Heidari, H., Garcia Nunez, C., and Dahiya, R. (2017) E-Skin Module with Heterogeneously Integrated Graphene Touch Sensors and CMOS Circuitry. In: IEEE Sensors 2016, Orlando, USA, 30 Oct - 02 Nov 2016, ISBN 9781479982875 (doi:10.1109/ICSENS.2016.7808760)

E-Skin Module with Heterogeneously Integrated Graphene Touch Sensors and CMOS Circuitry

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***Abstract*—This paper presents a flexible electronic skin (*e*-skin) module developed by heterogeneous integration of graphene based touch sensors and CMOS chips having basic capacitance-to-voltage converter (CVC) circuitry to acquire the sensor response. Graphene touch sensor was firstly transfer printed on a flexible polyvinyl chloride (PVC) substrate, thereafter the CMOS chip with 4×4 array of large transistors was integrated on the same PVC substrate. Then, resulting module was tested to verify the performance. The heterogeneous integration of graphene and Si based devices on the same flexible substrate is an interesting new approach that can be scaled up, opening a new opportunity for obtaining large area *e*-skin for robotic applications.**

Keywords—Electronic Skin; Graphene; Si-Chip; Flexible Electronics; Touch Sensing

I. INTRODUCTION

Flexible and large area electronics has attracted significant interest recently as many applications require electronics to be in conformal contact with non-planar surfaces. Some of these applications include electronic skin (*e*-skin) for robots and artificial prosthetic limbs [1], surgical instruments [2], and non-invasive wearable systems for health monitoring [3]. The functionalities such as conformability or stretchability of electronics are not possible with today's silicon based planar electronics [4]. For this reason, a number of fabrication strategies including printing of semiconducting materials have been explored [5]. In terms of materials, thus far the research in the field has largely focussed on organic semiconductors, whose response is inherently slow due to low charge career mobility. However, many emerging applications such as internet of things, smart cities, cognitive robotics, and smart cities, etc. require fast computation and communication responses (e.g. wireless communication above radio frequency (RF) range), and therefore, high mobility materials such as single crystal silicon, and graphene, etc. have also been explored recently for flexible electronics [6].

Graphene has emerged as an interesting material for flexible electronics because it is ultra-flexible, strong and can provide high-performance electronics, owing to its superior electrical properties [7]. However, the zero-band gap currently poses a significant challenge for graphene based electronics and circuits. Nonetheless, the excellent properties of graphene can be exploited to develop multiple functionalities such as sensors or optoelectronic devices. As for electronics, with careful integration strategy, the Si based electronics (in particular the CMOS chips) could still be used to read or drive the devices [8]. This paper demonstrates our research in this direction through the development of an *e*-skin module. The e-skin module presented here has the graphene based touch sensors integrated with CMOS based circuitry on the same flexible polyvinyl chloride (PVC) substrate. The graphene based capacitive touch sensors presented in this paper have interdigitated electrodes. As shown in later sections, the graphene based touch sensor can detect capacitance changes in the order of pF. For this order of capacitance detection the required amplification circuitry is relatively much simpler than for other alternatives such as CMOS capacitive sensors, which detect capacitance change is in range of aF ~ fF [9]. To read the sensor response, we demonstrate here the heterogeneous integration of sensors and CMOS integrated circuit (IC) on same flexible PVC substrate (Fig. 1). The CMOS IC provides capacitance-to-voltage (CVC) conversion for the graphene based touch sensors.

