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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 compatible process with dimension of $90\,\mu m \times 20\,\mu m \times 3\,\mu m$. SiNWs with the size of $2\,\mu m \times 90\,nm \times 90\,nm$ (length × width × height) are embedded at the edge of the cantilever fixed end to experience the maximum air flow induced strain. Compared with recently reported air flow sensors, our device shows a better sensitivity of 198 Ω/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]

Microelectromechanical systems (MEMS) based flow sensors have been researched upon for decades since its first debut in 1974 based on thermal sensing scheme.[1] Although these thermal based flow sensors provide good sensitivity and stability, their higher power consumption (in the range of few or tens of mW) (Refs. 2 and 3) and relatively narrow sensing range (usually below 30 m/s) (Ref. 3) remain unsolved issues. To overcome these problems, the non-thermal sensing flow sensors based on the mechanical working principle were introduced, and the piezoresistive based cantilever flow sensor was the one of the most popular sensing schemes among all non-thermal based designs. Such air flow sensor not only has the advantage of simplified mechanical structure, their lower power consumption also fulfills the current market demands. However, these recently reported piezoresistive cantilever air flow sensors suffer problems such as poor hysteresis[4] and relatively large non-linearity.[5] In addition, their fabrications are not complementary metal-oxide-semiconductor (CMOS) compatible,[4–6] which raises the potential integration problem during the fabrication with standard CMOS devices/circuits. Zhang *et al.* demonstrated the monolithic integration of the piezoresistive air flow sensor with doped bulk silicon wires as sensing elements.[7] An external instrumental amplification circuit was successfully integrated based on their CMOS compatible fabrication method. Nevertheless, the bulk silicon wire based piezoresistive air flow sensor shows poor linearity and relatively normal piezoresistive performance in contrast to the performance of other piezoresistive sensing elements, i.e., Pt and conductive elastomer.[4–6] However, compared with the inferior piezoresistive effect of bulk silicon wires, the excellent piezoresistive performance has been reported for single crystal silicon nanowires (SiNWs) with the cross section area below 100 $nm^2$ by many research groups.[8,9] The consistent superior piezoresistive effect of SiNWs in ⟨110⟩ crystal orientation under tensile stress[10] makes them the 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.[11] 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 $mm^3$ 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 × 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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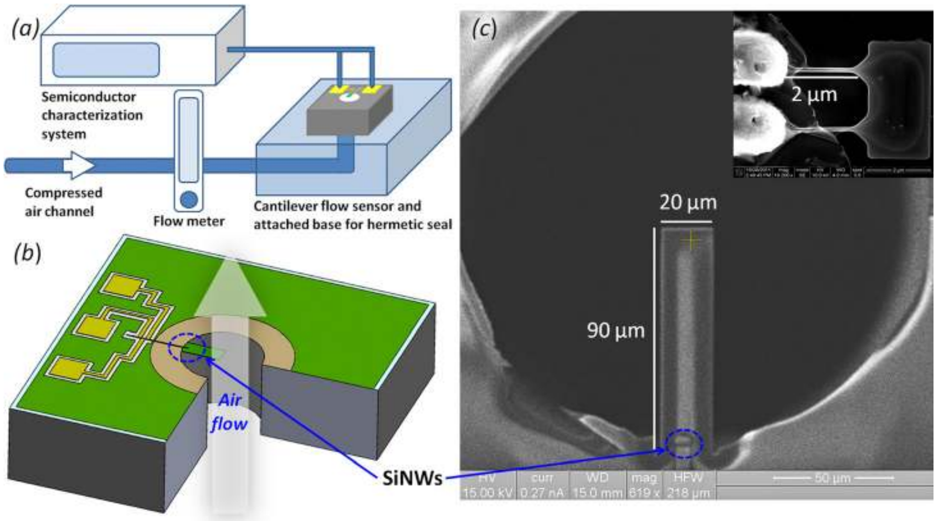


FIG. 1. (Color online) (a) Testing setup of NEMS cantilever air flow sensor, (b) schematic drawing of reported NEMS cantilever air flow sensor, and (c) SEM photo of the fabricated device with inset showing a zoom in view for the 2 $\mu$m SiNWs after etching back all passivation layers.

the SiNWs based cantilever air flow sensor is given in Fig. 1(c). The inset shows the 2 $\mu$m 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 $\mu$m) 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 $\mu$W 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.

