Materials and Microsystems Integration Teardown Report: Samsung S20 Pressure Sensor LPS22HD

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Abstract

This teardown report examines the pressure sensor LPS22HD used in Samsung S20 smartphone, a mass-produced component in MEMS Systems, to uncover the specifics of its design and functionality. The objective is to dissect and analyze the sensor, highlighting its role in advancing sensor technology in various applications such as altimetry, GPS, and portable devices. The methodology entails a detailed disassembly, followed by optical, X-ray, and electron microscopy to investigate the sensor's internal structure, including its piezoresistive elements, materials, and integrated ASIC. Findings from this teardown reveal comprehensive insights into the sensor's construction, packaging, bonding techniques, and the integration of its electronic components. These results contribute significantly to understanding MEMS technology's current state, offering a window into the sensor's application potential and guiding future advancements in electronic systems.

Nomenclature

Abbreviations:

ASIC	Application Specific Integrated Circuit
BEI	Backscattered Electron Image
BLM	Ball Limiting Metallurgy
CMOS	Complementary Metal Oxide Semiconductor
CTE	Coefficient of Thermal Expansion
DRIE	Deep Reactive-Ion Etching
EDS	Energy-Dispersive X-ray Spectroscopy
GPS	Global Positioning System
IC	Integrated circuit
MEMS	Micro Electro Mechanical Systems
PCB	Printed Circuit Board
RDL	Redistribution Layer
*S*20	Samsung Galaxy 20
SEM	Scanning Electron Microscopy
SiP	System in Package
UBM	Under Bump Metallization

Symbols:

ρ	Resistivity, Ωm
A	Cross-sectional area, m^2
GF	Gauge Factor, -
L	Length, m
R	Resistance, Ω

I. Introduction

The field of microelectronics and in particular integrated circuits (ICs) and their integration have seen significant advancement through out the years. This lab report will cover in-depth teardown and analysis of integration of Micro-Electro-Mechanical Systems (MEMS) component, the Samsung S20 Pressure Sensor LPS22HD.

The LPS22HD stands out as an ultra-compact piezoresistive absolute pressure sensor, distinguished by its digital output barometer with a range of 260 to 1260 hPa. It features also low current consumption, embedded temperature compensation, and significant shock survivability.

During the labwork the sensor undergone analysis utilizing optical, X-ray, and electron microscopy. These techniques provided a detailed view on the internal structure of IC package from different stand points complementing each other.

The aim of this analysis was to dissect and understand the packaging and bonding techniques of the sensor. Elements such as the membrane, wire bonding, solder joint, and the Application-Specific Integrated Circuit (ASIC) were focal points of our study, as most of the integration technologies were concentrated around them. These components will be examined one by one, utilizing microscopic imagery as experimental results and contents of this course as a theoretical basis.

Subsequent sections of this report will delve into the specifics of our methodology (Section II), present the results and their implications (Section III), and finally, synthesize our findings in the conclusion (Section IV).

II. Methods

This section will describe the method used in the lab work to investigate the packaging of the pressure sensor. First, the sample preparation will be discussed in Subsection A, then the optical microscope in Subsection B. To also be able to see the inside of the pressure sensor an X-ray was used which will be explained in Subsection C. Lastly, the use of an electron microscope will be discussed in Subsection D.

A. Sample preparation

As the goal is to study the composition of the packaging the sensor will need to be cut in half to study the composition. As the sensor is very small it is difficult to just cut it so it has first been inserted in an epoxy mould, this mould is then ground so it reveals the inside of the sensor after which it is again inserted into an epoxy mould to not have the sensor exposed. After this, the mould is polished with a coating that allows the two microscopes to properly image the sensor.

B. Optical microscope

The optical microscope is a typical microscope to see more details on the sensor. The following magnifications have been used, 5x, 10x, 20x, 50x, and 100x have been used to make the image. With the optical microscope first images of the entire sensor were taken and then later added together to form one big image, which can be seen below in Figure 1. Afterwards, images were taken of all specific components that will be discussed in Section III.

