# Multi-Dimensional Integration and Packaging of Devices for Internet-of-Things Applications

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*Abstract*—**IoT applications are increasingly becoming widespread with more stringent system requirements. In this work, we demonstrate a nature-inspired integration and packaging technology that achieves self-powered multi-functional systems with optimized performance and small footprint area. The integration technique is based on bifacial usage of the substrate where devices on both sides are interconnected via through-substrate-vias. Multiple substrates are then integrated and folded into a 3D architecture using side-interlocks following a puzzle-like fashion. On the outer sides of the 3D architecture, sensors, RF devices and energy harvesters are integrated while on the inner faces, a solid-state battery in addition to power-management and data-management circuitry are embedded. To package the system, a polymeric encapsulant is used to protect the inner circuitry and enhance the mechanical resilience of the system. Finally, the system is used to send the collected data wirelessly to a phone using an embedded Bluetooth Low Energy unit.**

*Keywords—integration, packaging, system-on-chip, system-in-package, sensors.*

## I. INTRODUCTION

Since its emergence, Internet-of-Things (IoT) has brought myriads of benefits to our lives across multiple fields including healthcare, defense and transportation, where "intelligent" sensors intercommunicate seamlessly over the internet without the need for human intervention [1-16]. In this light, the promise of a smart environment has been exceptionally attractive where the physical and the artificial worlds interact and generate data that contributes to a smarter and more comfortable world. Nevertheless, the advances in IoT resulted in more and more stringent requirements at all levels including hardware, software and communications. More specifically, IoT devices need to be more multifunctional than ever with high performance, low power consumption and small footprint area. As a result, the prevailing integration and packaging technologies are continuously developing to meet such requirements.

The most popular integration and packaging approaches have been using system-on-chip (SoC) and system-in-package (SiP) techniques. However, each of these technologies has its own shortcomings. For instance, the SoC technique is restricted to what can be accomplished within a single wafer process leading to an imperfect performance of multiple components while SiC is bulky and is restricted to the performance of CMOS components which are not always optimal for specific applications [3-31]. To bridge the gap between the two technologies, here, we propose an approach based on multi-dimensional integration and packaging of devices where both sides of a substrate are utilized for thin-film based device fabrication. Both faces of the substrate are interconnected via through-substrate-vias (TSVs). The multiple faces of the multidimensional integrated circuit (MD-IC) are interconnected using side interlocks to achieve a small form factor. Finally, a solution-processable polymer is used to encapsulate the system and improve its mechanical resilience. The MD-IC integration and packaging technique enables an optimized performance of the system since each side can be

based on a different substrate material with heterogeneous devices. In addition, since the devices on each side can be fabricated separately, then heterogeneous devices can be integrated with no need for costly and complicated lithography masks.

## II. INTEGRATION OF DEVICES

Inspired by nature, where human's different sensors are integrated on the body outer side such as touch, smell and sight (Fig.1), while the memory, logic and power are embedded inside the body (i.e. brain), our proposed MD-IC integrates sensors on the external sides of the 3D electronic architecture while the power management and data management circuitry are added on the internal sides.

