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Modular Lego-electronics

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Corresponding Author:	Muhammad Mustafa Hussain, Ph.D. King Abdullah University of Science and Technology KAUST Thuwal, SAUDI ARABIA
Additional Information:	
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<p>Please submit a plain text version of your cover letter here.</p> <p>If you are submitting a revision of your manuscript, please do not overwrite your original cover letter. There is an opportunity for you to provide your responses to the reviewers later; please do not add them here.</p>	<p>7th June 2017 Dr. Esther Levy Editor-in-Chief, Advanced Materials Technologies</p> <p>Dear Dr. Levy,</p> <p>Please find the manuscript titled, "Modular Lego-electronics". Electronic system components have thousands of individual field effect transistors (FETs) interconnected executing dedicated functions. Assembly yield of >80 % will guarantee system failure since a single interconnect failure will result in undesired performance. Hence, a paradigm shift is needed in the self-assembly or integration of state-of-the-art integrated circuits (ICs) for a physically compliant system. Traditionally, most ICs share same geometry with only variations in dimensions and packaging. Here we show, a generic manufacturable method of converting state-of-the-art complementary metal oxide semiconductor (CMOS) based ICs into modular Lego-electronics with unique geometry that are physically identifiable to ease manufacturing and enhance throughput. We grove various geometry at the backside of the silicon die and on the destination site having the same geometry with relaxed dimension (50 m extra) allows targeted site binding like DNA assembly. Different geometries, angles, heights for different modules provide a unique identity to each of the ICs. The two level geometric combination presented here helps in maintaining the uniqueness of individual module to assemble at exact matching site like a perfect lock-and-key model. The performances of assembled ICs offer uncompromised electrical performance, higher yield and fabrication ease. In future, this method can further be expanded for fluidic assisted self-assembly.</p> <p>As reviewers we suggest the following leading authorities:</p> <ol style="list-style-type: none"> 1. William E. Ayer Professor of Engineering Roger Howe, Stanford University (rthowe@stanford.edu) 2. Extended Tarr Family Professor of Materials, David Clarke, Harvard School of Engineering and Applied Sciences (clarke@seas.harvard.edu) 3. Lynn H. Matthias Professor in Engineering and Vilas Distinguished Achievement Professor Jack Ma, University of Wisconsin – Madison (mazq@engr.wisc.edu) 4. James A. Friend Family Distinguished Professor of Engineering Lynden Archer, Cornell University (laa25@cornell.edu) 5. TSMC Distinguished Professor in Microelectronics Tsu Jae King Liu, University of California Berkeley (tking@eecs.berkeley.edu) 6. Board of Trustees Professor Fraser Stoddart, Northwestern University (stoddart@northwestern.edu) <p>We sincerely hope this paper addresses a timely topic which will receive your thoughtful consideration. Should you need any further information about our</p>

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Corresponding Author Secondary Information:	
Corresponding Author's Institution:	King Abdullah University of Science and Technology KAUST
Corresponding Author's Secondary Institution:	
First Author:	Sohail F Shaikh
First Author Secondary Information:	
Order of Authors:	Sohail F Shaikh
	Mohamed T Ghoneim
	Rabab R Bahabry
	Sherjeel M Khan
	Muhammad Mustafa Hussain, Ph.D.
Order of Authors Secondary Information:	
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Sohail F. Shaikh¹, Mohamed T. Ghoneim¹, Rabab R. Bahabry^{1,2}, Sherjeel M. Khan¹, and Muhammad M. Hussain^{1}*

¹ Integrated Disruptive Electronic Applications (IDEA) Lab and Integrated Nanotechnology Lab, Computer Electrical Mathematical Science and Engineering Division, King Abdullah University of Science and Technology (KAUST), Thuwal 23955-6900, Saudi Arabia

² Integrated Nanotechnology Lab and Integrated Disruptive Electronic Applications (IDEA) Lab, Material Science and Engineering, Physical Science and Engineering Division, King Abdullah University of Science and Technology, Thuwal 23955-6900, Saudi Arabia

