European Cooperation in the field of Scientific and Technical Research - COST -

Secretariat

Brussels, 5 December 2006

COST 322/06

MEMORANDUM OF UNDERSTANDING

Subject :	Memorandum of Understanding (MoU) for the implementation of a European Concerted Research Action designated as COST Action MP0602: Advanced Solder Materials for High-Temperature Application- their nature, design, process and control in a multiscale domain

Delegations will find attached the Memorandum of Understanding for COST Action MP0602 as approved by the COST Committee of Senior Officials (CSO) at its 166th meeting on 20/21 November 2006.

MEMORANDUM OF UNDERSTANDING
FOR THE IMPLEMENTATION OF A EUROPEAN CONCERTED RESEARCH ACTION DESIGNATED AS

COST ACTION MP0602

Advanced Solder Materials for High-Temperature Application- their nature, design, process and control in a multiscale domain

The Signatories to this 'Memorandum of Understanding', declaring their common intention to participate in the concerted Action referred to above and described in the 'Technical Annex to the Memorandum', have reached the following understanding:

1. The Action will be carried out in accordance with the provisions of document COST 299/06 'Rules and Procedures for Implementing COST Actions', or in any new document amending or replacing it, the contents of which the Signatories are fully aware of.

2. The main objective of the Action is, through investigations on the meso-, macro- and micro-scale, to increase the fundamental knowledge of the crucial properties of alloys that can be used as environmentally friendly lead-free alternatives to existing high-temperature solders.

3. The economic dimension of the activities carried out under the Action has been estimated, on the basis of information available during the planning of the Action, at approximately 24 million EUR in 2006 prices.

4. The Memorandum of Understanding will take effect on being signed by at least five Signatories.

5. The Memorandum of Understanding will remain in force for a period of 4 years, calculated from the date of the first meeting of the Management Committee, unless the duration of the Action is modified according to the provisions of the document referred to in Point 1 above.

COST Action MP0602

**Advanced Solder Materials for High-Temperature Application-
their nature, design, process and control in a multiscale domain**

A. ABSTRACT AND KEYWORDS

Abstract: The focus of the COST Action is the investigation of Pb-free replacements for high-Pb solders for high-temperature applications. This comprises a study of the chemical, physical and mechanical properties of alloys containing a large number of permutations of different alloying elements. A multiscale approach will be used:

meso-scale: The application of thermodynamics and kinetics to the study of alloying behaviour; the development of materials property databases.

macro-scale: The creation of a phenomenological description of corrosion and deformation processes occurring in a solder joint during fabrication and service,

micro- (nano-) scale: The investigation by experiment and modelling of the initial stage of the formation of intermetallic phases at the solder/substrate interface. This will involve the consideration of diffusion.

This will be most efficiently achieved through coordinated international cooperation providing a basis for interdisciplinary research. The action will increase the basic understanding of alloys that can be used as Pb-free alternatives to high-temperature solders for practical applications, for example in the aerospace and automotive industries.

Keywords: High-temperature soldering, Pb-free solder alloys, multiscale modelling, materials properties, reliability.

B. BACKGROUND

Public awareness of environmental issues including the use and disposal of potentially toxic materials has never been greater, with lead being the subject of particular scrutiny. Lead containing materials are among the most important posing a great threat to human life and the environment. The main reason is the danger of lead accumulation in the human body; it leads to disorders in the nervous and reproductive systems, delays in neurological and physical development, it causes cognitive and behavioural changes and reduces the production of haemoglobin resulting in anaemia and hypertension. Currently, lead poisoning is assumed to have occurred if the level of lead in the blood exceeds 500 μg/ml, but recent studies have found that a level of lead well below the official threshold could be hazardous to a child's neurological and physical development.

In industry, there is now increasing pressure to eliminate lead containing materials, which is significantly supported by the legislative process currently in motion throughout the EU. Despite the fact that the electronics industry is not the largest user of lead and lead containing chemicals (the electronics industry is only the 6^{th} largest consumer of lead but 80% of its consumption is in solders), electronic products and processes were (and still are) significant sources of lead contamination, both through occupational exposure and through waste disposal of electronic assemblies, causing e.g. the contamination of underground water sources. In addition, there is the possibility of lead containing effluents entering sewage disposal systems. Although there seems to be no clear understanding of how lead from discarded electronic products enters the ground water stream and from there the animal or human food chain, it is generally agreed that the effect occurs.

One theory is that it is connected with the action of water containing oxygen, carbon dioxide, and possibly chloride on the lead containing solder materials.

Recent EU legislation (DIRECTIVE WEEE (**W**aste from **E**lectrical and **E**lectronic **E**quipment) and DIRECTIVE 2002/95/EC, Restriction of the use of certain Hazardous Substances (RoHS) in electrical and electronic equipment) prohibited the use of lead containing solders in many industries from July 1st, 2006. Despite the fact that materials for high temperature soldering are amongst those currently not affected by this deadline, the pressure to remove hazardous substances will continue and spread to other, currently exempt fields. Moreover, market pressures resulting from economies of scale are already having an impact on exempt industries owing to a dwindling availability of Pb-containing high-temperature solders, thereby causing a *de facto* switch to lead free. This European research project, specifically targeted to the needs of Europe, its people and its industry, is of great importance particularly since it will draw on established areas of European expertise while benefiting from any relevant progress taking place in other parts of the world.

