V_2O_5 nanowires coated yarn based temperature sensor with wireless data transfer for smart textiles

Gaurav Khandelwal[1], Abhishek Singh Dahiya[1], Ajay Beniwal[1] and Ravinder Dahiya[2]*, *Fellow, IEEE*

***Abstract*—Smart textile with capabilities to sense different stimuli like temperature, pressure etc. are of considerable interest in applications such as sports, fashion, healthcare and robotics etc. The seamless integration of various sensors is desired for effective use of smart textiles in these applications. To this end, here, we present a yarn based wireless temperature sensor developed by modifying a P(VDF-TrFE) coated stainless steel yarn with vanadium pentoxide (V_2O_5) nanowires (NWs). The current-voltage (I-V) characteristics and the temperature sensing performance of the devices are evaluated between 5-50°C with a step increase of 5°C. The unpacked device exhibits a sensitivity of 3.7 %/°C with a response time of 9s. The device is encapsulated with nanosilica/epoxy polymeric layer and its influence on sensors performance is also analyzed. After encapsulation, the device showed more linear response, but with slightly reduced sensitivity of 2.18 %/°C. Moreover, the effect of mechanical bending cycles on sensing performance of packaged device is studied. The sensor showed linear response even after 2000 bending cycles, but sensitivity was reduced to 1.257%/°C. Finally, the temperature sensor data is wirelessly transferred to demonstrate the potential use of developed sensors in above applications.**

***Index Terms*— Fiber electronics, nanowires, smart textile, temperature sensor, vanadium pentoxide, yarn sensor.**

I. INTRODUCTION

THE interactive textiles with soft electronic devices in fabric or textile form factor (generally termed as ‘e-textiles’) are being explored to capture opportunities in several emerging applications such as internet of things (IoT), digital health monitoring, fashion industry etc. [1-5]. For example, smart textiles with sensing and therapeutic capabilities could sense vital health parameters such as temperature, blood pressure, heartbeat, and breath rate etc. and could help develop novel approaches for personalized digital healthcare [6-13]. The above applications require textiles to have different sensory functionalities without sacrificing wearer’s comfort and normal working.

The smart or e-textiles today uses thin film based devices or off-the-shelf sensors attached to the fabrics [14]. However, the integration of such sensors in yarns is either not possible (e.g., industrial textile techniques like braiding, knitting and weaving etc. are not compatible) or involves a complex process at the risk of damaging the yarn. Further, these sensors have limited flexibility, poor aesthetics and they cannot adjust with the biomechanical motions, eventually leading to discomfort for the wearer. Such challenges can be overcome through textile-printing technique i.e., direct printing of functional materials on the textile substrates [10, 15, 16]. Whilst this is better than stitching off-the-shelf stiff components, this approach is still a step away from a seamless integration of functionalities and the type of printed devices are limited by availability of functional inks that are difficult to re-use and wash. In this regard, the fiber-coating technique to coat functional materials on the pre-fabricated fibers offers better solutions and hence fiber-based wearable devices have been reported for various functionalities [17-20]. However, use of fibers for the development of sensor could damage the surface structures during weaving or knitting leading to a poor sensor response. In this regard, yarn composed of interlocked fibers can be a better starting point to design sensors for smart or e-textiles. Yarn can undergo weaving, knitting or braiding while offering low complexity, ease of modification and integration [17]. Thus, compared to fibers, the yarns offer lower complexity. The advances in nanomaterials, and surface functionalization methods also provide opportunity to develop yarns with unique properties to sense different parameters such as humidity, temperature, strain and light etc. [21, 22].

In this work, we present a flexible yarn-based temperature sensor developed by modifying a P(VDF-TrFE) coated stainless steel yarn with vanadium pentoxide (V_2O_5) nanowires (NWs). Such yarn-based temperature sensors are useful for unobtrusive monitoring of body temperature, which is vital for detection of fever, infection, diabetic foot ulcers and other conditions such as homeostasis etc. [23-27]. The flexibility of yarn-based temperature sensor allows conformal contact with non-planar surface of skin and hence could improve the reliability of measured data and the response and recovery times. The work presented in this paper extends our preliminary results presented at IEEE International Conference on Flexible

This work was supported by the Engineering and Physical Sciences Research Council through NextGenT-TENG Standard Grant (EP/V003380/1).
(*Corresponding author*: Ravinder Dahiya).
G. Khandelwal, A. S. Dahiya, A. Beniwal are with the James Watt School of Engineering, University of Glasgow, Glasgow G12 8QQ, U.K.
R. Dahiya is with Bendable Electronics and Sustainable Technologies (BEST) Group, ECE Department, Northeastern University, Boston, MA 02115, USA. This work in this paper was initiated by R. Dahiya’s Bendable Electronics and Sensing Technologies (BEST) Group when he was at University of Glasgow, UK. The work got completed after he moved to Northeastern University, USA, where his group is known as Bendable Electronics and Sustainable Technologies (BEST) Group (email – r.dahiya@northeastern.edu)
An earlier version of this paper was presented at 2022 IEEE International Conference on Flexible and Printable Sensors and Systems (FLEPS) (DOI: 10.1109/FLEPS53764.2022.9781506).

and Printable Sensors and Systems (FLEPS) 2022 [28]. The preliminary results describe the sensors fabrication by controlled adherence of high density V_2O_5 nanowires on modified stainless-steel (SS) yarn. The sensor exhibited an excellent sensitivity of 3.7 %/°C in the temperature range of 5-50°C with a response time of 9s. We extend our previous work by studying the structural and morphological properties of the sensing material, influence of packaging and bending on the sensor performance. Finally, we also demonstrate wireless temperature sensing using the SoC based Wi-Fi module in this extension.

This paper is organized as follows: Section II presents state-of-the-art of flexible and yarn-based temperature sensors. Section III describes the experimental procedures, device fabrication and characterisation techniques. Section IV presents the detailed discussion on the results of the study. Section V summarizes the key outcomes of the study.

