Freeform Compliant CMOS Electronic Systems for Internet of Everything (IoE) Applications

S. F. Shaikh, *Student Member*, M. T. Ghoneim, *Student Member*, G. A. Torres Sevilla, *Student Member*, J. M. Nassar, A. M. Hussain, *Student Member*, and M. M. Hussain, *Senior Member*

Abstract— State-of-the-art electronics technology has been an integral part of modern advances. The prevalent rise of the mobile device and computational technology in the age of information technology offers exciting applications that are attributed to sophisticated, enormously reliable, and most mature complementary metal oxide semiconductor (CMOS)-based electronics. We are accustomed to high performance, cost-effective, multi-functional, and energy efficient scaled electronics. However, they are rigid, bulky and brittle. The convolution of flexibility and stretchability in electronics for emerging internet of everything application can unleash smart application horizon in unexplored areas, like robotics, healthcare, smart cities, transport, and entertainment systems etc. While flexible and stretchable device theme are being remarkably chased, the realization of the fully compliant electronic system is unaddressed. Integration of data processing, storage, communication, and energy management devices complement a compliant system. Here, a comprehensive review is presented on necessity and design criteria for freeform (physically flexible and stretchable) compliant high performance CMOS electronic systems.

Index Terms— Flexible electronics, stretchable electronics, freeform compliant system, healthcare, internet of everything.

I. INTRODUCTION

Electronics have been an integral part of our today's digital life. We enjoy comfort, convenience and safety through variety of electronic applications in the general area of computation, communication, infotainment, medical instrumentation, healthcare, automobiles, and smart cities. In 2005, International Telecommunication Union (ITU) suggested connecting all objects in sensory and intelligent manner, coined as Internet of Things (IoT) and described four dimensions in IoT: things tagging (item identification), thinking things (embedded systems), feeling things (sensors and wireless sensor network), and shrinking things (nanotechnology) [1]. Internet of Everything (IoE) is realization of interconnection of living beings (people, plants and animal etc.) and non-living things (data, process, devices, vehicles, etc.). The notion of IoT and IoE gives connectivity of anything-anytime-anyplace for more intelligent health, smarter energy-efficient cities, transportation, and smart grids, etc.

Complementary metal oxide semiconductor (CMOS)

technology has been instrumental in this rise of the digital age, with micro-and-nanofabrication processes being indisputably the most reliable and advanced existing technologies and continues to be perfected. CMOS-enabled electronics are omnipresent in the technology domain on account of ultra-large-scale-integration (ULSI) density, reliable device manufacturing, energy efficiency, and enhanced performance per cost. In the coming age of IoT and IoE, their difference comes from the fact that natural living species have irregular body contours and asymmetric soft tissues and skin surfaces. Therefore, the status quo rigid and bulky electronics and ICs are not in compliance with them. Hence, implementation of the holistic electronic system on asymmetric and complex geometries necessitate incorporation of flexibility, stretchability, and reconfigurability like features not only in individual module elements (logic, memory, communications, power supply, etc.) but also in the system. Individual freeform elements must meet the status quo, which account for better performance and multifunctioning of a compliant system.

Hence, we present here the design criteria of compliant systems for future IoE applications that are often unaddressed due to hyperbolized attention on presenting flashy applications by showing flexibility and stretchability in one or two modules wherein other modules are still rigid and bulky. We review different methods of achieving flexibility and stretchability with the rationale for why CMOS-based processes and novel integration techniques are the way forward for next generation electronics that can bring truly flexibility of the system.

II. DESIGN CRITERIA FOR FLEXIBLE ELECTRONICS

Natural living beings are marvelous creations at the epitome of most complex engineering and architecture, illustrating intricate asymmetric contours and soft skin and tissue surfaces. Their designs make integration of symmetric and uniformly shaped electronics difficult with them. Consequently, it is critical to introduce a new dimension in electronics to transform into freeform physically flexible and stretchable electronics. Although IoE is still germinating in its early stages, we strongly believe that electronics will capitalize on flexibility and stretchability, incorporating interactive system integration of data acquisition (sensors), data processing and decision making

Fig. 1. (a) Typical data generated from a real-time ECG monitoring system at different sample rate (500 Hz, 1 kHz, 2 kHz, 4 kHz and 44 kHz). (b) The increase in form-factor (area) and operating frequency as increase in cache memory shown in percentage change for different processors through years from Intel, and (c) consistent increasing trend in operating frequency, cache memory and form-factor for different generation of Intel processors as high computational demands rise.

(logic circuits and elements), data storage (memory devices), communication (radio-frequency and li-fi elements), decision accomplishment (actuators), and efficient power management (energy scavenging and energy storage). In real-time healthcare monitoring applications, electronic devices might be deployed all the time on curvilinear body locations (joints, neck, shoulders, wrists etc.), questing for constant twisting, bending, contracting, and stretching; offering opportunities to exploit flexibility and stretchability of user-friendly electronics. Besides these external body parts, internal organs (heart, brain, kidney, etc.) introduces a different level of challenges (biocompatibility and biodegradability). Environmental aspects like marine monitoring, plant monitoring for agricultural productivity are applications besides healthcare that enliven capitalization of the physical flexibility, stretchability, and reconfigurability of electronic devices.

Recently there have been several efforts to improve human life using multi-functional gadgets for monitoring health conditions example electrocardiogram (ECG), blood pressure, and pulse oximeter etc. Applications related to human central processing unit - *the brain*, include neural prosthetics (cochlea, vision, and brain-computer interface); diagnostics like electrocorticography (ECoG) and electroencephalogram (EEG); treatment of neuro-degenerative diseases by neuro-stimulation and deep-brain stimulation. Soft electrodes mimicking mechanical properties like soft tissues play a pivotal role in implantable monitoring applications. However, bulky and rigid base stations, wireless connectivity, reliability, sensitivity, and battery life are major downsides of available devices. Furthermore, biocompatibility and mechanical mismatch with surrounding environment lead to fibrosis, tissue damage, and consequent signal degradation over time.

Despite remarkable progress in material and fabrication development, we have not encountered (to the best of our knowledge) any fully flexible health monitoring system that has integrated circuitry for processing, data storage capability for handling big data, communications system, and power supply. Few case studies that emphasize immediate addressable challenges and needs in data storage, integration for higher performance, and energy management capacities are presented.

Case Study A: Biological signals are mostly low amplitude

signals (in mV) with DC to very low frequencies (0-150 Hz for ECG and EEG, 10-200 Hz for electromyography (EMG), and sphygmomanometer 0-200 Hz) except speech signal (0.1-4 kHz). The processing of these signals for extracting different parameters and conditions of need sampling at a minimum Nyquist rate, though a higher sampling provides reliability and accuracy. Typical ECG signals are sampled at a minimum frequency of 500 Hz which corresponds to a data generation of *1.8 MB per hour* accumulating into *1.2 GB per month* for a single subject. For increased accuracy and reliable processing higher sampling rates are desired and corresponding humongous data that would be generated is depicted in Fig. 1 (a).

Case Study B: For brain and neural mapping applications where even simplest of brains have 10–1000s of neurons located in multiple locations (cerebral cortex of rat have 15-20 million neurons, a cat have approximately 300 million, and more than 50 billion neurons in human being) [2], required implantable electrodes will generate humongous data. An electrical signal in the neuron is a result of electrical potential fluctuations, response to the fluctuations, and then generating a required action, all these activities are repeated hundreds of time per second. For instance, recording the electrical activity of 200 electrodes from 10 subjects which make ~ 1 million neurons, 1000 times per second would generate *1 GBps* and *4 TB per hour* data that sharply reaches *100 TB per day*. This big data generated even if compressed by a factor of 10, will result in approximately *3 PB annually* which is as much of data as generated by 17-mile long large Hadron Collider, most advanced astronomical observations, and other complex science projects [2].