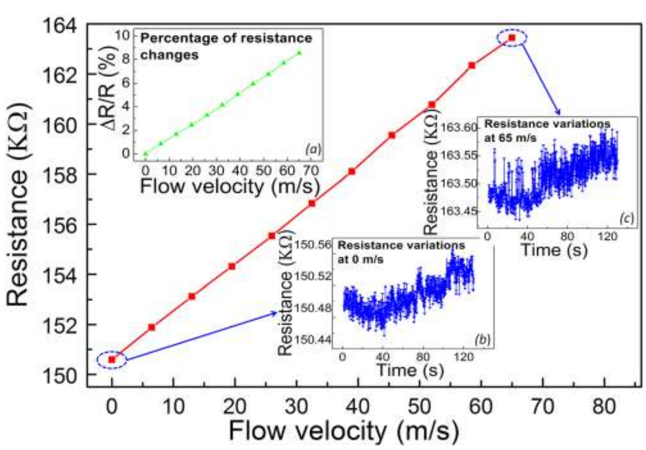


FIG. 2. (Color online) The plot of piezoresistance changes with respect to the air flow velocity increment up to 65 m/s. Inset (a) percentage changes of piezoresistance over air flow velocity increment up to 65 m/s, (b) piezoresistance variations at flow velocity of 0 m/s, and (c) piezoresistance variations at flow velocity of 65 m/s.

A sensitivity of 198 Ω/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 viberation noise, variations of the piezoresistance for 2 $\mu$m 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 Ω 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 Ω/m/s). When flow velocity reaches 65 m/s, a resistance variation within 170 Ω 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 $\mu$m thick $SiN_x$), the piezoresistance change under the unit flow velocity increment (198 Ω/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.

TABLE. I. Comparisons between the reported SiNWs cantilever air flow sensor and recent research works.

| References | Sensing range (m/s) | Piezoresistive material | Effective sensing area of single cantilever ($L \times W$) | Dimension of piezoresistor ($L \times W \times H$) | Initial resistance | Sensitivity of single cantilever | Gain of external amplify circuits | Sensitivity after normalization of amplification (ΔΩ/Ω/m/s)[a] | Sensitivity after normalization of effective sensing area (ΔΩ/Ω/m/s/$\mu m^2$) |
|---|---|---|---|---|---|---|---|---|---|
| Lee *et al.*[b] | 0–45 | Pt resistor | $400 \times 4000\ \mu m^2$ | $50 \times 4450 \times 0.4\ \mu m^3$ | 304 Ω | 0.0533 Ω/m/s | N/A | $1.757 \times 10^{-4}$ | $1.1 \times 10^{-10}$ |
| Lee *et al.*[c] | 0–45 | Pt resistor | $(2000 \times 2000 + 400 \times 2000)\ \mu m^2$ | $50 \times 1500 \times 0.4\ \mu m^3$ | 350 Ω | 0.0785 Ω/m/s | N/A | $2.243 \times 10^{-4}$ | $4.67 \times 10^{-11}$ |
| Zhang *et al.*[d] | 3–170 | P-type silicon wire | $400 \times 1100\ \mu m^2$ | $150 \times 25 \times 1\ \mu m^3$ | 2.5 KΩ | 0.71 mV/m/s | 6.5 | $4.733 \times 10^{-5}$ | $1.08 \times 10^{-10}$ |
| Song *et al.*[e] | 5–16 | Conductive elastomer composite | $3500 \times 600\ \mu m^2$ | $1900 \times 110 \times 13\ \mu m^3$ | 700 KΩ | 14.5 mV/m/s | 6 | $7.25 \times 10^{-4}$ | $3.45 \times 10^{-10}$ |
| Our reported design | 0–65 | P-type silicon nanowire | $20 \times 90\ \mu m^2$ | $2 \times 0.09 \times 0.09\ \mu m^3$ | 150 KΩ | 198 Ω/m/s | N/A | $1.32 \times 10^{-3}$ | $7.33 \times 10^{-7}$ |

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

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.

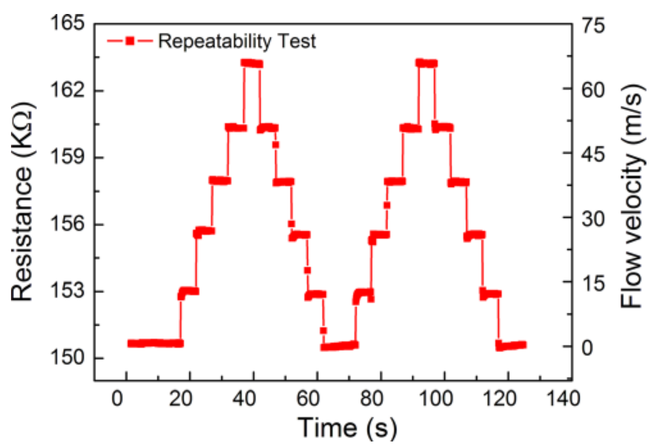


FIG. 3. (Color online) The repeatability test of reported SiNWs based cantilever air flow sensor.

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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