NFC-Enabled, Tattoo-Like Stretchable Biosensor Manufactured by "Cut-and-Paste" Method

Hyoyoung Jeong, *Student Member*, *IEEE*, Taewoo Ha, Irene Kuang, Linxiao Shen, Zhaohe Dai, Nan Sun, *Senior Member, IEEE*, and Nanshu Lu

***Abstract*— The wearables industry is lacking in devices that have the ability to provide valuable biometrics data in a soft, wireless and disposable system. Such a system should be high performance, multifunctional, but battery-free and low cost. Near field communication (NFC) is a wireless communication protocol built in many smartphones nowadays that can read data from battery-free passive tags. As a result, NFC-enabled wearable biosensors have been reported, but they are either unstretchable or have to be manufactured by labor- and time-intensive photolithography and transfer-printing processes. Using a dry and freeform "cut-and-paste" method, we have built a wireless and low-cost stretchable biosensor that integrates temperature sensor, light source/sensor, NFC chip, and antenna. It is battery-free and can be laminated on any part of human skin like a temporary transfer tattoo. The sensor can fully follow the stretching and compression of skin without mechanical failure or delamination. Thus, it is imperceptible to wear and can perform high-fidelity sensing. Potential applications include, but are not limited to, skin thermography and photometry.**

I. Introduction

Limitations of functionality, form factor, and high power consumption are three major roadblocks of the wearables industry. Wearable devices were once anticipated as a solution to many healthcare challenges by providing continuous tracking of clinically-valuable biometrics and real-time analytics. However, after over a decade of development and large sum of investments, today's commercial wearables are still largely taking the form of a wristband. Only limited physiological signals can be measured on the wrist and motion artifacts can be severe when the wristband slides against the skin. Overall, there is a lack of valuable biometrics that can be monitored naturally but accurately to make wearable devices useful for clinical or fitness training applications.

Ultrathin and ultrasoft epidermal biosensors have demonstrated unprecedented sensing fidelity and multifunctionality [1]. They can be laminated on any part of