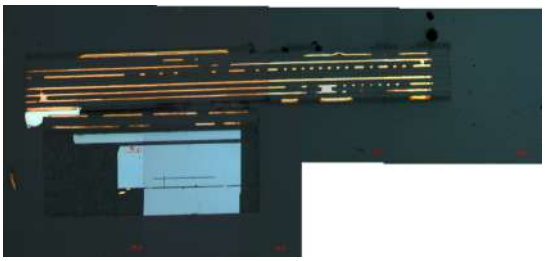


Figure 1: The pressure sensor image is composed of multiple images taken by the optical microscope

C. X-ray

An X-ray was used to look at through the material in the sensor. A CT Portable from ProCon X-ray was used which has a voltage of 50kW, has a 1 MP pixel with a pixel size of 48 μm [1]. The images have been taken on all three axis to inspect the sensor from all sides. The X-ray machine can be seen in Figure 2 below.

Figure 2: X-ray machine

D. Electron microscope

Lastly, an electron microscope was utilised to see the components in an even higher magnification and also to detect the concentration of elements in the sensor. The JIB-4700F electron microscope of JEOL has been used, this electron microscope has a variable voltage between 0.1-30.0 kV, magnifications between 20 and 1000000 and an image resolution of 1.2-1.6 nm [2]. The set up of the electron microscope can be seen in Figure 3.

(a) Electron microscope **(b) The controls**

Figure 3: Set up of the electron microscope

III. Results and Discussion

This section will provide the results of the measurements taken with the optical microscope, X-ray, and electron microscope. The pressure sensor has been divided into four different points of interest, the membrane which will be discussed in Subsection A. The wire bonding will be covered in Subsection B, while the solder joint will be the point of discussion in Subsection C. Lastly, the application specific integrated circuit (ASIC) will be covered in Subsection D.

A. Membrane

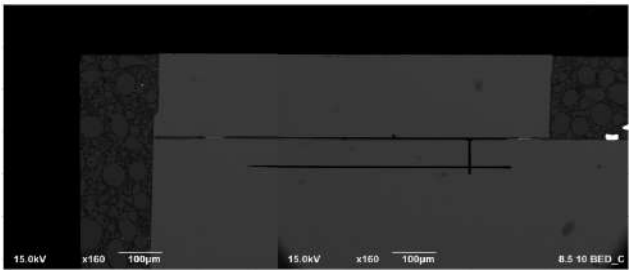


Figure 4: SEM image showing diaphragm

The sensing element senses the change in pressure which can be explained by the piezoresistive effect. A coefficient generally used to characterise the piezoresistive effect is the gauge factor (GF), which is a dimensionless figure of merit for strain gauges.

$$GF = \frac{\Delta R/R}{\Delta L/L} \tag{1}$$

Also,

$$GF = 1 - \frac{\Delta A/A}{\Delta L/L} + \frac{\Delta \rho/\rho}{\Delta L/L} \tag{2}$$

where R is resistance(Ω), L is length, A is the cross-sectional area, ρ is resistivity and ΔR, ΔL, ΔA and Δρ stand for change in them.

The larger gauge factor indicates significant resistivity change along with the geometrical changes due to external factors. As silicon has a large gauge factor compared to other elements such as Al, Cu, Ni, and Pt, it is chosen as the sensing element for the diaphragm to measure the pressure changes. [3]

