Transformational Electronics Are Now Reconfiguring

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ABSTRACT

Current developments on enhancing our smart living experience are leveraging the increased interest for novel systems that can be compatible with foldable, wrinkled, wavy and complex geometries and surfaces, and thus become truly ubiquitous and easy to deploy. Therefore, relying on innovative structural designs we have been able to reconfigure the physical form of various materials, to achieve remarkable mechanical flexibility and stretchability, which provides us with the perfect platform to develop enhanced electronic systems for application in entertainment, healthcare, fitness and wellness, military and manufacturing industry. Based on these novel structural designs we have developed a silicon-based network of hexagonal islands connected through double-spiral springs, forming an ultra-stretchable (~1000%) array for full compliance to highly asymmetric shapes and surfaces, as well as a serpentine design used to show an ultra-stretchable (~800%) and flexible, spatially reconfigurable, mobile, metallic thin film copper (Cu)-based, body-integrated and non-invasive thermal heater with wireless controlling capability, reusability, heating-adaptability and affordability due to low-cost complementary metal oxide semiconductor (CMOS)-compatible integration.

Keywords: Reconfigurable electronics, stretchable, flexible, bulk silicon (100).

1. INTRODUCTION

The concept of Internet-of-Things (IoT) has emerged to welcome innovative and promising electronic devices with the potential of fulfilling the requirements set to build such technology [1-3]. Given the complexity and variety of shapes and surfaces of all “things”, it is not only desirable but also necessary to equip such devices with characteristics such as lightweight, tunable-shape, and conformability, in addition to the present standards of high performance, multi-functionality, interactivity, ultra-mobility, affordability and energy efficiency (also seen as long battery lifetime). The industry’s response to this demand is to allocate more resources towards innovative development of new technologies with novel characteristics such as wearable electronic gadgets with limited flexibility, as it is evident with the arrival of new smartphones and TV sets with bent bodies and displays (such as featuring devices from companies like LG and Samsung). The rising market of wearable electronic devices, like smart clothing, watches and glasses, promise to provide extended functionalities for a smarter living, but they also require the aforementioned characteristics for full compliance. More importantly, when we think of medical and wellness devices, such as drug delivery systems or health monitors, the capability for *in-situ* monitoring, diagnosis and treatment would be a game changer. Nevertheless, in order to be really biologically integrated and compatible, the electronic devices need to be not only curvilinear and flexible, but also contain the ability to reconfigure its shape to adapt to the ever-changing shapes of the biological tissues. Thus, stretchability becomes an equally important characteristic for bio-integrated systems, smart bionics and integrated cyber-physical systems, as well as it will allow such systems to be ubiquitous and easy to deploy.

Furthermore, stretching capabilities would allow for complex and 3-dimentional geometries that can change dimensions for added functionalities, as for example the tuning of different length-associated properties (optical focus, thermal differences, diverse sensor responsiveness, *etc.*). Such capabilities would be otherwise impossible to obtain with the standard rigid, planar electronics.

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At first sight, organic/polymer-based electronics appears as the most promising technology to deliver mechanical flexibility, stretchability, lightweight and even optical transparency, and nowadays it is indeed the backbone for several flexible screen technologies. Nevertheless, organic/polymer-based electronics are fundamentally constrained in terms of electrical performance and thermal instability in comparison with the state-of-the-art silicon-based technologies [4-8]. Such drawback would hinder any kind of application in high amounts of data processing and storage, like those required for big-data, cloud computation as well as with Internet-of-Things. In contrast, silicon-based electronics, the building block that represents nearly 90% electronics of today's digital era, provides not only excellent electrical performance but it is also the platform of over 50 years of continuous industry evolution, which now-a-days allows an astonishing sub-20-nm patterning capability with a density of billions of transistors per centimeter square. It is such overwhelming transistors count that has enabled the multi-functionality of today's powerful smartphones and other portable devices. Although such computing power is highly desired for wearable and bio-integrated systems, the mechanical rigidity and planar nature of silicon-based technologies goes against the shape conformability and reconfigurability required to develop the full potential in such applications. Several research groups are trying to come up with innovative ideas to overcome this gap. Some have suggested transfer-printing techniques to combine the mechanical properties of polymers with the electrical performance of silicon, where polymeric elastomers can be used as supportive substrates, while small silicon islands will host the electrical devices [9-12]. In principle one can potentially achieve both, shape reconfigurability and high computing power, but current techniques are yet to demonstrate nano-scale transistor dimensions and ultra-large-scale-integration (ULSI) density.

