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A Compendium of Nano Materials and their Applications in Smart Nano Textiles

[1]E. Jebamalar Leavline, [2]D. Asir Antony Gnana Singh, [3]S. Prasannanayagi and [4]R. Kiruthika

[1]Department of Electronics and Communication Engineering, Anna University,
[2]Department of Computer Science and Engineering Anna University,
[3]Department of Electronics and Communication Engineering Anna University,
[4]Department of Electronics and Communication Engineering Anna University, BIT Campus, Tiruchirappalli, Tamilnadu, 620024, India

Corresponding Author: E. Jebamalar Leavline, Department of Electronics and Communication Engineering, Anna University, BIT Campus, Tiruchirappalli, Tamilnadu, 620024, India Tel: +91-8220222044

ABSTRACT

This review article deals with the recent developments in smart Nano-textiles that have the potential to revolutionize the functionality of clothing and the fabrics in our surroundings. The traditional markets of apparel and home textiles continue to be influenced by nanotechnologies, towards a new direction of value added textiles through finishing and coating using nanomaterials. Nano scale manipulation results in new functionalities for intelligent textiles, including self-cleaning, sensing, actuation and communication. This is achieved by development of new materials, fibers and finishings, Inherently Conducting Polymers (ICP), carbon nanotubes and antimicrobial nano-coatings. These additional functionalities extend their application to various fields like healthcare, sports, military applications and fashion design. With the help of the smart nano-textiles, the wearer and the surrounding environment may be monitored by continuously updating health status of the individual or environmental hazards without making any harm to the wearer. In addition, smart textiles have become a critical part of the body sensor networks that carry out sensing, actuation, control and wireless data transmission. This study reviews current research in nanotechnology applications to textiles, from fiber manipulation and development to end uses of smart nano-textiles.

Key words: Smart nano-textiles, nanoscale manipulation, inherently conducting polymers, antimicrobial nano coatings, fiber manipulation and development

INTRODUCTION

Technology is becoming increasingly prominent in our daily lives, in many ways. The recent developments in technologies alleviate the demands of modern living in this technology age (Coyle *et al*., 2007; Qian and Hinestroza, 2004). Nano technology is a recent development in the past decade that is playing a key role in optimizing the performance and providing smart solutions for the future developments and needs. Nanotechnology has vast and versatile applications in almost all fields of technology. Especially in textiles, nanotechnology extents its applications in manufacturing stain resistance garments, flame and wrinkle resistance finishes, UV protection, moisture management, soil release properties and antimicrobial qualities. Incorporating nano materials into a textile can affect a set of properties including shrinkage, strength, conductivity and flammability (Jeevani, 2011).

Nanotechnology enhances the durability of fabrics since, the nano-particles have a high magnitude of surface area to volume ratio and high surface energy. This offers better affinity for the fabrics and its coating does not affect the human breathing ability or touch feel (Sawhney *et al*., 2008; Wong *et al*., 2006).

The functionality and the performance of nano textiles are greatly influenced by nanotechnology. Nanoscale manipulation of fabrics results in new functionalities such as self cleaning, sensing, communication and actuation. The first generation intelligent clothes used conventional materials and components and practiced the textile designs for fixing the external elements such as e-apparel (textile with electronics) with these materials and components. The first successful wearable e-apparel ICD+ outerwear line namely mooring was introduced in late 20th century. Figure 1 shows the mooring and its design that accommodates the existing setups including: A microphone, an earphone, a remote control, a mobile phone and an MP3 player. Figure 1 shows the mooring jacket with communication systems, speakers and microphones. However, all these setups including wiring are needed to be removed before it moves for wash thus requires huge maintenance cost.

The next generation intelligent textiles are comparatively 'smarter' due to the advances of material science, yet it is a hybrid technology (Bashir, 2013) as shown in Fig. 2. Smart textiles use smart materials to sense the environmental changes and react accordingly. These smart materials

Fig. 1(a-c): Mooring jacket with (a) Communication systems, (b) Speakers and (c) Microphones