B.1. State of the art

A considerable amount of research has already been conducted on the formulation of new Pb-free soldering materials, not only in Europe, but also in the USA and Japan. A number of promising materials, for example SnAgCu-alloys, have been developed to replace the (near-) eutectic Sn-Pb solders for mainstream applications (melting temperature of ~200°C), despite the fact that there is still no 'drop-in' alternative for these traditional alloys. Nevertheless, companies, firstly in Japan and now in Europe and the U.S.A, are ready to comply with lead-free requirements in order to maintain access to the European market. On the other hand, many low-cost producers, especially in China, are currently not able to comply with existing European lead-free legislation.

However, research is seriously lacking into replacements for high-temperature, high-Pb containing alloys, where the lead levels can be above 85% by weight, and this is reflected in the fact that these materials are, at present, exempt from the new RoHS legislation. Some of the problems associated with replacement of these alloys have been discussed in recent papers by both Japanese and American authors [1-5]. However, only at the beginning of this year, a major research programme addressing the issue of high-temperature Pb-free soldering has been initiated in Japan. This activity is sponsored by the major Japanese car manufacturers.

The main applications for high-temperature ($T_m \geq 230°C$) solders within the electronics industry are for advanced packing technologies, e.g. die-attach and BGA (Ball Grid Array) solder spheres, chip-scale package (CSP) and multi-chip modelling (MCM). The die-attach material should withstand normal working temperatures, thermal loading during soldering and also be sufficiently thermally conducting to transfer heat away from the device. High-Pb alloys in die-attach applications are generally used in power circuits where very high levels of conductivity are required. These are normally found in automotive under-bonnet applications owing to the high current and low voltages produced by car batteries and the high temperatures occurring within the engine bay.

In the case of MCM technology, a so-called step soldering approach is employed. This method is used to solder various levels of the package with different solders of different melting temperatures. One of the solders currently used in this technology is the Pb95-Sn5 alloy, which has a melting temperature between 308-312°C. New Pb-free high-temperature solders should replace the current alloys for a broad range of melting temperatures, and therefore, a good understanding of the melting behaviour is paramount. The upper limit of the process temperatures in MCM technology is around 350°C, which is determined by the polymer materials used in the substrate. Subsequent processing temperatures are below the melting point of the previously used solders.

A soldered assembly may also be subject to large mechanical or long-term thermal fatigue stresses. Solder interconnects should also not corrode in the presence of high humidity at elevated temperatures. They must also be resistant to air pollutants, such as NO_2 and H_2S. The recent elimination of cleaning materials containing ozone-depleting compounds in electronic assembly has initiated the development of fluxless technologies. It is also clear that the reliability of solder joints is related to the wettability of the substrate by molten solder and to the morphological evolution inside interconnects during fabrication and service. In addition, the drive towards miniaturization in the electronics industry poses serious questions concerning reliability, since a clear size effect has been demonstrated for solder joints [6]; with a decrease in the size of the solder gap, the joints become considerably more brittle and the effects are exacerbated with high Sn solders typical in Pb-free applications. Traditional barrier metals used in Si device manufacture are also proving to be unsuitable for use in high technology, unpackaged, miniaturised devices, such as flip chip technology. In these instances, high Sn content solders in combination with multilayered metallisations (e.g. Ag, Ti, W, Cu, Ni, V) result in complex interactions occurring during soldering and operational life, leading to galvanic corrosion and destruction of the chip-side interconnections. This results in a barrier to miniaturisation for some devices [7]. Additionally, the influence of reaction products at the solder/substrate interface on the mechanical behaviour of the joints becomes more significant. Last, but not least, the problem of material cost plays an important role in the selection of the solder.

Ongoing research in the field of high-temperature lead-free solders indicates that it is necessary to abandon Sn-based materials, which exhibit a combination of properties that correspond closely to those of eutectic Pb-Sn but for a lower melting range. Attempts to adjust the melting temperature of Sn-based solders by the use of appropriate alloying elements have not yet been successful, as possible additives tend to lower the melting temperature. Therefore, attention has turned towards different base elements, and at the present time several combinations are under consideration. Hypo-eutectic Bi-Ag alloys, among the most promising under investigation, are very good from the point of view of liquidus temperature and exhibit mechanical properties close to those of Pb-based solders; and are affordable. Other interesting materials include those based on a Zn-Al eutectic alloyed with Mg, Ge, Ga, Sn or Bi, and also those based on Sb-Sn and Au-Sb-Sn systems. Some materials are already in use – e.g. Au-Sn based solders, but replacements are being sought since these alloys are quite expensive.

