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Silver nanowire-functionalized cotton fabric

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ABSTRACT

In this study, general functionalization of cotton fabric by loading silver nanowires (AgNWs) on cotton surface is reported. Initially, AgNWs were synthesized by a polyol process and then were conformal coated onto individual cotton fibers through a simple "dip and dry" process. SEM images revealed a thin and uniform AgNWs coating on the cotton microfibers which was supported by a surface chemical analysis by EDX. The average electrical surface resistivity of the fabric coated with conductive network of AgNWs was measured to be 27.4 Ω/sq. Incubating the modified fabric with either *Escherichia coli* or *Staphylococcus aureus* demonstrated that the fabric had substantial antimicrobial capacity against both Gram-positive and Gram-negative bacteria (100% microbial death). The fabric also showed excellent UV-blocking ability with the UV protection factor of 113.14. The fluorosilane coated AgNWs-loaded fabric displayed stable superhydrophobicity with CA and SHA values of $156.2^\circ \pm 3.2^\circ$ and 7°, respectively.

1. Introduction

After the emergence of nanotechnology, new challenges appeared in various areas of research toward the design of functional materials and technological processes. A nanowire is a nanostructure, with the diameter of the order of a nanometer (10^{-9} m). Many different types of nanowires exist, including metallic (e.g., Ni, Pt, Au), semiconducting (e.g., Si, InP, GaN, etc.), and insulating (e.g., SiO_2, TiO_2). Nanowires have many interesting properties that are not seen in bulk or three-dimensional materials. There are many applications where nanowires may become important in electronic, opto-electronic and nanoelectromechanical devices, as additives in advanced composites, for metallic interconnects in nanoscale quantum devices, as field-emitters and as leads for biomolecular nanosensors (Hyun, Zhang, & Lauhon, 2013; Penner, 2012; Rojo, Calero, Lopeandia, Rodriguez-Viejo, & Martín-Gonzalez, 2013).

Silver nanowires (AgNWs) have attracted more and more attention because of their intriguing optical (solar thin films, solar crystalline silicon, medical imaging, Raman spectroscopy, optical limiters, surface plasmons), conductive (light emission diodes, touchscreen displays, computer boards, conductive adhesives and sensors), antimicrobial (bandages, films, air & water purification, sterile equipment, food preservation and clothing) and chemical and thermal (catalysts, sensors, pasts, polymers and thermal adhesives) properties (De et al., 2009; Langley et al., 2013; Liu & Yu, 2011; Yogeswaran & Chen, 2008). These multiple properties make AgNWs as a suitable candidate to be used in fabrication of multifunctional products.

Over the past few decades, surface modification of fibers and functional finishing of textiles have attracted tremendous attention (Abidi, Cabrales, & Hequet, 2009; Alongi, Carosio, & Malucelli, 2013; Bacciarelli-Ulacha, Rybicki, Matyjas-Zgondek, Pawlaczyk, & Szynkowska, 2014; Bedford & Steckl, 2010; Broasca, Borcia, Dumitrascu, & Vrinceanu, 2013; Carosio et al., 2013; Khalil-Abad, Yazdanshenas, & Nateghi, 2009; Nateghi, Dehghan, & Shateri-Khalilabad, 2013; Nateghi & Hajimirzababa, 2014; Pereira et al., 2011; Shateri-Khalilabad & Yazdanshenas, 2013a,b,d,e; Shim, Chen, Doty, Xu, & Kotov, 2008; Tang et al., 2013; Wang, Zhou, Gestos, Fang, & Lin, 2013; Wu & Long, 2011; Yazdanshenas & Shateri-Khalilabad, 2013; Zhang & Yang, 2009; Zhu, Gao, Guo, Yang, & Shen, 2011; Zhukovskyi, Sanchez-Botero, McDonald, Hinestroza, & Kuno, 2014). Nanostructured materials can impart desired functional properties to the fibers and textiles for their applications, such as ultraviolet (UV) protection (Abidi et al., 2009; Broasca et al., 2013; Shateri-Khalilabad & Yazdanshenas, 2013a), antibacterial resistance (Bacciarelli-Ulacha et al., 2014; Khalil-Abad et al., 2009; Nateghi & Hajimirzababa, 2014; Tang et al., 2013), flame retardancy (Alongi et al., 2013; Carosio et al., 2013), antistatic (Zhang & Yang, 2009), electrical conductivity (Shateri-Khalilabad & Yazdanshenas, 2013b,e; Shim et al., 2008), self-cleaning (Bedford & Steckl, 2010;

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Wu & Long, 2011) and superhydrophobicity (Nateghi et al., 2013; Pereira et al., 2011; Shateri-Khalilabad & Yazdanshenas, 2013d; Wang et al., 2013; Yazdanshenas & Shateri-Khalilabad, 2013; Zhu et al., 2011). Ideally by using nanomaterial, multifunctional textiles can be designed to have integrated functionalities that work in synergy to provide advantages that reach beyond that of the sum of the individual capabilities. Textiles of this kind have tremendous potential to impact future structural performance by reducing size, weight, cost, power consumption, and complexity while improving efficiency, safety, and versatility.

