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Silver nanowire-containing wearable thermogenic smart textiles with washing stability

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Abstract. Conventional fabrics that have modified in to conductive fabrics using conductive nanomaterials have novel applications in different fields. These of fabrics can be used as heat generators with the help of the Joule heating mechanism, which is applicable in thermal therapy and to maintain the warmth in cold weather conditions in a wearable manner. A modified fabric can also be used as a sensor for body temperature measurements using the variation of resistance with respect to the body temperature deviations. In this study, polyol synthesized silver nanowires (Ag NWs) are incorporated to commercially available cotton fabrics by using drop casting method to modify the fabric as a thermogenic temperature sensor. The variation of sheet resistance of the fabrics with respect to the incorporated mass of Ag NWs was measured by four probe technique while the bulk resistance variation with respect to the temperature was measured using a standard ohm meter. Heat generation profiles of the fabrics were investigated using thermo graphic camera. Electrically conductive fabrics, fabricated by incorporating 30 mg of Ag NWs in 25 cm^2 area of cotton fabric can be heated up to a maximum steady state temperature of 45°C, using a commercially available 9 V battery.

Keywords: cotton; heat generating; silver nanowires; smart textiles; temperature sensing

1. Introduction

Specific functional changes occur in smart textiles due to their responses to the changes in the environment such as mechanical forces like strain, electromagnetic radiation, temperature and existence of microorganisms such as bacteria. Therefore, these textiles can be utilized to enhance the inter connection between the humans and their environment. Among different types of smart textiles, humidity sensing, shape memory, antibacterial, strain sensing, thermostatic, solar cell, hydrophobic, anti-infrared, electrically conductive textiles and wearable antennas stand out (Doganay *et al.* 2016, Cui *et al.* 2015, Jeong *et al.* 2019, Souri and Bhattacharyya 2018, Castano and Flatau 2014, Hu *et al.* 2012, Liem *et al.* 2007). Various applications of smart textiles have received considerable attention due to the rapid development in global textile industry in the past few decades (Cui *et al.* 2015).

Among the above-mentioned different types of smart textiles, electrically conductive textiles are one of the main research areas. Some commercially available conductive fabrics are made by incorporating thin solid metal wires with conventional non-conducting threads or completely non-conductive threads coated with conductive coatings (Stoppa and Chiolerio 2014, Liu *et al.* 2016). However, these fabrics are not the best for wearable applications due to the discomfort that is experienced by the wearer. Therefore, enhancing electrical conductivity in normal fabrics like nylon, cotton or polyester without changing the conventional properties will be a great invention that opens up lots of opportunities to novel application in the textile industry.

Rahman and Mieno (2015) have demonstrated a method to use carbon nanotubes (CNTs) to fabricate electrically conductive textiles. Though a single carbon nanotube is highly conductive, the connecting junctions between two CNTs have higher resistance. Therefore, complete network of CNTs may not be the best for the conductive textiles (Doganay *et al.* 2016). Cheng *et al.* (2016) have investigated on copper nanowires (Cu NWs) based highly stretchable fibers. But Cu NWs are highly unstable and rapidly oxidized in normal environmental conditions. By using both copper nanoparticles and silver nanoparticles, Hong *et al.* (2018) have modified a polyester fabric in to a multifunctioning fabric with antibacterial, super hydrophobic and conductive properties. Compared to other nanomaterials, silver nano-materials are more electrically and thermally conductive and relatively stable. Therefore, silver can be considered as one of the most suitable materials that can be used to fabricate smart textiles. In this context, Xue *et al.* (2012) have fabricated a silver nanoparticles layer on

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a bare cotton fibers by reducing $[Ag(NH_3)_2]^+$ complex using glucose. But using Ag NWs with high aspect ratio is better for modifying textiles, since it is easy to obtain physical connections between wires rather than particles. Atwa *et al.* (2015) have demonstrated a method to fabricate Ag NW-coated threads for the electrically-conductive textiles. Properties of modified textiles with various physical parameters have been investigated by Doganay *et al.* (2016) and Yu *et al.* (2016) by incorporating Ag NWs in to a cotton fabric using dip and dry method (dipping of the fabric in Ag NWs solution, followed by drying). Electrical properties of highly stretchable fabrics have been investigated by Cui *et al.* (2015) using relatively long (60-100 μm) Ag NWs.

The continuous measuring of body temperature is significant for monitoring the human health (Husain *et al.* 2013). In conventional methods, thermometers such as mercury, electronic and infrared thermometers, etc. are used for discrete measurements of human body temperature. All these methods are difficult to use for continuous body temperature measurements without affecting the daily activities of a person. Song *et al.* (2018) have carried out a method for continuous body temperature measurements using a complicated method with the aid of pre-fabricated sensors. Husain *et al.* (2013) have reported a wearable temperature sensing fabric by incorporating bulk metal wires of copper, nickel and tungsten into a fabric in a specific pattern.

