Bi-facial Substrates Enabled Heterogeneous Multi-Dimensional Integrated Circuits (MD-IC) for Internet of Things (IoT) Applications

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The primary focus of modern electronics technology is to increase its functionalities within a smaller footprint at an affordable cost. This creates a new set of design challenges for the already-existing complex integration and packaging schemes. Here, we show CMOS-compatible and heterogeneous multi-dimensional integrated circuits (MD-IC) as smart electronic systems for Internet of Things (IoT) applications. We use both sides of bulk monocrystalline Si (100) substrate for device fabrication which are connected via through-silicon-via to transform it into bi-facial CMOS electronics system. As a proof-of-concept, we show cubic, pyramidal and buckyball shaped MD-ICs, with broad variety of devices including humidity, temperature, pressure and pH sensors, solar cells, antenna, microcontroller, light emitting diode and micro lithium-ion battery. In these MD-ICs, adjacent sides are interconnected through side-interlocks. We also show that polymeric encapsulation and heterogeneous materials (Si, Ge, and GaSb) can be integrated in the MD-IC architecture to meet the rigorous requirements of IoT devices. Compared to folded rigid or flexible Printed Circuit Board based electronics, this report shows unprecedented usage of area by device fabrication on both sides which are also connected through-silicon-via as state-of-the-art tool for 3D-IC manufacturing.

Driven by the growing demand for big data, wearable and Internet of Thing (IoT) devices, existing integrated circuits (IC) packaging is being pushed beyond its technology limitation to meet new requirements such as increased compact integration and functionalities, high performance RF and analog electronics, low-power consumption, and low-cost fabrication process.^[1-3] So far, the most successful integration and packaging technologies have been based on System-on-Chip (SoC) and System-in-Package (SiP), especially with the introduction of the 3D vertical integration concept. In fact, the SoC technology, driven by Moore's law, has been the focus of several IC manufacturers for many years due to its ability to deliver high performance systems with small form factor, high density integration and low power consumption.^[4-5] Advances in lithography, improved materials combinations and larger wafers have thus been the key enablers of this integration technology. However, while it has several advantages, SoC is limited to what can be realized within one wafer process resulting in either limited functionalities or compromised performance of multiple components. In addition, SoC faces challenges including long design times due to the complex integrations demanding dozens of mask steps, designs verification, high wafer fabrication costs and Intellectual Property (IP) problems.^[6] In that context, key advantage of SiP lies over SoC, in its capability to integrate into the package not only heterogeneous ICs but also added functionalities such as antennas, passive components, Bluetooth, imaging, etc. to create a complete system. Because SiP is based on the integration of electronic components on a printed circuit board (PCB), it shows additional benefits over SoC in terms of faster time-to-market, faster implementation of system changes, simpler designs, processing with lower number of mask steps, integration of large memories, IP reuse, etc. Nonetheless, SiP is not considered as a complete system technology but a package integration; its performance is limited to the CMOS performance which is not always optimal for certain electronic components and it is bulkier than SoC.^[7-9]

Herein, we show a new integration technology based on multi-dimensional (MD) integration of thin-film components to combine between the best of SoC IC integration and the best of SiP package integration. The MD-IC will provide a complete multifunctional system with a small package instead of the bulky PCB used in SiP. The resulting system is a complete, multi-functional, lightweight, high-performance and compact packaged system. Even though the SoC and SiP based systems can include 3D integration of electronic components, however, MD-IC surpasses the limited functionality challenge of the SoC scheme and the large size and poor usage of area in SiP. Due to the folding into different shapes and bi-facial usage of Si, the area footprint of MD-IC is lower than other technologies. An additional benefit of the MD-IC is the enhanced yield and cost of the system due to the capability to fabricate and test the smaller dies separately before integrating them into a complete package as opposed to SoC where large dies are manufactured with much lower yield. In this work, as a proof-of-concept, we demonstrate a prototype of a cubic MD-IC that includes multi-functional sensors, antenna, microcontroller, light-emitting-diode (LED), a micro-lithium-ion battery in addition to a solar cell. Devices are fabricated on both sides of each substrate and are interconnected using via and side interlocks. The MD-IC is nature inspired where all sensors are integrated on the outer sides while logic, memory and battery are embedded on the inner sides. Finally, we encapsulate the interconnects in the system with a bio-friendly polymer for harsh environment applications.