The purpose of present work is to fabricate multifunctional cotton textiles with AgNWs, according to its multiple properties, by a one-step simple "dip and dry" treatment. To this end, AgNWs were synthesized by polyol process and then were dispersed in ethanol to form stable colloidal solution for coating cotton fabric. The treated cotton fabrics were found with high electrical conductivity, excellent UV protective property and antibacterial activity simultaneously. In addition, after coating of a layer of low-surface-energy fluorosilane, superhydrophobicity was obtained. Among the various morphologies of silver nanostructures such as spherical, polygonal, prism and flakes, AgNWs show high one dimensional conductivity due to the unique morphology. Moreover they can be physically attached to the fibers since of their penetrating capability.

2. Experimental

2.1. Materials

Reagent-grade ethylene glycol (EG), silver nitrate ($AgNO_3$), polyvinylpyrrolidone (PVP), sodium chloride (NaCl), ethanol and acetone were purchased from Merck. Danasylan® F 8815 (modified fluoroalkyl siloxane, waterborne) was kindly supplied by Evonik Co. Ltd., Germany. Commercial 100% cotton fabric was obtained from Yazdbaf Textiles Co., Yazd, Iran. The fabric was desized, scoured, and bleached before being used. Milli-Q grade (resistivity 18.2 M Ω/cm) water was used throughout the experiments.

2.2. Preparing AgNWs

AgNWs were synthesized based on the reported method (Coskun, Aksoy, & Unalan, 2011). Briefly, 10 mL of 0.9 M EG solution of PVP (vinylpyrodine-based calculation) was prepared and 10 mg of NaCl was added into it. The solution was heated to 170 °C in a two-necked round flask. In the meantime, a 0.12 M $AgNO_3$ solution in 5 mL of EG was prepared and added drop wise into the PVP solution at a rate of 5 mL/h. The solution was stirred at a rate of 1000 rpm by a magnetic stirrer during the whole process. Upon the completion of drop wise addition, the nanowire solution was annealed for 30 min at 170 °C and finally air-cooled to room temperature. In order to separate PVP from the Ag nanowires, the solution was diluted with acetone (in a ratio of 1:5) and centrifuged three times at 4000 rpm for 10 min. Then, the nanowires were dispersed in ethanol and again centrifuged at 4000 rpm for 10 min. The final product was dispersed in ethanol for further characterization and use. The obtained dispersion did not contain any visible solid and were stable for days. The concentration of the dispersion was adjusted to 1 g/L by drying 1 mL dispersion and weighing the remained solid.

2.3. AgNWs loading on cotton fabric

Cotton fabric was immersed in the AgNWs dispersion for two min, then removed and dried at room temperature. This process was repeated 10 time to increases the AgNWs loading in the cotton. The fabric was subsequently dried at 90 °C for 30 min.

2.4. Surface modification by low-surface-energy layer

The pristine and AgNWs-loaded fabrics were modified by dipping the fabric into the 10 vol.% aqueous solution of Danasylan® F 8815 and reacted for 10 min. After the reaction, the samples were removed, dried and cured in an oven at 110 °C for 60 min.

2.5. Characterization

The absorption spectrum of AgNWs colloidal solution was recorded by ultraviolet–visible (UV–vis) spectroscopy with a Cary 100 spectrophotometer, using 10 mm path length quartz cuvettes. Microscopic investigations of the synthesized AgNWs and fabric samples were carried using KYKY-EM3200 scanning electron microscope (SEM). SEM images of AgNWs were taken without conductive coating. However, the fabric samples were mounted on conductive carbon adhesive tabs and images were taken after the samples had been sputter-coated (SC 7620 EMITECH) with a very thin layer of gold. In order to measure the length and diameter of AgNWs, dispersion of AgNWs was deposited onto glass slide substrate. About 50 nanowires were individually measured and calculated their average length and diameter using imaging processing software Microstructure Measurement with the scale bar obtained during SEM as a reference. To determine the elemental composition of the fabrics surface, an energy-dispersive X-ray (EDX) detector was used with Phenom pro X SEM. EDX spectra of the fabric samples were taken without conductive coating. Transmittance/reflectance spectra of the fabric samples were determined using a Perkin-Elmer Lambda 35 UV–vis spectrophotometer. Air was used as the reference. The spectra were recorded in the range of 400–700 nm. The three coordinates (L^*, a^*, and b^*) of the CIELAB color system and the color difference (ΔE) of the fabrics were measured by colorimetry software. Measurements were performed under standard illuminant D65 and at a 10° observing angle. Electrical surface resistivity of the fabrics was measured in the warp direction using a standard two-probe method (AATCC test method 76-2005, electrical surface resistivity of fabrics) by means of Sa-Iran digital multimeter model 8515. UV-blocking properties of the cotton fabrics were evaluated according to AATCC test method 183-2004 (transmittance or blocking of erythemally weighted UV radiation through fabrics). The ultraviolet protection factor (UPF) rating system measures the UV protection provided by fabric. The UPF is defined as the ratio of the average effective irradiance calculated for skin to the average UV irradiance calculated for skin protected by the test fabric. The UPF was calculated using mean percentage transmission in the UVA region (315–400 nm) and mean percentage transmission in the UVB region (280–315 nm) by the equation

$$UPF = \frac{\sum_{280\,nm}^{400\,nm} E_\lambda \times S_\lambda \times \Delta_\lambda}{\sum_{280\,nm}^{400\,nm} E_\lambda \times S_\lambda \times T_\lambda \times \Delta_\lambda}$$

