale et al.[830]

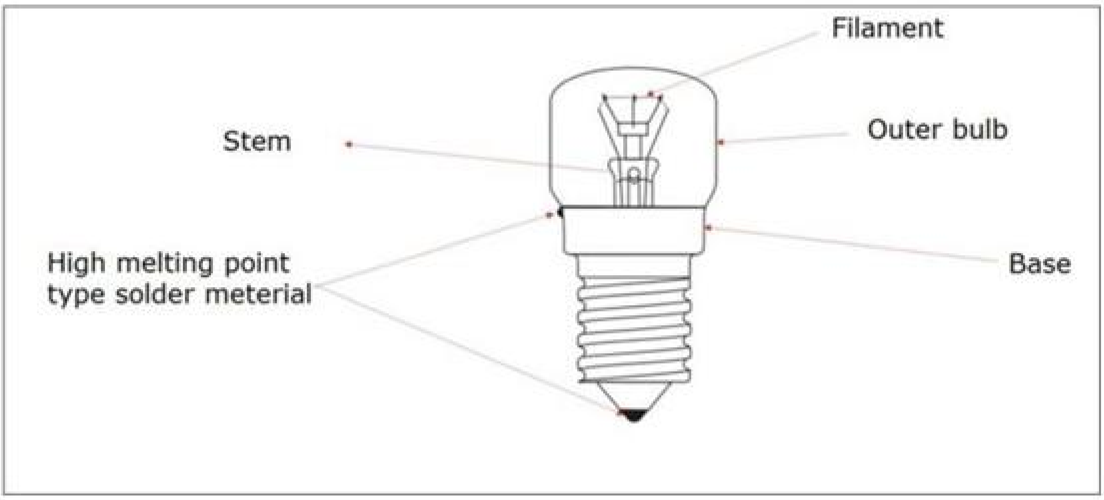
[829] Ibid.
[830] Ibid.

Figure 21-16: Schematic view of a HID lamp



Source: Freescale et al.[831]

Figure 21-17: Oven lamp with LHMPS



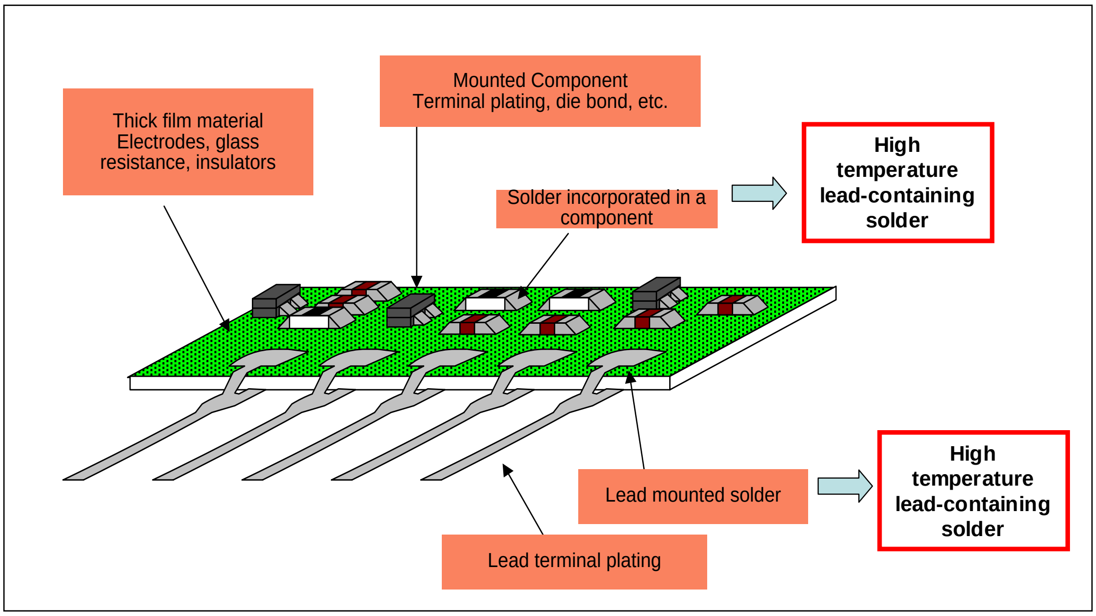
Source: Freescale et al.[832]

[831] Ibid.
[832] Ibid.

Examples for mounting electronic components onto sub-assembled modules or sub-circuit boards with LHMPS

Figure 21-18 shows examples for how LHMPS are used to mount electronic components onto sub-assembled modules or sub-circuit boards.

Figure 21-18: Schematic view of a circuit module component



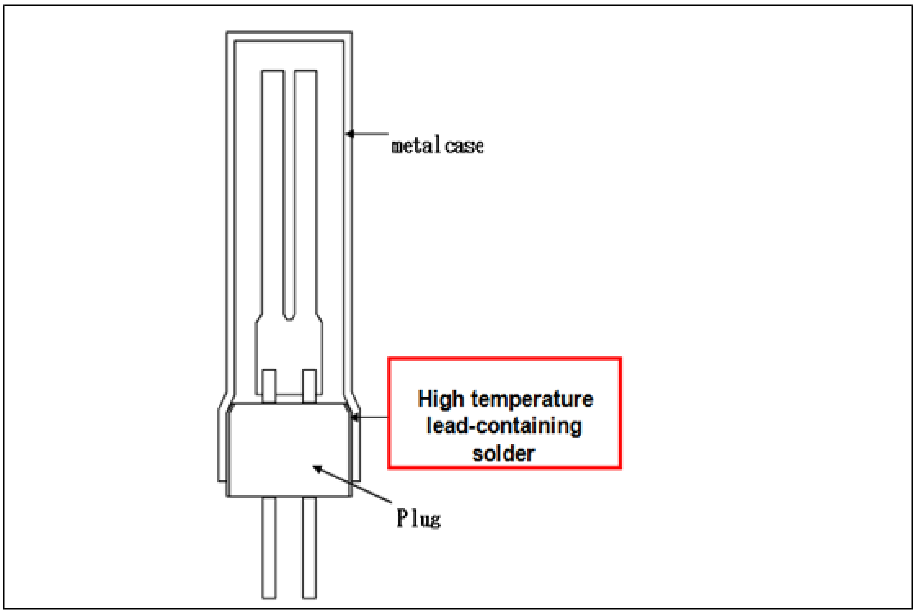
Source: Freescale et al.[833]

LHMPS uses as sealing material between a ceramic package or plug and a metal case

In Figure 21-19, Freescale et al.[834] illustrate the use of LHMPS for sealings between a ceramic package or plug and a metal case.

833 Ibid.
834 Ibid.

Figure 21-19: Schematic view of a crystal resonator



Source: Freescale et al.[835]

LHMPS in High PowerTransducers (Bosch)

Bosch[836] describes that high power transducers (both low and high frequency in professional sound applications) are used with power amplifiers capable of producing output greater than 200 V and 30 A. This amount of energy creates a significant amount of heat dissipated in the voice coil. The temperatures for low frequency transducers exceed the melting point of lead-free solders in less than 100 seconds, resulting in catastrophic failures. In addition, the solder used must be compatible with copper and aluminium wire.

In Bosch's[837] high power loudspeaker designs it is necessary to transition between a high flexibility, high cross sectional area conductor, down to the very fine gauge wire used to make the coil of wire that provides the electromotive force to drive the transducer. These solder joints must be made in close proximity to the magnet wire coil for a variety of reasons.

A primary reason for the proximity is structural integrity. The fine gauge magnet wire is often not able to withstand the high amounts of vibrational energy in the coil structure. This magnet wire can be aluminium, copper-clad aluminium, or copper. All of these magnet wires experience bending fatigue. If the solder joint is too far from the coil of magnet wire, this conjoining section of wire will mechanically fail due to highly

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[835] Ibid.
[836] Op. cit. Bosch Security Systems GmbH 2015
[837] Ibid.

repetitious bending modes. These fractures can create an electrical arc across the break in the wire that can ignite nearby materials.[838]

This proximity of the solder joint to the magnet wire coil in conjunction with the high temperatures of the magnet wire in the coil, make HMP solder a necessity.[839] Figure 21-20 and Figure 21-21 describe the situation.

Figure 21-20: Inner diameter of a typical high power woofer voice coil

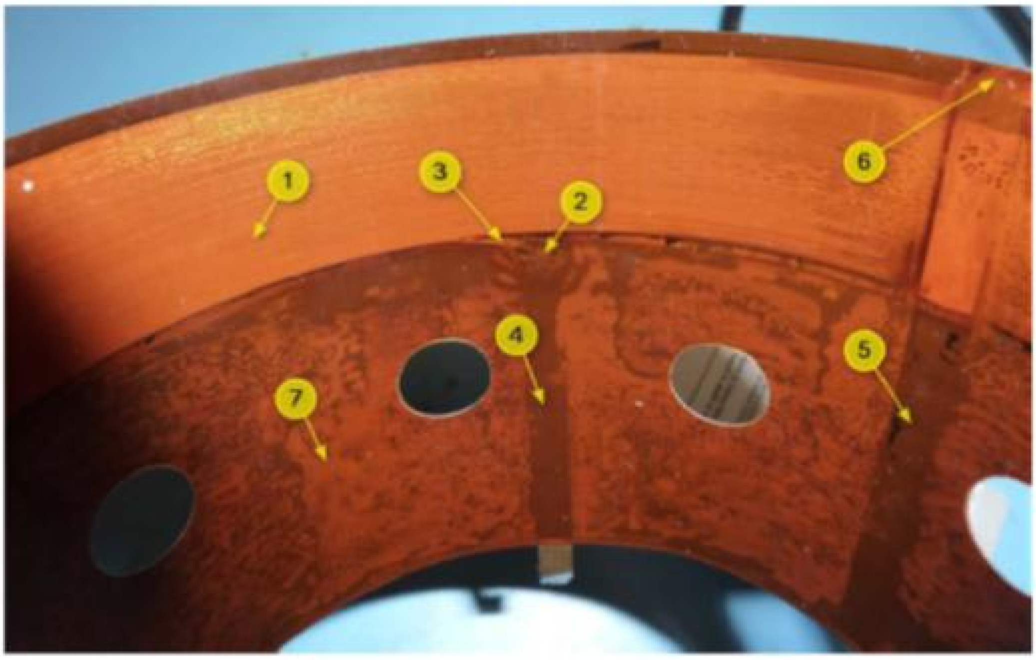

Image of the inner diameter of a typical high power woofer voice coil.

In this image;

1) Shows the coil of magnet wire. Visible through the coil bobbin (item 7).
2) The Upper solder joint. This joint is layered between the bobbin (7) and another high temperature resistance electrically insulating polymer. The magnet wire (3) is soldered to the flexible conductor (4) with HMP solder.
3) The magnet wire splitting off the coil (1) to go to the upper solder joint (2)
4) .1mm x 6mm flexible conductor (e.g. Phosphor Bronze.)
5) Same as 4 but extending under the coil of wire to make Lower Solder Joint (6)
6) The Lower Solder joint. This joint is layered between the bobbin (7) and a high temperature resistance adhesive. The magnet wire (3) is soldered to the flexible conductor (5) with HMP solder.
7) Bobbin – High temperature resistance polymer (e.g. Polyimide film)

Source: Bosch[840]

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[838] Ibid.
[839] Ibid.
[840] Ibid.

Figure 21-21: Outer diameter of a typical high power woofer voice coil

Source: Bosch[841]

Figure 21-21 shows the black area which is the high temperature adhesive that overcoats the Lower Solder Joint and the magnet wire as it splits away from the coil of wire.

Although Bosch[842] started research two years prior to RoHS being required they have not discovered an alternative to LHMPS. Bosch[843] sells several products using these transducers in Europe. They are used in large installations including stadiums (e.g. World Cup stadiums), they have EN54 certifications for life safety applications.[844]

According to Bosch[845], these large installations are not large scale fixed installations, which would be excluded from the scope of the RoHS Directive.

21.1.4 Amount of Lead Used Under Exemption 7(a)

In 2000, the annual worldwide use of LHMPS in the scope of exemption 7(a) was investigated to be around 11,000 t corresponding to around 9,400 t based on the minimum lead content of 85 % mentioned in exemption 7(a).[846] In the 2008/2009 review, JBCE estimated the amount of LHMPS put on the EU market with 3,600 t/year,

[841] Ibid.
[842] Ibid.
[843] Ibid.
[844] For product examples c.f. http://www.electrovoice.com/family.php?id=117; source as referenced by Bosch
[845] Bosch Security Systems GmbH 2016a “Answers to first questionnaire, document "Exe_7a_Questionnaire-1_Bosch_2016-03-13.docx", received via e-mail by Dr. Otmar Deubzer, Fraunhofer IZM, from Erich Pudelko, Bosch, on 23 March 2016” unpublished manuscript,
[846] Otmar Deubzer 2007 Explorative study into the sustainable use and substitution of soldering metals in electronics: Ecological and economical consequences of the ban of lead in electronics and lessons to be learned for the future, Design for Sustainability Program publication 15 ([S.l.]: [s.n.]), http://repository.tudelft.nl/view/ir/uuid%3Af9a776cf-57c3-4815-a989-fe89ed59046e/; page 73 et seqq.

corresponding to at least 3,100 t of lead. This figure did not include the HMP solders contained in products imported into the EU market.[847]

In the current review, Freescale/NXP et al. [848] estimate the amount of LHMPS put on the EU market with around 2,700 t, which corresponds to at least 2,300 t of lead. The calculation below shows that this figure does not contain the lead from LHMPS in products imported into the EU.

Figure 21-22: Calculation of LHMPS solders in the EU

1,590,000 tonnes / year =	Electrolytic Pb consumption in Europe
X 1.3%	Ratio of Pb used in Pb solder applications
X 12.9%	HMP lead (Pb) solder ration of all solders
2,667 tonnes / year =	HMP lead (Pb) solder entering EU market

Source: Freescale/NXP et al.[849]

Bourns estimates the worldwide amount of lead from LHPMS based on some of its products with around 960 kg.[850]

IXYS[851] indicates the annual amount of LHMPS in power semiconductor devices containing more than 90% of lead with around 50 t/a for the EU market.

Bosch[852] estimates that they will place a mass of less than 15 kg of lead into the field per year in their high power loudspeaker products, less than 40 % of that quantity, around 6kg, will be used in the EU. This figure does not include lead that other manufacturers would use as LHMPS in high power transducers.

Overall, the figures differ depending on the applied calculation base and depending on the data quality and the product spectrum taken into account. The figures of JEITA et al.853 and of Deubzer854 have the broadest product scope and can therefore be assumed to be closest to the actual magnitude of HMPS solder use and related lead on the global and EU level, even though the data of Deubzer should be considered to reflect the magnitude of lead rather than the actual amounts since this data is now 16 years old.

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[847] Op. cit. Gensch, Carl-Otto, Oeko-Institut e. V., et al. 20 February 2009
[848] Op. cit. Freescale Semiconductors/NXP et al. 2015a
[849] Ibid.
[850] Bourns Inc. 2015b "1st Questionnaire (Clarification Questionnaire) Exemption 7a: Document "20150815_Ex_7a_Bourns_1st-Questionnaire_2015-07-14.pdf"," http://rohs.exemptions.oeko.info/fileadmin/user_upload/RoHS_Pack_9/Exemption_7_a_/Bourns/20150815_Ex_7a_Bourns_1st-Questionnaire_2015-07-14.pdf
[851] Op. cit. IXYS Semiconductor GmbH 2015a
[852] Op. cit. (Bosch Security Systems GmbH 2016a)
[853] Op. cit. Freescale Semiconductors/NXP et al. 2015a
[854] Otmar Deubzer 2007 Explorative study into the sustainable use and substitution of soldering metals in electronics: Ecological and economical consequences of the ban of lead in electronics and lessons to be learned for the future, Design for Sustainability Program publication 15 (Delft: TU Delft), http://repository.tudelft.nl/view/ir/uuid%3Af9a776cf-57c3-4815-a989-fe89ed59046e/

The actual use of lead thus is probably in the lower range of several thousand tonnes in the EU.

21.2 Applicants' Justification for the Continuation or Repealment of the Exemption

Freescale et al.[855] are requesting the renewal of exemption 7(a) in its current wording for categories 1 to 7, 10 and 11 of Annex I for an additional validity period of 5 years. They state that alternative technologies with similar ductility and strength as lead (Pb) that can survive one or several standard reflow processes with either leaded or unleaded solders are unavailable for the following uses:

- For combining elements integral to an electrical or electronic component:
  - a functional element with a functional element; or,
  - a functional element with wire/terminal/heat sink/substrate, etc.;
- For mounting electronic components onto sub-assembled modules or sub-circuit boards;
- As sealing materials between a ceramic package or plug and a metal case.

21.2.1 Substitution of LHMPS by Lead-free Solders and Conductive Adhesives

Freescale et al.[856] state that the RoHS Directive has encouraged the transition from lead solders to lead-free solders for external terminations and board attachment. Due to the higher melting points of lead-free solders, soldering temperatures in production processes have risen to between 250 °C and 260 °C for lead-free solders mainly composed of Sn-Ag-Cu. Soldering temperatures in production processes for solder joints were 230 °C to 250 °C for lead-containing solder joints. The increased processing temperature for lead-free solder joints expanded the requirement for HMP lead (Pb) solder. These high melting temperature solders typically contain more than 85 % lead.

Freescale et al.[857] present the Table 21-4, showing the current commercially available lead-free solders and their melting points.

The solders with a solidus line of less than 250 °C are not appropriate. In Table 21-5, Freescale et al.[858] explain the advantages and disadvantages of lead-free solders with a solidus line temperature of 250 °C or higher and electrically conductive adhesives. Those are the candidates for the replacement of high temperature type lead-containing solders.

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[855] Op. cit. Freescale Semiconductors/NXP et al. 2015a
[856] Ibid.
[857] Ibid.
[858] Ibid.

Table 21-4: Composition and melting temperatures of main lead-free solders

Category	Solder Type	Alloy Composition [wt %]	Melting Temperatures (Solidus Line / Liquidus Line)
Lead-free solders (Solidus Line 250°C or lower)	Sn-Zn (-Bi)	Sn-8.0Zn-3.0Bi	190~197 °C
	Sn-Bi	Sn-58Bi	139 °C
	Sn-Ag-Bi-In	Sn-3.5Ag-0.5Bi-8.0In	196~206 °C
	Sn-Ag-Cu-Bi	Sn96Ag2.5Bi1Cu0.5	213~218 °C
	Sn-Ag-Cu	Sn-3.0Ag-0.5Cu	217~220 °C
		Sn-3.5Ag-0.7Cu	217~218 °C
		Sn-4Ag-0.5Cu	217~229 °C
	Sn-Cu	Sn-0.7Cu	227 °C
	Sn-low Sb	Sn-5.0Sb	235~240 °C
Lead-free solders (Solidus Line more than 250°C)	Bi system	Bi-2.5Ag	263 °C
	Au-Sn system	Au-20Sn	280 °C
	Sn-high Sb	Sn->43Sb	325~>420 °C
	Zn-Al system	Zn-(4-6)Al(Ga,Ge,Mg)	About 350~380 °C
	Sn system & high melting temperature type metal	Sn+(Cu, Ni, etc.)	≧about 230~ >400 °C

Source: Freescale et al.[859]

[859] Ibid.