Additional novel materials can also be great candidates for reconfigurable electronics. Especially, 1D and 2D materials (including carbon nanotubes, graphene and transition metal dichalcogenides (TMDs)) are of great scientific interest given their display of both robust electrical and mechanical properties [13-15]. Stretch ratios in order of tens of percent are possible while exhibiting and retaining interesting electrical performance. Yet again, practical demonstrations with the state-of-the-art ultra-large-scale-integration density, manufacturability and such are still a long-term objective.

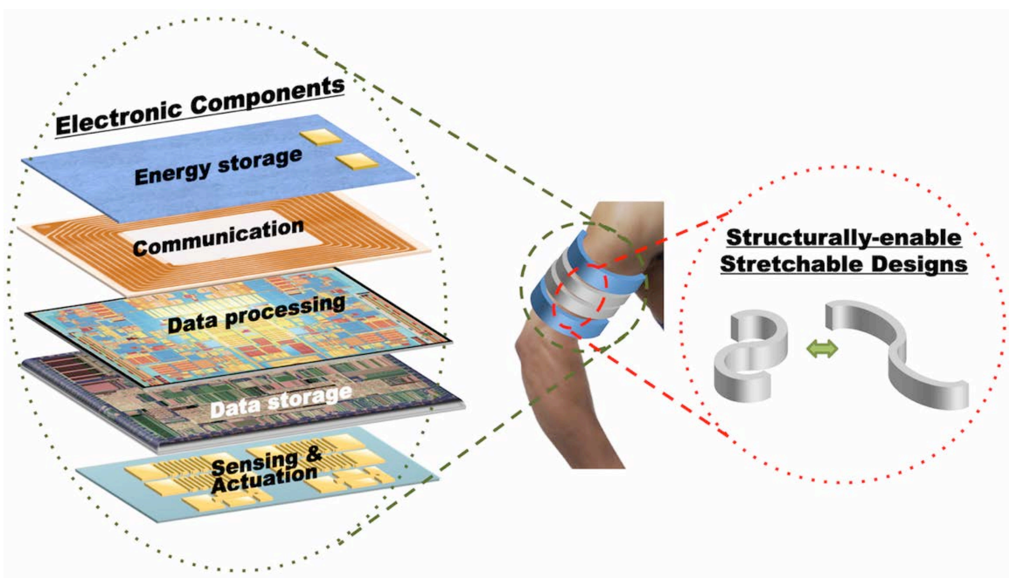

Figure 1. Schematic representation of structurally-enable designs to integrate various electronic components into stretchable systems.

The challenge with inorganic materials (metals and semiconductors) is different; today's rigid electronics are not yet capable to be foldable, wrinkled, wavy and compliant with complex geometries and surfaces as it is essential in several applications. The dream consists on offering the same high performance of silicon-based integrated circuits with super fast and nano-sized electronic devices and ultra-large-scale-integration (ULSI), along with truly flexible, stretchable and compliant mechanics. Several research-oriented institutions along with academy and the semiconductor industry are joining efforts to reach this elusive goal. A way to reconfigure the inherent rigidity of most inorganic materials is needed and it is only through recent developments with innovative structural designs, that nowadays it is possible to reconfigure them to achieve mechanical flexibility and stretchability, which would be otherwise inconceivable with the traditional

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layout. For instance, designs such serpentines or fractal-based structures have been introduced to achieve remarkable stretchable capabilities up to ranges in the thousands of percent for metals and up to hundreds of percent for silicon nanomembranes [16-18]. Therefore, relying on this novel structural designs we have been able to reconfigure the nature of semiconductors and metals to achieve remarkable stretching ratios, which provides us with the perfect platform to develop enhanced electronic systems for application in entertainment, healthcare, fitness and wellness, military and manufacturing industry (Figure 1).

