Research of Wearable Piezoresistive Pressure Sensors

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Abstract. Wearable flexible sensors, as a product with huge potential, have attracted wide attention. In the commercial sector, various smart wearable devices products such as iWatch eagerly welcome the addition of new features, presenting great business prospects. In the medical field, new detection methods are needed for detailed monitoring of patients around the clock. This article roughly introduces the research results on the materials required for wearable flexible sensors, focusing on carbon-based materials and also mentioning sensors made from other materials. Overall, current research on this type of sensor still faces practical application challenges, particularly in the inability of materials to meet multiple key indicators required for practical use. The challenge lies in balancing. This makes the development of this sensor promising but still in the early stages of research and development. The ongoing research and development are poised to bridge this gap, heralding a new era of seamless and smart health monitoring solutions.

Keywords: Piezoresistive, Pressure sensor, Wearable.

1. Introduction

Wearable flexible sensors have been a hot topic in recent years. People have been imagining a sensor that can be worn on the wrist like a watch, or attached to the body like a bandage to scan subcutaneous tissue data for a very long time. Such imagination has filled the pages of science fiction works. In another way to say, it is also a reasonable extension of non-invasive medical sensors such as CT and MRI. It is a transition from large medical equipment to portable healthcare and sports equipment. Attempts in this area have already entered people's daily lives, such as smart watches and smart bracelet. However, current devices in the market have not yet ventured into pressure sensors, mostly traditional heart rate sensors, blood oxygen sensors, etc. The reason for not involving pressure sensors is because this type has obvious challenge and difficulty. But researchers cannot help trying to put pressure sensor onto human bodies, because it also has obvious potential. The potential lies in the fact that this sensor can provide better pulse data than existing optical pulse sensors in simple applications; in deep applications, it can play a crucial role in detecting cancerous lesions.

In the design of sensors for critical data, there are three key indicators: sensitivity, detection range, and stability. Finding materials that can simultaneously meet these three indicators well enough for commercial production is not easy. Currently, researchers mainly focus on similar research directions in this field. There are two main aspects this paper will mention, which are carbon-based materials and other kinds of materials. Because that most of the researchers as focused on it, which is a fact that carbon nanotube (CNT) and rGO materials indeed have many amazing physical properties. For carbon-based materials, combining carbon materials with ther materials has become a consensus [1].

Detection range is easy to understand, it is the range that the sensor can display a clear data. Stability is largely related to manufacturing processes and materials used. The calculation of sensitivity needs to be emphasized, as its data cannot be intuitively expressed through charts alone. There is a formula for the calculation of sensitivity. $\lim\Delta x \to 0 \Delta y/\Delta x = dy/dx$ [x] [2]. Generally, according to the output value under each pressure (pin), the relationship curve of the output voltage value/current value with the pressure is made, and then the curve is fitted in a straight line, and its slope is found to be the sensitivity.

This paper mainly summarizes the current achievements of some industry researchers and provides relevant data for readers to understand the current achievements.

2. Carbon-Based Materials

There have been multiple papers that are talking about graphene based flexible materials and their preparation methods. Researchers commonly believe that this kind of materials is the possible solution to make viable wearing pressure sensors. Typically, achievements are focused on reduced graphene oxide (rGO), with certain ways to synthesis, researchers construct special 3D graphene-based-piezoresistive-sensors, and during the process, they seek out the specific structure that can make the sensors sensitivity high and working range wide. After reviews, this paper finds that there are 2 typical categories researchers in China normally interests in and devote themselves in. First, fabricate a special structure on a certain basement, normally polydimethylsiloxane (PDMS) based. This special structure often is learned from nature, such as a geometrical shape, the shape of a leaf, eta. And the fabrication process is often completed in different ways, that researchers can achieve different effects. Second, researchers maybe interested in improving a specific performance of the pressure sensors. For example, the price and productibility. In a general way to say, these tempts usually comes with certain defects in other performances.

Y. Shi mentioned that PDMS-based sensors' fabrication normally is achieved using a complicated and expensive lithography machine [3]. While other ways such as moulding is low-cost but not reusable. This paper will show some researchers creative PDMS fabrication process and achievements with different effects, as well as some other based sensors.

