Supplementary data for

Out-of-plane high-density piezoresistive silicon microwire/p-n diode array for force and temperature sensitive artificial whisker sensors

Akihito Ikedo, Makoto Ishida and Takeshi Kawano

Toyohashi University of Technology,
Department of Electrical and Electronic Information Engineering
1-1 Hibarigaoka, Tempaku-cho, Toyohashi, Aichi 441-8580, Japan

Polycrystalline silicon layer surrounding the silicon wire base

Using Si_2H_6 gas-based VLS growth parameters (gas pressure=0.6 Pa, growth temperature=700 °C, growth time = 30 min), a p-type ~1 μm thick polycrystalline silicon layer was deposited over the SiO_2 layer (figure S1(a)) [1]. After VLS growth, the conductive polycrystalline layer needed to be removed for the electrical disconnection between silicon microwires. Although gas etching with XeF_2 removed the majority of the undesired polycrystalline silicon layer and the VLS-silicon wire section was covered with a spray-coated photoresist, the ~20 μm wide polycrystalline silicon layer could not be etched due to limitations in projection printing-based lithographical patterning of the photoresist over the wire (figures S1(b–c)).

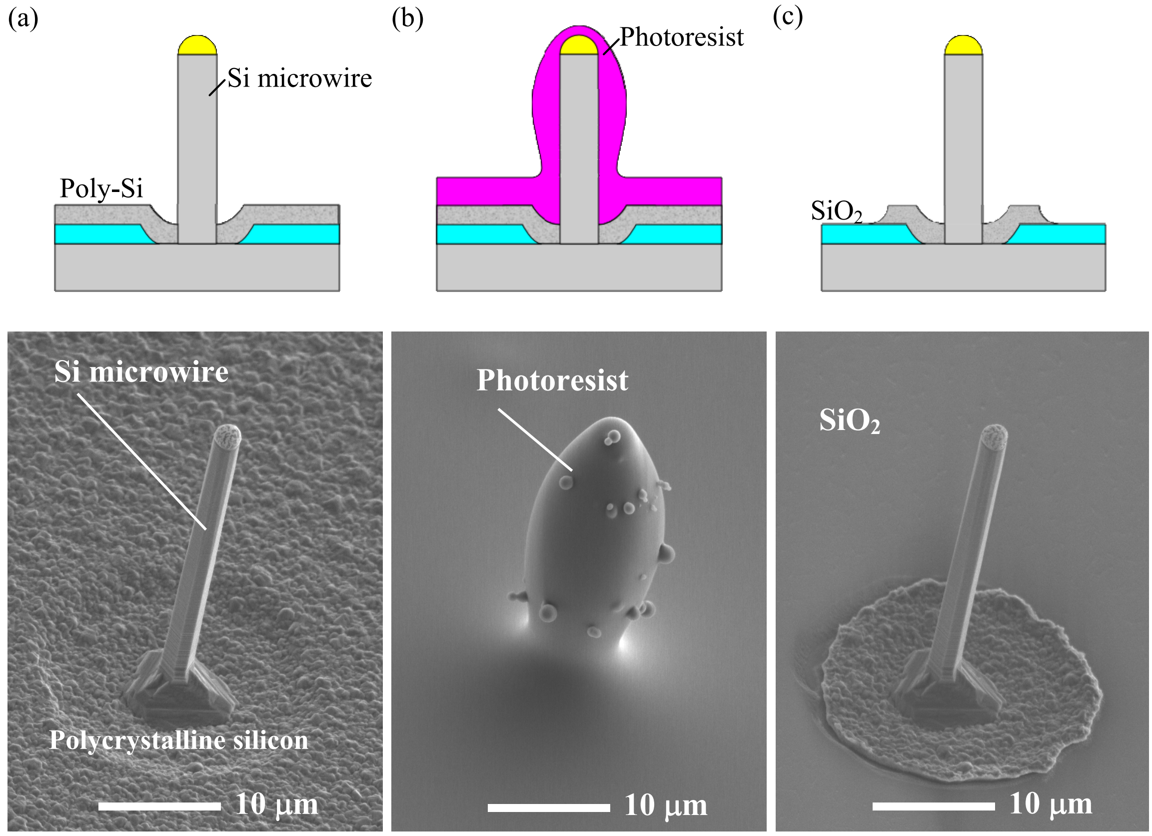

Figure S1. Polycrystalline silicon layer surrounding the silicon wire base. (a) SEM image and cross sectional image of a silicon wire with polycrystalline silicon deposition due to Si_2H_6 gas-based VLS growth. (b) Silicon microwire covered with a spray-coated photoresist and (c) after patterningthe polycrystalline silicon layer by gas etching with XeF_2.