where E_λ is the relative erythemal spectral effectiveness, S_λ is the solar spectral irradiance, T_λ is the average spectral transmission of the specimen, and Δ_λ is the measured wavelength interval (nm). Antibacterial activity of the fabrics was studied through AATCC 100-2004 (antibacterial finishes on textile materials: assessment of). *Escherichia coli* (*E. coli*, ATCC 1399, Gram-negative bacterium) and *Staphylococcus aureus* (*S. aureus*, ATCC 1431, Gram-positive bacterium) were used as model challenge microorganisms. The samples were tested in two cultured bacteria based on the McFarland standard, 1×10^{-3} CFU/mL (0.5 McFarland). The fabric samples were immersed in one mL of an appropriate dilution in a bacterium test tube (according to the McFarland standard). The test tubes contained fabric sample and bacteria solution were transferred to an incubator with a temperature of 37 °C for 24 h. The tubes were then removed from the incubator and the solution was dripped onto a plate to assess antibacterial properties. From each test tube, 0.1 mL of bacterial suspension mixed with trypticase soy agar (45 °C) and placed in the incubator at 37 °C for 24 h. After incubation, bacterial colonies were counted. The reduction percent of bacteria was calculated by the equation

$$R(\%) = \frac{B - A}{B} \times 100$$

where R is the bacterial reduction ratio in percentage CFU/mL, B is the number of bacterial colonies formed on the control fabric, and A is the number of bacterial colonies formed on the treated fabric. Static water contact angle (CA) measurements were completed on a self-developed goniometer apparatus coupled to a high-resolution camera based on previous works (Shirgholami, Shateri-Khalilabad, & Yazdanshenas, 2013; Shirgholami, Shateri Khalil-Abad, Khajavi, & Yazdanshenas, 2011). Water droplets with a volume of 5 μL were dispensed from a syringe onto the sample surface. The water CA was measured 60 s after the droplets were placed on a fabric surface. For statistics, four separate measurements were performed in different locations, and the results were averaged to obtain the mean and standard deviation. Water shedding angle (SHA) measurements were determined according to the previous work (Shateri-Khalilabad & Yazdanshenas, 2013c). Briefly, the fabric sample was attached to a glass coverslip with double-sided adhesive tape and placed on a custom-built tilting table. A syringe containing water was mounted above the tilting table with a fixed 2-cm needle-to-fabric distance. Droplets of water with a volume of 10 μL were released onto the samples at a minimum of four different positions. The lowest inclination angle at which all of the droplets completely rolled or bounced off the surface was noted as the water SHA. The liquid repellency of the modified fabrics was evaluated by observing the fabric's resistance to wetting by a series of ethanol–water mixtures of different surface tensions. The surface tension values of ethanol–water mixtures were obtained according to the literature (Vazquez, Alvarez, & Navaza, 1995). Drops of test liquids with a volume of 50 μL were placed on the fabric surface in three locations and observed for wetting and wicking at a 45° angle. The aqueous repellency grade corresponding to test liquid having lowest surface that did not penetrate or wet the fabric surface at the liquid–fabric interface and for which no wicking occurred around the drops within 10 ± 2 s.

3. Results and discussion

AgNWs were synthesized by polyol process. The polyol process is based on reduction of an inorganic salt by a polyol at an elevated temperature. A surfactant is used to prevent agglomeration of the colloidal particles. In polyol method, EG is used as both solvent and reducing agent, PVP is used as stabilizing agent, and $AgNO_3$ is used as Ag source (Sun, Mayers, Herricks, & Xia, 2003).

UV–vis absorption spectrum of the synthesized solution is shown in Fig. 1. The plasmon absorption peak appeared at 389 nm demonstrates formation of AgNWs. A shoulder peak appeared at about 350 nm is an optical characteristic of bulk silver. Absence of absorption peak at wavelengths higher than 400 nm indicates that the final product is thoroughly AgNWs (Hu et al., 2004). Nevertheless, it may be containing of a small amount of other morphologies such as nanorods or nanoneedles and spherical nanoparticles.

SEM images of the synthesized AgNWs at different magnification are shown in Fig. 2. From the images it can be observed that the AgNWs are very homogenous in morphology. The diameter of the nanowires is found to be 46.4 ± 4.5 nm.

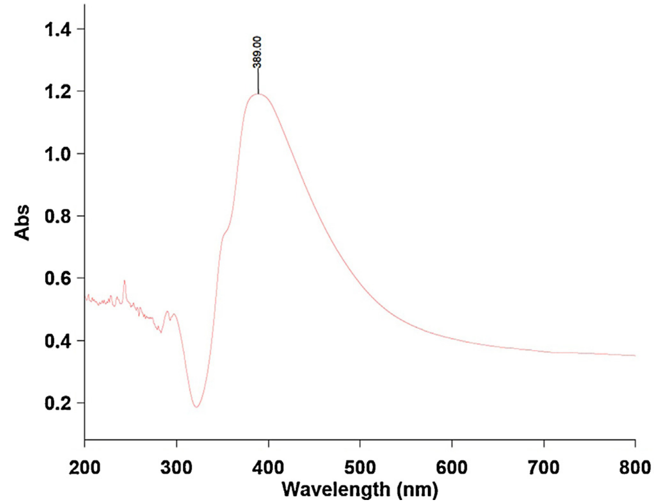

Fig. 1. UV–vis absorption spectrum of the synthesized AgNWs colloidal solution.