Corresponding author's e-mail: muhammadmustafa.hussain@kaust.edu.sa

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Abstract

Electronic system components have thousands of individual field effect transistors (FETs) interconnected executing dedicated functions. Assembly yield of >80 % will guarantee system failure since a single interconnect failure will result in undesired performance. Hence, a paradigm shift is needed in the self-assembly or integration of state-of-the-art integrated circuits (ICs) for a physically compliant system. Traditionally, most ICs share same geometry with only variations in dimensions and packaging. Here we show, a generic manufacturable method of converting state-of-the-art complementary metal oxide semiconductor (CMOS) based ICs into modular Lego-electronics with unique geometry that are physically identifiable to ease manufacturing and enhance throughput. We grove various geometry at the backside of the silicon die and on the destination site having the same geometry with relaxed dimension (up to 50 μm extra) allows targeted site binding like DNA assembly. Different geometries, angles, heights for different modules provide a unique identity to each of the ICs. The two level geometric combination presented here helps in maintaining the uniqueness of individual

module to assemble at exact matching site like a perfect lock-and-key model. The assembled ICs offer uncompromised electrical performance, higher yield and fabrication ease. In future, this method can further be expanded for fluidic assisted self-assembly.

Introduction

Architecture and appearance are often used as means of identity. Living beings such as Japanese male puffer fish - otherwise invisible in the sea environment, naturally creates magnificent architecture in the sand to attract the female counterpart. ^[1] Living cells demonstrates countless examples of functional self-assembly in addition to being able to self-assemble themselves. Such exciting phenomena in nature have inspired research community to study, understand, and design self-assembled objects for applications in assembly, manufacturing and robotics in future. ^[2]

The construction of the modern man-made artefacts like computers, cell-phones, automotive etc. rely on modular assembly of its components, assisted by robotic assembly lines to place, package, and interconnect variety of modules at different scales; extensively in millimetre and higher scales. Complementary metal oxide semiconductor (CMOS) technology which has been the driving force for today's digital world, depends on scaling of the devices. Miniaturized devices with complex fan-outs are increasingly challenging for automated manufacturing. Large number of tiny pins on each side of the integrated circuits (ICs) requiring greater accuracy and precision are key reason for such complexity. Thus, the assembly and interconnection of such scaled components is one of the bottle necks in modern CMOS technology lowering the throughput of the entire manufacturing process. ^[3]

Different approaches to achieve parallel assembly as an alternative to robotic assembly are presently under investigation, including parallel transfer of chips to a donor wafer which typically contains three steps: fabrication of devices on donor wafer with a sacrificial release layer, pick up using an intermediate elastomeric transfer stamp followed by transfer onto the

final substrate. However, this approach is not feasible when the conventional substrates are replaced by curved topologies and flexible platforms which are emerging as new frontiers in the electronics industry. Directed and engineered self-assembly is an alternate route in which maintaining orientation, alignment, and functional density over large areas is possible. Among different directed assembly techniques, surface tension driven assembly has attracted major attention. Smith *et al.* ^[4] pioneered in this field by demonstrating the quasi-monolithic integration of Gallium Arsenide (GaAs) light emitting diodes (LEDs) on Silicon (Si) substrate by combining geometry and fluidic direction for self-alignment. Several other reported methods for self-assembly use the surface tension in combination with either solder bumps ^[5–7], magnetic ^[8,9] or electrophoretic ^[10,11] forces, or capillary transport. ^[12] Smith *et al.* and Jacob *et al.* ^[13] have reported higher yields for the assembly process in their works.

Other interesting works presented in the area at a scale of hundreds of micrometer are: Cylindrical display fabrication using capillary interaction, ^[13] sequential-shape-and-solder-directed- self-assembly (SSSDSA), ^[14] mesoscale building blocks assembly using capillary interactions, ^[15] single angular orientation and contact pad registration based alignment and integration of semiconductor dies in SSSDSA. ^[16] Sub 100 μm scale devices are reported to be assembled by liquid-liquid-solid surface tension driven approach. ^[17,18] All of the above approaches of the assembly have a combination of either shape, surface tension driven or gravity driven approach in addition to using liquid or molten solder paste on the connecting pads.

