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LEAD FREE INTERCONNECTION TECHNOLOGY AND THE ENVIRONMENT

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Abstract: Trends of growing consumption, decreasing product lifetime and new application fields in nearly all industry segments lead to an enormous increase of electronics products. The production of raw materials and products, their use as well as the end of life treatment of these products cause considerable environmental impacts. To minimise hazards to human health and the environment, an economic growth in a sense of sustainable development has to be realised and new products and process technologies should proof that they contribute to the solution of global environmental issues.

In this paper the interconnection technologies as key technologies for future products are discussed in correlation to their environmental behaviour. At the present a transition to lead free soldering takes place worldwide. In that respect various environmental aspects of the different lead free interconnection systems (solders and surface finishes) should be compared in order to find the best solution from an ecological point of view.

Tehnologije povezav brez svinca za ohranjanje okolja

Ključne besede: tehnologije povezav, spajkanje brez svinca, zaščita okolja

Izvleček: Trendi povečanja porabe, skrajševanja življenjske dobe izdelkov in nove možnosti uporabe v skoraj vseh vejah industrije, peljejo k velikemu povečanju števila elektronski izdelkov. Proizvodnja surovin in izdelkov, njihova uporaba in nazadnje njihova obravnava ob koncu življenjske dobe, imajo močan vpliv na okolje. Z namenom zmanjšati nevarnost za človekovo zdravje in za okolje, moramo zagotoviti tako ekonomsko rast, ki bo omogočala razvoj takih novih tehnologij in izdelkov, ki bodo prispevala k rešitvi nekaterih globalnih okoljevarstvenih problemov.

V tem prispevku opisujemo tehnologije povezovanja kot ključne tehnologije za bodoče izdelke v povezavi z njihovim vplivom na okolje. Dandanes na svetovnem nivoju poteka prehod na spajkanje brez svinca. V tem kontekstu analiziramo različne sisteme povezovanja brez svinca (spajke in površinske obdelave) z namenom najti najboljše rešitve s stališča varstva okolja.

1. INTRODUCTION

The last 10 years were characterised by an explosive growth of electronics and information technology and this trend continues. Microelectronics and microsystems technology make highly miniaturised products possible with high performance, quality and reliability, and they become more and more important for nearly all product applications in leading industry segments.

However, the present trends of growing consumption, decreasing product lifetime and pervasive distribution are leading to serious environmental issues in respect to electronic products, associated with raw material production, product manufacturing, use of these products and their end of life treatment.

By means of miniaturisation the environmental impact of microelectronic products could already be reduced in some respects. Their material and energy consumption is already small (in a first estimation) and their waste volume, too.

But because of the increasing production numbers the quantity of waste of electrical and electronic equipment (WEEE) with the complex mixture of materials is growing. Estimates suggest that the amount will be doubled in 12 years within the EU. The waste of electrical and electronic equipment (WEEE) grows three times faster than municipal waste. And the recycling of products, which are becoming smaller, is more and more difficult, mainly because of the use of inseparable material compounds. Furthermore, there is a tendency towards material compositions that are less suitable to an economical recycling and the small products are more difficult to collect (the users often put them into the waste bins). Moreover, up to now only around 10 % of all products are taken back and recycled. About 90% of it is landfilled, incinerated or recycled without pre-treatment.

The key technologies for future miniaturized products are the assembly and packaging technologies. At present a transition to lead-free soldering takes place. This process was initially driven by new environmental protection legislation (e.g. RoHS) /1/, however it is now more likely driven by marketing reasons. Despite these particular driving forces, new technologies nowadays must be designed in such a manner, that they not only comply with technical/ technological and economic requirements, but incorporate ecological demands for a sustainable industrial development. That means a EcoDesign or Design for Environment (DfE) has to be implemented.

2. DRIVERS FOR APPLICATION OF ECODESIGN

EcoDesign or Design for Environment (DfE) is a term for a systematic approach to environmentally conscious product development and design. The integration of environmental aspects must take place as early as possible during the planning, development and design process and the aspect "environment" must be added to other classical criteria of product development.

Fundamental to EcoDesign is life cycle thinking, the consideration and minimisation of the environmental impacts in all life phases of a product: the extraction of raw materials for the product as well as the production process, the distribution, the use of the product, its recycling and finally the disposal of product parts.

There are several drivers for companies to integrate DfE in their working flow.

