Nanoscience and Nanotechnology Letters
Vol. 3, 1–5, 2011

Design and Characterization of Microelectromechanical System Flow Sensors Using Silicon Nanowires

Liang Lou[1,2], Chengkuo Lee[1,*], Guo Xiang Xu[3], Rama Krishna Kotlanka[2], Lichun Shao[2], Woo-Tae Park[2], and D. L. Kwong[2]

[1] *Department of Electrical and Computer Engineering, National University of Singapore, 4 Engineering drive 3, Singapore 117576, Republic of Singapore*
[2] *Institute of Microelectronics, The Agency for Science, Technology and Research (A∗STAR), 11 Science park road, Singapore 117685, Republic of Singapore*

Cantilever structures were reported to be used for flow sensing purposes. Herein, we present silicon nanowire (SiNW) based cantilever flow sensor. Five cantilever flow sensors with different depths are modeled and simulated (fluid-structure) with water flow velocity from 50 cm/s to 200 cm/s. SiNW is embedded in the cantilever as piezoresistive transducer at the anchor, and a maximum resistance change of 11.2% is obtained. Based on the results, increasing depth will not only contributes to lager cantilever deformation at fixed flow velocity, but also improves its sensitivity. However when the depth become larger to certain degree, this effect tends to saturate.

Keywords: MEMS, Flow Sensor Silicon Nanowire.

1. INTRODUCTION

The flow measurements are usually needed in all fields of engineering. Various flow sensors were designed in the past few years, such as lift force sensor, drag-force sensor, impedance-based flow sensor, and haircell sensors and so on.[1–4] Piezoresistive transduction method is one of the methods to convert flow-induced strain into resistance change. When the semiconductor industry migrates from microfabrication technology to nanofabrication technology, the silicon nanowire (SiNW) is appeared as a new generation of peizoresistive sensors because of its nano-scale features and superior piezoresistive sensing properties. In 2006, He and Yang reported the giant piezoresistance effect of $\langle 111 \rangle$ direction P-type SiNW with largest value of -3550×10^{-11} Pa in the longitudinal direction.[5] By using the $\langle 110 \rangle$ direction SiNW, Reck et al. showed an increase in the piezoresistive effect of 633% compared to the value of bulk silicon in 2008.[6] In 2010, Neuzil et al. reported the electrically enhanced giant piezoresistance in $\langle 110 \rangle$ SiNW.[7] It is a rational approach that a cantilever is integrated with the SiNW as transducer to form a microelectromechanical system (MEMS) flow sensor. To investigate influence of cantilever in flow and the flow sensor characteristics, a quasi-3D fluid-structure interaction modeling is deployed in this paper. In the proposed curved-up cantilever flow sensor design, the effects of sidewall depth underneath the cantilever on the velocity vector of the flowing fluid are mainly discussed. Besides, the SiNW resistance change versus flow velocity is investigated computationally.

*Author to whom correspondence should be addressed.

2. DESIGN, MODELING AND SIMULATION

The three dimensional (3-D) model was built using Solidworks, the cantilever is suspended in the middle of the top edge of a block as shown in Figure 1(a). The block length and width are 360 μm and 80 μm respectively. To investigate the effect of the underneath sidewall depths, the block of different sidewall depths are built, i.e., 20 μm, 50 μm, 100 μm, 200 μm and 400 μm. The cantilever is assumed to be made of silicon oxide with length 250 μm, width 12 μm and thickness 2 μm, while the SiNW is embedded within the cantilever at its anchor. Due to the residual stress of silicon oxide, the cantilever will curve up after fabrication. In this model the cantilever is assumed to have circular profile with free end curved up to 80 μm. Figure 1(c) shows a tube with diameter of 6 mm for liquid or gas to pass through. The location of cantilever sensor chip is set to be at the entrance of this tube as shown in Figure 1(c).

 1941-4900/2011/3/001/005 doi:10.1166/nnl.2011.1160

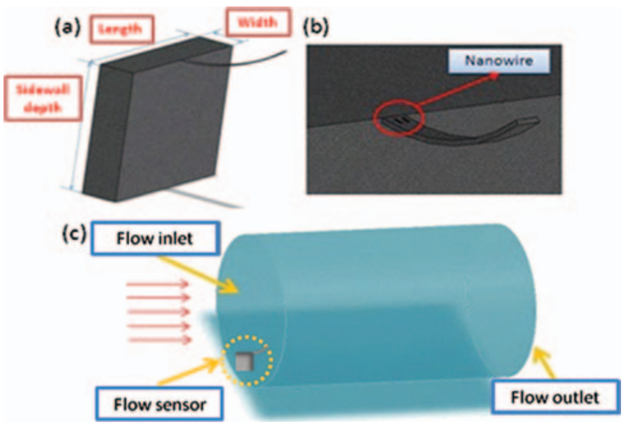

Fig. 1. (a) The cantilever flow sensor model; (b) Zoom-in cantilever with embedded SiNW at the anochor; (c) The schematic drawing of 3-D tube model with cantilever flow sensor chip at inlet.

