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Two dimensional carbon nanotube based strain sensor

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ABSTRACT

This paper presents a 2-dimensional carbon nanotube (CNT) strain sensor with high sensitivity. The sensors, single-walled CNTs and multi-walled CNTs synthesized by thermal chemical vapor deposition, are grown directly on the suspended cantilever beams to measure external strain. The design of the sensor allows effective adhesion between CNTs and the cantilever beams, which results in CNT lengthwise strain and piezo-resistivity change. The suspended cantilever beams are fabricated by micromachining techniques. Experimental results show that the sensor achieves a high strain resolution of 0.00099%. The maximum piezo-resistivity gauge factor of the sensor is 744. The two-dimensional strain sensor presents the advantage of high sensitivity, which is beneficial for integration in a CMOS process of mass production.

1. Introduction

Due to their structural, electrical, mechanical and electromechanical properties [1–3], carbon nanotubes (CNTs) have received much attention. The compatibility of CNTs with strain sensors has been demonstrated both experimentally and theoretically. CNTs, which are modeled under axial strain and torsion, have predictable chirality dependent band-gap changes in response to strain [4]. The effect of the band-gap of CNTs on the piezo-resistive gauge factor of a strain sensor has been investigated with atomic force microscopy. The gauge factor of a small band-gap semiconducting single-walled carbon nanotube (SWCNT) is as high as 1000. CNTs have been integrated into strain sensors on silicon nitride membranes using electron beam (E-beam) lithography technology, with measured gauge factors of 210–700 [5–9]. These techniques, normally used to fabricate a short SWCNT, consume a lot of processing time for a one-dimensional strain sensor. Recently, the focus has turned to SWCNT devices on flexible substrates for flexible electronic applications [10,11]. Polyimide (PI) and CNTs were combined to fabricate pressure sensors by *in situ* polymerization using multi-walled carbon nanotubes (MWCNTs) as fillers. The resulting gauge factor was lowered to 2.6 [12]. A one-dimensional CNT-based strain sensor fabricated on plastic flexible substrate achieved a piezo-resistive gauge factor of 269 using the post-transferred technique [13]. However, the gauge factor of such techniques is low or requires a complicated process using a post-transfer technique in the one-dimensional strain sensor. Moreover, slipping between the CNTs and substrate often occurs, resulting in reduced sensitivity in bending tests in a one-dimensional direction.

Presented in this work is a novel design to measure two-dimensional strains in one plane simultaneously. The sensor design allows effective elongation of the CNT due to strains of the two-dimensional cantilever beams, resulting in a change in piezo-resistivity of the CNT. The advantages of the two-dimensional strain sensor presented in this paper are threefold. First, the design can simply and simultaneously measure two-dimensional strain in one plane. Second, the unique structure of a CNT lying on the majority of the sensor surface between the suspended cantilever beams provides a highly sensitive element. Third, the fabrication of two-dimensional CNT strain sensors can be effectively integrated into the CMOS process. Fabricated two-dimensional CNT strain sensors with high strain sensitivity are demonstrated in this work.

2. Two-dimensional sensor design and fabrication

2.1. Sensor design

To measure the strain of two dimensional orientations, the strain sensor was constructed with four layers: electric wires 1, a pair of short cantilever beams 2, a long cantilever beam 3, and carbon nanotubes (CNT) 4, in a one-dimensional sensing element. The design includes 4 sensor modules, X_1, X_2, Y_1, and Y_2, as shown in Fig. 1. Modules X_1 and X_2 measure the bending strain in the X direction. Modules Y_1 and Y_2 measure the bending strain in the Y direction. Each module contains two sensing elements, CNT 4-1 and CNT 4-2. CNT 4-1 is grown between two short suspended cantilever beams, and CNT 4-2, between a long suspended cantilever beam and a fixed end. The CNT is pulled by the deformation of

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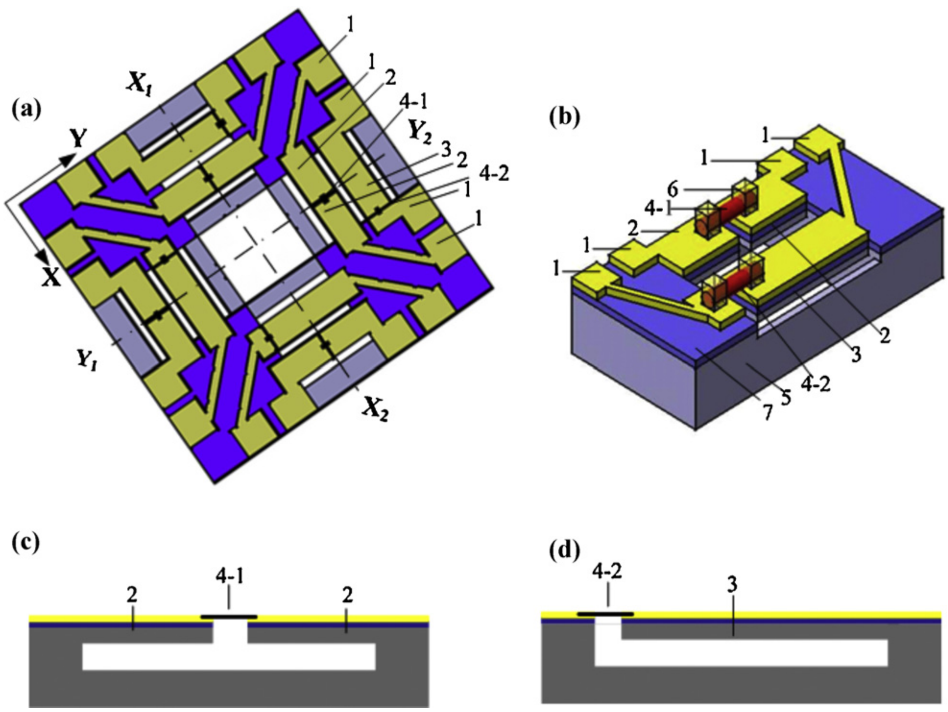

