FLEXIBLE THERMAL SENSOR ARRAY ON PI FILM SBUSTRATE FOR UNDERWATER APPLICATIONS

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ABSTRACT

Fully flexible thermal sensor array was developed for underwater applications. To minimize conductive heat loss to substrate and shorten response time nickel thin film resistors are fabricated on polyimide film substrate. This flexible sensing belt can be applied onto highly curved non-planar surfaces to measure flow with minimal invasion. Polymer compatible micromachining technology with consideration of waterproof coating was developed. Through calibration performed under constant-current excitation, high temperature coefficient of resistance (TCR) and low time constant of sensor were obtained. Hydrodynamic experiments in water channels were carried out, and it indicates dynamic wave flow can be sensed promptly with this sensing belt.

INTRODUCTION

Micromachined thermal sensor is of essential importance for flow dynamic measurement for its compact structure and good environmental adaptability [1]–[3]. However, almost all micromachined thermal sensors are developed for aerodynamic rather than hydrodynamic applications. Yong Xu has reported one type of micromachined thermal sensor to measure underwater wall shear stress [3]. It was a polysilicon resistor sitting on a nitride diaphragm with a vacuum cavity underneath. The vacuum-insulated diaphragm can provide an excellent thermal isolation from silicon substrate. However, it is a pressure susceptive structure in nature, so pressure crosstalk exists, and deep-water applications may be limited.

In this work, a new type of flexible hot film sensor array for underwater applications was developed, as shown in Fig.1. Ni thin film resistors are deposited on a polyimide (PI) film substrate and each resistor can be connected to external electric circuit with copper leads. Fully flexible structure with very low thickness of 80μm enable the sensing belt to be taped on highly curved non-planar surfaces to measure flow parameters, such as wall shear stress or flow velocity, with minimal invasion. Polyimide (e.g., Kapton) was selected as substrate material not only for its good structural flexibility and excellent chemical stability, but also for its low thermal conductivity, which is of key importance to decrease heat loss from substrate and reduce sensor's thermal inertia so as to get high sensitivity and short response time. Nickel was adopted as the sensing material for its highest bulk TCR of 6800ppm/°C among platinum, tungsten, and other conventional thermo-sensitive materials. Moreover, nickel possesses a lower melting point, so polyimide substrate compatible annealing at lower temperature might be possible [4]–[5].

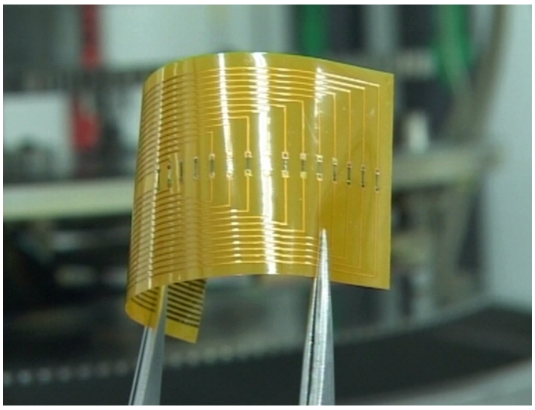

Figure 1. Fully flexible thermal sensor array on PI film substrate

FABRICATION

Polymer compatible micromachining technology for flexible sensor array was developed. The fabrication processes involve PI substrate preprocessing, resistor forming, heat treatment, waterproof coating, etc.

PI substrate preprocessing

Cleanliness, activity, and microscopic topography of substrate surface have influence on adhesion of deposited thin film. Wet cleaning was used to remove metallic and organic impurities on polyimide substrate. The cleaning solutions include dilute hydrochloric acid solution, acetone, alcohol, and deionized water. Different from conventional inorganic substrate materials (e.g., semiconductor, ceramic, and glass), polymer has lower surface energy. There is some difficulty for nickel particles strongly adhered to polyimide surface while sputtering [6]-[7]. Therefore, plasma activation was employed to increase surface energy and decrease surface roughness of the polyimide substrate, as show in Fig.2. The plasma gas was trifluoromethane, which is chemically inert.

