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Low-dimensional carbon based sensors and sensing network for wearable health and environmental monitoring

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ABSTRACT

With the advent of the era of big data and Internet of Things, wearable electronics are becoming more imperative than ever before, which prompts the continuous and fruitful research on wearable sensors and sensing network for health and environmental monitoring. This article presents an in-depth overview and review of this fertile area, focusing on sensors and sensing networks for strain, pressure, surface bio-potential, gas and temperature, which are made from low-dimensional carbon nano-materials and their composites. It covers materials, device structures, fabrication, performance and applications. It's evident that the appropriate and deliberate selection of low-dimensional carbon materials, matrix and substrate materials, and their interactions, as well as effective structural designs, are essential for highly sensitive and stable performance. Finally, the current status of industrial application is presented, possible hindrances for the adaptation of the technology are discussed, and future directions of development are indicated.

1. Introduction

Both the global aging population and the continuous improvement of human living standard create a growing demand on personalized wearable health and environmental monitoring equipment. Wearable sensor technology, a key member of these wearable monitoring devices, has achieved marked progress in recent years. Among which, wearable low-dimensional carbon based sensors have long been a research focus in both academia and the industrial sector, because of their extraordinary electrical and mechanical properties. However, only a few products based on these sensors are available in the market. In this article, therefore, we will conduct a comprehensive overview and review on the development of wearable low-dimensional carbon based sensors for health and environmental monitoring during the past decade.

The low-dimensional carbon nano-materials normally refer to zero-dimensional (0-D), one-dimensional (1-D) and two dimensional (2-D) carbon allotropes. Their nano-sized assemblies are also included like carbon nano-particles (carbon black) and graphite particles. Representatively in a wearable setting, they are 0-D carbon black (CB), 1-D carbon nanotubes (CNTs) and 2D graphene. 1-D carbon materials also include carbon nanofibers and carbon nanotubes, which however are seldom used in wearable devices because of doubts on safety. Therefore, this review involves wearable sensors based on these three types of conductive materials.

Among all the requirements for wearable devices, the most basic is arguably safety and non-toxicity. The 0-D CBs are non-toxic and they are widely used in vehicle tires. The 2-D graphene is non-toxic either. Graphene can be simply exfoliated from graphite [1], what we use in pencils for centuries. However herein, it should be emphasized that CNTs may pose serious hazardous concerns for human health and the environment [2–4]. Such toxicity is more worrying in the scenarios of wearable devices, because these devices involve large-area manufacturing technologies and the final products may come into direct contact with the human skin. The future roll-to-roll mass production may speed up the spreading of CNTs to the environment, while direct skin contact means higher risks of toxicity. Therefore, we hope in all seriousness that scientific peers could seriously consider the potential toxicity of CNTs in the research on wearable electronics.

This review is organized as follows. First, wearable strain and pressure sensors, the basic types of mechanical sensors, will be

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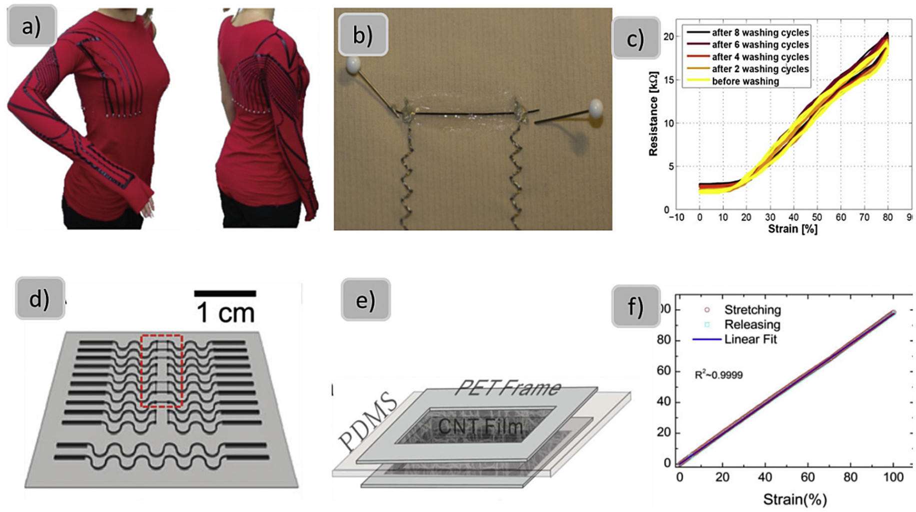