The integration and packaging of the MD-IC is successfully completed through a CMOS compatible approach using a combination of laser etching and deep reactive ion etching (DRIE) (**Figure 1a**). Each side of the MD-IC has a number of isolated interlocks to connect adjacent sides in addition to two through-silicon-vias (TSVs) to connect the top and bottom sides of each substrate (front and backside of a Si wafer). The double face usage of the silicon wafer helps in area preservation and cost reduction. While double-side polished silicon wafers

could be used, however, for a cost effective system, antenna and other components that do not require Si as an active material can be fabricated on the backside of a single-side polished Si wafer, whereas transistors, memory devices and solar cells can be fabricated on the polished front-side of the wafer which has a low density of defects (**Figure 1b**). Finally, the MD-IC interconnects are encapsulated in a bio-friendly polymer: Poly-dimethylsiloxane (PDMS) to isolate the inside circuitry from the outside environment. A multilayer of PDMS is applied (6-layers) to reduce the probability of a defect causing the failure of the system. The PDMS on the outer sides of the MD-IC is then patterned to keep the outer electronic components (i.e. sensors, solar cell, antenna, etc.) exposed to the external environment (**Figure 1c**).

In the fabricated prototype, every two adjacent sides are interconnected via four separate interlocks which acts as input/output pins of the circuitry/devices fabricated on each side (**Figure 2a**). Outer side and inner side electronics are interconnected using TSVs (**Figure 2b**). Each side interconnect is coated with metal and a pad is patterned for device interconnections (**Figure 2c**). Then, sensors, solar cell, and antenna are fabricated on the outer sides of the system, while data management circuitry (bare die microcontroller IC) and a solid micro-lithium-ion state battery are embedded on the inner sides of the MD-IC. The temperature sensor is based on standard resistive temperature detection (RTD), the humidity/pressure/PH level sensors use interdigitated electrodes and a graphene monolayer as the sensing medium. It is worth to mention that graphene based on-chip RF systems can also be included in the MD-IC and graphene-based storage devices.^[10-11] The solar cell is based on crystalline Si cells with interdigitated back contacts, and the antenna is based on a copper ring structure. It is important to mention that the number of interlocks and TSVs, size of the MD-IC and shape can be customized according to the application requirements (**Figure 2d,e**).

To confirm that the proposed system is functioning, in the following, we assess the performance of the fabricated sensors and embedded microcontroller IC. We also study the

suitability of the system for harsh environment applications and its scalability. The cubic MD-IC, as a standalone temperature sensor, is tested by programming the microcontroller such that an LED turns on when the temperature of the MD-IC system is above a threshold value (30°C) (**Figure 3a**). In this test, the temperature sensor, LED, solid-state lithium ion battery and microcontroller are all fabricated on different faces of the MD-IC (sensor and LED are fabricated on two outer sides, while the solid-state battery and microcontroller are embedded on two inner sides of the MD-IC (**Figure 2a**). In this case, the battery is used to power the microcontroller; the temperature sensor provides the sensed temperature as an input to the microcontroller while the output of the microcontroller is connected to the LED. The LED is turned ON when the temperature is increased above 30°C which confirms the reliability of the interconnects and TSVs in interconnecting the devices different sides and faces of the MD-IC. This confirms the capability of the MD-IC to integrate various CMOS devices fabricated on different faces in a 3D fashion: on the inner and outer sides of each Si face.

To study the efficiency of the PDMS encapsulation, the MD-IC was exposed to high temperatures and the heat distribution is compared to an MD-IC with no encapsulation. In fact, PDMS has a low thermal conductivity ($0.15 \text{ W m}^{-1} \text{ K}^{-1}$) which aids in significantly reducing the heat transfer through the encapsulation components ^[12] as shown in the thermal image obtained using an infrared microscope (**Video S1**). It is worth to mention that for harsh environment applications, multiple faces of the MD-IC on which sensors do not require direct contact with outer environment (e.g. temperature sensor, pressure sensor, etc. as opposed to gas sensor where the gaseous chemicals need to be in direct contact with the sensing film on the MD-IC face) can be completely encapsulated in PDMS and sensitive data-management components can be fabricated on the back side of these faces, which further improves the resilience of the full system to heat and external mechanical impact. The effect of the encapsulation material on the sensors can then be mitigated by taking into consideration the properties of the PDMS when calculating the various sensed elements in the environment