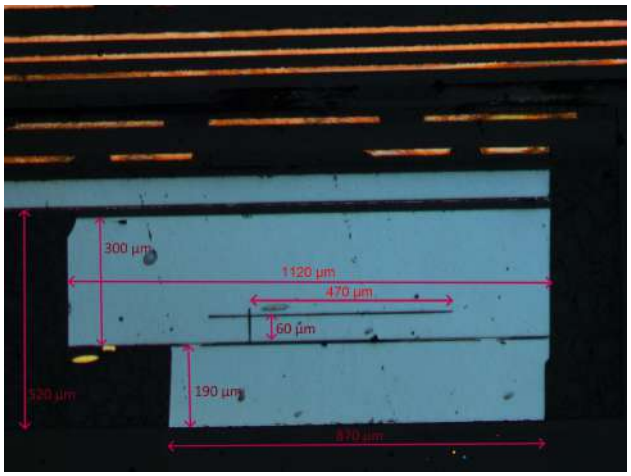


Figure 5: Optical microscope image of sensing membrane structure

From the optical image in Figure 5, the dimensions of the layers can be estimated as marked in the image. The sensing diaphragm is about 60µm x 470µm, which hangs freely between two silicon layers of 300µm x 1120µm and 190µm x 870µm.

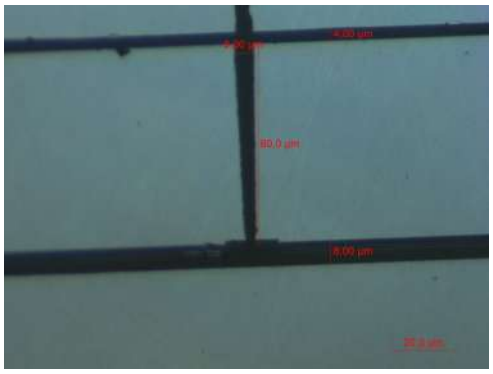


Figure 6: Optical microscope image at the junction of membrane layers

It can be observed in Figure 6 that the gap between the silicon layers is in the range of 4-8µm. Manufacturing at this scale can be accomplished by micro-machining technologies.

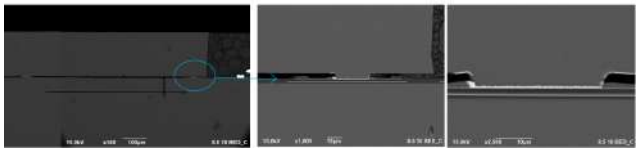


Figure 7: SEM image at the interface of the top and the sensing membrane layers

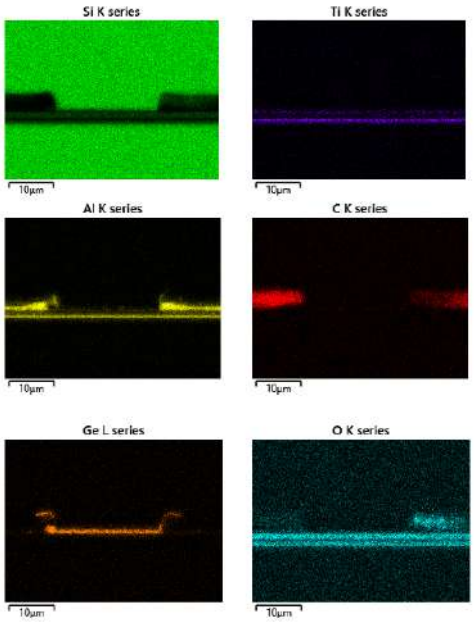


Figure 8: Spectroscopy results at the interface of the top and the sensing membrane layers

From Figure 8, it is evident that the material used to build the sensing membrane is silicon. Between these two interfaces, there also exist layers of aluminium for the electric interconnection. Underneath the aluminium, runs a layer of titanium. The usage of Ti in such a position can be to ensure the longevity and reliability of the sensor as Ti has excellent corrosion resistance. It can

also provide effective bonding between the layers in this multi-layer structure. In order to protect the layer from diffusion, silicon dioxide layers are deposited between Al & Ti and Al & Ge. Here Al-Ge form a metal bonding which is a high-strength bond keeping the membrane intact. Along with it, this also facilitates the small footprint of the layer. However, intrinsic stresses can be an issue in such a bonding method.