II. State-of-the-art

Textile based temperature sensors uses non-fibrous materials, conductive fibers, carbon-based fibers and temperature sensitive fiber. However, yarns are not explored much for temperature sensors [29]. These include, the yarn-based temperature sensors designed by integrating a thin film flexible sensor within a textile yarn [24]. For thin film-based temperature sensor, different organic, inorganic, metallic, hybrid materials and their composites including carbon nanotube (CNT), Nickel (Ni), graphene and PEDOT: PSS etc. have been explored [30-34]. The metallic materials are expensive and composites exhibits large hysteresis and high response time. Further, the latter suffer from issues such as difficulties in getting stable dispersion formation. Embedding such flexible sensors in yarn restricts their direct contact with the measurement surface, thus leading to high response and recovery time due to thermal resistance and restricted flow of heat [24]. In this regard, the one-dimensional (1-D) semiconducting materials like vanadium pentoxide (V_2O_5) NWs offer better alternative for temperature sensing. Their attractive properties include high crystallinity, high surface area to volume ratio, ease of synthesis and small activation energy [35-37]. The modification of yarn with such heat sensitive material is an enticing approach with no trade-off between flexibility and performance of the temperature sensor.

III. Experimental section

A. Materials

The hundreds of micrometres long V_2O_5 NWs, with 50-80 nm diameter, were purchased from Novarials corporation. Polyvinylidene fluoride trifluoroethylene P(VDF-TrFE), Piezotech FC30 was purchased from Arkema group. SS yarn was purchased from Pimoroni Ltd.

B. Fabrication of V_2O_5 NW network on SS yarn

The mechanical stability and durability of the SS yarn was enhanced by coating a thin layer of P(VDF-TrFE). The 0.5 wt.% of V_2O_5 NWs were dispersed in deionized (DI) water. The P(VDF-TrFE) coated SS yarn was placed vertically in beaker containing the NW dispersion. Then the V_2O_5 NW network was allowed to form on the yarn by slow and controlled evaporation of water at 70 °C. The V_2O_5 NW network was formed on the yarn by Van der Waals interactions. The unattached NWs were removed by washing the yarn with DI water. Finally, for device measurement, two copper wires were attached on the yarn (using silver epoxy paste) to form a channel of 1.25 mm.

C. Material characterization

X-ray diffraction was taken on P'Analytical X'Pert with Cu Kα (λ = 1.541 Å). Bruker Vertex 70 spectrometer was used to collect the Fourier transform infrared spectroscopy (FT-IR) spectra. The FEI Nova Field-emission scanning electron microscope (FE-SEM) was used to capture the morphology of the uncoated and V_2O_5 NW coated yarns.

D. Device characterization

The yarn-based temperature sensor was placed on a Peltier stage (LinkPad, Linkam scientific instruments ltd.). The stage was operated at a ramp rate of 10 °C/min to achieve the desired temperatures. The current profile of the device was measured using a source measuring unit (B2912A, Keysight instruments).

IV. Results and discussions

A. Structural and morphological characterization

Fig. 1a shows the XRD spectra of V_2O_5 NWs. The diffraction peaks at 2theta 15.2°, 20.2°, 26, 31° and 34° corresponds to (200), (001), (110), (301) and (310) planes, respectively. This confirms the orthorhombic crystal structure of V_2O_5 NWs. However, the small shoulder peak at 25.2° also shows the presence of V_2O_5 NWs, although in small amount, having tetragonal crystal structure [38]. Fig. 1b shows the FT-IR spectra of V_2O_5 NWs. The peak at 742 cm^{-1} is attributed to V-O stretching vibrational mode. The peak at ~1004 cm^{-1} is from the terminal stretching of oxygen in V=O bond [39]. Fig. 1c and

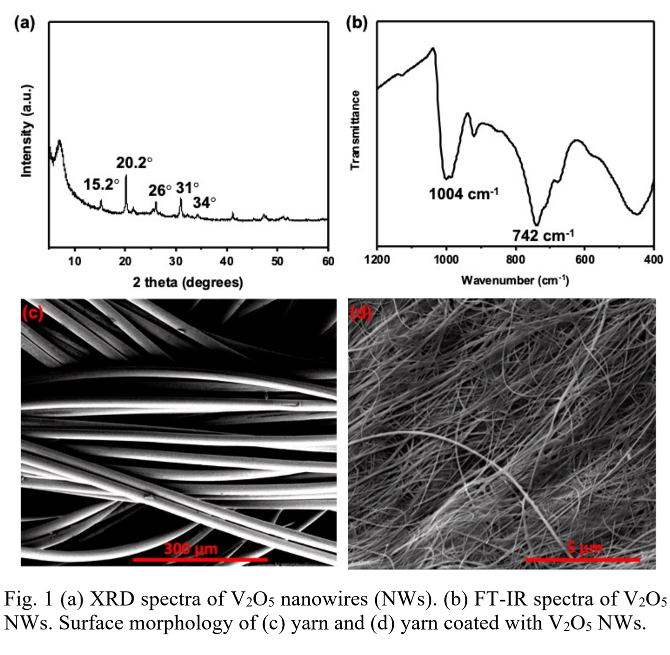

Fig. 1 (a) XRD spectra of V_2O_5 nanowires (NWs). (b) FT-IR spectra of V_2O_5 NWs. Surface morphology of (c) yarn and (d) yarn coated with V_2O_5 NWs.

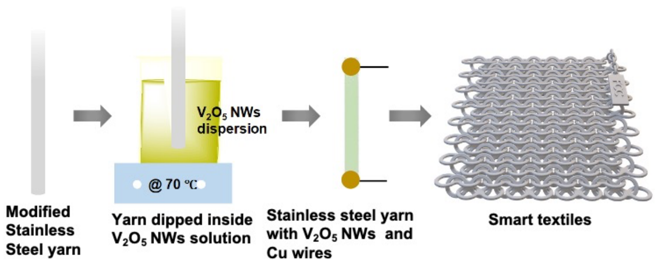

Fig. 2 Fabrication process flow for the yarn-based temperature sensor for smart textiles.

1d show the surface morphology of yarn and that of the yarn coated with NWs. The yarn is composed of interconnected fibers in the diameter range of 20-25 μm. The FE-SEM confirms the presence of dense V_2O_5 NW network on the yarn. The NWs are in the diameter range of 50-80 nm and hundreds of microns in length.

B. Fabrication of yarn-based temperature sensor

Fig. 2a shows the simple approach for the fabrication of the yarn-based temperature sensor. Firstly, a thin layer of P(VDF-TrFE) was coated on yarn via dip coating and dried at 80°C. Followed by this, the yarn was dipped in a beaker containing V_2O_5 NWs dispersion. A yarn of 15 cm was obtained in a single dipping cycle. The controlled evaporation and uniform dispersion are vital for the formation of dense V_2O_5 NW network on the yarn. Such developed yarns can be weaved into fabric for designing e-textiles.