Case Study C: Integration of more functionalities due to continuous transistor scaling have enabled ULSI densities for energy efficient high-performance computational processors and ICs. However, higher the demand of processing speed larger gets the cache memory, which implies increased form factor. For example, Intel Atom Processor 330 operating at 1.6 GHz frequency (1 MB cache) occupy 484 mm² area which increases to ~ 2362 mm² (388% increase) for Core i7-5930K (15 MB cache) operating at 3.5 GHz (250% rise in frequency), the trend is plotted in Fig. 1 (b). Also, a similar pattern is depicted

in form factor, frequency, and cache memory increment in processor variants charted in Fig. 1 (c).

From prospects of energy, wireless communications networks like Bluetooth, Wi-Fi, and ZigBee are ubiquitous in portable electronic systems, need 10-100s of mWs of peak power while an average power in tens of microwatts to lower mWs for low duty cycle [3]. High energy demands for the flexible electronics makes solar harvester not feasible due to area constraints, e.g. with a 100% charge efficiency, 100 mWh of storage charging for one hour would need 1 m² solar panel. Directed efforts toward making robust, flexible, and low-cost energy harvesting and storage devices for intuitive truly flexible systems are critical.

Hence, it is extremely important to address the big data challenges for handling and storing data generated, not only from implantable and wearable healthcare devices but also the amount of data from the trillion sensors predicted to be connected by 2020 [4]. Furthermore, the increasing form factor for high computational processes and higher data requirements demand new integration and packaging strategies. With these prerequisites in mind, next sections review progresses in flexible logic elements, memory devices, and RF communication, followed by sections focusing on different processes of flexing electronic devices with a brief discussion on stretchability imparting to conclude with future outlook.

III. COMPONENTS OF A COMPLIANT SYSTEM

The rapid expansion of flexible and stretchable electronics have opened the myriad of applications in wearable electronics, seamless sticker electronics, smart textile integrated

electronics, soft robotics, neural prosthetics, and transient implants. These devices have grabbed unmatched attention towards futuristic IoT and IoE age. The core of a compliant electronic system incorporates: processing unit (logic), main memory and storage, communication, and power management unit. Transistor logic implementation is inherent to a processing unit for logical execution while temporary short-storage (or cache) for quick access is characteristics of main memory also known as primary storage or random access memory (RAM). Following section highlights advances and opportunities in processing units (logic/transistors), flexible memory, communication using RF antenna, with actual demonstrated functional devices.

A. Logic Module (Transistors)

Transistor is a fundamental entity of the processor (or logic unit), evaluated by transistor switching speed, subthreshold slope (SS), drain-induced barrier lowering (DIBL), and subthreshold voltage (V_{th}) stability. The majority of the work in recent years have been directed on thin-film transistors (TFTs) achieving outstanding performances [5]. Organic transistors have illustrious reports highlighting best individual performances for SS, minimum bending radius, high I_{ON}/I_{OFF} ratios. However, improving one metric adversely affects other: e.g. increasing the thickness of the $Ba_{0.7}Sr_{0.3}TiO_3$ (BST) gate dielectric in organic TFT have reduced threshold voltage and increased the effective mobility, at the same time reduction in I_{ON}/I_{OFF} and increase in subthreshold slope have been reported [6]. The general trend of low mobility (<10 cm²V⁻¹s⁻¹) is observed in organic transistors while high flexibilities up to 100 μ m bending radius and 10⁴ endurance cycles are reported [7], [8]. Large operation voltages (in orders of 10 volts) and high SS restrict their practical implementation as energy efficient devices. Hybrid FET device where inorganic FETs are flexed and transferred onto flexible polymers, show better performances than organics, exhibiting reduced SS and V_{th} , higher I_{ON}/I_{OFF} , and greater mobility, compromising with lower flexibility [9], [10].

CMOS-technology based FETs are cutting-edge devices and have established performance matrices over decades. Flexing them using approaches like spalling, trench-protect-etch-release (TPER), soft-etch-back (SEB), and back grinding emerges out to be the future devices for the IoT and IoE era, where integration and compatibilities of hybrid processes will be the key to product development. Consistent improvements have been reported in SS, V_{th} , minimum feature size, and fast switching achieved with minimum bending radius of up to 0.5 mm [11]. Sevilla *et al.* have demonstrated nanoscale flexible high-performance FinFETs using SEB method for flexibility. Exceptional performances like high I_{ON}/I_{OFF} ratio (10⁵), lower V_{th} (0.36 V for NMOS), reduced SS (63 mV/dec for PMOS) with bending radius of 0.5 mm were achieved that are comparable to the state-of-the-art bulk devices and better than other flexible devices reported [12]. Corresponding transfer and output characteristics of high-performance nanoscale flexible PMOS with gate length 250 nm has is replicated in Fig. 2 (a) and (b) respectively. Lately, a truly flexible digital circuit element (an

Fig. 2. Unbent and bent (a) transfer (b) output characteristics of flexible PMOS FinFETs with gate length of 250 nm. Reprinted with permission from [12] Copyright (2014) American Chemical Society.

inverter) with high-k metal was demonstrated by Sevilla *et al.* reflecting lower V_{th} (0.2 V for NMOS and -0.25 V for PMOS), better SS (80 mV/dec for NMOS and 63 mV/dec for PMOS), high endurance of more than 1500 bending cycles, and superior circuit performance in terms of gain, power consumption, and speed were observed [13]. Fig. 3 shows the voltage transfer curve (VTC) and inverter performance for flexible inverter fabricated with bending measurements showing no change in circuit performance. In conclusion, monolithic integration, uncompromised reliability, and inherent superior electronic properties pave the path for CMOS based flexible transistors for generation next flexible electronics.

B. Memory Management Module

There has been a steep shift towards the non-volatile memory (NVM) categories in solid-state drives (SSD) that provide faster switching speeds, ULSI, and low-voltage operations making emerging NVM storage preferable. Interesting and intuitive reviews have been presented in past on flexible NVM technologies [14], however, we provide an overview on flexible NVM presenting status quo in flexibility, reliability, performance, and the ability of monolithic integration with prospects and requisites of IoE and bioelectronics interfaces.

ReRAM (commonly known as *Memristors*) are passive elements switching between high and low resistance states. Simplistic architecture and fast switching characteristics have attracted their applications in neuromorphic computations, for example, mimicking synaptic functions by combining CMOS neurons and memristors in cross-bar configuration [15]. Organic and flexible memristors with the highest retention of 5×10^6 at the cost of low endurance, switching speeds, and low-temperature range are demonstrated [16]–[18]. Kim *et al.* [19]

demonstrated Si-based inorganic memristors transferred onto organic substrate showing reasonably moderate parameters with a very low yield (60-85%) and higher operating voltage. By far most promising results were obtained by inorganic memristor deposition on plastic substrates at low temperature, with the highest endurance 10^6 , high operating temperature up to 200 °C but at lower flexibilities, and the best form factor of 2 (at device level, the form factor is a unit less entity defined as the lateral area of the single memory cell (1bit) divided by the

Fig. 3. VTC and inverter performance for fabricated flexible inverters at different bending conditions, and 1MHz operation frequency. (a) VTC for bulk sample, (b) VTC of flexible inverter from 0.5 cm to 4.5 cm upward bending radii, (c) inverter performance at 2 cm upward bending, and (d) inverter performance after 1500 cycles of bending. Reprinted from [13], with the permission of AIP Publishing.

TABLE I
KEYWORDS ON MEMRISTOR AND PCRAM SINCE 2012

Type	PCRAM					Memristor		
Reference	[16]	[71]	[72]	[73]	[20]	[21]	[22]	[23]
Approach	All organic		Hybrid (Low Temp. deposition)		Hybrid (Org. device + Inorganic flexible substrate)	Hybrid	Hybrid (Low Temp. deposition)	Hybrid (transfer + Low Temp. deposition)
Operating Voltage (V)	-2 to +3	0.78	0 to +14	-0.5 to +2	-0.5	1.8	1.8	8.5
Speed (ns)	--	--	50	5×10^5	--	30	--	1000
Retention(s)	5×10^6	10^4	5×10^4	10^4	10^5	--	--	10^4
Endurance (# cycles)	100	10^6	400	10^6	100	--	--	100
Bending radius (mm)	4	3.2	6	10	0.35	--	2.25	10
Bending cycles	1000	160	300	1000	1000	--	100	1000
Yield (%)	--	--	70	--	--	--	--	66
Operating temp. (°C)	25	-70 to +70	25	85	25	25	25	25
Form Factor (F ²)	--	--	--	2	--	--	--	--

square of the smallest feature (technology node). For example, a memory cell that is $1\ \mu\text{m} \times 0.5\ \mu\text{m}$ built at $0.25\text{-}\mu\text{m}$ node would have a form factor of $8F^2$, smaller number is better). Lowest operating voltage ($\pm 0.5\ \text{V}$) and lowest bending radius ($0.5\ \text{mm}$) has also been achieved using a flexible inorganic substrate (Al foil) with organic cellulose nanofiber paper [20].