AgNWs were loaded to the fabric via "dip and dry" method. The process was repeated 10 times to increase amount of AgNWs loading. After the coating, the original cotton fabric changed its color from white to green due to the greenish color of the AgNWs colloidal solution. The reflectance spectra of pristine and AgNWs-loaded fabrics in the range of 400–700 nm are shown in Fig. 3. The reflectance percentage of pristine fabric reduced from about 65% to 20% due to the AgNWs loading. The CIE color coordinates (L^* a^* b^*) and color differences (ΔE), quantitatively characterizing the observed color of the fabrics, are given in Table 1. The obtained results indicated darker color of AgNWs-loaded fabric compared with the pristine one. The L^* value of pristine fabric is reduced from 84.11 to 52.33, after AgNWs loading. The AgNWs-loaded fabric showed strong increase in the yellow color component (increased value of b^* from 0.03 to 5.40) and in the red color component (increased value of a^* from −0.22 to 0.08), which indicated a color change from white to green. The ΔE value of 32.23 demonstrate high loading of AgNWs on cotton surface.

The surface morphologies of pristine and AgNWs-loaded fabrics were investigated by electron microscopy. The corresponding SEM images are shown in Fig. 4. Low-magnification images (at 500×) show that AgNWs-loaded fabric looked similar to pristine one. The high-magnification images reveal a smooth longitudinal fibril structure of pristine cotton fibers, whereas treated cotton fibers were coated with AgNWs. It is obvious that AgNWs coated on the cotton fabric were random and have good connection to each other.

The chemical composition of the surface of the fabrics was analyzed by EDX spectroscopy (Fig. 5). The spectrum of the pristine sample showed peaks for carbon and oxygen, but no silver was detected. However, the EDX spectrum of AgNWs-loaded fabric yielded carbon, oxygen, and silver peaks. EDX semi-quantitative analysis of AgNWs-loaded fabric showed the weight percentage of 22.5% for silver. The presence of the silver peak indicates the successful coating of AgNWs on the surface of the fabric.

To create an electroconductive textile, a layer of conductive coating must be present to the fiber surface. Loading of AgNWs to the fiber surfaces converted the cotton fabric into an

Table 1
Color coordinates (CIE L^* a^* b^*) and color differences (ΔE) of pristine and AgNWs-loaded fabrics.

Sample	L^*	a^*	b^*	ΔE
Pristine fabric	84.11	−0.22	0.03	–
AgNWs-loaded fabric	52.33	0.08	5.40	32.23

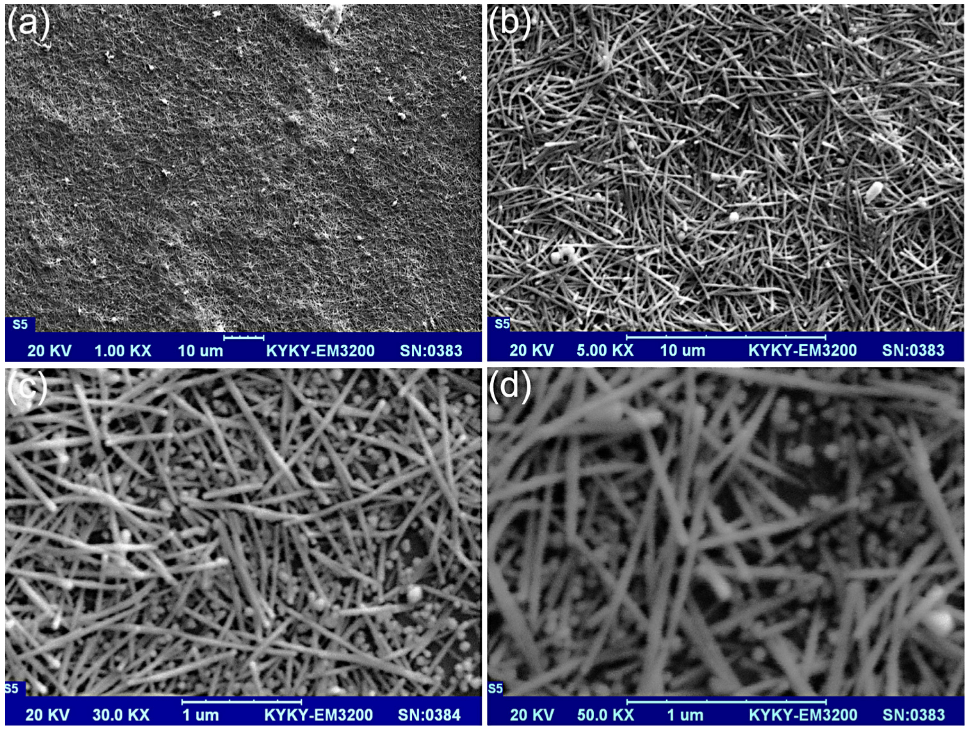

Fig. 2. SEM images of AgNWs at different magnification: (a) 1000×, (b) 5000×, (c) 30,000× and (d) 50,000×.

electroconductive substrate, presumably due to the conductive paths formed by the AgNWs interconnected with each other. To achieve a good degree of electroconductivity, the coating process was repeated 10 times. The average surface electrical resistivity of AgNWs-coated cotton fabric was measured to be 27.4 Ω/sq and showed no significant difference among samples on either side. The functionalized fabric is very flexible and AgNWs layer cannot brittle and cracks easily under bending stress. The conductivity