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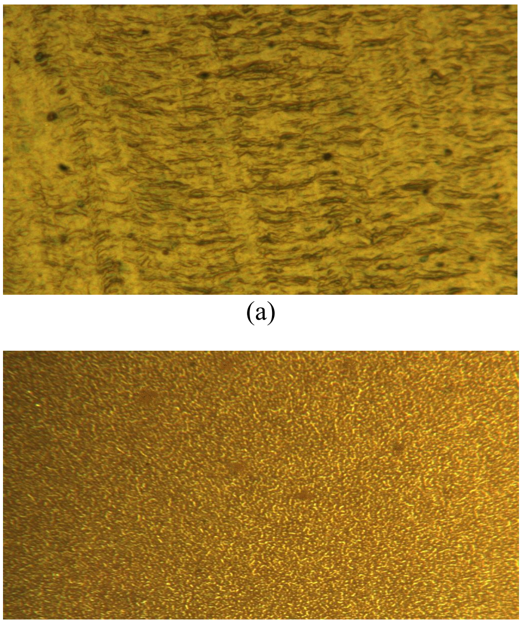


(a)

(b)

Figure 2. PI surface (a) before and (b) after plasma preprocessing

Thin film resistor forming

Ni thin film thermal resistors were sputtered and patterned on PI substrate. Deposited film thickness, sputtering power, argon gas pressure have influence on its resistance-temperature behavior, especially on the TCR. Normally, high film thickness is helpful for a high TCR. However, thick Ni film tends to induce cracks for increased internal stress. Sputtering power and argon pressure were optimized by monitoring and analyzing the sheet resistance of Ni thin film. It shows relatively low sputtering power and argon pressure with about 1μm deposited thickness of Ni thin film benefits high TCR.

Thin film resistor and its array were patterned with lift-off or etch-back processes using photo resist as processing mask with sputtering or etching, and so is the forming of copper leads, as shown in Fig.3.

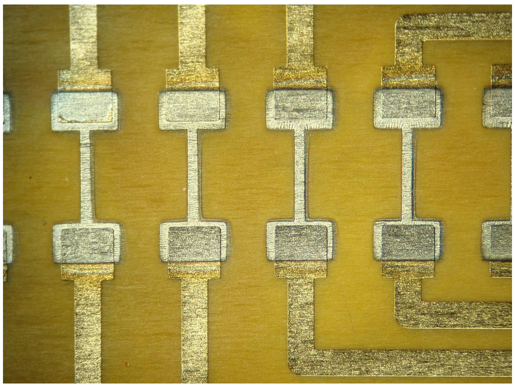
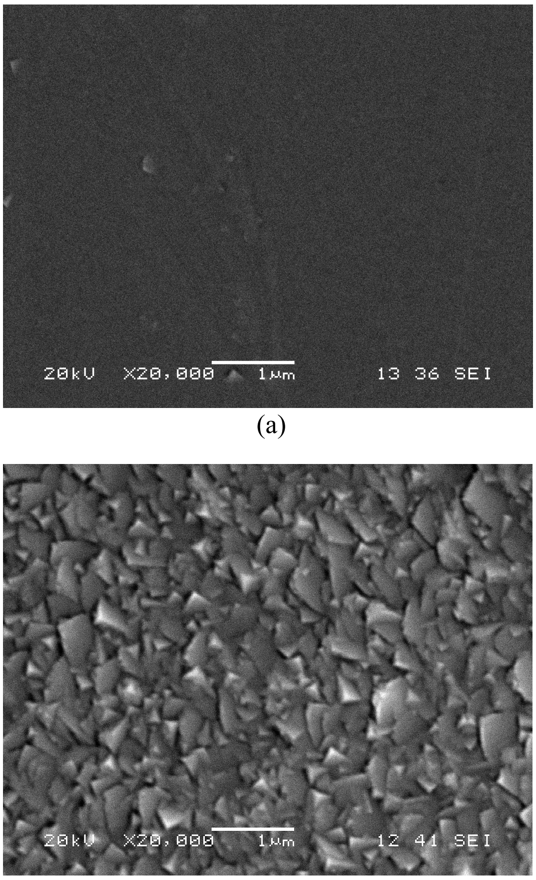


