Pico-watts Thermal Convective Accelerometer Based on CNT Sensing Element

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Abstract—**This paper presents the design and characterization of a novel micro motion sensor using Carbon Nanotube (CNT) sensing element. This sensor is based on thermal convective sensing theory, and uses CNT bundles manipulated by dielectrophoretic (DEP) forces to form the motion sensing element. The heat generation CNT bundle is first heated up in a micro chamber using constant current. External acceleration causes thermal convection within the chamber, which is detected by the fluctuation of the output voltage of the CNT sensing element working as a temperature sensor. The thermal sensing properties of CNT bundles are tested and analysed first. Then, the sensor's responses to acceleration are monitored and reported. The effect of the driving current level is also investigated and reported. It is found that by using this detection method, the sensing block requires only tens of pico-watts to function as motion sensors.**

I. Introduction

Micro thermal convective motion sensors have been developed for more than a decade now [1]. The operation principle of this type of motion sensors is based on the detection of thermal disturbance caused by acceleration-induced convection in a sealed chamber. By using this sensing method, only micro heater and temperature detectors are needed, and no moving parts (proof-mass) are used. So this type of accelerometer is more robust to shocks compared to conventional micro motion sensors. Meanwhile, the fabrication process is simple and reliable.

However, because micro heaters and thermal detectors are used, the sensor often consume much higher power. This problem originates from the properties of the heating and sensing material. The first implementation of this type of sensor [1] chose *p*-doped polysilicon as heater/detector material. A prototype using polysilicon thermopiles as detector and suspended polysilicon as heater was designed and tested also [2]. Platinum thin film was used as heater/detector in a different prototype by other researchers [3]. For all reported prototypes, power consumption for the sensing block is between tens of mW to hundreds of mW. This is because to meet the sensing capabilities of the thermal detectors, the heaters have to be heated to very high temperature, leading to high power consumption. To reduce the power consumption, alternative thermal detecting materials should be used.

Our group have been working on integrating CNTs into micro sensors since 2003 [4]. Dielectrophoretic force is used to manipulate harvested CNTs dispersed in liquid, and finally CNTs are aligned between micro electrodes. This aligned CNT bundle can then work as sensing element. Thermal sensor [5], flow sensor [6], pressure sensor [7] and chemical sensors [8], [9] using CNT as sensing elements have been developed since then, utilizing different properties of CNTs. We have also developed an inclination sensor using CNTs with liquid convection medium [10]. One of the advantage of CNT sensing elements is that they require very low power to operate.

Recently, we found that when using air as convection medium, a single CNT bundle can response to motion induced convection, if the input heating power is appropriately controlled. Experiments were carried out to determine the effect of the input power. The acceleration responses were also investigated. Results show that CNT bundle could sense sinusoidal vibration at an operating power as low as several tens of pico-watts.

II. Design & Setup

The structure of the CNT based thermal convective motion sensor consists of a sensor chip and a chamber to seal the convection medium.

The sensor chip is fabricated using conventional micro fabrication method along with DEP manipulation of CNTs (see Fig. 1(a)). 1mm thick glass is selected as the substrate. Due to its low thermal conductivity, it can better insulate the CNT heater, leading to higher heater temperature [11]. 100nm thick Cr layer and 300nm Au layer are then deposited onto the substrate using DC sputtering. Au layer is used as the main electrode material, while Cr layer improves the adhesion between Au and glass substrate. The electrode pairs are then patterned by standard contact mask UV photolithography and wet etching method. The tip of the electrode has a width of 5μm, and the gap between the two tips is also 5μm (see Fig. 1(b)). Harvested Multi-walled Carbon Nanotubes (MWNTs) are then manipulated using DEP force to form a bundled linkage within the gap of the two electrodes. More information about sensor fabrication and DEP manipulation can be found in [10]. The deposition result is shown in Fig. 1(b), in which three CNT bundles are deposited.

A PDMS chamber is fabricated using soft replica molding method [12] to work as the convection chamber (see Fig. 1(c)). The chamber is bonded to the glass substrate after both are exposed to Oxygen plasma for activation. The finished prototype is shown in Fig. 1(e).