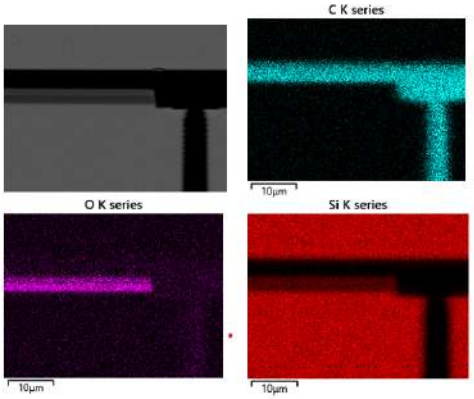


Figure 9: SEM image at the junction of the layers

At the junction of the interfaces, we can observe that the membranes of the sensor structure are made up of silicon and a layer of silicon dioxide is deposited forming a fusion bond between silicon and silicon dioxide. The fusion bonding method is a high-strength bonding method with high stability at various temperatures. However, it requires a high-temperature operation for formation. The carbon visible from the spectroscopy is the material of the encapsulation.

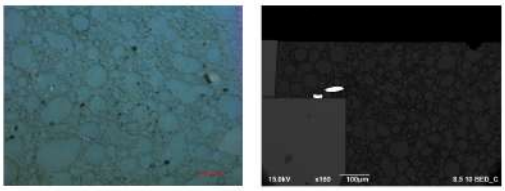


Figure 10: Optical microscope and SEM image of the encapsulation

As the pressure sensor needs to interact with the external environment, it is encapsulated non-hermetically using low-viscosity epoxies or silicon materials. By the package information and the material used, it can be stated that this MEMS device is a molded leadless package.

The membrane's fabrication process begins with a silicon wafer. The process involves thermally growing silicon dioxide, which provides electrical insulation. This step is complemented by photolithography, which precisely defines the membrane's geometry. Following this, layers of polycrystalline silicon or other piezoresistive compounds are deposited to imbue the membrane's pressure-sensitive properties. Concurrently, metals such as titanium and aluminium are sputtered or evaporated onto the wafer to form the electrical interconnects and contact areas essential for signal transduction.

Techniques such as deep reactive-ion etching (DRIE) then sculpt the membrane to the desired thickness, a critical factor in defining the sensor's sensitivity to pressure. A passivation layer, possibly of silicon nitride, is deposited to protect the piezoresistive materials and the membrane's integrity against environmental and operational stresses.

Finally, the sensor undergoes a packaging phase where it is encapsulated in an epoxy resin or another suitable material. This step is not just for stabilization during the manufacturing process but also ensures the sensor's durability and reliability when integrated into the target electronic systems.

Proposed manufacturing

Step 1: A silicon wafer is prepared which serves as the base substrate for the sensor.
Step 2: Oxidation is performed to grow a silicon dioxide layer on the wafer's surface. This layer can provide insulation and define the structure of the membrane.
Step 3: Photolithography is applied with a wax layer to pattern the protective layer, which will define areas for etching and doping.
Step 4: Oxide etching removes the silicon dioxide selectively where the sensor structures, like the membrane and piezoresistors, will be formed.
Step 5: Potassium Hydroxide (KOH) etching creates the cavity under the membrane. Thermal oxidation follows, possibly to grow a high-quality oxide layer for passivation and to define the membrane's final thickness.
Step 6: A second photolithography step defines the areas for additional oxide etching.
Step 7: Further oxide etching shapes the membrane and possibly the piezoresistors.
Step 8: Bulk silicon etching from the back side of the wafer is performed to release the membrane. This creates a thin diaphragm that can flex in response to pressure changes.
Step 9: Piezoresistor patterns for oxide etching are created. These piezoresistors will change resistance as the membrane flexes, converting pressure changes into an electrical signal.
Step 10: Phosphorus diffusion introduces dopants to create the piezoresistive elements. This step creates the electrical properties necessary for the piezoresistors to function.
Step 11: Aluminium deposition forms the electrical contacts and interconnections. This metal layer will connect the piezoresistors to external circuitry.