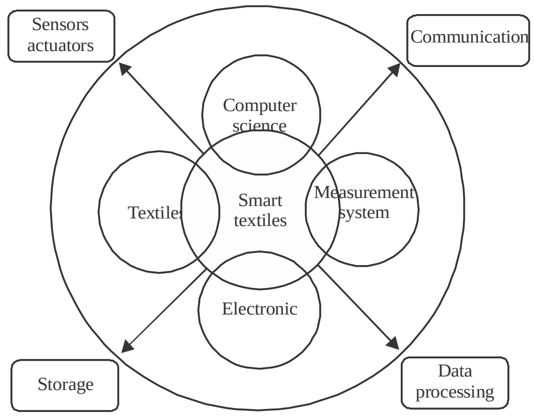

Fig. 2: Smart textiles as a hybrid technology

Fig. 3(a-c): (a) Photochromic-responds to light and change colour, (b) Microscopic capsules to yarn or fabric surface give off a fragrance and (c) Phosphorescent materials

also can sense mechanical, thermal, chemical, electrical and magnetic sources. Smart textiles are useful in many applications starting from military and security to the most personalized issues such as healthcare and entertainment.

Smart textiles are roughly classified into two categories namely "passive" or "active". A passive smart textile monitors the wearer's physiology or the environment such as a blouse with in-built thermistors to monitor body temperature over time. In case of integrated actuators, textile becomes an active smart textile as it may respond to a particular stimulus, for example, the temperature aware top may automatically rolls up the sleeves when body temperature becomes elevated (Coyle *et al*., 2007). Some of the examples of smart materials (Gandhi and Thompson, 1992) are shown in Fig. 3.

The remainder of this study covers the discussion on the various nano materials used for fabrication of nano textiles and presents an insight into various applications of nano textiles.

MATERIALS AND METHODS

Nanomaterials: Nanomaterials are chemical contents or materials that are fabricated in very tiny size with the diameter between 1-100 nm. These materials are present in the form of metals, optical fibres and conductive polymers in nanotextiles to provide electrical conductivity, sensing and communication.

Metallic fibers: Metallic fibers or naturally conductive fibers are evolved from electrically conductive metals such as nickel, titanium, copper, ferrous alloys, stainless steel, aluminum and carbon (Meoli and May-Plumlee, 2002; Meoli, 2002). Metal fibers are very thin metal filaments of diameters ranging from 1-80 μm. The fineness of the metallic fiber of 1 μm is illustrated in Fig. 4 in comparison with the human hair. The fineness of up to 1 μm is achieved by shaving off the edge of a coil of a thin sheet of metal (Meoli, 2002) as shown in Fig. 5.

Optical fibers: Optical fibers of about 120 μm are utilised to manufacture interactive electronic textiles. Optical fibers are made by a mixture of silicon dioxide sand, borates and trace amounts

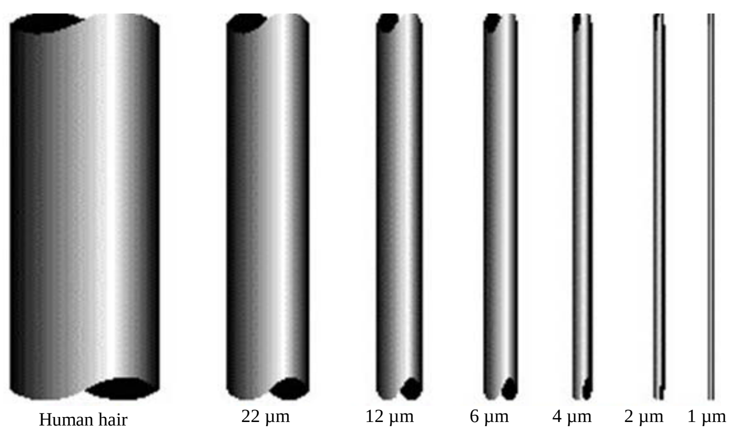

Fig. 4: Metallic fiber diameters compared to human hair

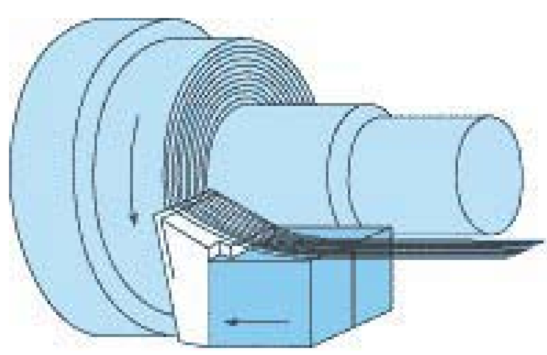

Fig. 5: Shaving process

of speciality chemicals. In order to make optical fibers, first this mixture is homogenized and fed into a chamber to dissolve the sand mixture into liquefied glass. Then the liquified glass flows to heat resistant platinum trays with tiny tubular openings known as “Bushings”. Then the liquified glass is drawn out through the bushings to a particular diameter and cooled by air and water to line the diameter and the filament is made. Then the filaments are coated with a liquid chemical mixture with a process referred to as “Sizing” to guard the filaments. This process of making optical fibers is completed once the sized filaments are wound and packaged. Optical fibers provide good strength and that they are not affected by daylight exposure (Bashir, 2013).