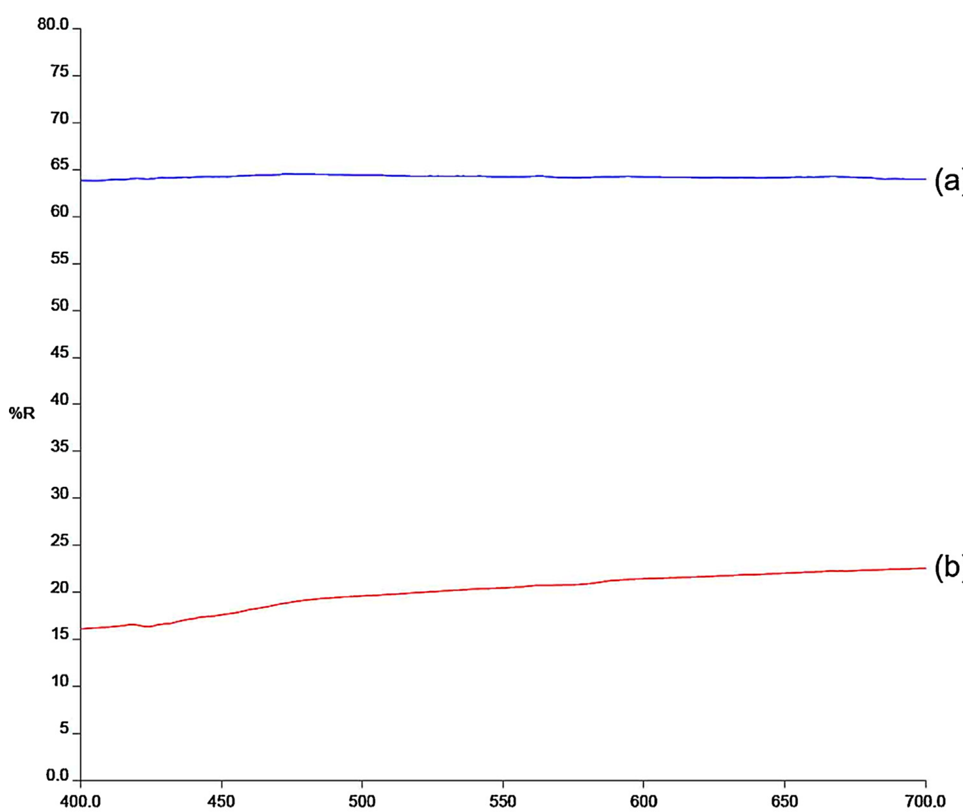

Fig. 3. Reflectance spectra of (a) pristine and (b) AgNWs-loaded fabrics.

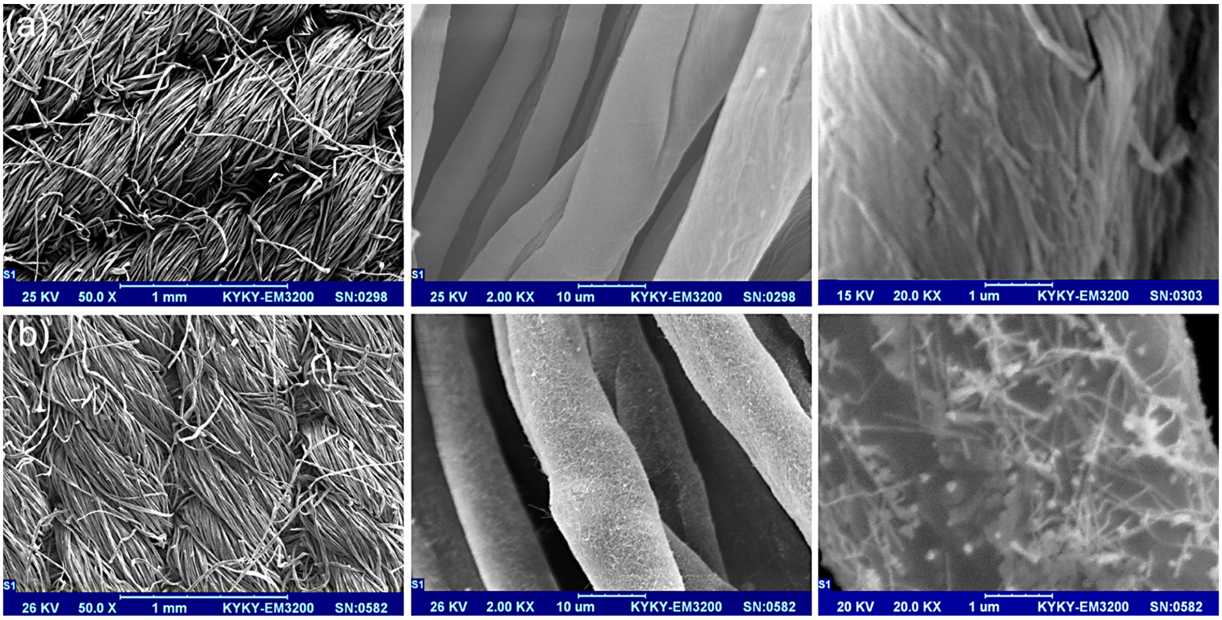

Fig. 4. SEM images of (a) pristine and (b) AgNWs-loaded fabric. Magnification from left to right: 500×, 2000× and 20,000×, respectively.

value does not change after repeated bending. The unique network structure and high electrical and wear resistance properties of AgNWs-loaded fabric possess great potential for use in flexible and stretchable electronics and other devices.

