New MEMS Sensor process by TSV technology for smaller packaginge

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***Abstract*— MEMS (Micro Electro Mechanical System) Motion sensor such as Accelerometer and Gyroscope are composed by MEMS die which manufactured by surface micromachining process and signal processing die which is made by standard CMOS process. These two types of dies are assembled in single package of plastic mold called LGA. Current standard products have almost 3x3mm square package size for Accelerometer, and 4x4mm or less for gyroscope and combo of accelerometer and gyroscope. To realize smaller package for MEMS sensors with same performance to meet market requirement, new process technology for surface micromachining must be introduced. Key process technology is TSV (Through Silicon Vias) approach.**

We introduced original TSV technology for MEMS sensor products called SMERALDO, MEMS die size is reduced over 20% in average with keeping same mechanical structure. This can make realize smaller packaging, or higher performance, or multi functions sensor like smart sensor module which integrated multiple motion sensor and microprocessor.

Keywords*— *MEMS;Accelerometer; Gyroscope; Magnetometer; Pressure sensor; Smart sensor; Stacked package; Plastic mold; Through Silicon Vias; Deep RIE; Bosch process; Micromachine;

I. INTRODUCTION

The MEMS product history started in 1990s. The first application in market was for automobile like airbag shock sensor. For the next a decade, there were no major changes or spreading on MEMS market, but in middle of 2000s, some HDD manufacturer stated to use single chip 3-axis accelerometer into HDD unit for head protection function. This is the first major application of MEMS sensor in consumer market in high volume. This first step is brought by improvement on package size, power consumption and performance of MEMS sensors.

Next big evolution happened by game console market, 3-axis Accelerometer was innovated into game controller, this is also big innovation of user interface technology on consumer equipment. This new application introduced very big impact on production technology of MEMS by requiring very higher volume no MEMS manufacturer ever experienced [1].

The latest break through on MEMS market has happened around 2010, which was led by Smartphone market explosion. Apple's iPhone and Android smartphone require integrating 3-axis accelerometer, 3-axis gyroscope and 3-axis magnetometer to control user interface. In addition to them, air pressure sensor, ambient light sensor, temperature sensor are going to integration on the system to realize the new functionality.

Market spreading of MEMS sensors still continue, IoT and wearable devices are ramping up rapidly in 2014, these kind of application also require having various MEMS sensors.

Technology points of view, the key factor of growing of market of MEMS in this decade are led by improvement on performance, power consumption, costs and package size. Especially recent mobile equipment has very limited space not only for surface area but also height. Small and thin package size is put higher priority by market requirement.

Package dimension and height of MEMS sensor is restricted by sensor die size. Therefore to make sensor die size smaller is the key to reduce package size to meet market requirement,

For this requirement, most effective approach is to reduce wire bonding pad area by using TSV technology. TSV replaces traditional signal routing on silicon with short vertical interconnects. TSV utilizes short, vertical structures to connect multiple silicon dice stacked vertically in a single package, offering greater space efficiency and higher interconnect density compared with wire bonding.

This technology has high level compatibility with current process for mechanical elements, assembling and packaging. In this paper we present new technology for reducing die size, especially about TSV process for MEMS sensor.

II. STANDARD MEMS SENSOR PROCESS

Typical MEMS Sensor production process is based on surface micro machining technology on silicon wafer. STMicroelectronics have developed own process of surface micro machining for MEMS sensor products, that is called THELMA (Thick Epitaxial Layer for Micro gyroscope and Accelerometer). THELMA process can adapt to build micro mechanical structure for accelerometer and gyroscope on silicon wafer.

The sensors die manufactured by THELMA is consisted by 2 wafers, one is sensor wafer which have micromechanics to sensing the motion, and second is a cap wafer to seal the cavity of mechanical elements composed on sensor wafer. These two wafers are processed independently and bond each other on wafer level just before dicing.

In this paper we describe on the assumption that THELMA is used as surface micro machining process.

A. Wafer Process flow for MEMS sensor

Surface micromachining like THELMA forms structures in a "thick" crystalline layer grown on top of a silicon wafer. Processing of this layer-typically up to 25 μm thick, maximum is 60 μm, the minimum geometry is 0.8μm as shown in Fig 1, deposition of new material and cutting and photolithographic masking, creates the mass of the mechanical structure in the MEMS device. It needs 7 masks and a metal layer [2]. The size of this mass is linked to the physical sensitivity and S/N (Signal Noise) ratio. Therefore we can't reduce unlimitedly mass size even if using the latest fine pitch process rule.