Figure 3. Sensor array and copper leads

Heat treatment

Generally, TCR of thin film is much lower than that of its bulk counterpart. Crystallite size, dislocation density, and internal stress of thin film all have influence. To improve thermal sensitivity, vacuum annealing is necessary. Normally, high enough heat treatment temperature is desirable so long as polymer substrate can withstand. And heating-up as well as cooling rate should be controlled carefully, too. With grain growth in annealing heat treatment the amount of grain boundaries and dislocation density decreased significantly, as shown in Fig.4.



(a)

(b)

Figure 4. SEM photo of Ni thin film (a) before and (b) after vacuum annealing

Waterproof coating

Waterproof coating is necessary both for sensor's electrical insulation and for its physical protection from underwater environment. However, the coating should possess good thermal conductivity. Therefore the alumina film was used in this work. It has high-endurance to harsh underwater environment. Alumina can be deposited uniformly covering the thin film resistors with a thickness 300nm by sputtering, as shown in Fig.5.

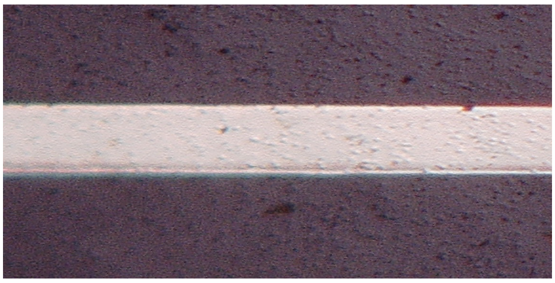


Figure 5. Ni thin film resistor with alumina coating

CALIBRATION

Temperature coefficient of resistance

TCR is very important for its direct influence on sensor's sensitivity. The calibration was conducted in an oil bath with precision temperature controller. The thermal sensor was driven by constant current supply. To reduce the self-heating effect, the current was limited to be merely 150μA. In order to exclude the interference from the lead wires and external circuits, four-point probe configuration was used. The relationship between the resistance and temperature was characterized, as shown in Fig.6, and a TCR of 4250ppm/°C with good linearity was obtained.

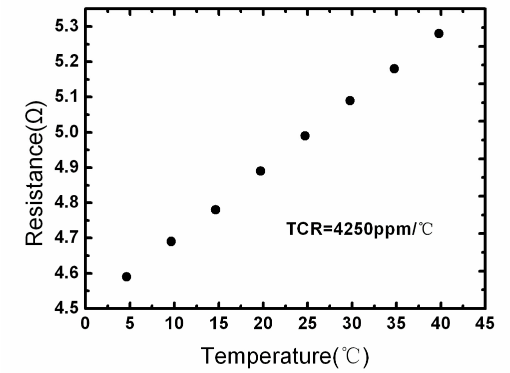


Figure 6. Temperature coefficient of resistance

Time constant

High response speed is essential for dynamic flow measurement tasks. Thermal-isolated polymer substrate and small resistor dimensions benefit short response time. Time constant of the sensor was examined with step response analysis. In other words, when inputting a step current excitation, time constant can be determined through its transient voltage response. To capture the dynamic transient response, sampling frequency is set to be 100 kHz. The step response was shown in Fig.7, and the time constant was only about 30ms.