The emerging era of flexible, stretchable and reconfigurable electronics for the applications in healthcare monitoring, displays, electronic papers, and environmental monitoring demands the compliance and high throughput assembly process which can be applied to a compliant systems. Parviz *et al.* ^[5,19–21] has demonstrated assembly of single crystal field effect transistors and diffusion resistors on the plastic substrate which is mediated by

fluidic agitation at moderate temperatures of 60-90 °C to have good interconnection using molten solder pads.

The yield of above mentioned microscale level assembly approaches have been reported to be as high as 80% which enables the assembly of individual devices like field effect transistor (FET), PIN diode etc. Most of the applications in flexible electronics and internet of things domain that include health monitoring, wearable gadgets, flexible displays, and lab-on-chip devices, rely on integration of sensors network, data processing units, data storage, communication module, system-on-chip (SoC), and power management. In all these applications, the yield of 80% assembly at individual device level will lead to failure in achieving the desired performance from system, since the devices are part of the major components and even a single device interconnect failure means failure of the block which implies entire system failure.

To tackle this problem here we show a holistic approach of assembling technique at the level of system integration using modular Lego-electronics. Lego based modular approach fundamentally uses the geometry of the two blocks/pieces that fit exactly into each other transforming the blocks into a system. These individual blocks can easily be detached and reconfigured into another completely different and independent system when rearranged in different manner. A typical electronic system will include the microprocessor/microcontroller, memory, energy storage, and communication modules. We present a method of converting these individual integrated circuits (ICs) into a specific geometry that provides a unique identification to each IC –physically identifiable without microscopic details. A typical CMOS based IC consist of the isolated connecting pads ($\sim 55 \mu\text{m}$ - $120 \mu\text{m}$ square pads) on top of the die for establishing interconnects with the outer interface circuitry or fan-out. We convert the IC into one part of the Lego-module (part A or male-Lego) by transforming it into a specific shape without compromising the performance of the chip. This module can be assembled onto its inverse replica (part B or a female-Lego) on the flexible substrate bridging the designed

system schematic. We first demonstrate the complete flexible system that implements an AND and OR logic gate like functionalities by fabricating both male-Lego and female-Lego modules on flexible polyimide substrate. Later we have translated this approach to transform the commercially available ICs to Lego-electronic modules that promises the new opportunities and approaches of integrating and assembly techniques for flexible electronic systems. We also demonstrate for the first time how this geometrical modular Lego-electronic approach empowers the blind assembly of the modules in its position with great accuracy which opens tremendous opportunities for visually impaired beings.

Results and discussion

Two major studies are presented on this work.

Part A - Flexible Lego Concept: The concept realisation that has two-layer geometrical shape recognition for modular assembly. Two-layer shape recognition need arises from the fact that the device geometry itself has to be made unique enabling quick identification, however, presence of two devices with same geometry will need the additional features (layer) to identify. Thus, a unique combination of two layered architecture of module and a very well defined binding sites will ensure the accuracy and ability of the host to accept only designated Lego module at their sites. First, we fabricate the inverted binding site replica (host) on Kapton sheet following the schematic presented in **Figure 1A** and millimetre scale male-Lego modules using fabrication scheme in **Figure 1B** – both detailed in later section. Fabricated host and Lego modules are depicted in **Figure 1C and 1D**. Three different component geometries: heart, circle, and square - all with same teeth shape (defined by square at second layer) and with different teeth design (heart, circle, and square) were fabricated. The dimensions of the devices were chosen to be $3\text{ mm} \times 3\text{ mm} \times 0.25\text{ mm}$ which mostly resemble typical IC dimensions at die level. Surface mount red LEDs were then mounted on the binding sites at dedicated pads which will act as our output signal for implemented logic gate like AND and OR design.

