Extreme-Low-Power Thermal Convective Inclination Sensor Based on CNT Sensing Element

Yu Zhang and Wen J. Li*
Centre for Micro and Nano Systems, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong

***Abstract*—This paper presents the operation principle and development of a micromachined thermal convective inclination sensor using Carbon Nanotube (CNT) sensing elements. The operation principle of this type of inclination sensor is based on sensing the convection of fluids in a micro chamber. External motion will lead to redistribution of the temperature profile around a heater and will be asymmetric. The temperature difference over two detectors is converted into resistance difference as sensed by the CNT sensing elements. The inclination sensors developed by our group using the above sensing principle have shown very good sensitivity, and the power consumption for these CNT sensors is extremely small (around μW). We have demonstrated that such a sensor can be built using a glass substrate bonded with a PDMS cover to encapsulate liquid as the convection medium.**

I. Introduction

Conventional micromachined motion sensors usually contain a proof-mass which is connected to a reference frame through spring elements. The displacement of the proof-mass is then measured capacitively, piezoresistively, or by other methods. In terms of a motion sensor without a proof-mass, A. Leung et al. reported the first micromachined thermal convective accelerometer without the convention spring-mass sensing system in 1997 [1]. Since then, thermal convective accelerometers have been studied in various groups all over the world [2]–[8].

The operation principle of thermal convective motion sensor is based on heat transfer by convection (See Fig. 1). A small volume of air or liquid is heated up by a micro heater. Two temperature sensors are placed symmetrically around the heater along the sensitive axis. Under inclination or acceleration, the temperature distribution around the heater becomes asymmetric with respect to the heater due to induced convection. Thus the resistances of the two thermal detectors will be different. Inclination or acceleration is then derived which is proportional to the resistance difference between the two sensors. As there is no solid proof-mass, thermal motion sensors can work under high acceleration and can survive under shocks with the magnitude of up to 50,000g [9]. The fabrication process is simple and reliable also. However, thermal-sensing based motion sensors generally require large bulk micromachined cavities, and thus can not be miniaturized. Meanwhile, wafer bonding process is also needed to seal the cavities. As the environment around the heater has to be heated up using polysilicon or metal heaters, relatively large power consumptions is required, which is especially unacceptable in portable electronic devices.

* Contact Author: wen@mae.cuhk.edu.hk

Our group has been working on the integration of Carbon Nanotubes (CNTs) into MEMS microsensors using DEP process since 2002 [10]. Thermal sensor [11], [12], flow sensor [13], pressure sensor [14] and alcohol sensor [15] based on CNT sensing elements have been developed by our team since then. The greatest advantage of CNTs is the ultra-low power required when using them as sensing elements. Also, the overall size of CNT sensors could be very small. This paper presents the our preliminary investigation on integrating CNTs into thermal convective motion sensors. A prototype was designed and some tests were performed to characterize the sensors. We have shown that the prototypes are capable of detecting static inclination variations, i.e., they are sensitive to gravitational effect. In the future, we will conduct experiments to show their response to dynamic acceleration.

II. Design & Fabrication

A. Design Consideration

Leung et al. [1] have developed a simple model to describe the response of thermal accelerometer which showed that the response is linearly proportional to the Grashof number Gr, given by

$$Gr = \frac{a\rho^2\beta\Delta T l^3}{\mu^2} \tag{1}$$

where a = acceleration, ρ = density of gas, l = linear dimension, β = coefficient of expansion, ΔT = heater temperature and μ = viscosity.

According to (1), a high heater temperature is required in order to increase sensor response. Under given power input, the substrate must provide a large thermal resistance to increase the heater temperature, as well as to reduce the energy consumption. The preferred approaches to achieve thermal isolation are either to use a suspended heater or fabricate the heater on a membrane. However, the CNT deposition process requires the electrodes to be fabricated on a substrate. Goustouridis et al. [5] reported that a substrate with low thermal conductivity can also work as good thermal isolation material, and they have successfully built a thermal convective accelerometer based on Porous Silicon thermal isolation layer. Due to the fact that glass has a smaller thermal conductivity (1.1W/(cm·k)) than Porous Silicon (1.2W/(cm·k)), and no extra fabrication steps are needed, glass was chosen as the substrate material in our experiments.

