Highly sensitive pressure sensors employing 3C-SiC nanowires fabricated on a free standing structure

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Abstract

This paper presents highly sensitive pressure sensors using piezoresistive nanowires. Our approach is based on nanowires locally fabricated on free standing structures with a high strain concentration. This strain concentration phenomenon amplifies the strain induced into nano-scaled sensing elements while the bulk materials are still at small strain regime, therefore enhancing the sensitivity of the sensors. For proof of concept, we utilized SiC nanowire fabricated using focused ion beam from an epitaxially grown thin film. Experimental results show significant 3-fold enhancement in the sensitivity in comparison to conventional structures, which is in good agreement with analytical modeling and numerical simulation. The proposed design shows potential for the development of miniaturized highly sensitive but robust nano mechanical-sensors.

Keywords: Piezoresistance, Nanowires, Pressure sensors, SiC

1. Introduction

Nanowires have been considered as an important building block for the next generation of Nano Electro Mechanical Systems (NEMS) sensors [1]. The use of nanowires provides numerous advantages over conventional bulk materials including device miniaturization, high sensitivity, and superior optical properties [2, 3, 4, 5]. For instance, by assembling multiple silicon nanowires on a single chip, the Lieber group has developed miniaturized computers which can perform the basic logic states including AND, OR, NOT, and NAND with a relatively low gate voltage [6]. In addition, the sub-wavelength diameter and the capability of tuning energy gaps also make nanowires a promising platform for the generation, detection and modulation of light. As such, Liu *et al.* reported wavelength tunable lasers by modulating the alloy composition in $\text{Zn}_x\text{Cd}_{1-x}\text{S}$ nanowires [7]. Furthermore, the nanoscale

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dimensions allow charge carriers to be exposed on the surface of nanowires, making them sensitive to stimuli from surrounding environments. A well-known exemplar application of this property is Si nanowires for label-free biosensors, which exhibit fast response and large signal-to-noise ratios owing to their large surface area [8].

Nanowires have also been employed in highly sensitive mechanical sensors such as strain and pressure sensors. The use of a nanowire as the channel of a field effect transistor (FET) could enhance strain-sensitivity by modulating the top gate [9, 10, 11]. A number of studies have been conducted to improve the sensitivity of MEMS pressure and strain sensors using this phenomenon in nanowire FETs [12, 13, 14].

In addition to their exhibiting excellent electrical and optical properties, the nanoscale nanowires have also been proven to be much stronger than bulk materials due to the smaller defect concentrations [15]. In our previous studies, we have demonstrated that Si nanowires can withstand strain of at least 2.5%, whereas bulk Si generally exhibits brittleness at less than 1% strain [16]. The Cui group has demonstrated the use of Si nanowire forests instead of bulk electrodes in lithium batteries, showing significant enhancement in long-term stability of nanowires over bulk materials due to their tolerance to tensile strain during charging/discharging processes [17]. The strong mechanical properties of nanowires imply that in mechanical sensing applications, it is desirable to concentrate mechanical impact on nano structures, while maintaining lower stress/strain on micro structures so that the sensors could offer higher sensitivity and improved robustness [18].

In the present work we propose an effective approach to develop highly sensitive pressure sensors employing nanowires fabricated at the center of a dogbone-like structure. The key concept of our design relies on the strain concentration phenomenon to maximize mechanical stimuli applied to nanowires, enhancing the sensitivity of the sensors. Experimental results show an approximately 3-fold improvement in the sensitivity of SiC nanowire pressure sensors in comparison to bulk-material-based sensors of the same dimensions.