Antibacterial properties of the fabrics were evaluated against Gram-negative *E. coli* and Gram-positive *S. aureus* bacteria, according to AATCC 100-2006 standard method. As expected, no reduction of *E. coli* and *S. aureus* colonies was found on the pristine fabric. On the contrary, there was even an increase in the number of bacteria recovered from the inoculated pristine sample after 24 h of incubation in comparison to "zero" contact time, indicating that bacteria can use pure cotton as a substrate (Yazdanshenas & Shateri-Khalilabad, 2012a,b). From the obtained results, it was determined that the AgNWs-loaded fabric can kill 100% of both *E. coli* and *S. aureus* bacteria, indicating that the fabric is very effective against Gram-positive and Gram-negative bacteria. The excellent antibacterial activity of the fabric could be attributed to its high surface coating with AgNWs.

Despite the vast number of papers touting the beneficial antimicrobial effects of silver nanomaterials (Chernousova & Epple, 2013; Marambio-Jones & Hoek, 2010; Sharma, Yngard, & Lin, 2009), a modest number of studies have attempted to elucidate antimicrobial activity of AgNWs and its comparison to other forms of Ag. In a study (George et al., 2012), it is demonstrated that AgNWs have less toxicity (cell death) against fish gill epithelial cell line and zebrafish embryos, at same dose, in comparison to Ag nanospheres and Ag

Fig. 5. EDX spectra of (a) pristine and (b) AgNWs-loaded fabrics.

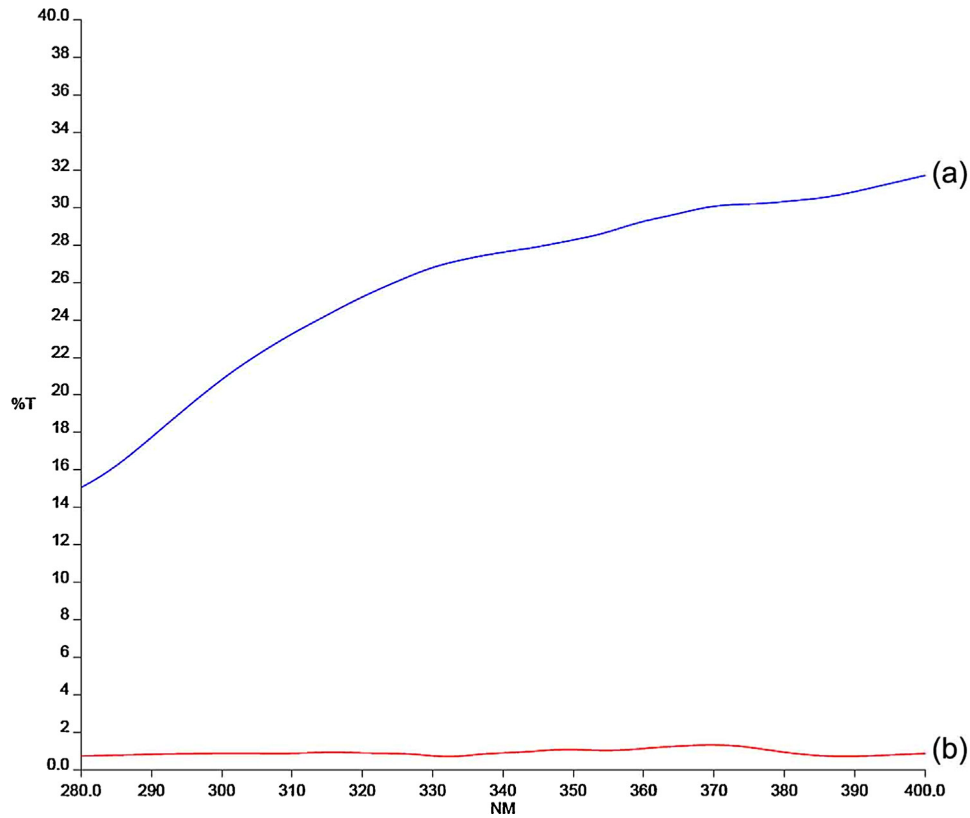

Fig. 6. UV-transmittance spectra of (a) pristine and (b) AgNWs-loaded cotton fabrics.

Table 2
UV-blocking properties of pristine and AgNWs-loaded fabrics.

Sample	Percentage of transmittance (%)			UPF value
	UV-R 280–400 nm	UV-A 315–400 nm	UV-B 280–315 nm	
Pristine fabric	26.11	28.70	19.87	4.27
AgNWs-loaded fabric	0.91	0.95	0.84	113.14

nanoplates. However, in another research (Ivask et al., 2013) it is found that the pathways involved in bacterial responses to Ag nanomaterials are highly dependent on physicochemical properties of the nanoparticles, particularly the surface characteristics.

UV–vis transmittance spectroscopy is a technique for studying the effect of coating on the optical properties of fabrics. Transmittance spectra of pristine and AgNWs-loaded fabrics over the wavelength range of 280–400 nm are shown on Fig. 6. UV transmittance curve of pristine fabric indicates that high percentage of UV-A and UV-B, more than 25%, light can penetrate in cotton fabric. Pristine fabric absorbs about 75% of the radiation over the entire UV region. UV-blocking ability of pristine fabric on UV-B region is higher than UV-A. UV transmittance curve of AgNWs-loaded fabric indicates that the fabric can block high percentage of both UV-B and UV-A radiation. It is obvious that more than 99% of the radiation is absorbed by AgNWs-loaded fabric over the entire UV region. Transmittance spectra reveal that AgNWs loading can provide excellent UV-blocking to the cotton textiles in the whole UV region.

