# Chapter 2
# Interconnection Materials – Technical Research Status

**Abstract** This chapter briefly summarizes some of the history and the technical research status of the wide field of interconnection materials and associated plating materials. The overview of different materials sets the scope and perspective of the following environmental life cycle assessments discussed in Chaps. 5 and 6. Solder pastes based on nanosized metal spheres are introduced. Research exploring ways to produce electronics without interconnection materials is considered. Extensive technical-based research has been done by several groups and the present summary is by no means comprehensive.

## 2.1 Solders

Solders are by far the most common of interconnection materials and the solders used in wave soldering for hole mounting are by mass and volume used more than solder pastes in reflow soldering.

An even smaller share is occupied by solder alloys for bumping of microchips. In the US, John R. Barnes is compiling a massive bibliography for "designing lead-free, RoHS-compliant, and WEEE-compliant electronics".

By July 2009 Barnes concluded that 254 books and 216 PhD/MSc theses and thousands of different kinds of articles had been published about interconnection materials and closely related topics [1]. Barnes compilation manifests that monumental amounts of ideas and research have been produced within the multidisciplinary area of interconnection, meaning that it is an intriguing area for study.

A genuine understanding of soldering demands several research disciplines to come together.

For Sn–Pb solders the reliability is fairly well understood but the Pb-free solders are so far much less investigated. The correlation between scientific disciplines involved in soldering is shown in Fig. 2.1.

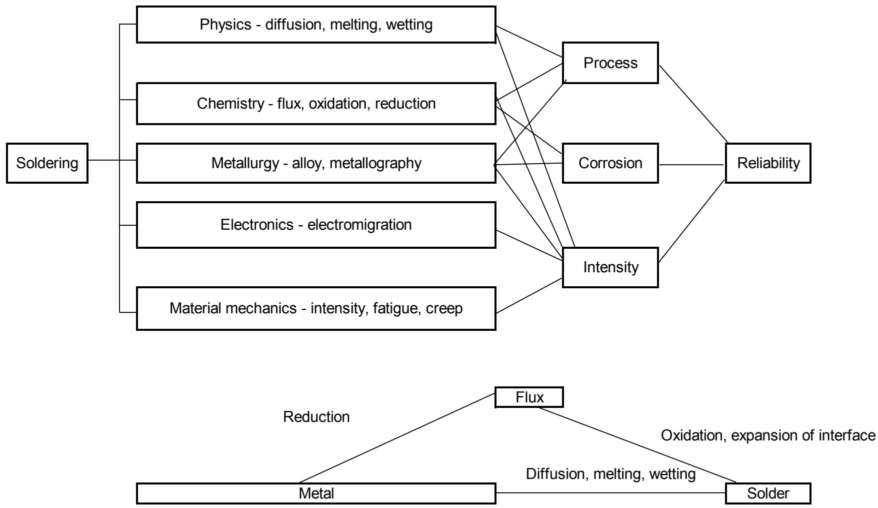


**Fig. 2.1** The correlation of scientific disciplines determining the reliability of solder joints

## *2.1.1 Pb-based Low-melting-point Solders*

The most common and oldest solder is the eutectic 63Sn–37Pb solder. It has been in use since the birth of the electronics industry. 63Sn–37Pb has a relatively low melting point, good wetting behavior, high electrical conductivity and can be used in hierarchical soldering. It is relatively common to use Sn–Pb solders having up to 2wt% Ag.

## *2.1.2 Pb-based High-melting-point Solders*

In Europe, an EU directive on restrictions on the use of hazardous substances (RoHS) required the elimination of Pb in LMP solders, by July 1 2006.

However, the Pb-based HMP solders are exempted from the Pb ban of the RoHS but this is not expected of a forthcoming update of the Chinese version of RoHS [2].

The reasons behind the exemption are the relatively small amounts used of these kinds of solders, around 10wt% of the solder alloy production, and the difficulties in finding a technically viable substitution.

HMP Pb-based paste is applied before the main PWB is processed, using LMP solder/ECA and temperature sensitive components which would otherwise be damaged by the processing temperature required by HMP Pb-solders.