Table 21-5: Properties of lead-free solders with solidus line temperatures of 250 °C or higher

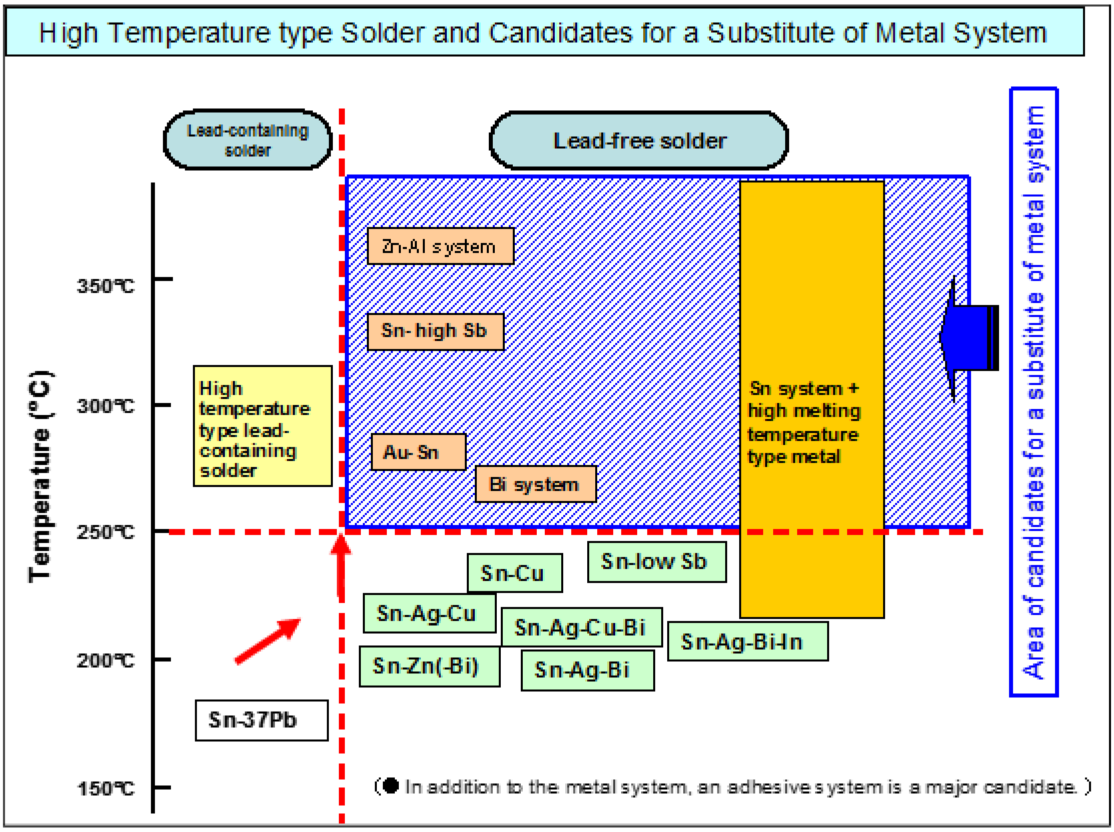
Candidate for Substitution		Advantages	Disadvantages
Metal System	Bi system	· Solidus line is high · Joint operating temperature is comparable with conventional high temperature type solders · Relatively low-cost	· Low ductility · Low strength · High electrical resistivity
	Au-Sn	· Solidus line is high · Joint operating temperature is comparable with conventional high temperature type solders · Strength is high	· Low ductility · Low melting point compared to LHMPS
	Sn-high Sb	· Solidus line is high	· Low ductility · Concern of Sb toxicity · Temperature required to solder is ~50 oC higher than Pb-based solder and is too hot for some processes
	Zn-Al system	· Solidus line is high	· Brittle or low ductility · Susceptible to corrosion and early failure · Temperature required to solder is significantly higher than Pb-based solder and is too hot for some processes.
	Sn system + High melting temperature type metal	· It is still retentive even if it is remelted. The joint operating temperature is comparable with that of conventional high temperature type solder, depending on a combination of remelting. · Solidus line is high if all can be made inter-metal compounds.	· For a resin mold, there is fear that a molten part may exude to outside of a component. · Joint operating temperature is high, extending solder duration, which might lead to high intermetallic growth which is often brittle and leads to a reliability issue. · Fragile or low ductility because joint is mainly made by inter-metal compounds.
Electrically conductive adhesive system		· No concern of remelting due to thermal hardening.	· Poor heat conductivity · Poor electrical conductivity which can deteriorate with age · Susceptible to humidity · Difficult to repair

Source: Freescale et al.[860]

[860] Ibid.

As a synopsis of Table 21-3and Table 21-4, Freescale et al.[861] show the relationship of types and melting temperatures of lead-containing and lead-free solders in Figure 21-23.

Figure 21-23: Relationship diagram of solders and melting temperatures



Source: ACEA, referenced in Freescale et al.[862]

Freescale et al.[863] conclude that both lead-free solders with solidus line temperatures of 250 °C or higher as well as electrically conductive adhesives presented in Table 21-5 have important disadvantages which do not qualify them for substituting LHMPS. No lead-free materials currently on the market meet or exceed the required functionality and reliability of LHMPS. Yet the materials industry continues to develop potential future alternatives in conjunction with component manufacturers.

Freescale et al.[864] state that additionally the proceeding trend of miniaturization of components and structures increases the thermal and mechanical load on components. The unique properties of LHMPS described on page 373 et seqq. ensure less defects

[861] Ibid.
[862] Ibid.
[863] Ibid.
[864] Ibid.

during manufacturing and high reliability throughout the life of the component, thereby also resulting in longer life of components and reduced waste[865].

In addition, Freescale et al.[866] claim a very careful scrutiny to be required in the event that a substitute production technology becomes available, so as to maintain the required high quality of components in the process, to avoid failure in the field, so that such new technology can be adopted.

The justifications of Bourns[867] and IXYS[868] for their uses of LHMPS follow the same rationale like Freescale/NXP et al. and are therefore not specifically explained.

21.2.2 Elimination of LHMPS

Besides for die attach, Freescale et al.[869, 870] do not mention any efforts or possibilities to eliminate the use of LHMPS with bonding technologies others than soldering.

21.2.2.1 Alternative bonding technologies without LHMPS use

Compression-bonded contact systems

IXYS[871] mentions that for very high power semiconductor systems, compression bonded contact systems are in use. Packaging is mostly realized as voluminous ceramic cases as illustrated in Figure 21-24. Alternatively, the ceramic was tried to be replaced by plastic cases, but still with compression bond technology,[872] which was, however, not successful because it is not reliable due to humidity leakages of the plastic housing.

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[865] Freescale et al. 2015b reference the document by the UK's BERR (now UK's BIS) at http://www.berr.gov.uk/files/file40576.pdf on page 18

[866] Ibid.

[867] dddOp. cit. Bourns Inc. 2015a

[868] Op. cit. IXYS Semiconductor GmbH 2015a

[869] Op. cit. Freescale Semiconductors/NXP et al. 2015a

[870] Freescale Semiconductors/NXP et al. 2015b "1st Questionnaire (Clarfication Questionnaire) Exemption 7a, document "Ex_7a_Freescale_Response_to_Clarification_questions_2015_0817_Final_to_Oko_Questions_of_2015_0716.pdf": Questionnaire 1 (clarification questionnaire)," http://rohs.exemptions.oeko.info/fileadmin/user_upload/RoHS_Pack_9/Exemption_7_a_/Freescale_Semiconductor/Ex_7a_Freescale_Response_to_Clarification_questions_2015_0817_Final_to_Oko_Questions_of_2015_0716.pdf

[871] Op. cit. IXYS Semiconductor GmbH 2015a

[872] For details see patent DE2825682C2; referenced by IXYS 2015b

Figure 21-24: Compression bonded contact systems for very high power semiconductor systems

Source: IXYS Semiconductor GmbH[873]

According to IXYS[874], this technology is an alternative to LHMPS-bonded die components in “hockey pucks”, where steady state currents of more than 500 A, surge currents of at least 50 kA and silicon die diameters of more than 25 mm occur. IXYS[875] describes typical applications to be “hockey puck” stacks for high-voltage direct current (DC) transmission of electricity, which are used in the range between 200V/2,900A and 6,500V/3,000A.

Upon further request, IXYS[876] states that they are not aware of any other applications of such compression-bonded contact systems that are clearly within the scope of the RoHS Directive, and where these types of components can replace components that use LHMPS for die attach.

The compression bonding technology therefore will not be followed up further in the review.

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[873] Ibid.
[874] Op. cit. Freescale Semiconductors/NXP et al. 2015b
[875] IXYS Semiconductor GmbH 2016b “Answers to questionnaire 2, document "Exe-7a_Questionnaire-2_IXYS.docx", received via e-mail from Markus Bickel, IXYS, by Dr. Otmar Deubzer, Fraunhofer IZM, on 21 January 2016” unpublished manuscript,
[876] Ibid.

Direct Copper Bonding

IXYS[877] explains that the combination of larger power dies with copper plates is a root cause for the use of LHMPS. The more expensive electrically isolated package versions in DCB technology with metal bonded alumina or AlN ceramic isolator substrates have better CTE (coefficient of thermal expansion) matches, and more and more lead-free tin-silver-copper type solders are used. IXYS Germany[878] (formerly BBC, ABB) claims to be a pioneer to offer an alternative based on DCB technology, which has been under strong dispute among competitors in the past, but which now most competitors[879] have adopted. IXYS[880] already introduced such products in the 1980s, for example the wide range of lead-free standard power semiconductor modules with screw connectors.[881]

The DCB technology is more costly, however, it includes the electrical insulation.[882] IXYS[883]mentions in this context, however, that their ISOPLUS devices incorporating the DCB technology for applications in the SMT (**s**urface **m**ount **t**echnology) need LHMPS for internal connections while THT (through hole technology) components can be wire bonded. This is due to the fact that during SMT processing the devices have to survive temperatures exceeding the lead-free SAC (tin-silver-copper alloy) melting point[884]. Otherwise the internal lead-free solder connections in the plastic moulded devices would remelt and degrade their quality. THT uses LHMPS for internal die attach because subsequent wave soldering process is with lead-free SAC.

IXYS[885] [886] state that DCB with Au-Si eutectics are applicable for die edge sizes smaller than 3 mm, and presents an example of such a product. IXYS has such products in its portfolio. LHMPS is especially important when combining larger power dies with copper base plates (headers).

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[877] Op. cit. IXYS Semiconductor GmbH 2015a

[878] IXYS Semiconductor GmbH 2015b “1st Questionnaire (Clarification Questionnaire) Exemption 7a, document document "20150804_Ex_7a_Ixys_Questions_answered_amended.pdf": Questionnaire 1, clarification questionnaire,” http://rohs.exemptions.oeko.info/fileadmin/user_upload/RoHS_Pack_9/Exemption_7_a_/IXYS/20150804_Ex_7a_Ixys_Questions_answered_amended.pdf

[879] http://www.semikron.com/dl/service-support/downloads/download/semikron-flyer-semitop-2015-04-22 see under key features – “No baseplate design”; source as referenced by IXYS 2016b

[880] Op. cit. (IXYS Semiconductor GmbH 2016b)

[881] IXYS Semiconductor GmbH, http://ixapps.ixys.com/DataSheet/MCC95-08io1B.pdf; source as referenced by IXYS

[882] For more information see http://www.ixys.com/SearchResults.aspx?search=ISOPLUS&SearchSubmit=Go, and for fully isolated TO-220 special packages https://de.wikipedia.org/wiki/Liste_von_Halbleitergeh%C3%A4usen#Plastikgeh.C3.A4use_mit_und_ohne_K.C3.BChlfahne; source as referenced in Op. cit. IXYS Semiconductor GmbH 2015b

[883] Ibid.

[884] For details see IEC 60749-20, table 6 and Fig. B.9 as well as IEC61190-1-3, table B.2; source referenced by IXYS Semiconductor 2015b

[885] Op. cit. Freescale Semiconductors/NXP et al. 2015b

[886] Op. cit. IXYS Semiconductor GmbH 2015a

According to IXYS,[887] the DCB process includes an alumina carrier plus chemical and high temperature process and is therefore more costly compared to LHMPS use.

21.2.3 Substitution and Elimination of Lead in High Power Transducers (Bosch)

Bosch[888, 889] states that they need LHMPS because they can only solder the magnet wire close to the coil where it is exposed to high temperatures. Although Bosch started research two years prior to 2006, when the substance restrictions in the RoHS Directive started to apply, and they search for new solders at least 3 times per year, to date they have not found any new high melting point solders introduced into the market that do not contain lead.

In new designs for low frequency transducers, Bosch[890] will move the wire solder joints away from high temperature areas where lead-free solders can probably be used, but this approach has not been proven and is not applicable for high frequency transducers since high frequency designs have high temperatures at much lower power levels already. In previous attempts to move the solder joint further away from the heat source Bosch[891] have found that the fine gauge magnet wire can fatigue from the high vibrational energy and fracture. When the wire fractures it can cause enough heat, due to electrical arcing, to start neighbouring parts on fire. Further investigation of this has shown that aluminium and copper clad aluminium wires are more subject to this failure. In their newest designs, Bosch[892] use pure copper magnet wires and the joints can be moved far enough away to use a lead-free solder. Unfortunately this would not be possible for all designs.

In a recent low frequency transducer introduction, Bosch[893] attempted the new technique but in the length of magnet wire leading from the voice coil windings to the top of the voice coil bobbin the wire would stress fatigue and fracture. This was due to standing waves that formed in the wire at frequencies in the 800 to 900 Hz range. They tried many ways to reinforce the area but could not stop the fractures from occurring without making the acoustic performance unusable.

Bosch[894] claims that modifying most of their existing designs is not possible because they use aluminium-based wires. The mass and resistance differences make an acoustically/electrically backwards compatible redesign impossible. This is why Bosch’s

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[887] Op. cit. (IXYS Semiconductor GmbH 2016b)
[888] Op. cit. Bosch Security Systems GmbH 2015
[889] Op. cit. (Bosch Security Systems GmbH 2016a)
[890] Op. cit. Bosch Security Systems GmbH 2015
[891] Op. cit. (Bosch Security Systems GmbH 2016a)
[892] Ibid.
[893] Bosch Security Systems GmbH 2016c “E-mail communication, document "Exe_7a_Questionnaire-2_Bosch_2016-03-24.docx", received via e-mail from Erich Pudelko, Bosch, by Dr. Otmar Deubzer, Fraunhofer IZM, on 4 April 2016” unpublished manuscript,
[894] Op. cit. (Bosch Security Systems GmbH 2016a)

newest designs use pure copper magnet wires and the joints can be moved far enough away to use a lead-free solder.

Bosch[895] cannot put the new design into high frequency compression drivers because of mechanical reasons. The magnet wire cannot withstand the millions of cycles of flexing that occur in the suspension of the driver. This forces the transition from magnet wire to something that can withstand the flexing. This transition must be made very close to the source of heat and so it requires LHMPS.

Bosch[896] continues exploring possible solutions to resolve the issues that keep them from initiating new designs in all new low frequency transducers. The new design is not only better for the environment but it is easier to produce and less costly. Bosch has a financial incentive, besides the environmental one. This is a very strong motivator to resolve these issues. Even with that incentive Bosch has not been able to resolve all the issues. They will continue to use the new design in every application possible while they continue their investigations. Bosch expect to find techniques and materials that ultimately allow to no longer use the exemption in low frequency transducers, but they do not know when that solution will come. They also have strong doubts that they will find a solution that works in compression drivers in the near future as this would require an inventive step that cannot be predicted.

21.2.4 Other Stakeholder Contributions

21.2.4.1 TT Microelectronics/AB Mikroelektronik GmbH (AB)

AB[897] submitted information after the public stakeholder consultation on thick film copper bonding (TFCB) in the context of die attach where it could partially replace LHMPS and thus eliminate the use of lead. According to AB[898], thick film substrates are sintered structures so there is more flexibility in comparison to the laminated DCB substrates. This flexibility reduces stresses in the die attach materials as well as the large area soldering joint needed to contact to the heatsink or baseplates. In general, the thick film substrates can be directly substituted for a DCB for instance, when higher current applications demand thicker copper conductors electrically and thermally.

AB[899] has successfully tested TFCB on AlN (aluminium nitride ceramic) and Al_2O_3 (aluminium oxide ceramic) substrates. Organic substrates such as FR4 have not been tested as of yet, but the processing requires high temperatures of more than 800 °C.

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[895] Op. cit. (Bosch Security Systems GmbH 2016c)
[896] Ibid.
[897] TT Electronics/AB Mikroelektronik GmbH 2015a “Information on TFC, document "AB-Mikro_TFC.pdf", received via e-mail from Chris Burns, AB Mikroelektronik, by Dr. Otmar Deubzer, Fraunhofer IZM, on 8 January 2016” unpublished manuscript,
[898] TT Electronics/AB Mikroelektronik GmbH 2015b “E-mail communication, document "E-Mail-Communication_AB-Mikro.pdf", received via e-mail from Chris Burns, AB Mikroelektronik, by Dr. Otmar Deubzer, Fraunhofer IZM, on 14 March 2016” unpublished manuscript,
[899] Ibid.

AB[900] are a supplier to the automotive industry, and they have a sister company working in the aerospace industry, where TFCB has proven to be more effective concerning lifetime between zero and 350 °C.

The company's TFCB technology would require an in-depth review including a consultation with other stakeholders to evaluate whether and how far TFCB can eliminate the use of lead in applications under exemption 7(a) for EEE in the scope of the RoHS Directive. Given the considerable efforts undertaken already for the review of exemption 7(a) and the limited time and resources available, this in-depth review could not be performed in the course of this review process.

The stakeholder was, however, recommended to submit a separate exemption request applying for the partial revoke of exemption 7(a), where the company should explain where and how TFCB can be used in EEE in the scope of the RoHS Directive to eliminate the use of lead. This request can then be subjected to a public online stakeholder consultation and a subsequent review taking into account the applicant's and other information collected during the consultation. As the use of lead is also restricted in Directive 2000/53/EC (ELV Directive), AB Mikroelektronik can also apply the revoke of exemption 8(e) in Annex II of the ELV Directive, which is analogous to RoHS exemption 7(a).

21.2.4.2 Ministry of Environment, Finland

The Ministry of Environment in Finland and Finnish Safety and Chemicals Agency (Tukes)[901] contributed to the stakeholder consultation expressing concerns about purely material specific character of the exemption. They believe that the wording of exemption 7(a) is too wide and can be interpreted to cover all product categories. This may create problems for the enforcement of the RoHS Directive in Member States. In some applications there are already lead-free alternatives available so the wide use of exemption 7(a) is not consistent with aims of the RoHS Directive. From their point of view the exemption should be granted only for those applications and technologies where it is deemed necessary and where no lead-free alternatives are available.

The Finnish Ministry[902] demands that, if the exemption is needed in some applications or technologies and a more precise wording is not feasible at this stage, an end (i.e. an expiration date – consultants comment) should be set for the exemption as required in Article 5 (2) of the RoHS Directive.

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[900] Ibid.
[901] Ministry of the Environment, Finland 2015 "Document "Ex_7a_Finnish_Safety_and_Chemicals_Agency-comment_161015.pdf" submitted during the online stakeholder consultation," http://rohs.exemptions.oeko.info/fileadmin/user_upload/RoHS_Pack_9/Exemption_7_a_/Ex_7a_Finnish_Safety_and_Chemicals_Agency-comment_161015.pdf
[902] Ibid.

