Modelling and 3D printing of Packaging for Water Quality Sensor

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Abstract: - Nanoporous gold film can detect the presence of heavy metal ions in water. Nanoporous gold film based micro sensor is fabricated by layering copper on silicon substrate with an intermediate titanium layer acting as an adhesive. This film is formed through electroless plating by spraying potassium gold cyanide on the copper. It is proposed to fabricate this sensor using 3D printing, with nano resolution thickness of layering structure. 3D printing can address fabrication and packaging challenges. A variety of packaging materials and techniques are available. Ceramic packaging, plastic packaging and metal packaging techniques are prominent. 3D printed ceramic packaging with hermetic sealing is proposed for water quality sensors. A design of packaging prototype is presented and discussed. Micro-stereolithography, digital light processing techniques are suitable processes to prototype sensor contents and packaging model, which is 3D printing of the resin based cavity model. 3D Modeling of the sensor contents, packaging structures are modelled using Autodesk Maya3D2014, COMSOL software designs. The total electric energy through 3D modelling in COMSOL Multiphysics software is 25 joules. Electric potential (V) is estimated to be 2.0×10^{-18} volts. Digital light processing technique is proposed for this 3D printing of the resin based cavity model, FDM process for 3D printing working electrode and optomec lens process for the other electrodes involving metal 3D printing.

Key-Words: - 3D printing, packaging, micro resolution, water quality sensors

1 Introduction

Czochralski process is employed to manufacture wafers. Wafers are the basic building blocks of integrated circuits. Pure semiconductor material (usually Silicon) are grown in to cylindrical ingots of up to few hundred millimeter diameter which are then sliced to the required thickness (in the order of µm to mm); these ingot slices are then polished to obtain a flattened surface. The polishing is followed by deposition, removal, patterning and modification of electrical properties. The wafer is then tested. Wafers are tested and diced. Only the good and unmarked chips are packaged. Packaging of integrated circuits involves connecting the die pads to the pins on the external package and sealing the chip. Today high priority is accorded to sub micro and nano electronics research. The smaller the chips are, the higher the manufacturing cost. Packaging alone accounts to 75% of the total IC manufacturing cost implying that the packaging cost increases inversely with the chip size.

Additive Manufacturing (AM) or 3D printing is the process by which 3 dimensional objects are manufactured under computerized supervision. This process is quite economical and simple. The processes representing 3D printing involves modelling, slicing and hence the suitable phenomena of either using laser, digital light concepts, wax techniques, electron beams are of relative interest. The sensor layers involving multi material printing has a defined accuracy having micro-nano resolution thicknesses. Before the 3D printing happens, models are validated using 3D softwares, sliced for definite accuracy. Relevant packaging concepts are analyzed and recommended to prototype a technologically experimental packaging concept, for a layered sensor structure. The problems are analyzed for packaging arena with a recommended feasible conceptual solution, based on 3D modelling / printing concept.

2 Packaging concepts

Yuki et al. [1], proposes a soft nano-printing technology using printing plates made of elastomer. Such printing plates have the capacity to realize nanoscale printing.

Elastomers can be stretched to many times their original length but they always regain their initial shape and size. But beyond a limit they experience permanent deformation. Deformation of printing plate occurs if stretched enough for a long time, such that the molecules become crystallized [4]. Gravure Offset Printing with elastomer printing plate provides high throughput and spatial resolution with well controlled cross-sectional profile and overcomes the side etching problem. But under excess pressure, the printing plate gets deformed.

Additive manufacturing is called 3D Printing, whereas subtractive manufacturing is the process of mechanical machining and laser cutting, in which the unwanted parts are removed. Sung-Yueh et al. [2], proposes 3D printing as a method to construct 3D microstructures with embedded metallic elements by means of fillings of liquid metal paste to produce a variety of basic microelectronics components, such as resistors, capacitors, and inductors. This method uses the combination of 3D additive polymer printing with liquid metal paste so that the process can be employed for practical applications. By connecting these resistors, capacitors and inductors, more complex circuitry can be built.