Figure 2 shows the flow behavior-simulation by using Finite Element Modeling (FEM) software ANSYS Fluent. The model in the ANSYS Fluent is meshed using Gambit, and the element type is Tet/Hybrid. Figure 2(a) shows that the liquid flows into the tube and cross the cantilever and the top surface of the block. The arrow marks with different colors represent the fluidic trajectory (velocity vector), showing magnitude and direction. The flow behavior can be easily observed accordingly. Figure 2(b) shows the zoom-in region near by the cantilever flow sensor. Water was deployed as the liquid with density of 1000 kg/m^3 and viscosity of 0.0007 kg/m-s in the modeling. In ANSYS fluent, all the model surfaces are considered as rigid, which means that they have no deflection under the fluidic impact. However, in real applications the mechanical behavior of structure under certain flow environment needs to be taken into account. To address this problem, the pressure distribution on the cantilever top and bottom surface elements are extracted from the fluidic simulation results and then fitted using Matlab. Later the same pressure distribution was applied to the cantilever solid body model with identical dimensions using FEM software Abaqus as shown in Figure 3(a). In the Abaqus

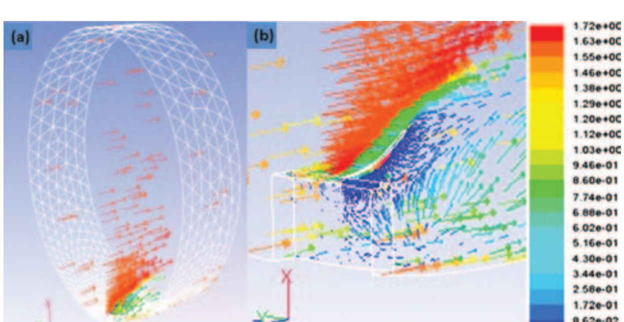

Fig. 2. Results of ANSYS Fluent model show the fluidic behavior: (a) The whole scene of the model; (b) zoom-in region nearby the cantilever flow sensor.

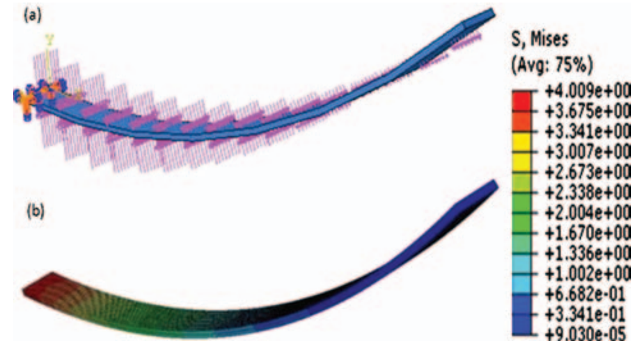

Fig. 3. Abaqus FEM modeling. (a) Pressure distribution applied to the cantilever top and bottom surfaces. (b) The stress distribution map along the cantilever.

modeling, the cantilever end at the anchor is fixed, and the curved-up end is free. The material property and the element type of the cantilever are silicon oxide and C3D8R respectively. The above modeling methodology is valid when the deflection of the cantilever is small enough that the flow behavior could be approximately considered as unchanged. Figure 3(b) shows the cantilever strain distribution results, in which the red part indicates the largest strain area of the whole cantilever. As mentioned above, the SiNW was made on surface at the junction of block edge and the anchor of the cantilever, where the maximum strain lies. By measuring the change in the nanowire resistance due to the strain of cantilever, the correlation between the strain of cantilever and flow velocity can be further obtained. Following this approach, an approximate fluid-structure interaction relationship, and curves of SiNW resistance change versus flow velocity relationship can be derived finally.

