Wearable Interdigitated Capacitive Sensor with Flexible Analog Front End for Superficial Skin Hydration Measurements

Alexandar R. Todorov*, Huanghao Dai*, Russel N. Torah*, Michael R. Ardern-Jones†, Stephen P. Beeby*
*School of Electronics and Computer Science, University of Southampton, Southampton, United Kingdom
†School of Clinical and Experimental Science, University of Southampton, Southampton, United Kingdom
Email: a.todorov@soton.ac.uk

***Abstract*—Wearable sensors and e-textiles have had an impact on many fields of healthcare, including dermatology. Superficial skin hydration is a biomarker for conditions like atopic dermatitis (AD), yet most hydration sensors are not optimised for measurement in the outermost layer of the skin - the stratum corneum (SC). In this paper, the authors present an interdigitated capacitor (IDC), tailored specifically for monitoring the shallow SC layer. The sensor is printed onto a wearable textile strap and is complemented by a custom flexible analog front end (AFE) to allow for continuous monitoring of the SC. The IDC is tested on volunteers, and the results reveal a 7% change in capacitance between skin with dry SC layer and skin with hydrated SC layer. The sensor can also be used to monitor treatments and shows that a particular commercial cream's effect wears off after 2.5 hours. The e-textile IDC can also survive a standard ISO wash test with limited electrical defects.**

Keywords—interdigitated capacitor, e-textile sensor, skin hydration, reverse offset printing, flexible electronics

I. Introduction

Wearable sensors are a rapidly growing sector in the IoT industry, allowing accurate health and activity tracking while offering seamless integration [1]. This has revolutionized personal health monitoring by enabling continuous, non-invasive tracking of physiological parameters. The technology has seen adoption in many applications, including electrocardiogram (ECG) and heart monitoring, respiratory measurement, gait analysis, and biomarker detection [2-5]. Wearable skin hydration sensors have gained attention due to their continuous data collection functionality and minimally invasive form-factor suitable for dermatological studies. The hydration of the skin is one of many skin biomarkers, which, when monitored continuously, produces insight into symptoms and pathogenesis of skin diseases. The skin has a complex, multilayered structure, and the properties and hydration of each of these layers are not constant throughout. Varying levels of hydration of individual layers can be indicators of different skin conditions, and thus, separation of the hydration measurements in these layers is important for correct diagnosis [6]. Skin hydration is commonly measured in the literature using an interdigitated capacitive sensor which detects changes in the water content of the material under test [7]. In most of those works, the skin is treated as a single unified layer, which does not produce clinical significance to distinguishing skin conditions empirically. Here, the authors use an optimized sensor solution for measuring hydration in the outermost skin layer - the SC.

The SC serves as the primary barrier against environmental influences, such as allergens or bacteria, and plays a crucial role in preventing excessive water loss. Dysfunction of this barrier is a key characteristic of dermatological conditions such as atopic dermatitis (AD) and psoriasis [8]. In AD, this results in a specific dehydration of the SC layer, and therefore measuring the SC hydration is of clinical significance when diagnosing AD [9]. Commercial hydration devices are used for this purpose - the Corneometer® (Courage+Khazaka GmbH, Cologne, Germany) and the MoistureMeterSC® (Delfin Technologies Ltd., Kuopio, Finland). These devices can only capture single-point measurements at discrete instances in time, cannot perform continuous monitoring and can only be used in a clinical setting.

In a previous publication the authors introduced a sensor for monitoring SC hydration using an IDC with a bespoke pattern, optimized for screening within the SC [10]. The IDC was fabricated onto a flexible, printable format to allow for continuous measurements, providing a new dimension of data beyond what the current commercial solutions are capable. This work presents the flexible sensor printed onto an e-textile strap and tested on healthy volunteers, whose skin is artificially hydrated using emollient cream that strengthens the SC barrier. A flexible analog front end (AFE) was designed to complement the e-textile sensor and convert the capacitance to digital values. A wash test on the durability of the e-textile IDC wearable sensor was also performed.

II. Materials and Methods

A. IDC and Operation

The IDC consists of interwoven, comb-like electrodes. It operates like a scatter-field capacitor: changes in capacitance result from the dielectric properties of the surrounding medium. The IDC presented in this paper achieves an electric field penetration within the SC and thus high sensitivity to dielectric changes in that layer. If the SC barrier is damaged, the layer will have a lower water concentration, leading to a reduced relative permittivity. This decrease in permittivity corresponds to lower capacitance readings. The IDC presented here features 32 electrodes of width 100 µm and length 6 mm, separated by gaps of 100 µm, for a total sensing area of 0.384 cm^2.