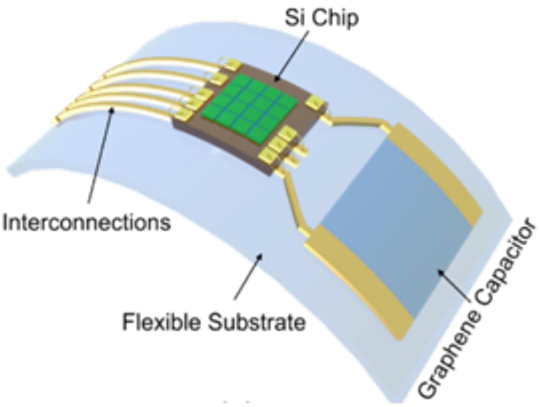

Fig. 1. 3D schematic illustration of single layer graphene based touch sensors and CMOS IC on flexible PVC.

II. GRAPHENE BASED TOUCH SENSOR

Capacitive touch sensors based on chemical vapor deposited (CVD) graphene were fabricated by transfer printing as-grown graphene on PVC substrates by using hot lamination method as further explained elsewhere [7]. Figure 2 shows the schematic illustration of the fabrication steps, comprising: a) CVD growth of graphene on Cu, b) hot lamination to obtain graphene-on-PVC, c) direct toner printing on the back side of the graphene to hold Cu where needed, d) wet etching of Cu using Fe_3Cl etching solution, e) ink removal to define the shape of the circuitry, f) blade cutting to shape the graphene based capacitor, and finally, g) the deposition of a

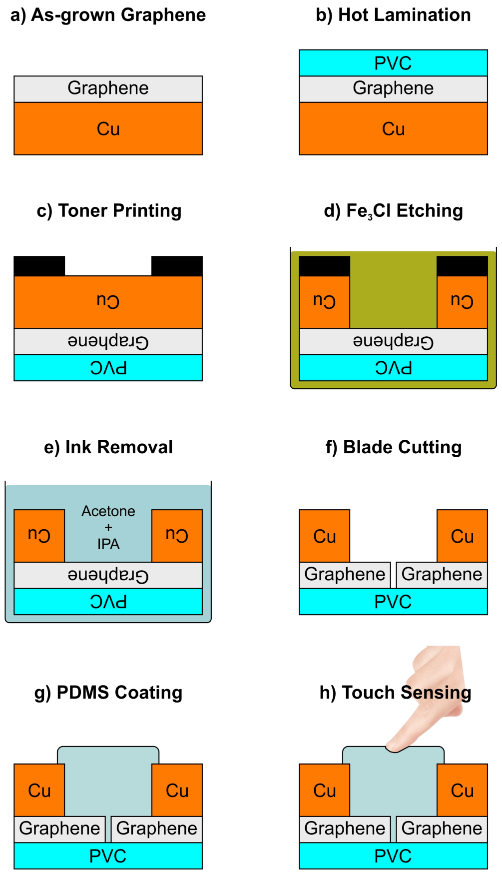

Fig. 2. Schematic illustration of the experimental procedure utilized to fabricate flexible touch sensors based on CVD graphene.

polydimethylsiloxane (PDMS) protective layer atop the active area of the sensor (Fig. 2(h)). The latter encapsulates the sensor, which prevents the oxidation and doping of graphene from environment, and makes the resultant device robust and stable for touching.

III. CMOS CHIP WITH CIRCUITRY

The translation from passive elements like graphene capacitance to voltage requires incorporating a CVC for capacitive touch sensors, which can measure both statically and dynamically. The obtained voltage can either feed into an analog-to-digital converter (ADC) for digital processing or measure the output voltage directly [10]. In this work, we have used a chip (Fig. 4) with 4×4 array of transistors specifically developed for tactile sensing application [11]. This chip was fabricated in a non-standard 4-µm CMOS technology with Al gate and NMOS transistors on p-well. For sensors readout, we used a variant of source follower (SF) circuit, which is similar to a 3T APS CMOS image sensor [12]. For a sensor module, three n-type transistors on the chip were connected as reset switch, bias switch, and SF amplifier transistor in an area of 0.9×0.6 mm^2, as shown in Fig. 3. Then, the graphene touch sensor is connected between the sensing node of the SF gate and ground, where the reset switch will pre-charge the capacitor at reset time. To alleviate the headroom issue of source follower's drop and the gate leakage, thick gate devices for 1.8 V supply voltage are used in transistors.