### A. Devices Integration

Traditionally, the process flow of integration and packaging of devices consists of the fabrication of the devices on a silicon wafer followed by dicing it into smaller dies which are then packaged using a ceramic material. Our CMOS-compatible integration and packaging technique introduces a few variations to the traditional approach to achieve MD-ICs. First, on the polished-side of a 4 inch silicon wafer, multiple devices are fabricated such as high-performance microprocessors, which is a fabrication process that require a high thermal budget. The devices are then protected using a mask and fabrication of devices on the back-side of the wafer takes place.
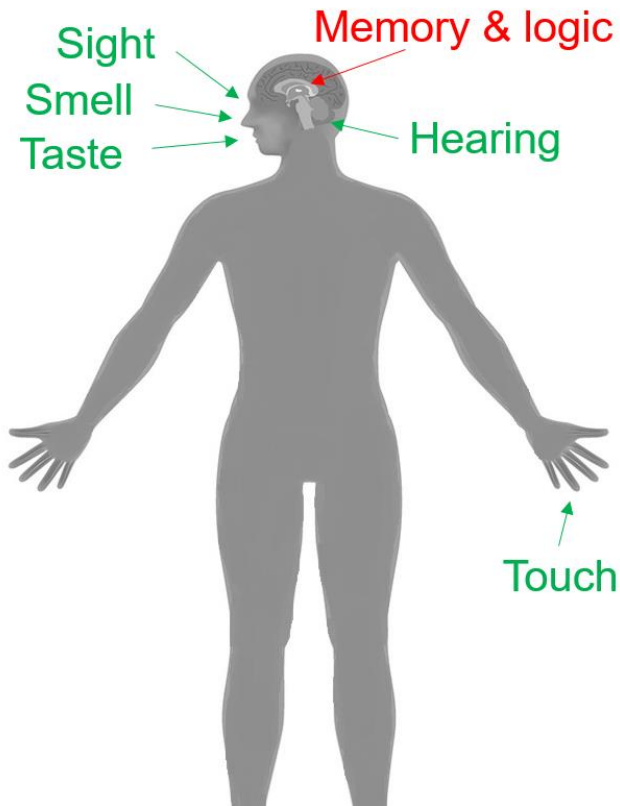


Fig. 1. Nature inspiration for the demonstrated MD-IC where sensors are integrated on the external faces while power and data management circuitry are added on the internal faces.
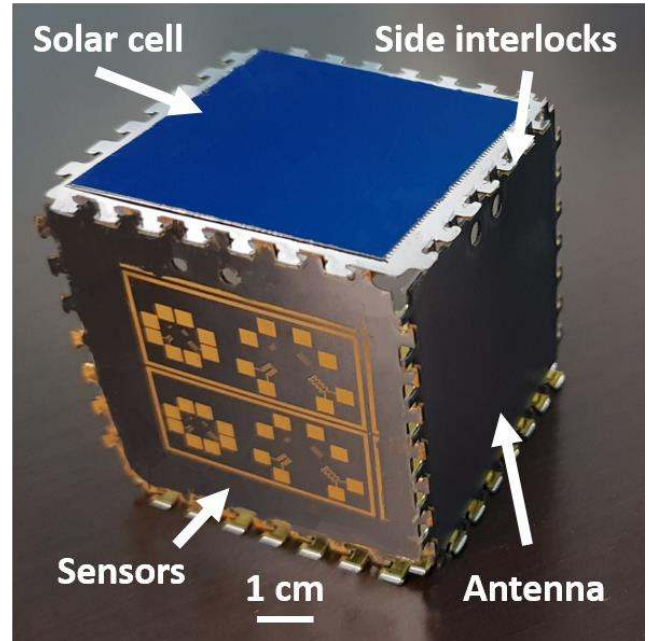


Fig. 2. Cubic MD-IC with integrated sensors, RF and energy harvesters on its outer sides.

The back-side of the wafer is unpolished and shows a higher defects density, thus, devices that do not need the substrate as an active material would be integrated such as sensors. It is also important to mention that the fabrication on the rear-side of the Si sample should require a low thermal budget to avoid deteriorating the already embedded devices on the top polished side. Next, the backside of the wafer is protected with photoresist and a kapton mask and patterned using a $CO_2$ laser.