However, these types of sensors are somewhat uncomfortable for wearable applications. Therefore, developing a comfortable and flexible temperature sensor for continuous body temperature measurements is of utmost importance. This can be achieved by using conductivity enhanced Ag NWs incorporated fabrics. Since the wearable textile is well in contact with the wearer's body, this type of a sensor can respond quickly to the body temperature changes. Therefore, by fine tuning the properties of Ag NWs incorporated fabric, it can be improved to work as both a temperature sensor as well as a heater.

In this reporting study, electrical conductivity of insulating bare cotton fabrics has been enhanced by incorporating polyol synthesized Ag NWs by a simple drop casting method. The drop casting method for Ag NWs incorporation helps to increase the conductivity without altering the conventional wearable properties of the cotton fabric. The modified conductive fabric can also be used as heat generating fabric that operates through Joule heating mechanism by supplying a voltage. According to the Joule heating mechanism, heat generation of the fabric can be denoted by Eq. (1) (Doganay *et al.* 2016)

$$P = I^2R \tag{1}$$

where, P is a heat generating power, I is a current flown through the sample and R is a resistance of the sample. This type of a fabric can be used specifically in medical field for the thermotherapy or as the wearable jackets. As for the best of the knowledge of the authors, this kind of study regarding the dual-purpose fabric has not been carried out up to date.

2. Materials and methods

Ag NWs were synthesized by using silver nitrate ($AgNO_3$, 99.8%, Daejung), polyvinyl pyrrolidone (PVP, Mw = 44,000, BOH Laboratories), glycerol (Surechem products LTD) and sodium chloride (NaCl, 99.5%, Sigma-Aldrich) using a method reported elsewhere (Yang *et al.* 2015, Kumari *et al.* 2019). A final product was qualitatively characterized by using ZEISS EVO LS15 scanning electron microscope, Shimadzu UV-1800, UV-visible spectroscope and quantitatively analyzed by using Agilent 4200 Microwave Plasma Atomic Emission Spectroscope (MP-AES).

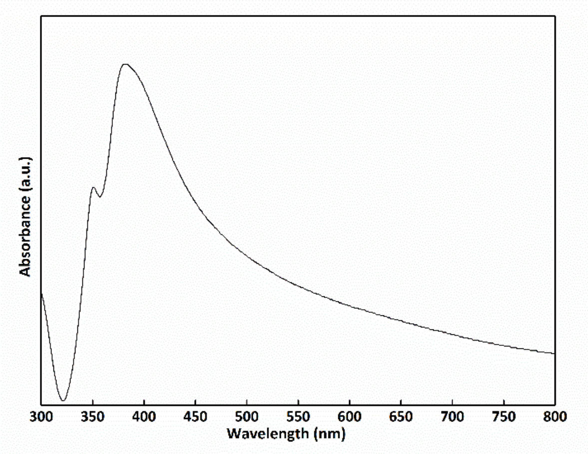
The bare cotton fabric (hand woven cotton fabric without artificial fibers) was cleaned using acetone (99.8%, Sigma-Aldrich), isopropyl alcohol (99.8%, Sigma-Aldrich) and finally with deionized water. After drying the cleaned fabric, it was cut in to 5 × 5 cm size squares. Then, 10.0 mL ethanol (98%, Sigma-Aldrich) solutions with 10, 20, 30, 40, 50, 60, 70 and 80 mg of Ag NWs were prepared and drop casted on to different fabric pieces prepared. Afterwards, the samples were characterized to determine the optimum amount of Ag NWs which can be incorporated. The sheet resistances, heat generation abilities and bulk resistance variations with respect to the temperature were measured using standard four probe technique, FLIR T640 infrared thermo graphic camera and ohm meter respectively. Interactions between Ag NWs and the cotton fabric was investigated by using the Fourier-Transform Infrared Spectroscopy (FTIR).

Later a 4% polyacrylonitrile (PAN, Mw = 150,000, Sigma-Aldrich) solution was prepared by dissolving in dimethylformamide (DMF, Sigma-Aldrich) and drop casted on to the fabric which was fabricated by incorporating the optimum amount of Ag NWs to act as a protective layer. Then, the washing stability of the Ag NWs incorporated fabrics with and without the protecting polymer layer was investigated under the simulated washing conditions using the MP-AES measurements. The time dependence and reproducibility of the temperature profiles of the coated optimized fabric was investigated. All the temperature values of the fabrics were obtained by the infrared thermo graphic camera.

