Research Letters

A Picowatt Powered Carbon-Nanotube-Based Thermal Convective Motion Sensor

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***Abstract*—We report a thermal convective motion sensor with carbon nanotubes (CNTs) as sensing elements. This sensor uses CNT bundles manipulated by dielectrophresis as both, a heater and thermal detector. This sensor can respond to sinusoidal vibrations, and requires only several picowatts to operate. We have thus far demonstrated that this CNT-based motion sensor can detect linear acceleration as low as 0.02 m/s, and respond to at least 10Hz vibrations.**

***Index Terms*—Convective sensor, convective accelerometer, CNT motion sensor, nanotube sensor.**

I. Introduction

MICROMACHINED thermal convective accelerometers have been under development for more than a decade. Their operating concept is based on using thermal detectors to measure the temperature change around an enclosed micro-heater, caused by an acceleration induced forced convection disturbance within the enclosure. Leung *et al.* [1] reported the first implementation of this type of sensor, which used *p*-doped polycrystalline silicon heater and sensors in bridge structures over a bulk-etched cavity on a silicon substrate. Milanović *et al.* [2] reported another CMOS-compatible implementation using thermocouples as temperature detectors. Then a Platinum thin film was used by F. Mailly *et al.* in their thermal accelerometer as both heater and sensors [3], [4].

However, large power consumption and overall size limit the applications for this type of motion sensor. For proper operating conditions of these solid-state sensing elements, heaters need to be powered up using a large current (9 mA and 18.3 mW, as stated in [5]), in order to reach a very high temperature. Besides, thermal detectors need to be placed at a distance away from the heater to achieve an optimum response, making the overall size very large.

Our group has been investigating the integration of carbon nanotubes (CNTs) into microsensors by using dielectrophoresis (DEP) method since 2002 [6]. It was demonstrated that the CNT bundles could work as thermal sensors with an ultralow power consumption and a fast frequency response [7]. This letter reports our recent progress on building a thermal convective accelerometer with CNT sensing elements. The sensor is fabricated by conventional microfabrication methods and DEP manipulation of CNTs. The sensor's response to sinusoidal acceleration has been demonstrated. Performances under different powering currents are tested and are reported here. The most exciting result is that by using CNT bundles as thermal detectors, the power consumption can be reduced to several picowatts, while reducing the size of the sensing block.

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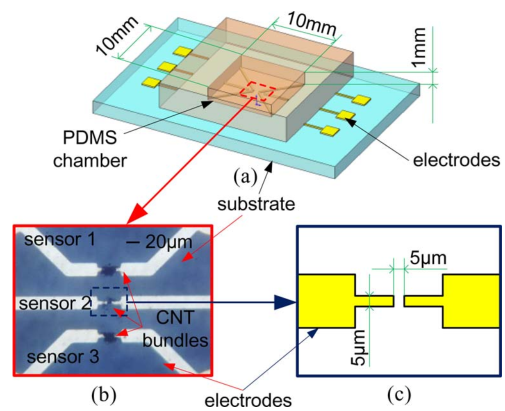

Fig. 1. Sensor prototype. (a) Gold electrodes are fabricated on glass substrate, and a PDMS enclosure is bonded to the substrate to form the convection chamber. (b) Enlarged view of the electrode pairs. Three CNT bundles are deposited here. Each bundle works as one CNT heater/sensor. (c) Geometry of the electrode tips.

II. Results and Discussion

The sensing block of our sensor is fabricated by conventional micromachining methods. A 1-mm-thick glass is selected as the substrate, as low thermal conductivity materials can reduce the heat loss from the CNT bundles to the substrate and improve the overall sensor sensitivity [7]. A 100-nm-thick Cr layer and a 300-nm-thick Au layer are deposited onto the substrate by dc sputtering. Electrode pairs are then patterned by contact-mask photolithography and wet etching. The tip of the electrode has a width of 5 μm, and the gap between the two tips is 5μm also (see Fig. 1(c)).

Harvested multiwalled carbon nanotubes (MWNTs) prepared by chemical vapor deposition are dispersed in an ethanol solution and then is treated by ultrasonic agitation for 20 minutes to minimize aggregation. The two electrodes are excited by 16 V peak-to-peak ac voltage at a frequency of 1 MHz. Then, approximately 2 μL of the solution is dropped onto the substrate to cover the two electrodes. The DEP force, viscous force, electrothermal force and the gravitational force are acting on the suspended MWNTs. The dominant DEP forces aligns the MWNTs between the Au electrodes and, finally, a CNT linkage is formed between the two electrodes, as the ethanol solution evaporates. Fig. 1(b) shows the CNT deposition result captured by optical microscope, in which three CNT bundles are deposited. More information about the DEP process can be found in the paper by Fung *et al.* [7]. The sensor chip is then baked in an oven to remove the ethanol completely. The convection enclosure for the sensor is a PDMS chamber prepared using replica molding [8]. The PDMS chamber and the sensor chip are both exposed to an oxygen plasma and then pressed against each other to be irreversibly sealed. The structure of the prototype is shown in Fig. 1(a).