The high-melting-point solders are used in at least three areas: 1) as non-collapsible spheres (solder balls) in ball grid array joints between low temperature co-fired ceramic multichip modules and the mother PWB [3], 2) in ball grid array (BGA) joints between BGA components and the mother PWB, and 3) as solder within power device packages where the die is soldered to a leadframe. Figure 2.2 shows a hole mounted integrated circuit package where Level 1 is where high-melting-point solder is needed and at Level 2 low-melting point.

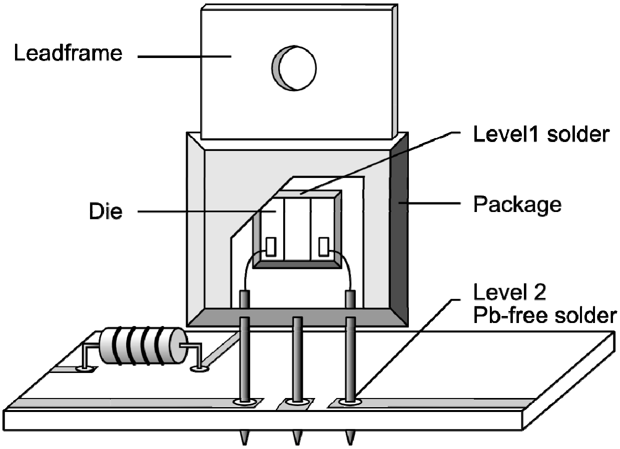


**Fig. 2.2** Different usage of high- and low-melting solder in hole-mounted integrated circuit

BGA is a kind of semiconductor packaging technique. The solder manufacturers Indium and Kester call the Level 1 solders “die attach solders”. These solders can also be used as alloys in wave soldering and reflow soldering as solder paste. The composition usually is usually more than 85wt% Pb and the rest Sn.

More than 900 combinations of ternary and quaternary Pb-free alloys could theoretically replace high Pb alloys but no “drop-in” alloy has been identified [4]. Section 2.1.4 mentions the latest research in high temperature Pb-free.

## *2.1.3 Pb-free Low-melting-point Solders*

For the last decade Pb-free solders have been heavily researched. A wide variety of material combinations have been tested for many kinds of hypotheses. Consumer electronic applications are the primary target of the Pb-free solders. However, they are not just drop-in substitutes for traditionally used Pb solders due to solder melt temperature, processing temperature, wettability, mechanical and thermo-mechanical fatigue (TMF) behaviors, etc. [5]. An advantage of Pb-free solders is the higher service temperature capability provided to the solder joints. Figure 2.3 shows resistors through-hole mounted using Pb-free solder.

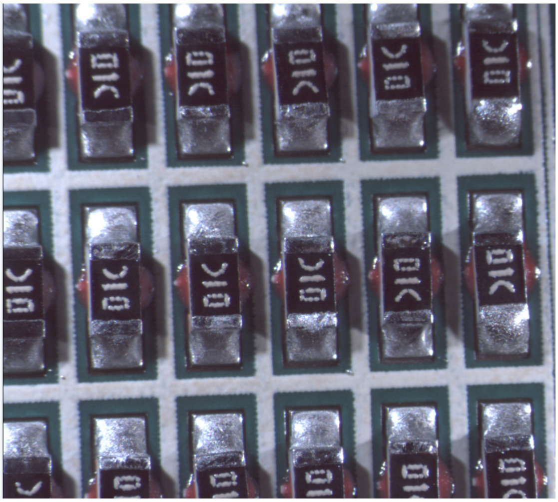

**Fig. 2.3** Resistors mounted using Pb-free solder

Figure 2.4 shows the under side of a printed wiring board where an integrated circuit has been through-hole mounted.

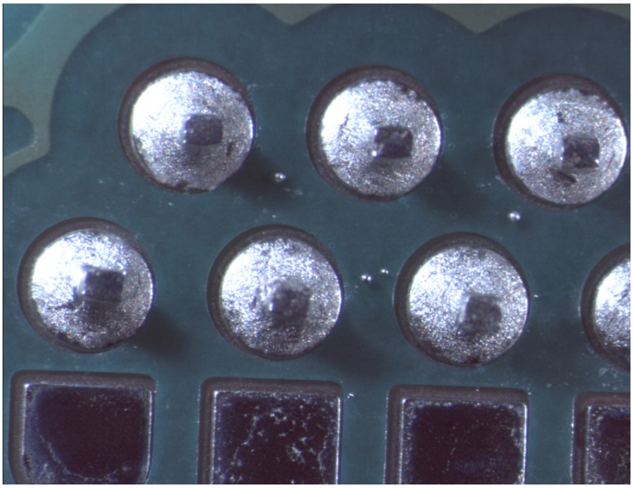

**Fig. 2.4** Solder joints of an integrated circuit shown from the below of a printed wiring board

However, at the high temperatures required to reflow Pb-free alloys, moisture absorbed into the package can result in delamination and failure. On the other hand, the Pb-free alloys in general seem to improve the thermomechanical fatigue and electromigration performance, but then again induce risks for mechanical shock and whiskering.

