V_2O_5 nanowires coated yarn based temperature sensor for smart textiles

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***Abstract*— Smart textiles can sense different stimuli such as pressure, temperature etc., to allow users to react and adapt. Such features are accomplished through integration of various fiber-based sensors and electronic components in textile structures. Yarn is 1-dimensional structure which can be modified to behave as a sensor and can further be integrated with other sensors or electronics to form smart textile by techniques like weaving, knitting, and braiding. In this work, a flexible temperature sensor is reported by modifying a stainless-steel yarn with V_2O_5 nanowires. The current profile and temperature sensing performance is measured from 5 to 50 °C. The device exhibits sensitivity of 3.7 %/°C and response time of ~9s. 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.**

Keywords— smart textile, flexible electronics; temperature sensor; nanowires; yarn; vanadium pentoxide

I. Introduction

Flexible and wearable electronics have potential to enhance the quality of human lives by enabling advances in next-generation technologies such as soft robotics, high performance transistors, electronic-skin, interactive objects, energy storage devices, and mobile healthcare etc [1-11]. Among various configurations, the electronic devices in fibre form factors or on textiles could revolutionise the next generation of applications such as mobile healthcare, internet of things etc. [12, 13]. Smart textiles can sense different stimuli such as pressure, temperature etc., react and adapt to them. For instance, these smart textiles can be used to monitor wounds, infections, and COVID-19 without any discomfort to the patients [14-17]. Temperature is an established marker during wound healing processes and to detect infections. Further, the increase in temperature during the infections can also enhances the bacterial growth [18, 19]. Therefore, flexible temperature sensors in fibre form factors are well-suited for unobtrusive monitoring of skin temperatures which can help detection of infections at early stages. This requires the modification or merging the textile with temperature sensing devices without compromising the human body motions.

Yarn is an ideal starting point for designing a smart functionalised textiles due to low complexity, ease of modifications and formation of different textile by weaving, knitting or braiding [20]. The recent advancements in the functionalised nanomaterials allow an easy modification of the yarn to endow them with sensing properties. Thus, the modified yarns can be integrated to form a textile that can sense different parameters like temperature, humidity, strain and photodetection etc. However, there are limited reports on the yarn-based temperature sensors. The reported yarn-based temperature sensors were mainly designed by embedding the thin film or commercially available temperature sensor with the yarns [21]. The thin film sensors are difficult to incorporate in the textile and can damage the textile [21]. Such sensors have limited deformability which leads to a poor aesthetics and cannot adjust with the different human motions. Further, these sensors are not compatible with the industrial textile manufacturing techniques like weaving, braiding, knitting. The modification of yarn with a biocompatible and heat sensitive material is an attractive approach to achieve high flexibility without compromising the sensing performance. Different metallic, organic, inorganic materials and their composites including nickel (Ni), carbon nanotube (CNT), graphene and PEDOT: PSS have been explored for the fabrication of temperature sensor [22-27]. The metallic materials are expensive while composite materials showed poor response time and large hysteresis and also have an issue with the formation of stable dispersion. Alternatively, 1-dimensional (1D) metal-oxide materials like V_2O_5 nanowires are excellent candidates for temperature sensor due to high crystallinity, ease of synthesis, offers high surface area to volume ratio and has smaller activation energy [28-30]. The V_2O_5 nanowires can also form a stable dispersion in water thus avoiding the use of toxic solvents. Irrespective of these exciting thermal sensing traits, V_2O_5 NWs-based temperature sensor in fibre form factor have not been reported.

Driven by these motivations, herein, we present the development of a flexible yarn-based temperature sensor by integrating high density of V_2O_5 nanowires on a modified stainless-steel (SS) yarn using a facile approach. The electrical measurements were performed in the temperature range of 5 °C to 50 °C to obtain the working range, sensitivity, and response time of the sensor.

This paper is organised as follows: Section II details the experimental procedures, device fabrication and characterisation techniques. Section III discusses the results of the temperature sensor. Section IV summarises the key outcomes of the study.

