Piezoresistive silicon nanowire based nanoelectromechanical system cantilever air flow sensor
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Piezoresistive silicon nanowire based nanoelectromechanical system cantilever air flow sensor

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We present nanoelectromechanical system based cantilever air flow sensor using silicon nanowires (SiNWs). The cantilever is fabricated in the complementary metal-oxide-semiconductor (CMOS) compatible process with dimension of \(90 \mu m \times 20 \mu m \times 3 \mu m\). SiNWs with the size of \(2 \mu m \times 90 nm \times 90 nm\) are embedded at the edge of the cantilever to enhance the device immunity to the air flow induced vibration. Compared with recently reported air flow sensors, our device shows a better sensitivity of 198 \(\Omega/\text{m/s}\) and a flow sensing range up to 65 m/s. In addition, improvements in terms of linearity, hysteresis, and lower power consumption are reported as well. © 2012 American Institute of Physics. [doi:10.1063/1.3675878]

Promising candidates as sensing elements in nanoelectromechanical system (NEMS) piezoresistive sensor design, i.e., SiNWs based air flow sensor, Lou et al. have indicated the potential of using a microcantilever integrated with piezoresistive SiNWs for flow sensing based on modeling results. In this work, we present a CMOS compatible NEMS cantilever air flow sensor using SiNWs as sensing elements. The detailed device characterizations in terms of sensitivity, linearity, and hysteresis are conducted to prove its better air flow sensing performance in contrast to recently reported designs. Additionally, the effective sensing area in our report is shrunk down to 20 \(\mu m \times 90 \mu m\). Without compromising the flow sensing performance, this significant device size reduction demonstrates the great scalability of SiNWs based NEMS flow sensors. Such excellent scalability increases the potential for the device level miniaturization in many applications. For instance, an implantable biomedical piezoresistive blood flow sensor has the entire chip dimension less than 1 mm\(^2\) to avoid the vessel blockage.

The fabrication starting with a (100) single crystal silicon-on-insulator (SOI) wafer with 117 nm device layer on top of a 145 nm box SiO\(_2\) layer, P-type implantation using BF\(_2\) with a dosage of \(10^{14}\) ion/cm\(^2\) was performed, and an annealing step for activation was done to make the piezoresistive patterns. After photolithography and (110) direction SiNWs patterning, 2 \(\mu m\) SiNWs with an average cross section of 90 nm \(\times\) 90 nm was obtained. A 400 nm SiO\(_2\) passivation layer was deposited sequentially. After via open and metallization, a 2.5 \(\mu m\) low stress SiN\(_x\) layer was coated to compensate the initial compressive stress and significantly enhance the device immunity to the air flow induced vibration noise. Lastly, backside deep reactive-ion etching (DRIE) was conducted to define a through wafer hole with diameter of 200 \(\mu m\) as the air flow channel. In addition, the cantilever with SiNWs embedded at the edge was released. With this multilayer structure, SiNWs will experience the maximum tensile stress when the air flows from the bottom to the top of the channel as shown in schematic drawing of Fig. 1(b). The scanning electron microscopy (SEM) image of

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the SiNWs based cantilever air flow sensor is given in Fig. 1(c). The inset shows the 2 μm long SiNWs after wet etching of top passivation layers.

The test was conducted under room temperature (25 °C) with the supply voltage as low as 0.1 V. As illustrated in Fig. 1(a), the compressed air was directed to the air flow channel (diameter of 200 μm) through the flow meter for flow velocity control. A semiconductor characterization system (Keithley 4200-SCS) was used to measure the piezoresistance variation with respect to the change in flow velocity. Based on the measurement results plotted in Fig. 2, the resistance increases almost linearly against the air flow increment. The non-linearity of the device is calculated to be less than 0.1%, which is an order of magnitude improvement in contrast to the recently reported piezoresistive cantilever air flow sensors.5,7 A maximum resistance of 163.5 kΩ was found at a flow velocity of 65 m/s. With respect to the initial piezoresistance around 150.5 kΩ, a total resistance increment is above 8.6% as shown in Fig. 2 inset (a). Moreover, with such low supply voltage and the high piezoresistance, a total power consumption below 1 μW is achieved. This ultra low power consumption overcomes the limitation of relatively low output power delivery from current MEMS energy harvesting devices.12 Taking advantages of this ultra low power consumption and the CMOS compatibility, our reported flow sensor could be integrated with the MEMS energy harvester to establish a self-sustainable sensing network. Such self-sustainable sensing network could be implemented in current heating, ventilation, air conditioning (HVAC) system, or even biomedical body sensing network.