Mechanical and other properties of joints involving high-temperature solders also need to be understood. In fact, little work has been done for any lead-free solder joints. It is important to characterize the associated diffusion processes in ternary and in particular in quaternary alloy solder joints and their subsequent effect on the long-term mechanical properties of the joint. The formation and growth of intermetallic phases during solder joint reflow and service has been extensively addressed in the literature, though almost exclusively for alloys of the binary Cu-Sn alloy system. Studies on the effect of intermetallic compound growth on resulting solder joint strength have been focused primarily on lead-based binary solder alloy systems. These studies have demonstrated that, owing to their brittle nature and lattice mismatch with the copper substrate, increased intermetallic thickness weakens the solder joint, especially when subjected to thermal or mechanical fatigue. The limited research conducted has treated only the kinetics of alloy formation, evolution, and corrosion [8-12] separately and also independently from their corresponding effect on the mechanical properties of the joint [13-15]. Furthermore, very few researchers considered the effect of variable surface concentration on the corrosion mechanism. In an analogous way, the modelling of stress is restricted almost entirely to thermal stresses, viscosity effects and to ideal systems.

B.2. European Dimension of the Action

Research into lead-free replacements for high-temperature soldering applications is gaining momentum in developed countries, but at the moment there are no real and immediate replacements for traditional lead-based alloys. It is important for Europe to keep pace with other leading industrial powerhouses (USA, Japan) in this field - this requires a programme of concerted scientific collaboration across Europe. From this point of view, the COST framework, which provides coordination of research projects across Europe, is very appropriate and timely. Many different topics may be studied by various research teams following diverse paths with respect to materials selection, experimental and theoretical techniques used and properties studied. The instruments available within the scope of COST actions - namely, STSM missions, workshops and narrowly focused conferences - offer opportunities to find common interests between research teams, resulting in more focused research, and offers the potential to develop further international collaborative projects (bilateral projects, European Framework Programmes, etc.). The more open framework of collaboration available through COST also encourages participation of research teams within the industrial sector and the sharing of pre-competitive information. This COST Action will enable solder manufacturers and users to participate and to coordinate their research effort on a European level. This is important for the advancement of European R&D in lead-free soldering in view of the strong competition from Japan and the United States.

Currently, some of the participants of the FP6 ELFNET programme are involved in this COST Action. The mutual cooperation between this COST Action and ELFNET (and any successor) will be very useful for both programmes. This had already been demonstrated by the level of collaboration achieved between COST 531 and ELFNET.

This COST Action brings together leading scientists from 17 EU countries working in universities, research institutes, together with several industrial partners. This is essential from the point of view of reaching the main objectives, which will be specified in the following chapter.

C. OBJECTIVES AND BENEFITS

The main objective of this COST Action is to increase the fundamental knowledge of the crucial properties of alloys that can be used as environmentally friendly alternatives to high-temperature solders. The aim is to identify promising materials with a set of suitable properties, such as melting point, wettability and surface tension, which will allow them to be used successfully in a variety of industrial applications. Furthermore, health and economic issues will be taken into account during the evaluation in addition to physical, chemical and mechanical behaviour.

This COST Action will provide a cooperative basis for interdisciplinary research that is necessary to fulfil this aim and will allow a further reduction in the use of lead in society. A study of these materials from a fundamental scientific point of view is necessary in order to complement the applied aspects of the research and will result in a broadening of the impact of any new knowledge obtained, as current fundamental research in this field is quite limited. The participation of partners from industry will facilitate the transfer of knowledge and will ensure that feedback can be provided to the research programmes carried out in the scope of this COST Action.

C.1. Specific goals

The identification and characterisation of lead-free solder materials for high-temperature applications will be achieved through a multidisciplinary and multiscale approach *via* a set of specific goals.

- On a *meso*-scale: The application of thermodynamics and kinetics of multicomponent systems and the establishment of materials property databases for Pb-free alloy systems suitable for high-temperature solder applications. The extent of existing information about key Pb-free systems up to now deemed suitable for high-temperature soldering is limited and in many cases inconsistent. The aim is to compile a set of databases containing information on phase diagrams, thermodynamic, structural, physical, chemical, electrical, mechanical and process related properties of possible solders and corresponding joint materials.
- On a *macro*-scale: The creation of a phenomenological description and models for the prediction of corrosion behaviour, deformation processes, failure modes and other

mechanically related problems occurring in the soldered structure during fabrication and service at high temperatures. In particular, this COST Action will develop processing-structure-property relations, an understanding of thermo-mechanical fatigue, scale and constraining effects of the thermo-mechanical response, the durability of interfaces and intermetallics and identify optimum process conditions.

- On a *micro- (nano-)* scale: Reactive phase formation remains the most mysterious and least understood problem in solid-state science. This involves the formation of intermetallic compounds at solder/substrate interfaces, the development of texture in the reaction products in concentration gradients and the development of defect structures in the vicinity of the reaction interface. The existence of sharp concentration gradients and huge diffusion fluxes in the proximity of the interphase interface (in the region of nucleation) changes the thermodynamics as well as the very notion of critical nucleus and incubation time. Therefore, the main objective here is to develop an experimental and theoretical approach that can be used to elucidate the role of competitive nucleation and growth of intermediate phases in the morphogenesis of the interdiffusion system.