II. Experimental section

A. Materials

Vanadium pentoxide (V_2O_5) nanowires with diameter of 50-80 nm and length of few micrometres were purchased from Novarials corporation. Polyvinylidene fluoride trifluoroethylene (PVDF-TrFE), Piezotech FC30 was purchased from Arkema group.

This work was supported by Engineering and Physical Sciences Research Council (EPSRC) through NextGenT-TENG Standard Grant (EP/V003380/1).

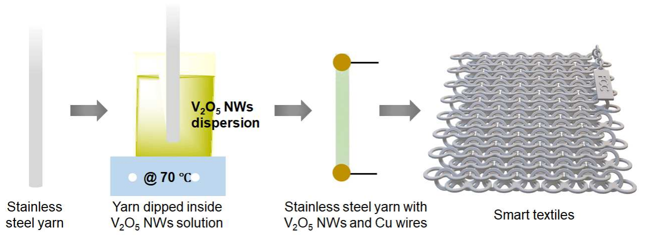

Fig. 1 Fabrication process flow for the yarn-based temperature sensor for smart textiles

B. Fabrication of V_2O_5 nanowire network on the SS yarn

The SS yarn was coated with a thin layer of PVDF-TrFE to enhance the mechanical stability and durability of the yarn. The commercial V_2O_5 nanowires (0.5 wt.%) were dispersed in deionized (DI) water. The PVDF-TrFE coated SS yarn was placed vertically in beaker containing the nanowire dispersion. With slow and controlled evaporation of the water at 70 °C, the V_2O_5 nanowires network was formed on the yarn by Van der Waals interactions. The yarn was then washed with the deionized water to remove the unattached nanowires. Finally, two copper wires were attached to form a channel of 1.25 mm for the device measurements using silver epoxy paste.

C. Device characterisation

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).

III. RESULTS AND DISCUSSIONS

A. Fabrication of yarn based temperature sensor

The simple and facile approach used for the fabrication of yarn-based temperature sensor is detailed in Fig.1. Firstly, a V_2O_5 nanowires dispersion was prepared in the DI water. The dispersion was poured into a petri dish with PVDF-TrFE coated SS yarn placed in the centre of it. The controlled evaporation allows the integration of the nanowires on the SS yarn. Finally, copper wires are placed to form a channel of desired length (1.25 mm) for the measurements.

B. Electrical characterisation of yarn based temperature sensor

To understand the type of metal-semiconductor (MS) contact formed, a voltage sweep from -1 V to +1 V was performed at different temperature. Fig. 2a shows the I-V curve of the device at different temperature. The results indicate the linear behaviour at different temperature, suggesting the formation of the ohmic contacts [31]. The stable increase in the current revealed the improved conductivity at higher temperature. The charge transport in V_2O_5 is defined by electron hopping between V^{5+} and V^{4+} impurity centers [28]. This I-V curves are used to extract the activation energy of the device through analysis of electrical conductivity of transition-metal oxides proposed by Mott, where 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 $V^{4+}/(V^{4+} + V^{5+})$, R the average hopping distance, W the activation energy, T the temperature, and α the rate of wave function decay. The data is extracted from Fig. 2a for Arrhenius plot and further used for the extraction of activation energy as shown in Fig. 2b. The fabricated sensor showed an activation energy of ~0.15 eV which is comparable to thin film-based sensors and previously reported multi-NW network-based devices [32, 33]. The activation energy depends on the network of the nanowires which influences the electron scattering and the metal-semiconductor contact. The low activation energy confirms the formation of excellent NW-network and ohmic contacts.