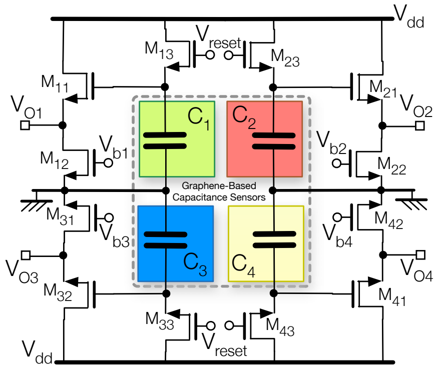

Fig. 3. Schematic of the source follower readout for presented sensors.

The readout operation starts with a reset to provide a steady-state DC bias for the sensing node via the reset switch. The reset switch is controlled by an external clock with high potential less than the threshold voltage of the SF transistor to ensure normal turning off. During low potential of external clock, the sampling operation is initiated when the pre-charge signal is brought low, hence that charge is removed from the sensing node. Accordingly, the output node falls in proportion to the value of the capacitive sensor. By touching the capacitive sensor, the output signal is high and the charge is injected into the sensing node through the readout circuit. At this time, the voltage of the sensing node, is raised above the threshold voltage of the SF transistor, turning it on and forming an amplifier with the bias transistor. The output voltage generated by the SF is then measured over time during the measurement period.

IV. INTEGRATION OF DEVICES ON FLEXIBLE SUBSTRATE

Figure 4 shows a photograph of graphene based touch sensor electrically connected to the Si chip, after mounting both on a flexible PVC substrate. The Si-chip contact pads were connected to the Cu routings on the flexible PVC with Al wire ball bonder. An external clock of 800 Hz frequency was used to control the reset transistor. The readout operation starts with a reset phase to charge the capacitor. Afterwards, the capacitor discharge curves were measured over time. When the sensor is touched, the capacitance increases by tens of pF (Fig 5). This increase is mainly dependent on the touch and time.

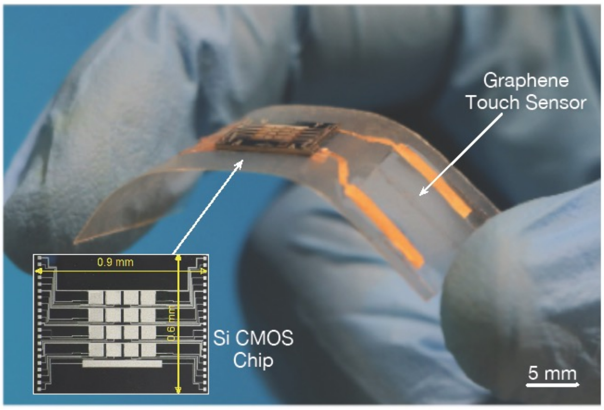

Fig. 4. Photograph of the graphene touch sensor with chip mounted on 125-µm flexible PVC substrate. Inset: Chip microphotograph.

V. EXPERIMENTAL RESULTS

Graphene based capacitive touch sensors were characterized by using a Keysight (E4980AL) LCR meter. First, we measured the parasitic capacitance (C_0) of sensors in air, obtaining values around 8.5 pF, as shown in Fig. 5. The sensitivity of these sensors was tested by periodic tactile touching as previously represented in Fig. 2(h), resulting in a variation of the capacitance up to reaching values around 13 pF. A conventional way to express this variation is by calculating the capacitance modulation, i.e. C-C_0/C_0 or also expressed as $\Delta C/C_0$. Fig. 5 also presents $\Delta C/C_0$ as a function of time in air and under touch conditions. From that figure, it can be observed that $\Delta C/C_0$ is about 54%, which demonstrates the high sensitivity of the sensors in range of pressures typically observed in tactile touching tasks [13].