AATCC 183 method defines the UPF rating for a fabric/textile as the ratio of UV measured without the protection of the fabric (compared to) with protection of the fabric. UPF tests are normally conducted in a laboratory with a spectrophotometer or a spectroradiometer. Typically, a fabric with an UPF of >40 is considered to provide excellent protection against UV radiation. The results of the UPF and transmittance of light in the range of UV (UV-B, UV-A and UV-R) for pristine and AgNWs-loaded fabrics are presented in Table 2. The UV-blocking property of pristine fabric showed that the fabric offered poor protection against UV radiation. The UPF value of pristine fabric was 4.27. An UPF value of <15 indicates no protection against transmittance of UV radiation through fabric onto skin. For AgNWs-loaded fabric, the UV transmittance decreased significantly (percentage of transmittance in the UV-B was lower than UV-A) and UPF value increased to 113.14, showing its excellent ability to block UV radiation.

There are two possible reasons for high UV blocking of AgNWs-loaded fabric. One reason is that the loading of AgNWs to the fabric causes high UV absorption as a result of fabric color change to dark green. Another possible reason is that the formation of AgNWs on the fabric surface imparts a very efficient UV scattering because of the large refractive index of silver nanomaterials.

Surfaces with very high water CA, particularly larger than 150°, are called superhydrophobic surfaces (Nosonovsky & Bhushan, 2009; Yan, Gao, & Barthlott, 2011). These surfaces are highly hydrophobic i.e., extremely difficult to wet. This is also referred to as the lotus effect, due to the superhydrophobic leaves of the lotus plant. Generally, there are two strategies to create a superhydrophobic surface: (a) introduction of dual-sized micro/nanoscale roughness on a low-surface-energy material and (b) creation of dual-sized micro/nanoscale roughness on substrate, followed by deposition of a low-surface-energy material on top of it. Cotton woven fabric is a rough and porous substrate produced by

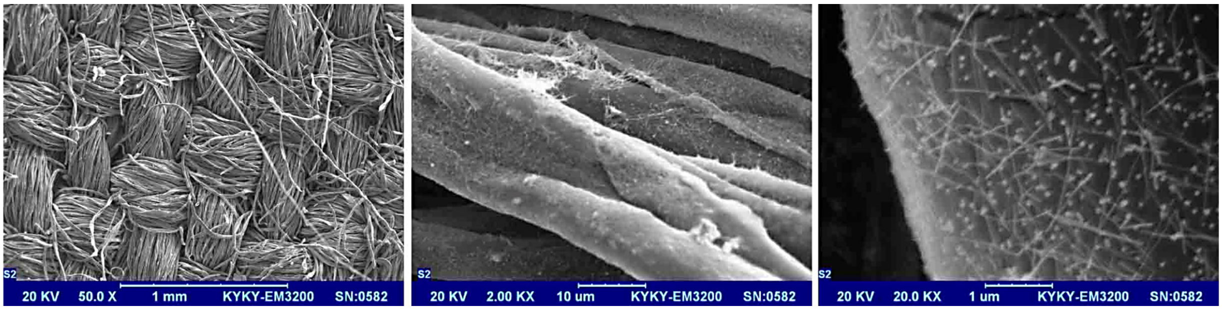

Fig. 7. SEM images of AgNWs-loaded fabric after coating with Danasylan® F 8815. Magnification from left to right: 500×, 2000× and 20,000×, respectively.

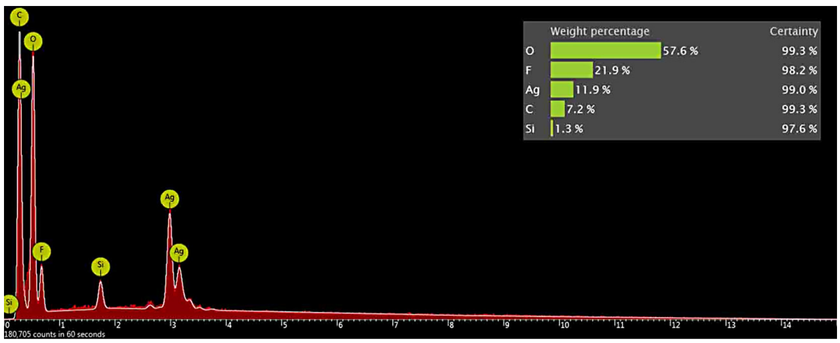

Fig. 8. EDX spectrum of AgNWs-loaded fabric after coating with Danasylan® F 8815.

interlacing threads, composed of micrometer-sized cellulose fibers, placed perpendicular to each other. Therefore, microscale roughness is naturally provided and further nanoscale roughness is necessary for the formation of dual-sized structure to become superhydrophobic substrate. As demonstrated from SEM images (Fig. 4), coating of cotton fabric with AgNWs caused formation of dual-sized structure, i.e., AgNWs on the surface of cellulose microfibers. In order to create a hydrophobic surface, the fabric was then modified by a low-surface-energy fluorosilane (Danasylan® F 8815) to reduce its surface-energy. SEM images of Danasylan® F 8815 coated AgNWs-loaded fabric, at different magnifications, are shown in Fig. 7. It can be seen that Danasylan® F 8815 forms a very thin layer on the fibers surface so that AgNWs are easily observable. EDX spectrum of the prepared fabric is shown on Fig. 8. EDX spectrum of the fabric yielded carbon, oxygen, silver, silicon and fluorine peaks. The presence of the silicon and fluorine peaks indicates the successful coating of Danasylan® F 8815 on the surface of AgNWs-loaded fabric.