The current profile of the device was measured by stepwise increment of 5 °C first in the lower temperature range (5 °C to 25 °C) and then in higher temperature range (25 °C to 50 °C). Fig. 3a shows the device characteristics with

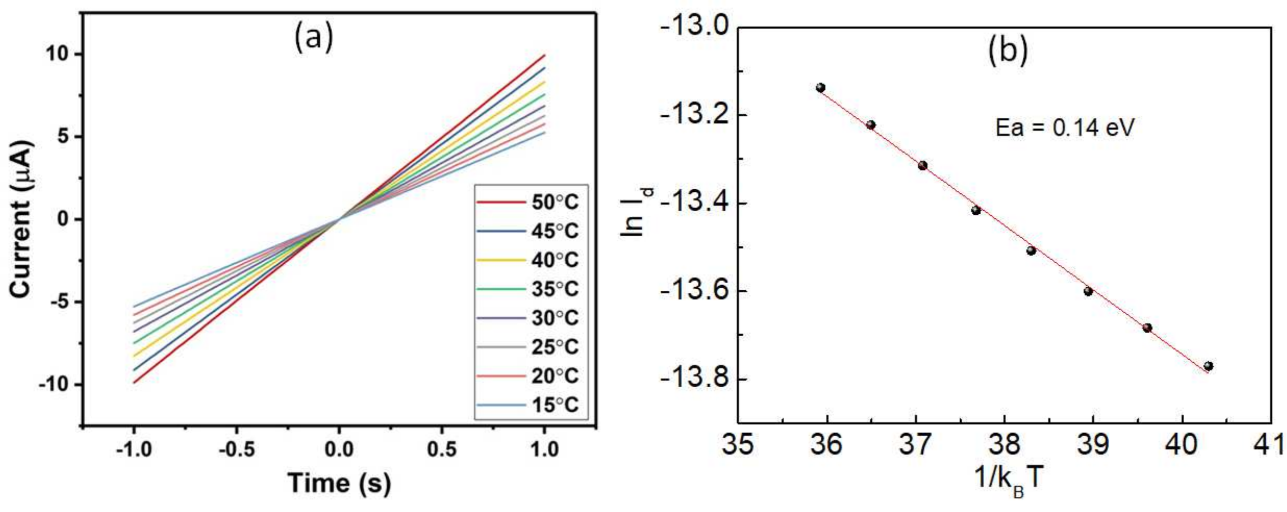

Fig. 2. Temperature dependent electrical (I-V) transport properties of V_2O_5 NWs network on SS yarn, and (b) Plot of ln (I_d) versus $1/k_BT$ (data extracted from the I-V results shown in figure panel (a)

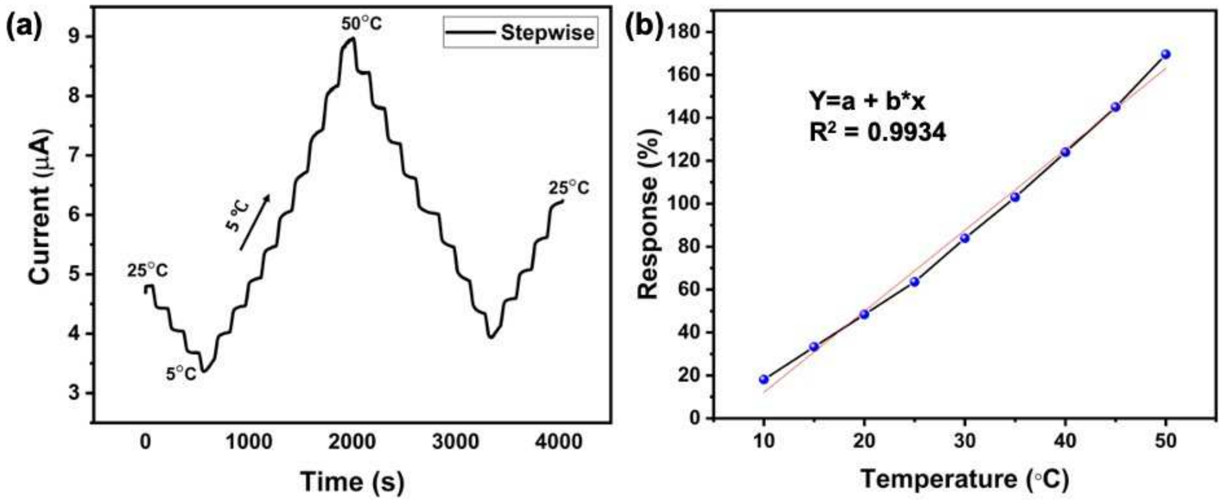

Fig. 3. Temperature sensing performance evaluation: (a) stepwise current profile with an increase of 5 °C in the temperature from 5 to 50 °C, and (b) response of the sensor and linear fitting.