The binding site dimensions for inverse replica of Lego were carefully chosen slightly bigger ($\sim 50\ \mu\text{m}$ bigger) than the male Lego-module in order to provide better placement without any added external pressure application when the modules reach the site. **Figure 2A, 2B, and 2C** show the binding sites before LED attachment, individual Lego-modules and site after LED attachment respectively before assembly. Manually assembled complete Lego-modules can be observed for its accuracy in **Figure 2D** while **Figure 2E** indicate the performance of the system when powered by turning ON of LEDs as output of the gates. Top left circuit trace in the Figure 2A represents an AND gate logic which requires combination of heart shaped Lego with one of the other modules to turn ON the LEDs while right circuit trace makes OR like gate logic.

A gentle pressure was applied to establish a good contact between Lego and site (see supplementary video S1) that will reflect enough voltage across LED to turn on momentarily. We used conductive silver hardener part B for ensuring the connection when Lego are assembled at the binding sites without any external pressure application. Comparison of both the assembled modules with and without epoxy is demonstrated in supplementary video S2 with an OR gate logic. LED turns ON only on application of pressure on Lego due to possibility of a small gap or voids at the interface of the Lego and pads on binding sites though they seem to be exactly fitting into each other. We countered this by applying a very thin $<10\ \mu\text{m}$ micro-drop of silver epoxy hardener resin on the electrodes at binding site to ensure the connection. This thin epoxy enabled improved adhesion resulting in instantaneous connection to turn ON LED without any external applied pressure reducing Lego damage risk.

The accuracy of Lego module identification by combination of two layer geometric identification is demonstrated in the supplementary video S3 where two same sized heart shaped Lego with different teeth (square and heart) are placed at same site one after another. We can conclude from the video that when teeth (second layer combination) does not match with host, it does not fit the site. And when both the combination matches, the acceptance is

evident and the connection is established easily and LED switches ON in the video. Additional geometric features like angles and heights at the second layer will further strengthen the unique identification during assembly in complex and large component set.

To investigate the contact establishment and optimising the process if conductive silver epoxy hardener is a must or not, we acquired cross-sectional scanning electron microscopic (SEM) images. **Figure 3A** represents the cross-section of a Lego-module assembled and fit into host without any external epoxy application. We can observe from the SEM image that, there is a void between two flexible layers meaning no connection between pads on Lego and pads on binding site. A very fine line of interconnect is possible between Lego module and its binding site, which occasionally completes the circuit resulting in momentary turning ON of the LEDs. Cross section SEM image of the assembled Lego-module with very thin epoxy application between pads and the binding site is presented in **Figure 3B and 3C**, seamless interconnection at the bonding site is observed. The possibilities of minor voids in epoxy is present, however, this can be neglected as there is enough contact establishment to counter it which eliminates the necessity of external pressure application on Lego. This is further confirmed by plotting the resistance across the circuit line trace after the assembly for both the cases. The resistance of the line across the metal trace is measured which shows the value of $<10\ \Omega$ ($7.6\ \Omega$) for Lego with epoxy whereas $\sim 475\ \Omega$ without epoxy plotted in **Figure 3D**. This high resistance restricts the current flow in the circuit in addition to have a maximum voltage drop across the Lego instead of LED to turn it ON.

The high yield of the assembly and geometrical identification is studied using a robotic pick and place tool (Datacon 2200) - custom designed for handling the flexible devices and substrate shown in **Figure 4A - 4C**. The tool has been programmed to accurately identify these Lego-modules having same component geometries with different teeth shapes. Tool assembly achieved 100% yield of exact placement of Lego seen in **Figure 4B and 4C** without and with epoxy (LEDs ON) application respectively. The assembly is also demonstrated by a

supplementary video S4 in which an OR gate has epoxy applied at sites while AND gate does not to compare connection establishment.

This robotic assembly due to geometrical unique identification allowed us to set up a novel experiment where a subject is blind folded to mimic the visually impaired person. A supplementary video S5 illustrates this, where a colleague has been blind folded and tasked to assemble the devices on the binding site manually identifying the physical geometries. Promising result of successful assembly of the flexible Lego-modular electronic were achieved which can open unprecedented opportunities in the CMOS technology especially for visually impaired people.

