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Stress-driven AlN cantilever-based flow sensor for fish lateral line system

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ABSTRACT

In this work, we report on the fabrication and characterization of stress-driven aluminium nitride (AlN) cantilevers to be applied as flow sensor for fish lateral line system. The fabricated structures exploit a multilayered cantilever AlN/molybdenum (Mo) and a Nichrome 80/20 alloy as piezoresistor. Cantilever arrays are realized by using conventional micromachining techniques involving optical lithography and etching processes. The fabrication of the piezoresistive cantilevers is reported and the operation of the cantilever as flow sensor has been investigated by electrical measurement under nitrogen flowing condition showing a sensitivity to directionality and to low value applied forces.

1. Introduction

The capability of the fish to swim, hold station, save energy during swimming, hide from predators, hunt for prey and school in very turbulent waters is due to an array of natural sensors which span the length of the fish body [1]. This array, the so-called "fish lateral line", consists of a spatially-distributed arrangement of neuromasts which is a collection of drag-based flow velocity sensors [2]. Each neuromast embeds hair cells made of vertical cilia which are connected to neurons. When the cilium of the hair cell is bent by the impinging fluid flow, the neuron attached to the cilium stretches and produces action potentials that result in information for the neuromotor system. The capability of the lateral line system to process information from the surrounding environment makes it an appealing nature-inspired device to be implemented in several fields such as human prosthesis, underwater autonomous vehicles, automotive etc.

In bio-inspired engineering, micro-electro-mechanical system (MEMS) technology has attracted particular attention due to their small physical footprint, sensitivity and frequency response. In fact, the high advances of micro-fabrication techniques, has facilitated the development of several approaches for a bio-mimicking design of an artificial lateral line based on different sensing principles such as: thermal transfer [3], pressure distribution [4], torque transfer [5] and mechanical bending [6]. This last approach exploits in-plane fixed-free cantilever with a vertical artificial cilium (artificial hair cell) attached at the free end. When a flow is applied to the sensor, a mechanical bending moment is transferred from the cilium to the horizontal cantilever beam, inducing strain at the base of the cantilever beam. The magnitude of the induced strain is sensed by piezoresistive elements placed near the cantilever hinge. As the fluidic momentum is transferred with high efficiency to the piezoresistor, it makes this approach very attractive due to its high sensitivity. However, these kinds of sensors, typically based on silicon cantilevers, are mechanically fragile and could fail by the fracture upon mechanical over-loading on the vertical cilium. Oppositely, out-of-plane bent cantilevers can be stronger, exploiting a suitable residual stress design in a multilayer beam structure. In this contest, aluminum nitride (AlN), due to its good electromechanical properties and to low temperature growth techniques (below 400 °C), such as sputtering, is fully compatible with standard silicon ICs technologies and suitable for the fabrication of stress-driven MEMS devices [7].

We report on the fabrication and characterization of stress-driven piezoresistive bent cantilever exploiting Nichrome 80/20 alloy as piezoresistor, for AHC sensors applications. We firstly introduce the fabrication of piezoresistors and AlN/molybdenum (Mo) multilayer cantilever, involving conventional micromachining techniques, including the sacrificial layer etching to release the structures from the substrate in post processing steps. Then electrical measurements of AlN based cantilevers under nitrogen flowing condition have been performed in order to determine their behavior as a sensor.

2. Experimental

Fig. 1a shows a schematic of the starting multilayered structure used to fabricate the cantilevers. The structures consist of an

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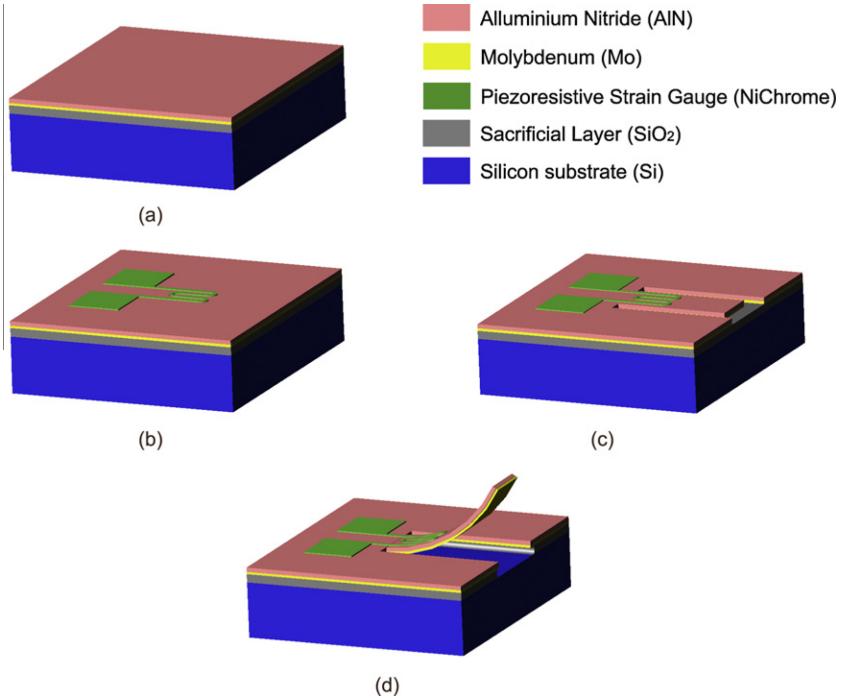

Fig. 1. Fabrication process of artificial lateral line sensor with integrated strain gauge. Processing steps (a–d) have been described in the text.