In order for this multiscale, multidisciplinary approach to succeed we will create a framework to enable scientists working in different disciplines and on problems involving different scale lengths to fully interact.

C.2. Expected benefits

At the end of this COST Action, a complete set of data will be available for different solder alloys. This effort will result in a number of environmentally friendly lead-free solder systems for high-temperature applications that exhibit properties suitable for industrial use and which can be considered as replacements for the existing high-lead solders.

This COST Action provides the opportunity for Academic Institutions as well as industry to participate and coordinate their research efforts on a European level, which will be important for the advancement of R&D in Pb-free interconnect technology. Realising the goals of this Action will provide a sound base for setting completely new quality and reliability standards for a wide range of electronic products. It will give European Electronics Manufacturers a market lead over strong competition from Japan, China and the United States, especially in areas where environmentally friendly and recyclable products are concerned.

In addition to the particular application in Pb-free electronics, the knowledge and understanding gained in this Action will be of such generic nature, that it will also be relevant to other branches of nanotechnology and materials science. This COST Action will contribute greatly to the strong position of the Universities and Research Institutions involved in the field of solid-state science dealing with the interrelations between structure, chemistry and mechanical (and functional) integrity of multi-materials systems. This will make these academic institutions more attractive for industrial (commercial) partners oriented towards sustainable technologies and operations relevant for the long-term needs of society and will help them to maintain a strong position in International Networks.

Furthermore, it is important for University academics to work at the cutting edge of materials science addressing globally important issues in order to maintain the educational standards of European students at a high level. This is obviously the primary goal of Universities.

D. SCIENTIFIC PROGRAMME

The scientific programme is built around the three objectives listed in Section C. The structure of this COST Action is flexible enough to incorporate a variety of projects ranging from fundamental research on materials properties to more narrowly focused projects aimed at specific applications.

All of the projects carried out by participating scientists and research organizations will be driven by the need to fulfil the objectives of this Action as outlined above. The scientific programme will combine fundamental scientific research on phase equilibria, mechanical and physico-chemical properties of high-temperature Pb-free solder materials as well as the issues associated with their practical application, namely reaction phenomena at solder/substrate interfaces.

This study is innovative in the sense that the behaviour of Pb-free replacement solders for high temperature applications will be studied at various length scales. It is necessary first to consider the length scale at which the relevant processes take place and then to determine the transitions between the various levels. Currently, there exists no effective formalism to bridge the gaps that separate the macro-behaviour of materials and the controlling phenomena. The main challenge here is to formulate a physically rational model (or family of models) for each level and to identify (near) “touch points” that bridge the various length scales important in describing the reliability of the soldered assembly. An example of such a bridge would be to link the meso-level (phase diagrams & thermodynamics) and the macro level (mechanical behaviour of solder joints). This will provide an understanding of the evolution of interfacial phases during the life-cycle of solder joints. The relationship between microstructural evolution and solder joint reliability will then be investigated through the combined use of micro-mechanical characterization at the phase level, suitable homogenisation methods and local failure criteria.

D.1. Materials properties

This COST Action will extend knowledge on potential high-temperature Pb-free solder alloy systems for high-temperature applications, using existing information about the component elements that can be taken into consideration for this purpose. Since the information in the open literature is by no means complete, it is necessary to coordinate and initiate experimental work on multicomponent alloy systems that are candidates for these types of materials. The research teams involved in this Action have access to all the necessary experimental techniques that can be used in the experimental programme carried out in the scope of multilateral cooperation, coordinated through this COST Action.

The materials property databases will cover phase diagrams of the most important alloy systems together with other important physico-chemical and mechanical properties and, if possible, process related information. As far as possible, all data dealing with the construction of phase diagrams, physico-chemical and mechanical properties will be collected, checked and transferred into a standardized format. They will be augmented by results of research carried out during this Action. This information will be collected in the form of computerized databases that will allow access to the data in an easy manner. All the collected information will be subject to scrutiny by experts in the respective areas for comments on accuracy, reliability, etc.

The first aim (phase diagram modelling) will be achieved by using *CALPHAD* modelling techniques and an experimental programme on the study of thermodynamics and phase equilibria for a number of key systems. This provides an optimum version of the phase diagram that is consistent with the thermodynamic data for the respective alloy system. Here, a team of experienced scientists has been gathered for this Action, having extensive expertise in the creation of self-consistent multicomponent thermodynamic databases to be used for the modelling of thermodynamic properties and phase diagrams (including liquidus surfaces). These databases may be used with the major software packages for the calculation of phase equilibria that are available in the scientific and engineering community. There are several databases already available (COST531 lead free solder database -11 elements, ADAMIS database from Japan – 8 elements, NIST database from the U.S.A.), but none of them is completely suitable for application to the field of high-temperature lead-free soldering. The basic COST 531 database will be used as the starting point, with the addition of other elements that play important roles in these materials – typical examples being Al, P, Mg…. In addition, it will be necessary to provide optimized versions of phase diagrams that relate to the joint between the prospective solder materials and substrates.