Carbon nanofibers and carbon nanoparticles: Carbon fibers are invented by Edison in 1879 and used as a most stern material in sophisticated industrial applications such as structural composites in aerospace, transportation and defence-related products.

Carbon nanoparticles are the powdered carbon that appears black in colour. Carbon nanofibers and carbon nanoparticles are the foremost nano sized filling materials are commonly used for various nanotechnology applications. The durability of the composite fibers is effectively increased by carbon nanofibers owing to high aspect ratio, whereas carbon nanoparticles will improve their abrasion resistance and toughness. However, carbon nanofibers and carbon nanoparticles have high chemical resistance and electric conductivity (Morshed *et al*., 2013; Smart Garments, 2007).

Nanotechnology in manufacturing composite fibers: Nano-structured composite fibers came into picture during the early blooming of nanotechnology. These fibers employ nano-sized fillers such as nano particles (clay, metaloxides, carbon black), Graphite Nano Fibers (GNF) and Carbon Nano Tubes (CNT). Nano-structured composite fibers can also be manufactured using foam-forming process (Kim *et al*., 2003).

Clay nano-particles: Clay nano particles or nano flakes are composed of many kinds of hydrous alumina silicates. Each sort differs in its chemical composition and crystal structure. Clay nano particles are able to block ultraviolet rays and having electrical, heat and chemical resistance. Therefore, composite fibers supported with clay nano particles showcase flame retardent, anti-UV and anti-corrosive behaviours (Morshed *et al*., 2013; Qian and Hinestroza, 2004).

Metal oxide nano particles: Some metal oxides possess electrical conductivity, ultraviolet light absorption, photocatalytic ability, photo oxidizing capability against chemical and biological compounds. Nano sized particles of such materials (Eg: ZnO, MgO, TIO_2 and Al_2O_3) are used in antimicrobial, self-decontaminating and ultraviolet light obstruction functions for military protection gears and personalised healthcare gadgets (Morshed *et al*., 2013; Qian and Hinestroza, 2004; Srivastava *et al*., 2011; Patel and Chattopadhyay, 2007).

Carbon nano tubes: Carbon Nano Tube (CNT) is one among the most promising components in the field of nanotechnology. Its higher strength and high electrical conductivity are not comparable to carbon nanofibers. The CNT consists of small shells of graphite rolled up into cylinders as shown in Fig. 6. The CNT looks great with a hundred times durability of steel at one-sixth weight, thermal conductivity higher than all materials except diamond, electrical conductivity almost like copper and with the power to hold much higher currents (Qian and Hinestroza, 2004; Siegfried, 2007; Raja *et al*., 2012).