(such as including the heat transfer coefficient (HTC) and thickness of the PDMS when calculating the actual outer temperature using the microcontroller). Additionally, a thermally conductive polymer can be used in the encapsulation of the MD-IC inner components in order to dissipate the heat generated on the inner sides of the MD-IC.^[13-14]

The prototype presented in this work is based on bulk Si (100) wafer, however, we also show that heterogeneous materials (Si, Ge and GaSb) can be integrated in the MD-IC to optimize the overall performance of the system (**Figure 3b**). The MD-IC will thus not be limited by the restriction of a common wafer process as in SoC, instead, optimized thin-film based devices can be integrated into the system: i.e. a GaAs heterojunction bipolar transistor RF can be integrated in one package with III-V solar cells on Ge substrate and sensors on Si, etc. (**Table S2**). This technology becomes even more promising with the advent of bio-electronic systems where microfluidic devices are integrated with bio-sensing components, wireless components, and control electronics.^[15-22]

In terms of scalability, the MD-IC size can be scaled up or down according to the application requirements. Cubic MD-ICs have been fabricated with different sizes: 4-cm, 2-cm, 1.5-cm, 8-mm, and 5-mm sides which can be smaller than the size of a medical pill (**Figure 3c**). In fact, a MD-IC can also be employed in biomedical applications as implantable/injectable microsystems. In addition, the capability to scale down the MD-IC and therefore to pack heterogeneous and high-performance sensors, communication systems and processors into millimeter-sized cubes makes the proposed integration scheme suitable for refining the performance of “smart dust” devices.^[23-25] Finally, to study the mechanical robustness of the system, a drop test is conducted on the encapsulated MD-IC by dropping it from a height of 15 m (**Video S2**). The system stays intact after the drop as the impact is absorbed by the PDMS which is mechanically very robust.^[26-28]

Since Rigid-Flex has gained attention in the last few years as a methodology to make foldable systems with small footprint,^[29] it is very important to note the differences between our system and the Rigid-Flex PCB and explain the benefits that our new integration technology adds. To begin with, our methodology is an integration scheme that results in a complete and packaged system as previously explained, while the Rigid-Flex PCB is a packaging technology. Therefore, in addition to the previously mentioned advantages of MD-IC over SiP (PCB based), the following merits of our system are added and discussed. First, Rigid-Flex PCB uses rigid PCB islands to host the electronics components and flexible PCB interconnects that allows the package to be folded. This results in a limited flexibility of the system where the bending radius is typically 3 to 6 times the thickness of the PCB.^[30] Due to the bulky nature of the PCB, the MD-IC can therefore provide a full system with a smaller form factor. In addition, we have shown that our MD-IC uses double sides of the Si wafer for hosting electronic components interconnected using TSVs. While Rigid-flex PCBs can also be double-sided, however, it has been shown that the fatigue life of vias rises with thinner PCB which further confirms the larger footprint required for a reliable Rigid-Flex system compared to the MD-IC.^[31] Moreover, in Rigid-Flex systems, soldering is used to connect different wires and components. However, soldering using robotic technologies is limited by the characteristic of deformation of the flexible PCB, as a consequence, manual soldering is currently being used which results in low efficiency, low speed and low output, whereas well-established and reliable interconnects such metal thin films and TSVs are used in MD-IC.^[32-33] Finally, Rigid-Flex PCBs are expensive and take longer time-to-market due to the complex designs.^[33]

In conclusion, Integrated Electron Device Manufacturers (IEDMs) are persistently being confronted with device integration challenges as consumers desire electronics to be of smaller size, lighter, effortlessly portable, cheaper and more multi-functional than ever. As a result,

the existing SoC and SiP technologies face unparalleled challenges. In this work, we introduced the concept of multi-dimensional integrated circuits (MD-IC) which combines between the best of the existing integration and packaging technologies. The MD-IC overcomes the limitations of SoC by enabling the addition of multi-functional and heterogeneous devices and materials in addition to surpassing the “bulky” attribute of the SiP package. The result is a complete, multi-functional, lightweight, scalable, and low cost system. As a proof-of-concept, a working prototype based on cubic MD-IC for IoT applications has been demonstrated with microcontroller, sensors, solar cell, battery, antenna and LED. We also showed that the MD-IC can be promising in harsh environment applications.