Cheng et al introduced a tapered microstructure graphene-based-piezoresistive-sensor, which shows great progress in fabricating a pressure sensor [4]. As they introduced, the tapered microstructure polydimethylsiloxane-Graphene Foam Pressure Sensor has a broad working range (0~25kPa) and a sensitivity of 0.177kPa-1, with many times pressure tests, it showed that the sensor has good repeatability and recoverability. The sensor offers good repeatability and recoverability according to pressure tests. They claimed the tapered microstructure has improved from the sensitivity of graphene foam pressure sensors that without a tapered microstructure's 0.14 kPa-1, to the figure of 0.177kPa-1. Data is in Fig 1. They used a lithography machine as their primary instrument to create this unique structure and underwent procedures like wet corrosion. These processes give the sensor an excellent detection range with relatively good sensitivity. And lithography machining gave a nice stability for long term usage.

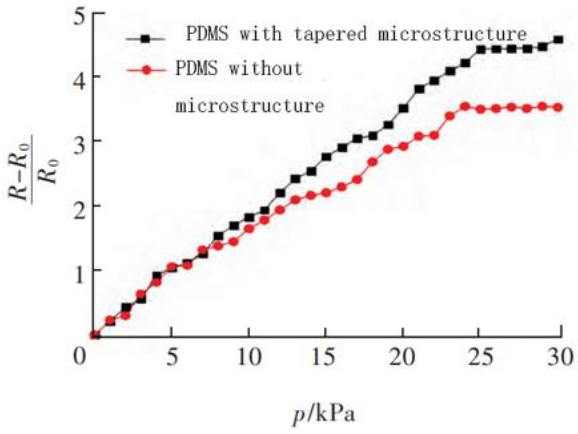


Figure 1. Black line refers to PDMS with tapered microstructure and red line refers to PDMS without microstructure [4]

Li et al introduced an rGO/PDMS based pressure sensor, with a hollow-sphere microstructure, based on a micropattern inspired by mimosas [5]. Their study presented a systematic proposal of the sensitivity of piezoresistive pressure sensors, based on experimental data and mathematical analysis. This microstructure leads to an enhancement in sensitivity to an ultrahigh level that is close to 2000 kPa-1. Of course, the sensitivity is by using relative current change vs applied pressure, which create a different figure. The sensitivity data is in Fig. 2. The sensor's reasonable ultralow detection limit is 0.075 Pa. they can achieve this level because they found ways to improve the rGO/PDMS structure.

They claimed that two important criteria might influence the sensor's sensitivity: its sharp microstructure and short channel length. After acknowledging that, they introduced a coplanar pressure sensor fabricated using microstructure PDMS layer and flexible polyethylene terephthalate (PET) film with predefined short-channel coplanar Au couple electrodes. They stick these two layers face to face; combine them as a coplanar structure. The fabrication processes are illustrated in Fig. 3. Thanks to its high sensitivity in current level and low detection limit, their teams achievement can be of good use in making a wearable sensor on wrist. But its detection range is within 0-1kPa. And stability is yet to be tested. There is still a way for Li to go.

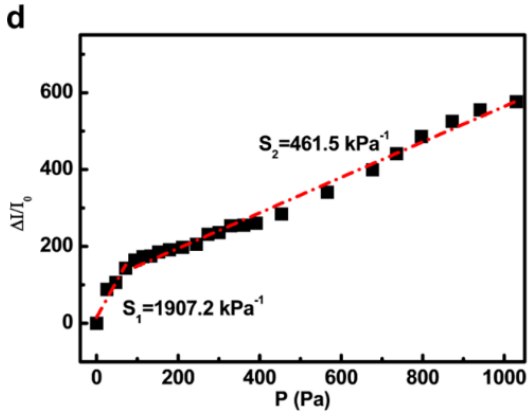


Figure 2. Relative current vs applied pressure sensitivity test [5]