B. Wire bonding

The interconnection forms electrical connections between the MEMS, Application Specific Integrated Circuit (ASIC) and the motherboard of the system. The connections are present for both internal and external

connectivity for each module that sum up to create the pressure sensor. From Figure 5, the orange copper lines (in both the motherboard and the package substrate below the MEMS module) and the golden circles (beside the ASIC) are clearly visible.

The first level of interconnection is formed between the MEMS module and ASIC. Figure 11 shows the X-ray cross-section of the pressure sensor. As can be seen, one high contrast wire is protruding from the MEMS module and coming down to the ASIC, this is essentially the main Gold wire bonding which enables the MEMS module to connect to the external world. This connection enables the transfer of electrical signals generated by the pressure-induced mechanical deformations in the MEMS membrane to the ASIC for further processing and measurement. From Figure 5 it can be analyzed that wire bonding is made out of gold metal (yellow in contrast).

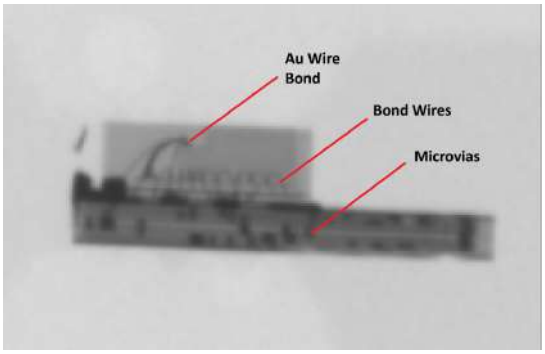


Figure 11: X-ray cross-section of the pressure sensor

The next level of interconnections are formed from the ASIC to the board of the system. From Figure 11 multiple bond wires (about 10 of them from the figure angle) can be spotted. These bond wires are thin metallic wires used in semiconductor packaging to connect the ASIC to the motherboard of the pressure sensor. They are used to transmit signals, distribute power, provide grounding, connect to package leads and assist in thermal dissipation within the package. The bonding pads, seen as rectangular back spots (about three from the figure angle) can be observed from Figure 11. These bonding pads also provide mechanical support from the motherboard to the MEMS Module.

Figure 12: Redistribution Layers (RDLs) in Motherboard and Package Substrate

The optical microscope image of Figure 12 depicts straight lines of interconnection (orange) in the motherboard. These are RDLs (Redistribution Layers) that form electrical connections in the motherboard and the package substrate. They form an internetwork of electrical connections between each layer, providing pathways for multiple connections to be formed from multiple dies. Together they form semiconductor packaging, inter-die communication, support layout adaptability, and contribute to signal integrity and thermal management in advanced packaging technologies.

In the investigated pressure sensor, there are two sets of these RDLs, one in the package substrate and one in the motherboard. As the pressure sensor is cut in cross-section for analysis, the RDLs are observed to be in broken lines. In reality, they are 3D connections all over the motherboard and package substrate, forming a vast internetwork. It can be observed that some RDLs can be as long as 1220 μm long and as short as 200 μm in length.

From Figure 11 above of the x-ray cross-section of the pressure sensor, tiny dark spots are observed in between the RDLs in the motherboard. These are tiny, laser-drilled holes in the motherboard called Microvias that connect different layers of the board. They serve the purpose of providing a compact and efficient way to establish electrical connections between different layers, facilitating the routing of signals and power between the densely packed RDLs. Figure 13 below depicts one microvia spotted in the motherboard RDL.