Further investigation was put onto the types of convection caused by acceleration. In total, there are two major principles

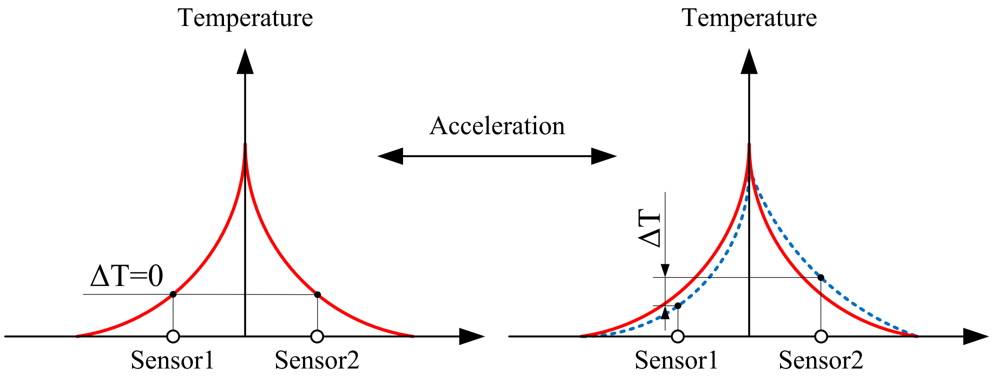

Fig. 1. Working principle of a thermal convective motion sensor.

for induced convection of fluids, both of which are caused by non-homogeneous density distribution of the fluids. The difference is that the non-homogeneous distribution can be the result of either the heating effect of fluid with single composition, or different fluid compositions. Compared with the heating induced convection, the later one is often more severe, thus leading to a larger response under the same acceleration.

B. Fabrication of the Sensor Chip

The fabrication process is described in Fig. 2. Au was used as the electrode material. A thin layer of Cr was first evaporated onto the glass substrate by sputtering to improve the adhesion before the deposition of Au using the same process. Then three pairs of electrodes were fabricated using photolithography process for CNT deposition. The interval within the electrode pairs varies from 20 to 150μm. The gap distance between one pair of electrodes was designed to be 5μm according to the requirement of the CNT deposition process. After CNT deposition, a Silicon Dioxide protection layer was patterned to improve the contact between CNTs and the electrodes.

C. CNT Deposition Process

The CNT deposition method utilizing DEP manipulation was developed by our group in 2003 [11] and have been adopted ever since. Multi-Walled Carbon Nanotubes (MWNTs) were ultrasonically dispersed in ethanol solution. A droplet of 2.5μL of the solution was transferred to the substrate between the electrodes. While the conventional DEP process can only achieve CNT bundles deposition of one pair of electrodes at one time, our improved sensor design managed to realize multiple CNT bundles deposition simultaneously using a power source connected is shown in the lower-right part of Fig. 3. During experiments, the AC voltage source provided a sinusoidal output of 16V (peak-to-peak) at the frequency of 1MHz, and MWNTs were then aligned between two electrodes within each pair due to dielectrophoretic (DEP) force. Once the two electrodes were linked by MWNTs, the source voltage would concentrate on the large resistors (R=10MΩ) connected serially with the CNT bundles (R$\approx$10kΩ) and prevent the burn out of CNTs by large power. After the evaporation of ethanol solution, the sensor chip was washed with IPA solutions to remove those MWNTs that were not aligned. The

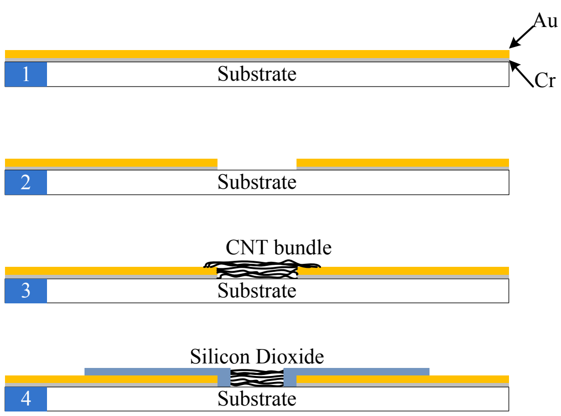

Fig. 2. Fabrication process of the sensor chip.