C. Electrical characterization of yarn-based temperature sensor

A voltage sweep from -1 V to 1 V was applied at different temperatures to identify the type of metal-semiconductor (MS) contact formed. The I-V characteristics of the device are shown in Fig. 3a. The linear variation in the current with the applied voltage at different temperatures confirms the ohmic contact formation [40]. Further, the V_2O_5 NWs maintain a stable network on yarn in the measured temperature range. The linear increase in current discloses the decrease in resistance and improve in conductivity at higher temperatures.

The conductivity improvement at higher temperatures can be attributed to the electron hopping between V^{5+} and V^{4+} impurity centers in V_2O_5 [35]. The electrical conductivity of transition metal oxides proposed by Mott was used to extract the

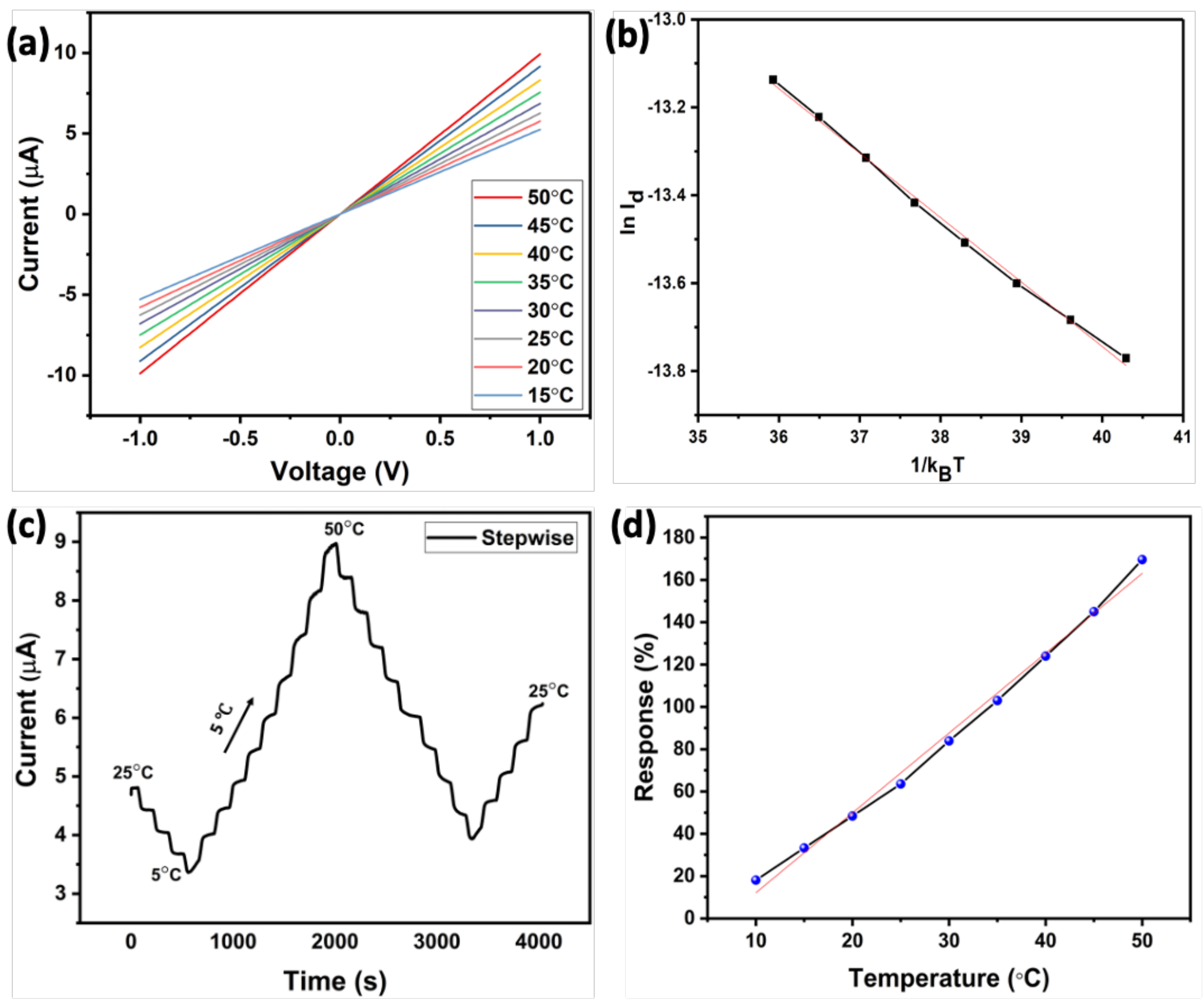

Fig. 3 Device characterization. (a) Temperature dependent electrical (I-V) transport properties of V_2O_5 NWs network on SS yarn. (b) Plot of ln (Id) versus 1/kBT (data extracted from the I-V results shown in figure panel (a). (c) Stepwise current profile with an increase of 5 °C in the temperature from 5 to 50 °C, and (d) response of the sensor and linear fitting.

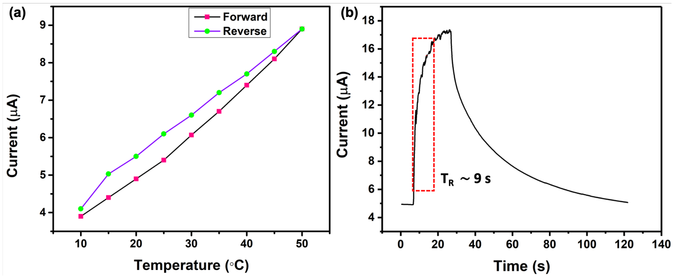

Fig. 4 Performance of the temperature sensor. (a) Hysteresis profile of the sensor with cyclic heating and cooling. (b) Response time of the sensor when heated at 50 °C.

activation energy from the I-V curve [41]. The conductivity is given by:

$$\sigma = \left(\frac{\vartheta_0 e^2 C(1-C)}{kTR}\right)\exp(-2\alpha R)\exp(-\frac{W}{kT})$$

where ϑ_0 is a phonon frequency, C the concentration ratio $V^{4+}/(V^{4+}+V^{5+})$, T is the temperature, R the average hopping distance, α is the rate of wave function decay and W is the activation energy. The data is extracted from Fig. 3a for Arrhenius plot and further used for the extraction of activation energy as shown in Fig. 3b. The yarn-based temperature sensor showed an activation energy of ~0.15 eV which is comparable to the previously reported multi-NW network and thin film-based temperature sensors [42, 43]. The activation energy is related to the NW network formation. The NW network influences the metal-semiconductor contact and electron scattering. The formation of excellent network of NWs and ohmic contact leads to a low-activation energy. An increment of 5°C was carried out first in lower temperature range (5-25°C) and then in higher temperature range (25-50°C) to observe the stepwise change in the current profile of the yarn-based temperature sensor. The designed temperature sensor can work in the temperature range of 5-50 °C, thus limited for the applications like human body temperature monitoring, green house monitoring.

