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3D stacked MEMS and ICs in a miniaturized sensor node

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Abstract-**3D integration of micro electromechanical systems (MEMS) is expected to reduce the foot print of existing MEMS products and enable production of miniaturized sensor nodes on a large scale. However, 3D integration of MEMS is in general different from 3D integration of planar integrated circuits (ICs) due to additional mechanical requirements. Specifications regarding properties like stiffness, volume, and mass must be taken into consideration when selecting stacking technologies for MEMS. A demonstrator with a 3D integrated MEMS and the ideas behind the selection of stacking technologies are presented in this paper.**

I. INTRODUCTION

3D integration provides the advantages of short interconnections, miniaturization, and compact packaging. Within the integrated circuit (IC) chip community, substantial research has been carried out lately with the objective of realizing 3D integrated chips. But to obtain a broader range of applications (“more than Moore”), IC chips need to be combined with sensors, actuators and power supplies. However, to integrate such devices into a 3D stack implies additional challenges compared to 3D stacks consisting solely of planar ICs. 3D integration of micro electromechanical systems (MEMS) is more challenging due to mechanical concerns. MEMS will typically have specific requirements regarding mechanical issues like stiffness, robustness, volume, and mass. MEMS wafers can be fragile and complicated to handle, there may be restrictions concerning polishing due to delicate mechanical structures and there may be inlets or released structures that rule out the possibility of wet post processing. The mechanical issues limit the range of applicable technologies, but stacking and interconnection technologies that are relevant for 3D integration of typical MEMS are presented in this work. The presented discussion of technologies is based on a demonstrator with a 3D integrated MEMS devices developed as part of the European project e-CUBES [1].

II. THE AUTOMOTIVE DEMONSTRATOR OF E-CUBES

Sensor networks are researched in various automotive applications, in particular in tire pressure monitoring systems (TPMS) installed as autonomous sensor nodes. A tire-mounted TPMS should ideally weigh less than 5 grams and have a volume of less than 0.5 cm^3. Typically, the miniature system must include a MEMS sensor, application specific integrated circuits (ASICs), power supply, a radio and an antenna. The given specification with regard to volume requires a close integration of the components. Three years of process development is about to result in a TPMS demonstrator with an overall tight integration where the MEMS sensor and the ASICs are 3D integrated. The automotive demonstrator is one out of four wireless sensor networks that are developed as part of the e-CUBES project. The original perception of a fully 3D integrated e-CUBE and the solution for the presently 3D integrable parts of the TMPS demonstrator can be compared in Fig. 1.

Various devices with different shapes and foot prints needed to be integrated in the final stack design. All 3D integrated layer levels were stacked using chip-to-wafer bonding. Wafer-to-wafer bonding was not an option for any of the layers due to non-matching wafer sizes and designs. The lower most layer was a processing unit delivered on 200 mm wafers with full wafer thickness from an external supplier. The second layer was a radio chip that was manufactured on 200 mm wafers within the e-CUBES project and through silicon vias (TSVs) could therefore be included using a “post back-end-of-line via” approach as defined in Ref. [2]. Post processing after all metallization layers had been patterned, demanded that areas were reserved and kept free for metal in regions there where the TSVs were defined. The redesign required a close collaboration between the ASIC wafer manufacturer and the post processing entity. The wafer with radio chips was thinned down to ~60 µm before it was diced and stacked onto the wafer with the processing units. A MEMS bulk acoustic resonator (BAR) device and a MEMS

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pressure sensor were included in the third and upper most layer of the stack. Both components were processed on 150 mm wafers and prepared by partners within the project. The BAR wafer was 200 µm thick whereas the pressure sensor was a stack of glass and silicon wafers with a total thickness of ~1 mm. TSVs were realized in the cap of the pressure sensor using a commercially available technology.

The overall stacking sequence had to be well planned and the individual demands of every device had to be taken into consideration [3]. The lower most layer with the processing unit was kept as wafer throughout the complete stacking process whereas the other devices were diced before stacking.