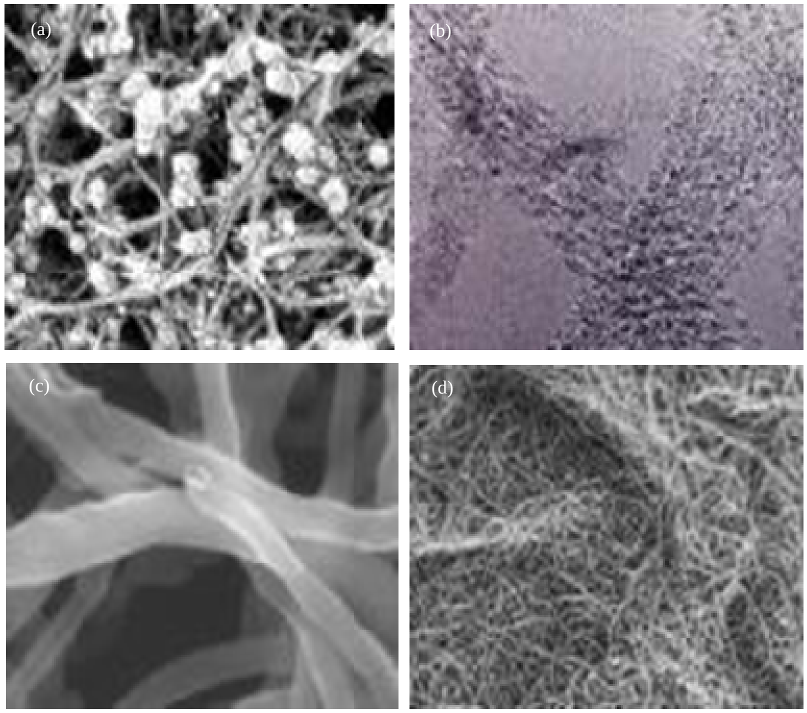

Fig. 6(a-d): Carbon nano fiber structures

Materials suitable for the development of smart nanotextiles

Conductive polymers: Conductive polymers are discovered in 1977. Intrinsically Conducting Polymers (ICPs) conduct electricity and have the ability to sense and actuate. Due to their high conductivity, lower weight and environmental stability, they have a very important place in the field of smart and interactive textiles.

Nanostructure based intrinsically conducting polymers: The fibers possess high electric conductivity; this achieves electromagnetic shielding functions in textiles. On the other hand, the synthetic textile polymers like polypropylene (PP) or polyethylene (PE) generally have low electric conductivity and hence, they act as isolators. The conductive material can be made to exhibit manufacturing favorable mechanical properties of the polymers such as small metal particles, conductive polymers (e.g. polypyrrole, polyaniline, polythiophene) and carbon nano particles (Carbon Nano Tubes (CNT), Carbon Black (CB), etc.) (Frederick, 2011).

The development of Intrinsically Conductive Polymers (ICP) has opened up new possibilities for conductive textile materials (Fig. 7). These polymers are conjugated polymers whose electrical conductivity is dramatically increased by doping. During the doping process, a small amount of chemical agent is added that results in change in the electronic structure. The doping process is reversible and involves a redox process. Conductive polymers are provided both as solid compounds and liquid dispersions or solutions. The liquid versions can easily be applied onto a textile substrate by coating methods (Wallace *et al*., 2002). These ICPs and CPCs (Conductive Polymer Composites) can introduce most of the necessary functionalities such sensing, actuation, energy generation, computation and energy storage in smart and interactive systems. Textile-based wearable sensors,

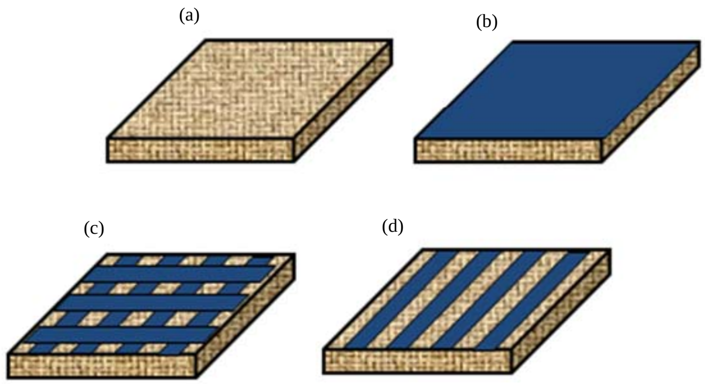

Fig. 7(a-d): Homogenous and heterogeneous textile structures, (a) Homogenous, untreated textile, (b) Homogenous, coated textile, (c) Conductive threads, grid and (d) Conductive threads, mono-directional

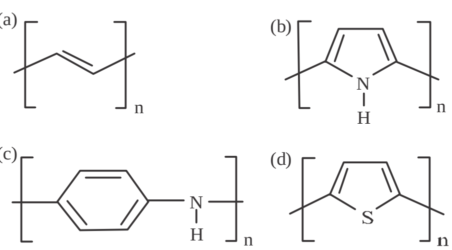

Fig. 8(a-d): Chemical structures of selected inherently conducting polymers in the undoped form, (a) Polyacetylene, (b) Polypyrrole, (c) Polyaniline and (d) Polythiophene

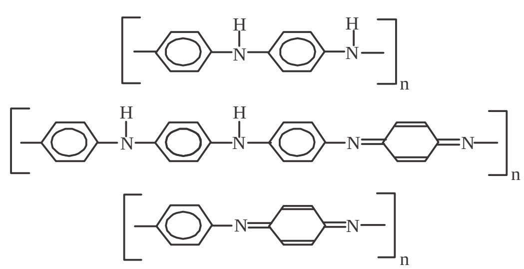

Fig. 9: Three possible oxidation states of polyaniline namely leucoemeraldine, emeraldine and pernigraniline

actuators and computational devices can be obtained either by coating commercially available textile materials with ICPs or by mixing thermoplastics with conductive components. The ICPs can be applied to the surfaces of textile materials homogeneously or heterogeneously.