21.2.5 Environmental Impacts

Freescale et al.[903] estimate the amount of Pb in HMPS for EEE to be less than 0.2 % of the total Pb placed on the market per year. A research paper from AIST concludes that substitution of Pb in solders has a very small impact concerning risk to ecosystems.[904] Freescale et al.[905] consider the paper to be a useful reference, notwithstanding the fact that research is limited to the recycling of four types of consumer electronics (household air conditioning, TV, electric refrigerators / electric freezer, electric washing machines / clothes dryers) in Japan.

21.3 Roadmap for Substitution or Elimination of Lead

Freescale et al.[906] report that the "Die Attach 5" (DA5 – a partnership between Bosch, Infineon, Freescale, STM and NXP) have been working with suppliers for several years to identify and evaluate alternatives to LHMPS. They have evaluated a variety of new materials from leading global suppliers of solders, adhesives, silver sintering and transient liquid phase sintering (TLPS) materials. The DA5 evaluations recognize continuous improvement in the evaluated materials over the past five years, but even the best of these materials do not meet the DA5 requirements for quality, reliability and manufacturability. They are not at least as good as the traditional LHMPS. Many solutions are still under development, constantly being revised and strictly guarded by suppliers under non-disclosure agreements. They are not available for mass production. Details on the assessed materials and test results are provided in Appendix A.5.1.

Freescale et al.[907] offer International Rectifiers' information for its evaluation of promising Ag epoxy materials from four different suppliers and five different partial melt solders (SnCu, SnAgSb, SAC, SnCuSbCo and SnAgCuSb). The Ag epoxy materials each suffered unacceptable reliability failures due to package delamination causing shifts in Rds(on) (MOSFET "On-state" Drain Source Resistance). The partial melt solders failed industry criteria for MSL (Moisture Sensitivity Level) preconditioning prior to reliability testing; those solders partially melted during 260 °C reflow and caused massive package delamination and solder squirt. Details are available in Appendix A.5.2.

Concerning whether, once the DA5 or International Rectifiers have identified one or more practicable solutions for lead-free die attach, such solutions would be applicable to all the other LHMPS applications as well, Freescale/NXP et al.[908] state that industry

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[903] Op. cit. Freescale Semiconductors/NXP et al. 2015a

[904] National Institute of Advanced Industrial Science and Technology (AIST): http://www.aist-riss.jp/main/modules/product/RTA_cleaners_J_downloadform.html?ml_lang=en; referenced in Freescale et al 2015a

[905] Ibid.

[906] Ibid.

[907] Ibid.

[908] Op. cit. (Freescale Semiconductors/NXP et al. 2016a:)

cannot test solutions that are not available on the market. Market availability for alternatives to LHMPS requires extensive research, development of manufacturing processes and equipment, and verification of functionality and reliability. These steps must occur sequentially for the raw material supplier, for the component manufacturers, and for EEE manufacturers. Freescale/NXP et al. hope to find a single solution that might be applicable to all LHMPS uses, but years of research have found no such perfect solution.

According to Freescale/NXP et al.[909], LHMPS manufacturers have invested significant resources into developing potential alternative solutions. The DA5 continues to work with these suppliers to modify the formulations to develop or improve the manufacturability and reliability. Some solutions look promising for die attach, especially for very small die sizes. The example applications of LHMPS identified by Oeko have unique thermal, mechanical and reliability requirements. Every Pb-free solutions eventually found for DA5 die-attach will subsequently require qualification for other LHMPS applications based upon their unique specifications. While 1:1 usability for a DA5 die-attach solution within other LHMPS applications cannot be guaranteed and is not likely, the anticipated future DA5 solutions will require further investigation into the feasibility of adoption for other applications.

Freescale/NXP et al.[910] report further on that the DA5 has concentrated on finding a proof of concept for high reliability Pb-free replacements to LHMPS die attach materials. Once available, the resulting materials *could* be useful for many applications. The initial research will not qualify material for other applications, but will help to develop materials that *might* work in different applications. The alternatives will require testing and verification for each industry application. In this sense, Freescale/NXP et al.[911] agree that different alternatives may be necessary for different LHMPS applications. Freescale/NXP et al.[912] claim the electronics industry will continuously research for alternatives, however, currently no lead-free alternative technology can be predicted for the future. If a possible substitute is identified for evaluation, widespread conversion from use of high temperature type lead-containing solders in related applications will require time for the appropriate EEE qualifications based on the long term reliability requirements. Conversions cannot begin until lead-free alternatives are developed and perfected by solder manufacturers; processes and equipment are installed and implemented within component manufacturing lines; components are qualified, and those components are made available to EEE manufacturers for:

- development,
- assessment, and
- replacement with alternative products.

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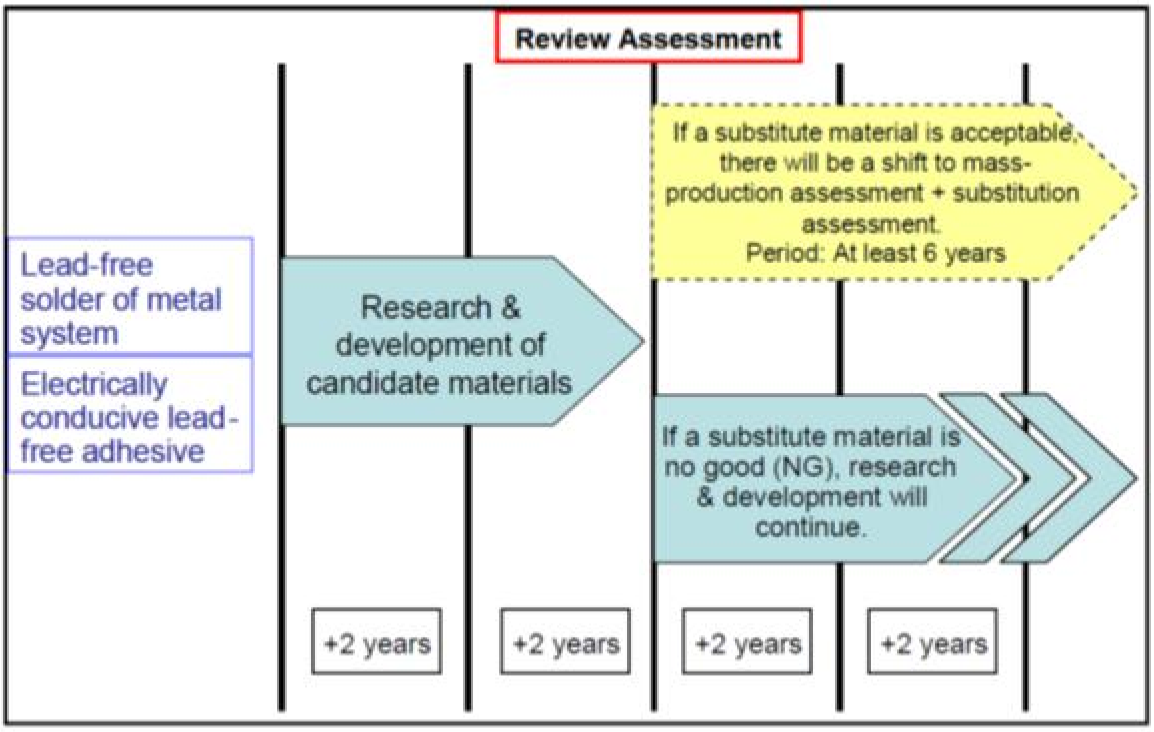
909 Ibid.
910 Ibid.
911 Ibid.
912 Ibid.

Figure 21-25: Material transition process

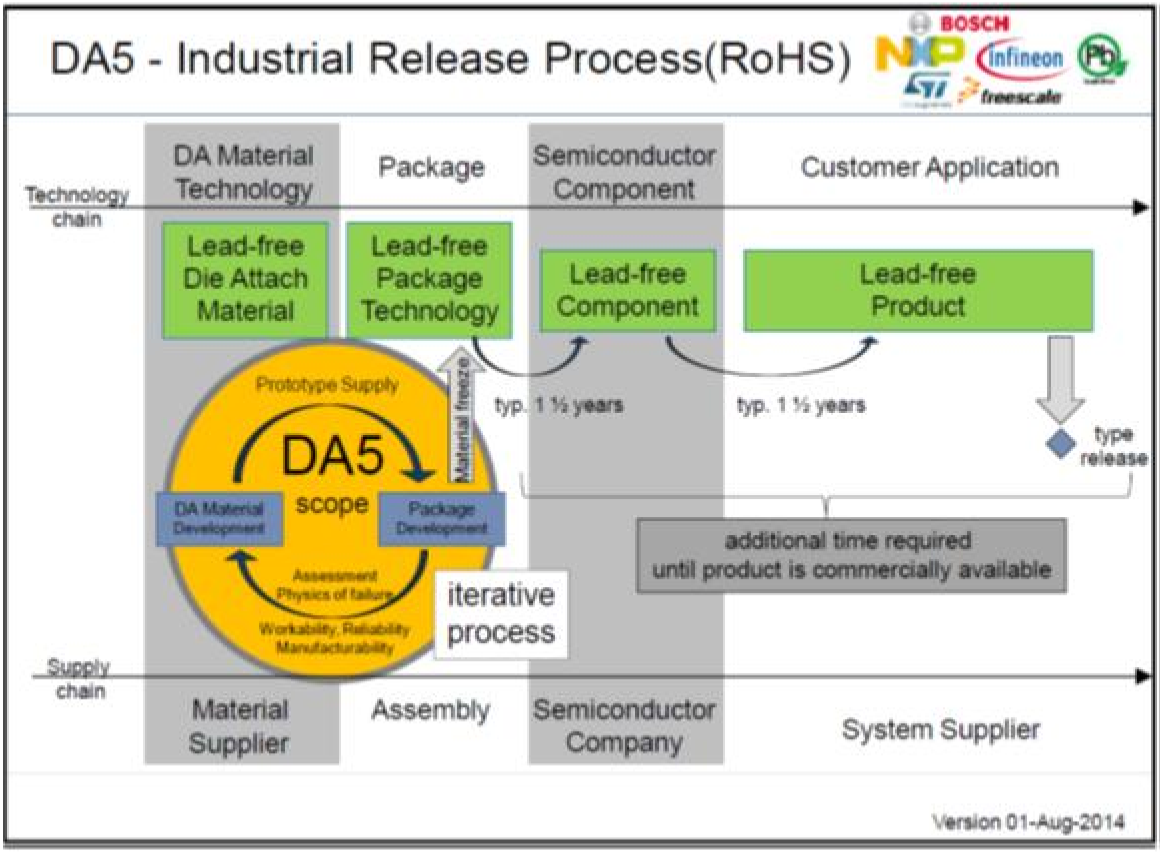


Source: Freescale/NXP et al.[913]

Looking at high-lead solder for attaching die to semiconductor packages, the DA5 consortium is working with selected material suppliers on the development of an appropriate replacement for lead solder (DA5 scope). The properties of the needed die-attach material is specified by the DA5 (material requirement specification) and provided to the material suppliers. Selected material suppliers offer their materials, which are evaluated by one of the DA5 companies together with the supplier. The detailed results are discussed with the material suppliers and all DA5 companies on a regular basis in face-to-face meetings. The results lead to further optimizations of the materials (development loop). The combined results are published by DA5 (c.f. Appendix A.5.1)[914]

[913] Ibid.
[914] Ibid.

Figure 21-26: Cycle time to conversion



Source: Freescale/NXP et al.[915]

After a material is chosen and material development is frozen, another 3 to 5 years will be required to qualify the new material through the whole supply chain. Based on current status, DA5 cannot predict a date for customer sampling as no suitable materials have yet been identified.[916]

Concerning further plans and steps in the next five years to substitute or eliminate lead in the various other types of LHMPS applications mentioned in their exemption request, Freescale/NXP et al.[917] want to support the overall RoHS objective of contributing to the protection of human health and the environment, including the environmentally sound recovery and disposal of waste electrical and electronic equipment. They remain committed to supporting the procedure for the adaptation to scientific and technical progress, and will continue developing, requesting the development and/or applying

[915] Ibid.
[916] Ibid.
[917] Freescale Semiconductors/NXP et al. 2016d “Answers to questionnaire 3a, document "Exe_7a_Questionnaire-3a_Freescale_2016-03-28.pdf", received via e-mail from Griffin Teggeman, NXP, by Dr. Otmar Deubzer, Fraunhofer IZM, on 1 April 2016” unpublished manuscript,

possible alternatives taking into account the practicability, reliability or environmental, health and consumer safety impacts of substitution.

21.4 Critical Review

21.4.1 REACH Compliance - Relation to the REACH Regulation

The exemption allows the use of lead. Annex XIV contains several entries for lead compounds, whose use requires authorization:

- 10. Lead chromate
- 11. Lead sulfochromate
- 12. Lead chromate molybdate sulphate red

In the applications in the scope of the reviewed exemption, lead is used in electronic components that become parts of articles. None of the above listed substances is relevant for this case, neither as directly added substance nor as substance that can reasonably be assumed to be generated in the course of the manufacturing process.

Annex XVII bans the use of the following lead compounds:

- 16. Lead carbonates in paints
- 17. Lead sulphate in paints

Neither the substances nor the application are, however, relevant for the exemption in the scope of this review.

Appendix A.1.0 of this report lists entry 28 and entry 30 in Annex XVII of the REACH Regulation, stipulating that lead and its compounds shall not be placed on the market, or used, as substances, constituents of other substances, or in mixtures for supply to the general public. A prerequisite to granting the requested exemption would therefore be to establish whether the intended use of lead in this exemption request might weaken the environmental and health protection afforded by the REACH regulation.

In the consultants' understanding, the restrictions for substances under entry 28 and entry 30 of Annex XVII do not apply. The use of lead in this RoHS exemption in the consultants' point of view is not a supply of lead and its compounds as a substance, mixture or constituent of other mixtures to the general public. Lead is part of an article and as such, entry 30 of Annex XVII of the REACH Regulation would not apply.

Entry 63 of Annex XVII stipulates that lead and its compounds…

- *"shall not be placed on the market or used in any individual part of jewellery articles if the concentration of lead (expressed as metal) in such a part is equal to or greater than 0.05 % by weight."*
  This restriction does, however, not apply to crystal glass as defined in Annex I (categories 1, 2, 3 and 4) to Council Directive 69/493/EEC (*), and to internal components of watch timepieces inaccessible to consumers
- *"shall not be placed on the market or used in articles supplied to the general public, if the concentration of lead (expressed as metal) in those articles or accessible parts thereof is equal to or greater than 0.05 % by weight, and*

those articles or accessible parts thereof may, during normal or reasonably foreseeable conditions of use, be placed in the mouth by children."
This restriction does, however, not apply to articles within the scope of Directive 2011/65/EU (RoHS 2)

The restrictions of lead and its compounds listed under entry 63 thus do not apply to the applications in the scope of this RoHS exemption.

No other entries, relevant for the use of lead in the requested exemption could be identified in Annex XIV and Annex XVII (status February 2016). Based on the current status of Annexes XIV and XVII of the REACH Regulation, the requested exemption would not weaken the environmental and health protection afforded by the REACH Regulation. An exemption could therefore be granted if other criteria of Art. 5(1)(a) apply.

21.4.2 Substitution and Elimination of Lead in High Power Transducers (Bosch)

Bosch contributed to the public stakeholder consultation stating that exemption 7(a) should stay unchanged or alternatively this specification should be added:

"Lead in high melting temperature type solders used in high-power transducers (loudspeakers)"

As the RoHS Directive requires exemptions to be as specific as possible, the consultants reviewed the proposed specific wording in light of the requirements of Art. 5(1)(a). Bosch states that they have to use LHMPS because they can only solder the fine magnet wire close to the coil where high temperatures occur, which would melt lead-free solders. While this basic fact is plausible and clear, several questions remained open in the further discussions with the stakeholder.[918, 919, 920]

Moving away the solder joint from the coil reduces the temperature the solder joint is exposed to and may facilitate the use of lead-free solders instead of LHMPS. It is understood that Bosch has verified this approach at least in some newer low frequency high power transducer designs. This approach seems to be viable in low and possibly in mid frequency, but not in high frequency transducers, whereas it is not clear whether it would make the substitution of lead practicable in all low and mid frequency power transducers.

Bosch states that they cannot modify their old designs so that lead-free solders could be used. A complete redesign is required, which raises the question whether this redesign would in all cases allow the substitution of lead, and why this redesign has not been performed already. Bosch also mentions that other manufacturers of high power

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[918] Op. cit. (Bosch Security Systems GmbH 2016a)
[919] Bosch Security Systems GmbH 2016b "Answers to second questionnaire, document "Exe_7a_Questionnaire-2_Bosch_2016-03-24.docx", received via e-mail from Erich Pudelko, Bosch, by Dr. Otmar Deubzer, Fraunhofer IZM, on 4 April 2016" unpublished manuscript,
[920] Op. cit. (Bosch Security Systems GmbH 2016c)

loudspeakers have new designs on the market, but it is unclear whether these new designs are actually produced without lead.

It was attempted[921, 922, 923] to narrow the scope of the exemption by demarcating “power” transducer from other transducers, which then would not require the use of LHMPS. The consultants and Bosch agreed on the below wording of the exemption to better describe the actual use of LHMPS in high power transducers:

Lead in high melting temperature type solders (i.e. lead-based alloys containing 85 % by weight or more lead) for electrical connections on or near the voice coil in power transducers.

Bosch’s information suggests that LHMPS is actually required where solder joints in high power transducers have to be exposed to high temperatures that exclude the use of lead-free solders. It remains unclear how far a redesign can help to avoid the higher temperatures enabling the use of lead-free solders, but the information submitted plausibly explains that this is currently not yet possible in all power transducers.

Taking into account the available information and in the absence of contrary information, the consultants recommend granting this exemption appraising the situation that LHMPS is required in high power transducers, justifying an exemption according to Art. 5(1)(a). However, it is recommended to grant the exemption for three years only as to further specify the scope of the exemption. This would still leave sufficient time for stakeholders to apply for the renewal should the exemption still be required in three years.

Granting the exemption would also allow splitting this use of LHMPS from the presently material specific exemption 7(a). Vice versa, the use of LHMPS in the high power transducers could still be permitted under exemption 7(a) even though there are prospects of eliminating or substituting lead.

21.4.3 Substitution and Elimination of Lead Die Attach

The information submitted by Bourns, Freescale/NXP et al. and IXYS suggests that generally, the substitution or elimination of lead is scientifically and technically still impracticable. IXYS provided, however, examples of components where alternative technologies such as direct copper bonding (DCP) eliminate the use of lead.

Freescale/NXP et al.[924] comment on IXYS’ statements and achievements:

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[921] Op. cit. (Bosch Security Systems GmbH 2016a)
[922] Op. cit. (Bosch Security Systems GmbH 2016b)
[923] Op. cit. (Bosch Security Systems GmbH 2016c)
[924] Freescale Semiconductors/NXP et al. 2015c “Document "7aEx__RoHS_Freescale_Consultation_Response_2015_1015_Final_to_Oeko.pdf", submitted during the stakeholder consultation: Consultation questionnaire,” http://rohs.exemptions.oeko.info/fileadmin/user_upload/RoHS_Pack_9/Exemption_7_a_/7aEx__RoHS_Freescale_Consultation_Response_2015_1015_Final_to_Oeko.pdf

- DBC solution with AuSi die attach material does not address any LHMPS applications besides die attach. AuSi eutectic die attach on a bare copper leadframe may become brittle and unreliable.
- The IXYS solution addresses only THT (through hole technology), but not SMT (surface mount technology) packages.
- Operating power: IXYS only suggests converting LHMPS customers to their DBC alternative in low and medium power ranges, but Freescale/NXP et al. are not aware of a standard industry definition for low, medium and high power products. The IXYS power definition may be specific to their technologies.
- Freescale/NXP et al. agree that the IXYS solution may be reliable for certain applications with very small die size. The 3 x 3 mm die size lacks industry consensus. Vishay tested a gold-silicon solder process and determined the maximum reliable die size to be 0.5 x 0.5 mm rather than 3 x 3mm as indicated by IXYS. Reliable die size for DCB may vary by manufacturing process, equipment, materials and/or power range. Failure points for power and die size are not known.