A thorough literature search will be carried out for any information relating to thermodynamic and phase equilibrium data for binary and higher order systems. Consistency with existing data will be checked and experimental programmes will be initiated where any important information is not available in the literature. For this purpose, the different experimental techniques available to scientists in this Action will be exploited.

In order to obtain thermodynamic data necessary to determine the stability of the alloy systems as well as to carry out theoretical calculations, a variety of thermochemical methods will be employed, such as vapour pressure measurement, emf (**e**lectro**m**otive **f**orce) measurement, calorimetry and DSC (**D**ifferential **S**canning **C**alorimetry). Phase diagrams and melting temperatures of the alloys will be determined by experimental methods, such as thermal analysis (e.g. DTA, **D**ifferential **T**hermal **A**nalysis), X-ray techniques, transmission and scanning electron microscopy and electron probe microanalysis (EPMA) and metallographic methods. Taking into account the fact that most current solder alloys are near-eutectic, the influence of dopants on properties and the alloying process will be investigated. These theoretical and experimental studies will be enhanced by extensive international cooperation.

The development of the other databases will be addressed by scientists studying physico-chemical and mechanical properties and fabrication. As in the case of the database of thermodynamic properties, careful literature searches supplemented by experimental programmes carried out within this Action will be conducted in order to gather important information about physico-chemical properties (surface tension, wettability, viscosity). Similarly, other scientific teams will investigate the mechanical behaviour of the solid solder materials and of solder joints. Standard experimental test methods will be defined for materials property measurement allowing direct comparison of data from different sources to be made. There is room for extensive cooperation with other projects and programmes currently running in the EU (Using e.g. the experience obtained during the cooperation between the programmes COST531 and ELFNET). The main work will be to combine new and literature data on ductility, strength and fatigue of the solid alloys as well as information on thermally induced stress, thermal mismatch and interfacial shearing stress in joints at different temperatures. The effort of these two teams will lead to the development of separate databases for physico-chemical and mechanical properties.

D.2. Properties of solder joints

The second objective of this Action will be the phenomenological description of corrosion behaviour and deformation processes occurring in the soldered structure during fabrication and long term service. Studies of how solder materials act in different chemical environments and how they react to stress as a function of joint geometry, for example, is of importance. The understanding of reliability issues leading to acceptable failure levels is another specific aim.

The multi-parameter dependency of the mechanical and corrosion response of high-temperature lead-free solder joints will require specific design of experiments and characterization methodologies in order to quickly identify the most reliable solder alloys. Tests such as constant strain rate, cyclic loading, isothermal creep and thermo-mechanical fatigue of solder joints will be conducted to provide data for the quick selection of solder alloys and for the development of detailed life-time prediction models. The effect of environment (moisture, pH, temperature, electrical current, vibration) on the reliability of high-temperature solder joints will also be studied for a better understanding of their impact on the reliability of final products. Another factor influencing strength is polymorphism under which the formation of other phases occurs owing to changes in temperature, pressure or other parameters. The appearance of a new phase can result in microstresses and other defects that can aggregate and promote the breaking of the joint. In order to avoid this process, the addition of special dopants is required to suppress the polymorphic transition.

In parallel with the construction of the experimental mechanical property database (D.1), the development of analytical and numerical models of the mechanical behaviour of the proposed candidate solders will be necessary for the life-time prediction of electronic packages and will accelerate the adoption of lead-free replacement solders in industrial applications. Special interest will be devoted to the study of the interdependency of the mechanical and corrosion behaviour of solder joints as functions of several parameters, such as temperature, stress level, strain rate, processing parameters, geometry and microstructure of the solder joint. Mass transport and chemical reactions in advanced solder joints during their formation and service (oxidation) will be investigated **on both the meso- and macro-scale**. Reactive diffusion as well as interdiffusion owing to selective and concurrent oxidation of the solder joint will be computed on both the meso- and macro-scale. In particular, the following mechanisms will be numerically addressed:

(i) interdiffusion of elements owing to compositional differences,

(ii) stress generation/relaxation during interdiffusion and variable temperature excursions,

(iii) structural transformations owing to interdiffusion (e.g. precipitation of new phases),

(iv) displacement and degradation of selected elements resulting from oxidation.

The model will be verified experimentally and then used for the design and production of solder joints with improved thermo-mechanical fatigue and corrosive oxidation resistance. Furthermore, the **effect of scale** on the thermal stability of the solder/substrate system, i.e. comparison of the thermal stability of the solder joint between the submicron and millimetre scale will be evaluated.

Another key task will be to characterize the mechanical properties of the main phases of solder joints at the micro-level with specific micro testing methods (nano-/ micro-indentation, micro-testing in AFM/SEM) in order to allow detailed predictions of the life time of solder joints taking into account microstructural changes such as phase coarsening and intermetallic layer growth. This multi-scale approach will allow different levels of description of the solder materials to be linked; for example the use of homogenization and finite element modelling techniques relating the micro-structural level properties to the macro-level response of a real electronic package. When a good understanding of the phenomenological behaviour of the best solder candidates has been achieved, specific solder-level and package-level accelerated reliability tests will be conducted, such as vibration and thermally based accelerated tests. The database and specific methodologies developed in these studies will serve as a basis for solder material selection for specific high-temperature applications (automotive industry, high-power electronics) and also for the optimization of the design of electronic packages and products.