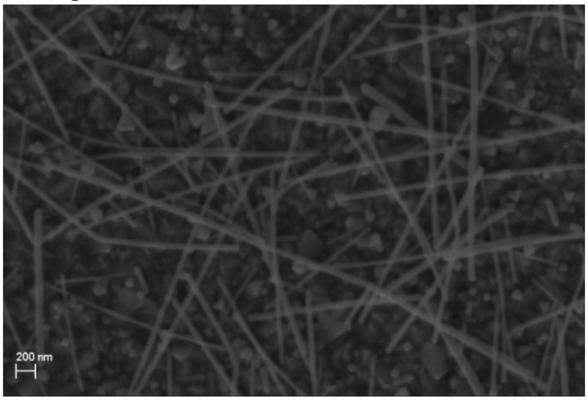
3. Results and discussion

3.1 Characterization of Ag NWs

The UV-visible spectrum obtained for the synthesized Ag NWs is shown in the Fig. 1(a). The two peaks shown at ~ 350 nm and ~ 380 nm in the spectrum are attributed to the longitudinal and transverse surface plasmon resonance of Ag NWs respectively (Zhang *et al.* 2017). The existence of these two peaks confirms the formation of Ag NWs. The surface morphology of the synthesized Ag NWs was studied using SEM under a 10 kV beam. Fig. 1(b) shows an SEM image of the synthesized Ag NWs. The average diameter and length of the synthesized Ag NWs were found to be ~ 80 nm and ~ 3 μm respectively. The grain like structure in

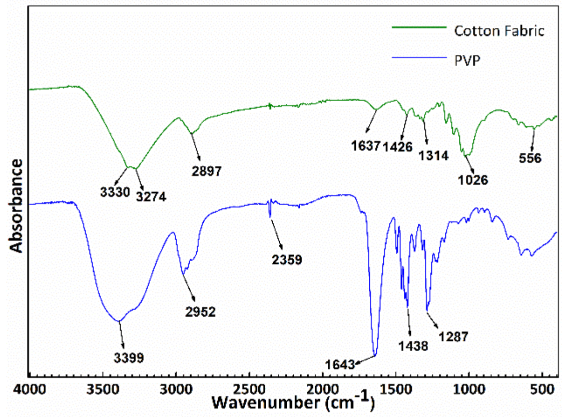


(a) UV-Visible absorption spectrum of synthesized Ag NWs

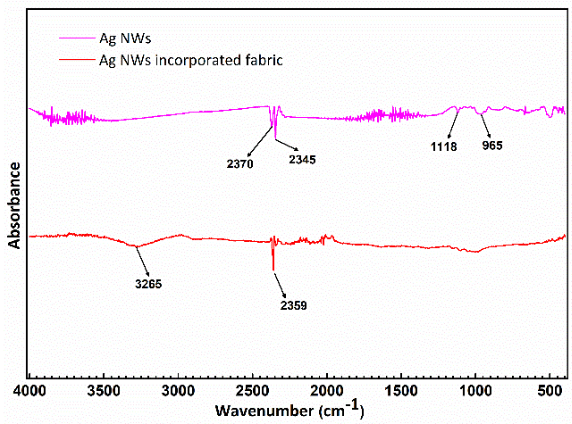


(b) A SEM image of synthesized Ag NWs

Fig. 1 Characterization results of synthesized Ag NWs



(a) FTIR spectra of the cotton fabric and PVP



(b) FTIR spectra of the Ag NWs and Ag NWs incorporated cotton fabric

Fig. 2 FTIR analysis to investigate the interactions between Ag NWs and cotton fabric

the background was identified to be the Fluorine doped Tin Oxide (FTO) surface of the substrate where Ag NWs were deposited for imaging. The concentration of the Ag in the synthesized stock solution was estimated using the MP-AES results. According to the results, the Ag NWs concentration of the stock solution was found to be 4.1 mg cm^{-3}.

3.2 Characterization of the samples

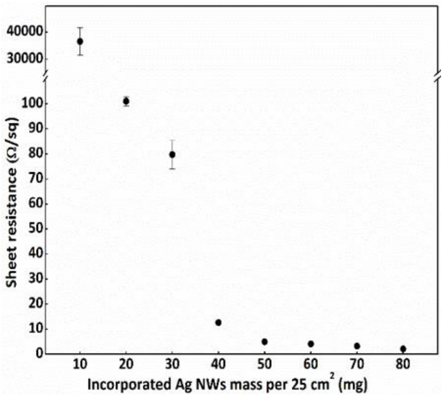
3.2.1 Interactions

Cotton fabrics are mainly composed of cellulose with minor amounts of non-cellulosic materials including wax, pectin and proteins (Chung *et al*. 2004). Also, small amount of PVP can remain on the surfaces of polyol synthesized Ag NWs surface which can make some interactions with the cotton fabric. In order to predict the interactions between the Ag NWs and the cotton fabric, FTIR spectra of the pure cotton fabric, PVP, Ag NWs and Ag NWs incorporated cotton fabric were obtained (Fig. 2). As shown in Fig. 2(a), a broad peak can be seen around 3330 cm^{-1} in the FTIR spectrum of the pure cotton fabric due to stretching vibration of O-H bonds. The overlap of two peaks (3330 cm^{-1} and 3274 cm^{-1}) in the spectrum could be possibly due to O-H functional groups present in cellulose and pectin. Therefore, the main functional group that can lead to interactions with guest molecules in the cellulose is hydroxyl group in the cotton fabric.

