PARTS SYNTHESIS APPROACH FOR 3D INTEGRATION OF MEMS AND MICROSYSTEMS LEADING TO SYSTEM-ON-PACKAGE

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Abstract: This paper aims at developing Parts Synthesis Approach (PSA) for three-dimensional integration of MEMS and Microsystems leading to System-On-Package (SOP). This eliminates the interconnection related problems that arise when MEMS and its associated circuitry are packaged separately. A gas sensor array microsystem illustrates this. The novelty is that the electronics block at room temperature and the sensor at sensing temperature (250°C – 550°C) coexist in the same SOP. Targeted specifications of the SOP are low power budget per sensor and low cost. Thermal and structural modelling and analysis has been done using ANSYS software. The SOP is modular in design and construction.

In PSA the six physical parts of the SOP are first designed, optimized and fabricated individually and then integrated to form the desired SOP. The substrate is an integral and active part of the SOP. Power management is done by reducing thermal mass of the hotplate, increasing thermal resistance between the hotplate and the rest of the substrate and using pulsed power operation. Designs of the cavity structure, the coverlid and the bottom support help in thermal management. This technique circumvents the difficulties of forming deep cavities in LTCC technology. Since the six different parts of the SOP are fabricated separately and then integrated together the final yield is high. Designing in parallel reduces required time and cost.

KEY WORDS: Cavity, LTCC, Microsensor, Microheater, MEMS, Packaging, Sealing, SOP, System-on-package
1. Introduction

Advanced integration of MEMS and other devices to form a complete system is a tough task. The requirement is to provide electrical, optical and fluidic buses without disturbing biological / thermal / mechanical / environmental conditions prevailing at the device. The cleaning, assembly and sealing processes must be chemically, thermally and mechanically compatible with MEMS and its protecting and assembly materials. This is a challenge as MEMS, specially BioMEMS are very sensitive to a large number of chemicals and to temperatures higher than about 60°C. Special tools will be required to handle MEMS. New processes may demand development of specialized equipment. The solution lies in the development of the System-On-Package (SOP).

At micro level advances have been made and solutions are being sought by wafer-level-packaging (WLP). At macro level 3D stacking of WLP structures is being researched. Some work has also been done at the intermediate level of packaging — termed as MESO level. Low Temperature Co-fired Ceramic (LTCC) Technology has emerged as a packaging technology because of its inherent advantages. Green ceramic tape can be easily cut in a desired shape and size, cavities maybe formed in the tapes and 3-D structures can be easily designed and constructed. This has made this technology very attractive for SOP. The Parts Synthesis Approach addresses the SOP at MESO level.