Polyacetylene, polypyrrole, polyaniline and polythiophene are some of the commonly used ICPs. The use of polyacetylene is limited due to the fact that it is unstable in air. Polypyrrole (PPy) has high stability in air, mechanical strength and electroactivity in both organic and aqueous solutions. One of the most widely studied ICP is Polyaniline (PANI). The PANI has three possible oxidation states and is relatively stable in the environment (Fig. 8 and 9). The PANI has good electrical conductivity; and, when PANI is oxidized in aqueous protonic acids, the magnitude of its conductivity increase. Polyaniline (PANI) nanoparticles; *nano* PANI-dodecylbenzene Sulphonic Acid (DBSA) can be synthesized using emulsion polymerization. The *nano*PANI-DBSA obtained has a conductivity of 34±7 S cm^{-1} with particle size in the range of 10±2 nm. The *nano* PANI-DBSA has been used as a mediator layer in biosensor applications. These nanoparticles are fabricated onto the conductive electrode using an electrodeposition method with subsequent immobilization of the enzyme Horseradish Peroxidase (HRP) (Ngamna, 2006). Polymer field-effect transistors for flexible logic circuits from polythiophene and its derivatives can be constructed and solar cells using polythiophene have low production costs, flexibility and reduced weight (Frederick, 2011; Saafan *et al*., 2005). Each ICP is blended with the acrylate binder, thickener and pH-regulator according to a proprietary recipe. The amount of conductive polymer dispersions was in the range from 74-78 wt% (weight percentage). This corresponded to 1 wt% polythiophene, 3.7 wt% polypyrrole and 4.7 wt% polyaniline due to the variations in material composition.

Applications of smart nano textiles: Textiles are ubiquitous to us and they are a sign of development and lifestyle. The traditional usage of textiles has been extended with the recent technological developments that added intelligence to textiles to create “smart” clothes. Apart from personal protection, smart textiles are designed to overcome challenges in healthcare, communication, sports, military etc where continuous monitoring, communication and control are essential (Jayaraman *et al*., 2006). Some of the interesting applications of smart nano textiles are discussed in the following sections.

Personalised healthcare: The idea of personalised healthcare evolved to empower the human being to monitor and manage their personal healthcare needs. Wearable devices aid to continuously monitor the bio-signals during regular activities that overcome the problem of in person clinical visits. However, it can provide only a brief window into the physiological status of the patient. On the other hand, smart clothing serves an important role in remote monitoring of chronically ill patients or those undergoing rehabilitation. It also supports the concept of preventive healthcare (Mantovani *et al*., 2010; Jamadar, 2013). Figure 10 shows the on-body sensors and electronics for monitoring vital body signs - a garment with textile ECG electrodes developed by the MyHeart project to prevent heart failure (Coyle and Diamond, 2010).

The product, the Sensatex SmartShirt is a patented wearable Smart Textile unisex T-shirt designed to acquire physiological information and move data from the human body. It is knitted using conductive fiber/sensor system designed specifically for the intended biometric information requirements. It is capable to sense and relay the heart rate, respiration status and body temperature in real time. The smart shirt system shown in Fig. 11, collects analog signals through conductive fiber sensors and transmits them through a conductive fiber grid knitted in the T-Shirt. A textile connector transmits the analog signals to a personal controller held in the shirt pocket. The personal controller digitizes the signal and transmits the signal to a wireless receiver connected to a base station where the information is monitored (PROETEX, 2013).

Similarly in another integrated sensor shirt, called “ITcares” (Intelligent Textile for Cardio Respiratory Sensing), bipolar ECG electrodes were applied inside of the T-shirt which is used to measure the ECG signals. The positions of the sensor are chosen as in the case of traditional ECG. The T-shirt will be connected with the hardware device for transmitting the cardio vascular activity through a wireless channel to the monitoring computer as shown in Fig. 12.