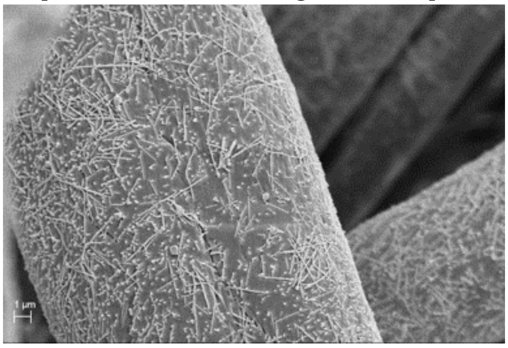
FTIR of Ag NWs does not show any significant peak in the spectrum, suggesting that it does not contain any peak responsible for functional groups present in the capping agent (PVP) that was used during the Ag NWs synthesis, confirming the complete removal of PVP during the washing process. According to the FTIR of the pure cotton fabric and the Ag NWs incorporated cotton fabric, the peak for O-H stretching of fabric is shifted to lower wavenumber (3265 cm^{-1}) indicating the interaction of Ag NWs with cotton fabric through O-H groups (Fig. 2) (El-Shishtawy *et al*. 2010).

3.2.2 Sheet resistance

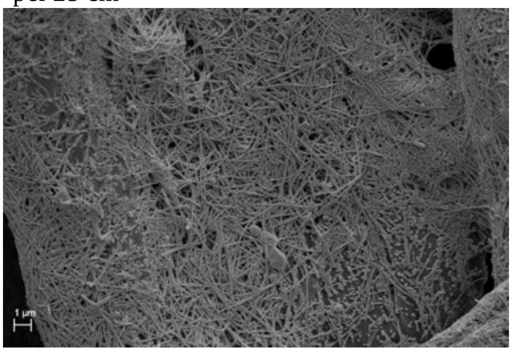
The drop casting method allows an estimation of the exact amount of Ag NWs mass incorporated to the fabric per unit area. Therefore, sheet resistances of the drop casted fabrics were measured by changing the mass of the incorporated Ag NWs from 10 to 80 mg (per 25 cm^{2}). Fig. 3(a) shows the variation of the sheet resistance of the smart fabric with the amount of Ag NWs incorporated in it. As can be seen from Fig. 3(a), the sheet resistance drastically decreases from ~ 36 ± 5 kΩ/sq to ~ 2 ± 0.34 Ω/sq with the increasing amount of the Ag NWs incorporated.



(a) Variation in sheet resistance of the smart fabrics with respect to the amount of Ag NWs incorporated

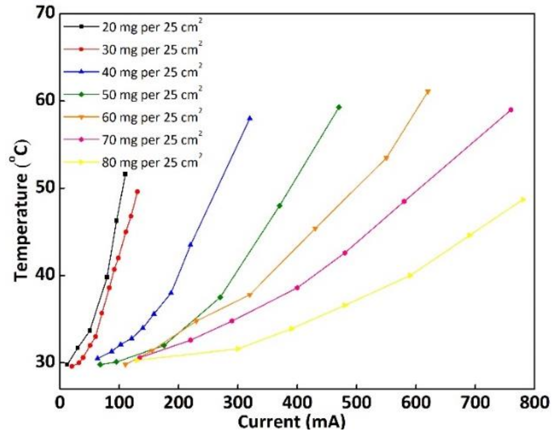


(b) SEM images of the sample with 10 mg of Ag NWs per 25 cm^2

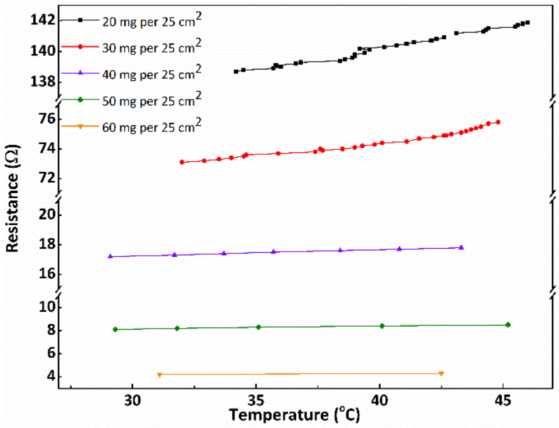


(c) SEM images of the sample with 80 mg of Ag NWs per 25 cm^2

Fig. 3 Sheet resistances and the SEM images of the fabricated samples



(a) Variation of the steady state temperature with the applied current for the fabric with different amounts of Ag NWs



(b) Variations of the resistances with the temperature of the samples having different amounts of Ag NWs

Fig. 4 Heat generation and resistance variation properties of the fabrics

The underlying reason for this drastic decrement of the sheet resistance can be understood from the SEM images of the fabrics with 10 and 80 mg incorporation of Ag NWs (per 25 cm^2) as shown in Figs. 3(b) and (c), respectively. The continuity and uniformity of the distribution of Ag NWs along fibers of the fabric with higher amounts of Ag NWs seems to have been enhanced. As a result, the sheet resistance of the fabric drastically drops with the increase in the amount of Ag NWs in it.