Freescale/NXP et al.[925] conclude that exemption 7(a) has broad usage for critical applications, but the DCB bonding method can only be adapted to limited applications. It is not obvious that these applications are easily categorized or that they represent a substantial volume of LHMPS reduction. More important, it is very difficult to determine whether a narrowed exemption scope would affect the applications, which really require LHMPS. Freescale/NXP et al. thus contend that the exemption wording should be kept in its present form.

IXYS was asked to comment the above statements. IXYS[926] agrees that gold-silicon DCB is useful for die attach only. There is also risk of brittleness. Concerning the die sizes that can accommodate DCB die attach, IXYS specifies that they spoke of die sizes less than 3 mm, and not sizes equal to 3 mm, which includes the 0.5 mm x 0.5 mm size which Freescale/NXP et al.[927] mention as a reliability limit for DCB.

IXYS' information and product examples show that at least in specific cases, DCB can eliminate the use of lead in LHMPS, but these are restricted to ceramic substrates, and SMT components require LHMPS in the internal interconnects. The discussion between Freescale/NXP et al. and IXYS remains inconclusive with respect to a clear definition of criteria for die attach where DCB can eliminate the use of lead from other die attach cases, where the use of LHMPS is still scientifically and technically impracticable.

[925] Ibid.
[926] Op. cit. (IXYS Semiconductor GmbH 2016b)
[927] Op. cit. Freescale Semiconductors/NXP et al. 2015b

Nevertheless, the consultants proposed a wording for a more specific scope for die attach with LHMPS in the context of a further specification of exemption 7(a) in order to start an in-depth discussion. Since Freescale et al. as well as IXYS speak of power semiconductors in the context of LHMPS required for die attach, an attempt was made to specify the scope of LHMPS in die attach to power semiconductors. IXYS[928] state that power devices should be capable to sustain steady state currents of more than 1 A and/or blocking voltages beyond 200 V with no upper limit. Additionally, Freescale et al.[929] mention Vishay's test results that the maximum reliable die size for DCB is 0.5 mm x 0.5 mm. These criteria were integrated into a wording proposal for die attach for a future exemption 7(a):

> *Lead in high melting temperature type solders (i.e. lead-based alloys containing 85 % by weight or more lead) used for die attach in power semiconductors with steady state currents of more than 1 A and/or blocking voltages beyond 200 V and die edge sizes larger than 0.5 mm.*

Freescale/NXP[930] et al. expressed their principal disagreement with splitting exemption 7(a), but did not comment directly on the wording proposal related to die attach. IXYS[931] agreed to the proposed wording, but Bourns[932] commented that the above wording would exclude several components that require LHMPS for die attach. Bourns was therefore asked to propose a wording that would include all their components where the use of LHMPS is still technically indispensable and came back with a modified proposal[933], which was sent out to all applicants for commenting:

> *Lead in high melting temperature type solders (i.e. lead-based alloys containing 85 % by weight or more lead) used for die attach in power semiconductors with steady state or transient/impulse currents of 1 A or greater and/or blocking voltages beyond 200 V, or die edge sizes larger than 0.5 mm*

Only Freescale/NXP et al.[934] reacted, this time including technical comments directly related to die attach. The core arguments were that the wording mentions

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[928] Op. cit. IXYS Semiconductor GmbH 2015b
[929] Op. cit. Freescale Semiconductors/NXP et al. 2015c
[930] Freescale Semiconductors/NXP et al. 2016b "Answers to first questionnaire to all stakeholders, document "Exe_7a_Questionnaire-1_All-Applicants_2016-02-16_NXP-et-al.pdf", received via e-mail by Dr. Otmar Deubzer, Fraunhofer IZM, from Griffin Teggeman, NXP, on 25 February 2016" unpublished manuscript, Answers to first questionnaire to all stakeholders
[931] IXYS Semiconductor GmbH 2016a "Answers to the first questionnaire to all stakeholders, document "Exe_7a_Questionnaire-1-All-Stakeholders_Reply-Ixys_2016-02-26.pdf", received via e-mail by Dr. Otmar Deubzer, Fraunhofer IZM, from Markus Bickl, Ixys Semiconductor GmbH, on 26 February 2016" unpublished manuscript, Answers to first questionnaire to all stakeholders
[932] Bourns Inc. 2016a "Answers to first questionnaire to all stakeholders, document "Exe_7a_Questionnaire-1_All-Applicants_Bourns_2016-02-16.pdf", received via e-mail by Dr. Otmar Deubzer, Fraunhofer IZM, from Cathy Godfrey, Bourns Inc., on 7 March 2016" unpublished manuscript, Answers to first questionnaire to all stakeholders
[933] Ibid.
[934] Freescale Semiconductors/NXP et al. 2016c "Answers to second questionnaire to all stakeholders,

transient/impulse currents. The inclusion of IMPULSE improves the wording compared to the previous one, but still does not capture all the key criteria driving the LHMPS. Other criteria would include peak transient currents, resistance and the size of the power region within the die. The wording still appears to exclude some products that require LHMPS. The immediately identified indicative examples include Zener diodes with die sizes less than 0.5mm; clip bonded diodes and other products with currents less than 1 A and 200 V and more; SMD diodes or axial diodes with less than 1 A and more than 200 V; SMD or axial diodes with less than 0.5 mm; some triodes for alternating currents or silicon controlled rectifiers with 1 A; and transient suppressors.

Freescale/NXP et al. [935] did not explain why LHMPS would be required in components with die sizes less than 0.5 mm x 0.5 mm despite Vishay's findings, and they did not provide any alternative formulation that would include those components claimed to be excluded in the current wording, nor did they provide information to show that the use of LHMPS in such components could not be avoided.

Based on the above feedback to the wording proposals and the other available information, the consultants conclude that it is currently possible to define criteria for a few individual companies, where the substitution and elimination of lead in LHMPS for die attach is scientifically and technically practicable depending on their product portfolio. It was however not possible to perform this exercise within the available time and resources of the current evaluation due to the multitude and high variety of components and criteria.

For LHMPS used in die attach, Freescale/NXP et al. present past research (DA5, International Rectifier) to substitute or eliminate lead and ongoing efforts planned for the next years. So far, even though progress has been made, no possibilities for elimination or substitution of lead have been reported, so that granting an exemption would be in line with Art. 5(1)(a). This was also the result when these efforts were evaluated in 2015 in the course of the review of exemption 8(e)[936] (the equivalent of RoHS exemption 7(a)) in the Annex of Directive 2000/53/EC (ELV Directive).[937]

The information provided suggests that all research efforts are focused on finding a drop-in solution for LHMPS in die attach, i.e. a lead-free material that can replace LHMPS 1:1. Besides searching for one single solution to accommodate all needs of die attach, research for replacements of LHMPS avoiding the use of lead in specific die attach

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document "Exe_7a Questionnaire-2-All-Applicants_2016-02-16_NXP.pdf", received via e-mail by Dr. Otmar Deubzer, Fraunhofer IZM, from Griffin Teggeman, NXP, on 22 March 2016: NXP answers to questionnaire to all stakeholders" unpublished manuscript,

[935] Ibid.

[936] Gensch et al. 2015 "7th Adaptation to Scientific and Technical Progress of Exemptions 8(e), 8(f), 8(g), 8(h), 8(j) and 10(d) of Annex II to Directive 2000/53/EC (ELV): Report for the European Commission DG Environment under Framework Contract No ENV.C.2/FRA/2011/0020"

[937] Directive 2000/53/EC of the European Parliament and of the Council of 18 September 2000 on end-of life vehicles, ELV Directive, European Union (21 October 2000)

applications could be a further option for progress. The at least partial viability of lead-free solutions like the IXYS DCB-based products show that specific solutions should be taken into account as well, including integrated approaches aligning die attach materials and the overall component design. Further research and new approaches may open possibilities for elimination or substitution of lead, possibly, if applicable also taking into account technologies like TFCB presented by AB Mikroelektronik.[938]

The accessible information suggests that the substitution or elimination of lead is still scientifically and technically impracticable so that granting an exemption would be in line with the requirements of Art. 5(1)(a). The applicants did not provide substantiated information that would have allowed clarifying where and under which conditions DCB is scientifically and technically practicable to replace lead, or why this should not be possible. It can thus not be excluded that the substitution of lead generally is scientifically and technicaly practicable within less than five years. The consultants therefore recommend granting the exemption for three years only, which on the one hand would allow to narrow the scope in order to gradually phase out the use of lead or otherwise clarify why this is scientifically and technically impracticable, and on the other hand still leave sufficient time for industry to apply for the continuation of the exemption should it still be required.

21.4.4 Substitution and Elimination of Lead in Other Applications of LHMPS

The applicants claim that the applications of LHMPS are numerous, and they explain this for various examples in their exemption request. They claim that once the DA5 have identified a solution, which should be a drop-in solution, they will transfer and adapt this solution into other applications using LHMPS (see Section 21.3 – Roadmap for Substitution or Elimination of Lead from page 401).

LHMPS offers the advantage to accommodate all needs of various applications by adapting the lead content of the LHMPS solder. In the consultants' understanding, however, it cannot be concluded that all applications of LHMPS will have a lead-free solution based on the same basic material and technology. The requirements in the various LHMPS applications are different, even though they all use LHMPS at present. For the various applications, different individual or combined properties of LHMPS are relevant to a different degree, and it is reasonable to assume that this requires different alternative solutions and thus also application-specific research to substitute or eliminate lead.

The applicants do not present specific future efforts towards the replacement of LHMPS in the provided example applications of LHMPS besides die attach. They state that they cannot test materials that are not available. In the consultants' opinion, however, this

[938] Op. cit. (TT Electronics/AB Mikroelektronik GmbH 2015a)

situation will continue if no research is started to find materials that can specifically accommodate the needs of particular LHMPS applications.

Based on the information made accessible, elimination or substitution of lead are still scientifically and technically impracticable for LHMPS applications as well as possibly for die attach. As there are no prospects that this situation will change within the next five years, it is recommended to continue the exemption for five years. The applicants will then, however, have to present clear and dedicated research efforts to find specific lead-free solutions for the various applications of LHMPS.

21.4.5 Specification of Exemption 7(a)

According to the RoHS Directive[939] "Exemptions from the restriction for certain specific materials or components should be limited in their scope and duration, in order to achieve a gradual phase-out of hazardous substances in EEE, given that the use of those substances in such applications should become avoidable."

Exemption 7(a) in its current wording has a purely material-specific scope. It allows the use of lead in high melting point solders regardless of where and how these lead-containing high melting point solders (LHMPS) are used. It is thus a priority within RoHS that the scope of both exemptions should be reduced now, where possible, and further in future exemption review rounds through the promotion of research and development of lead-free solutions, as well as through improvements in exemption wording specifications.

21.4.5.1 Consultant's Proposed Rewording of Exemption 7(a)

Based on information provided by the applicants in this review and in previous exemption reviews, the consultants formulated a wording, targeting a scope, which is as narrow as possible to exclude the abuse of the exemption and promote specific research into lead-free solutions. In parallel, the same proposed wording is as wide as necessary to ensure all applications are covered where substitution and elimination of lead is still impracticable. Following two rounds of discussions with the stakeholders[940, 941, 942, 943], the consultants modified their original proposal to the below wording.

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[939] Directive 2011/65/EU of the European Parliament and of the Council of 8 June 2011 on the restriction of the use of certain hazardous substances in electrical and electronic equipment (recast), RoHS 2, European Union (1 July 2011), recital clause (19)

[940] Freescale Semiconductors/NXP et al. 2016b "Answers to first questionnaire to all stakeholders, document "Exe_7(a)_Questionnaire-1_All-Applicants_2016-02-16_NXP-et-al.pdf", received via e-mail by Dr. Otmar Deubzer, Fraunhofer IZM, from Griffin Teggeman, NXP, on 25 February 2016" unpublished manuscript, Answers to first questionnaire to all stakeholders

[941] Knowles et al. 2016a "Answers to first questionnaire to all stakeholders, document "Exe_7(a)_Questionnaire-1_All-Applicants_Knowles-et-al_2016-02-16.pdf", received via e-mail by Dr. Otmar Deubzer, Fraunhofer IZM, from Stephen Hopwood, Knowles Capacitors, on 25 February 2016" unpublished manuscript, Answers to first questionnaire to all stakeholders

[942] IXYS Semiconductor GmbH 2016b "Answers to questionnaire 2, document "Exe-7(a)_Questionnaire-

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

- *a) for internal interconnections in electrical and electronic components, i.e.*
  - *i) for die attach in power semiconductors with steady state or transient/impulse currents of 1 A or greater and/or blocking voltages beyond 200 V, or die edge sizes larger than 0.5 mm*
  - *ii) in components with steady state currents of more than 1 A and/or blocking voltages beyond 200 V other than die attach*
  - *iii) for other internal interconnections in electrical and electronic components excluding those in the scope of exemption 24*
  - *iv) in HID lamps and oven lamps*
- *b) in solder balls for the attachment of ceramic BGA to the printed circuit board (second level interconnect)*
- *c) for the attachment of components to printed circuit boards (second level interconnect) in high temperature plastic overmouldings (> 220 °C)*
- *d) for mounting electronic components onto subassemblies (first level interconnect), i.e. modules or sub-circuit boards*
- *e) as a hermetic sealing material between a ceramic package or plug and a metal case*
- *f) other applications; expires on 1 January 2021 for EEE in cat. 1-7 and 10*

In a final round, this proposal was discussed with the stakeholders[944, 945, 946, 947] again. The following summarizes the applicants' comments.

2_IXYS.docx", received via e-mail from Markus Bickel, IXYS, by Dr. Otmar Deubzer, Fraunhofer IZM, on 21 January 2016" unpublished manuscript,

[943] IXYS Semiconductor GmbH 2016a "Answers to the first questionnaire to all stakeholders, document "Exe_7(a)_Questionnaire-1-All-Stakeholders_Reply-Ixys_2016-02-26.pdf", received via e-mail by Dr. Otmar Deubzer, Fraunhofer IZM, from Markus Bickl, Ixys Semiconductor GmbH, on 26 February 2016" unpublished manuscript, Answers to first questionnaire to all stakeholders

[944] Freescale Semiconductors/NXP et al. 2016c "Answers to second questionnaire to all stakeholders, document "Exe_7(a) Questionnaire-2-All-Applicants_2016-02-16_NXP.pdf", received via e-mail by Dr. Otmar Deubzer, Fraunhofer IZM, from Griffin Teggeman, NXP, on 22 March 2016: NXP answers to questionnaire to all stakeholders" unpublished manuscript,

[945] Knowles et al. 2016b "Answers to second questionnaire to all stakeholders, document "Exe_7(a)_Questionnaire-1_All-Applicants_Knowles-et-al_2016-02-16.pdf", received via e-mail by Dr. Otmar Deubzer, Fraunhofer IZM, from Steve Hopwood, Knowles Capacitors, on 21 March 2016" unpublished manuscript,

[946] Knowles et al. 2016c "Answers to third questionnaire, document "Exe_7(a)_Questionnaire-2_Knowles_2016-03-29.pdf", received via e-mail from Steve Hopwood, Knowles, by Dr. Otmar Deubzer, Fraunhofer IZM, on 4 April 2016" unpublished manuscript,

[947] Bourns Inc. 2016a "Answers to first questionnaire to all stakeholders, document

The applicants[948] disagree with the proposed rewording of RoHS Exemption 7(a). Further, they disagree with the need to reword the existing RoHS-2 exemption 7(a) and they voiced concerns with splitting the exemption into multiple sub-sections. In order to maintain a simple exemption renewal process, they also object to the proposed inclusion of an expiry date for any application that is less than the 5 years allowed under RoHS 2. They further urge Oeko-Institut and Fraunhofer IZM to recommend to maintain consistent wording for RoHS exemption 7(a) and ELV exemption 8(e) based upon the wording included in the related European Commission's draft legislative proposal to amend ELV's Annex II currently under scrutiny by the European Parliament and the Council of the EU.[949]

Freescale/NXP et al. [950] are concerned about the technical complexity to determine, which sub-exemption applies to each homogeneous material, and the lack of incremental environmental, health and consumer benefits resulting from this delineation since alternative Pb-free solutions are not available on the market. Furthermore, they do not believe that any one company or group of companies can currently adequately define the revised wording for a more detailed application and ensure that the new wording accounts for all required uses for LHMPS.

21.4.5.2 Applicants' Alternative Wording Proposals

Below, the applicants[951] attempt to enumerate the primary arguments related to the infeasibility of interpreting and applying the proposed exemption wording as given above:

- The 7(A)a)i structure is STATEMENT1 or STATEMENT2 and/or STATEMENT3 or STATEMENT4. The AND creates logic problems. [952]
- 7(A)a)i mentions "*transient/impulse currents*". The inclusion of "*impulse*" improves the wording in comparison to the prior questionnaire, but still does not capture all the key criteria driving the LHMPS. Other criteria would include *'peak transient currents'*, *'resistance'* and the *'size'* of the power region within the die.[953]
- 7(A)a)i and 7(A)a)ii appear to exclude some products that required LHMPS. The immediately identified indicative examples include Zener diodes with die sizes < 0.5mm; clip bonded diodes and other products with currents ≤ 1 A &

"Exe_7(a)_Questionnaire-1_All-Applicants_Bourns_2016-02-16.pdf", received via e-mail by Dr. Otmar Deubzer, Fraunhofer IZM, from Cathy Godfrey, Bourns Inc., on 7 March 2016" unpublished manuscript, Answers to first questionnaire to all stakeholders

[948] Op. cit. (Freescale Semiconductors/NXP et al. 2016c)

[949] Ibid.

[950] Ibid.

[951] Ibid.

[952] Ibid.

[953] Ibid.

≤ 200 V; SMD diodes or Axial diodes < 1 A and < 200 V; SMD or Axial diodes < 0.5 mm; some triacs or SCRs < 1 A; and transient suppressors.[954]

- 7(A)a)iii must cover LHMPS for all connections within a component, whether they are electrical or nonelectrical. The definition of internal connection does not provide this certainty. Some connections require LHMPS for electrical and / or electronic functions, others for thermal functions, and others for reliability under harsh conditions. As one example, it is not clear that this definition includes a heat shield that is attached to a component with LHMPS to allow subsequent Pb-free step soldering for mounting the component. This heat shield is part of the component when sold.[955]

  Knowles et al.[956] add that from some points of view, an 'interconnect' is only an electrical connection so that the consultants' rewording proposal does not cover a non-electrical connection such as heat sink attachment. They would suggest that 'interconnect' is replaced with 'connection' or simply 'joint'. Knowles et al. ask, whether with regards to the definition of 'internal' – it is meant to include all connections within the space envelope of a single component, or if it only means connections that are hidden internally in the design. They also stress the example of the shielding cover and heatsink assembled onto the top of a ceramic substrate as part of an electronic filter. As the finished component will be surface mounted to a circuit board using Pb free alloys, the cover is soldered in place using LHMP solder alloy with the resulting joint being visible on the outside of the component. The connection to shield the device is made as part of the component manufacture and as such is part of the component and internal to its design, but as the joint is on the outside of the component the term 'internal' for a connection like this could be disputed. Knowles et al. in this case suggest that the reference to 'internal' could possibly be removed or changed to 'integral', covering all joints made as part of the component manufacture.