A sensitivity of 198 kΩ/m/s was recorded during the measurement. In order to make comparisons to the recently reported cantilever air flow sensors, we first normalize the amplification effects due to supply voltage differences and the external amplification circuit. As tabulated in second last column of Table I, the sensitivity of our air flow sensor is almost doubled than that of others. Second, the effective sensing area is also normalized for further fair comparisons. The result shows that our air flow sensor improves the sensitivity by orders of magnitude as tabulated in last column of Table I. Again this validates the scalability of the SiNWs based flow sensor.

In order to verify the air flow detection capability and the immunity against the flow induced vibration noise, variations of the piezoresistance for 2 μm SiNWs are sampled over 130 s at both initial state (flow velocity = 0 m/s) and maximum flow state (flow velocity = 65 m/s), respectively. The resistance variation at initial state is around 100 kΩ as shown in Fig. 2 inset (b). That is approximately 0.066% of its corresponding piezoresistance and half of the piezoresistance change under a unit flow velocity increment (198 kΩ/m/s).

When flow velocity reaches 65 m/s, a resistance variation within 170 kΩ is observed and shown in Fig. 2 inset (c). This corresponds to only 0.11% of the initial piezoresistance. Such increment of resistance variations are caused by the cantilever vibration noise induced by the increasing air flow. However, due to the high mechanical stiffness of the top passivation layer (2.5 μm thick SiNx), the piezoresistance change under the unit flow velocity increment (198 kΩ/m/s) is still about 30 Ω higher than the noise induced resistance variation. Therefore, our flow sensor is able to differentiate a unit flow velocity change (per m/s) without being interfered by the vibration noise. As such, the detection capability of our cantilever air flow sensor has been proven over reasonably large sensing range.
As previously mentioned, the reported piezoresistive cantilever air flow sensor often suffers poor hysteresis.\(^4\) Thus, to verify the consistent device sensing behavior, a repeatability test was conducted for our reported device. A flow meter was programmed with a given increasing step of 13 m/s and starting from the flow velocity of 0 m/s. The duration between each step was set to 5 s. After reaching the flow velocity of 65 m/s, the air flow was decreased back to initial state with the same flow velocity step and duration to complete one cycle. There total 2 complete cycles were recorded over 130 s (limited by the maximum data storage capacity of semiconductor characterization system). As shown in Fig. 3, by leveraging the SiNWs as piezoresistive sensing element, our air flow sensor performs the consistent sensing behavior with constant piezoresistance changes over repetitive cycles with respect to air flow variations.

In conclusion, our reported SiNWs based air flow sensor shows the better hysteresis and the excellent linearity compared to that of other recently reported designs. In addition, without compromising the device sensitivity, the SiNWs based flow sensor demonstrates the great scalability. Furthermore, both CMOS compatibility and ultra low power consumption provide the higher feasibility in system level integration with other devices/circuits for future technology-oriented applications.

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### References

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<td>Lee et al.(^b)</td>
<td>0–45</td>
<td>Pt resistor</td>
<td>(400 \times 4000 \mu m^2)</td>
<td>(50 \times 4450 \times 0.4 \mu m^3)</td>
<td>304 (\Omega)</td>
<td>0.0533 (\Omega/m/s)</td>
<td>N/A</td>
<td>1.757 (10^{-4})</td>
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<tr>
<td>Lee et al.(^c)</td>
<td>0–45</td>
<td>Pt resistor</td>
<td>((2000 \times 2000 + 400 \times 2000) \mu m^2)</td>
<td>(50 \times 1500 \times 0.4 \mu m^3)</td>
<td>350 (\Omega)</td>
<td>0.0785 (\Omega/m/s)</td>
<td>N/A</td>
<td>2.243 (10^{-4})</td>
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<td>Zhang et al.(^d)</td>
<td>3–170</td>
<td>P-type silicon wire</td>
<td>(400 \times 1100 \mu m^2)</td>
<td>(150 \times 25 \times 1 \mu m^3)</td>
<td>2.5 (K\Omega)</td>
<td>0.71 mV/m/s</td>
<td>6.5</td>
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<td>Conductive elastomer composite</td>
<td>(3500 \times 600 \mu m^2)</td>
<td>(1900 \times 110 \times 13 \mu m^3)</td>
<td>700 (K\Omega)</td>
<td>14.5 mV/m/s</td>
<td>6</td>
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<tr>
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<td>0–65</td>
<td>P-type silicon nanowire</td>
<td>(20 \times 90 \mu m^2)</td>
<td>(2 \times 0.09 \times 0.09 \mu m^3)</td>
<td>150 (K\Omega)</td>
<td>198 (\Omega/m/s)</td>
<td>N/A</td>
<td>1.32 (10^{-3})</td>
</tr>
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</table>

\(^a\)Effects of external amplifications, different supply voltages and initial resistances are all taken into normalization.
\(^b\)Ref. 4.
\(^c\)Ref. 5.
\(^d\)Ref. 6.
\(^e\)Ref. 7.