Fig. 3c shows the yarn-based temperature sensors characteristics with increase and decrease in temperature. The current shows an excellent detectable variation with 5°C rise in the temperature. Fig. 3d plots the response versus temperature to evaluate the linear working range of the sensor. The degradation in sensors performance below 10°C was due to the condensation of water on the surface of yarn-based temperature sensor [37].

The percentage response of the sensor is defined as the $\frac{I_f - I_i}{I_i} * 100$, where I_f is the final current (after increasing the temperature) and I_i is the initial current (baseline). The sensor showed outstanding linear response with a coefficient of linearity (R^2) of 0.99 in the temperature range of 10-50 °C. The observed sensitivity in the temperature range was 3.7 %/°C. The high sensitivity of the sensor can be due to (i) formation of high density of V_2O_5 NW network on modified SS yarn, (ii) excellent electron hoping ability of the V_2O_5 NWs and (iii) low activation energy [44, 45].

The stepwise increase and decrease of the current profile were further used to find the hysteresis of the device. Fig. 4a depicts the hysteresis profile of the temperature sensor. The data showed significant hysteresis which can be attributed to moisture condensation happening at low temperature as mentioned earlier. Additionally, the wide hysteresis can also be due to the measurement conditions as the yarn was heated from the bottom and the change in current was measured from the top surface causing slow heating and fast cooling. The response

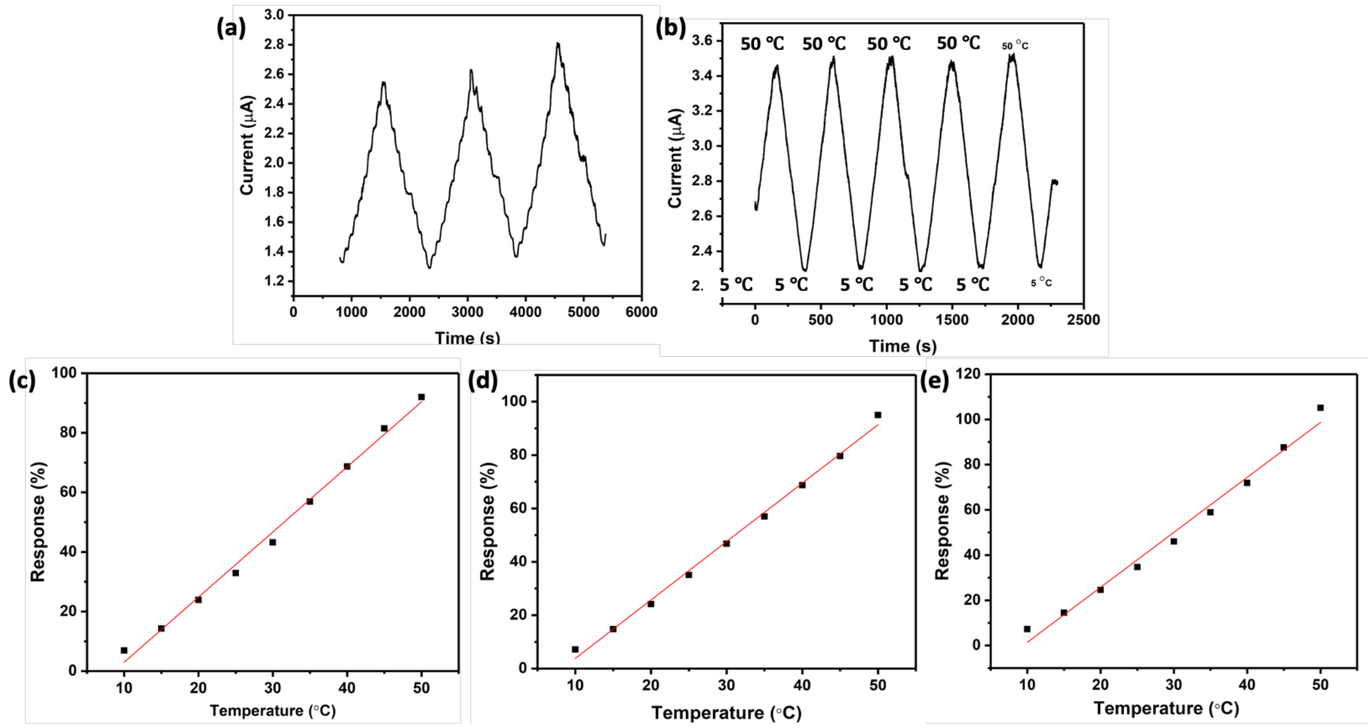

Fig. 5 (a) Stepwise current profile with an increase of 5 °C in the temperature from 5 to 50 °C after device packaging. (b) Cycling heating and cooling from 5 °C to 50 °C. Response of the sensor corresponding to (c) measurement cycle 1, (d) measurement cycle 2 and (e) measurement cycle 3 shown in figure (a).