The flexibility of the fabricated modules is observed by bending the substrate after assembly. Similar to our previous comparison analysis of both with and without epoxy hardener assisted assembly, we show both these methods to evaluate bending performances. **Figure 5A and 5B** show performance of an AND logic gate remain intact after it is subjected to a bending radius of 1.25 cm while OR gate logic configuration for the module does not turn ON. The reason for this is that we have used epoxy at the binding sites of AND gate logic while no epoxy was applied at OR logic sites. Since, both male-Lego and female-Lego parts are flexible, they pop out slightly when bend due to inability of micro-epoxy to hold on to higher pressures/stress induced on bending. This is dealt with smart packaging of the modules by spinning a thin 100 μm PDMS on top of it that holds the modules intact. Supplementary video S6 illustrates this in which Lego having no epoxy pops out even after packaging is applied and works when gentle tap is applied. Extreme bending can be achieved in these flexible Lego-modules as shown in **Figure 5C and 5D** which illustrates the bending of individual Lego modules up to a radius of 500 μm . even lower bending radii may be achieved.

Part B - Transforming an IC into Lego: In this study, we demonstrate transformation of a commercial IC into Lego-module by implementing a comparator circuit on a flexible substrate.

High precision OPAMP constitutes an integral part of many system-on-chip (SoC), microcontroller or microprocessor, and many other analog and digital systems. Here, we used a state-of-the-art commercially available OPAMP bare-die IC to convert into Lego-module. The fabrication/conversion procedure is presented in **Figure 6A** and detailed in the fabrication section of the paper. The integrity and reliability of the process conversion is validated by device characterisations of unprocessed bare-die module and the obtained Lego-module at the end of fabrication. A simple comparator circuit on flexible PI is fabricated using schematic in **Figure 6B**. The optical microscopic images for the as obtained bare-die IC and converted Lego-module are presented in **Figure 6C and 6D** respectively showing 100 μm contact pads. Digital images of the Lego-module when it is assembled on the destined sites can be observed in the **Figure 6E** from both front and rear side of the binding site on glass. Conversion of the state-of-the-art bare die ICs into the Lego-module could also be achieved by patterning specific geometry on the backside of the IC using laser etching and other techniques like soft-back-etch.

The comparator configuration of the OPAMP is implemented by providing a reference voltage (V_{ref}) (50 mV - 550 mV DC) at the inverting terminal of the device with a sinusoidal input signal ($V_{\text{in}} = 1.2 V_{\text{pp}}$ at 1 kHz frequency) applied at non-inverting terminal. Unprocessed OPAMP die characterisation for comparator configuration using semiconductor probe-station is recorded on digital oscilloscope in **Figure 7A** with $V_{\text{ref}} = 500 \text{ mV}$ and $V_{\text{in}} = 1.2 V_{\text{pp}}$ at 1 kHz. It is crystal clear from the waveforms that the output signal jumps to $+V_{\text{CC}}$ (upper saturation of supply) whenever the input signal goes higher than V_{ref} and it drops to $-V_{\text{CC}}$ (lower saturation) for the signal lower than V_{ref} . The peak-to-peak voltage for the obtained square waveform is 5 V that resembles the difference of $+V_{\text{CC}}$ and $-V_{\text{CC}}$. Pulse width of the output signal is measured to be approximately 18.5 % which is matching closely with the width of input signal $V_{\text{in}} > 0.5 \text{ V}$ ($= 18.3 \%$). The similar performance is reported for various reference voltages varying from 100 mV to 500 mV and is represented in supplementary **Figure S1**.

Obtained Lego-module OPAMP after conversion into desired geometry is characterised and the results are compared with the previous as-received OPAMP in comparator configuration. The exact performance is observed in **Figure 7B** for the converted Lego-module when compared to the unprocessed device which validates that the conditions during the conversion process do not alter device properties and hence, the performance is retained. Similar results were obtained for various V_{ref} which is compiled in supplementary **Figure S2**.