Phase change random access memory (PCRAM) are characterized by high transition speeds, for instance, $\text{Ge}_2\text{Sb}_2\text{Te}_5$ -based flexible PCRAM with 30 ns pulse for switching, ultra-high integration densities of up to terabits per square inch were achieved due to highly localized regions of phase change [21], [22]. However, lower yield of 66% and endurance of 1000 bending cycles for PCRAM are worth examining concerns restricting its practical implementation [23]. Key works on flexible ReRAM and PCRAM are summarized in table I with best performances highlighted.

FeRAM NVM based on lead zirconium titanate (PZT) – ferroelectric capacitor materials exhibit superior performance in flexible NVM in terms of low operation voltage (1.5 V), low cost per bit, and high switching speeds ($\sim 70\ \text{ns}$ for the actual array) [24]–[26]. Ghoneim *et al.* demonstrated the *highest ever level of endurance* (10^9 fatigue cycles for unbent and 10^{10} for bent) before losing $\sim 50\%$ polarization for PZT base capacitor and stability of non-volatile charges (as a difference of switching and non-switching polarization) shown in Fig. 4 (a) and (b). High temperature ($200\ ^\circ\text{C}$) operation plotted in Fig. 4 (c) with negligible effect on *extreme retention* (> 10 years) and fatigue are associated with flexible PZT FeRAM capacitor on Si substrate and charted in [27].

In contradiction, flexible flash memories have failed to reflect status quo benefits and performances close to their rigid commercialized counterparts (most matured NVM technology). All-organic approach limits the material choice while hybrid approach allows only low-temperature processes for flexible NVMs, consequently, operation voltages as high as $\pm 5\ \text{V}$ to $\pm 90\ \text{V}$ with a minimum channel length of $2\ \mu\text{m}$ for recent flexible flash memories have been reported [28]–[30] that provides opportunities to further explore.

To summarize, flexible NVM technology faces tougher challenges of matching their bulk counterparts due to immaturity and lack of diverse approaches to achieve flexibility. FeRAM presents a suitable candidacy for IoT and IoE applications since its transformation from bulk to flexible form are compatible with CMOS technology, in addition to bulk FeRAM technology being much more mature. Although flexible state-of-the-art CMOS transistors have been developed, flexible NVMs present challenging opportunities for the device community due to its current weak position in IoT and IoE chain. Thus, flexible FeRAMs can potentially achieve low power operations, ten year retention, high endurance, and CMOS compatibility by inorganic flexing approach.

C. Communication Module (Antenna)

Sophisticated data processing and handling are of critical importance for any electronic system. Constant data communication with smartphone or tablet like handheld devices

Fig. 4. (a) Non-volatile charges stability assessment as function of switching cycles, (b) Fatigue test for ferroelectric capacitors at 1 MHz fatigue frequency, polarization survive to $>50\%$ for more than 10^9 cycles, and (c) retention measurements at various temperatures. Reprinted with permission from [27]. Copyright John Wiley & Sons.

is essential in healthcare where body vitals' information, blood pressure, ECG, and other rhythmic activities are monitored continuously in real-time for corrective measures. Constant data communication may eliminate the necessity of large memory storage in the system but demands comparative high powers. Transistors and other devices are already shown to be flexed and stretched, however, antenna flexing and stretching has been a hurdle in obtaining a complete flexible wearable communication system. Exciting work was illustrated by Kubo *et al.* in 2010 on stretchable RF antennas based on microfluidics where liquid metal inside fluidic channels has been used as antenna. Kubo suggested excellent robustness and stretchability in terms of the tensile strain (120%) without significant degradation in RF radiation efficiency ($>95\%$) [31]. Song *et al.* [32] have presented a reversibly deformable and stretchable RF antenna based on silver nanowires. This mechanical stretchability of fabricated antennas may be helpful in tunable frequency and sensing applications (frequency variation attributed to modification in the antenna length). However, alternating frequencies and frequency ranges $<1.5\ \text{GHz}$ limits their applications in wearable and healthcare applications that demand constant frequency in a range around $2.4\ \text{GHz}$.

Hussain *et al.* [33] developed a novel stretchable antenna that can sustain far-field communications up to a distance of 80 m at 1.28 mW transmitting power with a constant radiating frequency of 2.45 GHz invariable with the stretchability. The flexibility was incorporated by metal/polymer approach whereas the constant frequency radiation was possible due to the innovative serpentine design of the antenna which do not alter the length on stretching. Additionally, this frequency and bandwidth fall in the defined industrial, scientific, and medical radio (ISM band) and hence presents the strong case in constant frequency transceiver electronics for wearable healthcare and IoT applications. Cheng *et al.* [34] came up with planar inverted cone antenna (PICA) based on inkjetting liquid metal into the microchannel of elastic dielectric material. The antenna radiation efficiency of >70% at 3-10 GHz frequency, 10 dB better return loss, and >40% stretchability without impacting electrical performance was highlighted for ultra-wideband (UWB) applications radiating at 2-10 GHz frequencies.

Graphene in 2D materials has been exploited fairly less for microwave to terahertz frequency applications. Few groups demonstrated graphene antenna [35]–[37] at terahertz frequency ranges. This presents an opportunity in future flexible electronics devices, however, the real challenge appears in unprecedented issues with uncertain growth, transfer process with sustainable performance, and establishing contacts. More focused efforts are indeed required for obtaining flexible antennas with different strategies and processing technology to complement other flexible system modules.

IV. FLEXING STRATEGIES

Three fundamental approaches of obtaining flexible electronic devices presented are all organic, hybrid non-CMOS

and inorganic (CMOS compatible) approach. The rationale of CMOS based flexing approach being superior is also explained.

A. Organic and Hybrid non-CMOS based approaches

Exploration of unorthodox materials for electronics date back to nearly three decades. The human mind is implicitly occupied by traditional natural polymers and plastic materials as flexible and stretchable materials due to their inherent elastic or flexing abilities. Two widespread pathways for realizing organic based electronics are 1. All-organic systems: integrating both devices and substrates made from organic materials or active materials devices inkjet (or screen-printed) on organic/paper substrates [38]–[42], and 2. Hybrid systems: combines the transfer of inorganic electronic devices onto flexible organic substrates using low-temperature direct deposition of inorganic on plastics using laser lift-off transfer or transfer printing techniques [18], [29], [43]–[46].

Organic materials have made remarkable progress in display technologies and are ubiquitous in large-area electronics triggering the commercialization of organic displays from hand-held to big screen and monitors [47], [48]. Organic devices are impressively cost effective due to low-cost materials and simple garage fabrication processing tools. Furthermore, biocompatibility of most of the organic materials has invoking applications in bioelectronics like organic electronic ion pump for selective stimulation of nerve cells by delivering neurotransmitters [49], [50], and ECG recordings from cardiac muscle using a conformable organic electrochemical transistor (OECT). Promising results in terms of high sensitivity, response time, high stability, and flexibility have been achieved both *in vivo* and *in-vitro* surroundings.

