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Flexible and highly sensitive three-axis pressure sensors based on carbon nanotube/polydimethylsiloxane composite pyramid arrays

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ABSTRACT

The development of flexible and sensitive three-axis pressure sensors is of great interest for various wearable applications, such as electronic skin, soft robotics, and health monitoring. This study aims to propose a highly sensitive and flexible pressure sensor that can measure three-axis pressure based on conductive microstructured carbon nanotubes (CNTs) and polydimethylsiloxane (PDMS) elastomer with a simple and large-scale fabrication method that uses a polymer wet etching process. The randomly exposed CNTs on the surface using PDMS wet etching improve the sensitivity of the pressure sensors. The fabricated sensors exhibit a high sensitivity of 1.39 kPa^{-1} for a pressure range of 250 Pa, excellent limit of detection capability of 1.26 Pa, fast response time of within 52 ms, and high reliability of over 10,000 times of pressure loading/unloading. As an application, the pressure sensors are demonstrated using electronic skin on human fingers for the detection of the pressure levels and pattern recognition of distributed pressure. Moreover, to measure the three-axis pressure, pressurization tests are conducted using artificial fingers, demonstrating that the fabricated sensor can successfully measure the pressures applied along the three axes.

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1. Introduction

Flexible pressure sensors have received significant attention in relation to a variety of wearable applications, such as electronic skin [1], soft robotics [2,3], and health monitoring [4–8]. In these applications, high sensitivity and short response times in a pressure range of ~250 Pa [9], which is the pressure imposed on normal adult fingers, are essentially for practical applications. The sensing mechanism involve piezoresistance [10–13], capacitance [14–16], and piezoelectricity [17–19]. Among these types, piezoresistive pressure sensors, which are typical sensors that transduce the pressure applied to an object to a resistance signal, have been widely used owing to such advantages as their simple sensing principle, low fabrication cost, and high adaptability.

To optimize the sensitivity of these pressure sensors, previous studies suggested various methods by which to enhance the sensing characteristics of piezoresistive pressure sensors. These methods can be divided according to two strategies: (1) microstructured polymer films and (2) nanomaterial-embedded composites. Microstructured polymer films improve the sensing performance due to their reduced elastic modulus and viscoelasticity. Composite films containing nanomaterials such as carbon nanotubes (CNTs), zinc oxide nanowires and silver nanowires have been proposed to improve the electrical properties. For example, Zhu et al. proposed a piezoresistive pressure sensor made by coating graphene on pyramid-shaped polydimethylsiloxane (PDMS) microstructures [11]. Ha et al. proposed a piezoresistive pressure sensor with a structure in which ZnO NWs and coated PDMS micropillar arrays are arranged to be interlocked with each other [20]. These sensors exhibit excellent sensing performance, such as sensitivity, response time, and reliability. Specifically, flexible pressure sensors capable of detecting of normal and shear forces are essential for use in practical applications. However, there remain challenges related to ensuring high accuracy of measurements of the forces acting in various directions, necessitating the use of rational strategies for these promising devices.

Recently, some researchers have introduced a three-axial force detection sensor based on multi-stacked layers and signal read-out

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