- legal requirements
  For reduction of the environmental impact of electronic products the European Commission has announced three legal directives.
  - The first dealing with take back and recycling/ reuse of waste from electric and electronic equipment (WEEE) /1/.
  - The second restricts the use of certain hazardous substances such as cadmium, mercury and lead from 1.7.2006 on (RoHS) /1/.
  - The third is a directive on the design and manufacturing of electronics (EEE).
- the possibility to reduce the liability risk by avoiding pollutants (risk management)
- the demands of the customers for environmental friendly products, for instance buyers in the public sector (customer value)
- the moving towards a good public image (environmental rating)
- the possibility to save money by reducing consumption of energy and materials or wastes and pollutants (cost efficiency)
- an improvement of the market position by innovative, environmental friendly products (market diversification)
- a larger motivation and commitment of the employees since they can take an interest in the responsibility for their actions (human resources).

In several regions the companies have worked out plans and strategies for integration of DfE in their product policy and established environmental roadmaps. Figure 1 shows as an example such a roadmap of the Japanese electronics industry (JEIDA).

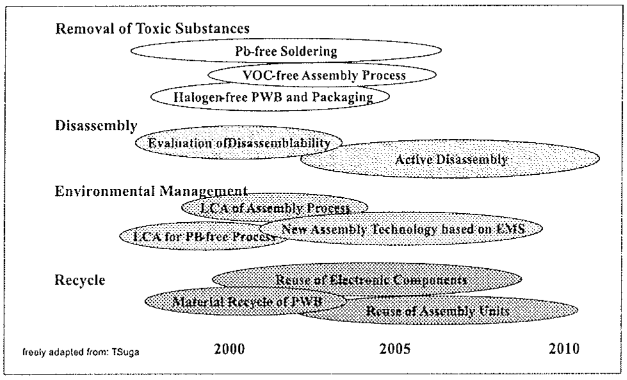

Figure 1: Environmental Roadmap of the Electronics Industry in Japan (JEIDA)

Key points are the removal of toxic substances, the recycling (including disassembly) and the implementation of environmental management systems. For special subjects there are special roadmaps, for instance for the implementation of lead free interconnection systems. The Japanese electronics industry has targeted the full implementation of lead free products not later than 2004/5.

Figure 2 shows a variety of lead free products which are already on the market.

Figure 2: Lead free products

3. ENVIRONMENTAL ASSESSMENT

In order to reduce the environmental impact of their products the industry is looking for tools to assess which products or processes is the best solution from an environmental point of view.

A number of different methods exists for an assessment of the environmental impact of electronic products.

The life cycle oriented approach "from cradle to grave" of products is described in the ISO 14040 and following standards. Balances of material and energy flows as well as emissions are compiled for all processes and aggregated for the product life cycle as production, use and end of life phase including transportation and distribution. The effects are characterized in impact categories like global warming, ozone depletion, acidification, human toxicity and others. Then, the environmental impacts of the emissions and consumption of resources are evaluated and weighted.

These life cycle assessment tools usually require a lot of information about the products components and manufacturing processes. Very often however, are these data not easily accessible. Especially in the case of very complex products, like electrical and electronic products, up to now the life cycle analysis (LCA) is not suitable for a quick assessment and therefore not applicable for optimisation during the design phase.

As for an environmental assessment of lead free products in comparison with conventional products, a whole life cycle analysis is not available at the moment. Two projects were started to carry out a life cycle assessment in the field of lead free soldering, one is the international IMS-project EFSOT with the cooperation of Japanese, Korean and European participants; the another is initiated by the American EPA in the frame of the DfE-project.

However, it is necessary and very important to describe the environmental impact before a new generation of products are mass produced. Simplified assessment methods are suitable to bridge this gap and to get a feeling of how alternative materials for interconnection systems would influence the environmental behaviour of electronic products.

With toolboxes or assessment matrices the environmental properties of a product can be considered from various sites in order to get a broad impression about the environmental impact of the product. In the case of the evaluation of solders and surface finishes, terms such as resource (energy and water) consumption for raw material production and manufacturing, toxicity and leaching behaviour in the end-of-life phase according to the US-American „Toxicity Characteristic Leaching Procedure" TCLP1311 are summarized. By means of the toolbox or the assessment matrices companies can choose which data and which assessment types to concentrate on first and then slowly evolve towards the more comprehensive and time consuming process gathering and evaluating life cycle data for their products.