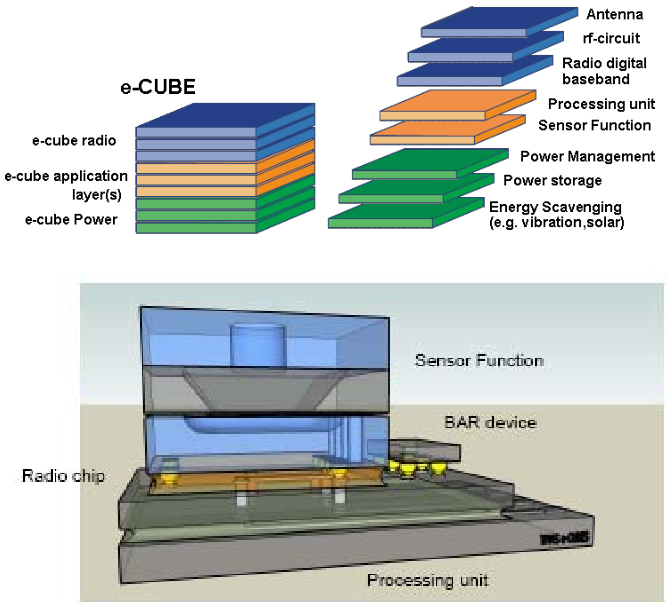

Fig. 1. Original idea for an e-CUBE [1] (top) and a sketch of the 3D integrated parts of an e-CUBE being realized for the automatic demonstrator within the e-CUBES project (below).

III. SELECTION OF TSVs FOR THE MEMS

Realizing TSVs for 3D integration of MEMS is both costly and technologically challenging. Thinning the cap wafer of the pressure sensor used in this demonstrator was not acceptable due to the mechanical aspects of the device. The required pitch for the TSVs was 100 to 150 µm, which allowed the via holes that need to be etched through the ~300 µm thick cap wafer to be about 50 to 75 µm in diameter. This corresponds to an aspect ratio (AR) of 4 to 6. Surface micromachined MEMS wafers normally only need a cap wafer on the top side of the sensor whereas this bulk micromachined pressure sensor also needed an inlet wafer at the bottom. By using a flip-chip solution the pressure inlet was oriented towards the top of the stack, which allowed for interaction with the environment. Several interesting TSV technologies published for MEMS were considered for the TSVs in the cap wafer, some of which were already commercially available. Si-glass compound wafers from PlanOptik [4] became the final choice. The TSVs in the compound wafers were highly doped silicon vias which were insulated by surrounding borofloat glass. Si-glass compound wafers can be made by combining deep reactive ion etch (DRIE) of silicon wafers, anodic bonding, glass flow and wafer grinding [5]. The via resistance was expected to be in the order of several ohms. A lower resistivity would probably have been needed if the device was an RF MEMS, but the values were acceptable for the pressure sensor. A tungsten-glass compound wafer, as commercially available from Schott [6], could have been an alternative offering via resistances in the order of milliohms, but such wafers were not available early enough for this demonstrator. As also the inlet wafer is a glass wafer, having a glass based compound wafer as cap wafer contributed to increased symmetry in the wafer stack which is important for stress control. The ease of bonding of the cap wafer to the sensor wafer was also an important factor. If the inlet wafer had been a silicon wafer or if there had been no inlet wafer at all, a cap wafer from Silex [7] could have been a valuable alternative. Silex offers a technology where silicon vias in silicon wafers are insulated by a trench of dielectric material. DRIE and grinding are key process steps for these TSVs which also promise a via resistance in the range of a few ohms. Earlier, SINTEF has presented a solution for hollow vias with a minimum pitch of 50 to 200 µm in 300 µm thick silicon wafers [8,9]. By keeping the vias hollow, the costly and time-consuming process of filling the via holes is avoided. Hollow vias also eliminate possible reliability concerns related to mismatch in coefficient of thermal expansion between wafer material and filling material (e.g. silicon versus copper). The achievable electrical resistance is in the same range as for the other mentioned technologies. A rather different approach for capping of MEMS with TSVs is offered by Hymite [10]. Wet etching of cavities in SOI (silicon on Insulator) wafers is used to thin cap wafers locally. Electrical signals are routed along the side walls of etched cavities and the TSVs are etched through the remaining material. This can be a solution if the mechanical requirements of the MEMS device allow a local thinning of the cap wafer.