Yong Ji and Yuyuan Cao [3] proposed a flexible packaging model to fabricate the polydimethylsiloxane protection directly onto the chips and then 3D print the wiring layer using liquid metal. Bowei Zhang et al. [4], propose a hybrid system of CMOS components and microfluidics to enable bio sensing and continuous bio marker monitoring which were previously unavailable.

Poly Di Methyl Siloxane (PDMS), is a soft elastomer widely used in microfluidics, flexible electronics [8][9] and micro-optics due to its low cost, easy fabrication, flexibility, biocompatibility and optical transparency [10]. Galinstan is a gallium-indium-tin eutectic alloy which is non-toxic, non-evaporative, and has a higher electrical conductivity and better wetting properties [11].

Challenge encountered in flexible integration of solid state ICs and microfluidics is the complex post processing and packaging steps required [13]. In solid IC packaging, wire bonding is used. This makes it difficult for microfluidic structures to be embedded on top [14].

Flip chip bonding packaging technique also results in flat device surfaces but active surface is buried within the package and is not accessible for microfluidic integration. The suggested method is encapsulation of IC with microfluidic hybrid integration of a single PDMS substrate integrated with Galinstan and other micro channels. The resultant packaging contains 2 layers: the top microfluidic layer and bottom CMOS layer.

There are mainly three types of micro packaging techniques used today: Ceramic packaging, Plastic Packaging and Metal Packaging. Hermetic sealing is used in ceramic and metal packaging. Plastic packaging is non-hermetic and includes pre and post molding. Ceramic type packaging has flip-chip or wire bonding. In metal packaging, there is ease of assembling and optimization on pin counts.

Over molded, exposed die surface and cavity package are commonly used industrial packaging techniques for micro devices. In electronic engineering, a through-silicon via (TSVs) are a high performance interconnect technique used as an alternative to flip chips and wire bond to create 3D packages and 3D integrated circuits. Ceramic packaging, which is an electrical type of packaging is extended to micro size packaging. Micro machined sensors use ceramic packaging.

Hermetic Packaging (a type of Cavity Packaging) is used in the packaging of devices that have to be protected from water vapor and foreign bodies in order to maintain their functionality. In order to achieve this airtight property, typically Hermetic packages are made up of a particular type of resin that have -OH group in their structures that can form strong polar attractions to oxides or other -OH surfaces [5]. This polarity property also contributes to high surface energy. In order to make hermetic seal for electric and electronic appliances, the package must bond with metals like copper, silver or brass so that wire leads can be taken out of the packaging.

3 Packaging of water quality sensors

Sub-surface science research being undertaken by the Department of Energy (DOE), USA in solving complex environmental problems associated with hazardous contaminants in soil and in groundwater at DOE sites [16]. These contaminants include hazardous metals like mercury, and Copper. Micro plasma generator that can be used for the detection of heavy metal ions has been fabricated and evaluated. It uses a simpler device structure that does not require nebulizer for water samples.

The packaging process is generally very challenging - where the process involves sensor layer layout, circuit design efficiency, coatings and surface treatments and sensor packing safety measures being considered. 3D printing of packaging ensures quality, strength and economic means. There could be an array of sensors designed for single ion detection or the selectivity/sensitivity measures tuned for multiple ion detection capabilities w.r.to heavy metal ion sensing in water.

Micro Plasma based atomic emission spectroscopy is one of the most effective methods. One of the difficulties encountered in micro plasma devices is the formation of aerosol from a liquid sample [15]. Semiconductor packaging has evolved from Through Hole technology (DIP, SIP) to Surface Mount Technology (PLCC, QFB) and then to Array Type Packages (BGAs) and then to 3D Packaging and finally to 3D Printed Packaging.