Figure 13: Microvia in motherboard RDL

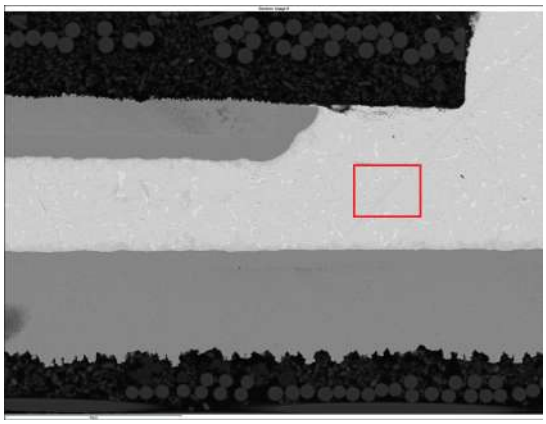


Figure 15: Solder joint connection within the red rectangle is the location where material analysis has been done.

C. Solder joint

The solder joint connects the pressure sensor chip to the motherboard of the Samsung phone. It can be seen below in Figure 14.

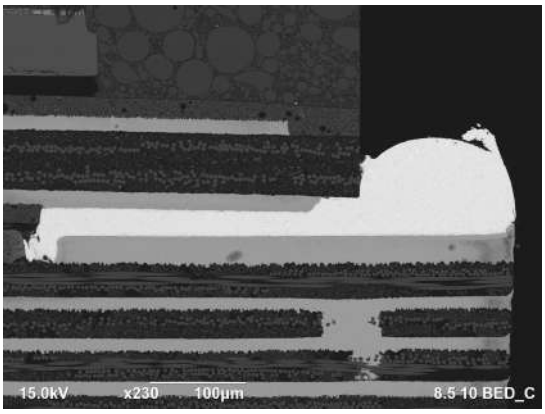
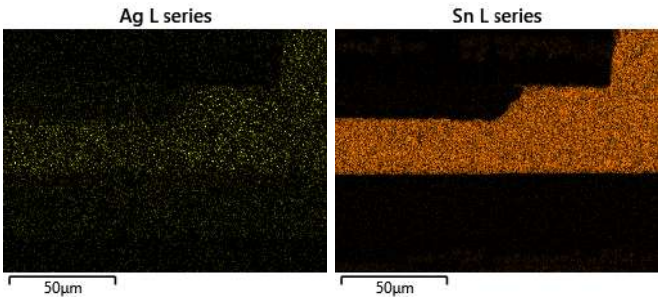
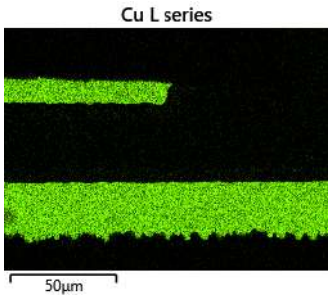


Figure 14: The solder joint connection



(a) Silver **(b) Tin**



(c) Copper

Figure 16: Material analysis done with the electron microscope on the solder joint in the red rectangle of Figure 15

Here it can be seen that the solder joint connects the motherboard of the S20 to the sensor. The solder joint is approximately 25.8 μm thick. When the solder joint is looked at with energy-dispersive X-ray spectroscopy (EDS) it can be determined which materials are used in the solder joint. For this the electron microscope was zoomed in more to the location and a small part was selected of which the chemical composition should be investigated. Figure 15 shows the red rectangle where the material analysis was performed, and the results of this material analysis are shown in Figure 16.

Using EDS it can be determined that the solder joint has 95.8% Tin, 3.61% Silver and 0.59% Copper. However, as can be seen in Figure 16c the copper is concentrated at the connection point of the solder and not necessarily in the solder itself. This can occur with EDS as a 3D section is studied. In the 2D image, only the solder part was selected but then the depth could have contained some copper, which also explains why the percentage is so low. It can then be assumed that the solder that was used was 96/4 Tin Silver. This solder material has a melting range of $221 - 246°$ C and a tensile strength of 96.53 MPa when attached to copper [4].

D. ASIC

Application Specific Integrated Circuit (ASIC) is the CMOS fabricated module which handles the processing of signal inputs from the MEMS module and provides the processed data. A typical ASIC carryout signal conditioning and it should have the capability to provide better pressure accuracy, and immunity against noise and radio frequency [5].