For an initial screening of products the so called Toxic Potential Indicator (TPI), the essential tool of the Fraunhofer IZM/EE-Toolbox, was used to make a quick environmental assessment in the following cases. This indicator is based on threshold values of the allowable workplace concentration, the water pollution classification and the R-values of the hazardous substances declaration in the EU and is used to evaluate the environmental impact of materials or products by their chemical contents /2/.

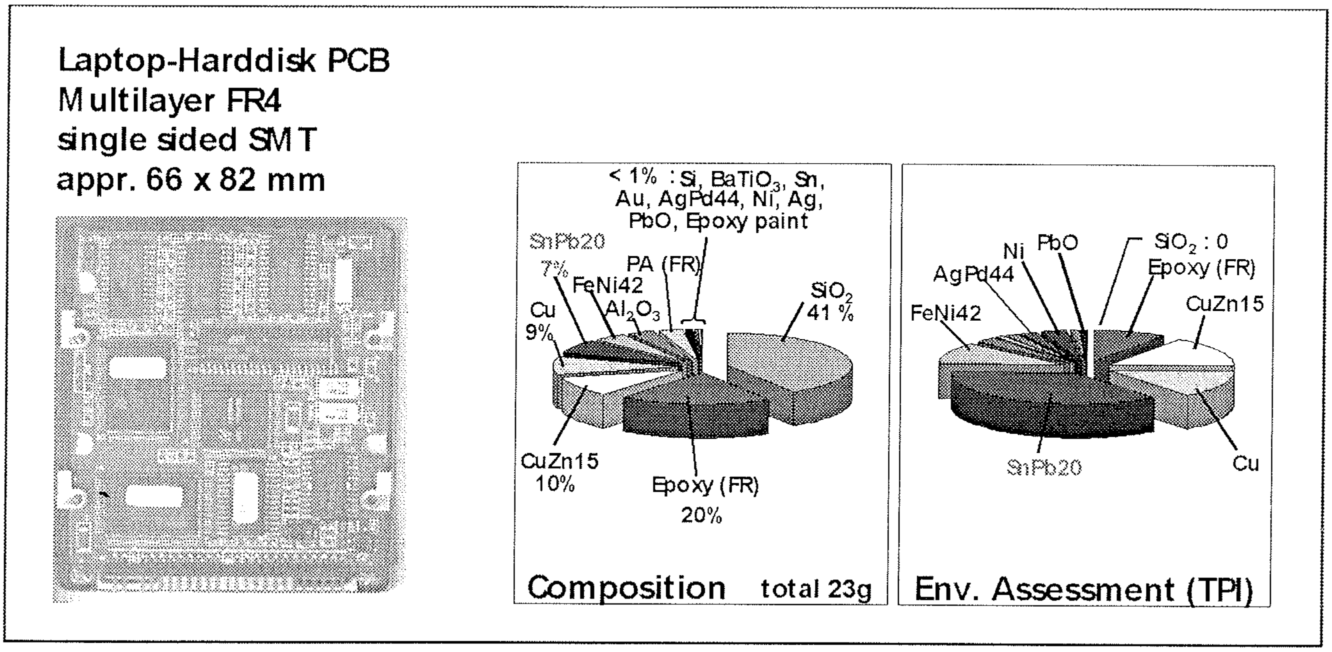

Figure 3: Composition and environmental impact of the materials of a selected PCB

4. LEAD ON PCBs

Even though lead is only used in small amounts on PCBs, due to their toxicity, it is one of the weak points in respect to the boards environmental impact. Figure 3 shows the materials for an PCB example and their parts on the environmental impact regarding the TPI of this PCB. Even though only 7 % of the PCB materials are SnPb it contributes around 25 % to the environmental impact of the this PCB.

With simultaneous consideration of the strongly increased numbers of electronic products, that was one reason for world-wide efforts in research and development to substitute lead in electronic devices.

It has been known for more than a hundred years that lead affects the human nervous system and causes a range of serious problems. Particularly children are concerned.

Most of the lead on PCBs is obtained in the interconnection system consisting of the surface finishes of the board and the component leads or terminations and of course of the solder itself.

Some components such as varistors, thermistors or multilayer capacitors obtain smaller amounts of lead and there are no alternatives at the present. Therefore, a transition to lead free electronic devices has to aim on the most heavily used parts, that will be the solders and surfaces finishes, and replace them.