4 Proposed design of 3D printable sensor packaging

The heavy metal ion sensor detects the contents of heavy metal ions in the water. It consists of multiple ionic electrodes which can simultaneously detect heavy metal ions like lead, cadmium, copper etc. The data is firstly transduced, then passed through a resistance measuring circuit which amplifies and filters the data. Finally, the data is converted to digital form. This enables the accurate detection and measurement of the quantity of heavy metal ion in water.

The proposed packaging concept of chemically-sensitive electronic micro dimension device using NPGF (Nano Porous Gold Film) electrode is provided. The fabricated layers having nano meter resolutions are 3D printed on top of one another. The efficiency of the electrical isolation and use of passivation layers as well as the epoxy encapsulation of input/output connections of the sensor device will be investigated with respect to protection of the electronic component from the surrounding liquid. Fig 1. explains the package contents, which will be 3D printed. The base substrate, titanium and copper layers are layered [17].

As one of the package contents, the unknown NPGF electrode resistance is determined using a Wheatstone bridge. Nano porous gold

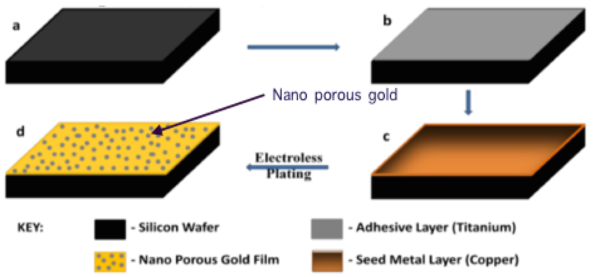

Fig 1–Schematic for fabrication of NPGF electrode using 3D printing, using a method similar to Fused filament fabrication. The nanoporous gold is formed at the top of copper layer after few hours of spraying PGC (c, d layers). The titanium epoxy is used for adhesion of silicon substrate to copper on top of it (a, b layers)

morphology plays an important role in the overall device operation. Therefore, precise fabrication, packaging control is inevitable to attain optimal device performance. The device can be made for sensing multiple ions using an array structure of multiple NPGF films having tuned porous phenomena. The most commonly used material for packaging is epoxy plastic due to its high mechanical strength. Enhanced 3D Printed hermetic packaging involves printing of the particular type of resin. Hermetic packaging offers design flexibility and robustness. In case of sensors, Hermetic Ceramic Cavity packaging is the commonly used Industrial Packaging Technique and this could be 3D printed using Digital Light processing or micro stereo lithography technique. The area of packaging can be compared for the sensor layers designed with circular and square layout sizes. Fig 2 demonstrates the COMSOL design of 3D printable water quality sensor having external leads and Fig 5 and 6 provides a 3D model of the hermetically sealed sensor, modeled through Autodesk Maya software.

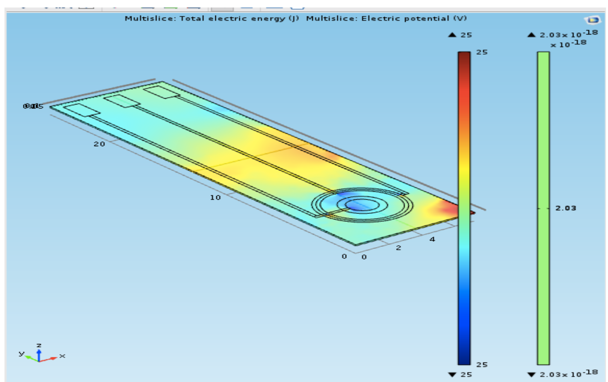

Fig 2 – COMSOL model of circular sensing layers connected to leads. The 3D printed hermetic ceramic cavity packaging technique could be applied to the printed sensor for packaging and sealing. Packaging would support the principle that, the area of contact with the ions should be exposed to the water sample.