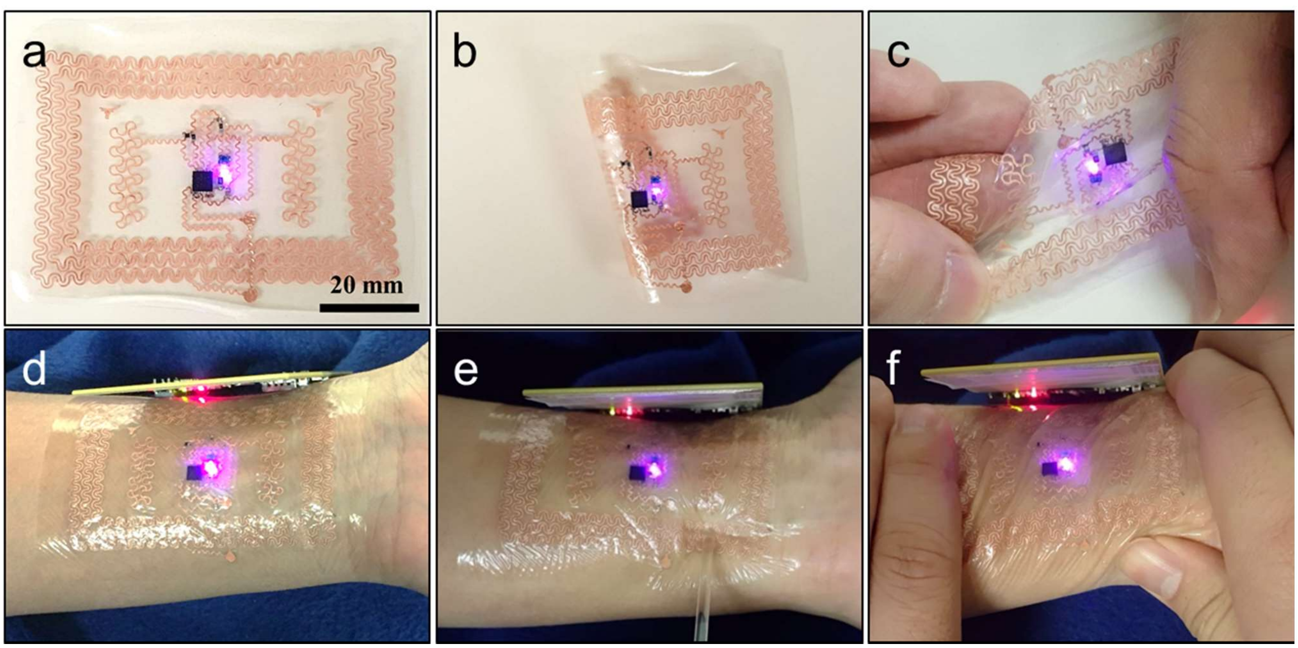

Figure 1. NFC-enabled stretchable E-tattoo. Wirelessly powered LED lights under different kinds of deformation. (a) Undeformed (b) Folded (c) Twisted (d) Undeformed on skin (e) Poked by a glass rod on skin (f) Twisted on skin.

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H. Jeong, T. Ha, L Shen, and N. Sun are with the Department of Electrical and Computer Engineering at the University of Texas at Austin, Austin, TX 78712, USA.

I. Kuang is with the Department of Biomedical Engineering at the University of Texas at Austin. Austin, TX 78712, USA.

Z. Dai is with the Department of Aerospace Engineering & Engineering Mechanics at the University of Texas at Austin. Austin, TX 78712, USA.

N. Lu is with the Department of Aerospace Engineering & Engineering Mechanics, Center for Mechanics of Solid, Structures and Materials, Texas Material Institute, and Department of Biomedical Engineering at the University of Texas at Austin, Austin, TX 78712, USA.

(Nanshu Lu is the corresponding author to provide phone: 512-471-4208; e-mail: nanshulu@utexas.edu).

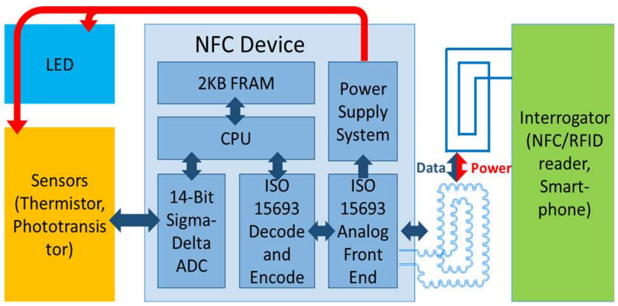

Figure 2. Block diagram of the system.

human skin like a temporary transfer tattoo and can fully conform to the microscopic morphology of human skin, which yields low electrode-skin interface impedance and enables high signal-to-noise ratio (SNR) [2]. When skin deforms, the sensor can closely follow skin deformation without sliding or detachment, which enables accurate measurement of skin deformation and significantly suppresses motion artifacts [2]. Attributing to their unique advantages, tattoo-like biosensors have been widely developed for electrophysiological [1], mechanical [3], thermal [4], optical [5], as well as electrochemical [6][7] sensing on human skin.

Another challenge of wearables lies in the high power consumption for wireless communication. Bluetooth low energy (BLE), the predominant wireless technology for wearables, is responsible for up to 98% of total power consumed [8]. Wireless powering through inductive antennas is a clear solution to this challenge. Thanks to the booming Internet of Things (IoT), commercial ultra-low power near field communication (NFC) chips that can wirelessly transmit power and data are now available. Hence integrating NFC chip and antenna on E-tattoos can enable wireless biometric sensing without having any battery on the tattoo. In fact, NFC-enabled epidermal sensors have been demonstrated [5]. But its fabrication relies on labor- and time-intensive photolithography and transfer-printing process.

Applying a dry and freeform "cut-and-paste" method [9], we demonstrate that an NFC-enabled tattoo-like stretchable biosensor can be fabricated within minutes without using any chemicals, inks, or masks/stencils. This electronic tattoo or E-tattoo is battery-free and hence fully stretchable and conformable to human skin. It has a light emitting diode (LED) that can be wirelessly turned on and can read skin temperature and light intensity through NFC.

II. Design and Implementation

A. Device Design

As shown in Fig. 1, the NFC-enabled E-tattoo has overall dimensions of 74 mm × 50 mm and a thickness less than 100 µm (excluding chip). The copper (Cu) antenna and interconnects were designed with serpentine-shaped coils and ribbons, providing stretchability and flexibility under various kinds of skin deformation [9][10]. The LED remained on even under severe deformation.

