A Multi-Axis MEMS Sensor with Integrated Carbon Nanotube-Based Piezoresistors for Precision Force Metrology

Michael A. Cullinan, Robert M. Panas, and Martin L. Culpepper
Massachusetts Institute of Technology, Department of Mechanical Engineering, USA
mcullin1@mit.edu

Abstract

This paper presents the design and fabrication of a multi-axis MEMS force sensor with integrated carbon nanotube (CNT)-based piezoresistive sensors capable of measuring forces in the z-axis as well as torques in the θ_x and θ_y axis. Through the use of proper CNT selection and sensor fabrication techniques the performance of the CNT-based sensors was increased by almost three orders of magnitude compared with current CNT-based sensor systems [1]. The range and resolution of the MEMS force sensor were determined to be 84 μN and 5.6 nN, respectively. The accuracy of the force sensor was measured to be better than 1% over the device's full range.

1 Introduction

Nanonewton level, multi-axis force sensing is required for many biology, materials science and nanomanufacturing applications. Unfortunately, these requirements are difficult to achieve given the size, sensitivity and fabrication limitations associated with existing small-scale sensing techniques. Carbon nanotube-based strain sensors have the potential to overcome some of the limitations in small-scale force/displacement sensing technologies due to their small size and high strain sensitivity. In this paper, we will show how carbon nanotube (CNT) based piezoresistive sensors can be used to improve the resolution of multi-axis MEMS sensor systems. We are able to do this by improving the sensor fabrication and controlling the chirality and number of CNTs in the sensor.

2 CNT Selection

In order to optimize the performance of the CNT-based sensors, the relationship between device performance and the structure of the CNTs was investigated both theoretically and experimentally as described in reference [2]. It was found that it is possible to change the strain sensitivity of the mechanical sensor system by controlling the chirality of the CNTs in the sensor. CNTs with similar diameters can have significantly different strain sensitivities based on their chirality. Figure 1a shows five different chiralities of CNTs each with a diameter of approximately 1.38 nm. Two of the CNTs show an increase in resistance with strain, two show a decrease in resistance with strain, and the (10,10) CNT shows no change in resistance with strain. By selecting CNT with the highest strain sensitivity we can increase the gauge factor of our sensor from approximately 78 for bulk samples to over 1000 [3].

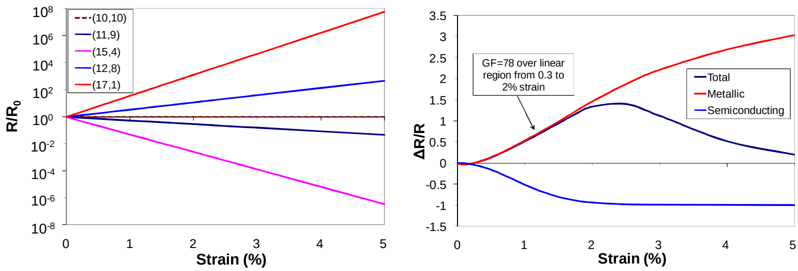

Figure 1: (a) Resistance vs. strain for single CNTs with diameters of 1.38 nm and (b) 100 randomly selected CNTs in a parallel resistor network

3 Device Design

A 3-degree-of freedom (DOF) force sensor was designed to fit on top of a Hexflex nanopositioner as shown in Figure 2a in order to accurately position and apply loads to a sample. This design allows the sensor to measure the torques and the normal force on the stage. Force feedback control can then be used to ensure that the stage is in contact and level with the sample. The 3-DOF MEMS force sensor shown in Figure 2b is composed of three coplanar flexures with integrated CNT-based piezoresistors at the base of the flexures. The flexures and sensors were sized using system level noise modeling and optimization [4]. The optimized sensor has 2.5 mm long, 35 μm wide and 10 μm thick flexures and a dynamic range of 83 dB.

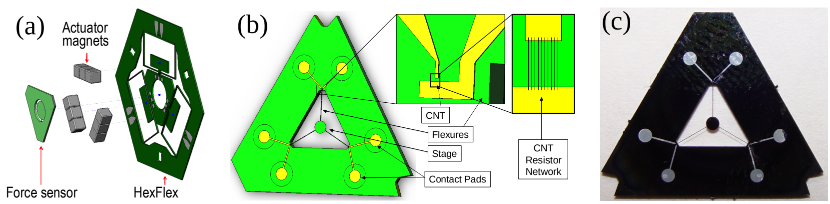

Figure 2: (a) Force sensor/HexFlex assembly (b) Schematic of CNT-based force sensor (c) Fabricated CNT-based 3-Axis force sensor

4 Device Fabrication

Several sensor fabrication techniques were investigated in order to reduce noise in the sensor. It was found that by annealing the CNTs and coating them in an aluminum oxide protective layer it is possible to reduce the noise in the sensor by two orders of magnitude as seen in Figure 3a. Also, by doubling the CNT deposition time, and thus approximately doubling the number of CNTs in the sensor, it is possible to reduce the noise in the sensor by another factor of two as shown in Figure 3b. Therefore, by controlling the structure and number of CNTs in the sensor it is possible to improve the performance of these sensors by several orders of magnitude and produce nanoscale sensors with a dynamic range of greater than 80 dB. This is about an order of magnitude better than current nanoscale mechanical sensor technologies [5].