2. Results and discussion

2.1. Concept of nanowire based pressure sensors

Figure 1 shows the concept of a nanowire pressure sensor, in which the nanowire is fabricated at the center of a free-standing micro bridge. The bridge is suspended on a thick membrane, which is used to transfer the strain from external air-pressure to the sensing element. The design was inspired by the dog-bone structure which is widely employed to test the tensile strength of materials. That is, when a sufficiently large mechanical load is applied to dogbone-structured materials, cracks always occur at the narrow section of the dog-bone due to the stress concentration phenomenon. Similarly, in

Figure 1: Concept of the pressure sensors. (a) Nanowire fabricated at the center of a free standing micro bridge; (b) Schematic sketch of strain induced into the free standing nanowire and micro bridge under pressure; (c) Estimation of the strain amplification rate when varying the dimension of nanowire arrays.

our structure, upon applying pressure the upper surface of the membrane will be deflected outward, and a large elongation is expected to be observed in the narrowed nanowires areas. This assumption can be quantitatively explained as follows.

Under the applied pressure p , the strain induced into the center point of the top surface of the membrane (ε_{sub}) is given by [19]:

$$\varepsilon_{sub} = \frac{0.1386 \times p \times b^2}{E \times t^2} \quad (1)$$

where b and t are the width and the thickness of the membrane; and E is the Young's modulus of the substrate.

Since the stiffness of the suspended structure (including the microscaled parts and the nanowires located at the center) is much smaller than the stiffness of the membrane, upon applying pressure, this free standing structure will be elongated following the deflection of the membrane. The change in the length of the suspended bridge is:

$$\Delta L = L \times \varepsilon_{sub} = L_1 \times \varepsilon_1 + L_2 \times \varepsilon_2 + L_3 \times \varepsilon_3 \quad (2)$$

where ε_i is strain induced into each component of the free standing dog-bone structure. For a symmetrical design, ε_1 and ε_3 are equivalent and $\Delta L = 2 \times L_1 \times \varepsilon_1 + L_2 \times \varepsilon_2$.

Due to the force equilibrium in the suspended structure, the following equation is established following Hooke's law:

$$F = K_1 \times \varepsilon_1 = K_2 \times \varepsilon_2 = K_3 \times \varepsilon_3 \quad (3)$$

where K_1 is the stiffness of the microscaled frame, and K_2 is the stiffness of the nanowires. From Eq. 3, the ratio of the strains induced into nanowires and micro frame is:

$$\varepsilon_2 = (K_1/K_2)\varepsilon_1 \quad (4)$$

Substituting Eq. 4 into Eq. 2, the strain induced into the nanowires is:

$$\varepsilon_2 = \frac{L}{2\frac{K_2}{K_1}L_1 + L_2} \times \varepsilon_{sub} = \frac{1}{1 - 2(1 - \frac{K_2}{K_1})\frac{L_1}{L}} \times \varepsilon_{sub} \quad (5)$$

It is evident from Eq. 5 that the softer ($K_2 \ll K_1$) and shorter ($L_2 \ll L_1$) the nanowires are, the larger is the strain concentrated in the nanowires (i.e. $\varepsilon_2 \gg \varepsilon_{sub}$), Fig. 1(c). In other words, the strain induced into the sensing element (i.e. the nanowires), can be significantly amplified from the applied strain (ε) by:

- (i) reducing the width of the nanowires (e.g. reduce the ratio of $K_2/K_1 \approx W_2/W_1$)
- (ii) shortening the length of the nanowires in comparison to the microscale parts (e.g. increasing the ratio of L_1/L)

It should be noted that the strain applied to the bulk material (ε_{sub}) remains small, allowing the sensors to function in a wider range of pressures while still offering the high sensitivity.

2.2. Characterization of nanowires based pressure sensors

To demonstrate the sensitivity enhancement in the proposed structure, we developed piezoresistive SiC nanowires on Si-membrane pressure sensors, Fig. 2. Cubic SiC was selected in this work due to the increasing demand for the development of wide-band-gap based mechanical sensors for applications in harsh environments including high temperatures and high pressures [20, 21, 22, 23]. P-type SiC films with thickness of 300 nm, was deposited on (100) Si using chemical vapor deposition at 1000°C. A detailed description of the deposition process and characterization of the as-grown film has been reported in our previous studies [24]. The SiC layer was then patterned using Inductive Coupled Plasma Etching through to the Si layer with an etching rate of 100 nm/min. Subsequently, Al was deposited and then wet-etched to form electrode pads. SiC micro bridges with dimension of 200 μm in length, 8 μm in width and 300 nm in thickness were released from the substrate by isotropic etching of Si using XeF_2 as the active gas [25].