Fig. 10: On-body sensors and electronics for monitoring vital body signs - a garment with textile ECG electrodes developed by the MyHeart project to prevent heart failure. (Source: Philips)

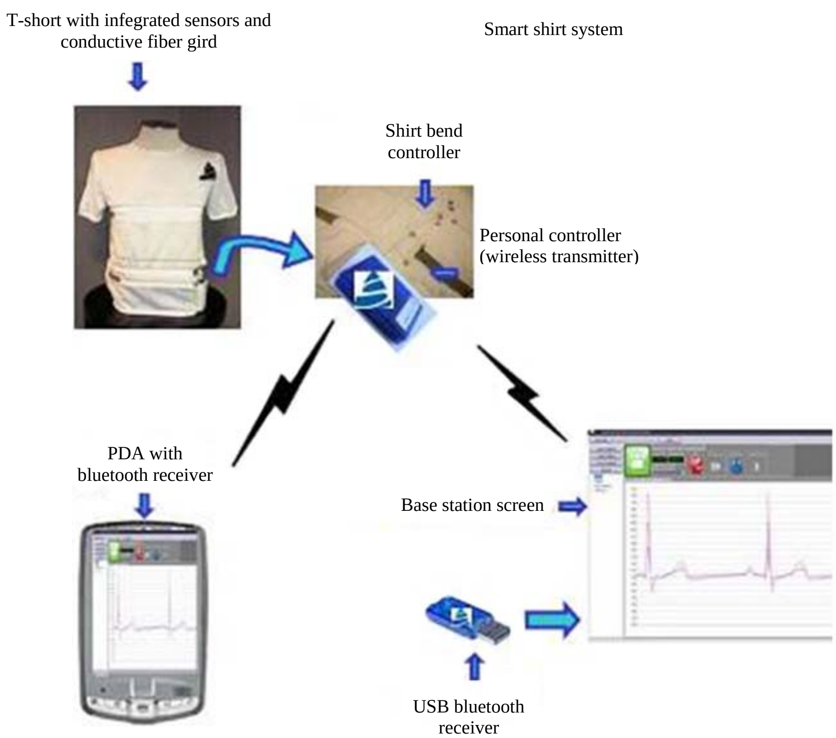

Fig. 11: Smart shirt system [Source: Sensatex, Inc.]

Anti-bacterial textiles: Anti-bacterial textiles are used to sanitize clothing. This kind of anti-bacterial arm cloth with off the shoulder seams to eliminate chaffing. Exclusive double layer PuckSkin cloth designed for hockey players shown in Fig. 13, has superior moisture wicking inner layer that keeps athletes dry, honey comb pattern within the exterior layer creates air pockets to extend evaporation to stay your blood heat regulated. PuckSkin's exclusive double layer

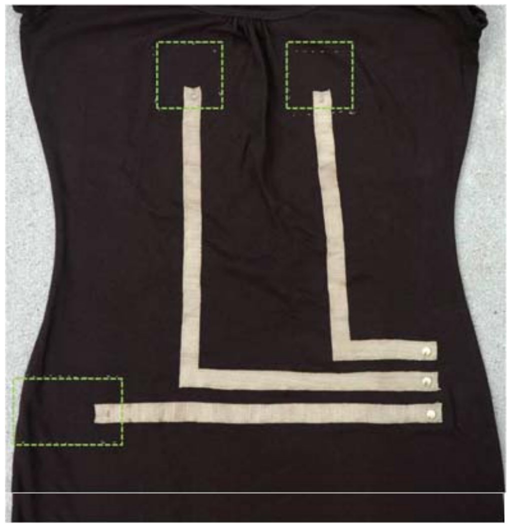

Fig. 12: Intelligent textile for cardio respiratory sensing

Fig. 13(a-d): Antibacterial, (a) Long sleeve, (b) Support mid short, (c) Socks and (d) Wrist band fabric is made of microfiber Charcoal Bamboo yarn and embedded nano silver ceramic ions. The Charcoal Bamboo yarn filters the sweat and increases wicking-ability. The nano silver particles naturally kill bacteria that cause skin irritation and smell that is associated with hockey equipment. This technology has been extended to a range of products that are essential for a professional hockey team as shown in Fig. 13 (PuckSkin, 2013).

Lifestyle applications: The development of high-tech advanced textiles for a particular purpose, in due course discovered its way to fashion industry, where designers are allowed to experiment their creativity with these high-tech textile materials. For example, microfibers were initially developed for space and military applications and are now used in sportswear, interior fabrics and fashion exclusively.