3. RESULTS AND DISCUSSION

3.1. Net Force Applied to Cantilever

Since the cantilever is very thin in thickness compared to its length, only the pressure distribution along its top and bottom surfaces is included in the calculation for extracting forces. The forces on both top and bottom surfaces of the cantilever along the direction perpendicular to the flow inlet direction are extracted. The net force is obtained by summing the top and bottom forces together. Figure 4 shows the net force application under fixed flow velocity when the depth varies from 20 μm to 400 μm. The negative net force means the net force pushes the cantilever downwards. The four fitting curves represent flow speed varies from 50 cm/s to 200 cm/s respectively. In the low flow rate region, e.g., 50 cm/s, the flow above and below the cantilever will contribute similar force to the top and bottom surface which may offset each other. Thus we observed the result of blue curve in Figure 4. In the higher flow rate region, e.g., 150 cm/s to 200 cm/s, the influence of sidewall depth is obvious. The net force increases

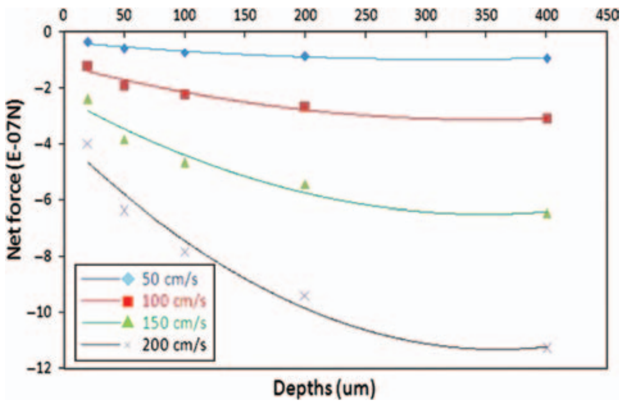

Fig. 4. The relationship between the net force applied to cantilever and its underneath sidewall depth at various flow velocities.

as the sidewall depth of block becomes higher, indicating higher deformation of the cantilever, and larger resistance change of the embedded SiNW as well. This indicates that for this kind of cantilever flow sensor design, larger space arranged underneath the cantilever will improve its performance. Moreover, the curve at velocity of 200 cm/s gives that the net force on the cantilever increases quickly when the depth changes from 20 μm to 200 μm; but the net force change does not increase so much from 200 μm to 400 μm. However, when the sidewall depth increases to certain degree, the net force in the high flow rate region will be saturated at maximum value eventually and is not affected by the sidewall depth, e.g., the curve of 200 cm/s in Figure 4. Because the water below the cantilever tends to be more stationary as the sidewall of block increases, the underneath water will apply less lifting force to the cantilever.

In Figure 5, it shows that the cantilever undergoes higher net force as expected when the flow velocity increases. Furthermore, the net force changes more rapidly as the sidewall depth increases, indicating that the sensitivity of the cantilever flow sensor becomes higher. Thus, we concluded that increasing the underneath depth will not only gain larger deformation of the cantilver, but also improve its sensitivity.

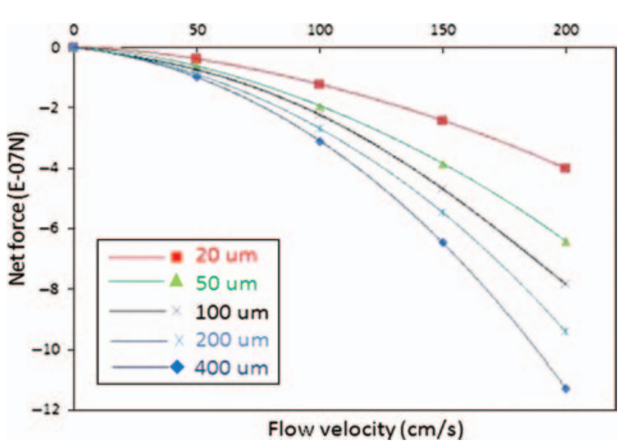

Fig. 5. The relationship between the net force applied to cantilever and the flow velocity with respect to various sidewall depths.

3.2. Eddy Currents

An eddy current is the flow induced in swirls. For example, when dragging an oar breadthwise, eddy current appears. In modeling, eddy current was observed as shown in Figure 6. Plane 1 and Plane 2 respectively show the flow behavior right across the cantilever and the region nearby the cantilever in Figure 6(a). In both cases, eddy current occurs. It indicates that cantilever is not the reason causing eddy current. According to the simulation data, there are two major combinations of parameters for results of apparent eddy current. The 1st combination is that the sidewall depth is 200 μm, and the flow velocity is 100 cm/s or higher; and the 2nd combination is that the sidewall depth of 400 μm at all kinds of velocity investigated in present study. It is concluded that the flow velocity and underneath sidewall depth is the main contributing factors to the eddy current, i.e., the eddy current is easily observed under higher sidewall depth and velocity. However, the eddy current doesn't seem to contribute to higher lifting force or to be able to make the cantilever bend upwards as we suspected initially. It appears as a minor effect from the aspect of flow sensor application.