- 7(A)c) appears to exclude second level interconnections for lead frame products where molding occurs at temperatures ≥ 180°C but ≤ 220°C. [957]

Freescale et al. [958] state that also at the consultants' urging, they reluctantly considered and shared the below preliminary suggestions for a more detailed and functional wording. *None* of the proposals is acceptable to all members of the Freescale/NXP et al. working group. The differences between these proposals indicate a variety of subtle issues that arise when changing the exemption wording.

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[954] Ibid.
[955] Ibid.
[956] Op. cit. (Knowles et al. 2016b)
[957] Op. cit. (Freescale Semiconductors/NXP et al. 2016c)
[958] Ibid.

- 7(a) LHMPS used for internal or external interconnections in or to electrical and electronic components, HID lamps, oven lamps, hermetic sealing materials between a ceramic package or plug and a metal case, or other applications.
- 7(a) Lead in high melting temperature type solders (i.e. lead-based alloys containing 85 % by weight or more lead) used:
  - for combining elements integral to an electrical and electronic component, including a functional element with a functional element; or, a functional element with wire/terminal/heat sink/substrate, etc.;
  - for mounting electronic components onto sub-assembled modules or sub-circuit boards;
  - as a sealing material between a ceramic package or plug and a metal case;
  - other applications.
- 7(a) Lead in high melting temperature type solders (i.e. lead-based alloys containing 85 % by weight or more lead) used for:
  - internal interconnections within electrical and electronic components;
  - die attach;
  - plastic overmoulding;
  - ceramic BGA;
  - high power applications;
  - solders for mounting electrical and electronic components onto sub-assembled modules or sub-circuit boards;
  - solders used as a hermetic sealing material between a ceramic package or plug and a metal case;
  - HID lamps and oven lamps.
- 7(a) Lead in high melting temperature type solders (i.e. lead-based alloys containing 85 % by weight or more lead) used:
  - for internal interconnections in electrical and electronic components;
  - in HID lamps and oven lamps;
  - in solder balls for the attachment of ceramic BGA to the printed circuit board;
  - for the attachment of components to printed circuit boards in high temperature plastic overmouldings;
  - for mounting electrical and electronic components onto subassemblies;
  - as a hermetic sealing material between a ceramic package or plug and a metal case; or
  - in other applications.

21.4.6 Conclusions

21.4.6.1 Continuation of Exemption 7(a)

The information made available to the consultants suggests that the substitution and elimination of lead in LHMPS generally is still scientifically and technically impracticable so that granting an exemption could be justified by Art. 5(1)(a).

The applicants present future efforts towards the substitution or elimination of lead in die attach. Such clear perspectives for future efforts are missing for other application examples of LHMPS, which the applicants present in their exemption request. Lead-free solutions for die attach are, however, available at least for some smaller die sizes where the applicants did not provide a sound justification as to why these lead-free solutions may or may not be generally practicable to a degree that would allow narrowing the scope of the exemption for the use of LHMPS in die attach.

The consultants therefore recommend explicitly mentioning die attach in the wording of Exemption 7(a) and to renew the exemption for die attach for three years.

For the use of LHMPS in high power transducers, the consultants can understand that substitution of lead via design changes is possible in some cases but not in others. In this application, the information submitted plausibly explains that LHMPS is currently still required, but the actual status of the redesign efforts remains unclear, and the substitution and elimination of lead may become scientifically and technically practicable within less than five years. Granting the exemption for five years would therefore not be in line with the stipulations of Art. 5(1)(a), and it is consequently recommended to re-evaluate the situation in three years.

To cover the manifold other uses of LHMPS that could not yet be specified, the consultants recommend adding a third clause exempting the use of LHMPS in all applications others than die attach and high power transducers.

Exemption 24 covers the use of lead-containing solders including LHMPS for the soldering to machined through hole discoidal and planar array ceramic multilayer capacitors. This application of LHMPS should be excluded from exemption 7(a) to avoid overlapping scopes of exemptions. The consultants propose different options for the wording of exemption 7(a) depending on whether or not the Commission decides to renew exemption 24 as recommended or to include it within the scope of exemption 7(a) (for details please refer to the review of exemption 24).

21.4.6.2 Further Specification of Exemption 7(a)

The discussion related to the consultants' rewording proposal for exemption 7(a) shows that a consensus on the technical details of such a rewording proposal requires further exchange with the various stakeholders to clarify the architecture and the definitions of terms. Obviously, the alternative proposals of Freescale/NXP et al. and the contributions of Knowles et al. also require further discussions to achieve a technical consensus among the stakeholders. The limited time and resources available for the review of this exemption did not allow further discussions with the applicants and other stakeholders. The above proposals and discussions can however, be a basis to a further specification of

Exemption 7(a) in a future review taking into account the then achieved status of elimination and substitution of lead.

In the consultants opinion, the slightly modified rewording proposal recommended in Section 21.5 for the time being is a first step towards a specification of exemption 7(a) maintaining the clarity of the wording, taking into account the applicant's current and future research efforts and narrowing the scope to phase out the use of lead.

In case the Commission would like to follow the stakeholders' principal arguments against any rewording of Exemption 7(a), it is recommended to grant the exemption in its current wording for three years.

21.5 Recommendation

21.5.1 Wording of Exemption 7(a)

The information made available to the consultants suggests that the substitution and elimination of lead in LHMPS generally is still scientifically and technically impracticable so that granting an exemption could be justified by Art. 5(1)(a).

For die attach, the applicants do not provide a sound justification why available lead-free solutions for small dies may or may not be generally practicable.

The use of LHMPS in high power transducers can at least partially be avoided via design changes. While the applicant plausibly explains that LHMPS is currently still required, the actual status of the redesign efforts remains unclear. It is consequently recommended to re-evaluate the situation in three years.

The consultants therefore recommend granting Exemption 7(a) for die attach and for the use of LHMPS in power transducers for three years. A period of five years would not be in line with Art. 5(1)(a) since substitution or elimination of lead at least partially may become scientifically and technicaly practicable within the next five years.

A further specification of Exemption 7(a) to better reflect the broad range of LHMPS applications and to exclude abuse of the exemption is currently not yet possible. The consultants therefore recommend to add a general clause allowing the use of LHMPS in all applications others than in die attach and in high power transducers, and to grant this part of the exemption for five years because there is no prospect that lead-free solutions will become available within the next five years. The applicants should by then present dedicated research efforts to find specific lead-free solutions for the various applications of LHMPS.

The use of LHMPS in Exemption 24 should be excluded from exemption 7(a) to avoid overlapping scopes of exemptions. The consultants propose the below wording options of exemption 7(a) depending on whether or not the Commission decides to renew exemption 24 as recommended or to include it within the scope of exemption 7(a) (for details please refer to the review of exemption 24).

Exemption 7(a)		Expires on
I)	*Lead in high melting temperature type solders (i.e. lead-based alloys containing 85 % by weight or more lead)*	*21 July 2021 for medical equipment in category 8 monitoring and control instruments in category 9* *21 July 2023 for in vitro diagnostic medical devices in category 8* *21 July 2024 for industrial monitoring and control instruments in category 9*
Lead in high melting temperature type solders (i.e. lead-based alloys containing 85 % by weight or more lead)		
Recommended wording if the Commission decides to renew exemption 24 as recommended:		
II)	*in all applications not addressed in items III and IV, but excluding applications in the scope of exemption 24*	*21 July 2021 for categories 1 to 7 and 10*
III)	*for die attach*	*21 July 2019 for categories 1 to 7 and 10*
IV)	*for electrical connections on or near the voice coil in power transducers*	
Alternative wording, if exemption 24 is not renewed:		
II)	*in all applications not addressed in items III, III and IV*	*21 July 2021 for categories 1 to 7 and 10*
III)	*for die attach*	*21 July 2019 for categories 1 to 7 and 10*
IV)	*for electrical connections on or near the voice coil in power transducers*	
V)	*in solders for the soldering to machined through hole discoidal and planar array ceramic multilayer capacitors*	*21 July 2021 for categories 1 to 7 and 10*

21.5.2 Applicants' Statements Concerning the Split of Exemption 7(a)

Bourns, Freescale/NXP et al. and Knowles et al. raised concerns on a splitting of exemption 7(a). These arguments refer to the proposed rewording with a more detailed split presented in chapter 21.4.5412. The consultants would like to nevertheless present those arguments, as they may also apply to the above proposed moderate rewording of exemption 7(a), as the split proposed above was not subject to further discussion in light of the lacking time and resources. The arguments of Freescale/NXP et al. are listed below as representatively reflecting the applicants' concerns.

Bourns, Bosch, Freescale/NXP et al. and Knowles et al. advocate the renewal of exemption 7(a) with its current wording. Freescale/NXP et al.[959] mention that the EEE industry and automotive industry have an extensive overlap in their supply chains. They

[959] Op. cit. (Freescale Semiconductors/NXP et al. 2015a)

would recommend that the EU maintain consistent wording between RoHS exemption 7(a) and ELV exemption 8(e) where feasible. [960]

According to Freescale/NXP et al.[961], splitting the exemption will not eliminate existing functional requirements for LHMPS, nor will it improve the availability of Pb-free alternatives. They are not aware of readily available and manufacturable Pb-free HMPS with the required melting points, conductivity, ductility and reliable performance. The proposed changes to the wording would likely divert resources to rework the existing EEE material content reports and conformity declarations in support of CE certifications. This might reduce resources investigating technical solutions.[962]

Furthermore, they[963] believe an application list of OEM EEE end-uses for LHMPS is not feasible. The supply chain cannot link LHMPS to all EEE applications or intended uses. Freescale/NXP et al.[964] do not understand the benefit of increasing the complexity of this exemption. They see no evidence that the language change will reduce the amount of lead placed on the EU market in the coming five years. LHMPS is a lead solder. LHMPS already represents a tangible application. They believe the existing wording already defines an application for upstream users (i.e. LHMPS). The proposed changes to the wording would increase the complexity for certifying and verifying compliance, resulting in increased errors. It would create challenges for regulatory compliance. [965] [966]

In case the Commission would like to follow the applicants' arguments, it is recommended to continue the current exemption for a minimum of three years period.

21.6 References Exemption 7(a)

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[960] Op. cit. (Freescale Semiconductors/NXP et al. 2015a)
[961] Op. cit. (Freescale Semiconductors/NXP et al. 2016b)
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A.5.0 Appendix 5: Exemption 7(a)

A.5.1 DA5 Research for Alternatives to LHMPS Die Attach

All information provided in this chapter is taken from the exemption request of Freescale/NXP et al.[1960] The numbering of the figures starts with “Chart2” like in the original document.

“Looking specifically at high-lead solder for attaching die to semiconductor packages, in 2Q 2010, Bosch (Division Automotive Electronics), Freescale Semiconductor, Infineon Technologies, NXP Semiconductors and STMicroelectronics formed a consortium to jointly investigate and standardize the acceptance of alternatives for high-lead solder during manufacturing. The five company consortium is known as the DA5 (Die Attach 5), and is actively supporting the demands of the European Union towards reduced lead in electronics.

Evaluations of different materials have been performed within the DA5 consortium together with several material suppliers specific to the die-attach application. This includes four main classes of materials:

- High Thermal Conductive Adhesives,
- Silver-sintering materials,
- TLPS (Transient Liquid Phase Sintering) materials, and
- Alternative solders.

At present, no material has been identified that fulfils the required properties of a replacement material. The slide images below provide a summary of results for the different material classes.

[1960] Op. cit. Freescale Semiconductors/NXP et al. 2015a

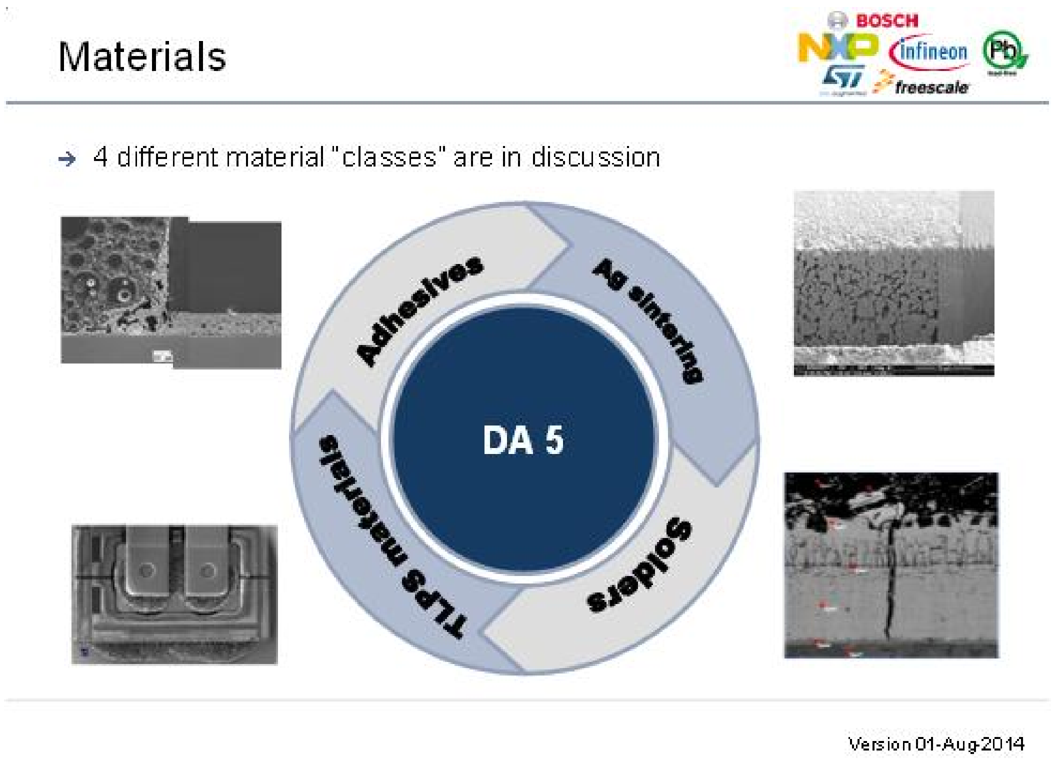


Chart 2: Potential alternative materials

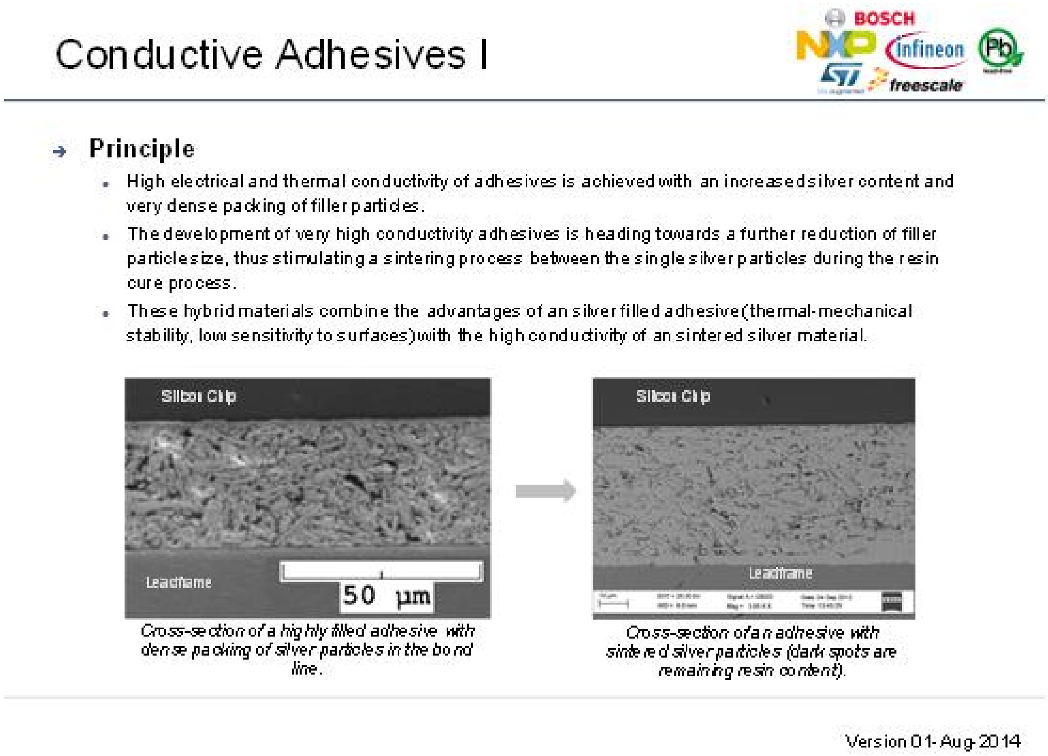
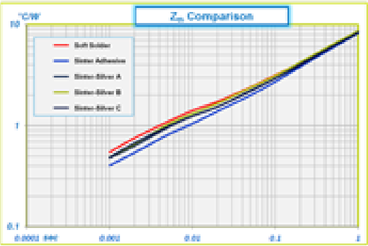


Chart 3: High Thermal Conductive Adhesives I

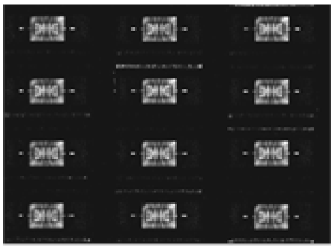
Conductive Adhesives II

Advantages

- Good adhesion to different types of chip backside and leadframe plating.
- Good thermal and electrical performance.
- Common production methods and equipment can be used for the application of the material and placement of the chip.
- Curing in box ovens under usual conditions in air or Nitrogen atmosphere.
- Pass automotive environment stress test conditions.



Comparison of transient thermal resistance of highly silver filled adhesive vs. high-lead soft solder and sintered silver materials.



Scanning acoustic microscopy shows no delamination of die attach after 2000cycles TC -50°C / +150°C.

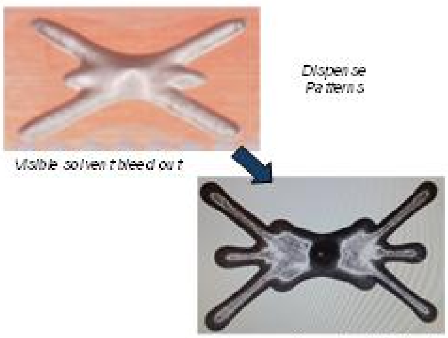
Version 01-Aug-2014

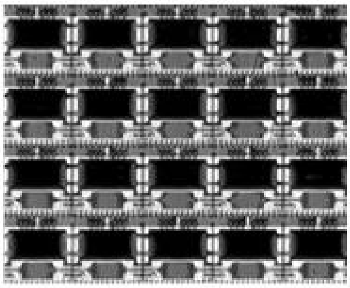
Chart 4: High Thermal Conductive Adhesives II

Conductive Adhesives III

Limitations

- Adhesive can contain solvents to improve rheology. This requires more careful handling and control of the manufacturing process. It also bears a risk of leadframe and die surface contamination.
- Material cost is higher compared to standard adhesives and solder.
- Application is limited to low and medium power devices and packages with moisture sensitivity level of MSL3/260°C.