Subsequently, arrays of SiC nanowires were fabricated using focused ion beam with Ga^+ ions [26, 27]. Finally, the Si membrane was formed by etching the Si substrates from the backside. For simplicity, a large scale Si membrane with dimension of 5 mm $\times$ 5 mm $\times$ 150 μm was fabricated using a UV laser with an etching rate of 60 $\mu\text{m}/\text{min}$ [28]. For comparison, a free-standing micro SiC resistor on Si-membrane pressure sensor was also fabricated. It should also be noted that, since the sensing element was p-type cubic SiC, the suspended bridge and the nanowires were aligned in [110] orientation to provide the highest sensitivity [29].

Figure 3(a) shows an array of 3C-SiC nanowires fabricated at the center of a suspended 200 μm -length bridge. The SEM image of the nanowires taken from a 45°-tilted-view shows that the Si layer underneath was removed by the isotropic dry etching. The average dimension of each nanowire was

measured at $5 \mu\text{m} \times 430 \text{ nm} \times 300 \text{ nm}$, Fig. 3(c). Figure 3(d) shows an SEM image of the back side of the Si membranes, with an etching-depth of approximately $500 \mu\text{m}$ measured using DektakTM150 Surface Profiler (Inset). The roughness of the laser-engraved Si surface was found to be approximately $20 \mu\text{m}$, Fig. 3(e). The SEM image of the SiC micro resistor used for comparison is shown in Fig. 3(f). The dimension of the Si membrane in the SiC microresistor based pressure sensor were similar to that of the nanowire based sensors ($5 \text{ mm} \times 5 \text{ mm} \times 150 \mu\text{m}$).

Figure 4 shows the current-voltage (I-V) characteristics of SiC micro resistors and SiC nanowires with an almost linear relationship in the I-V, indicating a Ohmic contact between Al and SiC films. Furthermore, from the geometry of the SiC nanowires and the SiC micro resistors, the resistivity of the nanowires and the bulk material were found to be almost the same ($4.2\text{k}\Omega/\square$), indicating that the FIB process did not significantly affect the electrical properties of the nanowires.

We then investigated the magnitude of the piezoresistive effect in non-suspended micro-sized SiC and nanowire SiC resistors. Non-suspended SiC micro resistors and SiC nanowires similar to that of the pressure sensors were formed on a Si beam with dimensions of $40 \text{ mm} \times 8 \text{ mm} \times 650 \mu\text{m}$, from the same SiC-on-Si wafer (Fig. 5 inset). The bending method was utilized to apply uniaxial strain to the SiC micro resistor and nanowires, where the Si beam was fixed at one end using a metal clamp (See the supplementary information). Figure 5 shows the relative resistance change of the SiC micro resistors and nanowires under strain varying from 0 to 350 ppm. A linear relationship between resistance change and applied strain was observed in both bulk materials and nanowires. The gauge factors ($GF = (\Delta R/R)/\epsilon$) of the nanowires was found to be approximately 33, which is in the same range of that of bulk materials ($GF \approx 30$). These results are reasonable as the dimension of the nanowires is well above the the quantum-effect-length.

The SiC nanowire and micro-sized pressure sensors were then mounted on an acrylic holder with

Figure 2: Fabrication process of the SiC nanowires pressure sensor

Figure 3: Photograph of fabricated devices. (a) SiC nanowires fabricated at the center of a suspended bridge; (b) Zoom-in SEM image of an SiC nanowires; (c) SEM image of the nanowire array from the top view, showing the nanowires are connected to two serial micro resistors; (d) SEM image of back side Si membrane; (e) Surface roughness of Si on the backside after laser engraving; (f) A pressure sensor with suspended SiC microresistors fabricated on a Si membrane for comparison to nanowire based sensor.