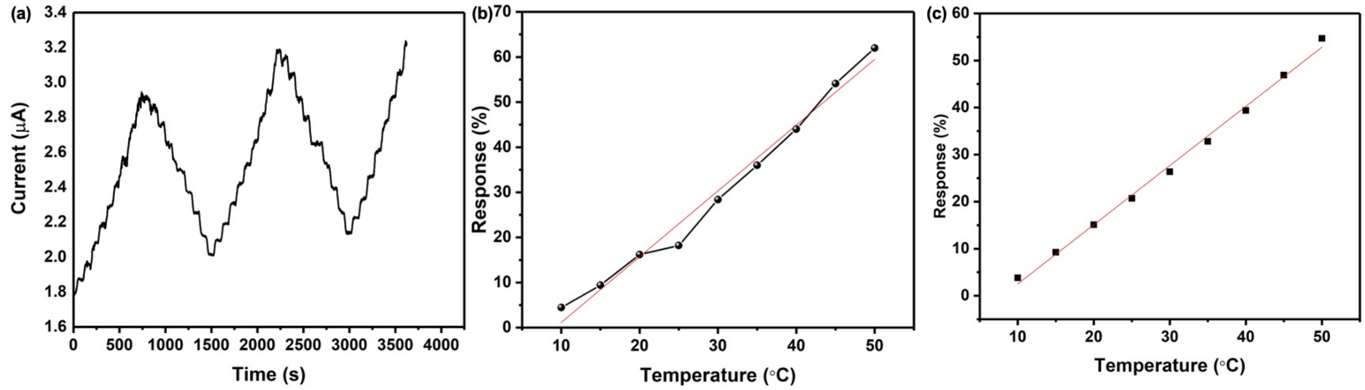

Fig. 6 (a) Stepwise current profile with an increase of 5 °C in the temperature from 5 to 50 °C after device bending for 2000 cycles. Response of the device after bending corresponding to (b) measurement cycle 1 and (c) measurement cycle 2 shown in figure (a).

time is vital consideration for real-time device application.

The response time of the sensor is defined as the time taken by the sensor to reach a 90% value of the stabilised measuring parameter at the given temperature [46]. Thus, response time of the sensor was measured by performing cyclic heating and cooling of the device. The temperature sensor was brought from room temperature to a preheated hot plate (50°C) and back to room temperature. The yarn-based temperature sensor showed a response time of ~9 s with high recovery time of ~70 s (Fig. 4b). Table I shows the comparison of yarn-based temperature sensor with sensor fabricated with other sensing materials.

TABLE I
PERFORMANCE COMPARISON OF STAINLESS-STEEL YARN/V_2O_5 NWS-BASED TEMPERATURE SENSOR WITH OTHER STATE-OF-THE-ART HEAT SENSITIVE MATERIALS.

Sensing materials	Sensitivity ($\%C^{-1}$)	Response time (s)	Recovery time (s)	Ref.
rGO/PET	0.635	1.2	~3	[47]
PEDOT: PSS/ CNTs/PET	0.85	< 0.05	N/A	[47]
Ag/PI	0.22	N/A	N/A	[48]
Graphene/PDMS	-1.05	N/A	~20	[49]
V_2O_5 NWs/SS	3.7	~9	>60	This work

Device packaging is crucial for smart or e-textile for better durability and stability during bending motions and washing. To this end, we coated the device with a thin layer of nanosilica/epoxy [37]. Fig. 5a shows the change in the current profile with a stepwise temperature increase of 5°C (5°C - 50 °C) for three cycles. The three cycles have significant variations in the current values. However, Fig. 5b shows repeatability of the device when heated from 5 °C to 50 °C for different cycles. The temperature sensor returns to same current value after multiple cyclic heating and cooling. The data from cyclic measurements (Fig. 5a) at different temperature values is used to measure the linear response and sensitivity of the device after packaging. Fig. 5c-e show the linear response of the device corresponding to three different cycles shows in Fig. 5a. All three cycles maintained an excellent linearity in the temperature range of 10°C to 50 °C with sensitivity of 2.18 %/°C (Cycle 1), 2.18 %/°C (Cycle 2) and 2.43 %/°C (Cycle 3). Despite of variations in the current values, all three measurement cycles in Fig. 5a showed similar sensitivity. The device showed obvious decrement in the sensitivity compared to the unpacked device.

The textile undergoes numerous cycles of bending during human motions. The sensor should remain stable during such bending or deformation of the textile. To confirm the mechanical robustness, the temperature sensor was subjected to 2000 bending cycles at a bending radius of 25 mm. The bending mechanical loadings were applied using Yuasa endurance testing system and subsequently, the electrical measurements were made. Fig. 6a shows the stepwise current profile of the temperature sensor after 2000 bending cycles. Fig. 6b and 6c depicts the sensors response corresponding to two cycles shown in Fig. 6a. The response of the device corresponding to measurement cycle one showed poor linearity compared to measurement cycle 2. However, the sensor showed better sensitivity corresponding to measurement cycle 1 (1.45 %/°C) compared to that of measurement cycle 2 (1.257 %/°C). The significant decrement in the sensors response after bending may

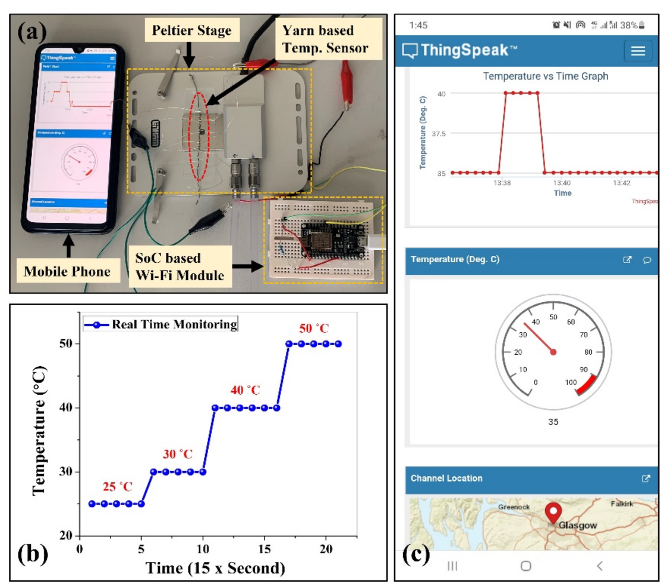

Fig. 7 (a) Real time temperature sensing system. (b) Real time monitored data displayed using temperature vs time graph in temperature range 25 ˚C to 50 ˚C. (c) Mobile phone screen displaying temperature vs time graph, numeric representation of temperature and geographical location of the data measurement point.

be due to the cracks in silver epoxy used for the contacts. Nevertheless, even after bending for 2000 cycles the fabricated sensor shows better sensitivity compared to the others shown in Table I.