Scanning acoustic microscopy shows delamination of large power transistor die attach after 1000cycles TC -50°C / +150°C

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Chart 5: High Thermal Conductive Adhesives III

In general, high thermal conductive adhesives have some favourable properties that may be acceptable for many applications within industry. Adhesives can be a solution for packages which don't need to be exposed to the higher soldering temperature (~400°C soldering temperature versus ~150°C glue curing temperature). E.g. Ball Grid Array (BGA) packages with organic substrates use adhesives for die attach. Adhesives are the typical solution for very thin lead frames (~200µm) due to unacceptable lead frame bending after a high temperature soldering process. In general adhesives have a bigger process window as compared to solder and can be used also for non-metalized chip backsides.

Nevertheless adhesives have severe limitations, especially in terms of performance, that justify the continued use of HMP lead (Pb) solders.

An overview in terms of key performance indicators of high performance adhesives in comparison with HMP lead (Pb) solder shows a significant gap that is still present with solutions available today. Especially for power devices there are major restrictions for the usage of adhesives. The bulk electrical and thermal conductivity of an adhesive is much smaller (<1*10^6 S/m and max. 25W/mK) as compared to a HMP lead (Pb) solder (~5*10^6 S/m and ~50W/mK). This keeps products that are covered with HMP lead (Pb) solder today from converting to conductive adhesives.

- Existing adhesives can only be used for chip thickness >120µm due to glue creepage on the side walls of the chips. Due to performance reasons, new chip technologies tend to go for 60µm or even thinner thickness è HMP lead (Pb) solder required
- Also the chip size for adhesive is limited to ~30 mm^2. This is due to the shrinkage of the glue during curing and thermo-mechanical instability. Mechanical strength is lower compared to HMP lead (Pb) solder (reliability issue).
- Another issue is the worse humidity behaviour of glue during reliability. Moisture uptake of adhesives can lead to moisture-induced failure during reflow soldering (MSL).
- Adhesives can't be used for products with a high junction temperature (>175°C). At such high temperatures the organic components of the glue tend to degrade.
- Conductive adhesives are based on an Ag/organic matrix. Ag tends to migrate under voltage and humidity. Higher power density increases the risk of electro migration.

As of mid 2014, the DA5 are not aware of any solution (glue or other materials) that can replace HMP lead (Pb) solder at the moment. The limitations of adhesives are detailed above. HMP solders and adhesives belong to completely different material classes and perform very differently.

The electronics industry naturally works toward eliminating HMP high-lead (Pb) solder because alternatives (e.g. conductive adhesive) are typically easier to manufacture; the HMP lead (Pb) solders are only used when no other options are available that enable the required product reliability and functionality.

The necessary uses for the exemption are outlined within Table 2, above. These applications require HMP lead (Pb) solder to reduce stress, to maintain reliability when subsequent temperatures after initial application exceed 250°C to 260°C, to achieve special electrical or thermal characteristics during operation due to electrical or heat conductivity, or to achieve reliability in temperature and power cycles.

Pb free adhesive alternatives that are available on the market today are not feasible for the types of products and applications where HMP solders are used.

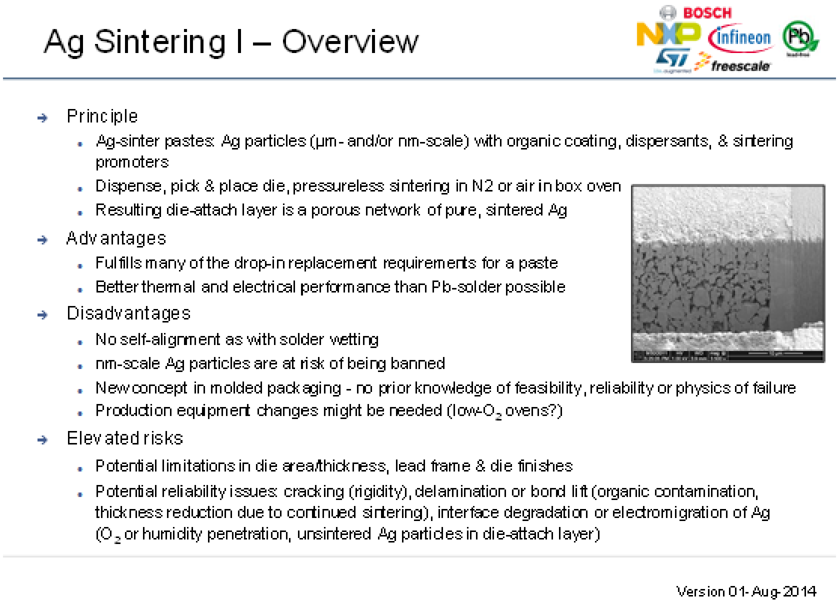

Chart 6: Silver Sintering I – Overview

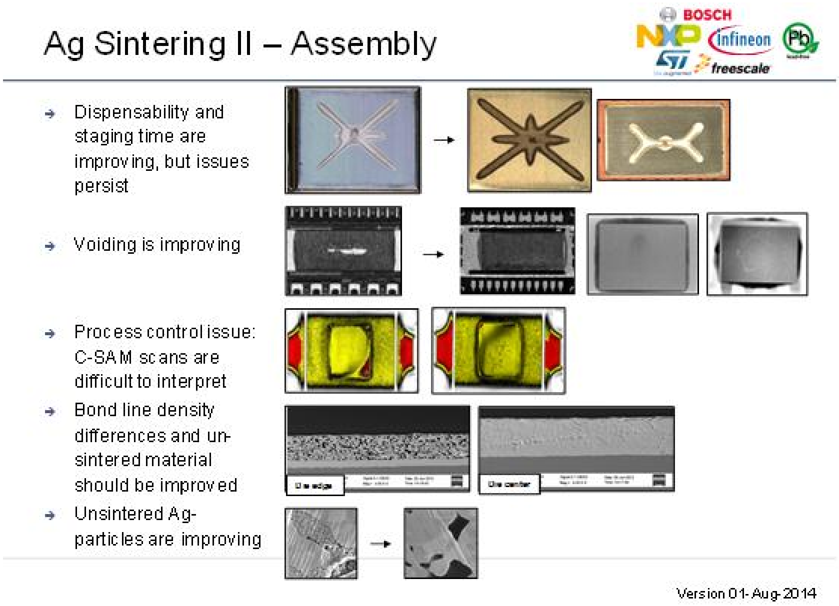

Chart 7: Silver Sintering II – Assembly

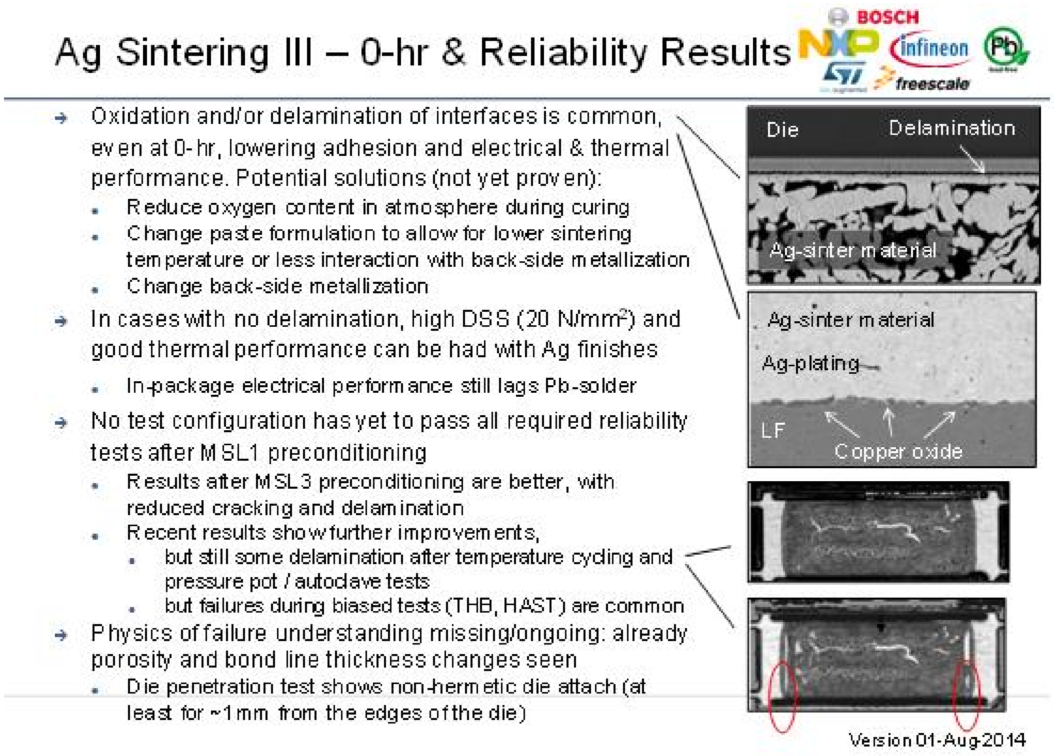

Chart 8: Silver Sintering III – 0-hr & Reliability Results

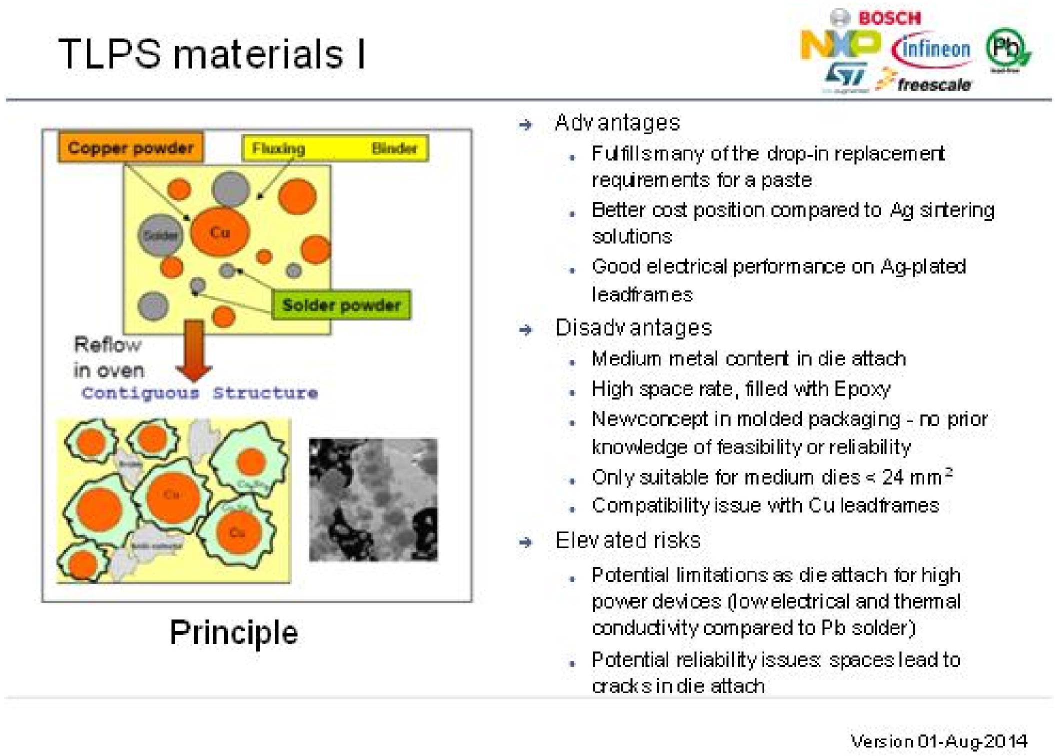

Chart 9: TLPS Materials I

TLPS material II

- The hybrid material showed a very high space rate. The spaces are filled with epoxy material
- The reflow process is very critical and has to be further optimized, the reflow profile seems to be product specific
- Reliability results are contradictory. Results are package/leadframe material dependant. A low space rate is mandatory to survive reliability
- Shear values at 260°C are low, barely above the minimum needed value (5N/mm²)
- Strong brittle intermetallic phase growth with Cu

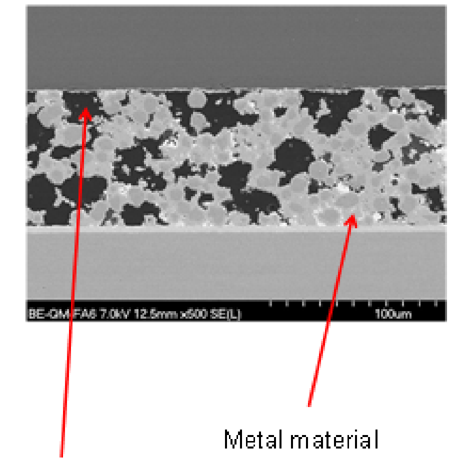

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Chart 10: TLPS Materials II

Alternative Solders I

Properties to be considered

- Robust manufacturing process
  - Repeatable solder application
  - Stable wetting angle
  - Surface compatibility (chip backside, lf finish)
- Reliability
  - Voiding / cracking / disruption after stress
  - Growth of brittle intermetallics at high temperature
  - Disruption during temperature cycling

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Chart 11: Alternative Solders I

Alternative Solders II

- Zn-based Alloys
  - Improved workability demonstrated
  - New formulations demonstrate lower mechanical stress and reduced die cracking, still further improvement required
  - Limited experience on reliability
  - Risk of Zn re-deposition can only be falsified in high-volume manufacturing
  - Material currently only available in wire form
- Bi-based Alloys
  - Low thermal conductivity & low melting point
  - Performance minor to high lead solder
- SnSb-based Alloys
  - Low melting point (new formulations show possible increase)
  - Workability challenging (increased voiding)
  - Limited surface compatibility (chip backside, leadframe finish)
  - Limited experience on reliability
  - Material currently only available in paste form

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Chart 12: Alternative Solders II

DA5 Conclusion on Alternative Solders: Although we find no mass market alternatives to HMP lead (Pb) solder, there are a few candidate materials in initial production as part of the long term manufacturability development efforts.

The DA5 customer presentation listed two potential alternative candidate materials based solely upon melting temperature evaluations in Chart 17 (below): Sn25Ag10Sb and Au20Sn. Considering only the brittleness and melting temperature, these alternative solders might be technically feasible – but only for very small die size when constraining die thickness, package geometry and surface materials.

KPI for Alternatives to HMP lead (Pb) Solders: As seen in the preceding charts, the DA5 evaluated the likely alternatives to HMP lead (Pb) solder against the required capabilities. The DA5 documented the suppliers and technical details for various alternatives within each alternative material category. The material suppliers prevent disclosure of this information due to their NDA with each DA5 company. The comparative strengths and weaknesses of the best tested material in each class are show in the following Key Performance Indicator charts.