Then acceleration source and sensor powering circuit are set up to characterize the sensor. Sensor prototype is installed on a vibration exciter which can provide sinusoidal acceleration. A laser vibrometer monitors the displacement and velocity

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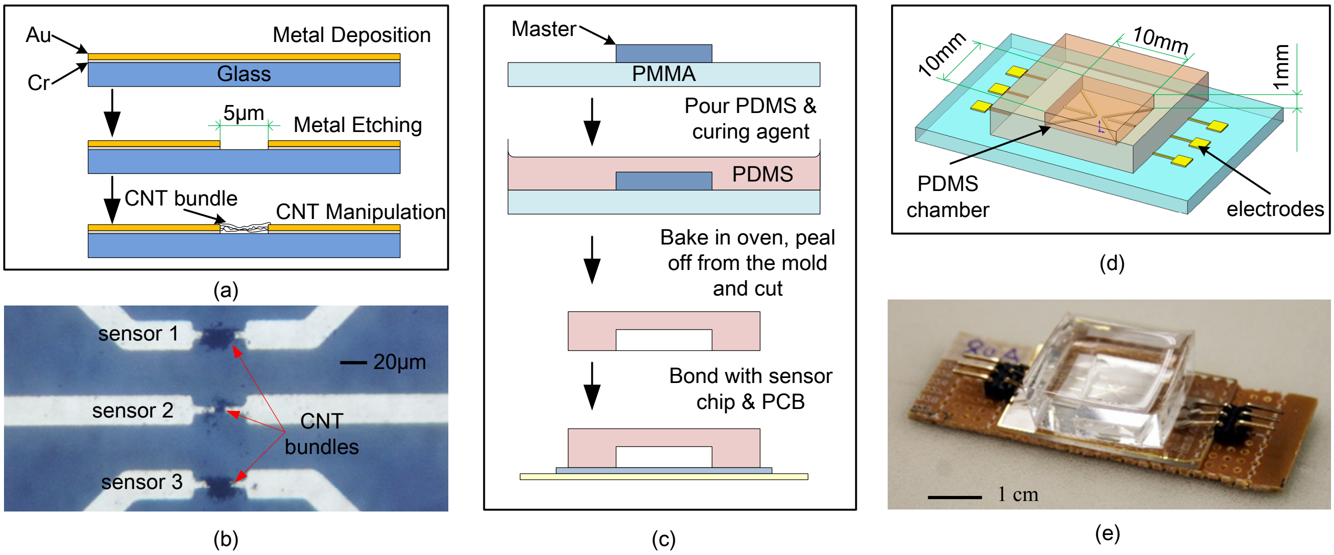

Fig. 1. Fabrication process of the sensor chip and the prototype. (a). Fabrication of the sensor chip and DEP manipulation of CNTs. (b). Deposition result of CNTs. Here three CNT bundles are deposited. (c). PDMS chamber is fabricated using soft replica molding. The chamber is bonded to the sensor chip after Oxygen plasma activation. (d). Illustration showing the dimensions of the prototype. (e). A finished sensor prototype.

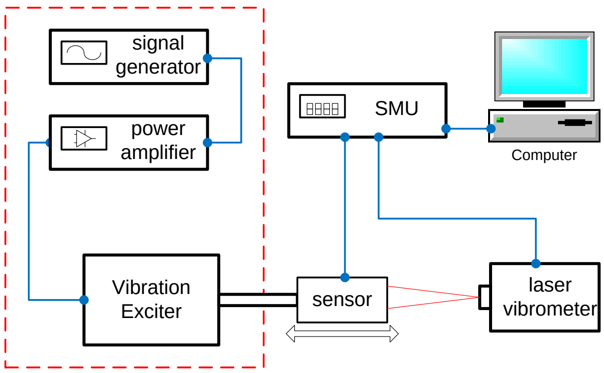

Fig. 2. Experimental setup used to measure sensor's output to vibration.

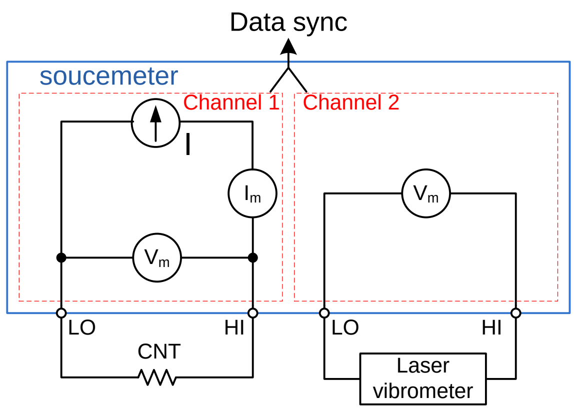

Fig. 3. Configuration of the sourcemeter during measurement. One channel of the sourcemeter powers up the CNTs using constant current mode. The current and voltage are both recorded. Another channel of the sourcemeter is configured as a voltmeter. The time stamps of readings of both channels are collected for synchronization.

of the sensor in real time, and the amplitude and phase of acceleration can be obtained through differentiation. One channel of a dual-channel sourcemeter (Keithley 2602) is used to power up the CNT bundle, and another channel of the sourcemeter collects the data from the laser vibrometer. The sourcemeter is connected to a PC via GPIB bus, which enables device control and data transmission. The set up with all equipments used is shown in Fig. 2.