However, their electrical performances are orders of magnitude inferior to inorganic counterparts due to inherent low mobility, limited thermal stability, and incompatibility

Fig. 5. Hybrid approaches of obtaining flexible electronics (a) Digital photo showing a twisted rGO/PI nanocomposite based strain sensor. Reprinted with permission from [74] Copyright (2015) American Chemical Society. (b) Digital photo of embedded MWCNTs/PDMS composite ink. Reprinted with permission from Macmillan Publishers Ltd: Nature Materials [55] copyright 2009. (c) Schematic illustration of flexible crossbar-structured memory fabrication on plastic substrate using laser lift-off transfer printing. Reprinted with permission from [43] Copyright John Wiley & Sons. (d) Three basic modes of transfer printing illustrated schematically. Reprinted with permission from [57]. Copyright John Wiley & Sons.

with CMOS-based processes; restricting their applications in data driven communication and computational applications. The standard figure of merit in electronic performance assessment is the charge mobility. The highest mobility ever reported for organic materials achieved using organic thin film transistor (OTFT) reached $43 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$ (two orders of magnitude lower than Si) [51]. Moreover, high operation voltages and device scalability for large-scale integration are still unresolved challenges in organic electronics.

1D materials like silicon nanowires, metal nanowires (NW), zinc-oxide nanowires, carbon nanotubes (CNTs) [52], [53] which are highly conductive and stretchable show promising features for various applications. However, complex arrangement into arrays (due to a limited charge carrying capacity) hinders area efficiency and provide insufficient current for logic operations. Recent developments in 2D materials like molybdenum disulfide (MoS_2), graphene, and dichalcogenide material based electronics illustrates the potential for fascinating future electronics which are transparent, flexible, and stretchable. However, unprecedented challenges from uncertain growth process, unstable transfer process, limitation of contact engineering, and semi-metallic nature curtail entrance to free-form electronics.

Initial works in hybrid stretchable materials focus on transferring electronics on polymeric substrates like polydimethylsiloxane (PDMS), polyethylene terephthalate

(c) using laser lift-off. Roll-to-roll printing, inkjet printing, and transfer printing are new dimensions in hybrid flexible device fabrication commonly classified as additive manufacturing and packaging process and are most widely preferred, schematic details illustrated in Fig. 5 (d) for polymer assisted transfer technique [56], [57].

Chemical functionalization and inkjet printing of paper provide a new route for making flexible electronics using cheap and garage fabrication techniques. Nassar *et al.* demonstrated multisensory platform for simultaneous environmental monitoring by scalable garage fabrication using inexpensive household elements (aluminum foil, paper, napkins, sponges, and scotch-tape) and silver ink, referred as ‘paper skin’ [58]. Integration of humidity, temperature, and pressure sensors array to mimic human-skin is achieved using 3D stacking of individual sensory arrays and its placement on the hand in Fig. 6 (a). Fig. 6 (b) (left to right respectively) shows performance of first ever recyclable, highly sensitivity touch, humidity, and temperature sensor, whereas record breaking proximity sensing (13 cm) is illustrated in Fig. 6 (c). Compatibility with CMOS-technology provides additional weightage on hybrid approaches for future systems. For example, the organic stretchable and flexible electrodes often demonstrated by several groups show good performances, however, for real life application on human body and internal organs where time is extremely critical in making corrective measures. A huge

Fig. 6. Multisensory platform for mimicking skin coined as ‘paper-skin’ (a) 3D stacking of humidity, temperature and pressure array (left), and digital photo of placement on hand (right). (b) Real time response to human touch (left), exhaled breathe cycles for 30 s (middle), and applied external flame stimulus response (right). (c) Real time monitoring of XY plane proximity sensing (top) and proximity sensing plot vs approaching distance in z-direction. Reprinted with permission from [58]. Copyright John Wiley & Sons.

(PET), or polyimide (PI). High risk of electrical failure due to delamination, cracking and slipping are associated with interconnecting metals on polymers. Advanced strategies to levitate the capacity of hybrid elastomers introduce preparing conductive polymers using silicone rubbers and electrically conductive 1D materials like CNT, NW, and graphene sheets are shown in Fig. 5 (a) and (b) [54], [55]. High-performance memory device development schematic is represented in Fig. 5

amount of signal processing is needed in order to convert obtained raw data from sensing electrodes to useful information (like heart-rate, blood pressure, oxygen saturation level etc.), it need fast computational capacities of CMOS based processors far superior than organic based devices and hence the hybrid integration become a key enabler for future generation cost-effective, compliant systems in all manner.

Fig. 7. (a) Schematic illustration of trench-protect-etch-release (TPER) process, (b) Flexible nanoscale fully depleted transistor and IC enabled by CST, schematic of removing prefabricated devices from rigid handle wafer (left), 100 mm flexible circuit (right), and cross-sectional TEM image of nanoscale ultrathin n-FETs, confirming the structural integrity of the flexible devices. Reprinted with permission from [11] Copyright (2013) American Chemical Society. (c) Fabrication process flow for SEB starting with fabricated FinFET devices on standard 90 nm SOI with 150 nm BOX, FinFET devices on flexible silicon substrate (50 μm thick) are obtained after PR removal at the end. Reprinted with permission from [12] Copyright (2014) American Chemical Society. (d) Optical images of Si islands obtained after patterning of spiral interconnects and releasing using vapor HF: area expansion test with 3 hexagon array (top) and 7 hexagon array (bottom) connected with double spirals. Reprinted from [65], with the permission of AIP Publishing. (e) Optical image of thermal patch after release (left), stretchability and conformability of the patch on elbow joint (top), and spring images before (bottom left), under (center) and after (bottom right) elongation cycles respectively. Reprinted with permission from [67]. Copyright John Wiley & Sons.

B. CMOS based approaches

Inarguably Si is the most affordable and abundant flagship material of CMOS state-of-the-art technology, and it is absolutely essential to impart flexibility in Si by thinning it to obtain flexible electronics systems. Here we present pragmatic methods to obtain flexible electronic devices by two different approaches: post-flexing device development and pre-flexing device development approaches. It should be clear that device development is performed in the final stage on flexed Si piece in post-flexing device development approach, on contrary, prefabricated devices on bulk Si are thinned down in pre-flexing device development approach.

i. Post-flexing device development

One of the most preferred processes of obtaining thin and flexible Si is the use of silicon-on-insulator (SOI) substrate. SOI has a thin (50-300 nm) single-crystal silicon (Si) layer electrically isolated from base Si substrate by silicon dioxide (SiO_2) layer known as buried oxide (BOX), applications determine the thicknesses of top Si and the BOX layer. SOI wafers are considered ideal for making flexible Si electronics since oxide can easily be etched away using hydrofluoric acid (HF) to release top thin Si transferable onto flexible substrate mediated by a polymer. The process simplicity, low-cost, low-temperature processing are major plus points of this process along with high yield of the transfer process. Transistors and RF components fabrication using SOI-based Si micro-ribbons are transferred onto flexible substrate [59], [60].

Major drawbacks of SOI-based processing are a large percentage of Si loss in etching, in addition to extremely challenging handling during the transfer process. Furthermore,

all the post-transfer processes must be performed at low temperatures. SOI have more defects than standard thick Si and tend to bend under stresses during thin film depositions in addition to the loss of materials and usage of expensive SOI makes it an expensive process. Isolated planar integrated devices (primary reason for CMOS based rising digital age) are not feasible due to thin Si on BOX having hardly any space to accommodate wells, and devices will disintegrate on BOX removal. Hence, SOI-based devices may never reach ULSI densities as CMOS.

ii. Pre-flexing device development

In this approach, state-of-the-art electronic devices can be built on bulk Si using advanced CMOS processes without any restrictions which are later flexed with described variants of flexing techniques. This technique can further be sub-classified based on the direction of thinning down Si into top-down (Si is released from top after device fabrication) and bottom-up (Si is thinned down by etching bulk Si from back side of substrate).