Fig. 2 offers the block diagram of the NFC system. A serpentine-shaped Cu antenna [9] on the tattoo receives power delivered from the interrogator (e.g. a smartphone) for the operation of the NFC chip (RF430FRL152H, Texas Instruments), which has a power consumption of around 24µW in standby mode. The power supply system in the NFC chip outputs a regulated power of about 1.5 mW to drive an LED and a phototransistor (TEMT6200FX01, Vishay Semiconductors) that is able to detect backscattered or ambient light. Analog signals from the sensors such as the thermistor (NTCG164KF104F, TDK) and the phototransistor are digitized with the analog to digital converter (ADC) inside the NFC chip, and this encoded data is transmitted wirelessly to the interrogator.

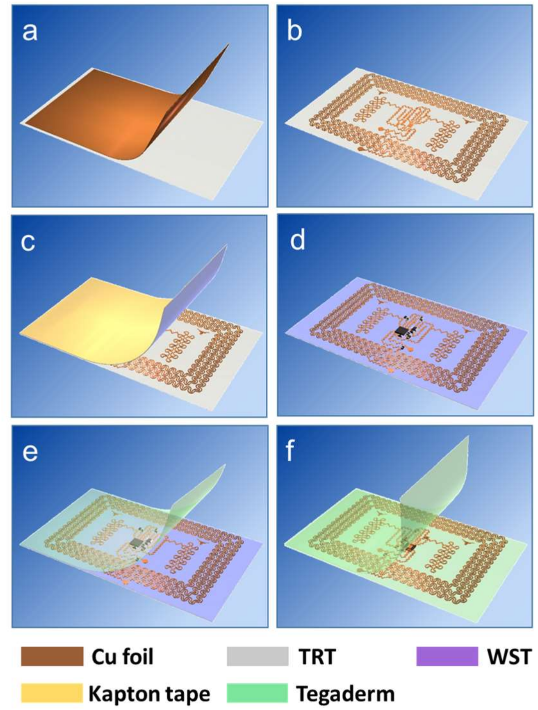

Figure 3. Schematic illustrations of the fabrication process. (a) Cu foil laminated on TRT. (b) Patterned Cu antenna and interconnects. (c) Transfer of Cu circuit onto WST backed by a Kapton tape. (d) Solder NFC chip, thermistor, LED, phototransistor, and other discrete components on the circuit. (e) Transfer to Tegaderm with WST dissolved. (f) Sandwich the circuit with another Tegaderm.

B. Antenna design and RF matching

As per NFC specification, the resonance frequency of the device should be near 13.56 MHz. Antenna inductance was calculated based on the geometric parameters of the stretchable coil: overall dimensions of 74 mm x 50 mm with 6 turns, ribbon width of 400 µm, ribbon gap of 400 µm, and ribbon thickness of 18 µm. The inductance is estimated to be around 4.5 µH [11]. The resonance frequency was measured by a network analyzer (N5225A PNA Network Analyzer, Agilent Technologies). To further tune the resonance frequency, an external capacitor was placed in parallel with the internal resonance capacitor. Skin loading induced frequency shift was noted [9] and this effect has been taken into consideration during antenna design.

C. "Cut-and-Paste" Fabrication

Our group invented a dry and freeform "cut-and-paste" process to manufacture stretchable biosensors within minutes [9]. A benchtop programmable cutter plotter allows for

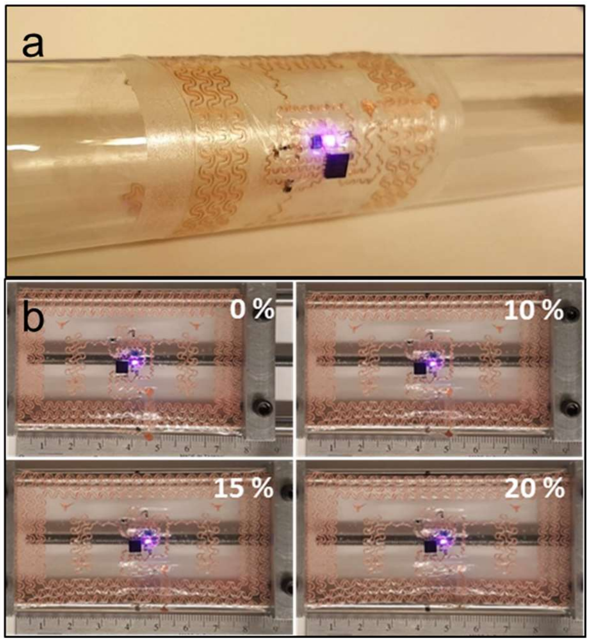

Figure 4. Flexibility and stretchability of E-tattoo: (a) Bending test with cylindrical tube. (b) Stretching test with 0%, 10%, 15%, and 20% uniaxial tension strain.

patterns or shapes to be cut out simply on a thin sheet of polymer, metal-coated polymer, or even atomic sheets such as graphene. Moreover, the "cut-and-paste" method is a fab-less process, making it more cost- and time-effective than a cleanroom process that involves photolithography patterning and chemical etching.