The CNT is powered up using the constant current mode of the source meter. The resulting output voltage and the actual current are both measured. Checking the value of the actual current is necessary in order to monitor current leakage when the input current is very low. In our test no current leakage was found for current as low as 1nA. The velocity data from the laser vibrometer is collected by another channel of the source meter configured as volt-meter, and is used to calculate the parameters of acceleration. By comparing the time stamps of the two channel data, the sensing output and the velocity input of the sensor can be synchronized (see Fig. 3).

III. Experimental Results

A. Thermal Detection

For the deposited MWNT bundles, their resistances vary between tens of kΩ to hundreds of kΩ. Because humidity will also affect the resistance of the CNTs, so the resistance-temperature relationship of this CNT bundle was tested in a climatic chamber. The climatic chamber can change the temperature between 20°C and 80°C, while keeping the humidity constant.

The relationship between temperature and resistance is often described using

$$R = R_{ref}[1 + \alpha(T - T_{ref})] \tag{1}$$

where R is the resistance at temperature T, R_{ref} is the resistance at reference temperature T_{ref} (often 20°C), and α is the Temperature Coefficient of Resistance (TCR). Test results show that under the same testing current, the values of TCR for all tested samples are very close. For a certain sample, the TCR under a certain testing current shows long time stability. For example, when using 1μA current to test, the TCR of all samples varies between -0.2%/°C to -0.1%/°C. However, when using higher testing current, the TCR value becomes larger. For example, when using 10nA to test, the TCR can reach as high as -1.4%/°C.

We note here that TCR changes with testing current is due to the definition of the ambient temperature T_{amb}, i.e., T_{amb} is considered to be the temperature of the tested sample T when calculating TCR. Although this estimation is acceptable when testing conventional materials, this cannot be applied to CNTs. Because the CNT bundle has ultra-low heat capacitance, and hence very low testing current will heat it up, making its temperature larger than the temperature of the climatic chamber. This can be proved using the CNT bundle's resistance change under different testing current, as explained below.

During the Joule heating effect by the current applied to the CNT bundle, the heating power increases as the square of current, i.e., $P_j = I^2R$. The CNT heater loses its heat to the air by convection and to the substrate and electrodes by heat conduction. This can be described by

$$P_{loss} = (A + B\sqrt{Re})(T - T_{amb}) \tag{2}$$

where A represents the conductive thermal flux density to substrate and electrodes, $B\sqrt{Re}$ represents the thermal flux density to the air caused by convection. For a certain sensor, the two values are constant. T_{amb} is the ambient temperature, and is around 25°C for a cleanroom. From $P_J = P_{loss}$ and (1), considering $T_{amb} \approx T_{ref}$ we can get

$$R = \frac{1}{\dfrac{1}{R_{ref}} - \dfrac{\alpha}{A + B\sqrt{Re}}I^2} \tag{3}$$

Here α is the TCR when $T = T_{amb}$, meaning that during the measurement no Joule Heating effect exists. The curve for R in Fig. 6 (dashed circle) can fit to this expression very well. Because the deposited CNT bundle has a very small heat capacitance, its temperature becomes very high even at very low current. But the resistance change is no longer significant when the current is larger than 100nA.

B. Vibration Test

The output of the sensor under 1Hz sinusoidal vibration is recorded and is shown in Fig. 4. The acceleration data is calculated numerically from the velocity data collected by the laser vibrometer. Sensor resistances are derived from the output voltage and the input current. From this figure it is clear

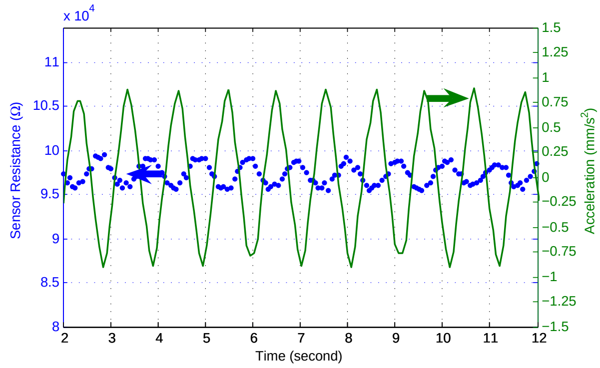

Fig. 4. Sensor's response to 1Hz vibration.