3.2.3 Heat generation ability

A network of Ag NWs can be obtained on a substrate by using various deposition methods. In this study, networks of Ag NWs were fabricated layer by layer using drop casting method and randomly distributed well connected three-dimensional networks of Ag NWs were obtained as depicted in Fig. 3(c). Here, the places where two different Ag NWs touch each other are called "point of contacts" (Song *et al*. 2014). When an external voltage is applied to the Ag NWs conducting network, the accelerated electrons collide with defects (mainly point contacts) in the accelerating path and generate the heat. The heat generating ratio between these points of contact and within the wire can be given by Eq. (2) (Song *et al*. 2014)

$$\frac{P_c}{P_w} = \frac{R_c}{R_w} \tag{2}$$

where, P_c is a power generation at point contact, P_w is a power generation within the nanowire, R_c is a resistance of point contact and R_w is a resistance of nanowire. It was experimentally found that $R_c + R_w$ is in the order of 10^{10} Ω and R_w is about 180 Ω. This implies that almost all the heat is generated at the point contacts. The heat generating power of the fabric due to Joule heating can be given by Eq. (1). When this heat generation rate is equal to the rate of heat dissipation from the sample, it reaches the steady state temperature, which remains constant thereafter.

Fig. 4(a) shows the variations of the steady state temperatures for different current flows through the samples investigated in this study. As it can be seen from the Fig. 4(a), with decreasing amount of Ag NWs incorporated in the fabric, the required current flow to achieve the same steady state temperature decreases. Further, it can also be observed that, for the fabric with 20 mg of Ag NWs (per 25 cm^2) to achieve the steady states temperature of ~ 40°C, it needs a current of 79.2 mA with 11.1 V, whereas the sample with 80 mg of Ag NWs required a current of 590 mA with 1.1 V to achieve the same steady state temperature. For wearable mobile applications it is better to use lower voltage values since the power has to be supplied by solid state batteries. Therefore, it is better to use fabrics with lower sheet resistance as wearable heat generators.

3.2.4 Temperature dependence of the resistance of the fabrics with Ag NWs

When the body temperature is measured continuously by any method with sensors, there should be a data acquisition system to collect data generated from the sensor. Generally, this type of a system consists with the programmable micro-controller circuit. From the micro-controller perspective, an input signal to the micro-controller is generally a small voltage that corresponds to a measured physical parameter. Therefore, in this study, input signals to the microcontroller should also be a voltage which varies according to the temperature of the body. This kind of varying voltage signal can be obtained from these fabrics due to resistance variation which occurs according to the temperature variations. However, accuracy of the measurement critically depends on the magnitude of the current value through the fabric. The current should not be too large to cause an increase in the temperature in itself by Joule heating.

In order to explore the possibility of using this smart fabric as a sensor for continuous body temperature measurements, the variation of the bulk resistance with the temperature was also studied in this investigation. Fig. 4(b) shows the respective results obtained. In this result, the bulk resistance of the sample has been measured instead of the sheet resistance as the variation of the voltage across the fabric is due to the bulk resistance variation of the fabric. The selected temperature range that the resistances were measured is around the average human body temperature range of 36.5-37.5°C (Burton 1935). Since the samples that incorporated either 70 or 80 mg of Ag NWs (per 25 cm^2) does not show a measurable resistance variation within the above selected temperature range, the resistance variation of the above two samples were not included in the Fig. 4(b). According to the Fig. 4(b), the resistance variation of the samples with respect to the temperature is higher if the initial resistance of the sample is higher. In order to act as a sensor, it is better to have a higher variation of the resistance even with respect to a small change in the temperature, since higher the variation in the resistance, higher the resolution of the sensor.