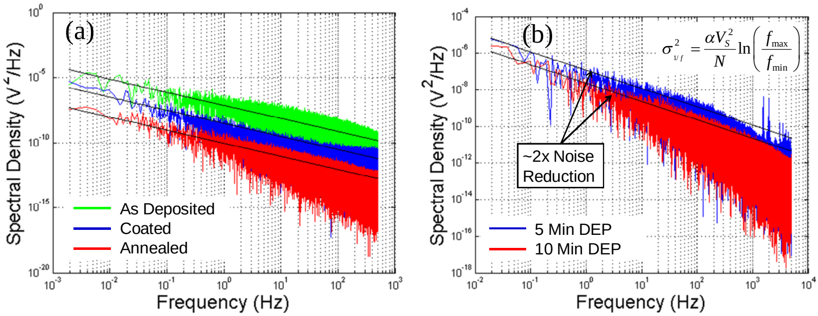

Figure 3: (a) Noise spectral density of CNT sensor system with different processing conditions (b) Noise spectral density of CNT sensors with different numbers of CNTs

4 Results

The CNT-based force sensor was calibrated using a digital micrometer with a 1 μm resolution as shown in Figure 4a. The micrometer was used to push on the center stage of the MEMS force sensor with a know displacement. The force applied to the center stage was calculated from the measured force sensor stiffness of 1.4 N/m. The stiffness was measured using a nanoindenter. The force sensor was calibrated by fitting a line to the measured output voltage vs. applied force curve for each of the sensors as shown in Figure 4b. The measured force sensitivity varied by about 25% between the sensors from about 790 μV/μN for sensor 1 to about 590 μV/μN for sensor 3. The uncertainty in the force calibration was low resulting in a measured accuracy for the force sensor of better than 1% over the device's full range.

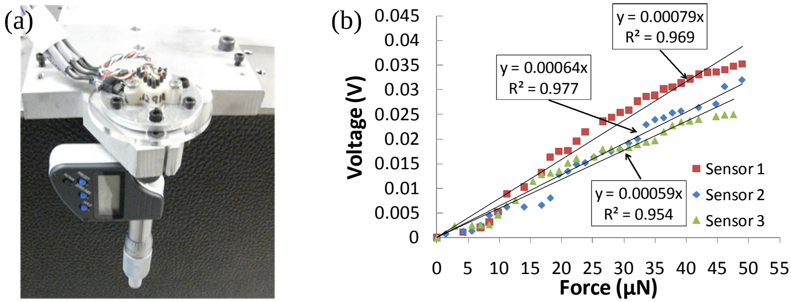

Figure 4: (a) Calibration setup (b) Calibration results for MEMS force sensor

In addition to the to the linear calibration curves, each sensor has a small sinusoidal component due to thermal variations over the testing period. The total test of 20 minutes is approximately equal to the thermal period of the room. Therefore, there is about one full thermal period in each sensor due to thermal variations of the room.

Table1: Results for each piezoresistor in the force sensor

	Sensor 1	Sensor 2	Sensor 3
Sensitivity	790 V/N	640 V/N	590 V/N
Noise	7.5 µV	7.5 µV	4 µV
Dynamic Range	78.4 dB	76.5 dB	81.3 dB

The resolution of each sensor was calculated by dividing the noise in each sensor by the sensitivity of each sensor. The results for each sensor along with the corresponding measured dynamic ranges are presented in Table 1. The measured resolution for sensor 1 was 9.5 nN and it was 11.8 nN and 6.7 nN for sensors 2 and 3, respectively. Overall, the range and resolution of the force sensor were determined to be 84 µN and 5.6 nN, respectively. This is equivalent to a dynamic range of 83.2 dB.

References:

[1] T. Helbling, C. Roman, and C. Hierold. *Nano Lett*. **10**, 3350 (2010).

[2] M. Cullinan and M. Culpepper. *Phys. Rev. B*. **82**, 115428 (2010).

[3] C. Stampfer, A. Jungen, R. Linderman, D. Oberfell, S. Roth, and C. Hierold. *Nano Lett*. **6**, 1449 (2006).

[4] R. Panas, M. Cullinan, and M. Culpepper. *Proceedings of the 2010 ASPE Control of Precision Systems Conference*. Boston, MA (2010).

[5] M. Cullinan, Ph.D. Thesis, Massachusetts Institute of Technology, 2011.