The wetting properties of the fabrics were evaluated by water CA and water SHA measurements. Pristine cotton fabric showed

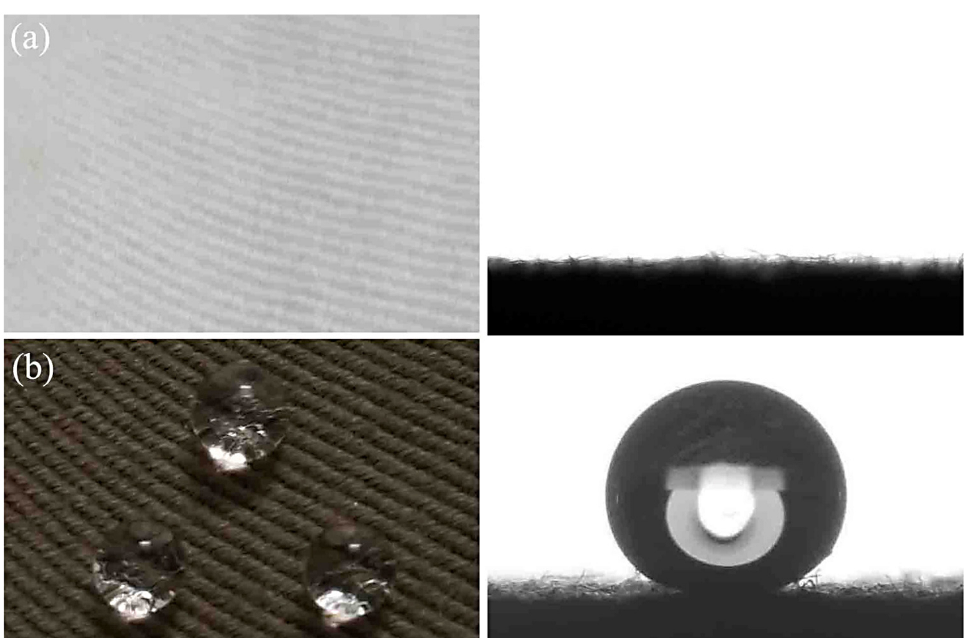

Fig. 9. Water droplets sitting on (a) pristine and (b) Danasylan® F 8815 coated AgNWs-loaded fabrics. Goniometer images for 5-μL droplets are shown on the right.

superhydrophilic behavior due to the presence of abundant hydroxyl groups on the surface of their fibers, so that water droplets were quickly absorbed and disappeared on its surface, as seen in Fig. 9a. After coating of fabric with AgNWs, the fabric showed a similar wetting behavior, indicating that AgNWs deposition did not change the well-known superhydrophilic property of cotton fabric. AgNWs-loaded fabric coated with Danasylan® F 8815 exhibited superhydrophobic behavior with a CA of $156.2^\circ \pm 3.2^\circ$ (Fig. 9b) and an SHA of 7°. Droplets of water that fell on the superhydrophobic fabric formed highly spherical beads that stood up on the surface and easily rolled off, effectively making the surface waterproof. In addition, the repellency was stable, and the droplets were not adsorbed after a long time until complete evaporation.

The liquid repellency of the prepared fabric was also determined by assessing the fabrics' resistance to wetting by a series of ethanol–water mixtures of different surface tensions. The obtained results demonstrated a reduction of the surface tension of AgNWs-loaded fabric after treatment with Danasylan® F 8815 so that it was able to repel liquid with a surface tension of greater than 22.72 mN/m. For comparison, the liquid repellency of pristine fabric treated with only Danasylan® F 8815 was evaluated. In this case, the fabric was able to repel liquid with a surface tension of greater than 25.01 mN/m. This result demonstrates synergetic effect of surface morphology (dual-size structure) and low-surface-energy layer in obtaining superhydrophobic fabric with lower surface-energy. According to the Cassie's state (Cassie & Baxter, 1944), it can be concluded that air bubbles trapped between water droplets and fabrics surface contribute to the high water repellency.

4. Conclusions

This study described a simple, versatile, and effective approach for creation new functionalities on cotton textiles. Multifunctional cotton fabric was prepared by the facile "dip and dry" coating of silver nanowires. It was demonstrated that loading of AgNWs on surface of cotton fibers can convert insulator cotton fabrics into textile based substrate conductors. The existence of AgNWs on the fabric surface caused significant antibacterial effect. The AgNWs-loaded fabric was capable of killing both Gram-negative and Gram-positive bacteria. Excellent UV-blocking property of the AgNWs-loaded fabric was demonstrated by UPF value of 113.14. After formation of fluorosilane layer on the AgNWs-loaded fabric, the superhydrophilic fabric turned into superhydrophobic substrate with the CA of higher than 150° and SHA of lower that 10°. The enhanced surface roughness imparted by AgNWs and the reduction of the surface-free-energy induced by the fluorosilane was responsible for the water repellency properties of the treated fabric. These AgNW-fabric compositions show great promise and may provide opportunity for development of advanced antimicrobial cellulosic textiles with novel properties.

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