For LMP solders, Sn will be the base but the Ag fraction might have competition from other materials such as Cu, Zn, Co, Bi, and rare earth metals [6–8].

The low-melting point Pb-free solders, e.g., the Sn–Zn system, have advantages compared to the Sn–Ag–Cu system. These are especially melting points near to the traditional Sn–Pb solder, low energy depletion, and no need for new surface mount technology (SMT) line.

Some low-temperature solders having melting point below 150 ºC can be used instead of conductive adhesives.

These are, e.g., 42Sn–58Bi, Sn50–In50, and 26Sn–53Bi–26Cd [9]. The latter is doubtful due to Cd toxicity.

### *2.1.4 Pb-free High-melting-point Solders*

Pb-free high-melting-point solders are rather scarcely researched at the moment. The reason is that Pb-based high-melting-point solders are exempted from European Union Pb-free legislations.

Anyway, the main alternatives are 80Au–20Sn solders, Cu–Sn diffusion bonding, and liquid solders.

Liquid solders, which are at the experimental stage, are encapsulated solder joints with Bi and Sb containing solders, liquefying at higher temperatures.

Cu–Sn interdiffusion bonding is currently used e.g., in wafer stacking or chip to wafer assembly for System-In-a-Package.

80Au–20Sn solders are thought to be used only in niche applications due to the high cost of Au.

For high-temperature situations the bases instead of Pb could instead be Zn or Bi [10, 11].

### *2.1.5 Pb-free Solder Paste Based on Nanoparticles*

One of the drawbacks with Pb-free solders similar to 96.5Sn–3.5Ag is their relatively high melting point being around 30 ºC higher than for 63Sn–37Pb eutectic solder.

The higher melting point brings about higher energy usage and also package reliability concerns such as substrate warpage and thermal stress [12].

When the sizes of the metal alloy spheres are reduced to nanometer size, the melting point can be reduced to from 217 to 213.9 ºC [13].

## 2.2 Conductive Adhesives

What is an electrically conductive adhesive (ECA)? One way of describing it is as a kind of polymeric solder that has been investigated by the electronics industry.

ECAs consist of a polymeric binder matrix (about 50vol% or 20wt%), usually bisphenol-A type epoxy resin, and metal fillers where the metal usually is Ag, Au, Cu, or Ni. It is also possible to have metal coated polymer spheres within the polymer matrix [14].

Li et al. suggest that ECAs generally are more environmentally friendly than solders as both Pb and flux cleaning are eliminated, and fewer overall processing steps are required [15]. Moreover, lower curing temperatures are thought to offer reduced energy use. Nevertheless, ECAs are not drop-in replacements for conventional solders due to different material properties and reliability issues such as low conductivity, unstable contact resistance, low joint strength, and Ag migration. Moreover, connected to the shift to Pb-free solders, ECAs need to be able to withstand considerably greater levels of thermal and chemical stress in order to prevent chip loss and component movement.

The wide usage of ECAs has so far only been for niche applications, especially to attach silicon dies to the microcircuit plastic capsules. ECAs are already used for attaching so called flip-chips on PWBs and for fastening parts of display units in, e.g., mobile phones, but have been considered too unreliable to be applied as full-scale interconnection materials [16].

Another application is bonding prior to wave soldering and surface mounting of electric components, for the latter isotropically conductive adhesives will be studied in the present research.

Furthermore, different surface plating metals are used to protect the pads of the printed wiring boards and the components leadframes.

Depending on the share of metal particles, ECAs are usually divided into three groups; isotropically conductive adhesives (ICA), anisotropically conductive adhesives (ACA), and non conductive adhesives (NCA) [17]. Moreover, ECA pastes can be used in standard processes, such as stencil printing and curing in conventional reflow ovens [18].