Top-down model: implements thin film Si device release after completion of whole device fabrication from the top surface of the wafer. Trench-Protect-Etch-Release (TPER) method is the most opted one, schematically detailed in Fig. 7 (a). The devices are protected in BOSCH process of deep-reactive-ion-etching (DRIE) for trench formation by using soft mask (photoresist) and hard mask (SiO_2). Deep trench formation is followed by atomic layer deposition (ALD) of aluminum dioxide (Al_2O_3) act as spacer to prevent lateral Si etching during subsequent exposure to XeF_2 in trenches. An intermediate reactive-ion-etching (RIE) is performed to get rid

of Al_2O_3 from top Si surface inside trenches. The spheres formed due to gaseous isotropic etching of Si merge into neighboring spheres, thus releasing top Si layered devices and bulk Si bottom can be reused after planarization. Various flexible electronic devices (MOSFETs, MOS capacitors, TEGs, and metal-insulator-metal capacitors) have been successfully demonstrated using TPER method [12], [13], [61].

Several advantages of TPER method include low thermal post-fabrication process (preventing high thermal exposure to the circuit), no significant degradation in performance of the devices after release and on bending, and thickness control of final flexible Si determined by trench depth [62]. Also, complete 100 mm wafer has been shown to be flexed by this process [63]. The leftover bulk wafer can be reused after undergoing chemical-mechanical-polishing (CMP). The trenches existing throughout the released Si sample though convey material loss with up to ~20% reduced usable area, adds fascinating transparency and heat dissipation. It also creates semi-spherical scallops that may hinder its integration while bonding.

Controlled spalling technique (CST) uses a tensile stressor layer on the top layer of the devices that helps in propagating cracks in the plane parallel to the surface. Shahrjerdi *et al.* have reported room temperature CST process on SOI circuitry and transferred thinned devices on flexible plastic substrate shown in Fig. 7 (b) [11] where Ni thin film deposition was used as a tensile stressor layer. Advantages of CST include room temperature processing, CMOS compatibility, and control over the thickness of final substrate by tuning thickness of stressor layer. Deposition of additional stressor layer alters the properties of Si like change in effective mass of carriers and their mobility by affecting the band structure which implies mismatch in the performance of p-type and n-type devices thereby leading malfunctioning in circuit alongside increased dynamic power consumption. Other processing of releasing top Si layer are epitaxial layer transfer (ELTRAN), epitaxial lift-off (ELO), and ChipFilm technologies, but expensive and slow process of growing epitaxial layers on top of devices make them lesser common for industry scale with lower throughput [53].

Bottom-up model: refer to bulk Si substrate thinning process by physical or chemical etching from backside after device fabrication on top. The top layer of devices is protected by using laminated protective tapes, thin film deposition or photoresist coating. The biggest disadvantage of this process is the loss of whole bulk Si. ‘Back-grinding’ –one of the first methods uses mechanical abrasives to reduce bulk Si thickness. Fast throughput due to high grinding speeds of ~300 $\mu\text{m}/\text{min}$ is advantageous while longevity of grinding wheel makes the process inexpensive. High thickness variations on the wafer and highly abrasive nature make it less precise, highly stressful (may lead to wafer breakage especially when grinding below 200 μm thickness). A less stressful and lower surface damaging variant of back-grinding is CMP, which implements mechanical and chemical abrasives for etching, significantly softer due to the usage of the chemical slurry. Slower and expensive processing are downsides of CMP.

Sevilla *et al.* in 2014 have developed a novel approach of thinning Si substrate coined as ‘soft-etch-back’ (SEB) process which involves DRIE for thinning down bulk Si substrate from

backend [12]. Device fabrication is followed by thick photoresist coating (on the top side for protection) and then DRIE on flipped substrate from backside in presence of SF_6 and C_4F_8 gasses at -20°C . Schematic depiction of the SEB process for flexible FinFET fabrication is shown in Fig. 7 (c). State-of-the-art flexible FinFETs have been illustrated using this technique. Low stress, CMOS compatibility, and highly controllable final substrate thickness make this process favorable for flexing any circuitry. Time consumption is one of the drawbacks of this process which can be optimized by merging back grinding and SEB process to improve throughput.

V. ACHIEVING STRETCHABILITY

There are several ways of imparting stretchability in electronics, mainly either by making stretchable materials electronic or making electronics stretchable. One route of impeding flexibility and stretchability is using natural elastomeric materials and embedding electronics in it making them functional. However, these materials have poor reliability and applicability in semiconductor-based devices due to poor thermal, electrical, and mechanical properties. Another route is to build inorganic electronics and make them stretchable by using novel design geometries. Huang *et al.* have investigated the stretchability in electronics using Si (100) on SOI and Si (111) by micromachining lateral springs on Si substrate [64]. SOI technique involves patterning the top Si layer into lateral spring structures using DRIE followed by BOX removal. Rojas *et al.* in 2014 [65] has presented the extension of this work by performing isotropic etching of BOX in SOI using HF and release the patterned Si substrates after etching top Si layer up to BOX. The spiral configuration of spring connectors between hexagonal flexible islands in 2D matrix is shown in Fig. 7 (d), can host CMOS devices acting as a stretchable fabric, and *more than 1000% lateral stretchability and 30 folds area expansion* was observed [65].

A serpentine or ‘horseshoe’ design for lateral springs are alternatives for the spiral designs [66]. The disadvantage of this design is housing electronic devices on the same thin flexible Si which implies stretching of the devices and impairing the performance, however, these can be taken care by designing better geometries to host device islands on the same Si. Stretchable interconnects present reasonable alternative for adding stretchability to the devices, however, similar to semiconductor materials, metals are inherently non-stretchable. An ultrastretchable and flexible smart patch for adaptive thermotherapy has been illustrated by Hussain *et al.* [67] using copper metal interconnects. Flexibility is achieved in the device by depositing and patterning thin Cu on PI whereas exceptional *stretchability (800%)* was the result of modified horseshoe lateral spring interconnect design shown in Fig. 7 (e). The developed thermal patch with its potentials of stretchability, flexibility is shown by its integration on a human forearm and elbow joint as shown in Fig. 7 (e). A similar approach for obtaining a metal/polymer based constant frequency stretchable antenna for far-field communications is demonstrated by Hussain *et al.* described previously [33]. Stretching these metals produce variation in its resistances ideally supposed to

retain properties on stretching. This process of impeding stretchability using metal interconnect designs is economic, flexible, compatible with CMOS-based integration, manufactural, and reusable implies to pursue several fascinating applications in freeform IoT and IoE applications.

VI. OUTLOOK AND CONCLUDING REMARKS

Electronics have become an indispensable part of our daily life, with constant CMOS scaling that leads to increased performances at lower costs and in constrained areas. Integration of microelectronics and nanoelectronics will be critical for achieving data-driven applications in healthcare monitoring (wearable and implantable electronics) and environmental applications. The big data generation from these devices imposes significant challenges to be addressed for handling, processing, and communicating data. Simple low-cost-garage-fabrication based electronics may be effective in free-form electronics, however, their inferior performances related to data management capabilities outweighs the noted advantages over CMOS based state-of-the-art technologies. Pertaining to the current CMOS technology, millimeter-sized chips are pragmatic for many applications, however, huge data processing and handling demands increased densities of basic logic and storage elements implying larger area needs. Heterogeneous 3D stacking of in-plane devices can be a realistic solution. These 3D stacked systems, system-on-chip (SOC), and super-chips [68], [69] promises a great deal, on the contrary, conformability, asymmetry, and biocompatibility emphasize flexibility and stretchability incorporation in these bulky and rigid structures.

Hussain *et al.* have been exploring the area of flexible and stretchable electronics for a compliant system that are truly flexible, stretchable, and biocompatible and matches both electrical and mechanical performances of their bulky and rigid counterparts. Sevilla *et al.* have illustrated flexible thermoelectric generators (TEGs) on Si substrate [61] which is compatible with CMOS integration for on-chip energy harvesting. Kutbee *et al.* have offered a new integration strategy for the development of *free-form, flexible, and biocompatible lithium-ion microbattery*. Better performance is achieved by flexing commercial lithium ion batteries (LIBs) and integrating its anode as a current collector [70]. Paper-skin platform by Nassar *et al.* illustrates hybrid integration strategies, flexible devices with extremely high performances never achieved earlier like 10^9 cycle endurance, high-temperature operations (200 °C). Hence, true multi-disciplinary approaches and heterogeneous integration of hybrid integrated flexible and stretchable electronic systems will enhance the mechanical adaptations of trivial CMOS semiconductor technologies.