Initially, we aimed to achieve flexible electronics devices that retaining high electrical performance and for that we relied on reducing the thickness of the silicon substrate, dramatically reducing its flexural rigidity, which is exponentially proportional to the thickness [19]. The way we have achieved that is through a low-cost generic batch process based on deterministic pattern of porous network formation in silicon followed by isotropic etching based release, which is capable of transforming the high-performing but conventionally rigid and planar electronics into a flexible and semi-transparent platform for full compliance to complex and irregular shapes. This simple but adaptable process is capable of transforming from semiconducting materials, such mono-crystalline bulk silicon (100), silicon germanium (SiGe) and III-V compound semiconductors, to dielectric and insulating materials. Several flexible electric devices have been demonstrated through this process, including metal-oxide-semiconductor capacitors (MOSCAPs), field effect transistors (MOSFETs), metal-insulator-metal capacitors (MIMCAPs) and state-of-the-art 3D-fin field effect transistors (FinFETs) [20-25]. Additionally, alternative flexible devices have been also demonstrated such micro electro-mechanical systems (MEMS), memory systems, and energy harvesting and storage devices [26-28]. In a following stage we have added stretchability to the equation by using structural reconfiguration of the silicon substrate. We have demonstrated a silicon-based network of hexagonal islands connected through double-spiral springs, forming an ultra-stretchable array for full compliance to highly asymmetric shapes and surfaces [29]. In order to remain below a maximum value of 1% of strain, the radius of the inner circles in the silicon spiral must be 50 times larger than the width of the spiral's arms [30]. We can easily get to this conclusion by following the definition of the nominal strain in a strained beam,

$$\varepsilon_{MAX} = \frac{w}{2R} \quad \Rightarrow \quad if \ \varepsilon_{MAX} = 1\% \quad \Rightarrow \quad R = 50w \qquad (1)$$

Where w is the width of the spiral's arms and R is the radius of the spiral's inner circle. Therefore, for an arm-width of 5 μm, the inner circle must have a radius of 250 μm.

On the other hand, we have also developed a serpentine design used to show an ultra-stretchable and flexible, spatially reconfigurable, mobile, metallic thin film copper (Cu)-based, body-integrated and non-invasive thermal heater with wireless controlling capability, reusability, heating-adaptability (heating is tuned based on the temperature of the swollen part) and affordability due to low-cost complementary metal oxide semiconductor (CMOS)-compatible integration [31]. The serpentine structures where designed in such a way that each individual spring could reach a maximum stretch ratio of approximately 800%. An array of such serpentine springs was then designed to get a total system-level stretchability of 270%.

2. FABRICATION PROCESS DESCRIPTION

The relatively complex spiral design can be actually completed with effortlessness through few standard microfabrication processes. It first starts with a 50-μm-thick top silicon-on-insulator (SOI) wafer with 10 μm of buried oxide layer (BOX). This substrate is expensive in comparison with the standard bulk monocrystalline silicon, but it was chosen for ease of the release process in the first demonstration experiment. The first step consists on the sputtering deposition of a metallic hard mask and the patterning of the structural spiral-based design with photolithography. Next, the structures are etched through the hard mask and the top 50 μm silicon layer with ion milling and deep reactive ion etching (DRIE) (Figure 2a). Then, the metal hard mask is wet etched and finally the release is done through BOX etching in vapor hydrofluoric acid (VHF) (Figure 2b). Large area hexagons are included where electronic devices and circuits can be accommodated and electric interconnects can be formed on the spiral structures. Further fabrication details can be found in our paper [29].