The exposed areas are then completely etched following the Bosch process in a deep reactive ion etching system (DRIE). This results in the various sides of the MD-IC with side interlocks and TSVs which are then coated/filled with a
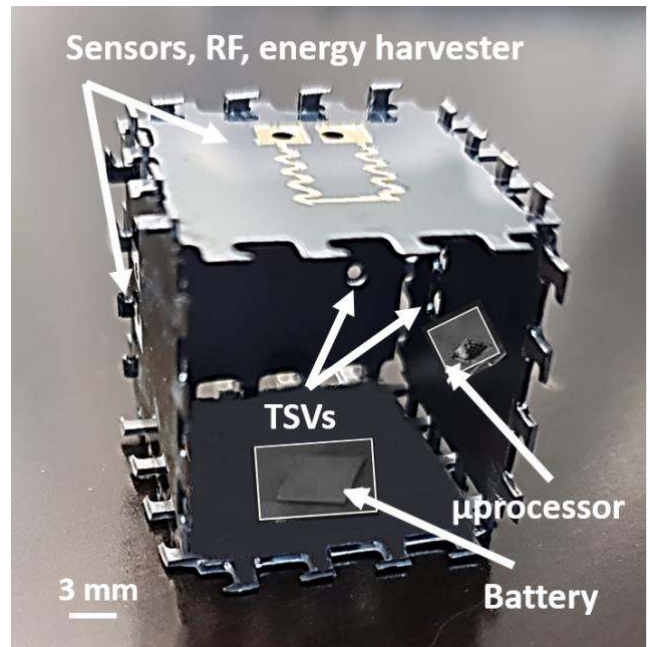


Fig. 3. Cubic MD-IC with integrated power and data management circuitry on its inner sides.
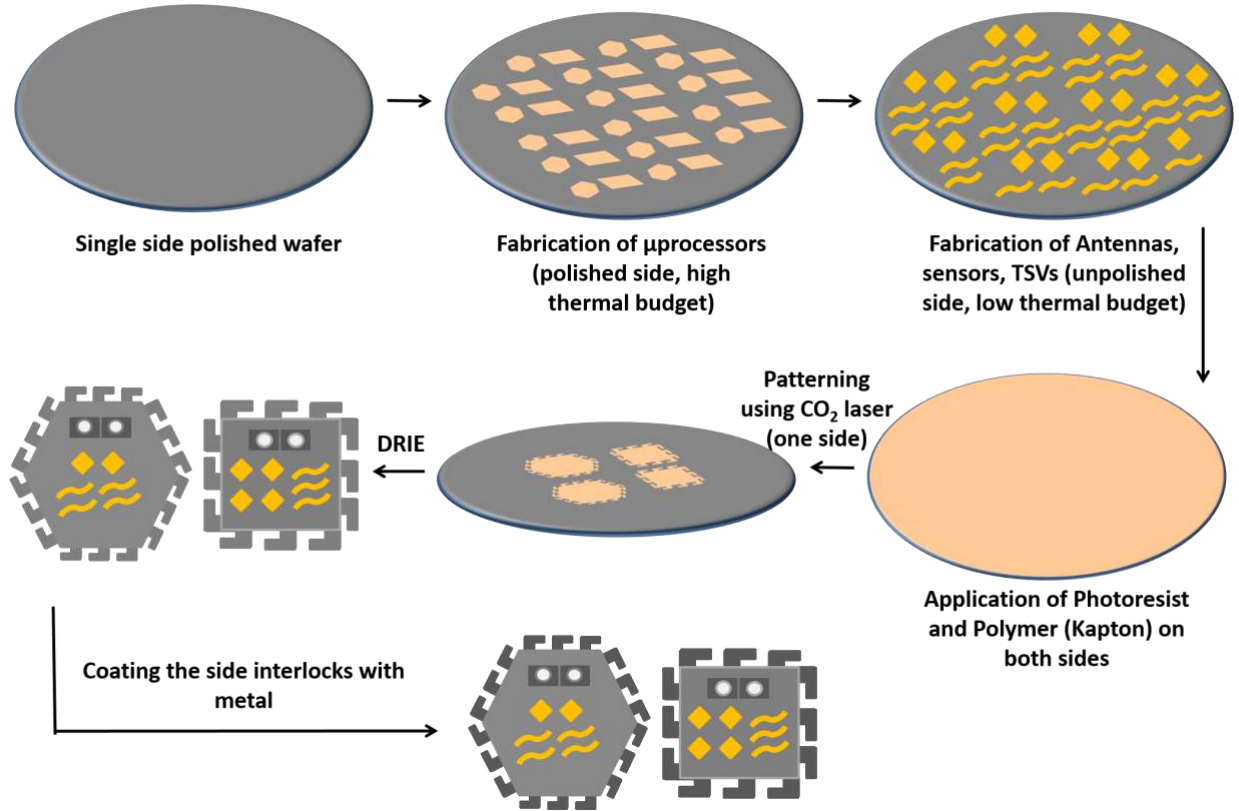
Fig. 4. CMOS compatible fabrication process flow of the MD-ICs. Devices on the outer-side and inner-side faces of the substrate are interconnected through TSVs while side to side devices are interconnected through side interlocks in a puzzle-like manner.