3.3. Strain of Cantilever and Resistance Change of SiNW

To directly reveal the relationship between the cantilever's maximum strain and the flow velocity, Abaqus simulation is used to investigate the data of the flow sensors with depth 50 μm, 200 μm and 400 μm in a more accurate way. As introduced above in the modeling part, the pressure

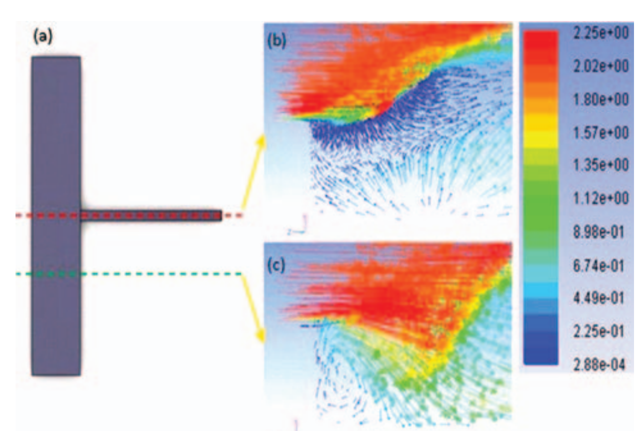

Fig. 6. (a) Top view of the flow sensor in which the red line indicates the cutting plane across the cantilever, the green line refers the plane without across the cantilever; (b) and (c) The fluidic trajectories corresponding to the two cutting planes. The inset shows the legend of flow velocity (m/s).

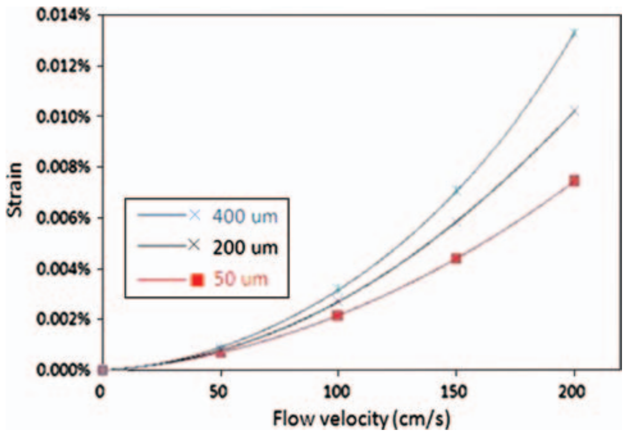

Fig. 7. The relationship between the strain measured at the cantilever anchor and the flow velocity.

distribution is exported from ANSYS Fluent and applied to the cantilever top and bottom surfaces accordingly for its mechanical deformation in Abaqus. As shown in Figure 7, the strain is derived at the anchor of cantilever versus the flow velocity. Larger strain is introduced by higher flow velocity. Moreover, the strain increases more rapidly in the case of larger underneath sidewall depth, indicating a higher sensitivity. This result coincides with the former analysis using the net force applied on the cantilever, and it is more convincing and straight forward.

The silicon nanowire embedded at the anchor of cantilever is supposed to experience an indentical strain as the cantilever. For bulk silicon the piezoresistive coefficient in longitudinal direction is 71.8E-11 Pa^{-1}. Based on Reck's report, an 633% increase of piezoresistance coefficient is found in $\langle 110 \rangle$ direction SiNW compared with bulk silicon. Under such conditions, the relationship of resistance change versus flow velocity can be further obtained using Eqs. (1) and (2),

$$\pi_l = \frac{\Delta R}{\sigma R_0} \tag{1}$$

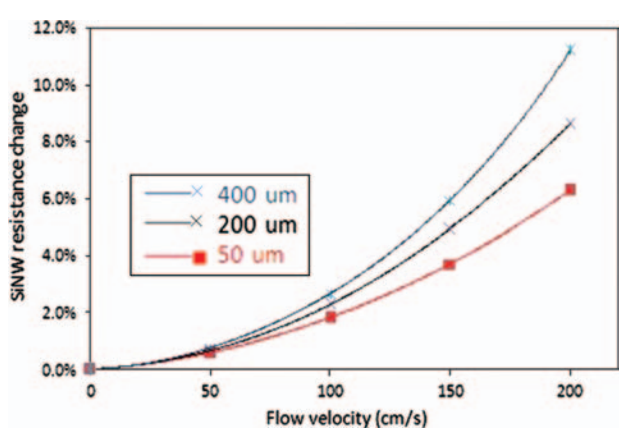

Fig. 8. The relationship between the resistance change of the SiNW and the flow velocity with respect to different block sidewall depths.