Musical Jeans originally developed in 1997, has been enhanced with new functionalities, hardware and related software. An interesting component of the musical jacket is the embroidered fabric keypad, produced with a mildly conductive stainless steel and polyester composite thread using ordinary embroidery techniques. The keypad is integrated into the Levi's Musical Jean Jacket (Fig. 14). This flexible and durable embroidered fabric keypad is highly sensitive and responsive to touch makes a wearable musical instrument that allows the wearer to play chords, notes, rhythms and perhaps to select and play internet MP3 file. At present the Levi's Musical Jean Jacket is being test marketed in Europe (Meoli and May-Plumlee, 2002; Meoli, 2002; Orth *et al*., 2013). It also has a control unit and takes power from solar, wind, movement and even fabric flexing.

Communicating textiles: The applications and prospects for electronic textile communications are everlasting. Some ideas presently being investigated including airline cabin crew uniforms with built in personal digital assistants and earpiece microphones for communicating with colleagues aboard and on the ground and digital business suits to support e-mail, video conferences and interaction with coworkers (Fig. 15). Communication devices may be easily worn in the future by being integrated into textile and apparel products. (Meoli and May-Plumlee, 2002). Also, Eleksen

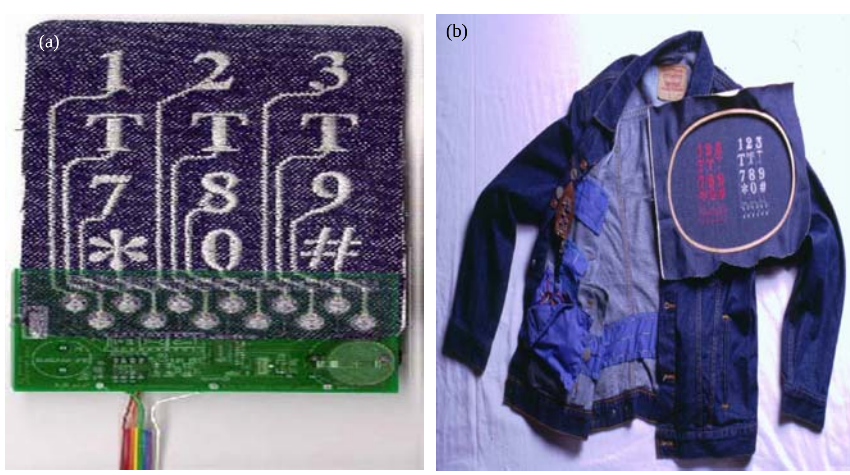

Fig. 14(a-b): Embroidered (a) Fabric keypad and (b) Levi's musical jean jacket

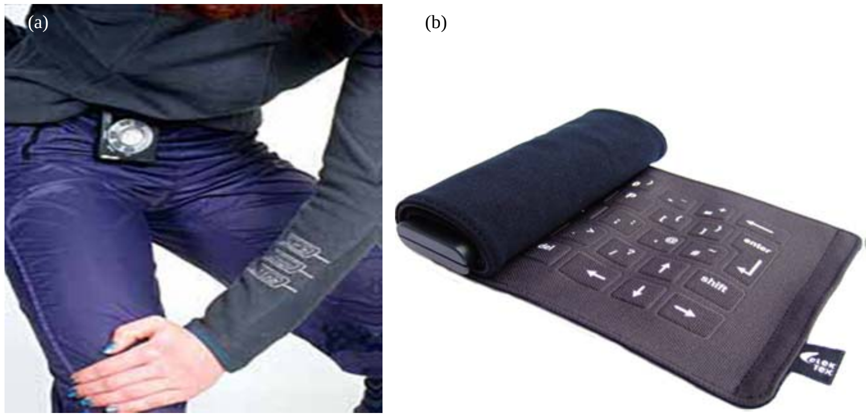

Fig. 15(a-b): (a) Sleeve integrated communication device and (b) A fabric keyboard

Fig. 16(a-b): (a) Fire fighter outer garment and (b) Boot with gas sensor

has developed a fabric keyboard for Personal Digital Assistants (PDAs) that can be rolled out, easily stored and transported (Coyle *et al*., 2007).

The European project 'PROeTex', developed dedicated textile for fire fighters. It has an inner garment, an outer garment and a pair of boots. Gas sensors are placed at the boots. The outer garment collects posture, position and information about the environmental parameters and transmits through an Electronic Box hosted in the outer garment to a distant station that monitors and coordinates the operation. Specially designed communication and GPS antennas are used for this purpose as shown in Fig. 16.