metallic layer. It is worth to mention that the size of the faces, the dimensionality (cube, pyramid, etc.), the number of TSVs and side interlocks can be adjusted and tailored based on the application requirements. Finally, the various faces of the MD-IC are folded together into a 3D architecture in a puzzle-like fashion. Fig. 2 and Fig. 3 show a cubic MD-IC with multiple sensors and a silicon solar cell [32-33] integrated on the outer faces while power and data management circuitry are embedded on the inner faces, respectively. The thorough fabrication process flow is shown in Fig. 4. It is important to mention that each side of the MD-IC can use a different material in an attempt to boost the performance of the full system.

*B. Devices Characterization*

As a proof of concept, multiple sensors ae fabricated and integrated in the MD-IC including pH, pressure and ammonia level sensors. The pH sensor is resistive based and uses a graphene monolayer as the active material. The sensor is developed by first depositing an $SiO_2$ insulating layer using plasma enhanced chemical vapor deposition system (PECVD) on a Si wafer. Next, interdigitated contacts are deposited using a sputtering system and patterned using a reactive ion etching tool (RIE). Finally, a graphene monolayer is transferred onto the interdigitated contacts and left to dry at room temperature. The sensor is then tested using solutions with different pH values. The resistance of the sensor is shown to reduce at larger

pH values. In fact, the $OH^-$ and $H_3O^+$ result in a doping effect in graphene which affects its conductivity. $OH^-$ ions are shown to cause a greater conductivity in the graphene layer than $H_3O^+$ ions (Fig. 5).

The pressure sensor uses the same structure as the pH sensor with a graphene monolayer as the active material. In this
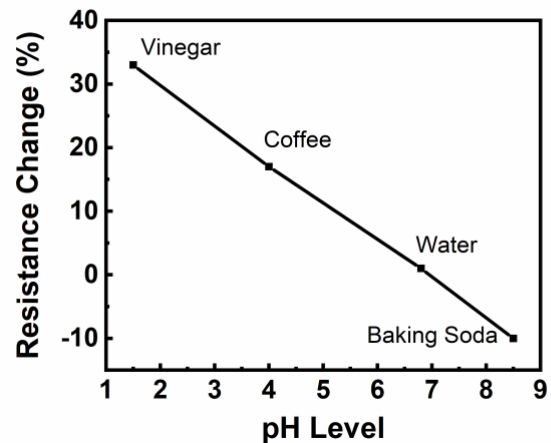


Fig. 5. pH sensor response when exposed to solutions with different pH values.
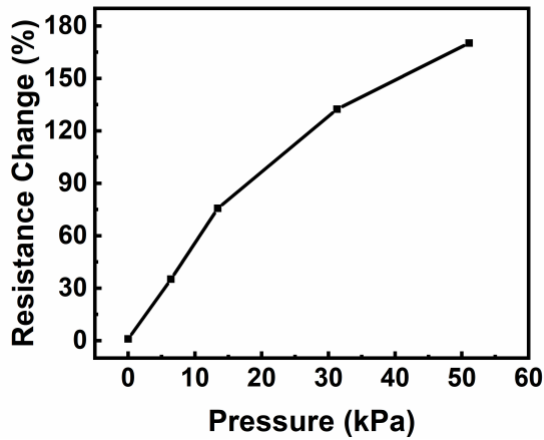
Fig. 6. Pressure sensor response when exposed to different weights.

case, the pressure sensor shows an increased resistance with pressure (Fig. 6), in fact, it has been reported that as the applied pressure on the graphene increases, the electron density increases while the electron mobility decreases. However, the electron mobility degradation over-compensates the electron density enhancement which results in an overall increase in resistance [34-42].