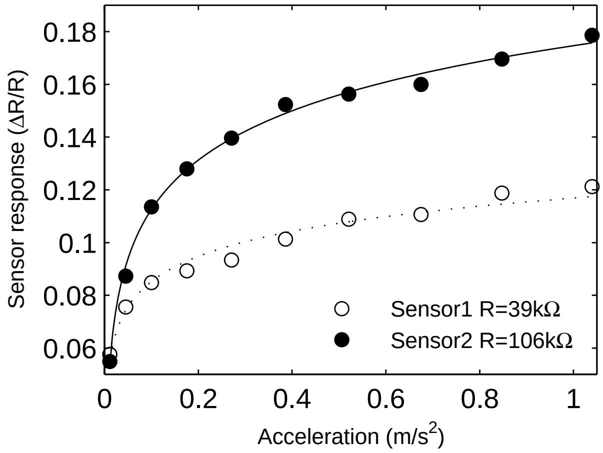

Fig. 5. Sensor output under different acceleration. Two sensors are tested. It can be seen that for both sensors, the output has a linear-log relationship with the acceleration peak.

that the sensor can trace the vibration quite well. (Note: the Multi-walled CNTs used in this sensor has a negative TCR.)

The sensor is then tested under different sinusoidal acceleration input. The current setup can generate and measure vibration with the peak from $0.01m/s^2$ to $1m/s^2$. The sensor's response within this range is shown in Fig. 5. A linear-log relationship between the sensor response and acceleration is observed. When acceleration is smaller than $0.1m/s^2$, the response changes very significantly. This means the CNT sensor is very sensitive to small acceleration. But the sensor goes to saturation when applied with large acceleration. The saturation phenomena is identical to other thermal motion sensors [3], [13].

C. Effect of Heating Power

As mentioned previously, this sensor can only function under certain input current. Hence, another test is carried out to determine the relationship between input current and sensor output. The driving current is set to values between the lower limit of the sourcemeter (around 0.1nA) to 10μA, at the same time the sensor's response to 2Hz vibration with fixed amplitude is recorded. The result is shown in Fig. 6.

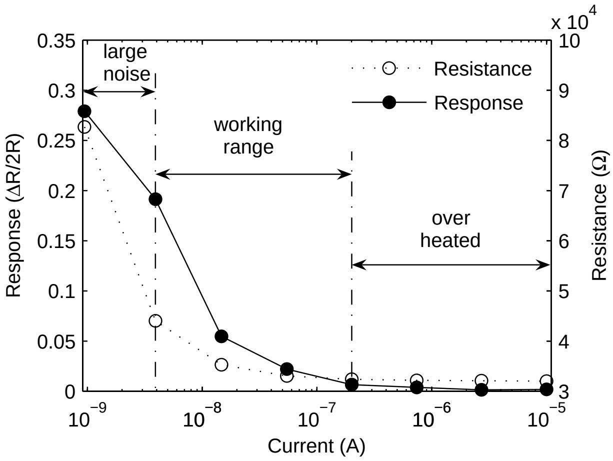

Fig. 6. Sensor output under different input current levels. The input vibration has a frequency of 1Hz. Under each input current, the output voltage is collected by sourcemeter. For each current, 100 cycle of the output is collected, and the max-min value of all data is calculated. This calculated value is plotted as one dot in this figure. The sensor's average resistance under different testing current is also plotted for comparation.

The sensor's response can be divided into three sections. When the heating current is less than several nA, very large noise is observed. In one aspect, measurement noise of the instrument is large under low current. Also when heating current is low, the temperature of the CNT is close to the ambient temperature. So the sensor signal will be saturated easily, leading to unstable response.

When the heating current is several hundreds of nA, sensor response becomes too low to be detected. The reason is that, under significantly large current, not only the CNT and the air around it, but also the substrate and electrodes are heated up. As induced convection cannot affect the temperature of the CNTs remarkably, then the CNTs show resistance change that is too low to be detected.

Only between a heating current of several nA to hundreds of nA, the sensor can give responses accordingly, as shown in Fig. 6.

For all tested sensors, the resistance is around tens of kΩ to hundreds of kΩ. Therefore, when they are powered up using 10nA current, the power consumption is between several pico-watts to tens of pico-watts. The common power consumption for thermal convective accelerometers that use solid thin film heater and detectors is tens of mW to hundreds of mW, hence by using CNT as sensing element, the power consumption of convective accelerometers can be greatly reduced.

IV. Conclusion

A new thermal convective accelerometer based on CNT was designed and demonstrated. A DEP manipulated CNT bundle was deposited on a glass substrate, and a PDMS chamber was bonded with the substrate to form a convection chamber. The forced convection in the chamber generated by vibration was sensed by the CNT bundle working as anemometer. Experiments show that the CNT bundle can sense sinusoidal vibration. The corresponding input-output relationship was determined too. However, the bandwidth and frequency responses still need to be examined.

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