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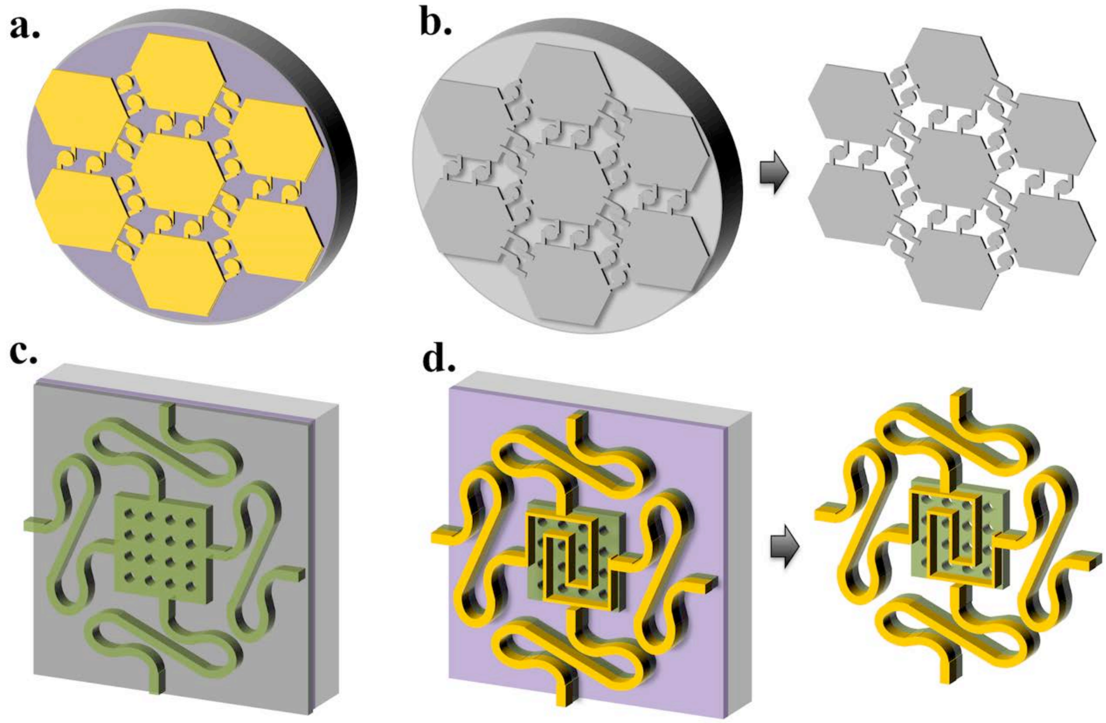

Figure 2. Two fabrication flows for stretchable Si spiral-based array and stretchable Cu serpentine-based structure.

For a follow up system development, low-cost and most-widely used bulk silicon (100) substrate is currently being used with our deterministic pattern based release method. In summary, our transformational method starts with a wafer with pre-fabricated devices, which are then protected with a hard mask. Next, we form a deterministic pattern of porous network of vertical channels all over the area to be released. Channels are etched into the silicon to a certain depth, which is selected for a specific desired final substrate thickness. Lateral wall protection is next produced through deposition of a conformal protective layer and its selective removal from only the bottom of the trenches, so the silicon sidewalls are shielded from the subsequent etching gas (XeF_2), used to remove an inner layer of silicon at the bottom of the trenches and thus release the top silicon portion with the devices. The chemically reactive gas is highly selective to several materials, such polymers, metals and dielectrics commonly found in integrated circuits (IC) fabrication), and therefore this method is also compatible with complementary metal oxide semiconductor (CMOS) post-processing. Moreover, this method is also cost-effective since the rest of the substrate can be reused afterwards to get several layers or flexible fabrics with devices from a single wafer. Further fabrication details can be found in our paper [32].