Lastly, the device characterisation after Lego-modular assembly on the host circuit is carried out. We observed no significant performance degradation or variation in the comparator configuration of the device which is prominent from **Figure 7C**. Similar to other results, the plots for output waveform for multiple V_{ref} are depicted in supplementary **Figure S3**. A careful attention in this process has to be given to the conductive epoxy application that helps in improving the interconnection of the two modules together. However, in previous studies the molten solder was used that needs to be heated for binding at the site thereby may affect the performance. The thickness of the conductive epoxy hardener has to be controlled which will allow the male-Lego module to be able to fit on the site and does not fill the trenches completely on the site leaving no exact inverse for Lego-module to match.

Thus, the implementation of the modular Lego electronic concept has been realized at the IC level with a higher yield and a good rationale for not pursuing the previous self-assembly of microscale components mainly FET, PIN diodes etc. The integration of major components of an electronic system at macroscale can be further investigated.

Conclusion

Ordered assembly of the different geometries that attract human beings is considered a motivation to demonstrate a concept of Lego based modular electronic systems that is compliant and feasible to be applicable for wearable gadgets, health monitoring, flexible displays etc.

We provide a unique two level identification to each module that helps in recognising and binding of the modules at exact allocated sites. This has been demonstrated by fabricating

devices with same geometries like heart, square, and circle, and same size providing the specific geometrical identity to each device. The second level identification has been incorporated to these devices with different designs on layer two. These different designs allow the devices to accurately assemble at the binding site that is specific to a unique combination of two geometries like a lock-and-key model approach. Blind folded assembly for Lego-electronic modules is demonstrated for the first time which can be foreseen to open multitude of opportunities for the visually impaired people. Flexibility of these Lego-modules will certainly enable the opportunities to implement applications in flexible sensor networks, wearable devices, health and environmental monitoring, and especially for the internet of things and internet of everything applications. Further, we believe that fluid directed self-assembly can be studied in future to complement modular Lego electronics.

Methods

We divided our study on modular Lego electronics module in two parts. Part A for flexible modular system fabrication and assembly, and Part B for converting the state-of-the-art commercially available integrated circuits (ICs) into Lego-modules for modular electronic.

Part A - Flexible Lego Concept: A complete flexible system concept of Lego-modular approach on polyimide (PI) based flexible substrate. Fabrication schematic of the female-Lego module (host substrate) for this part is shown in Figure 1A, which is essentially an inverse replica (with AND and OR logic gate circuit traces) of its male Lego-module counterpart fabricated using the processing scheme illustrated in Figure 1B. Both the fabrication schematics are exclusively designed to have a low cost fabrication involving no lithography step.

Fabrication of female-Lego module host site starts with the glass carrier substrate (7 cm × 5 cm × 0.1 cm) on which a 125 μm Kapton (DuPont polyimide sheet) is attached carefully. This is to ensure that there are no air bubbles created under the Kapton which may create difficulty in further processing steps by expansion of air bubbles during processing steps. A shadow mask is applied to this substrate followed by DC sputtering of 180 nm Au layer with 10 nm of Ti as

adhesive layer. After sputtering Ti/Au layer, shadow mask is removed and second Kapton sheet of thickness 100 μm is adhered on this patterned interconnect structure to replicate second level geometry. The inverse replica of the geometry of the male Lego-module is imprinted selectively on this top layer using CO₂ laser engraving with optimised combination of 30% power, 40% speed, and 75 kHz pulse frequency. A second engraving for the additional two level unique geometric identification is repeated on the bottom Kapton layer. Finally, the substrate module is removed easily from glass carrier and is shown in Figure 1C.

Male Lego-modules are fabricated in a similar fashion, starting with two Kapton sheets of 100 μm and 125 μm thickness stacked over one another on a glass carrier substrate. Using CO₂ laser engraving technique, different shapes are outlined on this top layer of the stack which will act as a teeth for each piece. A second laser engraving is applied on the bottom layer to complement the shapes from the female-Lego module fabrication. This is followed by Ti/Au DC sputtering in exactly same manner as mentioned previously. Different shapes of the modules (heart, square, and circle) with each different shapes of teeth can be observed in Figure 1D.