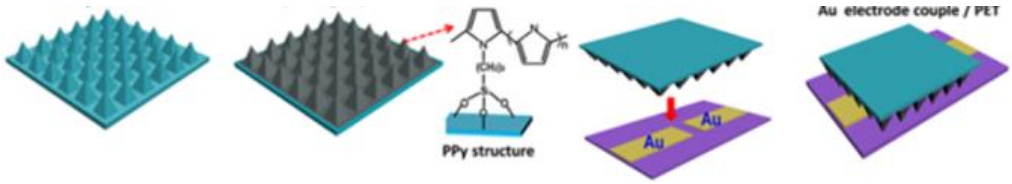


Figure 3. Fabrication procedures and structure of coplanar pressure sensor [5]

Gao J introduced a MXene/rGO based 3D porous skeleton structure, which is different to the papers this paper have mentioned [6]. Mn+1XnTx is the general chemical formula for MXene, where M is transition metal, X is carbon (C) and/or nitrogen (N) and Tx is the surface functional groups (-O, -F, or -OH). The value of n can be one, two, or three, and the stability of the material and the size of n are in a positive phase off the trend. This new type of material bringed new advantages for Gao. In Gaos research, Gao managed to deduced a reasonable sensing mechanism of MXene/rGO materials, and finally obtained the optimal material ratio through experiments, and fabricated the MXene/rGO asymmetric pressure sensor. This sensor shows sensitivities at 0-300 Pa, 0.3-10kPa, 10-28 kPa, with a sensitivity of 3.75, 0.031 and 0.0018 kPa-1 (Fig. 4). As for the stability, Gao showed a data that after 2000 times test, the sensor remained nearly no change. But its barely functioning as long as pressure is higher than 300Pa.

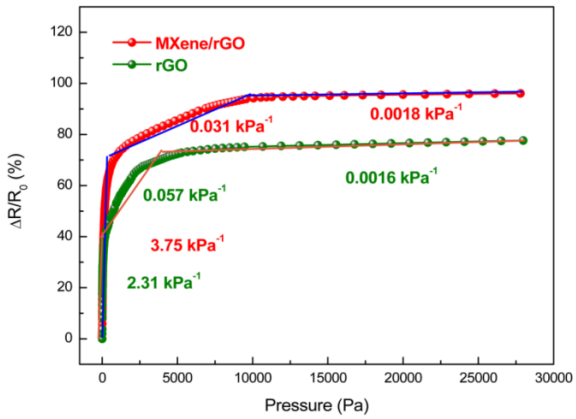


Figure 4. Comparison in sensitivity of MXene/rGO and pure rGO [6]

Meng. R et al have introduced a creative way to fabricate the sensors material, that rGO was used as the conductive filler material, and rGO/PDMS based flexible pressure sensor is prepared by imitating the production method of sugar blocks [7]. The relative resistance vs applied pressure figure is followed in Fig. 5. Here, simply explain briefly the fabrication process. Add a specific number of sugar particles and thoroughly mix rGO in place of water. Using a tablet press, the PDMS prepolymer is thoroughly mixed, pressed, and combined with a curing agent. The samples were taken out after being consolidated for 12 hours at 80°C in an oven. Submerge it in water to melt the sugar, then heat it up and remove the remaining water. It appeared to be a low-cost solution, considering the fact that theres no need for any accurate procedure. First, its detection range is not wide enough, which is limited in 0-5kPa. Second, they only tested the sensor for not higher than 500 times, data is not enough, there is a question about whether it can be practical for it to be used as a reusable sensor. Nearly all kinds of sensors hold at least one disadvantage, which conforms to Shi. Y. So rGO-based piezoresistive pressure sensors so far still need further development.

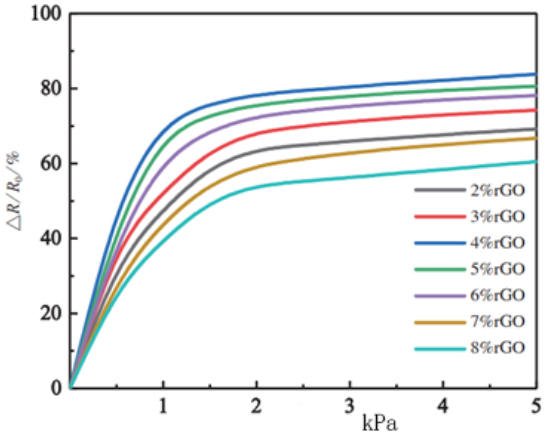


Figure 5. Relative resistant vs applied pressure [7]

3. Flexible Piezoresistive Sensors

Cheng et al and their works require lithography machine to be participated in the process. Other works presented in this paper often require the usage of carbon-based nanomaterials, which may include environmental issues or price issues, resulting in many of which are not environmental friendly or too expensive to be used for disposable purposes. Normally, this gives the sensors an impressive sensitivity. But suppose the primary goal of a hypothetical wearable sensor is to have an excellent productibility and low cost, in order to be a disposable instrument. In that case, the method can be greatly different.