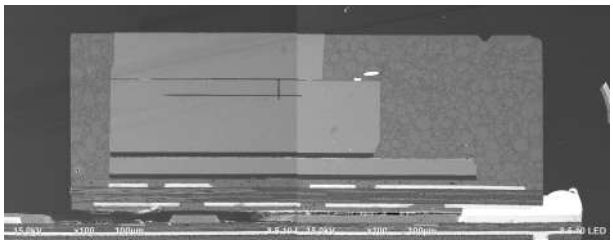


Figure 17: Microscopy image of the cross-section of the Pressure Chip, the ASIC module positioned on a board(similar to fiber glass strengthened PCB) and on top of it the MEMS pressure sensor attached.

Figure 17 shows the hermetically sealed pressure sensor on top and the ASIC below that which is placed on a redistribution board; this whole module is encapsulated and bonded with a board in the bottom.

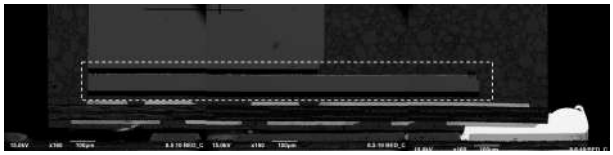


Figure 18: Three Backscattered electron Images from Scanning Electron Microscopy combined together and show the cross-section of the ASIC of the pressure sensor position in the package. The bottom part of the pressure sensor's MEMS module is visible on top.

Figure 18 is the BEI (Backscattered Electron Image) of the SEM micrograph joined together. The ASIC has around 50 μm thickness and one side of it has vias for the electrical interconnection leading to the IO pads(clearly visible in Figure 19). The interconnection vias and pads side of the chip is facing up and the bottom side is attached to the board below (There is no electrical interconnection needed and most probably it could be just adhesive-based mechanical attachment and could be for the thermal dissipation as well).

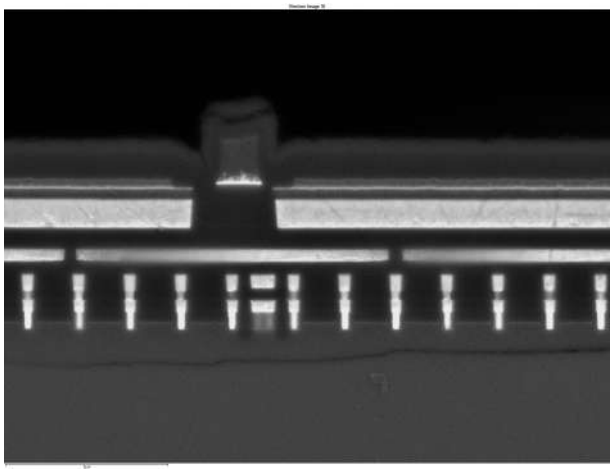


Figure 19: This is a Scanning Electron Microscopy (SEM) micrograph of the cross-section of the ASIC. The interconnection vias and redistribution metal layers are visible clearly.

Figure 19 shows the cross-sectional view of the vias and interconnections of the ASIC. Closely arranged vertical vias and layers of metal interconnections are clearly identifiable in the image. The crack below the die area could have occurred during the sample preparation for SEM.