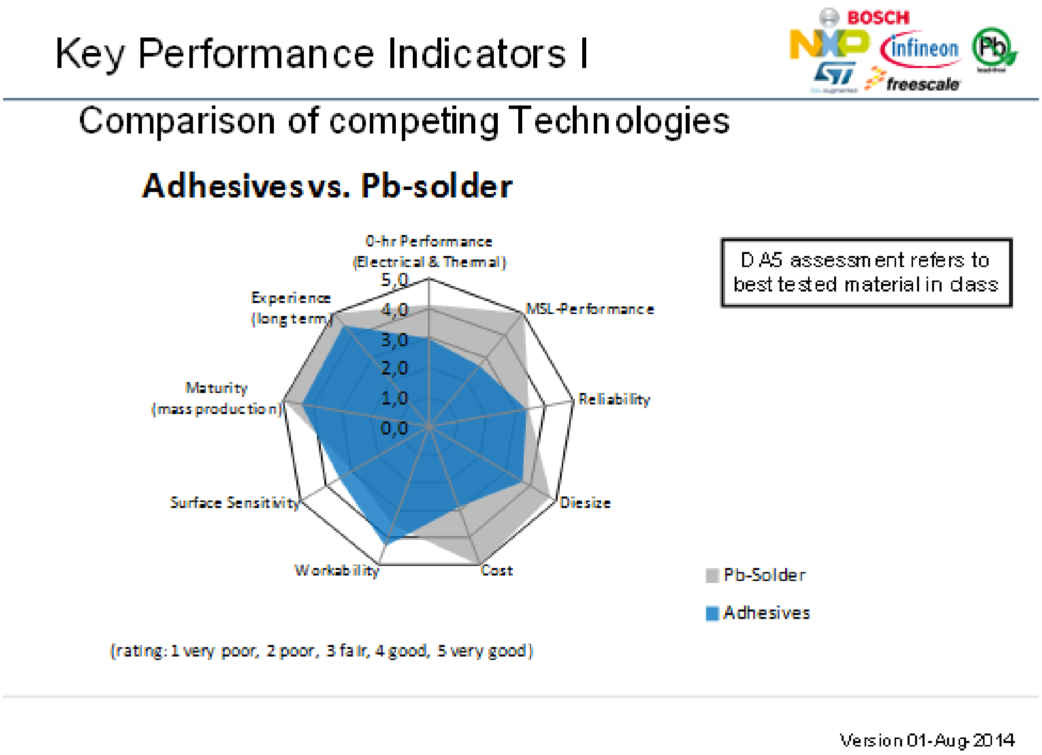


Chart 13: KPI-1 for Adhesives vs. Pb-solder

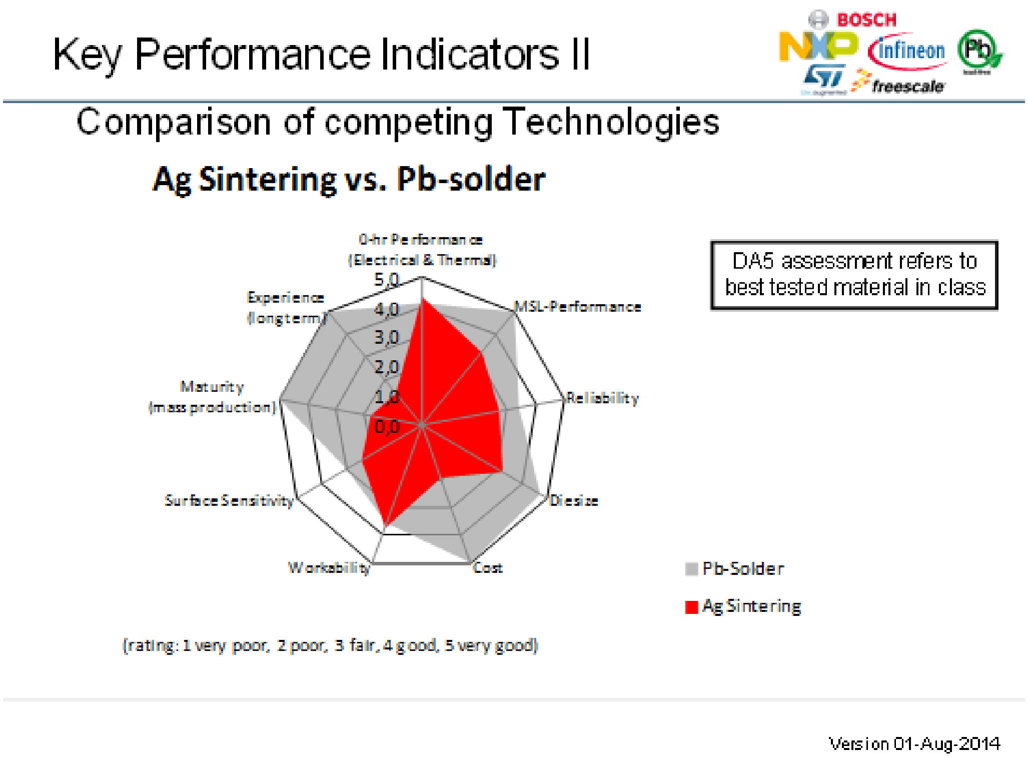


Chart 14: KPI-2 for Silver Sintering vs. Pb-solder

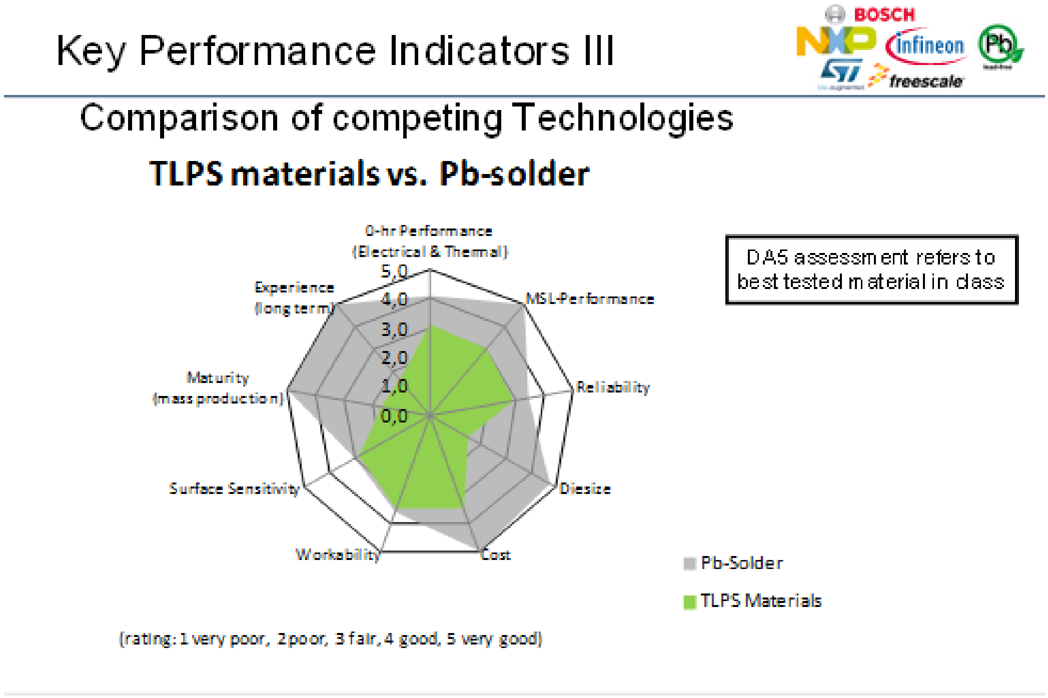


Chart 15: KPI-3 for Transient Liquid Phase Sintering (TLPS) vs. Pb-solder

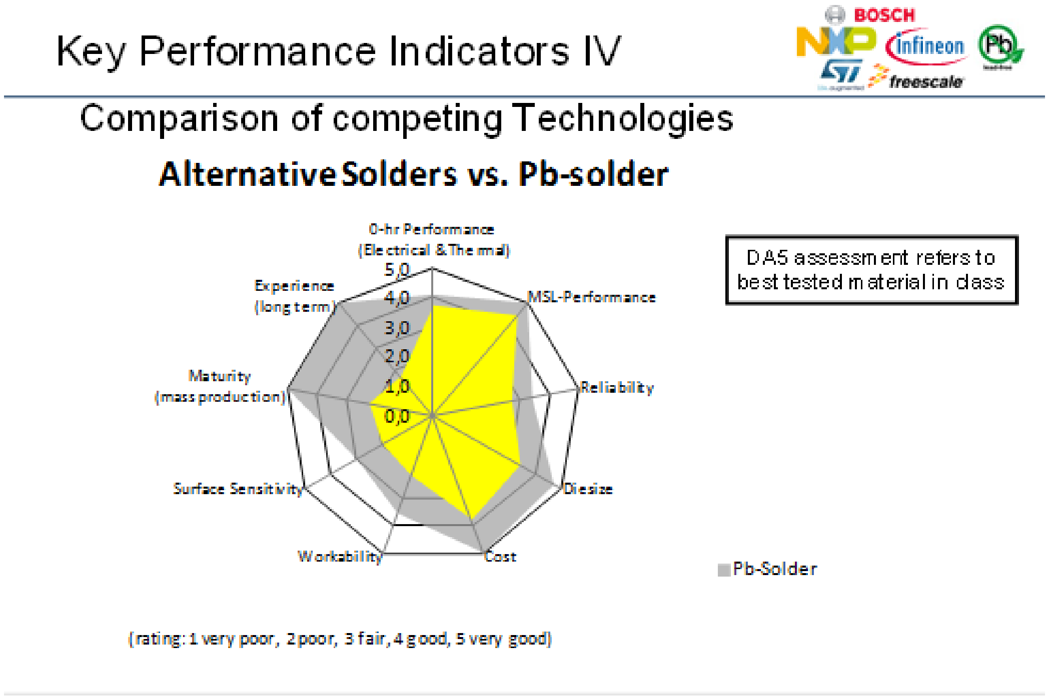


Chart 16: KPI-4 for Alternative Solders vs. Pb-solder

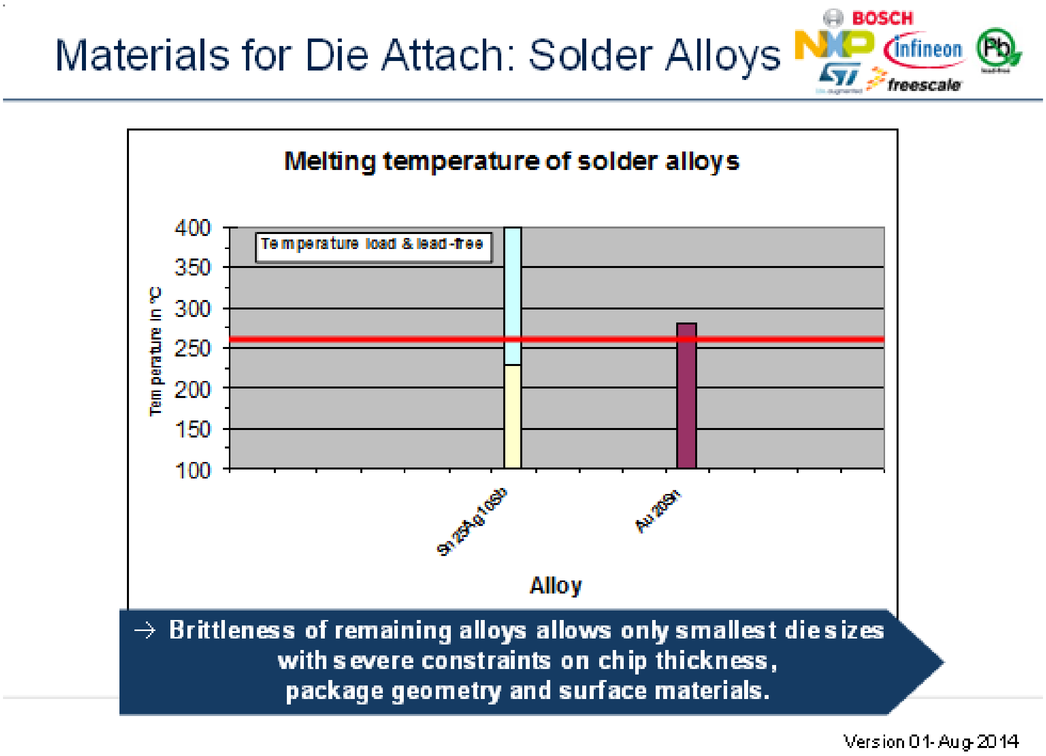


Chart 17: Melting Temperature of Solder Alloys

As noted in Chart 17, DA5 experience has shown that die size and melting temperatures are not the only requirements for alternative Pb-free solders. Additional design restrictions on chip thickness, package geometry and surfaces have to be carefully optimized to make such materials work at all. Optimization is difficult due to unfavorable mechanical properties of the die attach materials, like brittleness. Conversion would only be possible for new semiconductor products:

(1) that are specifically designed for these materials,

(2) where manufacturing processes and equipment have been designed and developed to support the change, and

(3) where the application can accept the material related limitations (e.g. design, functionality, reliability and/or manufacturability).

The resulting new semiconductor design will not be compatible with all customer applications.

In summary, the DA5 evaluation of alternatives to HMP lead (Pb) solder die attach materials determined that no current alternative solder materials can maintain product system performance and pass all qualification tests.

DA5 Note and Conclusion about Conductive Die Attach Films (CDAF): This alternative has not been mentioned in the DA5 evaluations above as an alternative for HMP lead (Pb) solder in die attach, although it is used as a die attach material in some products. Conductive Die Attach Films (CDAF, conductive glue prepared as a tape) are used to replace conductive glue but not to replace HMP lead (Pb) solder.

These conductive tapes are mainly used where clearance between die dimensions and die pad is very small and glue cannot be used due to bleeding which causes some glue constituents to start to migrate on the leadframe. Today, conductive tape is a potential improvement for products that use standard conductive glues. It cannot replace HMP lead (Pb) solder.

The thermal and electrical performance of available tapes is not comparable with HMP lead (Pb) solder. High power devices, particularly the so called "vertical current" devices where significant current flow is driven through the die attach material, would not work with conductive tape. The tape is too resistive and the maximum current that can pass through the tape is much lower than the current capability of HMP lead (Pb) solder.

So for the products which use HMP lead (Pb) solder today, a further exemption is still required. The DA5 evaluations have determined that no feasible alternative is available in the market."

DA5 References:

Latest DA5 Customer Presentation:

http://www.infineon.com/dgdl/DA5_customer_presentation_200813.pdf?folderId=db3a30433162923a013176306140071a&fileId=db3a30433fa9412f013fbd2aed4779a2

DA5 Material Requirement Specification can be provided on request:

Speaker of the DA5 consortium:

Bodo Eilken

Infineon Technologies AG

A.5.2 Efforts of International Rectifier (IR) for LHMPS Substitution

All information in this chapter was taken from Freescale/NXP et al.[1961]

International Rectifier Corporation (IR®) is a world leader in power management technology. Leading manufacturers of computers, energy efficient appliances, lighting, automobiles, satellites, aircraft and defense systems rely on IR's power management

[1961] Ibid.

benchmarks to power their next-generation products. Products range from discrete MOSFETs and IGBTs and high-performance analog, digital and mixed-signal ICs to integrated power systems, IR's innovative technologies.

IR has evaluated numerous suppliers and alternative Pb free high melting point materials to replace HMP lead (Pb) solder. This documentation recently became available to the industry organizations submitting this exemption extension proposal and provides more evidence of difficulties in identifying and qualifying alternative materials to replace HMP lead (Pb) solder. This includes the following Pb-free solders:

SnSb solders: The solidus temperature of SnSb is 235^{o}C and the liquidus is 240^{o}C which is still too low to stop the solder from completely melting during a customer's 260^{o}C reflow process. We did look at solder variants that include SnSb such as J-alloy (SnAg25Sb10) that still have a solidus BELOW 260^{o}C but a liquidus ABOVE 260^{o}C which meant that they would be pastey or partially melted during a customer reflow. This was not successful as the resultant board attach process window was not large enough to allow customers to reliably board mount the components without seeing degradation of the die attach joint internal to the package. IR frequently saw 'solder squirt' with the die attach solder being forced out of the package during board attach.

BiAg solder: Processability and application is limited as it does not form good intermetallics with Cu or Ni. Additionally any intermetallics formed are brittle and weak resulting in reliability fails. The electrical and thermal performance of the BiAg solder is worse than that of the existing solder options containing Pb. The electrical resistivity is 4.5X worse and the thermal performance is 4X worse. On very low rds(on) MOSFETs this can greatly reduce the current rating of a given part resulting in customers having to go for much larger solutions. There are BiAg solders currently being evaluated in the industry which include additives to improve wetting; however, these additives need to remain separate from the BiAg alloy prior to melting, which means that it is only available in a solder paste form. It would not be possible to use on packages that require solder wire or preforms for die attach. The combination of poor electrical and thermal performance and the solder-paste 'only' option means that these newer BiAg versions could be used on is limited and very niche products. The materials are still under investigation at this time.

AuSn solder: This has been around for quite some time in the industry but with limited use. The alloy is over 4X harder than Pb solders which results in a lot more stress being transferred to the die. The hardness causes die cracking problems on larger die sizes and has meant that the application of this material for die attach has been limited to die sizes smaller than many power semiconductors.

At present, no identified Pb-free materials pass reliability tests, especially moisture sensitivity preconditioning. See the detailed analysis slides below.

Introduction

- International Rectifier has been evaluating replacement materials for high lead die attach solder for over five years
- Our internal packaging R&D teams and our Operations teams have worked in collaboration with material vendors and our assembly subcontractors to evaluate all viable options
- We are all working based on an RoHS directive that currently would see an exemption for high Pb die attach solders dropped in June 2016
- Replacement material candidates are evaluated with respect to:
  - Performance
  - Cost
  - Reliability
  - CapEx requirements

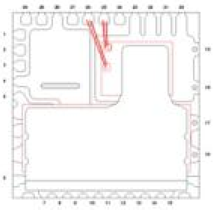
Solder	Solidus / Liquidus temp	Thermal conductivity	Electrical resistivity (uOhm.m)	Elastic Modulus
Pb5Sn	308'C/312'C	35W/m'K	0.19	9GPa

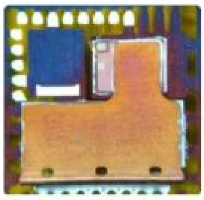
IR International Rectifier 2

Slide 1: Pb Free Evaluation Introduction

Project Test Vehicle

- **Test vehicle is IR3550MPBF**
  - 6x6 PQFN
  - Includes 2 FETs (Q1 and Q2) and 1 IC (U1)
  - Q1 mounted face up on leadframe, Q2 mounted face down
  - Cu clip connects source of Q1 to drain of Q2
  - Exclude IC from test parts as simplifies test process
- **Reliability Test**
  - MSL3
  - AC 121°C, 100%RH, 96hrs
  - TC -55°C to +150°C, 1000cyc
  - IOL 100°C ΔT_j, 12,000cyc
    - with RDSon shift data gathering





IR International Rectifier 3

Slide 2: IR Project Test Vehicle

Partial Melt Solders

- **5 new Pb free solder materials evaluated**
  - Evaluate performance of high liquidus temp solder vs. MSL @ 260°C
  - All materials have solidus less than 260°C
  - Electrical and thermal performance similar to Hi Pb solder

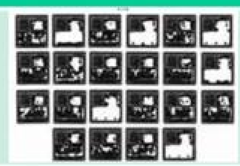
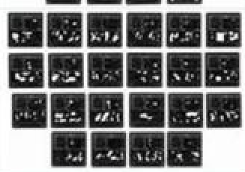
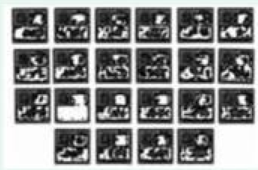
Solder	Solidus / Liquidus temp	Thermal conductivity	Electrical resistivity (uOhm.m)	Elastic Modulus
Pb5Sn	308'C/312'C	35W/m'K	0.19	9GPa
Alloy 1	227'C/300'C	65W/m'K	0.12	47GPa
Alloy 2	228'C/395'C	55W/m'K	0.15	25GPa
Alloy 3	217'C/353'C	55W/m'K	0.13	48GPa
Alloy 4	222'C/384'C	50-55W/mK	0.135	46-50Gpa
Alloy 5	220'C/356'C	50-55W/mK	0.135	46-50Gpa

- Samples assembled using all material options
  - Process optimisation required due to increased solder voids and insufficient solder coverage
  - Test yields all good with Rds(on) in line with existing product
- Samples submitted to reliability testing including MSL3 preconditioning

IOR International Rectifier 4

Slide 3: Partial Melt Solders (1)

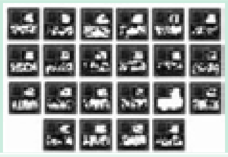
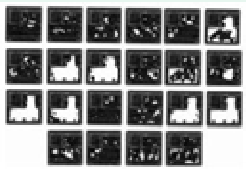
Partial Melt Solders

Solder solidus/liquidus	C-SAM after assembly	C-SAM after MSL3
Alloy 5 220°C/356°C		
Alloy 1 227°C/300°C		
Alloy 2 228°C/395°C		

IOR International Rectifier 5

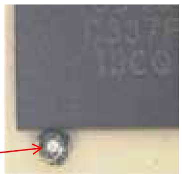
Slide 4: Partial Melt Solders (2)

Partial Melt Solders

Solder solidus/liquidus	C-SAM after assembly	C-SAM after MSL3
Alloy 4 222°C/384°C		
Alloy 3 217°C/353°C		

- In all cases significant die attach paddle and clip delamination observed after MSL3 preconditioning
- Visual inspection of parts show solder squirt from the edge of the package

Die and clip attach solder has squirted out of the side of the package after 3x 260 ° C reflows



IOR International Rectifier 6

Slide 5: Partial Melt Solders (3)

Partial melt solders- Conclusions

- All materials are unsuitable due to failure in MSL preconditioning prior to reliability testing
  - Solders partially melt during 260°C reflow causing massive package delamination and solder squirt
- Materials could be used to replace Pb based solders with little change in process or equipment set used today.
- Final test electrical performance looks acceptable with Rds(on) comparable with Pb based solder.