In this review, we have detailed necessity and design criteria for freeform compliant high performance CMOS electronic systems for Internet of Everything (IoE) applications. We have shown both scaling and physical freeform architecture is required to meet the basic compliance need for future generation electronics.

REFERENCES

- [1] L. Coetzee and J. Eksteen, "The Internet of Things - promise for the future? An introduction," *IST-Africa Conf. Proceedings, 2011*, pp. 1–9, 2011.
- [2] "The BRAIN Initiative: Surviving the Data Deluge." [Online]. Available: http://www.kavilfoundation.org/science-spotlights/brain-initiative-surviving-data-deluge#.V_evJY997IW.
- [3] J. D. MacKenzie and C. Ho, "Perspectives on energy storage for flexible electronic systems," *Proc. IEEE*, vol. 103, no. 4, pp. 535–553, 2015.
- [4] R. Bogue, "Towards the trillion sensors market," *Sens. Rev.*, vol. 34, no. 2, pp. 137–142, 2014.
- [5] L. Petti, N. Munzenrieder, C. Vogt, H. Faber, L. Buthe, G. Cantarella, F. Bottacchi, T. D. Anthopoulos, and G. Troster, "Metal Oxide Semiconductor Thin-Film Transistors for Flexible Electronics," *Appl. Phys. Rev.*, vol. 21303, pp. 1–57, 2016.
- [6] Z. R. Wang, J. Z. Xin, X. C. Ren, X. L. Wang, C. W. Leung, S. Q. Shi, A. Ruotolo, and P. K. L. Chan, "Low power flexible organic thin film transistors with amorphous Ba_{0.7}Sr_{0.3}TiO₃ gate dielectric grown by pulsed laser deposition at low temperature," *Org. Electron.*, vol. 13, no. 7, pp. 1223–1228, 2012.
- [7] T. Sekitani, U. Zschieschang, H. Klauk, and T. Someya, "Flexible organic transistors and circuits with extreme bending stability," *Nat. Mater.*, vol. 9, no. 12, pp. 1015–1022, Dec. 2010.
- [8] M. Yi, Y. Guo, J. Guo, T. Yang, Y. Chai, Q. Fan, L. Xie, and W. Huang, "The mechanical bending effect and mechanism of high performance and low-voltage flexible organic thin-film transistors with a cross-linked PVP dielectric layer," *J. Mater. Chem. C*, vol. 2, no. 16, pp. 2998–3004, 2014.
- [9] G. A. T. Sevilla, J. P. Rojas, H. M. Fahad, A. M. Hussain, R. Ghanem, C. E. Smith, and M. M. Hussain, "Flexible and transparent silicon-on-polymer based sub-20 nm non-planar 3D FinFET for brain-architecture inspired computation," *Adv. Mater.*, vol. 26, no. 18, pp. 2794–2799, May 2014.
- [10] H. Xu, J. Pang, M. Xu, M. Li, Y. Guo, Z. Chen, L. Wang, J. Zou, H. Tao, and J. Peng, "Fabrication of Flexible Amorphous Indium-Gallium-Zinc-Oxide Thin-Film Transistors by a Chemical Vapor Deposition-Free Process on Polyethylene Naphthalate," *ECS J. Solid State Sci. Technol.*, vol. 3, no. 9, pp. Q3035–Q3039, Jul. 2014.
- [11] D. Shahrjerdi and S. W. Bedell, "Extremely flexible nanoscale ultrathin body silicon integrated circuits on plastic," *Nano Lett.*, vol. 13, no. 1, pp. 315–320, Jan. 2013.
- [12] G. A. Torres Sevilla, M. T. Ghoneim, H. Fahad, J. P. Rojas, A. M. Hussain, and M. M. Hussain, "Flexible nanoscale high-performance FinFETs," *ACS Nano*, vol. 8, no. 10, pp. 9850–9856, Oct. 2014.
- [13] G. A. Torres Sevilla, A. S. Almuslem, A. Gumus, A. M. Hussain, M. E. Cruz, and M. M. Hussain, "High performance high-k/metal gate complementary metal oxide semiconductor circuit element on flexible silicon," *Appl. Phys. Lett.*, vol. 108, no. 9, pp. 0–5, 2016.
- [14] M. Ghoneim and M. Hussain, "Review on Physically Flexible Nonvolatile Memory for Internet of Everything Electronics," *Electronics*, vol. 4, no. 3, pp. 424–479, 2015.
- [15] S. H. Jo, T. Chang, I. Ebong, B. B. Bhadviya, P. Mazumder, and W. Lu, "Nanoscale memristor device as synapse in neuromorphic systems," *Nano Lett.*, vol. 10, no. 4, pp. 1297–1301, Apr. 2010.
- [16] S. K. Hong, J.-E. Kim, S. O. Kim, and B. J. Cho, "Non-volatile memory using graphene oxide for flexible electronics," *Nanotechnol. (IEEE-NANO), 2010 10th IEEE Conf.*, pp. 604–606, Aug. 2010.
- [17] H. Y. Jeong, J. Y. Kim, J. W. Kim, J. O. Hwang, J. E. Kim, J. Y. Lee, T. H. Yoon, B. J. Cho, S. O. Kim, R. S. Ruoff, and S. Y. Choi, "Graphene oxide thin films for flexible nonvolatile memory applications," *Nano Lett.*, vol. 10, no. 11, pp. 4381–4386, Nov. 2010.
- [18] F. Zhao, H. Cheng, Y. Hu, L. Song, Z. Zhang, L. Jiang, and L. Qu, "Functionalized graphitic carbon nitride for metal-free, flexible and rewritable nonvolatile memory device via direct laser-writing," *Sci. Rep.*, vol. 4, p. 5882, Jul. 2014.
- [19] S. Kim, H. Y. Jeong, S. K. Kim, S. Y. Choi, and K. J. Lee, "Flexible memristive memory array on plastic substrates," *Nano Lett.*, vol. 11, no. 12, pp. 5438–5442, Dec. 2011.
- [20] K. Nagashima, H. Koga, U. Celano, F. Zhuge, M. Kanai, S. Rahong, G. Meng, Y. He, J. De Boeck, M. Jurczak, W. Vandervorst, T. Kitaoka, M. Nogi, and T. Yanagida, "Cellulose nanofiber paper as an ultra flexible nonvolatile memory," *Sci. Rep.*, vol. 4, p. 5532, Jul. 2014.
- [21] S. H. Hong, B. J. Bae, H. Lee, and J. H. Jeong, "Fabrication of high density nano-pillar type phase change memory devices using flexible AAO shaped template," *Microelectron. Eng.*, vol. 87, no. 11, pp. 2081–2084, 2010.