Estimation of the applied compressive force to a wire

With a maximum compressive stress of −160 MPa (see equation (1) in the main text) and device modeling, the amount of the applied maximum compressive force was calculated by finite-element simulations with commercially available software ANSYS (Ansys, Inc., Canonsburg, USA). Here we used a two-dimensional axially-symmetric model of the device structure and the geometries of the silicon wire (3 µm in diameter and 30 µm long), surrounding SiO_2 (600 nm thick), and Al (500 nm thick). The calculation parameters used by the FEM were Young's moduli of 188 GPa, 72 GPa, and 68 GPa for silicon, SiO_2 and Al, respectively, and Poisson ratios of 0.177, 0.14 and 0.34 for silicon, SiO_2 and Al, respectively. Figure S2 shows the stress distribution of the device where wire stress was set to −160 MPa. The estimated applied maximum compressive force was ~2 mN.

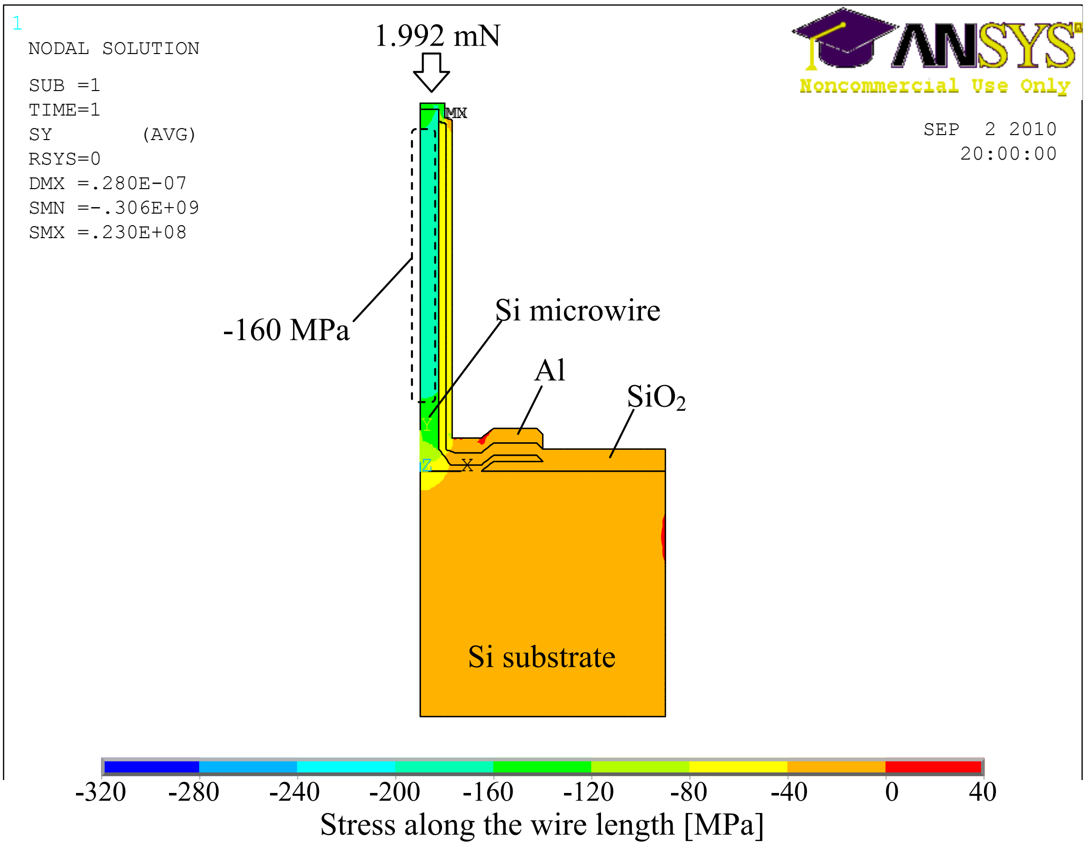

Figure S2. Stress distribution in the device when compressive force is applied at the wire-tip. With a maximum wire stress of −160 MPa, the amount of estimated applied maximum compressive force is ~2 mN.