L. Gao et al mentioned an All paper-based piezoresistive pressure sensor, with the definition of "low cost, facile craft, fast preparation and can be disposed easily" according to their paper [8]. Their work requires three components. A smooth-surfaced nanocellulose paper (NCP) was utilized as a flexible substrate for the direct writing method of printing silver interdigitated electrodes. With a coating of silver nanowires (AgNWs) applied by dip-drying, a porous tissue paper with a rough surface is utilized as a sensing material. Adhesive NCP is employed as the top encapsulating layer. The fabrication process from Gao is in Fig. 6. The relative current vs. applied pressure data is in Fig. 7.

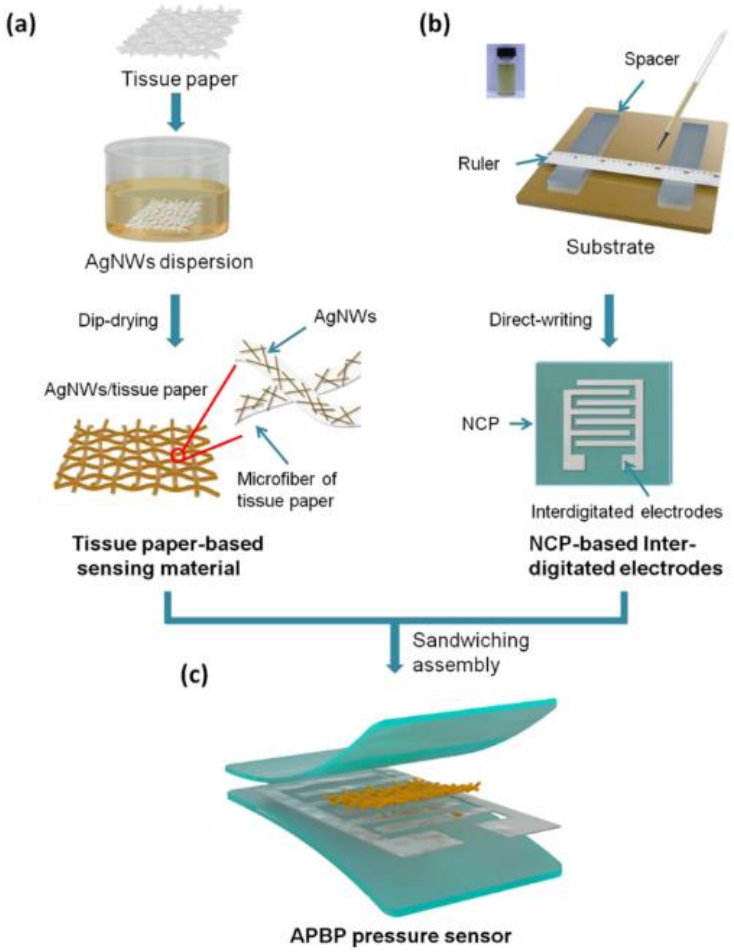


Figure 6. Schematic illustration of the fabrication of the All-paper-based-piezoresistive (APBP) pressure sensor. Preparation of (a) tissue paper-based sensing material by a dip-drying method and (b) NCP-based interdigitated electrodes by a direct writing method. (c) APBP pressure sensor with a sandwich [8]