Fig. 1. Illustration of the two-dimensional strain sensors. (a) Top-view, (b) sensing element, (c) sensing element design 1, (short cantilever beam) and (d) sensing element 2 (long cantilever beam) [1, connected electric wire; 2, a pair of short suspended cantilever beams; 3, long suspended cantilever beam; 4-1 and 4-2, CNT; 5, Si base; 6, catalyst for growing CNT; 7, SiO_2 thin film].

cantilever beams, which is the axial strain from the loaded external force. Therefore, the ideal strain sensor contains CNTs and two types of cantilever beams in two dimensions. For more sensitivity to various strains, two types of cantilever beams, short and long, were designed to measure the large and small strains in this work. The use of both short and long cantilever beams can provide increased sensitivity depending on morphology of the cantilever beams. The cantilever beams and the associated electric wires were fabricated by micromachining techniques. In this design, the strain of the cantilever beam causes mechanical deformation that pulls the clamped CNT grown on the suspended cantilever beams. The cantilever beams provide a mechanical interface to the CNT, resulting in localized deformation at the axial strain. In physical applications, the sensor will be glued on the structure surface, similar to the use of conventional metallic strain gauges, to measure the bending deformation of the structure. When the sensor substrate is bending along one axis, the suspended cantilever beam will be bent, and subsequently elongation and mechanical strain of the CNT will be induced.

2.2. Simulation of Si cantilever beam of the sensor

In this work, the sensor design included two sensing elements, the silicon (Si) cantilever beam and the CNT. The strain of the Si cantilever beam of the sensor was subjected to external force, which elongated the CNT. The deformation of the CNT caused variance in the resistance of the CNT, resulting in the high sensitivity of the sensor. Therefore, the finite element method (FEM) was employed to calculate the optimum morphology of the anisotropic Si cantilever beams due to the Inductive Coupling Plasma (ICP) anisotropic etching. For the two types of Si cantilever beams, the lengths were $500 \pm 5\ \mu m$ (short one) and $1000 \pm 5\ \mu m$ (long one), the width was $500 \pm 5\ \mu m$ for both cases, and the thickness was $40 \pm 0.05\ \mu m$. The Young's modulus of Si is 112.4 GPa, and the Poisson's ratio of Si is 0.27. The FEM simulated results in Fig. 2 show the relationship of the loading force and strain of 1-dimensional measurement. We varied the load from 0 to 500 mN to calculate the strain on the Si cantilever beams of the sensor. The strain on the Si cantilever beam increased as the load increased. The device of the strain sensor was 4 mm × 4 mm × 0.5 mm. Fig. 3 shows the strain dependent decrease in the gap between the cantilever beams. This result indicates that the length of the Si cantilever beam increased with a decrease in the gap size, leading to a reduction in the stiffness of the Si cantilever beam and raising the strain on that beam. For integration with the micromachining techniques, the gap between the cantilever beams was 50 μm. In addition, in the simulated results, the strain of the long cantilever beam was twice as great as that of the short strain cantilever beam, as shown in Fig. 4. In other words, the long cantilever beam definitely measured the small strain due to its small stiffness. Tuning the morphology of the cantilever beam allows increase in the sensitivity of the strain sensor in this work.

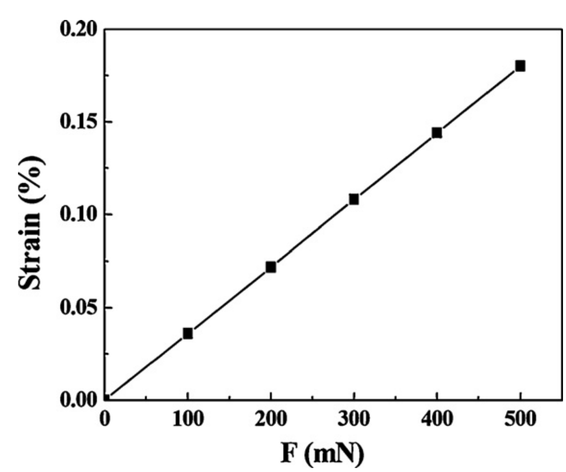

Fig. 2. The FEM simulation results show the strain of cantilever beam deformation increasing as load increases.