Building upon this process, we created an NFC-enabled E-tattoo. Fig. 3 illustrates the fabrication and transfer process. An 18-µm-thick Cu foil (ThyssenKrupp Materials) was laminated on thermal release tape (TRT) (Fig. 3(a)). A mechanical cutter plotter (Silhouette Cameo) carved the designed circuit pattern onto the Cu foil within minutes (Fig. 3(b)). After removing excess Cu foil, the Cu circuit was transferred onto a water soluble tape (WST) backed by a Kapton tape (Dupont) (Fig. 3(c)) which serves as a stable support for soldering. Solder paste (lead-free, ChipQuik, 170°C for 30 sec on hotplate) was applied to attach the NFC chip and other discrete electrical components on the Cu circuit (Fig. 3(d)). Dissolving the WST with water droplets, the whole circuit was transferred to the target substrate, water vapor permeable Tegaderm adhesive (47 µm thick, 3M^{TM}) (Fig. 3(e)). As the last step, another Tegaderm was applied from the other side as an encapsulation layer to isolate the circuit from directly touching the skin (Fig. 3(f)).

III. Results and Discussion

A. Mechanical Performance

Based on previous research regarding the mechanics of serpentines, a double-stranded serpentine design was adopted for the antenna coil to save space while maintaining stretchability and compliance [1][5][9][10][12]. As serpentines do not add much stiffness, the modulus of the E-tattoo will be dominated by that of Tegaderm (7.4 MPa), which is close to that of human skin (0.32 – 4 MPa) [10]. The E-tattoo may therefore laminate on epidermis like an imperceptible

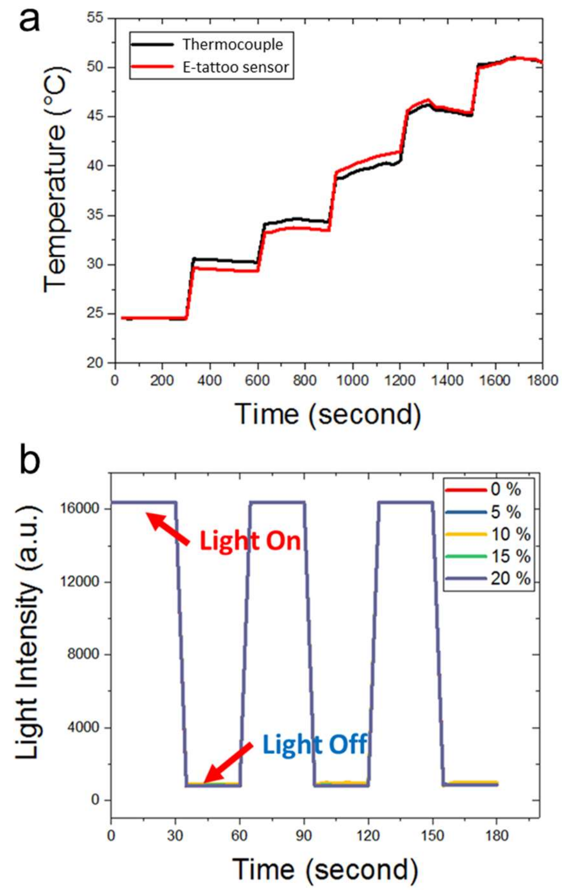

Figure 5. Wirelessly transferred temperature and light data from the E-tattoo. (a) Temperature measurements using an external reference thermocouple signal and a calculated value of a thermistor signal on the E-tattoo sensor. (b) Light intensity measurements associated with 0%, 5%, 10%, 15%, 20% uniaxial deformation of the device.

secondary skin without constraining the natural skin deformation.

Fig. 4(a) and 4(b) demonstrate the flexibility and stretchability tests on the E-tattoo sensor. Even after fully wrapping the E-tattoo around a 14 mm radius cylindrical tube or stretching it up to 20% (the "ouch" limit of human skin), the LED remained on, indicating that the antenna and the interconnects are insensitive to mechanical deformation.