increasing and decreasing temperatures. To evaluate the linear working range of the device, a response graph is plotted as shown in Fig. 3b. The device exhibited a linear response in the range of 10 °C to 50 °C with a coefficient of linearity (R^2) of 0.99. It is to note that below 10 °C degradation of the performance was observed due to the condensation of the water on the surface of temperature sensor. The yarn-based temperature sensor exhibited a sensitivity of 3.7 %/°C. The high sensitivity of the sensor can be ascribed to multiple factors: (i) high density of the V_2O_5 nanowires on the stainless-steel yarn, (ii) electron hoping ability of the V_2O_5 nanowires, and (iii) low activation energy of the device [34, 35].

The response and recovery of the sensor was evaluated by performing the cyclic heating and the cooling of the device. The data was further used to evaluate the hysteresis of the device. The hysteresis profile of the sensor is shown in Fig. 4a. The data exhibits poor device stability (hysteresis) due to moisture and/or condensation related issues, particularly at low temperatures (as mentioned above). The wide hysteresis profile can be due to the measurement conditions where yarn was heated from the bottom and measuring the current change from the top. Further studies are needed to evaluate the influence of the encapsulation layer on the sensing performance, and stability of the temperature sensor. The response time of the device is critical for real-time applications of the sensor. 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 [36]. The response time of the sensor was measured by bringing the sensor from room temperature to a heated hot plate (50 °C) and back to the room temperature. Fig. 4b confirms that the device has a relatively fast response time of ~9s. The fabricated yarn based temperature sensor showed high sensitivity compared to the other sensing materials, as shown in Table 1.

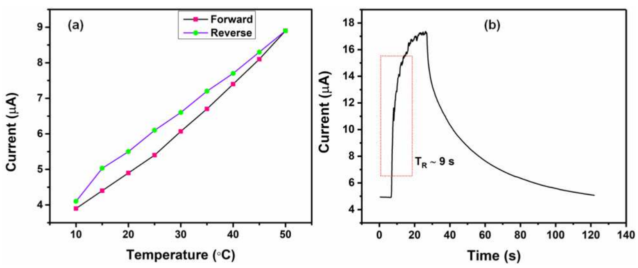

Fig. 4. Performance of the temperature sensor. (a) Hysteresis profile of the sensor with cyclic heating and cooling. (b) Response time of the sensor when heated at 50 °C.

Table 1. Performance comparison of stainless-steel yarn/V_2O_5 nanowires-based temperature sensor with the state-of-the-art heat sensitive materials. N/A – data not available

Sensing materials	Sensitivity (%C^{-1})	Response time (s)	Recovery time (s)	Ref.
rGO/PET	0.635	1.2	~3	[37]
PEDOT: PSS/ CNTs/PET	0.85	< 0.05	N/A	[37]
Ag/PI	0.22	N/A	N/A	[38]
Graphene/PDMS	-1.05	N/A	~20	[39]
V_2O_5 NWs/SS	3.7	~9	>60	This work

IV. CONCLUSIONS

In summary, a stainless-steel yarn based flexible temperature sensor that can be easily incorporated in the textile was reported. The high-density network of V_2O_5 nanowires was formed on the yarn using a facile and easy to scale-up approach. The device exhibited a fast response time of ~9s and a high sensitivity of 3.7 %/°C. The high sensitivity of the sensor suggests the formation of highly dense nanowire network and excellent charge transport properties of the material. Further studies will be carried out to evaluate the effect of encapsulation layer on the device performance and the mechanical robustness studies. The encapsulation layer will likely to further improve the wash durability of the developed sensor.

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