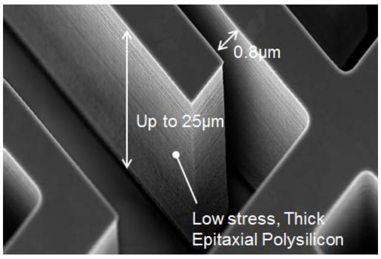

Fig. 1. SEM Picture of a Motion MEMS sensor's mechanics part. *(Mechanical element created by micro machining process. Each fins work as electrode to detect static capacitance)*

Cap die is used only for sealing mechanics die to protect from environmental stuff like dusts and to keep cavity pressure as ideal condition for each type of sensor. The cavity pressure defines damping factor of moving mechanics, accelerometer case it needs certain pressure in cavity to have a damping. The other hand, gyroscope does not need any damping so cavity should be vacuum condition.

Cap die has no electrical and mechanical functions. But it also need deep trench to define access to wire bonding pad area and ceiling, need only 2 masks in process.

The micromechanics wafer and cap wafer are bonded together by glue like shown in Fig.2. Sensor mechanics is completely sealed but wire bonding pads are opened through window on cap. After finishing this process, the bonded wafer is cut to each sensor chip.

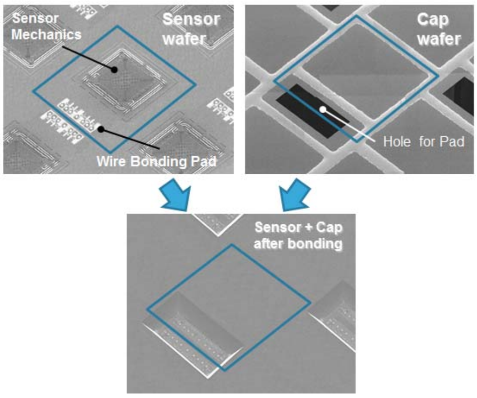

Fig. 2. SEM Pictures of Wafer to Wafer bonding. *(These pictures are before dicing. Blue rectangle shows a single chip area)*

The wafer level capping is needed to protect the micromechanical elements. It enables to use standard back-end technologies like testing, dicing, packaging and assure the reliability of the product overtime.

B. Die structure and Layout

Final image of structure and layer of the MEMS sensor is shown in Fig.3. Main structure of micromechanics is composed by epi-poly thick layer. Signals are connected by poly-silicon routing from sensor elements to pads, insulator between interconnections and substrate is made by thermal oxide.

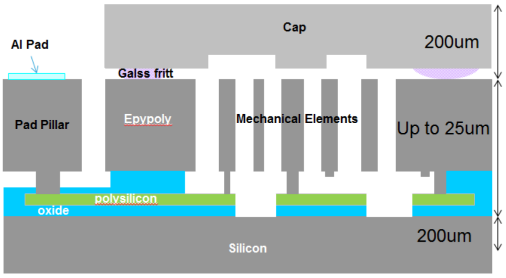

Fig. 3. Layer structure of MEMS sensor. (*Cross section image of a MEMS sensor. Main structure of micromechanics is composed by Epipoly thick layer. Signals are taken by polysilicon routing, insulator between Interconnections and substrate is thermal oxide.*)

An example of layout image of MEMS sensor is shown in Fig 4. This is a popular 3-axis accelerometer. There are two separated mechanics. One is for X-Y axis (horizontal plane) and second is for Z axis (vertical direction). Around sensor mechanics, there are sealing area for bond with cap. In addition to them there are 9 bonding pads for wiring connected to sensor element through to interconnection.