Part B - Transforming an IC into Lego: This is an extension of the part A in which we convert state-of-the-art commercial integrated circuit (IC) bare-die into male-Lego module whereas the female-Lego module is fabricated on flexible platform on the glass substrate. The male Lego-module conversion of bare-die IC is illustrated by schematic in Figure 6A. A commercially available bare-die IC (high precision operational amplifier OPA2340 from Texas Instruments-TI) is used here. The contact pads (100 μm) on the devices have to be converted into teeth by growing metallic columns of specific shape on these pads. First, we embed these bare-die (280 μm thick) onto uncured PDMS- spin coated on a Si/SiO₂ wafer to get the thickness of ~ 270 μm . This PDMS is cured at 65 °C for an hour followed by DC sputtered deposition of 150 nm Au seed layer for thick copper electroplating (or electrochemical deposition (ECD)). ECD Cu growth is carried out in a plating station with a DC current of 147 mA for 25 minutes growth which is controlled to grow in vertical direction by patterning a positive photoresist (PR) ECI

3027 using direct laser writer (μ PG501 Heidelberg). The PR removal follows seed layer removal using RIE to ensure that excess metal removal for avoiding any shorts in the die at metallic level. RIE for Ti/Au etching is performed in two steps; first step of Au etching in RIE by under Ar plasma at 10 °C and 5 mTorr pressure for 3 minutes followed by Ti etching with a mixture of SF₆, C₄F₈, and O₂ gases at 10 °C and 5 mTorr pressure for 30 s. Cu teeth grown on bare-die completes the male Lego-transformation which can easily be peeled from PDMS and cleaned from backside for removal of residues using acetone, isopropanol (IPA), and deionised (DI) water. State-of-the-art bare-die OPAMP IC after conversion to Lego-module can be seen in Figure 6C.

Female Lego module (or host site) fabrication starts with a glass carrier wafer followed by spinning 10 μ m polyimide (HD microsystems PI-2611) at 2000 rpm for 30 s. Spin coated PI is initially soft cured at 90 °C for 90 s followed by intermediate cure at 150 °C for 90 s and final hard bake at 350 °C for 30 minutes by gradually ramping the temperature from 150 °C to 350 °C at a rate of 4 °C /min. This step is followed by Ti/Au metal interconnect deposition using the same parameters mentioned above in part A while patterning is carried out using lift-off process. A positive PR ECI 3027 is used to pattern interconnects on PI after surface activation under O₂ plasma in reactive ion etching at 30 °C for 2 minutes. DC sputtering of 10/180 nm of Ti/Au is followed by PR lift-off in acetone sonication bath followed by rinsing in IPA and DI water. This patterned circuit is followed by second PI layer spinning for 20 μ m using the multiple step spinning using same recipe. This layer will host the teeth formed from the male-Lego piece counterpart. The vias/ inverse replica of teeth are etched on top PI by using RIE. A hard mask of 200 nm Al is deposited on PI to selectively etch PI in RIE by flowing a mixture of 10:1 O₂:CF₄ gases at 60 °C and at 80 mTorr pressure. Cyclic PI etching is performed with breaks in steps to cool the substrate. Finally, Al hard mask is removed using highly selective gravure Al wet etchant followed by cleaning step of acetone, IPA and DI water.

Supporting Information

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

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Figure 1. Fabrication schematics for A. flexible binding site (inverse replica) of the Lego module on PI, B. flexible Lego module fabrication. C. Digital image of binding sites after fabrication on glass substrate before release, and D. digital image of Lego modules in three different shapes (heart, square, and circle) with same and different teeth. Bottom right shows the contour of the step height for Lego teeth. Scale bar is 5 mm.

Figure 2. The process of assembly represented by A. empty binding sites having pads open for LED attachment and inverse Lego pattern, B. multiple Lego modules, C. binding substrate after LEDs are connected, D. Accurate assembly of Lego modules on dedicated sites represented by turning on of LEDs when powered by a DC power source. Scale bar is 3 mm.

Figure 3. Cross-sectional scanning electron microscopic (SEM) images of the Lego-modules acquired when they are attached at binding sites. A. Lego module and binding site fit accurately, however, there is a void at interconnecting pads that makes gentle external pressure application mandatory for connection establishment. B. Strong seamless interconnection of flexible Lego on PI at the site assisted by a minimal amount of conductive epoxy. C. Represents reliable connecting path between Lego and the host site even if there are voids in the epoxy application and D. resistance measurement for the connected Lego when epoxy is applied and without epoxy application (with a gentle tap applied to make some connection).