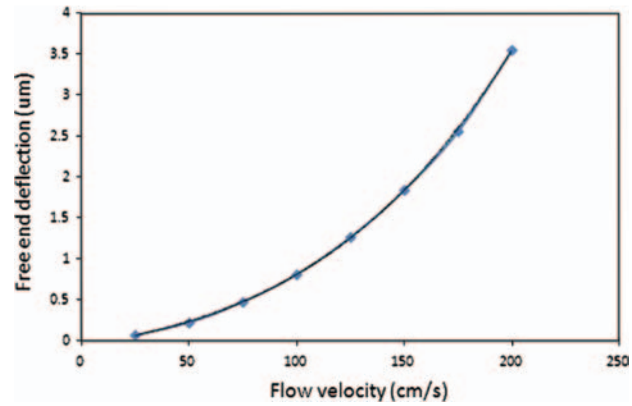

Fig. 9. The relationship between the deflection of cantilever free end and the flow velocity when the block sidewall depth is 400 μm.

$$\sigma = E\varepsilon \tag{2}$$

where π_l is the longituginal piezoresistance coefficient, R is the SiNW resistance, σ and ε are the longituginal stress and strain application to the SiNW, E is Young's modulus of silicon. Figure 8 shows the SiNW resistance change versus various flow velocity when the block sidewall depth are 50 μm, 200 μm and 400 μm respectively. It is observed that a maximum of 11.2% resistance in SiNW is achieved when the depth is 400 μm at flow velocity of 200 cm/s. Based on the above results, among all the flow sensor models, the one with 400 μm sidewall depth gains the largest strain at any given flow velocity. Thus to analyse the cantilever deflection in respect to the flow velocity, the flow sensor with 400 μm underneath sidewall depth is selected for such purpose. As shown in Figure 9, the maximum deflection of the cantilever free end is 3.5 μm in downward direction, in which it is only 4.4% of the initial curve-up height of the cantilever free end. In the case of such small deflection, the fluidic behavior is reasonably expected to be remaining the same. This means that other flow sensors with lower underneath sidewall depth should have even smaller deflection, indicating the modeling is valid for all the cases studied in this paper.

4. CONCLUSION

In this paper, a fluid-structure interaction modeling is introduced by using an approximation approach. Five cantilever flow sensor with different underneath depths are simulated with water flow velocity from 50 cm/s to 200 cm/s. Silicon nanowire is embedded at the anchor of the cantilever as a piezoresistive transducer, and a maximum change of 11.2% in resistance is obtained. Based on the results, Increasing underneath sidewall depth will not only contributes to lager cantilever deformation at a fixed flow velocity, but also improves the sensitivity. However when the sidewall depth is larger enough, e.g., 400 μm, this contributing effect does not affect a lot.

Acknowledgments: This work was supported by research grant from A-STAR, SERC Grant No. 09214 80069, and University Research Committee Fund R-263-000-475-112 and Academic Research Committee Fund MOE2009-T2-2-011 at the National University of Singapore.

References and Notes

1. N. T. Nguyen, *Flow Measurement and Instrumentation* 8, 7 (**1997**).
2. S. Radhakrishnan and A. Lal, *Proc. IEEE MEMS* 307 (**2003**).
3. N. G. Green, S. Tao, D. Holmes, and H. Morgan, Impedance based flow sensor, *Proc. SPIE, Smart Sensors, Actuators, and MEMS II*, edited by F. V. V. C. Cané and J. Chiao (**2005**), Vol. 5836, pp. 634–641.
4. J. Li, Z. Fan, J. Chen, J. Zou, and C. Liu, High yield microfabrication MEMS, and nanotech. conf. (4700), *Proc. SPIE's 9th Annu. Int. Symp. Smart Structures Materials*, San Diego, CA (**2002**), pp. 17–21.
5. R. He and P. Yang, *Nat. Nanotechnol.* 1, 42 (**2006**).
6. K. Reck, J. Richter, O. Hansen, and E. V. Thomsen, *Proc., IEEE MEMS* 717 (**2008**).
7. P. Neuzil, C. C. Wong, and J. Reboud, *Nano Lett.* 10, 1248 (**2010**).

Received: xx Xxxx Xxxx; Accepted: xx Xxxx Xxxx