D. Wireless data transfer

The real time temperature sensing was performed using the Node Micro Controller Unit (MCU) platform. The real time monitoring set-up for temperature sensing and monitoring, as shown in the Fig. 7a, consists of V_2O_5 NWs coated yarn-based temperature sensor, Peltier stage to set the desired temperature, mobile phone for real time data monitoring, signal processing unit and a 32-bit microcontroller with SoC based Wi-Fi module (ESP8266) with a ~3V supply to power the system. The design parameter for real time monitoring system includes stable and repeatable change in the electrical parameter of the developed sensor with temperature to predict the respective temperature levels. To monitor the change in temperature, software module was written in Arduino Software (IDE) and embedded C programming language is used to develop the control code. The generated source code was uploaded to microcontroller unit, after which the real time monitoring system was ready for temperature monitoring with a delay of ~15 seconds. ThingSpeak, an IoT analytics platform was used for acquisition and visualization of the live data streams (within the cloud display). The temperature response of the developed sensor was monitored in 25 ˚C to 50 ˚C range with step changes. The real time monitored data is displayed using temperature vs time graph in Fig. 7b. Further, the front-end visualization observed on smartphone display is shown in Fig. 7c, which displays the monitored temperature in real time along with the geographical location of the measurement spot.

V. Conclusion

In summary, we fabricated a flexible yarn-based temperature sensor using V_2O_5 NWs as sensing material. The effect of device packaging and bending on the sensor's performance was studied. The sensor exhibited linear response after packaging and bending but the sensitivity of the sensor reduced from 3.7 %/°C (unpacked) to 2.18 %/°C (encapsulated) to 1.257 %/°C after bending. The change in temperature was monitored using the yarn-based sensor and transferred wirelessly to a mobile device using a microcontroller. The present work demonstrates the potential of using yarn as a flexible temperature sensor that can be used to realize smart textile for wearable and healthcare applications.

References

[1] F. Nikbakhtnasrabadi, E. S. Hosseini, S. Dervin, D. Shakthivel, and R. Dahiya, "Smart Bandage with Inductor-Capacitor Resonant Tank Based Printed Wireless Pressure Sensor on Electrospun Poly-L-Lactide Nanofibers," *Advanced Electronic Materials,* vol. 8, no. 7, pp. 2101348, 2022.

[2] T. Tat, G. Chen, X. Zhao, Y. Zhou, J. Xu, and J. Chen, "Smart Textiles for Healthcare and Sustainability," *ACS Nano*, 2022. DOI: 10.1021/acsnano.2c06287.

[3] A. Libanori, G. Chen, X. Zhao, Y. Zhou, and J. Chen, "Smart textiles for personalized healthcare," *Nature Electronics,* vol. 5, no. 3, pp. 142-156, 2022.

[4] O. Ozioko, and R. Dahiya, "Smart Tactile Gloves for Haptic Interaction, Communication, and Rehabilitation," *Adv. Intelligent Syst.,* vol. 4, no. 2, pp. 2100091, 2022.

[5] A. Pullanchiyodan, L. Manjakkal, and R. Dahiya, "Metal Coated Fabric Based Asymmetric Supercapacitor for Wearable Applications," *IEEE Sensors J.,* vol. 21, no. 23, pp. 26208-26214, 2021.

[6] M. Fierheller, and R. G. Sibbald, "A Clinical Investigation into the Relationship between Increased Periwound Skin Temperature and Local Wound Infection in Patients with Chronic Leg Ulcers," *Advances in Skin & Wound Care,* vol. 23, no. 8, pp. 369-379, 2010.

[7] L. A. Lavery, K. R. Higgins, D. R. Lanctot, G. P. Constantinides, R. G. Zamorano, D. G. Armstrong, K. A. Athanasiou, and C. M. Agrawal, "Home Monitoring of Foot Skin Temperatures to Prevent Ulceration," *Diabetes Care,* vol. 27, no. 11, pp. 2642-2647, 2004.

[8] N. Mathur, I. Glesk, and A. Buis, "Skin Temperature Prediction in Lower Limb Prostheses," *IEEE J. Biomed. and Health Informatics,* vol. 20, no. 1, pp. 158-165, 2016.

[9] R. G. Nakagami PhD, R. H. Sanada PhD, WOCN, R. S. Iizaka MHS, M. T. Kadono PhD, T. H. MD, R. H. Koyanagi MHS, and M. N. Haga PhD, "Predicting delayed pressure ulcer healing using thermography: a prospective cohort study," *Journal of Wound Care,* vol. 19, no. 11, pp. 465-472, 2010.

[10] F. Nikbakhtnasrabadi, H. El Matbouly, M. Ntagios, and R. Dahiya, "Textile-Based Stretchable Microstrip Antenna with Intrinsic Strain Sensing," *ACS Applied Electronic Materials,* vol. 3, no. 5, pp. 2233-2246, 2021.

[11] G. Khandelwal, and R. Dahiya, "Self-Powered Active Sensing Based on Triboelectric Generators," *Advanced Materials,* vol. 34, no. 33, pp. 2200724, 2022.

[12] A. Christou, R. Chirila, and R. Dahiya, "Pseudo-Hologram with Aerohaptic Feedback for Interactive Volumetric Displays," *Advanced Intelligent Systems,* vol. 4, no. 2, pp. 2100090, 2022.

[13] O. Ozioko, P. Karipoth, P. Escobedo, M. Ntagios, A. Pullanchiyodan, and R. Dahiya, "SensAct: The Soft and Squishy Tactile Sensor with Integrated Flexible Actuator," *Adv. Intelligent Syst.,* vol. 3, no. 3, pp. 1900145, 2021.

[14] B. Arman Kuzubasoglu, and S. Kursun Bahadir, "Flexible temperature sensors: A review," *Sensors and Actuators A: Physical,* vol. 315, pp. 112282, 2020.

[15] G. R. Langereis, S. Bouwstra, and W. Chen, "Sensors, actuators and computing systems for smart textiles for protection," *Smart Textiles for Protection*, R. A. Chapman, ed., pp. 190-213: Woodhead Publishing, 2013.

[16] L. Manjakkal, A. Pullanchiyodan, N. Yogeswaran, E. S. Hosseini, and R. Dahiya, "A Wearable Supercapacitor Based on Conductive PEDOT:PSS-Coated Cloth and a Sweat Electrolyte," *Adv. Materials,* vol. 32, no. 24, pp. 1907254, 2020.