Fig. 5 summarizes the required voltage to heat the fabric sample to a temperature of 40°C and variation of resistance corresponding to a unit temperature change in the sample

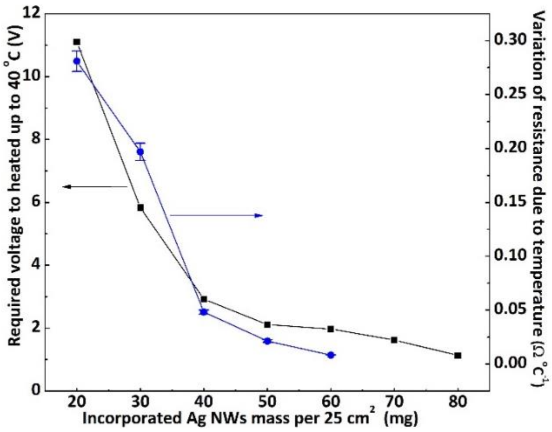


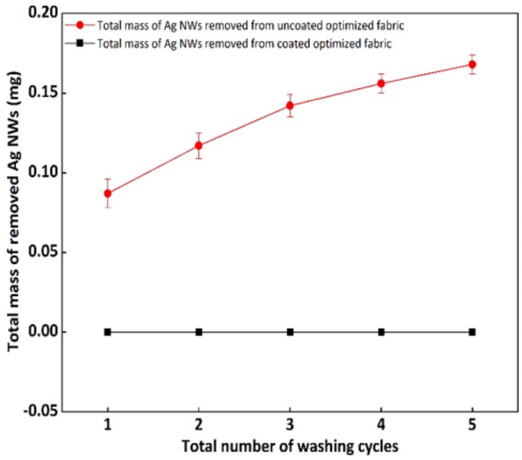
Fig. 5 Variation of resistance due to temperature and the required voltage to heated up to 40°C with respect to incorporated Ag NWs mass

with respect to different Ag NWs masses incorporated to the respective fabric samples. According to these data, the sample with 80 mg of Ag NWs incorporation (per 25 cm^2) required the lowest voltage (1.1 V) to heat the sample up to 40°C. However, it does not show an appreciable resistance variation within the body temperature variation range. Hence, the sample with 80 mg of Ag NWs incorporation (per 25 cm^2) is better as a heat generator but not as a temperature sensor. On the other hand, the sample with 20 mg of Ag NWs (per 25 cm^2) has higher resistance variation with respect to temperature (0.28 Ω $°C^{-1}$) but it requires higher voltage (11.1 V) to be heated up to 40°C. Therefore, the fabric with 20 mg of Ag NWs incorporation (per 25 cm^2) is better as a temperature sensor but not as a wearable mobile heat generator. The aim of the work is to develop a single fabric which can be actuated as both a heat generator and a temperature sensor. Therefore, according to the results, the sample with 30 mg of Ag NWs incorporation is better as both a wearable heat generator and a temperature sensor, as it has a good resistance variation value with respect to the temperature (0.20 Ω $°C^{-1}$) and can be heated up to ~ 40°C using relatively lower voltage (5.8 V). Further investigations were carried out based on this selected optimized sample.

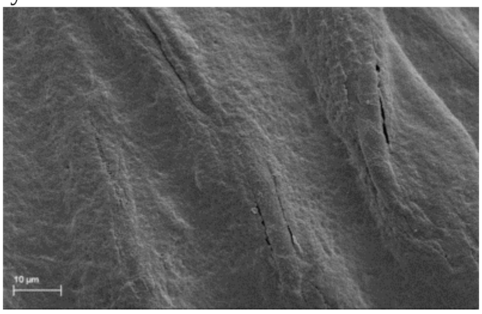
3.2.5 Washing stability of the conductive fabric

Since the incorporated Ag NWs are weakly connected on to the cotton fibers of the fabric, the washing stability of the conductive fabric can be poor due to the removal of Ag NWs during the washing conditions. Therefore, in order to prevent the removal of Ag NWs during the washing processes, a thin polymer coating (PAN) was coated on top of Ag NWs of the optimized fabric. Here, the protective layer is used to increase the washing stability of the fabrics. Therefore, the material which is used for the protective layer should be water insoluble. Due to this reason we have used PAN as the protective layer.

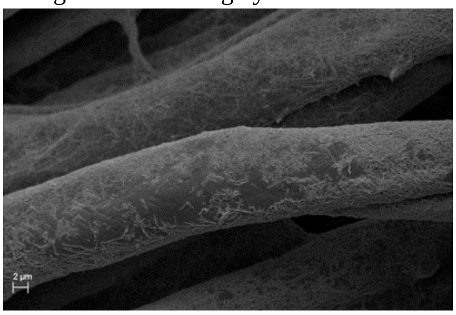
The washing stability of both the coated and uncoated optimized fabrics were then investigated. In order to simulate a washing cycle, fabrics were stirred at 500 rpm for 30 minutes in 50 ml of deionized water at room



(a) The total mass of removed Ag NWs for 5 washing cycles of uncoated and coated fabrics