Fig. 1. Typical CB and CNT based strain sensors. a) Garment printed with CB strain sensors for kinesthetic monitoring. Reprinted with permission from Ref. [10]. Copyright (2011), Cambridge University Press. b) A CB-PDMS fabric strain sensor and c) its performance during washing tests. Reprinted with permission from Ref. [11], Copyright (2008), Sensors. d) CB-PDMS strain sensors based entirely on elastomers. Reprinted with permission from Ref. [5], Copyright (2012), Advanced Functional Material. e) A CNT-PDMS capacitive strain gauge and f) its calibration curves. Reprinted with permission from Ref. [12], Copyright (2012), Smart Materials and Structures. (A colour version of this figure can be viewed online.)

summarized and analyzed in terms of materials, sensing mechanisms, fabrication technologies and their performance. Secondly, wearable bio-potential sensors and environmental sensors, will be fully reviewed including gas and temperature sensors. Thirdly, wearable sensing networks will be studied and promising applications of these sensors and sensing network will be indicated. Finally, conclusions will be drawn along with future outlook.

2. Wearable strain sensors

Strain sensors, or strain gauges, are sensors for deformation measurement. They transduce mechanical deformation into electrical signals. Traditional strain gauges comprise a patterned metal foil on a polymeric backing for easy attachment onto an object [5]. Highly precise as they are, the conventional metallic or silicon based strain sensors can hardly be used in wearable electronics, which is primarily due to their insufficient stretchability, conformability, and a limited strain measuring range, normally below 5%. In comparison, low-dimensional carbon based strain sensors can be stretchable, conformable and highly sensitive, thus more promising for wearable devices. In these devices, carbon materials are usually mixed with elastomers to make conductive composite. The elastomer renders the composite stretchable and conformable, while the conductive carbon components offer the composite piezoresistivity [6] thereby enabling a good strain sensitivity. Significant progress has been made in carbon based strain sensors over the past decade. The detailed review of the progress is arranged in an ascending dimensional order of the carbon materials.

2.1. 0-D carbon black

Carbon blacks, a 0-dimensional carbonaceous material, are made through incomplete combustion of hydrocarbon in a fixed gaseous atmosphere. Carbon blacks have long been used as conductive fillers in pressure sensitive rubbers (PSR) due to their low cost, safety, a high surface-area-to-volume ratio and good electrical conductivity [7]. When used in wearable sensors, the primary sensing principle is the piezoresistive effect of CB/polymer composites.

Being the most cost-efficient material in the low-dimensional carbon family, CBs have been effectively employed in the research of wearable strain sensors. According to the substrate material, there are two main categories of sensor: fabric strain sensors which are easy for garment integration, and polydimethylsiloxane (PDMS) based strain sensors ready for skin mounting.

2.1.1. CB composite coating on fabric

Clothing made from fabrics are an ideal platform for wearable sensors as they are soft, deformable, breathable, washable, and durable [8]. We wear garments made from fabrics almost 24 h a day. Next we will illustrate the evolution of CB based fabric strain sensors by introducing four representative sensors.

Early in 2007, Cédric et al. made a fabric strain sensor by printing a conductive polymer composite of CBs and Styrene-Butadiene-Styrene (SBS) co-polymer, onto a Nylon woven fabric using a mask and a blade. The sensor showed a linear resistance change upon strains above 15% and the gauge factor was 80 [9]. In the same year, De Rossi [10] at the University of Pisa reported a sensor-printed garment for kinesthetic monitoring (Fig. 1a). A composite of silicone matrix and CB powder was printed onto a Lycra®/cotton fabric. The composite functioned as both strain sensing materials and wire connections. This garment could provide real time feedbacks on limb orientation of the wearer. Although no specifications were provided for the strain sensors, this is a very typical work of early CB based wearable strain sensors. On year later, Tröster's group [11] at ETH Zürich presented a more systematic study on a sensor for measuring strain in textiles. A composite of Styrene-Ethylene-Butylene-Styrene(SEBS)-Block copolymer and CB particles was made into a thread through a self-developed wet spinning process. Then the sensor thread was integrated onto a knitted fabric using silicone and connected to silver-coated nylon yarns using conductive epoxy (Fig. 1b). This sensor measures a strain up to 80% with a gauge factor of 20. In addition, it has a fatigue life over 3800 cycles and can be washed for 8 times (Fig. 1c).

Our group at The Hong Kong Polytechnic University conducted an extensive study on wearable strain sensors and made distinct progress [6,12–14]. We developed a resistive fabric strain sensor with extraordinary fatigue resistance of over 100 000 tensile cycles at 50% strain. The sensor has a tunable gauge factor from 1 to 100. Moreover, it can be machine washed for over 35 times without