On the other hand, the method used to fabricate a serpentine-based thermotherapy device is done through state-of-the-art CMOS compatible processes to directly form the structure using copper lines on a polyimide (PI) surface making it thus a transfer-less process. The process starts with the deposition of 1 μm of amorphous silicon as sacrificial layer on top of a thermally oxidized wafer. Next 4 μm of polyimide are spin-coated on top and then patterned with O_2 plasma to form the serpentine structures using aluminum as hard mask (Figure 2c). 4 μm thick copper lines are electroplated on the PI by first defining a metallic seed layer and then performing the selective electroplating on the serpentine structures. The seed layer is then removed with ion milling and finally the structures are released by etching away the amorphous silicon sacrificial layer with a vapor phase etchant (XeF_2) (Figure 2d). This method can significantly reduce the cost of production because it does not disturb the oxidized silicon wafer used as carrier for the structures fabrication, which then can be reused after a cleaning process. The copper/PI interface can be controlled not to experience any stress during bending by controlling the thicknesses of the copper lines and the PI layer, so that the neutral axis during flexing is at the interface. Further fabrication details can be found in our paper [31].

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3. RESULTS AND DISCUSSION

From our mechanical tests (Figure 3a) the measured stretchability of the silicon spirals reached an outstanding value of about 1000%. This value can be actually designed by choosing the number of turns and could be even further increased by adding more of them or decide for specific values depending on the final application. Double spirals were tested as back up in case one of the spirals breaks. A larger distributed array of hexagons and spirals was also tested up to a 50% increment in area (or 2.25 times larger area) as shown in figure 3d. From the tests it is evident that sometimes the spirals un-wraps out of the XY plane, which could also lead to along the spiral's arms. Therefore, in future implementations the central spiral's disk could be restricted to move only on plane and thus improve mechanical reliability.

The complete characterization of our structurally enabled, stretchable designs was also analyzed through finite element simulation to assess their strain distribution. The simulation results of a fully extended single spiral with the corresponding strain distribution are shown in Figure 2c. A maximum strain of 1.2% was found at the beginning of the arms in the spirals, as it would be expected. A detailed description of the full mechanical tests and the finite element simulation can be found in our paper [29].