The CNT bundles work as both the thermal heater and detectors in the sensor. The thermal resistive characteristics are first tested. The resistance for the deposited MWNT bundles varies between tens of kΩ to hundreds of kΩ from sample to sample, when measured using a 1 μA current in a cleanroom. According to these tests, the resistance of the CNT bundle will be affected by temperature, humidity, and the testing current. Because humidity is fixed in the sealed chamber of the sensor, only the test current and temperature are investigated.

The relationship between temperature and resistance is often described as

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

where R is the resistance at temperature T, R_{ref}, resistance at reference temperature T_{ref} (20 °C), and α, the temperature coefficient of resistance (TCR). The sensor is put into an environmental chamber with fixed humidity and programmable temperatures between 20 °C and 80 °C. While fixing the test current, the temperature is programmed in a 5 °C steps. For each step, temperature is maintained for 30 minutes. Test results reveal that under the same testing current, the values of TCR for all tested samples are close. For example, when using 1 μA to test, the TCR varies between $-0.2\%/°$C to $-0.1\%/°$C. However, when using different testing currents the TCR value varies significantly. For example, the TCR for a test at 10 nA can reach as high as $-1.4\%/°$C.

The reason why the TCR changes at different testing current is that the ambient temperature T_{amb} is considered to be the temperature of the tested sample T when calculating TCR. Although this approximation is acceptable when testing conventional materials, it cannot be applied to CNTs. Because the CNT bundle has an ultralow heat capacitance, even a very low testing current will heat it up, making its temperature higher than the temperature of the environmental chamber. This can be proven using the CNT bundle's resistance change under different testing currents, as explained below.

Due to the Joule heating effect by the current applied to the CNT bundle, the heating power increases as the square of the current, i.e., $P_j = I^2 R$. The CNT heater loses heat to the air by convection and to the substrate and electrodes by thermal

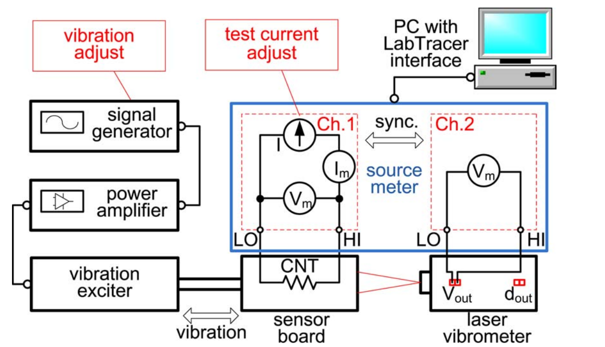

Fig. 2. Experimental setup. The sensor board is mounted on a vibration exciter which produces sinusoidal vibrations. A laser vibrometer measures the displacement and velocity of the sensor board. The sensor is powered in the constant current mode of a Keithley 2602 dual-channel sourcemeter. The sourcemeter also monitors the resulting output voltage of the sensor and the output of the vibrometer.

conduction. This can be described using the conductive and convective heat transfer model:

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

where P_{lose} is the heat dissipation of the CNT heater, A is the conductive thermal flux density to the substrate and electrodes, $B\sqrt{Re}$ is the thermal flux density to the air caused by convection. For a given sensor in stable state, the two values are constants. T_{amb} is the temperature of the ambient air and the substrate, which is around 25 °C for a cleanroom. From $P_j = P_{\mathrm{loss}}$ and (1), considering $T_{amb} \approx T_{\mathrm{ref}}$ we can get

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

In the acceleration test, the CNT bundle is powered in a constant current mode by a sourcemeter (Keithley 2602 Dual Channel), and the resulting resistance is monitored. The sensor chip is mounted on a vibration exciter. The vibration velocity is measured by a laser vibrometer. Another channel of the sourcemeter reads out the velocity and the displacement output of the laser vibrometer. From this, the amplitude and the phase of the acceleration is derived. A detailed illustration of the experimental setup can be found in Fig. 2.

Fig. 3 shows the sensor's response to 1 Hz vibration. The CNT bundle is powered by a 10 nA constant current. The vibration exciter can generate ± 11 mm/s^2 sinusoidal acceleration under the 1 Hz input. In correspondence, the CNT sensor's resistance gives a 5% fluctuation with a phase delay of around 180°. The phase delay is the sum of the delay of the vibration induced convection and the thermal sensing response time. As proven previously [7], the response time for a CNT sensor is within several microseconds, so the 180° is the delay from the induced convection.