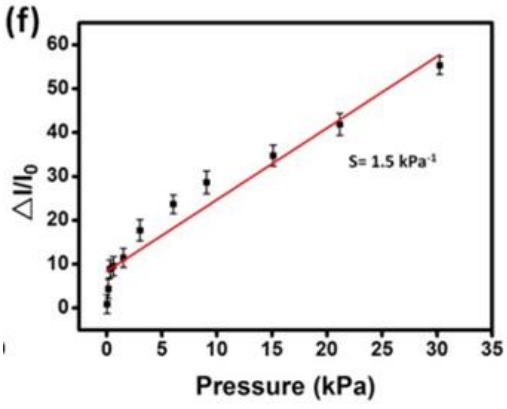


Figure 7. Relative current vs applied pressure [8]

This kind of sensor gives a wide detection range and can hold 1.5kPa-1 up to 30kPa. And according to Gao, it also has low working voltage (0.1V). Additionally, Gao claimed that it can keep stable after 200s of function time. This is good enough for a disposable device.

Shi. Y, who this paper mentioned above, also introduced a flexible pressure sensor based on Carbon nanotubes (CNT)/silicone rubber conductive composites [3]. Sensitivity test data in Fig 8. As for detection range, Shi did not mention but only mentioned that the detection range of the range of forces that the sensor can measure is 0-5N.

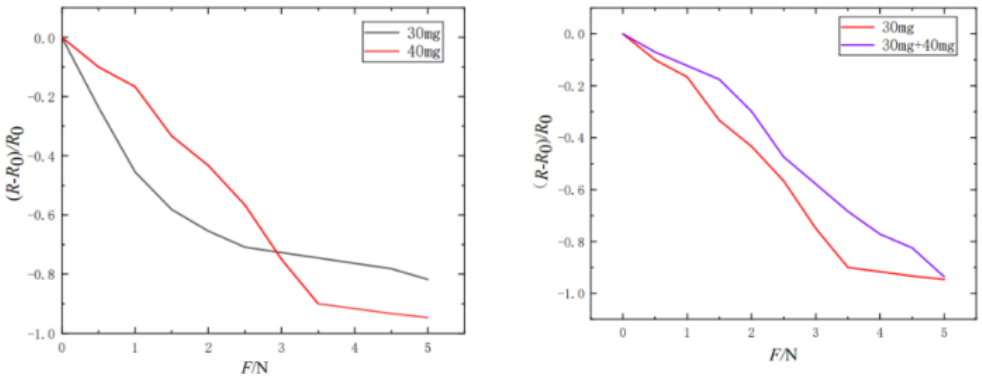


Figure 8. (a) Input-output curves for a single-layer conductive layer sensor, (b) Single/double layer conductive layer sensor input-output curves [3]

For the stability of these CNT/silicone rubber conductive composites, the material remained stable after 7000s tests, apart from Mullins Effect [9]. This introduces us to a new material that can be used for flexible pressure sensors.

These two types of sensors show us that by using other new generation materials and trying to find new methods, it is possible to fabricate a practical wearable pressure sensor without limited ourselves in the traditional carbon-based field.

4. Conclusion

It can be concluded that, at least for the time being, it is still challenging to fabricate a practical sensor that can be used in commercial applications instantly. But there have been achievements that can be considered quite promising works. Cheng et al. developed a sensor with an excellent detection range, while Li et al. introduced a sensor with impressive sensitivity. Gao et al. achieved success in developing a disposable APBP pressure sensor. Other researchers and their accomplishments meet at least one major indicator in three areas. These are all promising accomplishments, pushing the research in this field forward. However, it is clear that there have been some incremental achievements. Researchers make continuous efforts to improve material performance. Researchers are constantly advancing on the path of wearable flexible sensors, from various synthesis methods to innovative material selections, and creative theories being proposed. In the near future, advancements in sensitivity, range, and stability will be crucial for the development of wearable sensors. A practical, flexible pressure sensor requires a material that can function in humid, salty conditions and be continuously curved without losing its properties. With materials that can integrate all indicators, wearable sensors will become a part of our daily lives, enhancing our quality of life and facilitating more attentive patient monitoring and treatment. The trajectory of sensor technology is moving towards greater integration with wireless networks and the ability to process complex datasets. The future may see self-powered sensors with energy harvesting capabilities, enabling continuous operation without the need for battery replacement. This, combined with advancements in biocompatible materials, will likely lead to sensors that are virtually unnoticed by the wearer but constantly provide valuable health data.

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