B. Wearable IDC Sensor Fabrication

Reverse offset printing was used to deposit the custom IDC pattern onto a TPU transfer film, following a technique developed by Dai et al. [11]. This process involved coating a

This research was supported by EPSRC grant EP/T517859/1. The work of Stephen P Beeby was supported by the Royal Academy of Engineering under the Chairs in Emerging Technologies Scheme.

roller with Dupont 5000 silver conductor paste (Dupont, Bristol, UK) using a slot-die coater. The coated roller then came in contact with a cliché featuring the negative image of the desired print. Due to the high surface energy, unnecessary parts of the ink were removed, and just the desired pattern remained on the roller. Then, the pattern was deposited on the thermoplastic polyurethane (TPU) substrate [11]. The substrate used was Electrum Stretch HC, with a thickness of 80 µm (Policrom Screens S.p.A., Carvico, Italy).

The deposited ink was cured at 120°C for 15 minutes in a Carbolite box oven. The completed print was then laminated onto the skin-facing side of a textile elbow strap (Ionocore, UK) using a hot press at 160°C for one minute. This strap was chosen due to its cushioned inner layer, which ensures consistent pressure against the skin. Pressure is important as it enhances sensor-to-skin contact while reducing air gaps. To provide electrical insulation and improve conformal adhesion, the IDC electrodes were encapsulated with an additional TPU film layer – 50 µm thick Platilon U073 TPU film (Covestro Ltd., Cheadle Hulme, UK). The thickness of the encapsulation layer allows penetration of the electric field at the depth of the SC as shown in a previous publication [12]. Fig. 1(a) shows the finished e-textile IDC sensor.

C. *Flexible Analog Front End and Data Collection*

To convert the capacitance readings into digital values, a custom AFE using the FDC2214 integrated circuit (IC) by Texas Instruments was used. The FDC2214 features 4 channels with high 28-bit resolution and around 0.3 mA power consumption per channel at 3.3 V and 1 MHz resonance frequency operation. The scalability and low consumption of this IC make it a perfect fit for wearable and continuous monitoring applications. The FDC2214 operates by driving and measuring the resonance frequency of an external LC tank (set by the user) [13]. When an unknown capacitance is added, the resonance frequency shifts. One channel was used with an LC tank of 470 µH and 47 pF, resonating at 1 MHz. In a previous work the authors proved that this excitation frequency produces the greatest change in capacitance per change in the dielectric properties of the SC [6].

A custom flexible circuit was designed in Kicad® 7.0, following the design specifications outlined in the FDC2214 datasheet. The circuit featured all the necessary passive and active components to power and transmit data to/from the FDC2214 IC through I2C bus lines. The circuit was etched from a copper-polyimide laminate sheet (GTS Flexible Materials Ltd., Gwent, United Kingdom) [14, 15]. The flexible circuit was fixed to an adhesive Velcro pad, for easy assembly on the e-textile IDC sensor.

To collect the readings from the FDC2214, the EVM development board with the MSP430 MCU was connected to the flexible AFE board via power and I2C lines. The EVM board comes with a custom EVM GUI that can visualize the capacitance data [16]. Fig. 1(b) presents the finished device with the AFE attached, worn by a volunteer.

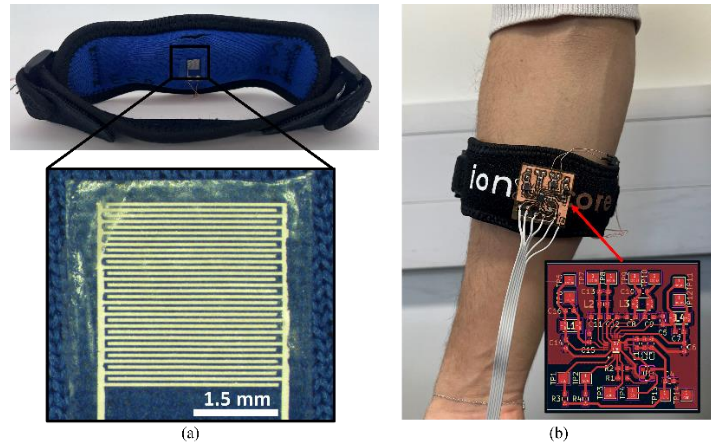

Fig. 1. (a) Photograph of the wearable e-textile IDC sensor with a zoomed-in micrograph of the IDC pattern printed on the strap band; (b) Photograph of the e-textile IDC sensor with flexible AFE, on a volunteer's forearm. An inset of the PCB schematic capture of the AFE is presented from Kicad® Software.