a through hole at the center using UV gel as shown in Fig.6(a). The holder was then fixed onto an enclosed metal chamber. Air pressure was applied to the backside of the Si membrane using a pressure controller (EveflowTM), Fig. 6(b). Finite element analysis using Comsol MultiphysicsTM was

Figure 4: Current-voltage characteristics of SiC microresistors and nanowires by sweeping applied voltage from -1V to 1V.

employed to estimate the strain induced into the SiC nanowires and the suspended micro bridge. Accordingly, the strain induced into the as-fabricated nanowires was derived to be approximately 5 times larger than that of the microresistors, Fig. 6(c). Using the gauge factor of the nanowires and microresistors obtained from Fig. 5, the strain amplification in the sensing element was expected to result in enhancement in the relative resistance change of the sensors by 3.5 folds in comparison to micro SiC resistors.

A pressure of 500 mbar was then cyclically applied with an interval of 8s for each pressurizing cycle. The resistances of SiC nanowires and SiC micro resistors were monitored and recorded using an AgilentTMB1500A Semiconductor Device Parameter Analyzer where the applied voltage was kept at 0.5 V. Figure 6(d) shows the response of the sensors (the change in current) subjected to cyclic square-pressure of 500 mbar. Both SiC nanowires and microresistor-based sensors showed excellent repeatability of the resistance change over several testing cycles. Evidently, the response of the nanowires pressure sensors was approximately 3 times larger than that of the pressure sensors using micro-sized SiC. The enhancement in the sensitivity of the as-fabricated sensors was in good agreement with the simulation result mentioned above. The difference between the experimental and simulation data could result from the surface roughness of the Si membrane due to laser engraving (Fig. 4(e)) or the sensor alignment error. It should also be pointed out that, in our experiments, for the sake of simplicity, the output of the sensors was monitored using the Device Parameter Analyzer, where a small change in the current can be detected after subtracting the initial current [30, 31, 32]. However, in practical applications, the use of Wheatstone bridge combined with an Op-amp to eliminate the offset the voltage and amplify the output is recommended. The data recording method using this circuit is described in

Figure 5: Comparison of the piezoresistive effect in non-suspended SiC nanowires and microresistors.

Figure 6: Characterization of SiC pressure sensors. (a) Photograph of SiC nanowire pressure sensor mounted on an acrylic holder; (b) Experimental setup of SiC nanowire pressure sensors; (c) Simulation of strain induced into the nanowires and microscaled frames; (d) A 3-fold increase in the sensitivity of nanowire sensors (blue) in comparison to SiC microresistors (red); (e) The output of SiC nanowire sensor under different input-pressures. (f) Response of the nanowire pressure sensors under ramp-up pressures from 0 to 500 mbar.

the supplementary information.

The nanowire-based sensors were then subjected to different applied pressure, showing that the current change increased linearly with increasing pressures, Fig. 6(e). The output of the nanowire pressure sensors against ramped-up pressure input (8 seconds/cycle) is shown in Fig.6(f), indicating fast time response and good repeatability with a variation of less than 3% between cycles. The sensor did not show any significant degradation after subjecting to 1,000 pressurizing-depressurizing cycles.

3. Conclusion

This work reports a novel structure for the development of highly sensitive pressure sensors using nanowires. The proposed concept includes a nanowire array locally fabricated at the center of a free standing micro structure on a pressure-membrane. A proof of concept pressure sensor was developed, showing approximately 3-fold enhancement in the sensitivity in comparison to the conventional design. The proposed structure can be optimized to obtain higher sensitivity-enhancement in the future.

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Graphical abstract

Highlights

- A smart mechanical design employing the stress concentration phenomenon in nanowires was proposed to enhance the sensitivity in piezoresistive sensors.
- A numerical analysis model was developed to estimate the amplification gain of the proposed nanowire structure.
- A proof-of-concept nanowire-pressure sensor was fabricated and characterized showing significant 3-fold enhancement in the sensitivity in comparison to conventional structures

Graphics Abstract

(a) Concept of pressure sensors

(b) Principle

(c) Numerical estimation

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

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