Figure 4. High yield robotic assembly process using pick-and-place tool is demonstrated. A. typical stage area shown at the machine site and few important components of the tool are labelled, inset shows different Lego modules. 100% yield of assembly achieved by programming the tool; B. without application of epoxy which results in off LEDs due to no external pressure to improve connection, and C. microliter of epoxy application before assembly results in enhanced interconnection and hence LEDs are turned ON for both AND and OR logic gates. Scale bar is 3 mm in B and C.

Figure 5. Performance of the assembled module A. and B. the LEDs are ON for the Lego that have intact connection due to epoxy application, LEDs turned off represents the popping out of the Lego which were assembled without epoxy application. C and D shows bending of individual Lego module at two different bending radii of 0.75 mm and 0.5 mm respectively.

Figure 6. Process flow for A. transforming any bare-die or CMOS base IC at wafer level into Lego-modular electronic component and B. Inverse replica formation to act as host that incorporates the complete system outline. C. Optical microscopic images of as-received bare-die for OPAMP in our study **having standard 100 μm contact pad size**, and D. transformed Lego OPAMP. Scale bar is 300 μm. E. Digital image transformed Lego-OPAMP assembled in comparator layout (top) and female-Lego binding site under Lego-OPAMP (bottom). Scale bar is 1.5 mm.

Figure 7. Output characteristic waveforms of OPAMP under study at three different stages of the entire assembly process with sinusoidal input signal of 1.2 V_{pp} at 1 kHz, and a reference voltage of 500 mV in comparator configuration. A. as-received bare-die, B. transformed Lego die after final Cu growth using electroplating for teeth formation, and C. output waveform after the assembly at the host site on flexible PI substrate.

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Keyword: modular, self-assembly, flexible, integration, CMOS

Sohail F. Shaikh¹, Mohamed T. Ghoneim¹, Rabab R. Bahabry^{1,2}, Sherjeel M. Khan¹, and Muhammad M. Hussain^{1}*

Corresponding author's e-mail: muhammadmustafa.hussain@kaust.edu.sa

Title: Modular Lego-electronics

A generic manufacturable method of converting state-of-the-art complementary metal oxide semiconductor (CMOS) based ICs into modular Lego-electronics is presented. Unique geometrical identity that are physically identifiable to ease manufacturing and enhance throughput by modular Lego like assembly enables myriad of potential for compliant systems.

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Supporting Information

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*Sohail F. Shaikh¹, Mohamed T. Ghoneim¹, Rabab R. Bahabry^{1,2}, Sherjeel M. Khan¹, and
Muhammad M. Hussain^{1*}*

Figure S1. Output characteristic waveforms of unprocessed as-received bare die OPAMP under study with sinusoidal input signal of 1.2 V_{pp} at 1 kHz, at different reference voltages A. $V_{ref} = 100$ mV, B. $V_{ref} = 200$ mV, C. $V_{ref} = 300$ mV, and D. $V_{ref} = 400$ mV in comparator configuration. Pulse width variation in output can be observed as V_{ref} varies.

Figure S2. Output characteristic waveforms of bare die OPAMP transformed into Lego-module under study with sinusoidal input signal of 1.2 V_{pp} at 1 kHz, at different reference voltages A. V_{ref} = 100 mV, B. V_{ref} = 200 mV, C. V_{ref} = 300 mV, and D. V_{ref} = 400 mV in comparator configuration. Similar trend in pulse width variation in output can be observed as V_{ref} varies compared to unprocessed die.

Figure S3. Output characteristic waveforms of transformed Lego-module after assembly on flexible binding site under study with sinusoidal input signal of 1.2 V_{pp} at 1 kHz, at different reference voltages A. $V_{ref} = 100$ mV, B. $V_{ref} = 200$ mV, C. $V_{ref} = 300$ mV, and D. $V_{ref} = 400$ mV in comparator configuration.

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