D. *SC Hydration Test Experimental Setup*

Three healthy volunteer adults, both male and female, were selected and the e-textile IDC sensor was positioned on their right volar forearm (Fig. 1(b)). The sensor sampled capacitance data continuously for 30 seconds before being removed, then Exomega Control commercial emollient cream for eczema-prone skin is applied onto the measured area (A-Derma, Lavaur, France). The cream strengthens the SC barrier, and its application increases the SC hydration. Fifteen minutes after applications the test was repeated. Three tests per volunteer were conducted and the results were averaged out.

A cream effectiveness monitoring test was performed on a fourth healthy adult volunteer also on the right volar forearm. IDC sensor readings were taken right before and after the cream application and then at every 15 minutes up to 3 hours.

E. *Washing Durability Test Experimental Setup*

A domestic washing machine (Beko WME7247W) was used to conduct wash tests following the ISO:6300:200 washing standard. The parameters were setup as follows: 40°C, 1000 rpm, 1 h, 2 kg loading. The flexible AFE pad was removed before washing, and the e-textile IDC sensor was placed in a plastic wash ball. Fairy® non-biological detergent was used.

III. RESULTS AND DISCUSSION

A. *Varying SC Hydration in Volunteers*

In all volunteer tests, the e-textile IDC sensor successfully measured the change in SC hydration arising from the improvement of SC barrier properties. Fig. 2 presents the results of the experimental study. The emollient cream contains ceramides which maintain the structure of the lipid matrix, of which the SC barrier is made [5]. With an improved barrier, the SC layer is losing less water through evaporation and therefore it is more hydrated. The average capacitance for dry skin across all volunteers is 34.86 pF, and the average capacitance for hydrated skin is 37.56 pF, revealing a difference of approximately 2.7 pF.

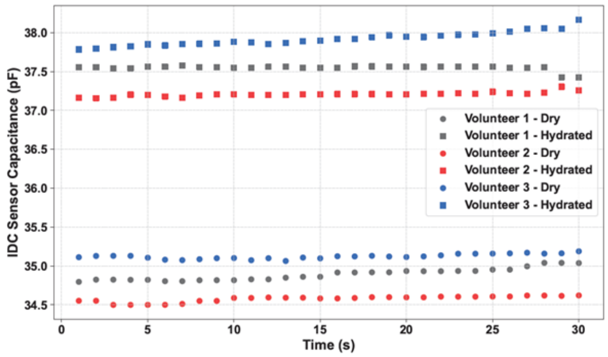

Fig. 2. IDC capacitance against time for varying SC hydration states of 3 healthy volunteers. Volunteers are colour-coded.

In a separate test, the SC hydration of another healthy volunteer was monitored for 3 hours, to determine the time course effectiveness of the commercial emollient cream. The readings, presented in Fig. 3, are in the same range as with the other volunteers, confirming the validity of testing. The IDC capacitance jumps from 33.8 pF to 38.25 pF immediately after cream application and then slowly decreases back to the 34 pF range within 3 hours.

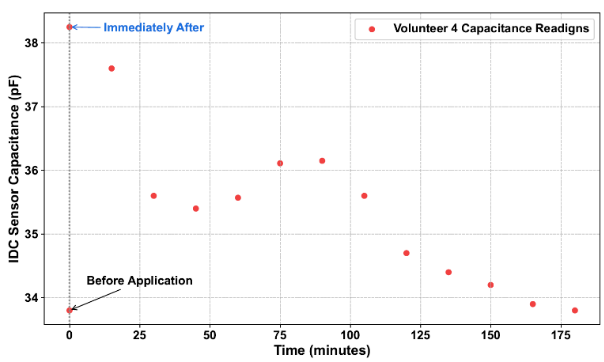

Fig. 3. Time-course IDC capacitance readings for healthy volunteer before and after the application of emollient cream. The application event is marked with a grey dashed line at time = 0 and the readings corresponding to before and after the event are labelled.