Finally, the ammonia level sensor uses laser induced graphene where a polyimide sheet was laser ablated using a $CO_2$ laser. The obtained graphene layer is around and shows defects. Such defects are favored because they increase the sensitivity of th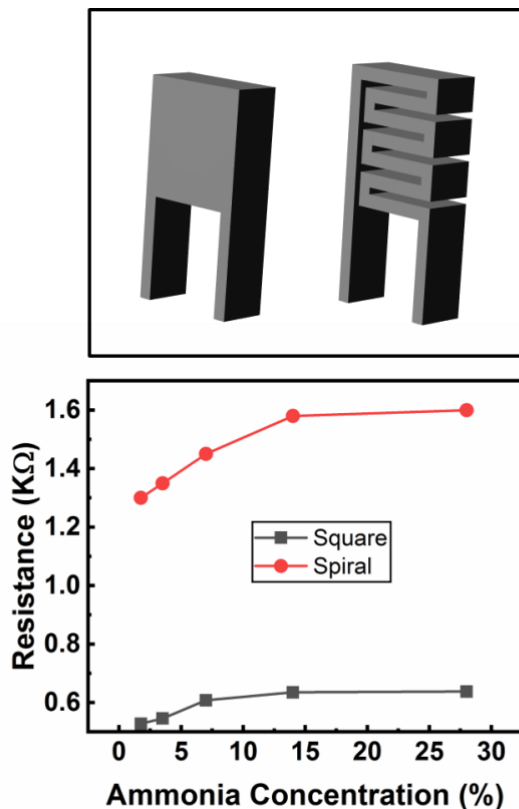e ammonia level sensor. Different structures are studied in this case, a square structure vs. a spiral structure with a higher surface area-to-volume ratio. Consequently, the sensitivity of the sensor in improved using the spiral structure as shown in Fig. 7.

## III. PACKAGING

Once folded into the 3D architecture (cubic architecture in the demonstrated prototype), the MD-IC is encapsulated using a solution processable polymer: polydimethylsiloxane (PDMS). The PDMS is prepared by mixing 10:1 ratio of silicone elastomer: curing agent. The solution is then further mixed under vacuum for 4 min to remove any air bubbles. Finally, the obtained PDMS is poured on each face of the cubic MD-IC and cured at 60°C for 2 hours. Next, $CO_2$ laser is used to pattern the PDMS and expose the sensors that necessitate direct contact with the external environment as shown in Fig. 8. The used laser power is 24 W with a speed of 2 mm/s and a height of 1 mm.

It is worth to mention that the faces that do not require exposure to the outer environment can remain fully encapsulated. PDMS has a very low thermal conductivity and thus contributes to reducing the heat transfer from the outside to the inner devices [43]. This characteristic would be helpful especially for applications of the MD-IC in harsh environments. To test this, a single side of the MD-IC was imaged under an infrared microscope when the chuck is heated up to 80°C. The encapsulated side showed around 20°C difference compared to the un-encapsulated side as shown in the thermal image depicted in Fig. 9.

Moreover, the PDMS enhances the mechanical robustness of the complete system. In fact, the encapsulated MD-IC was dropped from different heights (up to 15 m) using a drone tool empowered with a 3D printed object-dropping system where the PDMS was able to completely absorb the mechanical