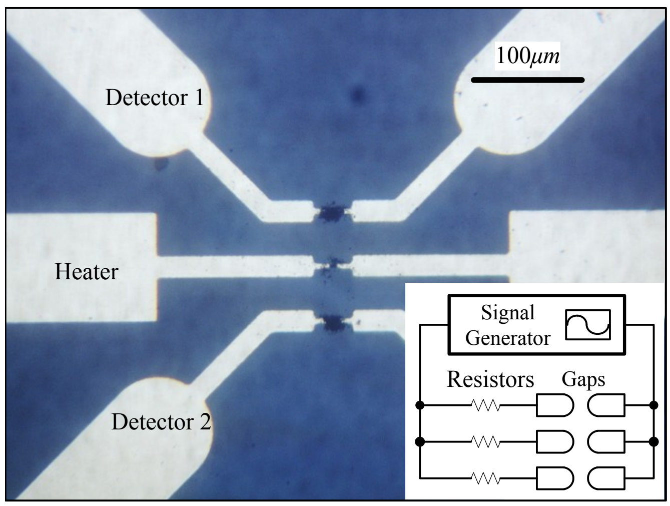

Fig. 3. DEP circuit and the deposition result.

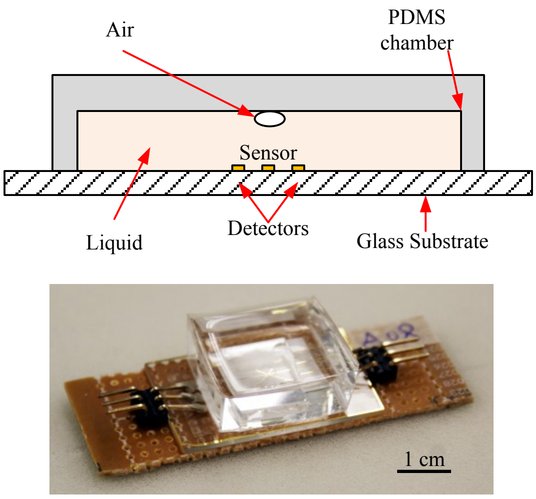

Fig. 4. Illustration of sensor chip structure and the final prototype.

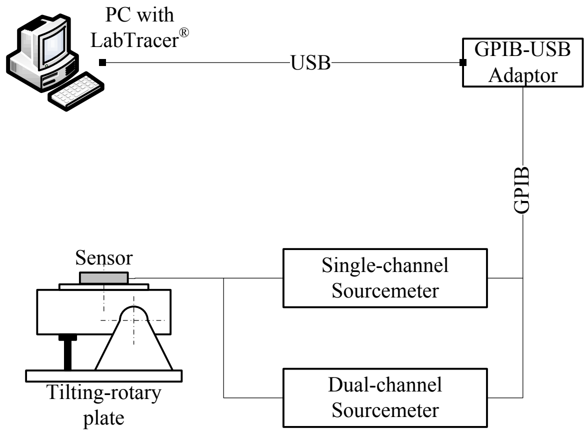

Fig. 5. Experimental setup of the tilting test.

final deposition result is shown in Fig. 3. In later tests, the CNT linkage at the center was used as a heater to heat up the local sensing environment, and the two bundles aside were used as thermal detectors for temperature changes.

D. Sensor Prototyping

A PDMS chamber was firstly prepared using replica molding process described in [16] with the dimension of the inner chamber as 10mm$\times$10mm$\times$1mm. After exposing both the sensor chip and the PDMS chamber to oxygen plasma, a pressure was then applied to enable the irreversible bonding between the sensor chip and the PDMS chamber.

After the bonding process, the sensor was then mounted to a PCB board for measurements. The bonding pads on the sensor chip were connected to external pins using conductive silver glue, then the whole chip was baked in the oven at 80°C for 2 hours to cure the glue.

Since the sensor chip was not sealed in vacuum, the PDMS chamber was initially filled with air. Also, we can use liquid as alternative by injecting with a clinical syringe. During the heating process, air or ethanol solution is heated up by the CNT heater. As the density of fluid varies according to temperature, the density distribution within the chamber will become non-homogeneous. Another configuration is that, by controlling the volume of the injected ethanol solution, a small air bubble is left in the chamber (Fig. 4). The different density of the air bubble and the ethanol solution will also lead to non-homogeneous density distribution. As the later configuration can introduce convections that are more severe, so it was chosen in the tilting test to get the maximum response.