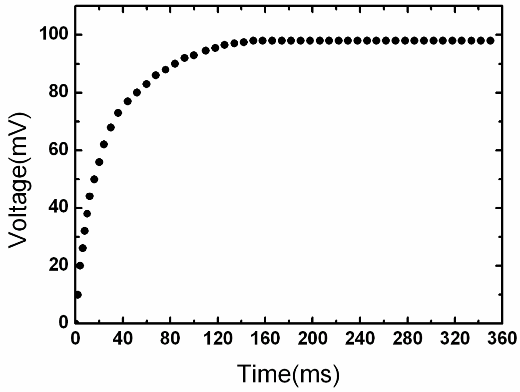


Figure 7. Step response of the thermal sensor

HYDRODYNAMIC EXPERIEMNTS

Hydrodynamic experiments were conducted with a test system and various water tunnels. Apart form the sensor array the measurement system include a drive current supply, a voltage meter, and a computer for signal acquisition, processing, and display, as shown in Fig.8. The sensing belts were always mounted flush to the bottom of water tunnels.

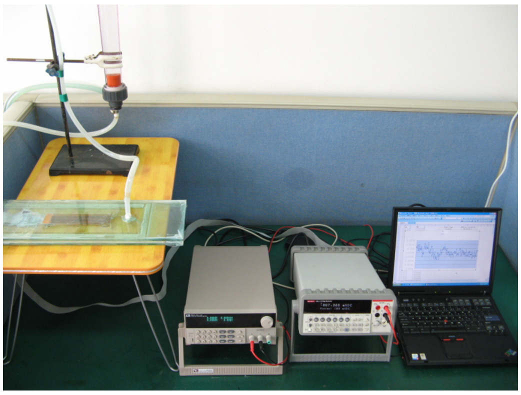


Figure 8. Hydrodynamic measurement system

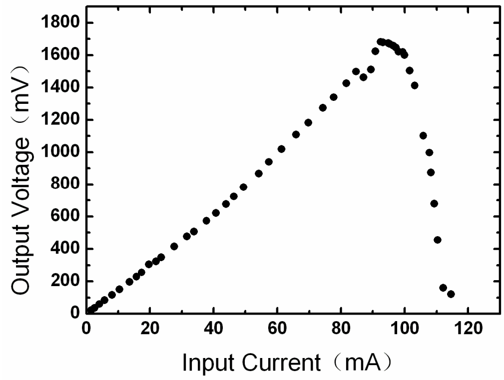


Figure 9. Voltage output versus drive current

High drive current is good to magnify output-signal, whereas too high drive current could affect the thermal performance of the sensor. So the relationship between drive current and voltage output was examined, and it shows the operating drive current should not exceed 80mA, as shown in Fig.9.

Hydrodynamic experiments of two-dimensional wave flow measurement were carried out applying the sensing belt on inner bottom surface of a long water channel. Cycle time of artificial wave, as shown in Fig.10, was set to be 1.2s. The measurement system worked in constant-current mode, too, and the drive current is 10-25mA. Sampling frequency is 40Hz. The results indicate the sensor’s output can promptly reflect dynamic change of the wave flow, as shown in Fig.11.

Figure10. 2D wave flow in a long water channel

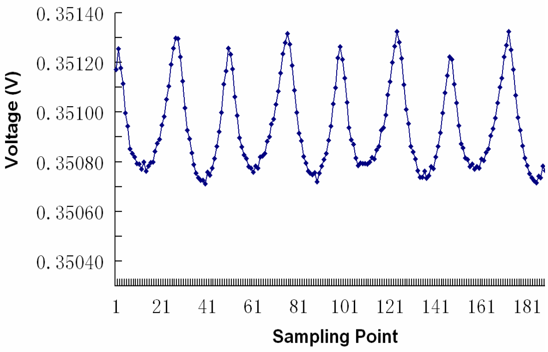


Figure11. Sensor’s output in wave flow

CONCLUSION

Fully flexible nickel thermal sensor array with a polyimide substrate was developed for underwater applications. Fully flexible structure with low thickness enables the sensing belt to be applied on highly curved non-planar surface to measure flow parameters with minimal invasion. Polymer compatible micromachining technology including PI substrate preprocessing, thin film resistor forming, heat treatment, and waterproof coating was developed. And a high TCR and a short response time were obtained. Hydrodynamic experiments for sensor test were carried out in water channels. It indicated dynamic wave flow can be sensed promptly with the sensor.

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