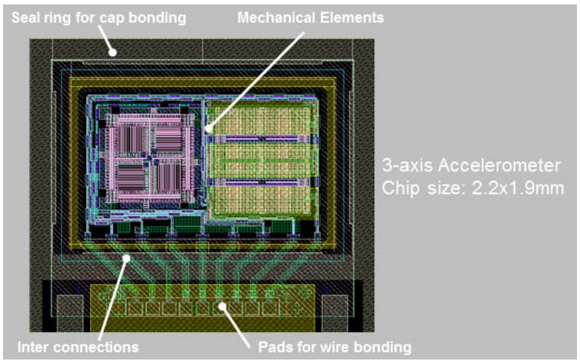

Fig. 4. Optical Picture of an Acceleromer. (*This picture shows typical layout design of a motion sensor.*)

In this product case, die size is 2.2mm x 1.9mm, and height is 0.5mm. The main sensor mechanics element share about 50% in die dimensions.

C. Packaging MEMS Sensor

A MEMS sensor includes mechanical part and electrical part. Mechanical part is for sensing by micromechanics manufactured by micromachining process as already described.

Electrical part performs signal processing like amplifier, A/D conversion, filtering and so on. It is manufactured by standard CMOS process.

To keep small size packaging finally these two parts must be stacked as Fig 5. This structure is standard for recent consumer motion MEMS sensors.

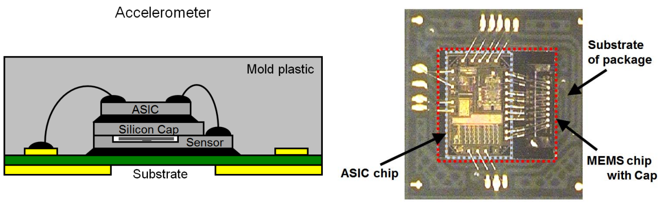

Fig. 5. MEMS sensor packaging *(Left side picture is cross section of accelerometer package. The sensor structure has covered by cap and ASIC is stacked on sensor chip / cap. Right side is picture of top view for accelerometer before the molding. The stacked structure of MEMS chip and ASIC is shown clearly.)*

To define the package size, dominant part is a mechanics die size. On the above examples of accelerometer, mechanics die size is 2.2 x 1.9mm, and then final mold package need to be around 3x3 mm. Gyroscope should have larger mechanics size, so mold package will be 4x4mm. Height is not matter in this case, it can have 0.8mm thick.

Recent requirement on market like mobile or wearable product, it must need to reduce to 2x2mm or less for accelerometer, and 3x3mm or less for gyroscope.

Thus reducing mechanics die size is mandatory to realize these requirements,

III. EVOLUTION FOR MEMS SENSOR PROCESS

There are several approaches to reduce die size of micromechanics of MEMS sensor.

As already described, size and mass of sensing elements is directly connected the performance such as a sensitivity, linearity and S/N ratio. So it is restricted to reduce mechanics size, even if we can use more fine pitch lithographic and etching technology.

Sealing area size is subject to technology of wafer bonding. Major technology is using glass flit as glue, it is very low cost and high reliability, but needs certain area size to sealing. To reduce this area, metal bonding technic is effective, it can reduce about 50% of sealing area, but it takes higher cost.

One of most effective approach is to reduce wire bonding pad area. To realize this, TSV must be introduced to process on micromechanics.

A. TSV process flow

TSV technology process is an additional option of current surface micro machining process such as THELMA to make interconnection between substrate and the pads can be taken from backside of wafer. STMicroelectronics have developed own process of TSV based on THELMA for MEMS sensor products, called SMERALDO

Typical layer structure is shown in Fig6. Technical point is to making interconnection in vertical through to silicon substrate, it can be made by deep etching oxide layer and depose poly silicon at same time with deposition for surface inter routing.

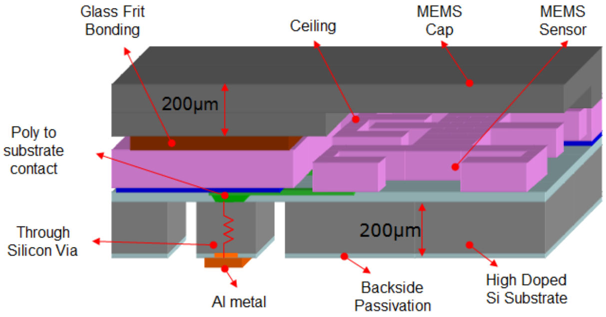

Fig. 6. MEMS Layer structure by TSV *(Mechanical element is same structure with convensional product. Key point of TSV is to make vertical interconnection through the oxide layer to silicon substrate)*

Process for sensing mechanical elements are completely compatible with THELMA, same mechanical design can be adopt.