This means that this particular emollient should be applied every 2 hours for maximum protection of the SC layer. A spike in capacitance is observed around 1.5 hours into the study, where the capacitance readings reach from 35.57 pF to 36.1 pF and then decay back to 35.6 pF. This is not caused due to a change of the environment, as the volunteer was kept stationary in the same room with RH of 40%. Therefore, this is attributed to absorption of the ceramides into the lipid matrix, increasing the SC barrier properties.

B. *E-textile IDC Sensor Washing Durability*

After machine washing, the printed IDC e-textile sensor was inspected and photographed using a microscope. Almost no visual damages were noticed. The lamination of both the IDC and the encapsulation layer remained intact, without any peeling on the edges. The soldered pads were also unaffected due to the strong encapsulation. Fig. 4 presents a micrograph of the only observed defect on the surface of the IDC - a stain on one of the electrode fingers, but it has not disconnected the electrode. DC continuity tests reveal no short circuit of the electrodes. Frequency sweeps with an impedance analyzer reveal a variation in the properties of the IDC, as immediately after the washing the IDC exhibits resistive behaviour, rather than capacitive. Fig. 5 shows plots of complex impedance and phase angle against frequency of the IDC e-textile before the washing durability test and at several instances after the test. The resistive component is observed when the phase angle becomes close to 0, and the impedance does not change with frequency. This behaviour slowly disappears with time, and capacitive properties replace it. It is reasoned that water molecules penetrated micropores in the encapsulation and provided a conductive path in parallel to the capacitive path. As time passes, the water molecules dry out, thereby conductance reduces while resistance increases, and thus capacitive properties re-emerge.

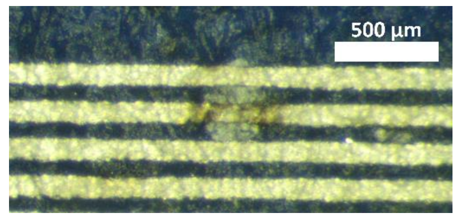

Fig. 4. Micrograph of a visible smudge after the wash test. The silver electrode is still connected, so no breakages are noted.

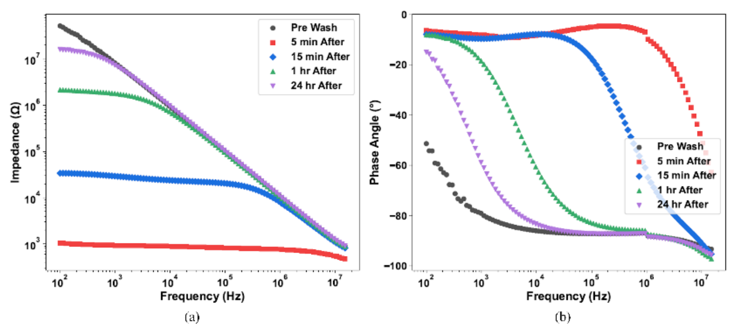

Fig. 5. (a) Complex impedance and (b) phase angle plots against frequency before and at different time intervals after wash test of e-textile IDC sensor.

IV. Conclusion

In this paper the authors have presented a wearable e-textile sensor capable of detecting changing levels of SC hydration, an indicator for issues with the SC barrier, responsible for protecting the skin against desiccation. The IDC sensor was printed with a high resolution onto a textile strap and a custom flexible AFE was created to digitize the capacitance readings. The e-textile device was successfully tested on healthy volunteers, whose SC was artificially hydrated using treatment creams for strengthening SC barrier in patients. The results show that e-textile IDC sensor can distinguish between two levels of SC hydration with a difference between them of 2.7 pF or 7% of sensor capacitance. The sensor is also capable of monitoring treatment in patients with SC hydration issues, as it detects when the effect of the cream has worn off. Future work will involve testing the IDC sensor on patients with severe SC dehydration and measuring the effect of various treatments on their condition.

References

[1] S. C. Mukhopadhyay, "Wearable Sensors for Human Activity Monitoring: A Review," IEEE Sensors Journal, vol. 15, no. 3, pp. 1321-1330, 2015, doi: 10.1109/jsen.2014.2370945.