IV. SELECTION OF STACKING TECHNOLOGY FOR THE MEMS AND THE BAR

After comparing different technologies [9], gold stud bump bonding (Au SBB) was found to be ideally suited for 3D stacking of the pressure sensor and the BAR in the TPMS demonstrator. One of the main advantages of using Au SBB includes the fact that there is no need for any wet processing that would be problematic for a sensor device with a pressure inlet. Also, with Au SBB the MEMS wafers did not need the deposition of any under bump metallization layers as would be the case when using conventional solder bumping. Another advantage of Au SBB is that the thermal budget can be kept low, especially when ultrasonic bonding is used. This was crucial for this demonstrator since this was the third layer to be stacked and the previously bonded layers should not be affected. Since stud bumping is a serial process, it is most cost-effective for interconnecting devices with low I/O counts like the MEMS devices of this demonstrator. Both the pressure sensor and the BAR device, as shown in Fig. 2, were bonded on top of a 60 µm thin radio chip that had previously been bonded to a wafer with processing units using soldered SnAg microbumps and an underfiller. AuSn could have been an alternative solder material for the electroplated bumps. However, SnAg has lower melting point, more ductile behaviour, and lower yield stress than AuSn. Therefore, SnAg solder bumps were preferred. To stack the third layer was definitely a technological challenge. The underlying devices had to withstand the temperature, force and energies that were used during the stud bump bonding process. Precautions were taken in the design of the stack by including microbumps under most positions where an Au stud bump was to be placed. The bonding parameters were optimized in order to obtain a good interconnect and at the same time reduce the risk of harming the devices.

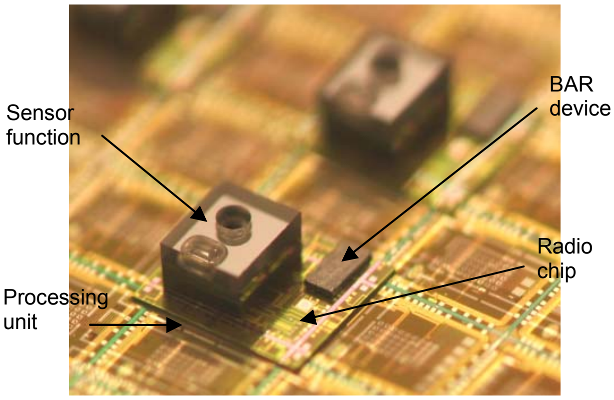

Fig. 2. An image of the final 3D integrated stack bonded for the automotive demonstrator of the e-CUBES project (Photo: Thor Bakke, SINTEF).

Kulicke&Soffa [11] did the stud bumping on the 150 mm pressure sensor and BAR wafers, using their so-called Accubump process. The bumps on the BAR devices had an average diameter of 47 µm, a height of 32 µm and a shear strength of 20 gf. On the sensors the bumps had an average diameter of 53 µm, a height of 30 µm and a shear strength of 23 gf. To improve the adhesion of the pressure sensor to the underlying radio chip, Epo-Tek 353ND underfiller was used. This is a non-conductive epoxy adhesive that was dispensed onto the underlying ASIC right before the flip-chip process. One of the main advantages of the Epo-Tek 353ND underfiller is its large range of operation temperatures. This makes the underfiller ideally suited for the severe reliability requirements that the automotive sector has. No underfiller was allowed below the BAR as it could interfere with its operation. However, the small height of this device relative to its extension in x-y direction gave relaxed requirements for the bond strength. This can be understood by studying the image of the final stack in Fig. 2. The bonds need to be strong enough to survive final dicing. After dicing the complete stack will be overmoulded which means there should be no more concerns for the bond strength. Alternative stacking technologies for the BAR would be soldered microbumps or so-called SLID bonding using Sn and Cu [12]. Those technologies would however be less suitable for the pressure sensor in this demonstrator as the wet processing involved in resist definition and plating would be problematic for the pressure inlets.

The presented selection made for TSVs and interconnects of the pressure sensor and the BAR in this work can be adapted to a wide range of MEMS devices. Glass based cap wafers with silicon or tungsten vias are favorable for optical MEMS devices that require both an optically transparent window and vertical interconnections. Fluidic devices based on interaction with light sources can also benefit from such a packaging solution. A transparent window is highly advantageous for visual inspection of packaged MEMS devices in general. A certain level of hermeticity is an additional requirement for most MEMS devices, in particular for vibrating devices operating in vacuum. A wafer bonding technology compatible with the glass based cap wafers must be applied to achieve the hermeticity requirements of the specific application. Possible technologies are e.g. anodic bonding, metal bonding and adhesive bonding. Finally, adding Au studs or plated microbumps to the bonded wafers yield wafer level packaged devices ready for dicing and surface mounting.

V. CONCLUSIONS

Despite the challenging task, a demonstrator with 3D integrated MEMS devices was processed within the e-CUBES project. The selection of stacking technologies turned out to be highly application specific, but several design rules were established that will be valid for 3D integration of most MEMS. Au SBB in combination with Si-glass compound wafers was found to be a versatile stacking technology for MEMS with low I/O counts and moderate demands for conductivity.

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