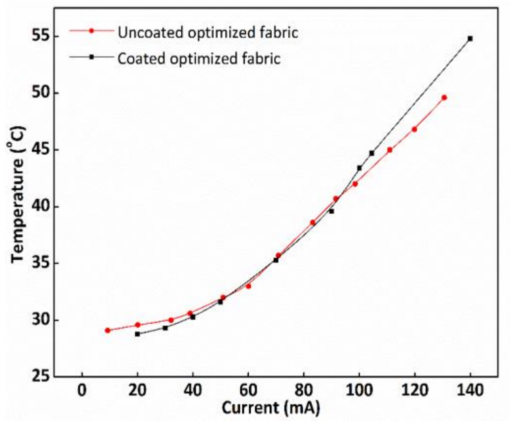


(b) SEM image of conductive fabric with the polymer coating after 5 washing cycles

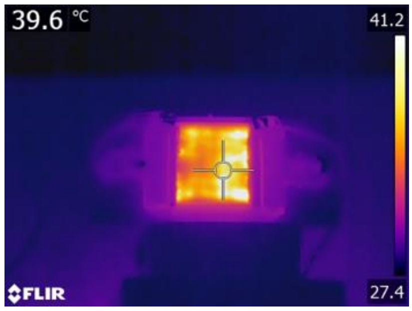


(c) SEM image of conductive fabric without the polymer coating after 5 washing cycles

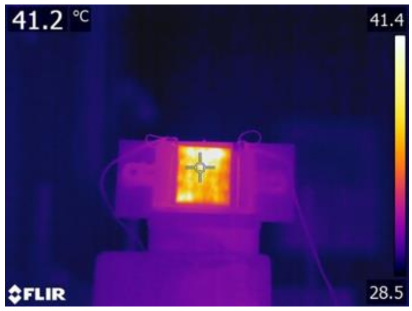
Fig. 6 Washing stability of coated and uncoated optimized fabrics



(a) Steady state temperature variations of uncoated and coated optimized fabric samples for different currents



(b) Temperature profiles of uncoated optimum sample at a current flow of 90 mA



(c) Temperature profiles of coated optimum sample at a current flow of 90 mA

Fig. 7 The graphical representation of the steady state temperatures of the uncoated and coated optimum samples and the thermographic images of the samples

temperature. The washing stability of both the coated and uncoated fabrics at the end of different washing cycles was determined by measuring the amount of silver released to the medium using MP-AES measurements. Fig. 6(a) shows the total amount of Ag NWs removed with respect to the total number of washing cycles for both the polymer coated and uncoated fabrics. As it is shown in the Fig. 6(a), mass of the removed Ag NWs increases with the number of washing cycles in the uncoated optimized fabric, whereas it was almost zero or negligible in the polymer coated optimized fabric. The amount of Ag NWs removed from the uncoated fabric at a single washing cycle decreased with the number of total washing cycles. This could be due to the easy removal of Ag NWs of the cotton fibers of the fabric during the initial washing cycles and slow removal of Ag NWs from closely packed inner cotton fibers later on. This is further confirmed by the SEM images of the above samples. Figs. 6(b) and (c) show the SEM images of the conductive fabrics with and without polymer coating after 5 washing cycles respectively. The SEM images reveal that the Ag NWs conductive network on the outer cotton fibers has become damaged while network on inner fibers remains almost unchanged. Therefore, according to these observations it can be concluded that the polymer coating is more effective in terms of usage of these conductive smart fabrics for a prolonged time due to its activity as a protective layer for these Ag NWs. Since the protective polymer layer completely covers the Ag NWs, as seen in

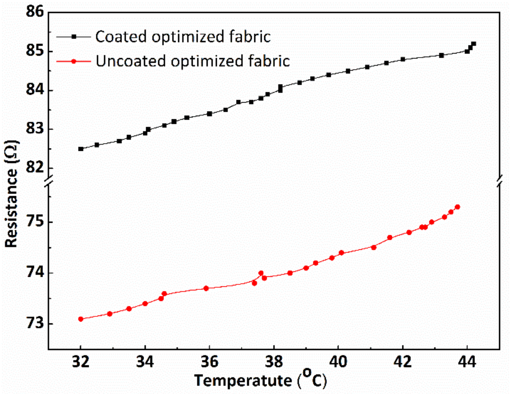


Fig. 8 Variation of the resistance of the Ag NWs optimized fabric with temperature

Fig. 6(b), sticking of weakly bound Ag NWs to another surface such as human's skin can be considered to be minimal.