2. The Parts Synthesis Approach

In the Parts Synthesis Approach\(^1,2\) the SOP is custom-designed and custom-fabricated for each application to optimize cost, performance, reliability and time-to-market the product. Initially the entire system is considered and basic structure of the SOP is designed. Then the six physical parts of the SOP are dealt with separately. These parts are: (a) the substrate (b) the cavity structure (c) Input/Output ports (d) Cover lid (e) the Bottom Support and (f) the Electronic Block. Each part is individually designed, fabricated and tested. An important part of the new approach is the integration of these parts to form the 3D structure resulting in SOP. The strategy adopted in this work is intelligent selection of existing materials and clever use of existing techniques. The novel features of this approach are: (1) the substrate plays an active role and is an integral part of the SOP. Majority of electronic interconnections, resistors, capacitors etc. are fabricated in or on it. (2) The cavity structure is designed and fabricated in such a way that each device (MEMS, MOEMS, VLSI etc.) is exposed ONLY to the atmosphere it is required to interact with and is completely shielded from any other environment that may be present. Performance specifications of the SOP govern shape and size (including height) of the cavity structure, material to be used and techniques used for forming and integration of cavity structure. (3) The shape, size, number, pitch and placement of I/O ports can be optimized to meet the required goal, (4) the coverlids can play an active role, if required to do so. In the new approach lids may provide a means of interaction between the MEMS and the environment. Lids may be of different design and material for each cavity depending upon its performance and sealing requirement. (5) The materials and techniques for fabrication of the six parts may be different and therefore can be individually optimized. Figure (1) schematically depicts the physical parts and the relation between them that together form the new approach PSA. The design of the multilayer LTCC substrate (part–a) has to solve the problems related with the interconnection of MEMS and other active and passive devices. Physical size of the add-on devices and their application environment are used as input in designing the cavity structure (part–b). Environmental specification governs selection of the material for fabricating the cavity structure the material and technique for sealing the cavity structure and the ports (part–d) with the substrate and the coverlids (part–c) with the cavity.
structure (part–b). In the hypothetical case depicted in fig (1) both sides of the LTCC substrate have been used to reduce dimensions, weight, volume and cost of the SOP. It also helps in reducing the interconnection length and thus improving the performance. The cavity structure has been divided into 5 parts. The cavity for MEMS-1 has either no cover lid or mesh type coverlid. This allows free interaction of the device and the surrounding atmosphere. The device–environment interface is not disturbed. For MEMS-2 inlet and outlet connections have been provided with the cavity. While the device is isolated from the SOP environment it can interact with a controlled environment (e.g. gas to be sensed). In this case also the device–environment interface is not modified. Coverlids for MOEMS-1 and MOEMS-2 may be optical filters of different wavelengths. While these devices are completely isolated from the surrounding fluids they may have different optical inputs/outputs. Finally the fifth cavity houses all other conventional components that require complete isolation from environment. Material for coverlid has the added consideration of permitting or blocking any input/output through it. The sealing of cavity structure and the lids is of prime importance. This determines the reliable performance of SOP over the desired life period in the intended environment.

3. Design and Simulation
The PSA treats electronic systems as convergent systems leading to system-on-package. In general this will involve three-dimensional integration of components as well as their interconnections. The SOP is therefore a 3D entity that utilizes best of on-chip integration (SOC) and best of package integration (SIP) that is available. SOC is procured from the market. SIP is designed and fabricated using LTCC technology and embedded components as far as possible. This also takes care of large number of interconnections. Design and fabrication of the cavity structure and 3D integration therefore become major issues. This is the step where one has to solve the problems related with budgeting —thermal, power, time and financial.

Thermal management and control of local environments: The SOP contains devices that may operate at elevated temperatures and/or may require exposure to special environments. In PSA this problem is solved by clever design of the cavity structure and the LTCC substrate. In this work a typical gas microsensor has been used to illustrate this approach (figs 2, 3). LTCC substrate has been designed in such a way that on micro scale thermal mass is minimized, thermal resistance between the microheater and the sensing element is minimized while the microheater is electrically and environmentally isolated from the sensing element. On the meso scale the thermal resistance between the microheater and the rest of the SOP is maximized to reduce power consumption and also to reduce flow of heat to other parts of the SOP\textsuperscript{3,4}. Further thermal management is achieved by proper design, placement and connection of heat pipes with in the LTCC substrate. Cavity structure has been specially designed to meet the performance goals, control local environments and thermal management. At present the design process is semiautomatic. The materials and the design parameters are manually varied. ANSYS software has been used for modeling and simulation. Geometric dimensions and material selection has been done by iterative process.

Integration of various parts: Once the different parts have been synthesized, optimized and fabricated they have to be integrated to form the SOP. Bonding of ceramic-to-ceramic and ceramic-to-metal is a special consideration for PSA. The choices include: (a) High Temperature processes such as Brazing, Soldering, Glass sealing, Thick film paste sealing, and (b) Low Temperature Processes such as Organic Adhesive bonding, Diffusion soldering, Inorganic cementing. For obvious reasons low temperature processes have to be preferred. In organic adhesive bonding the bond material may
react with the materials being finally used especially if these are organic or bio-materials. The bond is stable up to temperatures of ~ 100°C only. **Diffusion soldering** is an advanced joining technique. The mechanism of joint formation is intermetallic locking. The novelty of this technique is that the interconnection is made at a comparatively low temperature but is stable up to temperatures much higher than the temperature at which it was fabricated.