The used tools are COMSOL Multiphysics and

CAD import modules. The total electric energy is 25 joules. Electric potential (V) is estimated to be 2.0×10^{-18} volts. The Silicon thickness provided is 100 µm, Titanium thickness is 10 nm, Copper thickness is 100 nm, Au thickness 1 µm. Ag thickness 1 µm. Silicon layout of 7.2x25.5 mm size is used. Titanium is of layout size 1x2 mm. For the circular copper strip, radius of 0.8 mm is provided. Young's modulus provided is $120e^{-9}$Pascal. Poisson ratio is 0.34. Titanium young's modulus is $115.7e^{9}$ pascal. Poisson ratio is 0.321. These are the parameters used to model sensor layers with circular sensing structures. The porous gold sensing layer is provided with young's modulus of $70e^{9}$ pascal. Poisson ratio provided is 0.44. The circular structures contain Au-Gold, Ag-silver, Pt-platinum, Al- Aluminium leads and wires.

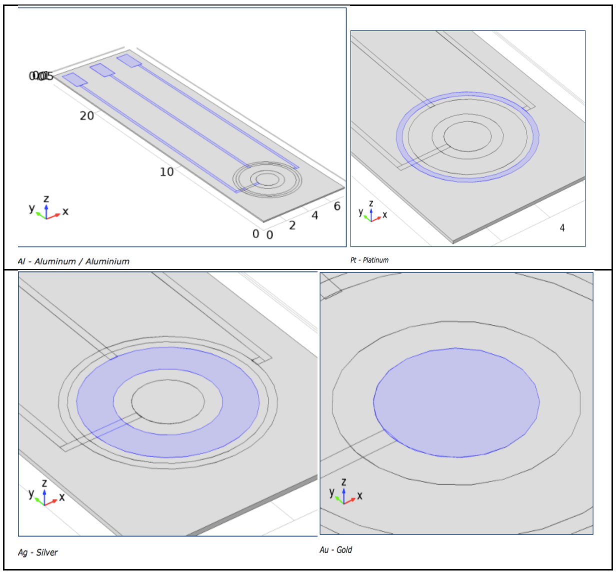

Fig 3 – Pictorial representation of aluminum, platinum, silver, gold parts denoting leads and circular sensing electrodes. Reference electrodes are included for the electrochemical sensing portion. The highlighted portion is given as foot note in the picture.

The electrostatic and charge conservation formulae are applied. Initial values are defined for the model. Electric potential is applied to leads for simulation. The mesh statistics are provided in the Table 1.

The mesh structure looks as in Fig 4. Number of triangular elements covered is 23128. Edge and vertex elements are provided in the mesh statistics for the free tetrahedral mesh structure. The model is compiled and executed for potential values. The total electric energy is 25 joules. Electric potential (V) is estimated to be 2.0×10^{-18} volts.

Table 1 – Mesh statistics

Mesh Statistics

Property	Value
Minimum element quality	1.494E-11
Average element quality	0.1791
Tetrahedral elements	40939
Triangular elements	23128
Edge elements	2702
Vertex elements	104

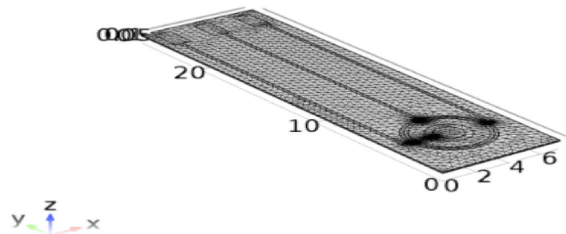

Fig 4 – Mesh structure of the modelled water quality sensor

Hermetic sealing structure is modelled in Fig 5, where the leads are seen along the package. The circular nano porous sensing layers provide the fine tuned selectivity/ sensitivity matching of the particular heavy metal detection. The sensor is capable of placing in water medium, which is sealed apart from the sensing area. The sensing part which contains nano porous strucures in the centre are not covered with packing. The reference electrodes and the leads are covered.