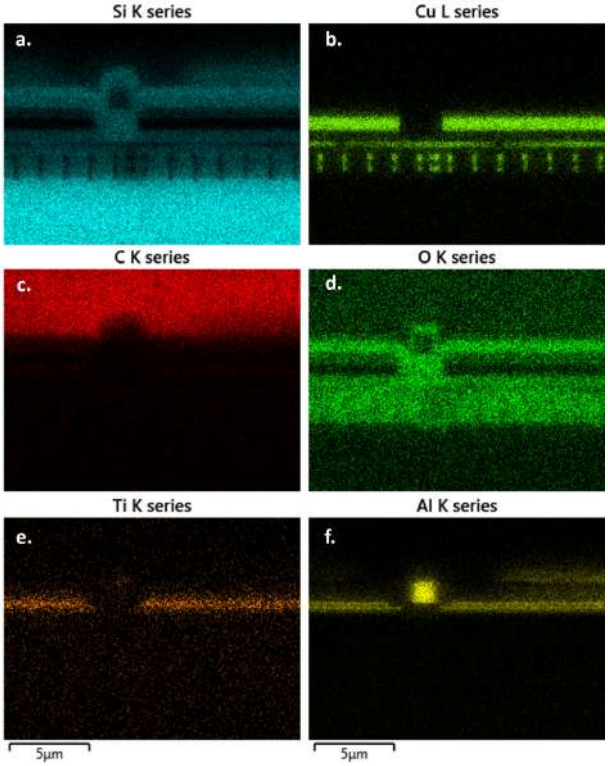


Figure 20: The Energy Dispersive X-ray Spectrometry of the site visible in Figure 19 shows the presence and distribution of different elements. Letter a represents the EDS of Si content and others represent Cu, C, O, Ti and Al respectively.

Figure 20.b shows the vias and the horizontal interconnection layers are of copper material except the single isolated pad in the top centre position. Figure 20.f sug-

gests that the isolated pad is of Aluminum, which is possible as the CMOS chips have the Al pads (Al Capture pads) before UBM (Under Bump Metallization) or BLM (Ball Limiting Metallurgy). Figure 20.c and Figure 20.d shows the presence of Carbon in the die attach area and the oxygen in high concentrations in the vias and interconnection regions. The reason for carbon could be from the organic adhesive used for die attach and the oxygen could be available as oxide which formed during the sample preparation procedures. Figure 20.e and Figure 20.f shows the Titanium and Aluminum layer, close observation suggests that the Al layer is on top of the Ti layer.

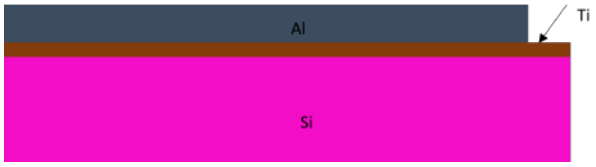


Figure 21: The illustration of the positioning of Al and Ti layers. The Ti layer separates the Al from the Si substrate.

As in the illustration Figure 21, the Ti layer is deposited to avoid migration issues of Al into Si due to the significantly high coefficient of thermal expansion(CTE) of Al with respect to Si and at high temperature and under compressive stress diffusion could speed up. The Ti layer is used to provide low contact resistance and good chemical, electrical and mechanical stability while addressing the migration problem [6].

The image from the X-ray microscope, Figure 11 reinforces the previous assumptions about the connections of ASIC with the substrate board using wire bond. There was no metallic connection between the bottom of ASIC and the package below it, thus it can be assumed that the parts are connected by compound for mechanical rigidity and highly likely for imported heat dissipation. Thus all electrical connections of ASIC are facilitated through IO pads. Finally, no new integration techniques were found under X-Ray, thus it can be concluded that ASIC is now fully analyzed.

IV. Conclusions

It is determined that the pressure sensor has packaged as a SiP (System in Package) where the MEMS structure of the sensor is attached on top of the ASIC and mounted on a board which is connected to the IO pads of the encapsulated chip. Wire bonding is used to establish electrical bonding between the MEMS, ASIC and board and the ASIC is sandwiched between the MEMS and board utilizing die attach process. The pressure sensor chip is bonded to the motherboard using 96/4 Tin Silver solder.

With this teardown analysis the packaging techniques used in this pressure sensor have been identified and the interconnections used for the electrical connections and bonding technique accompanied determined. The material composition of the solders, bonding layers and interconnections have been analyzed to identify the solder type and necessity of the adoption of particular bonding technique. Here, identifying the overall packaging and bonding techniques has been the primary target and further analysis needs to be done to determine the manufacturing process utilized for the MEMS structure and ASIC fabrication.

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