Not only lead free alternatives (solder and finishes) have to be developed, but highly reliable soldering technologies for interconnects of high quality as well. However, the implementation of a new lead free interconnection technology should not lead to higher environmental burdens. To prevent this, the environmental impact of possible substitutes must be considered during the selection of the new technology.

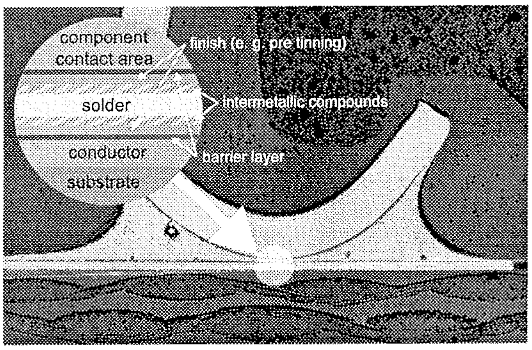

Figure 4: The interconnection system

5. INTERCONNECTION SYSTEM AND THE ENVIRONMENT

Figure 4 shows the interconnection system with the parts which have to be considered: the solder, the finish of the PCB (substrate and conductor) and the component contact area.

State of the art is the application of the eutectic SnPb for solder, Hot Air Solder Leveling (HASL) layers of eutectic SnPb on the PCB in many cases and eutectic SnPb an the components contact area.

5.1 Lead Free Solders

In various projects in Japan, USA and Europe alternative solders to the conventional eutectic SnPb are described from a technical/technological point of view (table 1). Up to now most of the examinations concern the wave soldering processes for the through hole technology and the reflow soldering process for the surface mount technology.

Project /organization	**Recommended solder for**		
	Reflow soldering	**Wave soldering**	**Repair**
ZVEI	SnAg3,9Cu0,6 (217 -219°C)	SnCu0,6 (227°C)	
IDEALS	SnAgCu (eut.:217°C)	SnCu0,7 (227°C); SnAg3,5Cu0,7 (217°C)	SnAg3,5 (221°C)
NEMI	SnAg3,9Cu0,6 (217 -219°C)	SnCu0,7 (227°C); SnAg3 (eut. 221°C)	SnAg3,5 (221°C)
NCMS	SnBi58 (138°C); SnAg3,5 (221°C); SnAg3,5Bi4,8 (205 -210°C)		
Soldertec (ITRI)	SnAg(3,4...4,1)Cu(0,45...0,9) (ca. 217°C)	SnAg(3,4...4,1)Cu(0,45...0,9) (ca. 217°C)	SnAg(3,4...4,1)Cu(0,45...0,9) (ca. 217°C)
JEIDA	SnAg3Cu0,5 (217 -218°C); SnAg(2 -4)Bi(2-6) (205-210°C), SnBi57Ag1 (138°C)	SnAg3Cu0,5 (217 -218°C)	

Table 1: Lead free solders recommended by several organizations/projects for different soldering processes:

ZVEI:	Zentralverband Elektrotechnik- und Elektronikindustrie e.V.
IDEALS:	Improved Design Life and Environmentally Aware Manufacturing of Electronics Assemblies by Lead-Free Soldering (Brite/EuRam Program)
NEMI:	National Electronics Manufacturing Initiative (USA)
NCMS:	National Centre for Manufacturing Sciences (USA)
JEIDA:	Japan Electronic Industry Development Association (now JEITA)

All of the alternative solders are Sn based alloys. Binary and ternary alloys are mostly examined. The melting temperatures - as the most important factor - differ a lot.

At present most of the activities are directed to tin-silver-copper or tin-silver for reflow soldering and repair and tin-copper for wave soldering.

For the Japanese electronics industry are also very important bismuth and zinc containing solders.

Table 2 shows an overview of the discussed environmental properties of lead free solders that are commonly seen as possible substitutes for SnPb.

Different aspects of the environmental impact of interconnection systems in electronics have been examined covering different phases of the life cycle.

First the Toxic Potential Indication (TPI), is used to give an overall rating. All lead free solders have a better TPI rating than SnPb37, especially tin/copper and tin/zinc solders have good properties. Even the use of the relatively bad rated silver is favourable, because only a small quantity is used in the solder. Information about bismuth is not enough available.