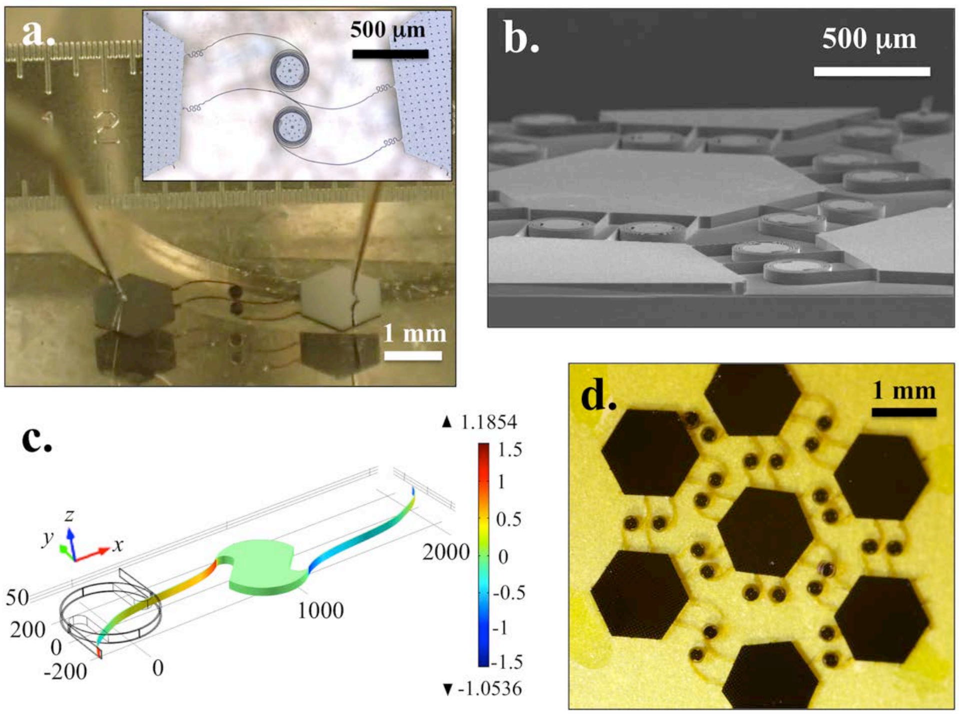

Figure 3. a. Digital photograph of a mechanical test with a double spiral structure being stretched (The inset shows the microscope zoom in picture). b. Scanning electron microscopy image (SEM) of double-spiral array. c. Finite element simulation of a single spiral showing the strain distribution along the arms. d. Digital photograph of an array of 7 hexagons connected through double spirals springs.

For our second device implementation, the serpentine-based stretchable thermal patch was tested to find its mechanical performance in the lateral springs under uniaxial tensile strain with a maximum stretching ratio of ~800% for an individual springs (Figure 4). Nevertheless, this maximum point goes beyond plastic deformation, so the actual elastic limit for the springs was found to be around 600% stretch and even after 100 cycles of stretching, the structure returned to their original state. In terms of the overall maximum stretchability of the whole patch device, a value of about 300% was successfully reached. An important figure of merit for stretchable conductors is the invariability of the resistance of the structures with diverse applied strains as well as with several strain cycles. From our tests we confirmed a small resistance variation of around 2%–3% within the elastic limit, which validated our design. This was thanks to the copper interconnect being at the neutral axis of the system where no strain is experienced.

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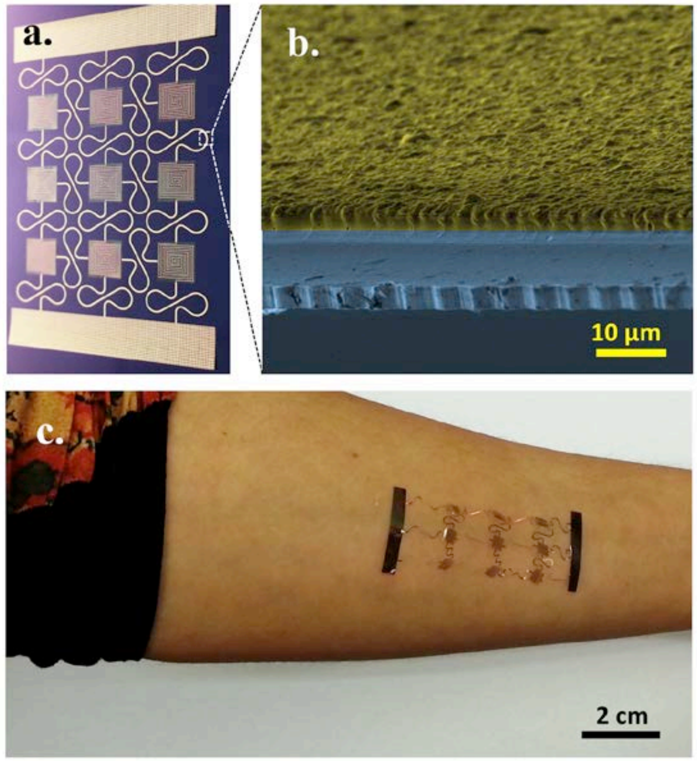

Figure 4. Ultra-stretchable and flexible, copper-based and non-invasive thermal heater. a. Digital photograph of one thermal heater array, b. Scanning electron microscopy image of the cooper-PI interface, c. Digital photograph while being stretched.

4. CONCLUSION

In summary we have extended the functionality of conventional electronic systems and transform them into a reconfigurable platform for full compatibility with foldable, wrinkled, wavy and complex geometries and surfaces. Innovative structural designs have allowed us to reconfigure the nature of materials such semiconductors and metals, to achieve remarkable mechanical flexibility and stretchability, which provides us with the perfect platform to develop enhanced electronic systems for application in entertainment, healthcare, fitness and wellness, military and manufacturing industry.

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