III. Experimental Results

A. Experimental Setup

A Keithley 2400 single channel sourcemeter and a Keithley 2600 dual channel source meter which in total can serve as three individual Source & Measure Units (SMUs) were set up to work as precise current sources as well as voltmeters. Each SMU was connected to one CNT bundle. The output of sourcemeters were set to be constant current (Bias Current Mode), and the actual currents and voltages across the CNTs bundles were measured to calculate resistances. The time stamps of each reading were collected and sorted to synchronize the responses of all the SMUs.

A tilting plate was used as the acceleration source, which can be rotated from horizontal to vertical with a resolution of 1°, so an acceleration of 1g at the maximum can be achieved. The experimental setup is illustrated in Fig. 5.

B. Measurement of TCR

Experiments were first conducted to determine the resistive sensitivity of MWNTs towards temperature change. Thermal sensitivity can be calculated using:

$$R = R_{ref}[1 + \alpha(T - T_{ref})] \quad (2)$$

where R is the resistance at temperature T, R_{ref} is the resistance at reference temperature T_{ref} which is often set to 20°C, and α is the (linear) Temperature Coefficient of Resistance (TCR) of the material.

The TCR of MWNT bundles was measured in a programmable climate chamber (BINDER KBF Constant Climate Chamber). The humidity was kept constant at 30% r.H., and the temperature was stepped up from 20°C to 75°C. The driven current was set to 1μA to prevent self-heating effect. The result is shown in Fig. 6, where the temperature coefficient is linear within this temperature range, and the value is around -0.11%/°C. TCR for other MWNT bundles were also tested and the values varied between -0.2%/°C to -0.1%/°C.

C. Local Heating & Sensing

The I-V characteristics of MWNT bundles were investigated. Driving current was stepped up from 0 to 0.3mA and the corresponding voltages were measured. The tested results and expectation are both shown in Fig. 7. Voltage was linearly proportional to current when the driving current was

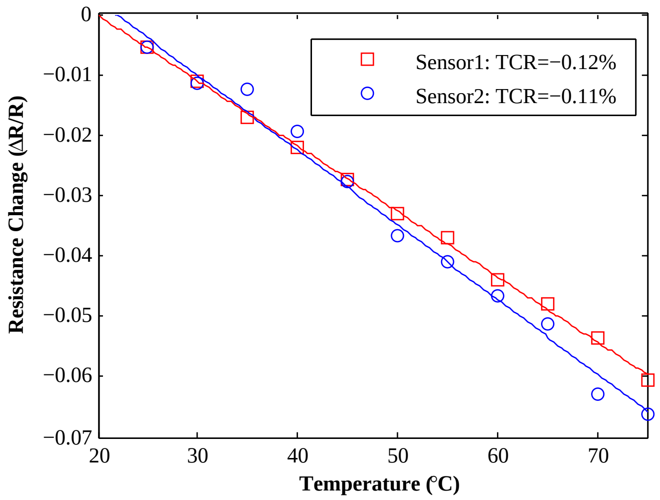

Fig. 6. Temperature-resistance relationship for MWNT.

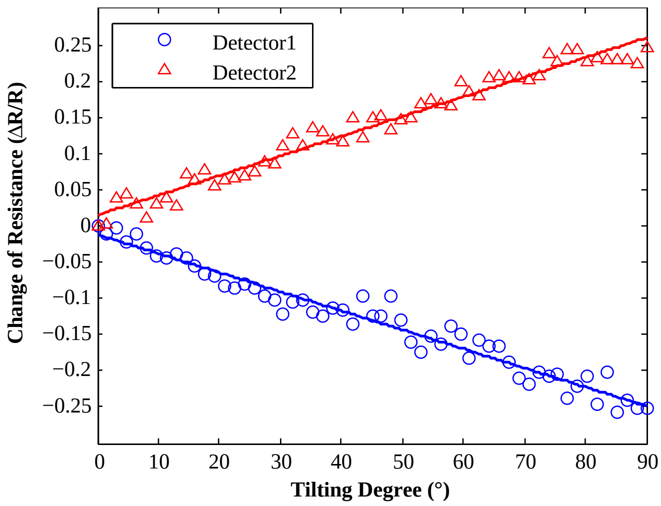

Fig. 8. Test result on tilting plate.