The on-chip integration of graphene touch sensors and CMOS readout IC on a flexible PVC substrate, allows us to measure the response of sensors without utilizing a LCR meter. In this regard, capacitance response in the range of pF was converted into a readout voltage. Fig. 6 presents the output voltage measured in air and under touching conditions, and corresponding sensitivity. The output voltage of SF circuit exhibits a maximum difference of about 50 mV after touching. The average power consumption is 1 mW at a nominal supply voltage of 1.8 V. The sensitivity reaches around 300% during the tactile touching, which is 6 times higher than the capacitive modulation obtained before the integration of the sensors. This means, we achieved increased dynamic range of the sensors by the conversion of capacitance into a voltage.

VI. CONCLUSION

We have demonstrated a graphene based capacitive touch sensor integrated with CMOS circuitry on flexible PVC substrates. Graphene's excellent mechanical flexibility and electrical conductivity combined with CMOS readout electronics yielded high sensitivity. The heterogeneous integration of graphene to Si based conventional electronics on same flexible substrate will open new avenues for a wide range of applications including wearable electronics and interactive *e*-skin. As future work, we will explore developing the circuits with a transimpedance amplifier and ADC on ultra-thin chips to facilitate the frontend of the acquired data.

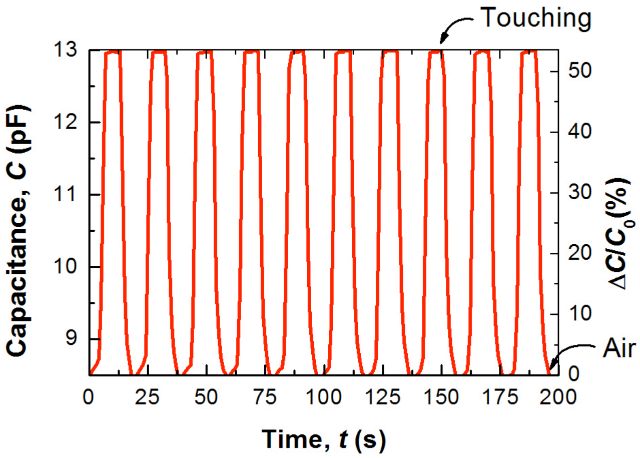

Fig. 5. Capacitance and $\Delta C/C_0$ measured overtime of a graphene touch sensor in air and under tactile touch conditions.

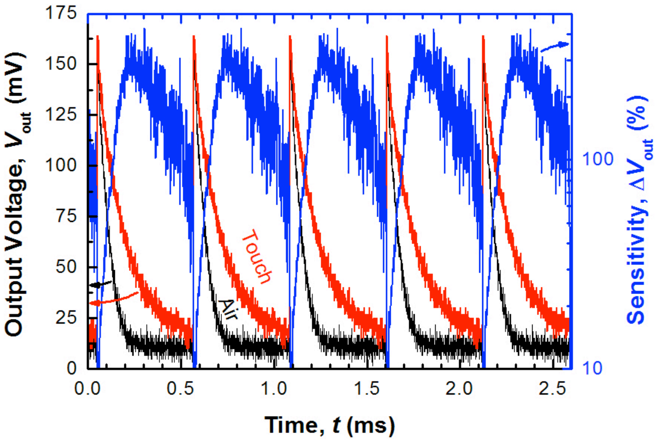

Fig. 6. Measured output voltage vs. time under air (black) and touching (red) conditions, and sensitivity (blue) of graphene based touch sensors.

ACKNOWLEDGEMENT

This work supported by the Engineering and Physical Sciences Research Council (EPSRC) Engineering Fellowship for Growth (EP/M002527/1) and EPSRC First Grant (EP/M002519/1). We are also thankful from James Watt Nanofabrication Centre (JWNC) and Glasgow Electronics Design Centre for their support in terms of fabrication and device design and characterization.

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