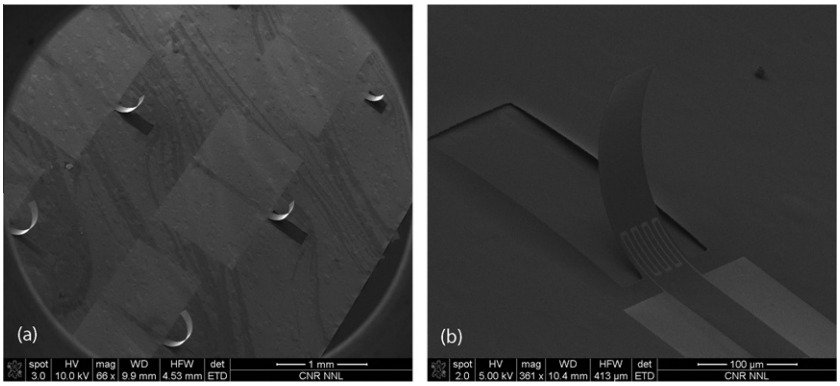

Fig. 2. (a) SEM on a cantilever array with different lengths taken at bird view; (b) SEM on a bent cantilever with a 200 μm length and a 50 μm piezoresistor clearly visible near the cantilever hinge.

aluminum nitride (AlN) thin film layer (600 nm) upon a 100 nm thick molybdenum (Mo) layer, deposited by DC magnetron sputtering on a 200 nm thick silicon dioxide (SiO_2) layer on (100) silicon (Si) template purchased by Siegert Consulting e.K. SiO_2 layer is exploited as sacrificial layer in the device fabrication process to release the cantilever beam. Molybdenum has been chosen to induce an high stress in the AlN film in order to reach a cilium height higher than 350 μm. AlN thin films are deposited in a mixed atmosphere of Argon (10 sccm) and Nitrogen (14.5 sccm) by means of reactive sputtering in a chamber pre-heated to 120 °C. The working pressure is set to 1×10^{-3} mbar, the power to the target is of 2.25 kW and a DC – bias of −50 V is applied to the sample during the growth process. Before the definition of the cantilever on the growth substrates, the strain gauge is realized by using conventional surface micromachining techniques involving thin film deposition and optical lithography (Fig. 1b). In order to reach a high sensitivity in all flow conditions, a Nichrome 80/20 alloy with a gauge factor up to 2.63 [8] is used. It has been structured in different lengths from 50 to 120 μm, with a periodicity of 12 μm (4 μm is the metal wire) and seven periods. Then, a cantilever array of different geometries (100 μm wide with a length ranging from 200 to 600 μm) consisting of AlN/Mo multilayer is fabricated by optical lithography and etching process, in order to create a pattern of cantilevers and to expose the SiO_2 sacrificial layer. The AlN and Mo layers are etched by a $SiCl_4$-based plasma by Inductively Coupled Plasma (ICP) dry etching using a photoresist mask. Dry etching has been performed by a $SiCl_4/N_2/Ar$ (20/25/7 sccm) gas mixture at a working pressure of 1 mtorr (Fig. 1c). Finally the cantilever is released from the substrate by isotropic etching of the SiO_2 sacrificial layer at room temperature in a HF-based solution. To prevent the cantilever from sticking to the underlying substrate during the final rinsing step, low surface-tension solvents are exploited to minimize the capillary forces. Because of the designed residual stress, after the releasing through the SiO_2 sacrificial layer etching, the AlN/Mo bilayer bends out of the cantilever plane (Fig. 1d).