The main driver for development of ECAs was environmental hazard concerns about the Pb content of solder.

Much more research has been done for Sn–Ag–Cu solders than ECAs [19]. Some of the technical drives for ECAs have been the possibility to be used together with non-solderable materials such as chip-on-glass or surface mounted devices-on-polyester materials as well as the ECA lower sensitivity to thermomechnical stresses due to higher flexibility than solder [20].

Moreover, it is possible that ECA could replace solder pastes for certain applications. Further for ECAs, as, e.g., the oxidation problems are overcome, materials such as Cu, Ni, and AlN can replace Ag [21–23].

## 2.2.1 Isotropically Conductive Adhesives (ICAs)

In an ICA, the electrical contact is obtained through a network of contact points between individual particles [24]. The volume fraction of conductive particles is around 25–30%. ICA research data has emphasized failure, rather than reliability [19]. The particles consist of pure Ag, Au-plated Ag, Ag-plated Cu, or Ag-plated Sn but even more materials have been tested.

## 2.2.2 Anisotropically Conductive Adhesives (ACAs)

Conventional ACA is an adhesive consisting of conductive particles dispersed in an adhesive matrix. The volume fraction of conductive particles is around 5–10 %. These particles can be pure metals such as gold, silver, or nickel, or metal-coated particles (see Sect. 2.2.2.1) with plastic or glass cores. Palladium-plated Ag particles are less prone to Ag migration than pure Ag particles.

The volume fraction of particles is well below the percolation threshold, with the particles typically ranging from 3 to 15 μm in diameter. Typical for ACAs is that there is no contact between individual particles, the electric contact is instead achieved perpendicular to the film. ACAs are available in paste or film form (ACF) [24]. The reliability of an ACA is chiefly decided by the thermomechanical properties of the conductive particles. Figure 2.5 shows a sketch of flip-chip interconnection made possible by ACA.

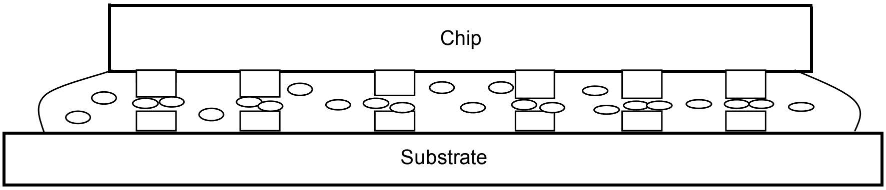


**Fig. 2.5** ACA role in flip-chip interconnection

### 2.2.2.1 Metal-coated Polymer Spheres

Metal plated microspheres to be used in ACA, or as replacement for solder balls within ball grid array, or chip scale package components, are under development. The first application is shown in Fig. 2.6.

One alternative is a divinylbenzene polymer core plated with Ni and Au [25]. Acrylates and styrenes also work as core material as the cores can be made using the Ugelstad process after which the polymer core is then step by step covered with metals.

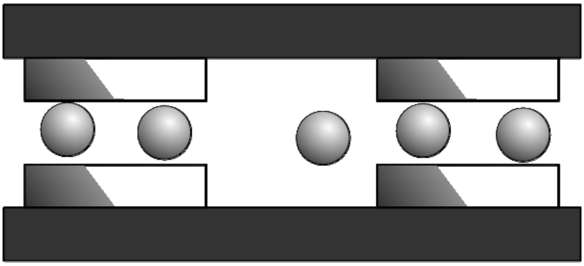

**Fig. 2.6** Metal-plated polymer spheres used in ACA

### *2.2.3 Non-conductive Adhesives (NCA)*

NCAs are characterized by zero volume percent added particles. The purpose of an NCA is to provide a mechanical connection between the contacts of a microchip and corresponding contacts on the substrate. The NCA bonding method relies upon direct electrical contact between the two conductor surfaces and the contact points are responsible for the transport of electrical current.

The epoxy filled cavities supply the adhesive forces needed to keep the materials together. After the connections are made, shrinkage in the cured adhesive and the mechanical properties of the involved materials will be responsible for the compressive force needed to maintain the electrical contacts [24].

### *2.2.4 Conductive Adhesives Based on Nanoparticles*

Professor Johan Liu's research group at Chalmers University in Sweden is exploring the nanosize effect in flip-chip interconnections. It is done via ACAs containing nanoparticles of Pb-free solder alloys as fillers [26].