IOR International Rectifier 7

Slide 6: Partial Melt Solders – Conclusions

Ag Epoxy Materials

IR

- **4 Ag Epoxy Materials evaluated**
  - Electrical and thermal performance comparable with Pb based solders – bulk properties to be confirmed in application

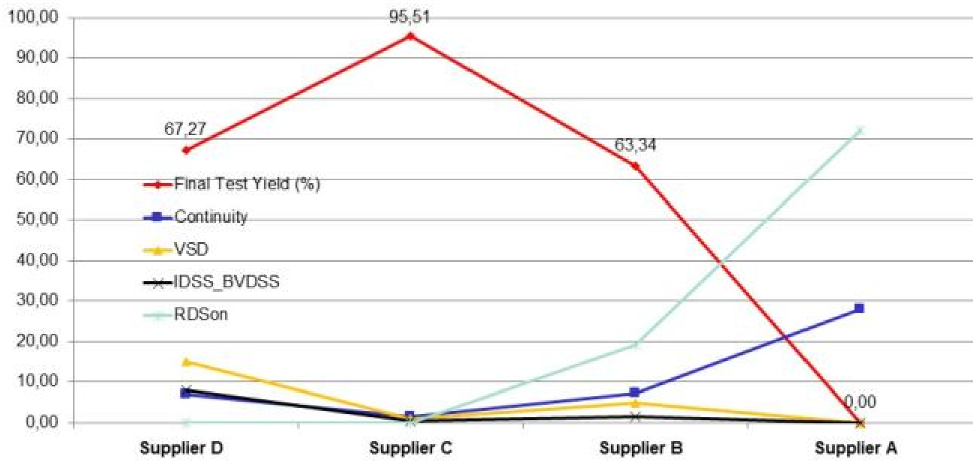
Epoxy	Cure Temp/Time	Thermal conductivity	Electrical Resistivity	Elastic Modulus	Tg	CTE1	CTE2
Supplier A	200°C/30min ramping + 200°C/60min cure	24W/m°K	50µOhm-cm	4.3GPA(25°C) / 1.4GPa(250°C)	44°C	60ppm	150ppm
Supplier B	150°C/30min ramping + 150°C/30min cure + 250°C/40min ramping + 250°C/90min cure	50W/m°K	30µOhm-cm	6.8GPa(25°C) / 5.4GPa(260°C)	63°C	25ppm	45ppm
Supplier C	180°C/50min ramping + 180°C/30min cure + 215°C/15min ramping + 215°C/60min cure	10W/m°K	100µOhm-cm	7.7GPa(25°C) / 0.45GPa(250°C)	-	35	-
Supplier D	230°C/40min raming + 230°C/90min cure	125W/m°K	5µOhm-cm	14.7GPa(25°C) / 8.9GPa(260°C)	100°C	20	50

IR International Rectifier 8

Slide 7: Ag Epoxy Materials

Ag Epoxy Materials – Final Test

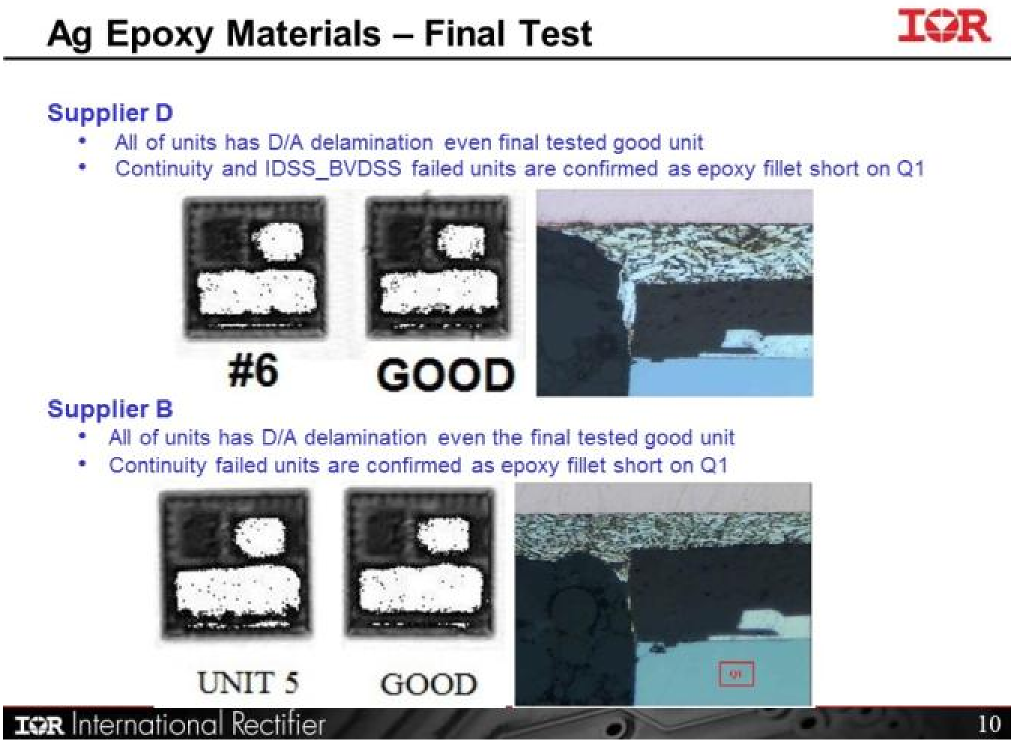
IR



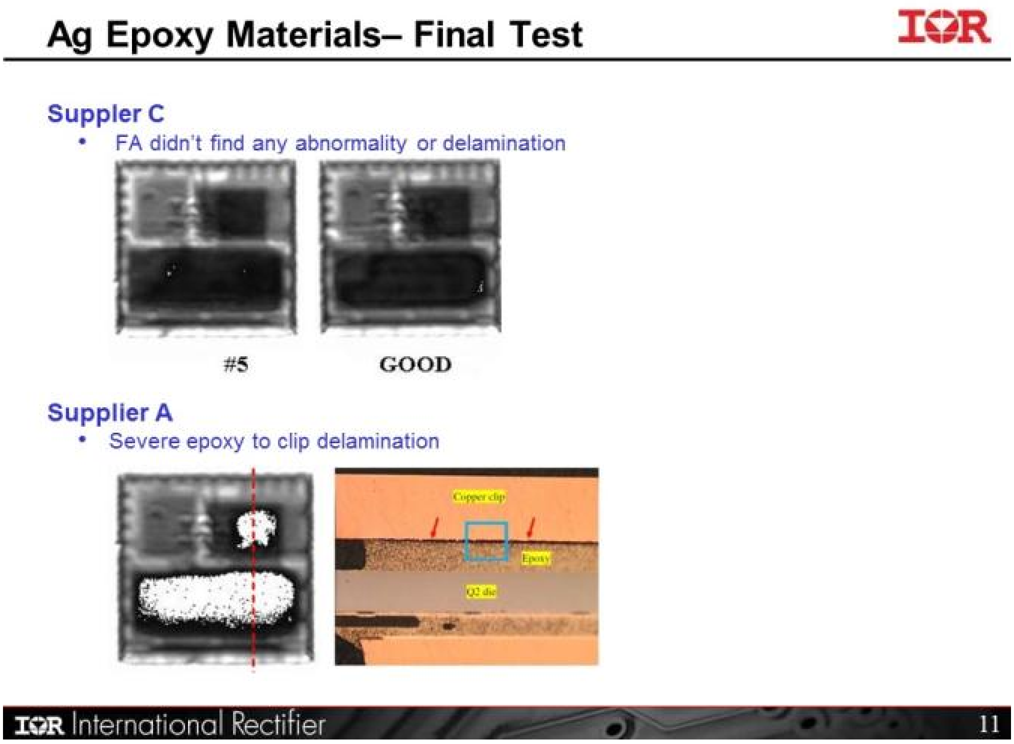
- **Severe Final test yield loss detected except Supplier C material**
  - FA confirmed
    - Continuity and IDSS_BVDSS failure as “Excessive epoxy on Q1 die”
    - RDSon failure as “D/A and Clip Delamination”

IR International Rectifier 9

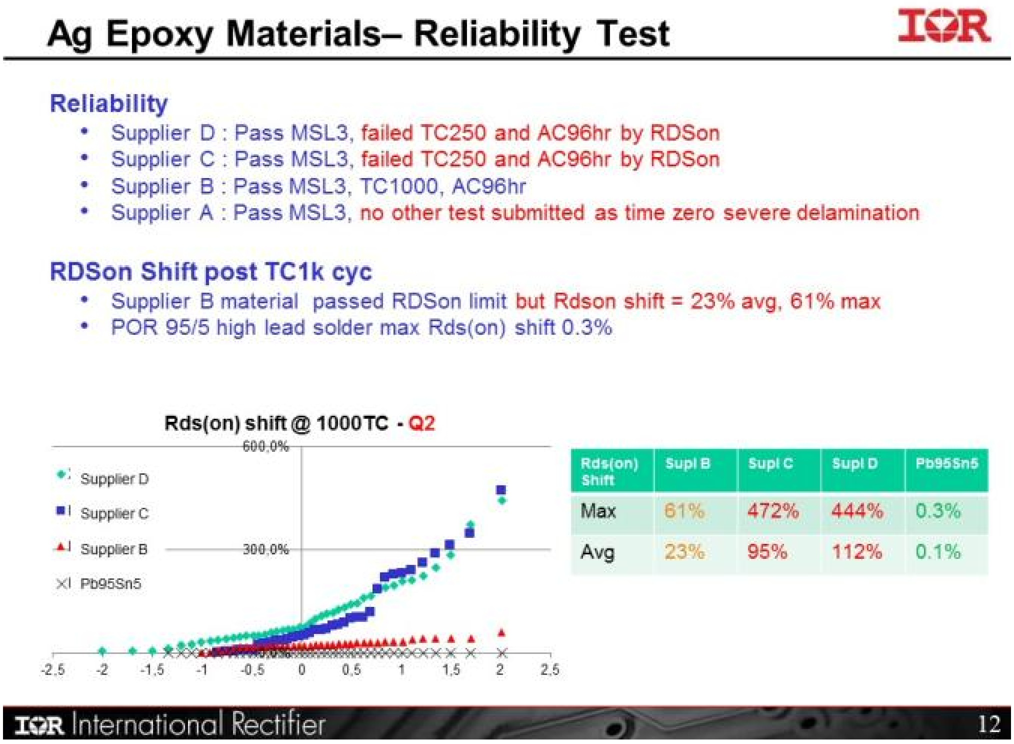
Slide 8: Ag Epoxy Materials – Final Test (1)



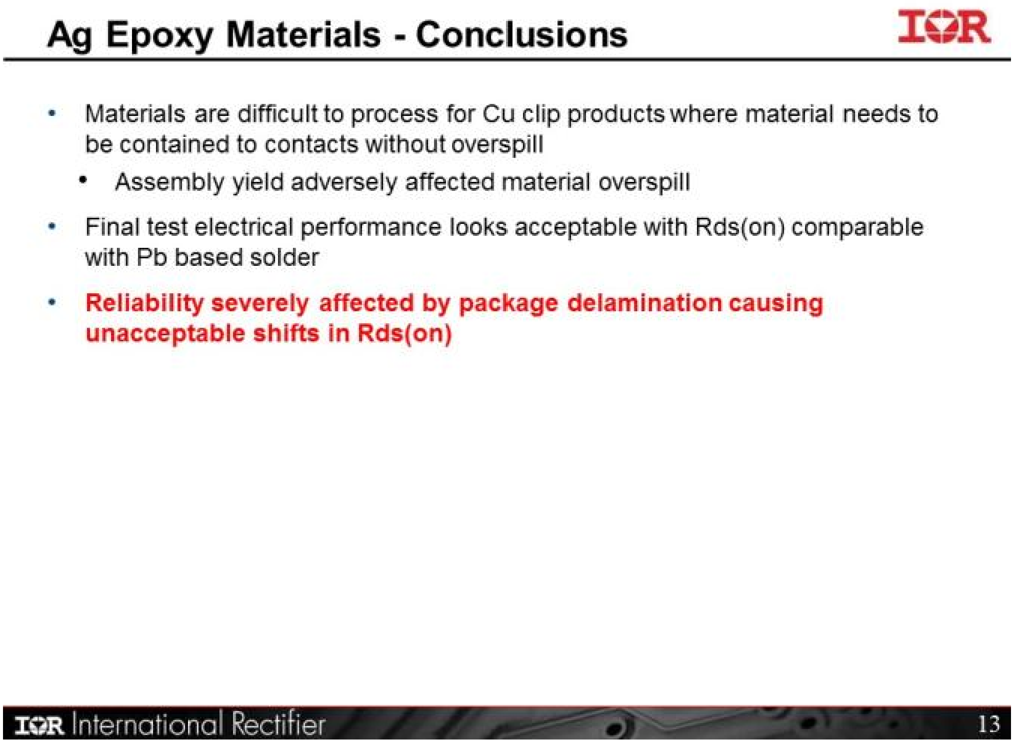
Slide 9: Ag Epoxy Materials – Final Test (2)



Slide 10: Ag Epoxy Materials – Final Test (3)



Slide 11: Ag Epoxy Materials – Reliability Test



Slide 12: IR Ag Epoxy Materials - Conclusions

A.5.3 Timing devices, which are quartz crystals and components including these, like oscillators of all kinds and real time clock modules (RTCs)

According to Freescale et al.[1962], quartz crystal resonators are available in metal cans not using any Pb, but these devices can withstand only lower process and storage temperatures. They require manual soldering due to the lower heat resistance caused by the use of Pb-free low melting solder for the cylinder sealing. However, it has been shown in the past 10 years that this lead-free sealing still bears the risk of tin whisker growth. Tin whisker growth can potentially short parts and has been found in “lead-free” sealed crystals of all manufacturers.

Freescale et al.[1963] explain that manual assembly soldering processes are used in some dedicated industries like in the watch industry. Nearly all other industries however cannot use this manual process due to process compatibility, meaning the compatibility with mounting processes for other components on the complex modules, and reliability reasons as machine soldered joints are more reliable and consistent than manual joints.

According to Freescale et al.[1964], the wider temperature range of SMD assembly/reflow soldering however requires the use of higher solder temperatures which would cause the sealing of low melting solders to leak. These processes require the use of higher temperature cylinder seals based on LHMPS. While manual soldering was quite common many years ago, it is not compatible with modern PCB production machines and would require a manual and thus labor intensive and expensive mounting process not compatible with the process and quality requirements for all other components on conventional PCBs.

Freescale et al.[1965] say that reflow solder processes run on higher temperatures and SMD-mounting requires the cylinder crystals commonly to be mounted on a lead frame by means of a first soldering process before this combination is molded into a plastic and undergoing a final reflow process for mounting onto customers printed circuit board. Due to the fact that the cylinder sealing is exposed to multiple soldering processes including reflow soldering with higher temperatures than manual soldering, the components are thermally more stressed during assembly and thus it is necessary to increase the melting point of the cylinder capsulation (hermetic sealing of the metal cylinder with a plug) in this cases compared to the one where the cylinder is directly hand-soldered onto the PCB. For these cases the use of LHMPS is needed, as no other material has been found so far which combines the high melting point and the mechanical characteristics (i.e. softness and ductility) required to assure prolonged

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[1962] Ibid.
[1963] Ibid.
[1964] Ibid.
[1965] Ibid.

reliable hermetic sealing between the metal cylinder and the plug over a wide temperature range during storage and operation.

Even more, Freescale et al.[1966] state, many applications can't work with a pure crystal, but need an oscillator of some type, i.e. Temperature-Compensated-Oscillators (TCXOs) for GNSS (Global Navigation Satellite System) applications or real time clock modules). In these cases, the hermetically sealed crystal resonator has to be mounted together onto a kind of module with an IC. So the same basic structure and arguments about the multiple soldering processes as mentioned above are valid in this case, as the cylinder crystal (where used) has to be mounted onto a PCB, lead-frame or similar together with the semiconductor before molding.

In other words, Freescale et al.[1967] put forward, LHMPS as sealing material is not only required for cylinder crystals to enable SMD soldering, but as well in widely spread components like RTC modules and others, where an IC and hermetically sealed quartz crystal have to be combined together inside one package/module to achieve desired specifications (e.g. accuracy).

Freescale et al.[1968] claim that metal can crystals with LHMPS cannot be completely replaced by crystals packed into ceramic packages, as the characteristics and covered frequencies are vastly different. The most remarkable differences are (Freescale et al.[1969]):

- Due to the different dimensions (fitting into the packages), the smaller crystals have a significantly different "pullability". This is the capability to change the frequency when external circuit parameters, namely the load capacitance of the oscillation circuit, are changed. This is a feature used to correct the initial tolerance and frequency drift over temperature as well as aging of the crystal and is required to meet standards for wireless and wired communication as well as GNSS applications. The high pullability of larger cylinder crystals is especially important in wide temperature applications like in automotive use, as the frequency temperature tolerance is far larger due to the wider temperature range which has to be covered which consequently needs a wider pulling range (so range in which the frequency can be changed).
- Due to the physical sizes of applicable ceramic packages, the crystals inside ceramic packaged quartzes are smaller compared to the ones inside metal cylinders. The smaller size of the quartz crystal however increases its internal loss (so called "ESR"; electrical serial resistance), thus requires oscillator circuits which can drive significantly more current and thus require more

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1966 Ibid.
1967 Ibid.
1968 Ibid.
1969 Ibid.

electrical energy in operation. As many of this cylinder crystals are used for so called "clock" applications, so using a 32.768 kHz crystal to derive a time signal out of it, these oscillators have to be operated all the time, even while the application is not in use, which would impact the standby and "off" current of applications as required by applicable EU regulations. Power consumption is for several reasons (legislations, enviro nmental, operation time on batteries) very important for nearly all applications. For this reason, nearly all Semiconductor Manufacturers are putting technologies in place to reduce the power consumption of their ICs. As a result, the available energy for the oscillator is going down as well so that many of the latest ICs require extremely low ESR crystals which can use today's technologies and can only be achieved with crystals packed into a metal cylinder due to size reasons as mentioned above.

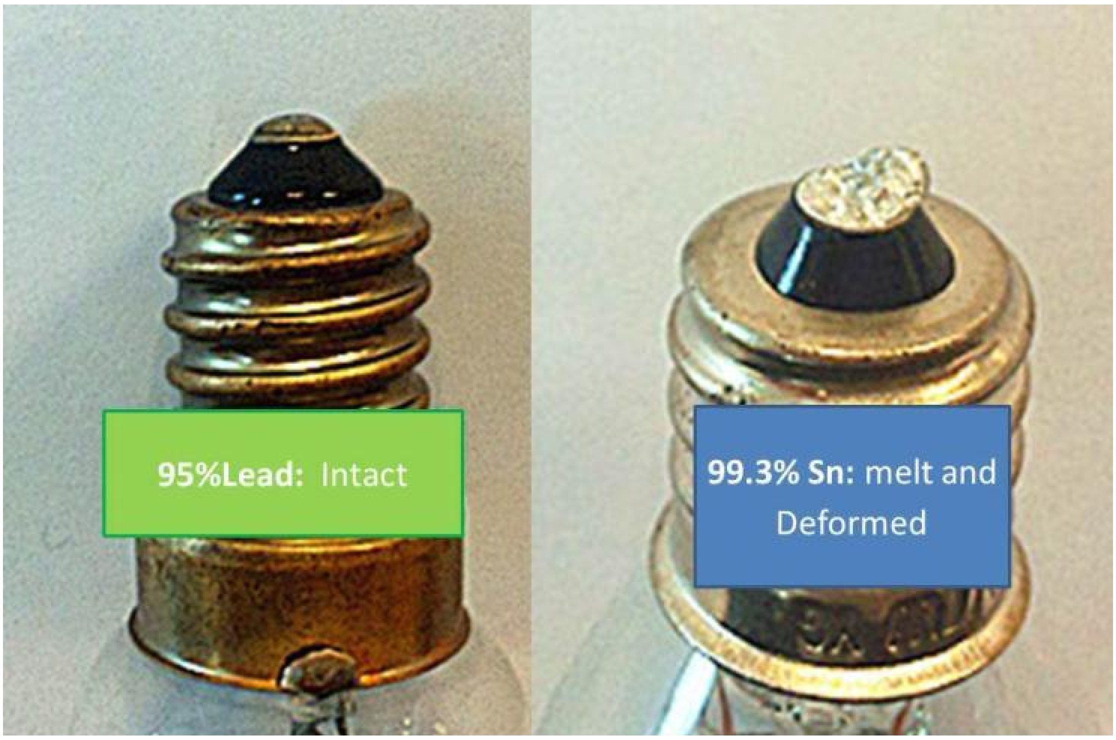
- Since the outer dimensions of the quartz crystal define its resonance frequency, the smaller ceramic packages do not allow to generate rather low frequencies like 4MHz, 6MHz or 8MHz, which however are often used to clock CPUs. Increasing this frequency would require different CPU chips and increase the power consumption in use unnecessarily.

A.5.4 Oven Lamps

Oven lamps are commonly used in many household ovens. Freescale et al.[1970] say that the temperature of the lamp during the baking process can reach 300 ^{C}. Alternative lead-free solders will 'melt' under these conditions. When the solder melts, the lamp fails and the consumer expects to replace the lamp. Lack of compatible replacement bulbs could result in premature oven replacement. The current technology (Incandescent, CFL, LED lamps) has no reliable alternative replacement light source available without LHMPS.

[1970] Ibid.

Figure 34-4: Oven lamp failure



Source: Freescale et al.[1971]

[1971] Ibid.