Experimental Section

Fabrication of the MD-IC: The integration and packaging of the MD-IC is successfully completed through a CMOS compatible approach. First, a photoresist followed by a polymer (Kapton) are applied on a bulk Si (100) wafer. Next, CO₂ laser is used to pattern the different sides of the MD-IC. The unmasked Si areas are then etched using sulfur hexafluoride (SF₆) and carbon fluoride (C₄F₈) in a deep reactive ion etch (DRIE) system. The interconnects (interlocks and TSVs) are coated with 500-nm silver using e-beam evaporation.

Fabrication of sensors and antenna: First a 300-nm SiO₂ layer is deposited using a plasma enhanced chemical vapor deposition (PECVD) tool, followed by the deposition of 10 nm Ti and 180-nm Au. Photolithography followed by dry etch in a reactive ion etching are used to pattern the sensors. The single-layer-graphene is grown using CVD on copper foil. The copper is then etched using FeCl₃ for 1 day. The graphene monolayer is then placed in a beaker with deionized water before being picked up on the Au metal contacts of the different sensors and dried at room temperature for 1 day.

The antenna is based on a copper ring structure, 200-nm copper is deposited using a sputtering tool and patterned using the lift-off. The solar cell is based on crystalline Si cells with Si_3N_4 antireflective coating and with Al interdigitated back contacts. On the inner sides of the MD-IC, a pre-fabricated bare die microcontroller IC is used with a solid-state micro-lithium-ion battery.

Encapsulation of the interconnects: Poly (dimethylsiloxane) (PDMS) is prepared by mixing the silicone elastomer to its curing agents in a 10:1 ratio, respectively. The mixture is then degassed in a vacuum mixer for 4 minutes at 100 KPa and 700 rpm speed to remove bubbles. The MD-IC is then encapsulated with PDMS and cured at 60°C for 24 hrs. A total of 6-layers are used to encapsulate the MD-IC. CO_2 laser is next used to pattern the PDMS on the outer sides of the MD-IC such that the interconnects are encapsulated and the sensors/antenna/solar cell are exposed to the external environment.

Heterogeneous integration: Ge is etched using $\text{SF}_6\text{-O}_2$ while GaSb is etched using $\text{Cl}_2\text{-Ar}$ in an RIE system.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Figures with captions

Figure 1. System integration and packaging. a) Detailed schematic of the CMOS compatible integration process of the MD-IC. b) Standalone cubic MD-IC system. c) PDMS encapsulated interconnects and TSVs to isolate the inner circuitry from the outer environment.

Figure 2. Cubic MD-IC system. a) The inner area of the MD-IC where the microcontroller IC and solid-state micro-battery are embedded. b) SEM image of the through-silicon-via shown in the figure inse. d) SEM image of the interlock. d) MD-IC with buckyball shape. e) MD-IC with cubic and pyramidal shapes with different dimensions.

Figure 3. Reliability, heterogeneity and scalability of the MD-IC. a) Current output from the microcontroller when connected to an LED. b) MD-IC with heterogeneous Si, Ge and GaSb sides for optimized IoT devices performance. c) Cubic MD-IC with different sizes showing the scalability of the proposed integration and packaging scheme.

In this work, we introduce the concept of multi-dimensional integrated-circuits (MD-IC) which combines between the best of the existing integration and packaging technologies. MD-IC is based on the integration of thin-film components and provides a complete, multi-functional, lightweight, high-performance and compact-packaged system. A working prototype for IoT applications has been demonstrated with microcontroller, sensors, solar cell, battery, antenna and LED.

Keyword: Multi-dimensional integrated circuits, packaging, through-silicon-vias

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Cubic shaped multi-dimensional integrated circuit for IoT applications

Supporting Information

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Video S1. Thermal test on the MD-IC. Video showing the temperature of the MD-IC with and without PDMS encapsulation when heated at 90°C for 2 hours.

Video S2. Mechanical robustness of the MD-IC. Video showing a 15 m drop test performed on the cubic MD-IC.