D.3. Processes at the Interface

The third objective is aimed at the study of phenomena occurring at the interface between Pb-free solders and various substrate materials, viz. Cu, Ni (P), Pd and Au, formed within the interconnect during fabrication and service.

Miniaturization continues to be one of the most important technological trends in modern electronic packaging, with the dimensions of the solder volume within the electrical interconnect decreasing markedly. This issue, and the relatively high temperatures at which Pb-free solders will be operational, pose very serious questions concerning the influence of reaction products at the solder/substrate interface on mechanical behaviour of the joints. The reliability of electronic products related to the mechanical properties of intermetallic reaction layers is even more important now than ever before. This is especially true for portable products, which frequently experience mechanical shock loading caused by dropping. In order to improve the performance (reliability) of the interconnects, it is imperative to be able to predict (and control) reactions occurring at the interfaces within the soldered assembly.

The problems associated with the formation of new phases by reactive diffusion are fundamentally more complicated than those that can be interpreted in terms of classical nucleation theory. In solid-state reactions, critical nuclei of a product phase are formed in a strongly inhomogeneous region – an interface between the initial reactants. This implies that the nucleation takes place in sharp concentration gradients and stress fields induced by the huge diffusion fluxes occurring in the vicinity of the interphase boundaries. At the initial stage of the interaction, the system chooses an evolution path. This choice determines the sequence of stable and metastable phase formation at the reaction interfaces. Therefore, the central question here is "What are the key internal and external parameters pertaining to the nucleation and growth of intermetallic compounds at the reaction interfaces and how can they be controlled?"

Clearly, the development of any predictive capability for materials whose properties (and performance) are controlled by interfacial reactions calls for a methodology describing the system behaviour on a nanometre scale. It is important to emphasize that since a general model for reactive phase formation is lacking, experiments will constitute the major part of the programme. However, modelling will promote and refine the interpretation of the results.

This COST Action will incorporate a systematic experimental and theoretical study of interfacial interactions between the substrate materials mentioned above and high-temperature Pb-free solder alloys. The programme will address the kinetics and thermodynamics of chemical reactions in the solder/substrate systems, explore the defect structure developing upon reactive diffusion and study the stress relaxation mechanisms operating during the interaction. The work will define and interpret:

1. The atomistic aspects of the initial stage of the reactive phase formation in relation to the product layer morphology and defect structure developing in the reaction zone.

2. The influence of the crystallographic orientation of the reactants and texture developing in the product phase layer on the stability of the microstructure within the soldered interconnect.

3. The significance of the Kirkendall effect and the diffusion-induced stresses in the morphogenesis of the interdiffusion system.

Based on the experimental results, the requirements and layout for suitable analytical and/or numerical modelling approaches to reactive phase formation will be formulated. If progress on characterization does not turn out to be an essential constraint, explorative modelling of phase selection in reactive diffusion as well as the possibility of nucleation at grain boundaries will be pursued for selected cases. This will put the diffusional aspects involved in the description of nucleation and growth of phases in Pb-free soldered interconnects on a sound footing.

The results of this work package will be highly important for a broad scientific community, because the resulting conclusions will eventually lead to a paradigm shift in the way we treat multiphase diffusion in the solid state.

The morphological evolution occurring in the reaction zones at interfaces will be simulated using the phase field approach. Phase field models are based on diffuse interface descriptions and can therefore predict the evolution of complex morphologies during phase transformations and coarsening processes. Various thermodynamic driving forces (such as those related to phase stabilities, interfacial energy and elastic strain energy) and various transport processes (such as heat and mass diffusion) can be considered in phase field simulations. They will allow the study of the role of diffusion, anisotropy and transformation strains on the growth of the interfacial reaction zone. By extension, the effect of temperature and external load on coarsening of the microstructure during the operation of the soldered assembly can be simulated as well.

Phase field simulations require as input, information on thermodynamic, kinetic and mechanical properties of the different phases and on the properties of the interfaces. Most of the thermodynamic information, crystal structures, mechanical properties, thermal expansion coefficients and surface tension will be taken from the material property databases (D.1). Information on diffusion coefficients and reaction kinetics will be compiled through literature search and, where necessary, experimental measurement.

E. ORGANIZATION

This COST Action will bring together European researchers from universities, research institutions and industrial research centres working on the development of new high-temperature Pb-free solder materials. The involvement of young scientists (including graduate students) is a natural part of the project (see part D of Additional Information). It is designed to encourage and support the exchange of scientific and technological knowledge and co-operation. The scientific effort will be split between three **W**orking **G**roups (WG), with fields of interest as shown in Fig. 1. These working groups will constitute the framework of the Action.