Solder	Toxicity (TPI)	Raw Mat. Prod.	Manufact. (Assembly)	Disposal
SnPb37	-	-	+	-
SnAg3,5	+/-	+	+/-	+
SnAg4 Cu0,5	+/-	+	+/-	+
SnCu0,7	+	+	+/-	+
SnBi58	+/-	+/-	+	+/-
SnAg3,5Bi4,8	+/-	+	+	+/-
SnZn9	+	+	-	+

Table 2: Overview about environmental impact of lead free solders in comparison with SnPb Rating the environmental compatibility: Dark grey: very poorly rated, grey: poorly rated, white: well rated

The environmental impact of metal production was measured by the EcoIndicator95 method. The data are available in the literature. The impact of ore mining, transportation and refining (energy consumption and emissions) are summarized to assess the metals. The lead free solders have remarkably good ratings, only bismuth is rated relatively bad because it is assumed that Bismuth is extracted together with lead in these cases. Still the rating of eutectic SnBi58 is better than SnPb37.

The manufacturing processes were coarsely rated according to the assumed energy demand and use of auxiliary materials (flux, cleaning agents, inert gases). Table 3 shows a comparison of energy demand of wave soldering for SnPb and SnCu as measured in a company. For estimation of the power input the heating up value and the energy demand for continuous production from Monday morning until Friday afternoon is assumed.

Solder	SnPb (250 °C)	SnCu (280 °C)
Power input until rated value	34 kWh	36 kWh
Time to reach rated value	3,5 h	5,5 h
Power input per h past reached rated value	5 kWh	5 kWh
Power input was determined without PCBs		

Table 3: Power Input for PCB Assembly

Under these conditions the overall power input for soldering with SnCu is 10 to 15 % higher than for the SnPb solder because of its higher melting point of 45 degrees.

Auxiliary materials (flux, cleaning agents) have an important environmental impact on the soldering process with the SnZn alloy which is slightly oxidised. Therefore very aggressive fluxes must be applied and the PCBs have to be cleaned after soldering. That is combined with a certain environmental burden.

To characterize the disposal performance of the solders, the US-American „Toxicity Characteristic Leaching Procedure" TCLP1311 was carried out. Leaching behaviour of SnPb solder is very bad compared to all alternatives. For copper, the leaching from the soldered joints is likely to be negligible compared to the copper PCB-layers. Zinc leaching has not been examined up to now.

At one glance, table 2 shows the potential for environmentally beneficial replacement of lead in the electronic interconnection systems, but also indicates the need for in-depth-studies to choose the appropriate solder.

All of the lead free surfaces are very thin in comparison to the SnPb HASL layers and therefore the layer masses are very small.

Table 5 shows an overview on various aspects of the environmental impact of the different surface finishes along their whole life cycle: the screening assessment by means of the TPI, the assessment of the environmental impact in the raw material production by means of the energy consumption, the assessment of the environmental impact in

Surface finish	**Density (layer material) in g cm^{-3}**	**Layer thickness (µm) and mass (mg cm^{-2*})**	**Layer properties**
HASL SnPb37	Sn: 7,2 Pb: 11,3	25 / 54,7	Not bondable, multiple solderable, T-stress
Chem Ni/Au	Ni: 8,9 Au: 19,3	5 /0,1 / 11,6	Bondable, multiple solderable, flat layers
Chem Sn	7,2	1 / 1,8	Not bondable, multiple solderable, flat layers
Chem Ag	10,5	0,1 / 0,3	Bondable, multiple solderable, flat layers
OSP	1 (est.)	<0,5 / 0,2	multiple soldering difficult, not bondable, flat layers

*Table 4: Characterization of the lead free finishes in comparison with the SnPb HASL layers (Assumption: *One quarter of the surface is metalized)*

the finish manufacturing by means of energy and water consumption and some short remarks about the environmental impact in the end of life phase.

The screening assessment by means of the TPI shows that the HASL and Ni/Au layers are relatively high (poorly rated) in comparison to the Sn-, Ag- and OSP layers. The reasons are the high toxicity and mass of lead in the HASL and Ni in Ni/Au layers.

5.2 Lead Free Surface Finishes

Up to now the mainly used surface finish is the SnPb Hot Air Solder Leveling (HASL). Alternative lead free surface finishes are

Chem Ni/Au

(Chem Ni/Pd/Au)

Chem Sn

Chem Ag

Organic solder ability protectants (OSP)

The Ni/Pd/Au surface was not included into the following considerations because the market of palladium is very unstable, its costs are difficultly to calculate.