Temperature dependent forward resistance of the p-silicon wire/p-n diode system

The effect of lattice scattering in a p-silicon microwire was observed as the wire current decreased and the device temperature increased. Lattice scattering dominated the carrier mobility in silicon, resulting in a change in the silicon conductivity. Figure S3 shows the measured forward resistances, which depended on the device temperatures (0 – 50 °C). The resistance values were collected in a forward bias range of 2 – 4 V. The measured resistance exhibited a temperature dependent behavior with $T^{2.7}$ (T temperature). Previous experimental studies have determined the values of $T^{2.5}$ [2], and $T^{2.20}$ for p-type silicon with an impurity concentration less than 10^{12} cm^{-3} [3]. Although the series resistance of the silicon wire depended on the device temperature, device temperature could compensate for the temperature effect on the wire resistance. The device temperature was measured with an embedded p-n diode (temperature sensitivity of the embedded p-n diode was –2.3 mV/°C at 0.1 µA, shown in figure 4(b)).

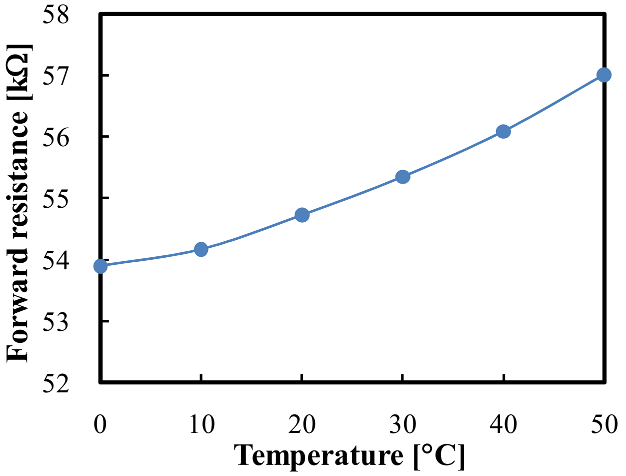

Figure S3. Temperature dependent forward resistance of p-silicon wire/p-n diode system measured between 0 – 50 °C. These resistances are acquired in a forward bias range of 2 – 4 V.

Force independent *I-V* characteristics of the embedded p-n diode

Decoupling the force and temperature signals is an important force/temperature sensing capability of the p-silicon wire/p-n diode sensor. The force and temperature signals can be individually measured using the force independent temperature sensitive embedded p-n diode in the same alignment. At forward biases between 0.1 and 0.25 V and a device stress of ~160 MPa, the p-silicon wire/p-n diode system experimentally shows force independent *I-V* characteristics because the measured *I-V* characteristics are mainly dominated by the characteristics of the p-n diode (figure S4.). In contrast, the significant force dependent *I-V* characteristics of the p-n diode require a device stress on the order of GPa [4,5], which is ten times larger than that the maximum stress used (~160 MPa).

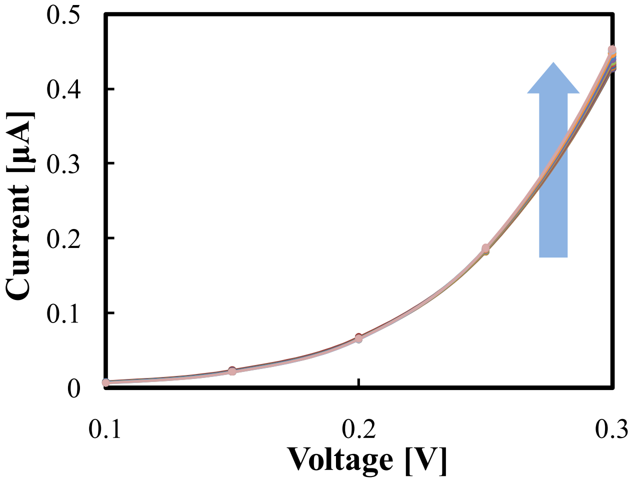

Figure S4. Force independent current *I* – voltage *V* characteristics of the p-silicon wire/p-n diode system at a forward bias of ~0.25 V. Data is from the measurement shown in figure 3(b) with a device stress of ~160 MPa.

Temperature measurements with hot W microneedle

W needle contact with the tip of the silicon wire was confirmed via a microscope image tilted 45 degrees. To prevent photocurrent effects on the measured *I-V* characteristics, the microscope light was turned on only while manipulating the W needle (figure 5(b)). When the hot W needle was in contact with the silicon wire-tip, a significant voltage shift of −7.9 mV occurred. Here the height of the manipulation, *z*, was reset to zero for subsequent quantitatively positioning of the manipulation height for *z*=2, 4, 6 µm.

References

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