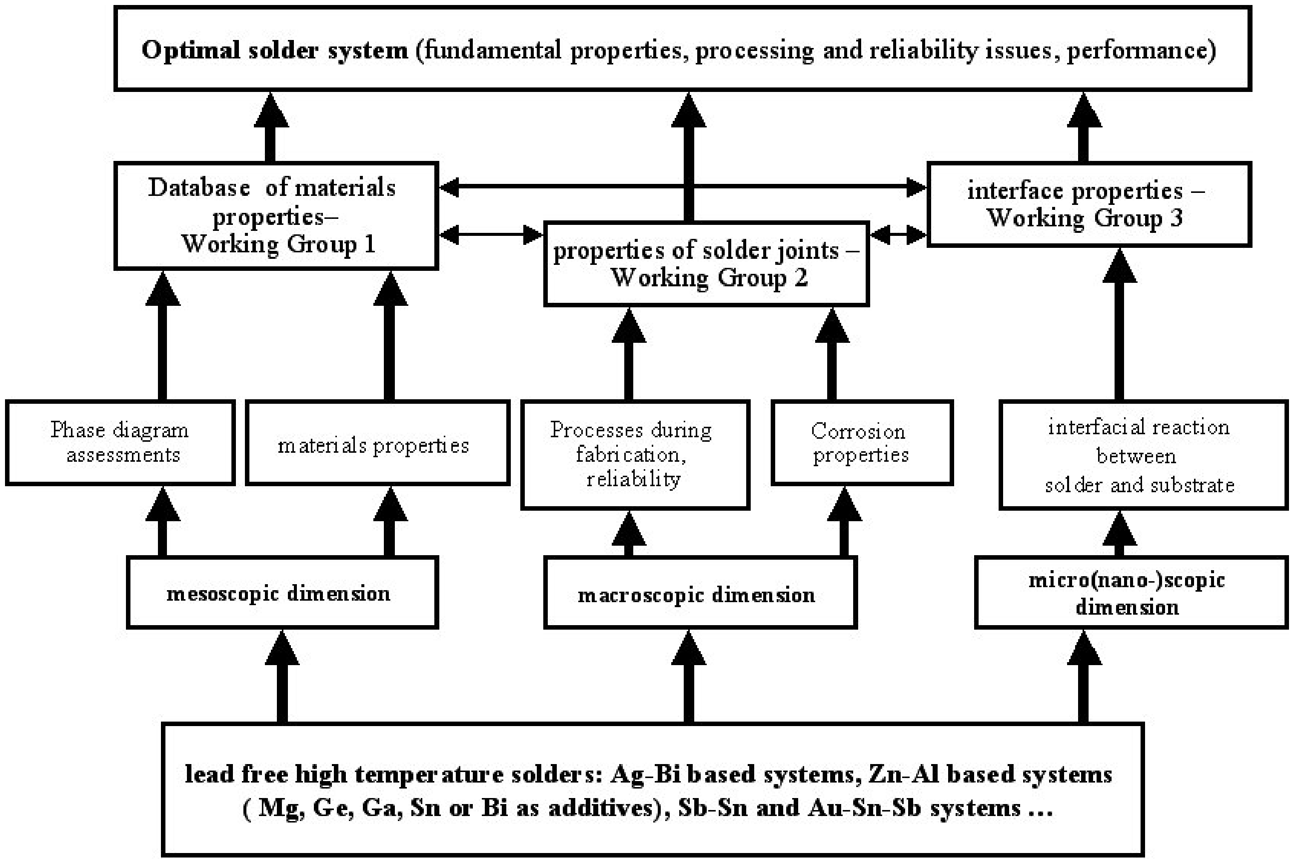

Fig. 1 - Schematic diagram of the Scientific Programme

The Management Committee (MC) of this COST Action will be organized and run according to “COST 400/01 Rules and Procedures for Implementing COST Actions”.

The research work will be divided between three Working Groups (see Fig. 1). The scientific programme of each Working Group covers one of three goals as specified in section C.1., and described in more detail in section D.1.-3.

A Chairperson will be appointed for each Working Group to coordinate the work within the group and represent the activity on the Management Committee. To relieve the administrative load on the members of MC and chairs of particular WGs, the structure of each WG will consist of several vice-chairpersons, who will be in charge of the coordination of particular aspects of the scientific programme. A typical example is WG1, where the vice-chairs will be in charge of development of the different databases. They will be responsible to the chair of the group and cooperate closely in selecting the most appropriate format for the dissemination of results. The scientific programmes will be carried out in close cooperation with other WGs and strong overlap between the members of these groups is expected in all fields of interest (see Fig. 1). This participation of individual researchers in more than one Working Group is encouraged to enhance information exchange between different groups.

The research programme will be conducted through multilateral group projects, which will be financed by the participating parties through their own research funds. Enhanced mutual cooperation will be supported by the COST Action in the form of workshops, conferences and Short Term Scientific Missions, which are very efficient tools for promoting collaboration and for increasing expertise, especially for young scientists. These missions also fulfil the need for short focused effort for specific periods of the project.