B. Electrical Performance

The E-tattoo sensor is battery-free and powered entirely by the inductive coupling with the NFC reader (e.g. smartphone) within a distance of 3 cm. The E-tattoo is composed of mainly three parts: 1) a stretchable antenna coil, 2) an NFC chip which includes wireless communication module (ISO 15693), analog to digital converter (ADC) (14 bit Sigma-Delta), power supply for battery-free system, low-voltage microcontroller, and a nonvolatile low-power Ferroelectric Random Access (FRAM) memory (2KB), and 3) sensors (thermistor, phototransistor) and LED. Data measured by the sensors is stored into the FRAM memory in the order it is sampled. After terminating the sampling and ADC process, data is transferred from the memory to the interrogator through the antenna coil. Since the output format for the temperature and light sensor is defined in a 16-bit format, the E-tattoo sensor has the capacity to store

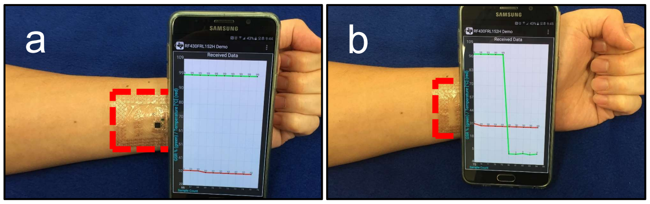

Figure 6. NFC-enabled smart-phone reads out from the E-tattoo on human wrist. Red curve indicates skin temperature and green curve shows ambient light. (a) Phototransistor is unblocked. (b) Phototransistor is blocked by the smartphone.

data over the course of nearly 10000 s under a 0.1 Hz sampling rate.

When the thermistor sampling is activated, approximately 2.4 μA current is emitted on the thermistor as well as the reference resistor. To verify the temperature sensing performance of the E-tattoo sensor, it was placed on a hot plate alongside a reference device (TMD-56 thermocouple, Amprobe). Then, the E-tattoo sensor was operated and the data was collected wirelessly with an adjacent NFC interrogator (sampling rate: 1 point/30 s, TRF7970A EVM, Texas Instruments). Fig. 5(a) shows experimental results of data collected at 6 temperature levels with a 5 °C increment. It is presented that the measured temperature from the E-tattoo sensor strongly parallels the measured temperature from the reference. Discrepancy between the data from the E-tattoo sensor and reference thermocouple (maximum 0.99°C) can be improved with further calibration by calculating the precise coefficients for the thermocouple [10].

The phototransistor is directly connected to the ADC pin on the NFC chip that allows for the 14-bit ADC. Hence, the measured light signal via phototransistor is digitized along the range of 0 to 2^{14}. Fig. 5(b) shows the light intensity (arbitrary unit) as a function of time associated with different uniaxial tension strain condition under the equal setting in Fig. 4(b) (0%, 5%, 10%, 15%, 20 %, respectively). Then, the light intensity data was acquired wirelessly (every 10 s) for the switching condition (every 30 s) of exposure to and blocked light. The observed discrepancy between measured data in 0 % and 20 % stretching condition is only 0.32%. Thus, as discussed in the mechanical performance section, the E-tattoo sensor is able to maintain full electrical function, even under 20% stretching deformation condition.

IV. Applications

The NFC-enabled E-tattoo sensor has direct and simple applications to skin thermography and photometry. For example, the E-tattoo can be mounted on wrist skin as shown in Fig. 6(a), and real time skin temperature and ambient light can be read wirelessly by an NFC-enabled smartphone. Skin temperature is displayed as the red curve and ambient light intensity is green. When the smartphone blocks the phototransistor on the E-tattoo (Fig. 6(b)), the green curve dropped radically, while the red one (skin temperature) remained constant.

V. Conclusion

The device design and fabrication method presented here grants new value to NFC technology with regards to its mechanical robustness and versatility in biometric wearables applications. More research will be conducted to expand its capabilities in sensing, sampling rate, and communication distance. Such tattoo-like form factor of biosensors will have a significant impact on mobile healthcare, allowing for more affordable, dependable, and unobstructed biosignal monitoring compared with current expensive and confining systems. We also expect that the invention of NFC-enabled E-tattoo will eventually contribute to the widespread solution of the IoT industry.

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