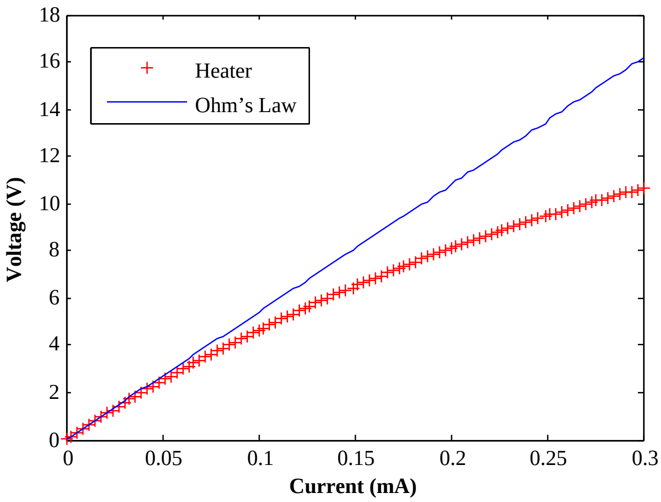

Fig. 7. I-V curve of MWNT.

small (<10μA), so the resistance during this range remains constant. This value was used to calculate the expected voltage based on Ohm's Law. However, when the driven current is larger (>50μA), the true resistance of MWNT bundle become smaller than the expected value, which means that the temperature of the bundle goes higher and higher since the TCR is negative. From the difference between the expected value and measured value, the temperature of the MWNT bundle can be calculated using (2).

During the I-V test, it was found that the resistance of the CNT bundle would become infinity if the sensor was heated by large current. It is believed that the CNT linkage was destroyed. Some experiments were conducted and the failure limit was determined. In later measurements, the maximum voltage applied to the CNT heater was set to half of the failure value. The driven current for the thermal detectors were selected within the linear region of the I-V curve (usually 0.1μA) to prevent heating effect of the detectors themselves.

D. *Tilting Test*

The prototype was then tested on a tilting plate. The sample was tilted from horizontal (0°) to vertical (90°) position. The responses of the two detectors were plotted in Fig. 8. Proportional relationships between the response of detectors and the tilting degree were observed. It has also been noticed that the temperature on one detector would increase, while it went down on the other detector. Also, the responses of the two detectors were symmetric for all tilting angles. During the tilting test, the resistance of the heater was also collected, and a constant resistance with little variation was observed.

For this prototype, the driven power for the two detectors was 2nW in total, while the driven power for the heater was 6μW. So the overall power consumption for this prototype is around several μW, which is much smaller than those thermal convective accelerometers (or inclinometers) equipped with solid heater and sensors ([2], [4], [17]) which require several tens of mW power consumption.

Due to the fact that the sensitivity (defined as resistance change per degree) of our sensors can reach 0.28%/°, which is very large, this prototype is ideal for tilting tests that require high accuracy. However, a large sensitivity also indicates that the sensor would possibly undergo saturation under large acceleration. So further experiments should be conducted to test whether this type of motion sensor can work as accelerometers or not. As the tilting plate currently used can only provide a maximum acceleration of 1g, other acceleration sources will be used in the future tests to determine the saturation point as well as other essential parameters.

IV. Conclusion

The working principle of the thermal convective motion sensor was first discussed in this paper. We used DEP manipulation process to integrate CNTs to serve as a heater and sensors of a thermal convective inclination sensor. Prototypes were developed, which have shown very good response to static inclination changes. The most attractive performance of these inclination sensors is their extreme-low power consumption characteristic, which will enables their application in portable systems. After these feasibility experiments, the performance parameters, as well as the factors that affect the sensitivity of the sensors will be studied in the future.

REFERENCES

[1] A. Leung, J. Jones, E. Czyzewska, J. Chen, and B. Woods, "Micromachined accelerometer based on convection heat transfer," in *Micro Electro Mechanical Systems, 1998. MEMS 98. Proceedings., The Eleventh Annual International Workshop on*, 1998, pp. 627–630.