The MC will seek actively to cooperate within other international projects, organized both under EU patronage and by other bodies (industrial, professional, committees etc.).

The MC will search for and invite leading academic and industrial colleagues in various subjects to give plenary talks during annual workshop meetings. All research groups will be strongly encouraged to participate in these workshops to promote the optimal exchange of ideas and information, especially between researchers from academic institutions and those from industry. In this way it will be possible to keep all participants continually informed about the status of the Action and to stimulate new research directions if and when necessary.

F. TIMETABLE

This COST Action will run for **four** years.

The length of this Action is based on previous experience with similar projects, as this is the optimal duration for starting extensive cooperation, the preparation and start of group projects and in order to obtain results from lengthy experimental programmes.

Each year, a series of Working Group workshops will be held in addition to the MC meetings. Each will be a one or two day event where the results obtained in the previous period of the project will be presented, and more importantly discussed. Part of the workshop will be devoted to ‘round table’ discussions where the work carried out can be assessed and future work planned. It is vital that the work carried out in the Working Groups be continually monitored and the effort adjusted accordingly, if and when necessary. The output of the meetings in the form of CD-type proceedings with abstracts and presentations is recommended as the most appropriate form of dissemination. As there will be close cooperation between the groups, the members of other groups will be encouraged to participate. Starting from the second year of the Action, Joint Working Group meetings will be held (two to three days) to increase the dissemination of results and mutual contacts. Experience from previous COST actions has shown how worthwhile such meetings are.

There are several international conferences and meetings that are held on a regular basis (annually, biannually), e.g. The Discussion Meeting "Thermodynamics of Alloys" that brings together experts from various fields relevant to some Working Groups of this Action. Although these events are completely independent of this COST Action it would be advantageous to attach relevant COST Annual Workshops to such events.

The timetable is shown in Fig. 2. The regular biannual MC meetings are not shown in this timetable.

A midterm conference, followed by midterm review will be held after a period of 2.5 years. At this review there will be a formal evaluation of the project and an assessment of further research work necessary to successfully complete this COST Action.

Task	Year 1	Year 2	Year 3	Year 4
Management of the Action	planning and kick-off meeting		Midterm report	final report
event	WG kick-off meetings	WG workshops	joint annual workshop	joint annual and final workshops
WG1: Material properties databases	Literature review Experimental programmes - study of material properties, experimental and theoretical assessments of phase diagrams Finalizing the databases			
WG2: Properties of solder joints	design of experiments and characterization methodologies Exp. programme – e.g. constant strain rate & cyclic loading, isothermal creep & thermo-mechanical fatigue of solder joints the development of analytical and numerical models of the mech. behaviour and for life-time prediction of the candidate solders			
WG3: Processes at the interface	systematic experimental and theoretical study of interfacial interactions between the substrate and high-temperature Pb-free solder alloys analytical and/or numerical modelling approaches to reactive phase formation			

Fig.2 – The timetable of the Action

G. ECONOMIC DIMENSION

Scientists from the following countries have actively participated in the preparation of the Action or otherwise indicated their interest: **Austria, Belgium, Bulgaria, Czech Republic, Finland, France, Germany, Italy, Poland, Portugal, Serbia, Slovakia, Slovenia, Sweden, Switzerland, The Netherlands, United Kingdom.**

On the basis of national estimates, the economic dimension of the activities to be carried out under the Action has been estimated at **24** Million € for the total duration of the Action.

This estimate is based on the assumption that only those countries indicated above will participate in this Action. Any departure from this will change the total capacity accordingly.

At least one half of this capacity is covered by the participation of PhD. students and other young scientists.

H. DISSEMINATION PLAN

The target groups for the results of this Action, especially the material properties databases and selection of prospective systems for high temperature soldering, are researcher teams working in similar fields, including those from the industrial sector. The results should simplify the development of modern replacement materials in many technological processes as the databases will allow modelling of a number of important properties of prospective systems, e.g. liquidus temperatures and surface tension, which are crucial for materials design and with a significant time saving in comparison with developments based mainly on experimental programmes.

Special attention will be given to communication of information about lead-free soldering to non-specialists both within and external to the Action.

The dissemination of results will be optimized by various routes:

- The main route to the dissemination of results will be *via* articles published in peer reviewed journals as well as oral presentations at key related conferences; which this Action will encourage. This will include scientific journals of a more general nature, where not only this Action will be publicised, but COST as well. All publications arising from research carried out under this COST Action will credit COST support, and the MC will encourage and promote joint publications.
- A second important route to dissemination will be the annual workshops aimed at discussing the progress achieved to date and to bring together researchers from academia and from industry.
- A web page will be created shortly after the start of the Action to disseminate the information among the participants and also to the public. Therefore, public and password protected sections of this webpage will be established to allow proper exchange of knowledge, reports, meeting minutes and other information.
- The material properties databases will be prepared and released in an appropriate way (as decided by the MC in conjunction with the COST office) during the final stages of the project. Preliminary versions will be released for use by the Action participants.