3.3 Characterization of the polymer coated conductive fabric with optimized amount of Ag NWs

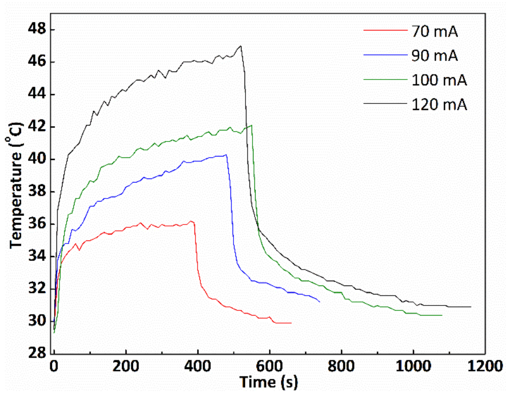
3.3.1 Heat generation ability and resistance variation with respect to temperature

Even though the polymer coating has improved the washing stability of the fabric, it is essential to investigate the performance of the coated optimized fabric as a thermogenic sensor. Fig. 7(a) shows the steady state temperature variation of both coated and uncoated fabrics when subjected to different currents. According to the result, it is obvious that the coating of the fabric has not altered the steady state temperature of the fabric. Therefore, it can be concluded that thermogenic ability of the fabric has not changed due to coating of the fabric. Thermographic images of the above polymer coated, and uncoated fabrics taken under a current of 90 mA are shown in Figs. 7(b) and (c). These images confirm similar characteristics in the temperature distributions of these fabrics irrespective of the polymer coating.

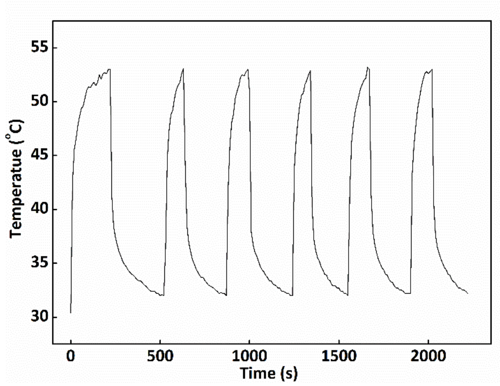
In order to investigate whether the coating of the sample has affected the sensing ability of the fabric, the variation in the resistance of coated and uncoated optimized fabrics with respect to temperature was investigated. The results are shown in Fig. 8. It was observed that irrespective of the polymer coating, the resistance variation of the fabric with respect to the temperature is about 0.20 Ω $^{o}C^{-1}$ in both cases. Therefore, it can be concluded that the polymer coated optimized fabric can also be used as a temperature sensor. According to the results shown in Fig. 6(a) to Fig. 8, it is evident that the polymer coated optimized fabric can be used as a heat generatable temperature sensing fabric. Hence further characterizations were done only for polymer coated optimized fabric.

3.3.2 The time dependence of the temperature profile of the polymer coated optimized fabric

The time dependence of the heat generation of the fabric



(a) Temperature profiles of the coated fabric for different current flows



(b) Reproducibility of the coated fabric for repeated on-off cycles

Fig. 9 Heat generation profiles of the polymer coated optimized fabric with respect to time

was investigated by using a thermo graphic camera under different currents. Fig. 9(a) depicts the temperature profiles of polymer coated fabric under different current flows. As it can be seen from the Fig. 9(a), each temperature profile comprised with a warming up period, steady state period and then a sudden decrease in the temperature after stopping the current flow. The average time that was required to reach the respective steady state temperatures under different currents is around 200 s, which is quite suitable for wearable applications. Also, sudden decrease in temperature shows that the heat releasing ability of the fabric is quite high. The heated fabric can cool down to 32-34°C within a few seconds, and to the temperature of the surrounding within few minutes without any special cooling mechanism.

Reproducibility is another important factor when it comes to the fabric's thermogenic ability. Therefore, temperature variation of the fabric was investigated for repeated on-off cycles under a current flow of 140 mA. According to the temperature profiles shown in Fig. 9(b), which was obtained by varying the temperature of the sample within a particular range in a cyclic manner over time, the fabric has shown good reproducibility in heat generation.

Doganay *et al*. (2016) has reported that the Ag NWs incorporated fabrics show a considerable performance drop with time when the fabrics are stored in the ambient conditions for a few months without a protective layer due to the oxidation of Ag NWs. However, in the reporting of study, the protective PAN layer may increase the durability the performance of the fabric by reducing the exposure to the ambient.

4. Conclusions

A commercially available cotton fabric was successfully modified into an electrically conductive smart fabric by drop casting of Ag NWs to function as a thermogenic temperature sensor. The optimum concentration of Ag NWs to be incorporated to actuate the fabric as a thermogenic sensor was found to be 30 mg of Ag NWs per 25 cm^2 of cotton fabric, which yielded a sheet resistance of 79.7 ± 5.7 Ω/sq. Adding a water insoluble PAN polymer layer on to the Ag NWs incorporated optimized fabric completely prevented the removal of Ag NWs without altering the temperature sensing and heat generating properties. PAN coated Ag NWs incorporated fabric can be heated up to maximum of 45°C using standard 9 V battery. According to the steady state temperature variations, the temperature of the modified fabric can be controlled by varying voltage through the fabric as desired. The time dependence of the temperature profiles suggests fast heating and high heat releasing ability of the fabric. Heat generation of the fabric was also found to be highly reproducible.

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