[2] E. Spano, S. Di Pascoli, and G. Iannaccone, "Low-Power Wearable ECG Monitoring System for Multiple-Patient Remote Monitoring," IEEE Sensors Journal, vol. 16, no. 13, pp. 5452-5462, 2016, doi: 10.1109/jsen.2016.2564995.

[3] M. M. Rodgers, V. M. Pai, and R. S. Conroy, "Recent Advances in Wearable Sensors for Health Monitoring," IEEE Sensors Journal, vol. 15, no. 6, pp. 3119-3126, 2015, doi: 10.1109/jsen.2014.2357257.

[4] M. Wagih, O. Malik, A. S. Weddell, and S. Beeby, "E-Textile Breathing Sensor Using Fully Textile Wearable Antennas," Engineering Proceedings 2022, Vol. 15, Page 9, vol. 15, no. 1, pp. 9-9, 2022/3// 2022, doi: 10.3390/ENGPROC2022015009.

[5] A. R. Todorov, R. N. Torah, M. R. Ardern-Jones, and S. P. Beeby, "Electromagnetic Sensing Techniques for Monitoring Atopic Dermatitis—Current Practices and Possible Advancements: A Review," Sensors, vol. 23, no. 8, p. 3935, 2023, doi: 10.3390/s23083935.

[6] A. R. Todorov, K. Goyal, R. N. Torah, T. Greig, M. R. Ardern-Jones, and S. P. Beeby, "Skin Model for Monitoring Atopic Dermatitis Using Interdigitated Capacitive Sensor," 2024: IEEE, pp. 1-4, doi: 10.1109/embc53108.2024.10782789.

[7] A. R. Todorov, R. Torah, M. Ardern-Jones, and S. Beeby, "Fabrication of a Screen-Printed E-Textile Interdigitated Capacitive Sensor for Measuring Stratum Corneum Hydration," in E-textiles 2023, 2024 2023: MDPI, doi: 10.3390/engproc2023052001.

[8] Y. Khan, A. Todorov, R. Torah, S. Beeby, and M. R. Ardern-Jones, "Skin Sensing and Wearable Technology as Tools to Measure Atopic Dermatitis Severity," *Skin Health and Disease*, vol. 4, no. 5, 2024, doi: 10.1002/ski2.449.

[9] E. E. A. Brenninkmeijer, M. E. Schram, M. M. G. Leeflang, J. D. Bos, and P. I. Spuls, "Diagnostic criteria for atopic dermatitis: a systematic review," British Journal of Dermatology, vol. 158, no. 4, pp. 754-765, 2008/4// 2008, doi: 10.1111/J.1365-2133.2007.08412.X.

[10] A. R. Todorov et al., "Design of a Flexible, Wearable Interdigitated Capacitive Sensor for Monitoring Biomarkers of Atopic Dermatitis," IEEE Sensors Journal, pp. 1-1, 2023, doi: 10.1109/jsen.2023.3342992.

[11] H. Dai, R. Torah, and S. Beeby, "Reverse-Offset Printing for Fabricating E-Textiles," 2024: MDPI, doi: 10.3390/engproc2023052014. [Online]. Available: https://dx.doi.org/10.3390/engproc2023052014.

[12] H. Dai, A. R. Todorov, S. Yong, R. Torah, M. Ardern-Jones, and S. Beeby, "High Resolution Reverse-Offset Printed Wearable Textile Capacitive Sensor for Continuous Monitoring of Atopic Dermatitis," Springer Science and Business Media LLC, 2024.

[13] Texas Instruments, "FDC2214: 28-bit, 4-channel capacitance-to-digital converter datasheet," Texas Instruments, SLDS208C, 2017. [Online]. Available: https://www.ti.com/lit/ds/symlink/fdc2214.pdf.

[14] GTS Flexible Materials Ltd., "GTS 7800 - Copper Polyimide Laminates, GTS Ultraflex Datasheet," ed, 1999.

[15] A. Komolafe et al., "Integrating Flexible Filament Circuits for E‐Textile Applications," Advanced Materials Technologies, vol. 4, no. 7, p. 1900176, 2019, doi: 10.1002/admt.201900176.

[16] Texas Instruments, "FDC2114 and FDC2214 EVM User’s Guide," Texas Instruments, SNOU138A, 2015. [Online]. Available: https://www.ti.com/lit/ug/snou138a/snou138a.pdf?ts=1740871626831.