The sensor is next tested under different vibration frequencies. The current setup can generate and measure vibration with peak values from 0.01 m/s^2 to 1 m/s^2. The sensor's response within this range is shown in Fig. 4. A linear-log relationship between the sensor response and acceleration is observed, which means

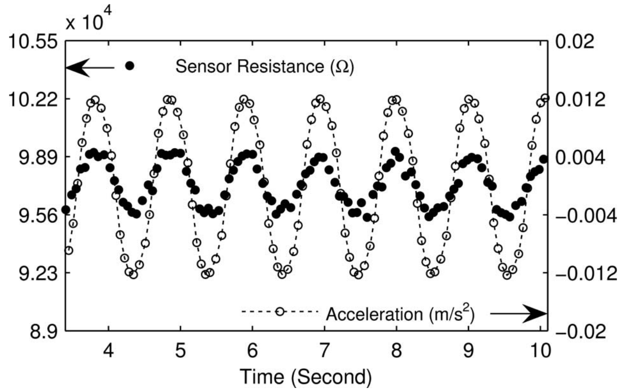

Fig. 3. Sensor's response to 1Hz vibration

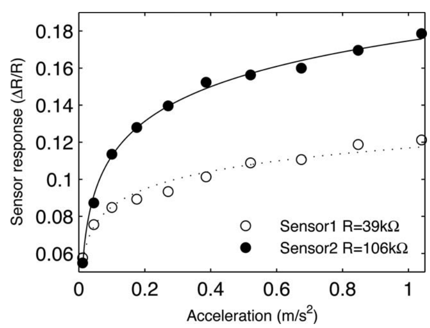

Fig. 4. Two Sensors' acceleration responses. One sensor has a resistance of 39 kΩ, while 106 kΩ for another.

the CNT sensor is sensitive to small accelerations, but will go to saturation when a large acceleration is applied. The saturation can be explained using King's Law, which shows that the heat transfer from the heated CNTs to the ambient medium saturates with increasing flow velocity.

For a thermal-type sensor, the heating power is the most important input parameter. Fig. 5 shows the sensor's response and resistance under input currents from 0.1 nA to 10 μA. Sensor resistance R in the figure is the average resistance $\bar{R}$, while sensor response is defined by $(R_{\max} - R_{\min})/R$. In this test, a 2 Hz vibration with a peak-to-peak value of 45.5 mm/s^2 is applied to the sensor. Each dot in the figure is ensemble averaged from eight periods of sampling data.

Sensor response can be divided into three sections. When the heating current is less than several nA, a high noise level is observed. In this situation, measurement noise from the environment and the instruments introduces errors. Also when the temperature of the CNT is close to that of the environment within the chamber, the sensor gets saturated quickly, after a very small temperature change. When the heating power is greater than hundreds of nA, the sensor response becomes too low to be detected. In this operating region, not only are the CNT and the air around it heated but also the substrate and electrodes are heated up too. Thus, induced convection cannot affect the temperature of the CNTs remarkably. Then the CNTs cannot respond to acceleration. Only in an operating region with a heating

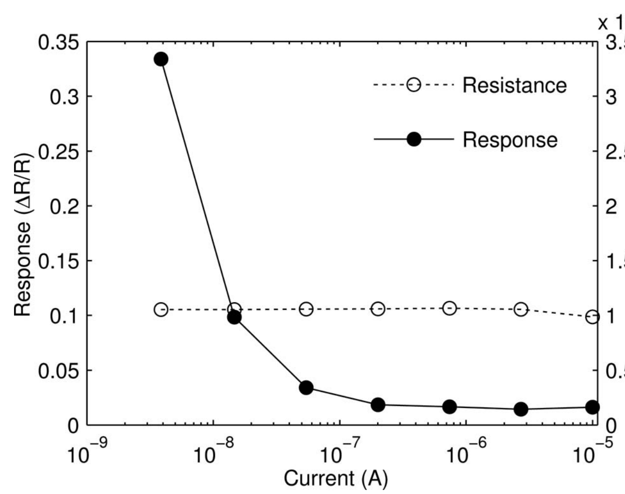

Fig. 5. Sensor's performance under different input current. When the heating current is around several nA, measurement noise and sensor saturation makes the response very unstable. If the heating current is larger than hundreds of nA, the over-heated CNT bundle also heats up the substrate around it, making the response too low to be detected.

current between several nA to hundreds of nA can the sensor respond accordingly.

III. Conclusion

For all the sensors tested, the resistance is around tens of kΩ to hundreds of kΩ. When they are powered by a 10 nA current, the power consumption is between several picowatts to tens of picowatts. The usual power consumption for thermal convective accelerometers that use a solid-state, thin-film heater and detectors is tens of mW to hundreds of mW [2], [3], [5]. So by using CNT as sensing element, the power consumption can be reduced by orders of magnitude.

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