- [22] J. M. Yoon, D. O. Shin, Y. Yin, H. K. Seo, D. Kim, Y. I. Kim, J. H. Jin, Y. T. Kim, B.-S. Bae, S. O. Kim, and J. Y. Lee, "Fabrication of high-density In(3)Sb(1)Te(2) phase change nanoarray on glass-fabric reinforced flexible substrate," *Nanotechnology*, vol. 23, no. 25, p. 255301, Jun. 2012.
- [23] B. H. Mun, B. K. You, S. R. Yang, H. G. Yoo, J. M. Kim, W. I. Park, Y. Yin, M. Byun, Y. S. Jung, and K. J. Lee, "Flexible one diode-one phase change memory array enabled by block copolymer self-assembly," *ACS Nano*, vol. 9, no. 4, pp. 4120–4128, Apr. 2015.
- [24] Takashi Eshita, Wensheng Wang, Kou Nakamura, Souichirou Ozawa, Youichi Okita, Satoru Mihara, Yukinobu Hikosaka, Hitoshi Saito, Junichi Watanabe, Ken'ichi Inoue, Hideshi Yamaguchi, and Kenji Nomura, "Development of Ferroelectric RAM (FRAM) for Mass Production," *J. Phys. Sci. Appl.*, vol. 5, no. 1, pp. 29–32, 2015.
- [25] S.-M. Yoon, S. Yang, S.-W. Jung, S.-H. Ko Park, C.-W. Byun, M.-K. Ryu, H. Oh, K. Kim, C.-S. Hwang, K.-I. Cho, and B.-G. Yu, "Organic/Inorganic Hybrid-Type Nonvolatile Memory Thin-Film Transistor on Plastic Substrate below 150°C," *MRS Proc.*, vol. 1287, no. 2, p. mrsf10-1287-f09-10, Jan. 2011.
- [26] M. T. Ghoneim and M. M. Hussain, "Study of harsh environment operation of flexible ferroelectric memory integrated with PZT and silicon fabric," *Appl. Phys. Lett.*, vol. 107, no. 5, p. 52904, Aug. 2015.
- [27] M. T. Ghoneim, M. A. Zidan, M. Y. Alnassar, A. N. Hanna, J. Kosel, K. N. Salama, and M. M. Hussain, "Thin PZT-Based Ferroelectric Capacitors on Flexible Silicon for Nonvolatile Memory Applications," *Adv. Electron. Mater.*, vol. 1, no. 6, pp. 1–10, 2015.
- [28] S.-J. Kim, J.-M. Song, and J.-S. Lee, "Transparent organic thin-film transistors and nonvolatile memory devices fabricated on flexible plastic substrates," *J. Mater. Chem.*, vol. 21, no. 38, p. 14516, 2011.
- [29] Y. Jeon, M. Lee, T. Moon, and S. Kim, "Flexible nano-floating-gate memory with channels of enhancement-mode Si nanowires," *IEEE Trans. Electron Devices*, vol. 59, no. 11, pp. 2939–2942, 2012.
- [30] Y. Zhou, S.-T. Han, Z.-X. Xu, and V. A. L. Roy, "Low voltage flexible nonvolatile memory with gold nanoparticles embedded in poly(methyl methacrylate)," *Nanotechnology*, vol. 23, no. 34, p. 344014, Aug. 2012.
- [31] M. Kubo, X. Li, C. Kim, M. Hashimoto, B. J. Wiley, D. Ham, and G. M. Whitesides, "Stretchable microfluidic radiofrequency antennas," *Adv. Mater.*, vol. 22, no. 25, pp. 2749–2752, Jul. 2010.
- [32] L. Song, A. C. Myers, J. J. Adams, and Y. Zhu, "Stretchable and reversibly deformable radio frequency antennas based on silver nanowires," *ACS Appl. Mater. Interfaces*, vol. 6, no. 6, pp. 4248–4253, Mar. 2014.
- [33] A. M. Hussain, F. A. Ghaffar, S. I. Park, J. A. Rogers, A. Shamim, and M. M. Hussain, "Metal/Polymer Based Stretchable Antenna for Constant Frequency Far-Field Communication in Wearable Electronics," *Adv. Funct. Mater.*, vol. 25, no. 42, pp. 6565–6575, 2015.
- [34] S. Cheng, Z. Wu, P. Hallbjörner, K. Hjort, and A. Rydberg, "Foldable and stretchable liquid metal planar inverted cone antenna," *IEEE Trans. Antennas Propag.*, vol. 57, no. 12, pp. 3765–3771, 2009.
- [35] M. Donelli and G. Oliveri, "Design of tunable graphene-based antenna arrays for microwave applications," *IEEE Antennas Propag. Soc. AP-S Int. Symp.*, vol. 2, no. 1, pp. 908–909, 2014.
- [36] M. Aldrigo, M. Dragoman, and D. Dragoman, "Smart antennas based on graphene," *J. Appl. Phys.*, vol. 116, no. 11, pp. 6–11, 2014.
- [37] T. Zhou, Z. Cheng, H. Zhang, M. Le Berre, L. Militaru, and F. Calmon, "Miniaturised tunable terahertz antenna based on graphene," *Microw. Opt. Technol. Lett.*, vol. 56, no. 12, pp. 1792–1794, 2013.
- [38] X. Liu, Y. Guo, Y. Ma, H. Chen, Z. Mao, H. Wang, G. Yu, and Y. Liu, "Flexible, low-voltage and high-performance polymer thin-film transistors and their application in photo/thermal detectors," *Adv. Mater.*, vol. 26, no. 22, pp. 3631–3636, Jun. 2014.
- [39] U. Kraft, M. Sejčić, M. J. Kang, K. Takimiya, T. Zaki, F. Letzkus, J. N. Burghartz, E. Weber, and H. Klauk, "Flexible Low-Voltage Organic Complementary Circuits: Finding the Optimum Combination of Semiconductors and Monolayer Gate Dielectrics," *Adv. Mater.*, vol. 27, no. 2, pp. 207–214, 2015.
- [40] S. Chung, M. Jang, S. Ji, H. Im, N. Seong, J. Ha, S. Kwon, Y. Kim, H. Yang, and Y. Hong, "Flexible High-Performance All-Inkjet-Printed Inverters: Organo-Compatible and Stable Interface Engineering," *Adv. Mater.*, vol. 25, no. 34, pp. 4773–4777, 2013.
- [41] T. Il Kim, Y. Hwan Jung, H. J. Chung, K. Jun Yu, N. Ahmed, C. J. Corcoran, J. Suk Park, S. Hun Jin, and J. A. Rogers, "Deterministic assembly of releasable single crystal silicon-metal oxide field-effect devices formed from bulk wafers," *Appl. Phys. Lett.*, vol. 102, no. 18, 2013.
- [42] L. Zhang, H. Wang, Y. Zhao, Y. Guo, W. Hu, G. Yu, and Y. Liu, "Substrate-free ultra-flexible organic field-effect transistors and five-stage ring oscillators," *Adv. Mater.*, vol. 25, no. 38, pp. 5455–5460, Oct. 2013.
- [43] S. Kim, J. H. Son, S. H. Lee, B. K. You, K. Il Park, H. K. Lee, M. Byun, and K. J. Lee, "Flexible crossbar-structured resistive memory arrays on plastic substrates via inorganic-based laser lift-off," *Adv. Mater.*, vol. 26, no. 44, pp. 7480–7487, Nov. 2014.
- [44] J. M. Kanervo and A. O. I. Krause, "Kinetic Analysis of Temperature-Programmed Reduction: Behavior of a CrO_x / Al₂O₃ Catalyst," vol. 50, no. 7, pp. 9778–9784, 2001.
- [45] M. Pope, H. P. Kallmann, and P. Magnante, "Electroluminescence in Organic Crystals," *J. Chem. Phys.*, vol. 38, no. 8, p. 2042, 1963.
- [46] C. W. Tang and S. A. Vanslyke, "Organic electroluminescent diodes," *Appl. Phys. Lett.*, vol. 51, no. 12, pp. 913–915, 1987.
- [47] T. Ricker, "Sony's rollable OLED display can wrap around a pencil, our hearts," *2Engadget.com*, 2010. [Online]. Available: <http://www.engadget.com/2010/05/26/sonys-rollable-oled-display-can-wrap-around-a-pencil-our-heart/>. [Accessed: 08-Aug-2016].
- [48] A. Nathan, A. Ahnood, M. T. Cole, S. Lee, Y. Suzuki, P. Hiralal, F. Bonaccorso, T. Hasan, L. Garcia-Gancedo, A. Dyadyusha, S. Haque, P. Andrew, S. Hofmann, J. Moultrie, D. Chu, A. J. Flewitt, A. C. Ferrari, M. J. Kelly, J. Robertson, G. A. J. Amaratunga, and W. I. Milne, "Flexible electronics: The next ubiquitous platform," in *Proceedings of the IEEE*, 2012, vol. 100, no. SPL CONTENT, pp. 1486–1517.
- [49] A. Campana, T. Cramer, D. T. Simon, M. Berggren, and F. Biscarini, "Electrocardiographic recording with conformable organic electrochemical transistor fabricated on resorbable bioscaffold," *Adv. Mater.*, vol. 26, no. 23, pp. 3874–3878, Jun. 2014.
- [50] A. Javey, H. Kim, M. Brink, Q. Wang, A. Ural, J. Guo, P. McIntyre, P. McEuen, M. Lundstrom, and H. Dai, "High-kappa dielectrics for advanced carbon-nanotube transistors and logic gates," *Nat. Mater.*, vol. 1, no. 4, pp. 241–246, Dec. 2002.
- [51] Y. Yuan, G. Giri, A. L. Ayzner, A. P. Zoombelt, S. C. B. Mannsfeld, J. Chen, D. Nordlund, M. F. Toney, J. Huang, and Z. Bao, "Ultra-high mobility transparent organic thin film transistors grown by an off-centre spin-coating method," *Nat. Commun.*, vol. 5, p. 3005, 2014.
- [52] C. Wang, D. Hwang, Z. Yu, K. Takei, J. Park, T. Chen, B. Ma, and A. Javey, "User-interactive electronic skin for instantaneous pressure visualization," *Nat Mater*, vol. 12, no. 10, pp. 899–904, Jul. 2013.
- [53] A. M. Hussain and M. M. Hussain, "CMOS-Technology-Enabled Flexible and Stretchable Electronics for Internet of Everything Applications," *Adv. Mater.*, 2015.
- [54] S. C. B. Mannsfeld, B. C.-K. Tee, R. M. Stoltenberg, C. V. H.-H. Chen, S. Barman, B. V. O. Muir, A. N. Sokolov, C. Reese, and Z. Bao, "Highly sensitive flexible pressure sensors with microstructured rubber dielectric layers," *Nat. Mater.*, vol. 9, no. 10, pp. 859–864, Oct. 2010.
- [55] T. Sekitani, H. Nakajima, H. Maeda, T. Fukushima, T. Aida, K. Hata, and T. Someya, "Stretchable active-matrix organic light-emitting diode display using printable elastic conductors," *Nat. Mater.*, vol. 8, no. 6, pp. 494–499, Jun. 2009.
- [56] J. M. Nassar, J. P. Rojas, A. M. Hussain, and M. M. Hussain, "From stretchable to reconfigurable inorganic electronics," *Extrem. Mech. Lett.*, 2016.
- [57] A. Carlson, A. M. Bowen, Y. Huang, R. G. Nuzzo, and J. A. Rogers, "Transfer printing techniques for materials assembly and micro/nanodevice fabrication," *Adv. Mater.*, vol. 24, no. 39, pp. 5284–5318, 2012.
- [58] J. M. Nassar, M. D. Cordero, A. T. Kutbee, M. A. Karimi, G. A. T. Sevilla, A. M. Hussain, A. Shamim, and M. M. Hussain, "Paper Skin Multisensory Platform for Simultaneous Environmental Monitoring," *Adv. Mater. Technol.*, p. n/a-n/a, 2016.
- [59] L. Sun, G. Qin, H. Huang, H. Zhou, N. Behdad, W. Zhou, and Z. Ma, "Flexible high-frequency microwave inductors and capacitors integrated on a polyethylene terephthalate substrate," *Appl. Phys. Lett.*, vol. 96, no. 1, p. 13509, 2010.
- [60] G. Qin, J. H. Seo, Y. Zhang, H. Zhou, W. Zhou, Y. Wang, J. Ma, and Z. Ma, "RF characterization of gigahertz flexible silicon thin-film transistor on plastic substrates under bending conditions," *IEEE Electron Device Lett.*, vol. 34, no. 2, pp. 262–264, 2013.