For an average of 50 % of the produced PCBs the surface finishes have to change if the lead ban will become reality. In Asia where consumer electronics is produced the low cost HASL finishes with lead are more applied. The alternatives have not only to comply with technical/technological requirements but should be more environmentally compatible than the conventional HASL SnPb layers.

In Table 4 the different surface finishes are characterized by their layer thickness, the resulting masses of the several materials on a square meter of a PCB and their layer properties.

For the environmental impact of the first life cycle phase - the raw material production - the energy consumption is considered. For the production of the precious metal Au a high energy demand is necessary. That means that the environmental impact for this process is very high.

For the assessment of the environmental impact of the manufacturing the water and energy consumption has to be considered. These results were taken from the PWB Project Surface Finishes of the EPA in USA /4/. There is a distinction between the non-conveyorized and the conveyorized process because of the large differences between them. For further examinations of the environmental process impact all chemicals of the processes have to be included.

As in table 5 is shown, five surface finishing processes consume less water than the reference HASL, non-conveyorized process, including the conveyorized versions of the HASL, chem Ag and Sn technologies, along with both versions of the OSP process. Two surface finishing processes consume more water than the reference process,

Surface Finish	TPI in 10^4 TPI/m^2 PCB	E $_{\text{Raw Mat.}}$ in 10^3J/m^{2}PCB	Manufacturing				End of Life
			E in 10^6 J/m^2 non-c./ conv		Water consumption in l/m^2 non-c./ conv		
HASL SnPb37	51,7	9615	2,48	1,51	50,5	40,3	Pb leaching
Ni/Au	47,2	73312	5,08	-	83,9	-	Ni-leaching Au-Recycling
Chem Sn	0,2	432	3,28	5,93	73,7	35,6	
Chem Ag	1,1	907	-	3,26	-	21,6	
OSP	0,17	40 (est.)	1,42	0,83	31,3	21,6	No Recycling

Table 5: Environmental impact of lead free surface finishes compared to HASL (conv: conveyorized, non-c: non-conveyorized) Rating the environmental compatibility: Dark grey: very poorly rated, grey: poorly rated, white: well rated

the non-conveyorized version of chem Sn and Ni/Au. The rate of water usage is primarily attributable to the number of rinse stages required by the processes. In general the application of the conveyorized process is generally better than the non-conveyorized process, that means, they consume less water.

Referring to the energy demand table 5 shows, that three of the process alternatives consumed less energy than the reference HASL, non-conveyorized process. Both the non-conveyorized and conveyorized versions of the OSP process, along with the conveyorized HASL process, consume significantly less energy than the reference process. The reductions were primarily attributable to the efficiency of these three processes and their short operating times. On the other hand the long operating time in the case of the Ni/Au process is responsible for the relatively high energy consumption.

For a screening assessment of the environmental impact during the end-of-life phase, especially the disposal behaviour of soldered PCBs, the leaching of the layer materials (only for metals) was examined by means of Toxicity Characteristic Leaching Procedure (TCLP). The results emphasize the well known high solubility of Pb but show that also Ni is very good solved.

Summarizing all facts of the surface finishes from an environmental point of view the OSP finishes should be the best and the NiAu finish should only preferred if technical reasons require it.

6. CONCLUSIONS

Lead free interconnection technologies and cleaner manufacturing will become reality in mass production.

To get a feeling of how alternative materials for interconnection systems would influence the environmental behaviour of electronic products assessment matrices of some solders have been prepared. These matrices show, that in nearly all categories alternative solders are better than tin-lead with a small question mark behind bismuth and Sn-Zn; and that from an environmental point of view the OSP finishes should replace the SnPb HASL layers if technical possible.

But a lot of issues still have to be solved, for instance:

- the environmental impact of solders containing bismuth should be better understood;
- the environmental impact of the manufacturing process with solders containing zinc has to be examined;
- the avoidance of Ni in the surface finish of the PCBs is desirable

However, the environmental impact of a single microelectronic product will be decreased by the various measures, but this positive tendency is still compensated by enormous growth of production numbers and short innovation cycles. Therefore further great efforts are necessary to bring down the burdens for the environment by electronic products.

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