This technique is specially suited for SOP if it contains temperature sensitive devices. The technique may be used for metal–metal or metal–ceramic or other joints. Advanced version of this technique uses metallic paste as an interlayer. **Inorganic cementing** is perhaps the cheapest and coolest solution. The method is specially suited for joining comparatively large parts together. Special feature of this method is that it can be easily used on non-flat surfaces also and with organic and bio samples. The joint is stable up to a temperature higher than that used in LTCC firing. The bonding material is electrically insulating. Commercially available materials may not be screen printable or photopatternable. The points to be considered in selecting a technique are materials that can be bonded, quality of the joint, temperature of operation, cost of joining, cost of materials and their shelf life, time taken for joining, additional processing steps required for the technique and condition and nature of the surfaces to be joined. CTE modifier coatings have been used to take care of the differences in CTE (Coefficient of Thermal Expansion) of materials to be bonded.

4. Results and Discussion

For a microsensor SOP the electric power budget becomes very important target specification. It is estimated that, using the PSA, about 350mW power would raise the temperature of a single sensor to 350°C with a 10 second response time. Power consumption per sensor will be further reduced for multiple sensors per MHP. This will give a long life to a battery for pulsed operation of small duty cycle. Inorganic cementing is a cool (room temperature) and cheap joining technique that can be used for sealing LTCC with metal, alumina or LTCC. Another major advantage is that it can be used for joining non-flat surfaces also. The design is well suited for a single sensor as well as for an array of sensors, at the same temperature or at different temperatures.
Figures 1, 2 and 3 are illustrative only and are not to scale.

Fig. 4b. Fired LTCC substrate bonded with metal (Kovar) package. (Photo shows side view of the joint)

Fig. 5b. Fired LTCC substrate bonded with alumina substrate.

* Figures 1, 2 and 3 are illustrative only and are not to scale.
* Figures 4 and 5 show typical results for use of inorganic cement. Fig. 5 shows cross section of LTCC – alumina bond. The bond is uniform. Photo of the cross section shows that structures with hanging areas can be created. The gap, intentionally kept between LTCC and Alumina, has come out as a black line in the photograph. The bonds were made at room temperature without the use of harmful chemicals.
The novelty of the approach is that only the sensing element is exposed to the environment to be sensed. All other parts are well protected. The number of microhotplates (MHP) is decided by the number of different temperatures to be used — one for each temperature. The number of sensors to be put on it governs the size of MHP. Based on these inputs the substrate is designed for LTCC technology. The cavity structure is crucial. It provides environmental, thermal and electromagnetic isolation wherever required. The Coverlids and the bottom support are designed to meet the requirements of thermal management, sensing environment and hermeticity. The SOP is designed to perform in hazardous environments. Therefore LTCC has been preferred over organic polymers that may degrade under certain conditions.

This paper has presented a microsensor SOP development approach that eliminates the problems associated with silicon microsensors on one hand and with traditional thick-film-on-alumina microsensors on the other hand while remaining in a tight electric power budget. Following PSA, the electronic block at room temperature and the sensor at the sensing temperature coexist in the same SOP. Every part of the SOP plays an active role — electrical, mechanical or thermal. Clever design and pulsed operation with small duty cycle not only minimizes electric power consumption but also reduces heat to be dissipated. In some cases the cavity structure may be made of LTCC tapes and may be laminated and cofired with the LTCC substrate. The walls of this structure may be used to provide electric, optic and/or fluidic buses. For achieving higher degree of integration such structures may be stacked one over another. Flexibility and modularity gets built-in. This will depend upon the number of interconnections, types and number of local environments, operating temperatures and heat to be dissipated. The PSA results in a SOP that is modular in construction and can be easily expanded. For each application the design, material and construction of all the parts may be individually optimized. As the parts are individually fabricated and then integrated to form SOP the final yield is high and the cost is low. Thus the product cost can be optimized. Development time is also reduced.

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