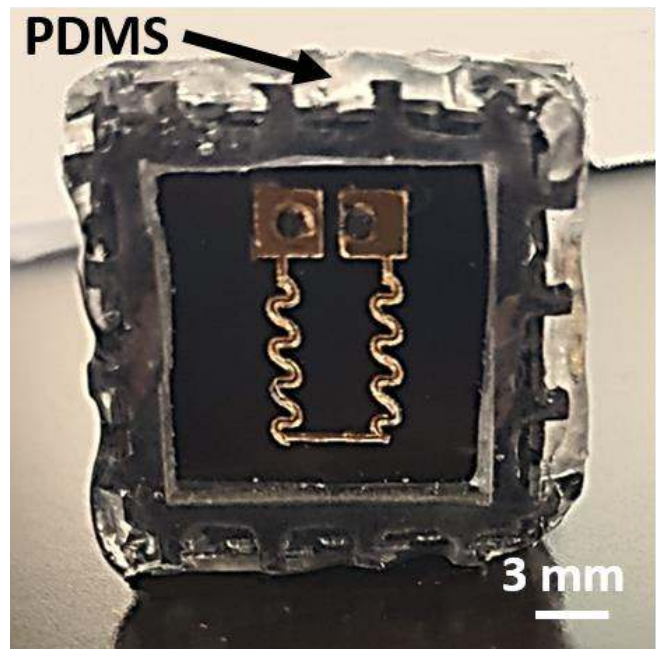Fig. 7. Ammonia level sensor response when exposed to ammonia concentrations where two distinct sensor structures are studied.



Fig. 8. Encapsulated side of the MD-IC using PDMS. $CO_2$ laser is used to expose the sensor to the outer environment.
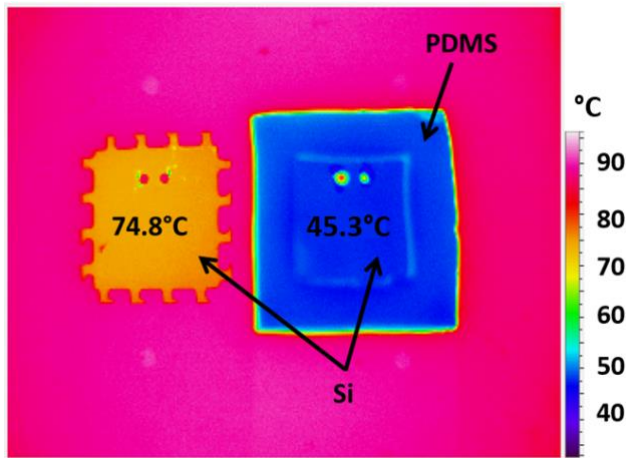
Fig. 9. Thermal image of the MD-IC side (encapsulated vs bare) when the chuck is heated up to 80°C.

shocks, while un-encapsulated silicon would completely crack when dropped from heights below 2 m.

Finally, a system reliability test is conducted on the MD-IC where multiple devices are embedded on the different sides and different faces such that they are interconnected through the TSVs and side interlocks. The devices include a temperature sensor, a solid-state battery and a microcontroller with a Bluetooth Low Energy chip (BLE). As a proof-of-concept, we show the data being read and processed by the microcontroller at and the result is sent by Bluetooth to a phone. A basic and free mobile application (CySmart™) is used to show the sent data by Bluethooth as a proof-of-concept. However, it is worth to note that more advanced applications can be developed to show multiple collected datasets on the same screen. In addition, more memory devices can be integrated to make the IoT system smarter [44-46]. In this reliability test, the encapsulated MD-IC with PDMS is placed in a beaker filled with water. The beaker is then placed on a hot plate, as a result, the detected temperature sent to the phone is shown to rise with time. The beaker is then placed on a cold surface where the temperature is shown to reduce again. This test verifies the potential of the MD-IC in integrating heterogeneous device on its different faces and sides.

## IV. CONCLUSION

In this work, we demonstrated a new design concept which is nature-inspired and specifically focused on standalone IoT systems. The multi-dimensional integration and packaging of devices bridges the gap between the most successfully existing integration and packaging technologies (SoC and SiP) and thus, it enables heterogeneous integration of materials and devices on different sides and faces of the system. The different sides are then folded into a 3D architecture in a puzzle-like fashion. The devices are interconnected through TSVs and side interlocks. The MD-IC allows for a high performance system for IoT applications with a small footprint area. In addition, since the heterogeneous devices can be fabricated on the different sides separately, then additional complicated lithography masks are not needed which reduces its cost. Finally, as a proof of concept, we show the application

of the MD-IC in collecting the temperature of water and sending it to a phone using the Bluetooth technology.

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