[17] K. Dong, X. Peng, and Z. L. Wang, "Fiber/Fabric-Based Piezoelectric and Triboelectric Nanogenerators for Flexible/Stretchable and Wearable Electronics and Artificial Intelligence," *Adv. Materials,* vol. 32, no. 5, pp. 1902549, 2020.

[18] A. Yang, Y. Li, C. Yang, Y. Fu, N. Wang, L. Li, and F. Yan, "Fabric Organic Electrochemical Transistors for Biosensors," *Adv. Mater.,* vol. 30, no. 23, pp. 1800051, 2018.

[19] Q. Li, L.-N. Zhang, X.-M. Tao, and X. Ding, "Review of Flexible Temperature Sensing Networks for Wearable Physiological Monitoring," *Adv. Healthcare Materials,* vol. 6, no. 12, pp. 1601371, 2017.

[20] W. Yan, A. Page, T. Nguyen-Dang, Y. Qu, F. Sordo, L. Wei, and F. Sorin, "Advanced Multimaterial Electronic and

Optoelectronic Fibers and Textiles," *Adv. Mater.,* vol. 31, no. 1, pp. 1802348, 2019.
[21] K. Dewangan, K. Shrivas, and R. Kurrey, "Chapter 9 - Hybrid nanomaterials as chemical sensors," *Multifunctional Hybrid Nanomaterials for Sustainable Agri-Food and Ecosystems*, K. A. Abd-Elsalam, ed., pp. 213-239: Elsevier, 2020.
[22] N. Sun, H. Yu, H. Wu, X. Shen, and C. Deng, "Advanced nanomaterials as sample technique for bio-analysis," *TrAC Trends in Analytical Chemistry,* vol. 135, pp. 116168, 2021.
[23] K. Hagberg, and R. Brånemark, "Consequences of non-vascular trans-femoral amputation: A survey of quality of life, prosthetic use and problems," *Prosthetics and Orthotics International,* vol. 25, no. 3, pp. 186-194, 2001.
[24] P. Lugoda, J. C. Costa, C. Oliveira, L. A. Garcia-Garcia, S. D. Wickramasinghe, A. Pouryazdan, D. Roggen, T. Dias, and N. Münzenrieder, "Flexible Temperature Sensor Integration into E-Textiles Using Different Industrial Yarn Fabrication Processes," *Sensors,* vol. 20, no. 1, pp. 73, 2020.
[25] G. E. Billman, "Homeostasis: The Underappreciated and Far Too Often Ignored Central Organizing Principle of Physiology," *Frontiers in Physiology,* vol. 11, 2020.
[26] C. R. Gomez, "Chapter 62 - Disorders of body temperature," *Handbook of Clinical Neurology*, J. Biller and J. M. Ferro, eds., pp. 947-957: Elsevier, 2014.
[27] W. P. Cheshire, "Thermoregulatory disorders and illness related to heat and cold stress," *Autonomic Neuroscience,* vol. 196, pp. 91-104, 2016.
[28] G. Khandelwal, A. S. Dahiya, and R. Dahiya, "V_2O_5 nanowires coated yarn based temperature sensor for smart textiles," IEEE Int. Conference on Flexible and Printable Sensors and Systems (FLEPS), Vienna, Austria, 2022, pp. 1-4, DOI: 10.1109/FLEPS53764.2022.9781524.
[29] Y. M. Gu, "Advances in Textile-Based Flexible Temperature Sensors," *J. Physics: Conference Series,* vol. 1790, no. 1, pp. 012021, 2021.
[30] Y.-F. Wang, T. Sekine, Y. Takeda, K. Yokosawa, H. Matsui, D. Kumaki, T. Shiba, T. Nishikawa, and S. Tokito, "Fully Printed PEDOT:PSS-based Temperature Sensor with High Humidity Stability for Wireless Healthcare Monitoring," *Sc. Reports,* vol. 10, no. 1, pp. 2467, 2020.
[31] M. Hilal, and J. I. Han, "Development of a Highly Flexible and Durable Fiber-Shaped Temperature Sensor Based on Graphene/Ni Double-Decked Layer for Wearable Devices," *IEEE Sensors J.,* vol. 20, no. 10, pp. 5146-5154, 2020.
[32] X. Li, S. Lin, J. Liang, Y. Zhang, H. Oigawa, and T. Ueda, "Fiber-Optic Temperature Sensor Based on Difference of Thermal Expansion Coefficient Between Fused Silica and Metallic Materials," *IEEE Photonics J.,* vol. 4, no. 1, pp. 155-162, 2012.
[33] M. Bhattacharjee, F. Nikbakhtnasrabadi, and R. Dahiya, "Printed Chipless Antenna as Flexible Temperature Sensor," *IEEE Internet of Things J.,* vol. 8, no. 6, pp. 5101-5110, 2021.
[34] L. Wu, J. Qian, J. Peng, K. Wang, Z. Liu, T. Ma, Y. Zhou, G. Wang, and S. Ye, "Screen-printed flexible temperature sensor based on FG/CNT/PDMS composite with constant TCR," *J. Mater. Sc.: Mater. in Electronics,* vol. 30, no. 10, pp. 9593-9601, 2019.
[35] J. Muster, G. T. Kim, V. Krstić, J. G. Park, Y. W. Park, S. Roth, and M. Burghard, "Electrical Transport Through Individual Vanadium Pentoxide Nanowires," *Advanced Materials,* vol. 12, no. 6, pp. 420-424, 2000.
[36] T. Zhai, H. Liu, H. Li, X. Fang, M. Liao, L. Li, H. Zhou, Y. Koide, Y. Bando, and D. Golberg, "Centimeter-Long V_2O_5 Nanowires: From Synthesis to Field-Emission, Electrochemical, Electrical Transport, and Photoconductive Properties," *Advanced Materials,* vol. 22, no. 23, pp. 2547-2552, 2010.
[37] J. Neto, R. Chirila, A. S. Dahiya, A. Christou, D. Shakthivel, and R. Dahiya, "Skin-Inspired Thermoreceptors-Based Electronic Skin for Biomimicking Thermal Pain Reflexes," *Adv. Sc.,* vol.9, 2201525, 2022.
[38] D. Govindarajan, V. Uma Shankar, and R. Gopalakrishnan, "Supercapacitor behavior and characterization of RGO anchored V2O5 nanorods," *J. Materials Science: Materials in Electronics,* vol. 30, no. 17, pp. 16142-16155, 2019.
[39] B. Pandit, D. P. Dubal, P. Gómez-Romero, B. B. Kale, and B. R. Sankapal, "V2O5 encapsulated MWCNTs in 2D surface architecture: Complete solid-state bendable highly stabilized energy efficient supercapacitor device," *Scientific Reports,* vol. 7, no. 1, pp. 43430, 2017.
[40] T. V. Blank, and Y. A. Gol'dberg, "Mechanisms of current flow in metal-semiconductor ohmic contacts," *Semiconductors,* vol. 41, no. 11, pp. 1263-1292, 2007.
[41] N. F. Mott, and R. H. Fowler, "The electrical conductivity of transition metals," *Proc. of the Royal Society of London. Series A - Mathematical and Physical Sciences,* vol. 153, no. 880, pp. 699-717, 1936.
[42] S. Sarma, and J. H. Lee, "Developing Efficient Thin Film Temperature Sensors Utilizing Layered Carbon Nanotube Films," *Sensors,* vol. 18, no. 10, pp. 3182, 2018.
[43] J. Wang, E. M. Lally, X. Wang, J. Gong, G. Pickrell, and A. Wang, "ZrO2 thin-film-based sapphire fiber temperature sensor," *Applied Optics,* vol. 51, no. 12, pp. 2129-2134, 2012.
[44] W. J. Shen, K. W. Sun, and C. S. Lee, "Electrical characterization and Raman spectroscopy of individual vanadium pentoxide nanowire," *J. Nanoparticle Research,* vol. 13, no. 10, pp. 4929, 2011.
[45] S. D. Perera, B. Patel, N. Nijem, K. Roodenko, O. Seitz, J. P. Ferraris, Y. J. Chabal, and K. J. Balkus Jr., "Vanadium Oxide Nanowire–Carbon Nanotube Binder-Free Flexible Electrodes for Supercapacitors," *Adv. Energy Mater.,* vol. 1, no. 5, pp. 936-945, 2011.
[46] I. A. Choudhury, A. Hossain, and S. H. Bhuiyan, "13.05 - Issues of Connectivity, Durability, and Reliability of Sensors and Their Applications," *Comprehensive Materials Processing*, S. Hashmi, G. F. Batalha, C. J. Van Tyne and B. Yilbas, eds., pp. 121-148, Oxford: Elsevier, 2014.
[47] G. Liu, Q. Tan, H. Kou, L. Zhang, J. Wang, W. Lv, H. Dong, and J. Xiong, "A Flexible Temperature Sensor Based on Reduced Graphene Oxide for Robot Skin Used in Internet of Things," *Sensors,* vol. 18, no. 5, pp. 1400, 2018.
[48] M. D. Dankoco, G. Y. Tesfay, E. Benevent, and M. Bendahan, "Temperature sensor realized by inkjet printing process on flexible substrate," *Mater. Sc. and Engineering: B,* vol. 205, pp. 1-5, 2016.
[49] C. Yan, J. Wang, and P. S. Lee, "Stretchable Graphene Thermistor with Tunable Thermal Index," *ACS Nano,* vol. 9, no. 2, pp. 2130-2137, 2015.