## 2.3 Solder-free Alternatives

Being rather "provocative" but nevertheless tremendously interesting and having inherently large implications for the whole Electronic Manufacturing Service industry, Californian company Verdant Electronics in 2007 boldly proposed a totally solder-free new production concept [27, 28]. However, it remains to be seen if solder-free alternatives will be successful in the interconnection market place.

## 2.4 Plating Materials and Metal Spheres for Ball Grid Arrays

The amount of plating materials, e.g., Pb-based alloys, involved within the components is less significant compared to the materials used to connect them to them the printed wiring board. For example a thin quad flad pack (TQFP) component having 176 connections by Xilinx and 0.5 mg solder paste per connection, the amount of 63Sn–37Pb solder paste to 85Sn–15Pb external plating would be 0.088 g to 0.016 g. The Pb content is 2 to 1. As for BGAs and CSPs, the solder balls are attached to the motherboard using traditional solders [29].

It is possible that some, but not all, BGA components need more solder from the solder balls and solder paste than a comparable surface-mounted QFP packages needs solder paste.

A metal-based BGA352 by Xilinx needs more than 0.8 g solder, 0.7 g 63Sn–37Pb solder for solder balls and around 352 (number of balls) × 0.8 (80% of area covered) × $0.08^2$ (area, $cm^2$) × 0.015 (solder height, cm) × 4.7 (density solder paste, $g/cm^3$) = 0.1 g for 63Sn–37Pb solder paste. TQFP176 only needs around 0.2 g for solder paste and plating.

The silicon die within these packages weighs 0.028 g but the Input/Output connections are more for the BGA.

Then on the other hand a plastic-based BGA596 from Philips needs 0.94 mg for solder balls and the comparable Philips QFP64 needs 32 mg. The silicon die inside these packages weigh 20 mg.

Packages are very different but, in order to be comparable, they have to 1) fulfill the same function, 2) divert heat equally and 3) withstand environmental pressures, e.g., moisture, equally efficient. Bearing these criteria in mind, there would be room for developing a road-map for the most eco-friendly packages.

Figure 2.7 shows how an identical die is used in different packaging technologies.

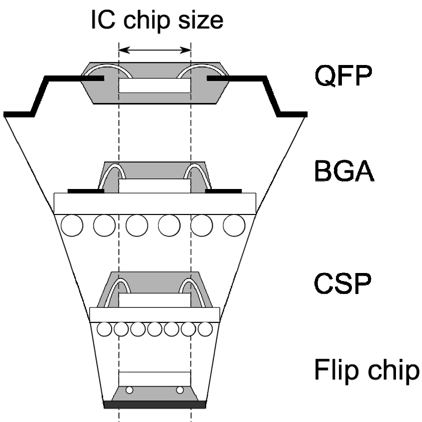


**Fig. 2.7** The “footprint” of different packaging technologies

### 2.4.1 Component Terminal Platings

Two of the most common component terminal platings are Sn–Pb alloys and Ag on Pd. 85Sn–15Pb has been reported by microcircuit manufacturers such as Xilinx. Also Au/Pd/Ni or only Sn is used [30].

### *2.4.2 Printed Wiring Board Pad Platings*

For PWB pad platings, bare Cu pads, Sn–Pb alloys or Au-plated boards are common. Also Au/Pd/Ni or only Sn is used [30].

### *2.4.3 Metal Spheres for Ball Grid Arrays*

The most common materials are 63Sn–37Pb and increasingly 96.5Sn–3Ag–0.5Cu [31–34].

## 2.5 Perspectives

Compatibilityfree with Sn–Pb with Sn–Pb alloys is an important criterion of a Pb-free alloy, as there are many areas of possible alloy inter-mixes which imply different degrees of reliability. Huang and Lee found that Sn–Pb balled/plated BGAs, CSPs, QFPs, or TSOPs soldered with Pb-free solders showed serious board level reliability risks [35]

Moreover, the replacement of high-melting-point Pb-based solders could prove to be somewhat difficult. The reason is that the minimum acceptable melting point for the “die attach solder” will have to increase as reflow temperatures of board level Pb-free solders could reach as high as 270°C [36]. Possibly high-temperature conductive adhesive technology will solve the aforementioned problem as these adhesives can withstand high temperatures, but at the same time do not require a high reflow temperature [37].

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