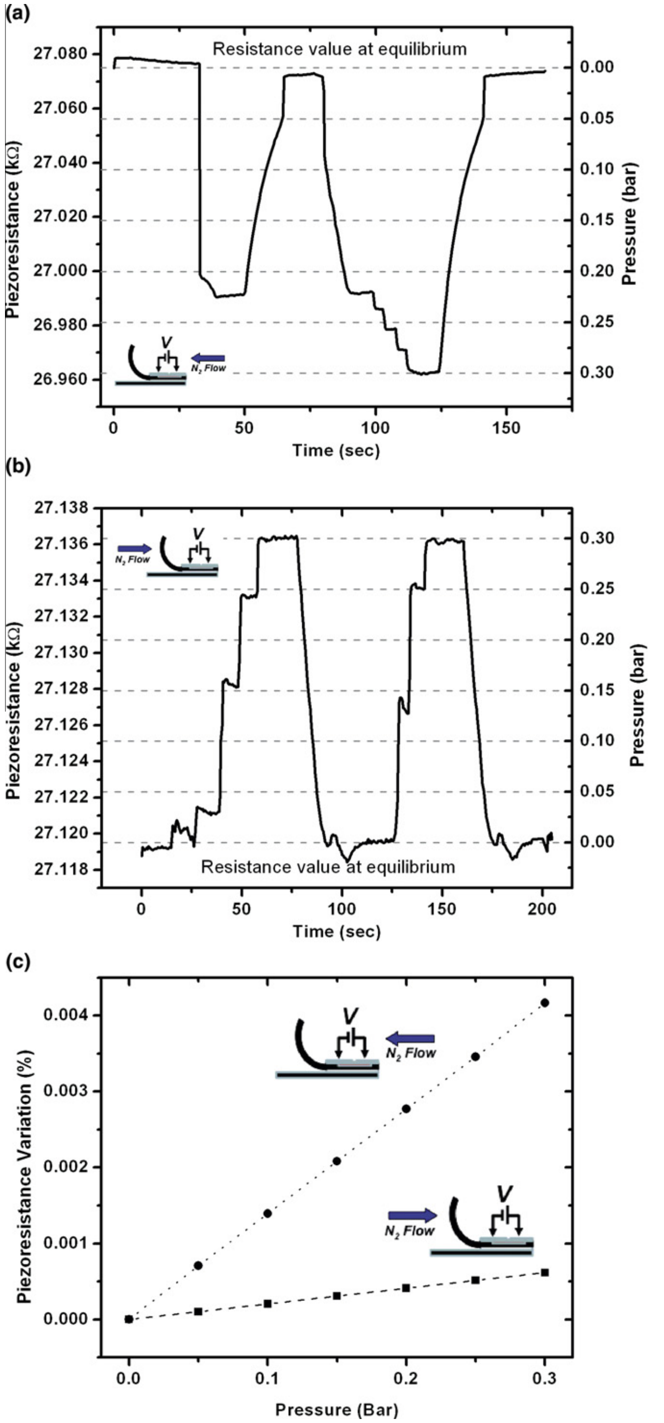

Fig. 3. Resistance measurements (left axis) with the correspondent pressure values (right axis) on a 600 μm long cantilever with a 80 μm long piezoresistor, when: (a) the flow is applied along the decreasing bending orientation; (b) the flow is applied along the increasing bending orientation. (c) Relative piezoresistance variation of the cantilever versus pressure in the two directions of flow; sensitivities (slope of the linear fit) for the flow conditions along and opposite the bending direction is 1.38%/mbar and 0.2%/mbar, respectively.

Fig. 2a and b show scanning electron microscopy (SEM) images of the previously described cantilever array and one 200 μm long cantilever with a 50 μm long piezoresistor, respectively. These pictures have been acquired by a FEI Nova NanoSEM 200 System and show the cantilever upwards bending due to the residual stress present inside the multilayer structure. The degree of bending of cantilevers related to the residual stress can be controlled through a careful optimization of the growth parameters and the device geometrical features, such as the DC bias applied to the substrate and the thickness ratio between electrodes and piezoelectric film [9].

3. Results and discussion

In order to verify the operation of the cantilever as a flow sensor, electrical measurements under nitrogen flowing stream have been performed. The measurement set-up is as follows: the piezoresistance changes have been measured by a Keithley 2400 sourcemeter, which also provides a 5 V constant direct voltage. A data acquisition board on a computer is connected to the sensor for data collection. In order to provide the electrical contacts the sample was mounted on a probe station and two microprobes were used to connect the cantilevers to the sourcemeter. A micropipe near the cantilever generates the stimulus on the cantilever/piezoresistor system and different flow rates can be obtained by means of pressure valve within the range of 0–0.3 bar.

Measurements have been carried out on a 600 μm long cantilever equipped with a 80 μm long piezoresistor while applying a nitrogen flow along the cantilever direction at a pressure up to 0.3 bar. Noteworthy, in Fig. 3a, a reduction in the resistance value is observed with pressure, if the flow is applied such as to decrease the bending and flatten the cantilever. In the same way, when the flow orientation is opposite, an increasing resistance value with the bent beam angle is measured (Fig. 3b). In particular when the flow is applied along the bending direction, the smallest detectable variation of pressure on the cantilever surface is typically 0.025 bar which is ∼6 times higher than that in the opposite direction as reported in Fig. 3c. This result demonstrates the possibility to discriminate the flow orientation by measurements of the resistance value and the capability of sensing with very low applied pressure.

4. Conclusion

In this work AlN-based piezosensitive cantilevers for fish lateral line system are successfully fabricated using conventional surface micromachining techniques. Due to the stress-driven out-of-plane position, the fabricated cantilevers are sensitive to directionality and to low value applied forces. This fabrication approach is very promising because of its simple fabrication process.

Acknowledgments

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