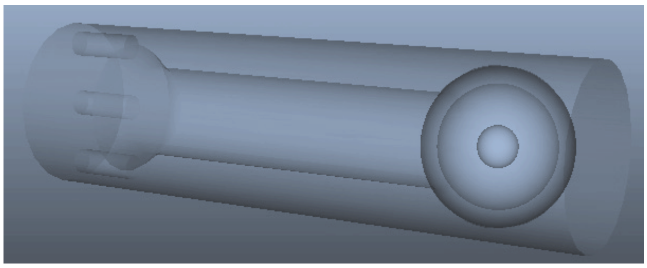

Fig 5 – A 3D model using Autodesk Maya 2014 software of the water quality sensor which could be hermetically packed and sealed, by 3D printing the same.

The lateral side view is shown in Fig 6, where the software showcases a picturesque model of 3D sensor structure. The package is proposed to be 3D printed using digital light processing process type of 3D printing. The modelled structures are provided and analyzed therein.

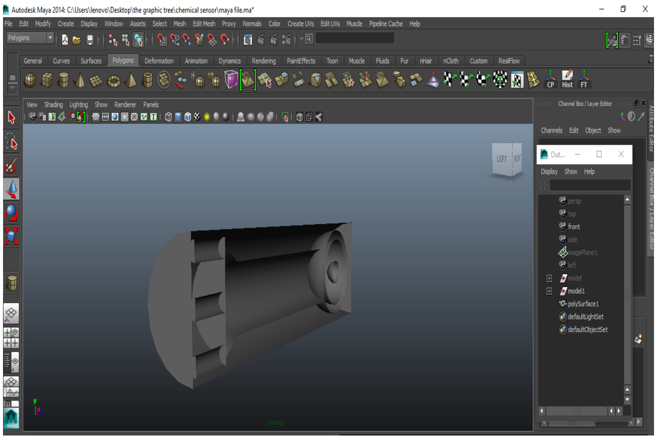

Fig 6 – Side view of a 3D model using Autodesk Maya 2014 software of the water quality sensor

5 3D Printing considerations

The sensor layer contents are proposed to be 3D printed using the metal 3D printing process, more specifically using the LENS technology. Optomec offers printed metal structures for core applications. LENS system uses a high power laser (500W to 4 KW) [19]. The LENS process is housed in a hermetically sealed chamber which is purged with argon to maintain oxygen and moisture levels stay very less. Oxidation is prevented during 3D printing. The respective metal powders for the sensor printing are fed to LENS system.

The hermetic packaging is proposed to be printed using Digital light processing (DLP) technique. DLP printing provides a clear and quality print, wherein the space between each micro-mirrors it uses in the 3D printing technology is less than one microns and the space between pixels is greatly limited. A DLP 3D printer projects the image of the objects' cross section onto the surface of the resin. The exposed resin hardens, when the build platform descends subsequently [18]. Post processing is required after 3D printing. The print quality and resolution of 3D printed packaging is expected to be high, considering the advantages.

6 Conclusion

Studies have found that the cost of packaging alone accounts to 75% of the total cost if IC Manufacturing. 3D printing is process is quite economical and simple. Out of the three commonly used micro packaging techniques i.e., Ceramic packaging, Plastic Packaging and Metal Packaging, it is proposed that ceramic packaging with hermetic sealing be used for water quality sensors; it is further proposed that this packaging be 3D printed. Such a packaging integrates the electronics and the microfluidics with the necessary isolation that is needed in a water quality sensor. A simple design of this packaging has been presented. The total electric energy through modelling is 25 joules. Electric potential (V) is estimated to be $2.0\text{x}10^{-18}$ volts. Optomec LENS technology and Digital light processing technique is proposed for this 3D printing of the resin based cavity model, as the further proposed steps. The results would be characterized for accuracy.

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