Gaurav Khandelwal is currently working as a post-doctoral fellow in the Bendable Electronics and Sensing Technologies (BEST) group at the University of Glasgow. He completed his Ph.D. (with excellence) from Jeju National University, South Korea, where he received the Brain Korea fellowship. He holds a Bachelor's and Master's degree in Nanotechnology from the Centre for Converging Technologies, U.O.R, India. He worked as Project Associate at the Indian Institute of Technology (IIT), Delhi, India. His current research area includes triboelectric nanogenerators, piezoelectric

nanogenerators, fiber/yarn-based devices, self-powered sensors, and nanomaterial synthesis and characterization.

Abhishek S. Dahiya is Research Associate in Bendable Electronics and Sensing Technologies (BEST) group at the University of Glasgow. He received Ph.D. from the GREMAN laboratory, Université François Rabelais de Tours, France in 2016. He has done postdoctoral work at various CNRS laboratories in France: GREMAN (2016- 2017), ICMCB (2018-2019), and IES/LIRMM (2019-2020). His research interest includes synthesis of nanomaterials, nanofabrication, energy harvesting, and printed and flexible electronics.

Ajay Beniwal received his B.Tech. and M.Tech. degree in Electronics and Communication Engineering from Kurukshetra University Kurukshetra, India, in 2013 and 2015, respectively, and Ph.D. degree from Indian Institute of Information Technology, Allahabad, Prayagraj, India in 2021. He is currently working as a Marie Curie Early-Stage Researcher with the Bendable Electronics and Sensing Technologies (BEST) Group at University of Glasgow, U.K. His current research interest includes material characterization and thin film technology, electronic sensor devices, printed and flexible electronics, for healthcare and agriculture applications.

Ravinder Dahiya (Fellow, IEEE) is Professor in ECE Department at Northeastern University, Boston, USA. He is the leader of Bendable Electronics and Sustainable Technologies (BEST) research group (*formerly*, Bendable Electronics and Sensing Technologies (BEST) group). His group conducts fundamental and applied research in flexible and printable electronics, tactile sensing, electronic skin, robotics, and wearable systems. He has authored or co-authored about 500 publications, books and submitted/granted patents and disclosures. He has led several international projects. He is President (2022-23) of the IEEE Sensors Council. He is the Founding Editor in Chief of IEEE JOURNAL ON FLEXIBLE ELECTRONICS (J-FLEX) and has served on the editorial boards of IEEE SENSORS JOURNAL (2012-2020) and IEEE TRANSACTIONS ON ROBOTICS (2012-2017). He was the Technical Program co-chair of IEEE Sensors 2017 and IEEE Sensors 2018 and has been General Chair/Co-Chair of several conferences including IEEE FLEPS (2019, 2020, 2021), which he founded in 2019, and IEEE Sensors 2023. He is recipient of EPSRC Fellowship, Marie Curie and Japanese Monbusho Fellowships. He has received several awards, including 2016 Microelectronic Engineering Young Investigator Award (Elsevier), 2016 Technical Achievement Award from the IEEE Sensors Council and 12 best paper awards as author/co-author in International Conferences and Journal.