[2] S. Billat, H. Glosch, M. Kunze, F. Hedrich, J. Frech, J. Auber, H. Sandmaier, W. Wimmer, and W. Lang, "Micromachined inclinometer with high sensitivity and very good stability," *Sensors & Actuators: A. Physical*, vol. 97, pp. 125–130, 2002.

[3] F. Mailly, A. Martinez, A. Giani, F. Pascal-Delannoy, and A. Boyer, "Design of a micromachined thermal accelerometer: thermal simulation and experimental results," *Microelectronics Journal*, vol. 34, no. 4, pp. 275–280, 2003.

[4] F. Mailly, A. Giani, A. Martinez, R. Bonnot, P. Temple-Boyer, and A. Boyer, "Micromachined thermal accelerometer," *Sensors & Actuators: A. Physical*, vol. 103, no. 3, pp. 359–363, 2003.

[5] D. Goustouridis, G. Kaltsas, and A. Nassiopoulou, "A CMOS compatible thermal accelerometer without solid proof mass, based on porous silicon thermal isolation," in *Sensors, 2004. Proceedings of IEEE*, 2004, pp. 848–851.

[6] A. Chaehoi, F. Mailly, L. Latorre, and P. Nouet, "Experimental and finite-element study of convective accelerometer on CMOS," *Sensors & Actuators: A. Physical*, vol. 132, no. 1, pp. 78–84, 2006.

[7] L. Lin and J. Jones, "A Liquid-Filled Buoyancy-Driven Convective Micromachined Accelerometer," *Microelectromechanical Systems, Journal of*, vol. 14, no. 5, pp. 1061–1069, 2005.

[8] O. Leman, F. Mailly, L. Latorre, and P. Nouet, "HDL modeling of convective accelerometers for system design and optimization," *Sensors & Actuators: A. Physical*, vol. 142, no. 1, pp. 178–184, 2008.

[9] "Application note an-00mx-001," MEMSIC Inc., Tech. Rep.

[10] V. T. Wong and W. Li, "Dependence of AC Electrophoresis Carbon Nanotube Manipulation on Microelectrode Geometry," *International Journal of Nonlinear Sciences and Numerical Simulation*, vol. 3, pp. 769–774, 2002.

[11] T. Wong and W. Li, "Bulk Carbon Nanotubes for Micro Anemometry," in *invited paper, ASME Forum on MEMS for Fluid Measurements, Fluid Engineering Division Annual Summer Meeting, Honolulu, Hawaii, July*, 2003, pp. 6–10.

[12] C. Fung, V. Wong, R. Chan, and W. Li, "Dielectrophoretic batch fabrication of bundled carbon nanotube thermal sensors," *Nanotechnology, IEEE Transactions on*, vol. 3, no. 3, pp. 395–403, 2004.

[13] C. Fung, M. Sin, T. Lei, W. Chow, K. Lai, and W. Li, "Flow rate measurement inside polymer microfluidic systems using carbon nanotube sensors," *Sensors, IEEE*, pp. 541–544, 2005.

[14] C. Fung, M. Zhang, R. Chan, and W. Li, "A PMMA-based micro pressure sensor chip using carbon nanotubes as sensing elements," in *Micro Electro Mechanical Systems, 2005. MEMS 2005. 18th IEEE International Conference on*, 2005, pp. 251–254.

[15] M. Ouyang, M. Sin, B. Tsoi, G. Chow, G. Wong, W. Li, P. Leong, and K. Wong, "Constant-power operation of functionalized carbon nanotube sensors for alcohol vapor detection," in *Nano/Micro Engineered and Molecular Systems, 2008. NEMS 2008. 3rd IEEE International Conference on*, 2008, pp. 747–752.

[16] D. Duffy, J. McDonald, O. Schueller, and G. Whitesides, "Rapid Prototyping of Microfluidic Systems in Poly (dimethylsiloxane)," *Analytical Chemistry-Washington DC-*, vol. 70, pp. 4974–4984, 1998.

[17] X. Luo, Y. Yang, F. Zheng, Z. Li, and Z. Guo, "An optimized micromachined convective accelerometer with no proof mass," *JOURNAL OF Micromechanics and Microengineering*, vol. 11, no. 5, pp. 504–508, 2001.