- [61] G. A. T. Sevilla, S. Bin Inayat, J. P. Rojas, A. M. Hussain, and M. M. Hussain, "Flexible and semi-transparent thermoelectric energy harvesters from low cost bulk silicon (100)," *Small*, vol. 9, no. 23, pp. 3916–3921, Dec. 2013.
- [62] A. M. Hussain, S. F. Shaikh, and M. M. Hussain, "Design criteria for XeF₂ enabled deterministic transformation of bulk silicon (100) into flexible silicon layer," *AIP Adv.*, vol. 6, no. 7, 2016.
- [63] J. P. Rojas, G. A. Torres Sevilla, N. Alfaraj, M. T. Ghoneim, A. T. Kutbee, A. Sridharan, and M. M. Hussain, "Nonplanar nanoscale fin field effect transistors on textile, paper, wood, stone, and vinyl via soft material-enabled double-transfer printing," *ACS Nano*, vol. 9, no. 5, pp. 5255–5263, 2015.
- [64] K. Huang, R. Dinyari, G. Lanzara, Y. K. Jong, J. Feng, C. Vancura, F. K. Chang, and P. Peumans, "An approach to cost-effective, robust, large-area electronics using monolithic silicon," in *Technical Digest - International Electron Devices Meeting, IEDM*, 2007, pp. 217–220.
- [65] J. P. Rojas, A. Arevalo, I. G. Foulds, and M. M. Hussain, "Design and characterization of ultra-stretchable monolithic silicon fabric," *Appl. Phys. Lett.*, vol. 105, no. 15, p. 154101, Oct. 2014.
- [66] J. Kim, M. Lee, H. J. Shim, R. Ghaffari, H. R. Cho, D. Son, Y. H. Jung, M. Soh, C. Choi, S. Jung, K. Chu, D. Jeon, S.-T. Lee, J. H. Kim, S. H. Choi, T. Hyeon, and D.-H. Kim, "Stretchable silicon nanoribbon electronics for skin prosthesis," *Nat. Commun.*, vol. 5, p. 5747, Dec. 2014.
- [67] A. M. Hussain, E. B. Lizardo, G. A. Torres Sevilla, J. M. Nassar, and M. M. Hussain, "Ultrastretchable and flexible copper interconnect-based smart patch for adaptive thermotherapy," *Adv. Healthc. Mater.*, vol. 4, no. 5, pp. 665–673, 2015.
- [68] T. Wu, C. Shen, J. Shieh, W. Huang, H. Wang, F. Hsueh, H. Chen, C. Yang, T. Hsieh, B. Chen, Y. Shiao, C. Yang, G. Huang, K. Li, T. Hsueh, C. Chen, W. Chen, F. Yang, and W. Yeh, "Low-Cost and TSV-free Monolithic 3D-IC with Heterogeneous Integration of Logic, Memory and Sensor Analogy Circuitry for Internet of Things," pp. 640–643, 2015.
- [69] K. Lee, "3-D Hetero-Integration Technologies for Multifunctional Convergence Systems," vol. 22, no. 2, pp. 11–19, 2015.
- [70] A. T. Kutbee, M. T. Ghoneim, S. Member, S. M. Ahmad, M. M. Hussain, and S. Member, "Free-Form Flexible Lithium-Ion Microbattery," vol. 15, no. 3, pp. 402–408, 2016.
- [71] L. Pan, Z. Ji, X. Yi, X. Zhu, X. Chen, J. Shang, G. Liu, and R.-W. Li, "Nonvolatile Memory: Metal-Organic Framework Nanofilm for Mechanically Flexible Information Storage Applications (Adv. Funct. Mater. 18/2015)," *Adv. Funct. Mater.*, vol. 25, no. 18, pp. 2630–2630, May 2015.
- [72] J. Yao, J. Lin, Y. Dai, G. Ruan, Z. Yan, L. Li, L. Zhong, D. Natelson, and J. M. Tour, "Highly transparent nonvolatile resistive memory devices from silicon oxide and graphene," *Nat. Commun.*, vol. 3, p. 1101, Oct. 2012.
- [73] S. C. Wu, H. T. Feng, M. J. Yu, I. T. Wang, and T. H. Hou, "Flexible three-bit-per-cell resistive switching memory using a-IGZO TFTs," *IEEE Electron Device Lett.*, vol. 34, no. 10, pp. 1265–1267, 2013.
- [74] Y. Qin, Q. Peng, Y. Ding, Z. Lin, C. Wang, Y. Li, F. Xu, J. Li, Y. Yuan, X. He, and Y. Li, "Lightweight, Superelastic, and Mechanically Flexible Graphene/Polyimide Nanocomposite Foam for Strain Sensor Application," *ACS Nano*, vol. 9, no. 9, pp. 8933–8941, Sep. 2015.