Sports textiles: The sports industry has driven much research with the textile industry to improve athletic performance, personal comfort and protection. A good number of products that are designed to improve the comfort of the wearer are commercially available; for instance, there are breathable waterproof fabrics such as Gore-Tex® and moisture-management textiles that taper the moisture away from the skin. Coolmax®, Gore-Tex® fabrics use a membrane of expanded poly (tetrafluoroethylene) (PTFE) for this purpose. To maintain the wearer's comfort, it is important that sweat is allowed to evaporate, maintaining the body's natural thermoregulatory function. High-performance moisture-wicking fabrics worn next to the skin transport perspiration away from the body to the outside of the garment where it can more quickly evaporate.

Invista unveils coolmax® air fibre: Coolmax® Air fabrics are designed with improved performance fibers to maximize comfort with outstanding moisture management, breathability and faster drying times. This technology works by absorbing moisture from the surface of the skin and dispelling to facilitate rapid evaporation. This keeps the wearer to feel cool and dry. This is achieved by the propeller cross-section whereby, the wicking channels quickly move sweat to the surface of the garment and gets evaporated. Further, the high air permeability results in the exchange of the microclimate, causing additional cooling. Fibers with hollow core provide insulation and added comfort on colder days.

Intelligent knee sleeve: The intelligent knee sleeve (Fig. 17) was developed for sports, where knee injuries are common due to excess bend of knee joints. It uses PPy sensors to monitor the wearer's knee joint motion during jumping and landing to emphasize the correct landing practice. The PPy-coated fabric works as a strain gauge and is connected to a microcontroller that triggers an alarm tone, when the knee bends beyond a pre-set angle. Apart from sports, the application of this intelligent knee sleeve may also be extended as a rehabilitation device after injury. This is a result of joint effort of Intelligent Polymer Research Institute and Biomedical Science at the University of Wollongong (Coyle *et al*., 2007; Wu *et al*., 2005; Munro *et al*., 2008).

Super smart textiles: The dress shirt is indispensable from men as well as women. Every one uses different kinds of formal or casual shirts at different occasions. But, shirts get dirty easily and cleaning the shies is a sturdy task. The smart textile technology offers a remedy for this too. The

Fig. 17: Intelligent knee sleeve with microcontroller driven alarm tone

company named wool and prince has introduced wearable super smart textile with micro-fibrous type of wool as the major ingredient (Fig. 18). This is more comfortable than the wool fabric and it resists dirt and wrinkle free upto 100 full wearing.

Another line of shirts called Appolo shirts, a joint project of MIT and Ministry of supply, USA uses the same materials used in NASA space suits. The phase change material used in this shirt absorbs the body heat and releases heat when the body is cold. It regulates body temperature, sweat and it is wrinkle free. It also has the anti microbial functionality and hence preventing body odour. This is a boon for the professionals too.

Solar power textiles releasing shortly: Solar power textile is yet another milestone in the applications of smart nano textiles which is under development today. The basic idea of this solar power textile is that, by integrating nano solar (photovoltaic) cells in the fabric, power can be generated and saved (Fig. 19). As stated by Mr. Lin Cheng-Chu, Vice Director of Research

Fig. 18: Super smart shirt from wool and prince

Fig. 19: Solar power textiles

Department at the Taiwan Textile Research Institute (TTRI), “In the near future, bags or jackets made with solar textiles will provide electricity for PDAs, cellphones or digital media players”. This solar power textile will be smooth and foldable as the normal fabric. A wide variety of applications may be possible including agricultural applications, aerospace, mounting for temporary accommodation (for refugees/emergency use/disaster areas), permanent fixtures on buildings (roofs/awnings), military and defence applications (PTL., 2013).

CONCLUSION

In this study, we presented a wide range of nano materials used for fabrication of smart nano textiles and discussed their properties. Further, innovative and interesting applications of smart nano textiles such as smart shirt system, musical jean jacket, antibacterial textiles, communicating textiles, intelligent knee sleeve and super smart textiles including the most recently emerging solar power textiles. Researches are being conducted across the globe to develop new nano smart materials and to use such materials in a vast variety of applications. These smart nano textiles are costlier than the normal fabrics, this restricts the spread and usage of these smart nano textiles among many people. However, it is expected that the smart nano textiles will find a place at each and every home to fulfill their needs at an affordable cost in near future.

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