After these process steps, it needs to do additional deep etching to make pad pillar at backside of the silicon wafer. This etching is very deep compare with micromechanics process, around 200μm, but this trench is for isolation from substrate, so it does not require so high fineness. Fig 7 shows a SEM picture of pad pillar at back side of wafer.

To add TSV option to conventional process, it need 3 additional mask and some extra steps of micro machining, but the other hands, Cap wafer does not need deep etching for pad window, and reduced total chip size, cost to manufacturing also reduced significantly.

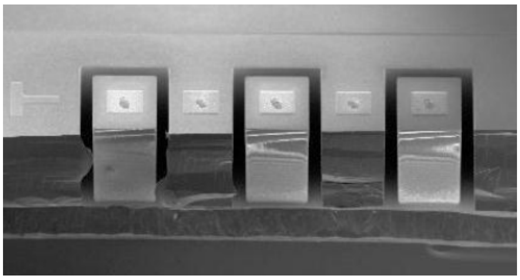

Fig. 7. SEM pictureof pad pillars by TSV *(Pad pillarsformed at backside of wafer. Height is about 200μm)*

B. Die size shrinking by TSV

In conventional MEMS die by manufacturing by THELMA process, Pads area is occupy the entire surface of about 30%. By using TSV, this area can be potentially reduced.

Fig.8 is the comparison on pictures of 2 chips, both has same size structure of micro mechanics elements of 3 axis Accelerometer. But one is manufactured by conventional THELMA which has bonding pads on same surface of mechanical elements. Another one was adopt TSV, and then bonding pads build at back side of device. Finally chip size is reduced about 40% in ares.

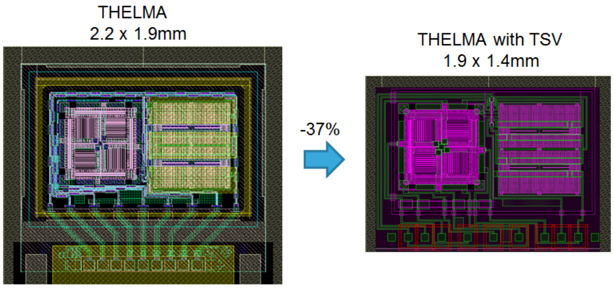

Fig. 8. Picture of die size reduction by TSV *(Left picture is an Accelerometer die by THELMA, Right picture is same mechanics with TSV technology. Die size is shrinked about 37%)*

For the other devices which have bigger mechanical elements like combo chip of accelerometer and gyroscope, size reduction effect by TSV becomes decreased. SMERALDO technology allows a 20% area reduction with respect to TELMA in average for MEMS sensor products.

C. Pacakaging of dies manufactured with TSV

Assembling the die manufactured by TSV is fully compatible with conventional dies case. We can use completely same technics in terms of die attachment, wire bonding and plastic molding. But sensor die is placed upside down on substrate like shown in Fig 9.

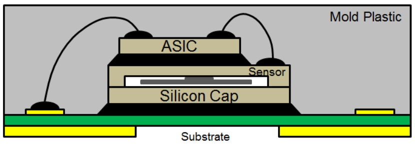

Fig. 9. MEMS sensor packaging by TSV *(Stack structure of dies which processed by TSV.)*

IV. CONCLUSION

We have already adopted TSV technology on several MEMS sensor products in high volume mass production. Especially for mobile products like wearable, smartphone and smart watch and so on, there is strong demand to reduce PCB size, therefore smaller package is required for MEMS sensors. Generally target is less than 2x2x0.8mm for 3 axis accelerometer, less than 2.5x2.5x0.8 mm for 3 axis gyroscope, and less than 3x2.5x0.8mm for combo of 3 axis accelerometer and 3 axis gyroscope. We already realized this target of size by using TSV technology on manufacturing of MEMS die without additional costs.

To realize further size reduction, we will adapt metal bonding for sealing the mechanics cavity by cap, it can be reduce seal ring area, and we also developed higher aspect ratio etching for make mechanical elements. Combinations of these technologies, we will be able to make smaller size MEMS sensor satisfy higher performance at same time.

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[2] Marco Ferrera, “3 D Integrated Solution for Motion MEMS”, Semicon West 2012