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Humidity sensing characteristics of focused ion beam-induced suspended single tungsten nanowire

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ABSTRACT

We demonstrated humidity sensing characteristics based on a suspended single tungsten nanowire. The nanowire is synthesized on batch-processed microelectrodes by focused ion beam-chemical vapor deposition (FIB-CVD) using tungsten hexacarbonyl [$W(CO)_6$] as the precursor gas. Two different humidity sensing mechanisms, electrothermal sensing and chemical sensing, were demonstrated using as-deposited and annealed nanowires. When the relative humidity level was increased from 30% to 80%, the DC resistance of the as-deposited nanowire immediately showed 5.68% decrease by electrothermal sensing mechanism. Since the as-deposited nanowire is amorphous structure, no chemical sensing response was observed for the as-deposited nanowire case. On the contrary, the tungsten nanowire annealed at 700 °C showed a 13.2% increase in its DC resistance by the chemical sensing mechanism when the relative humidity level was increased from 40% to 80%, revealing enhanced sensor responsiveness and improved linearity than the electrothermal sensing using as-deposited nanowire.

1. Introduction

Humidity sensors have been studied not only for environmental monitoring [1], but also for medical [2–5] and industrial [6] applications. Recently, humidity sensors using nanostructured materials as a sensing material [7] or microelectromechanical systems (MEMS) technology [8,9] have been investigated in an effort to improve sensitivity. Majority of these micro or nano scale humidity sensors can be categorized into two groups; one depending on the chemical adsorption of water molecules and reaction between the water molecules and the sensing materials [8–17], and the other depending on physical interaction such as the heat transfer between the sensing structure and water molecules [18–21]. Chemical reaction or physical interaction is monitored by resistive [8–14], capacitive [15], mass-spectrometric [16–18] or optical transduction techniques [22,23]. An electrothermal sensor, a type of physical interaction-based sensor, holds a few advantages over a chemical reaction-based sensor, such as fast response time and less restriction in the choice of sensing materials. However, its disadvantages are relatively low sensitivity than chemical reaction-based sensors and the necessity to heat the sensing structures up to a high temperature that typically results in high power consumption. On the other hand, a humidity sensor based on chemical reaction of water molecules achieves high sensitivity, even though its response and recovery times are longer. One of the difficulties of the fabrication of adsorption-based humidity sensors is the limited choice about sensing material that can chemically adsorb water molecules and change its properties significantly, which decides overall sensing performance [24–32].

Here we demonstrate humidity sensing characteristics of a suspended single tungsten nanowire. In general, the suspended structure is advantageous for improving the sensitivity due to the increase of the surface area to be exposed to the sensing target, and for avoiding the electrical disturbance from the substrate. Both physical (electrothermal) sensing and chemical sensing have been demonstrated with a single nanowire, either as-deposited (un-annealed) or annealed. An as-deposited single tungsten nanowire has an amorphous structure [33], and it detects the relative humidity level by the electrothermal sensing mechanism based on the thermal interaction between it and water molecules. As the relative humidity level is increased, the heat transfer from the heated nanowire to the water molecules is enhanced, and thus the equilibrium temperature of the nanowire is lowered. Consequently, the electrical DC resistance of the as-deposited nanowire decreases because the nanowire has positive temperature coefficient of resistance (TCR). The following annealing process leads to the formation of structural crystallinity and grain boundaries in the nanowire [33]. This crystalline structure enables the surface of the nanowire to chemically adsorb water molecules, and the electrical

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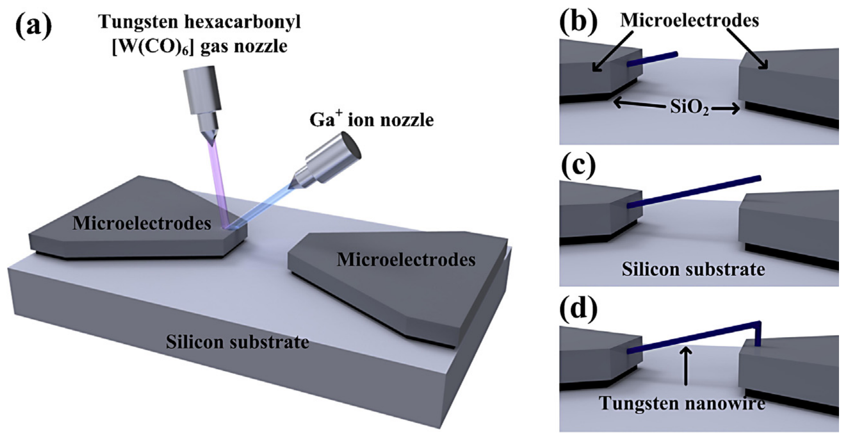

Fig. 1. Schematic illustration of microelectrodes (a) and FIB-CVD to form a single tungsten nanowire (b–d). The angle between the inclined part of the nanowire and the surface of silicon substrate is 30°. The inclined and longer part of the nanowire (b and c) is fabricated first and the vertical part of the nanowire is then formed (d), connecting two microelectrodes.

DC resistance of the annealed nanowire changes resultantly. Chemical sensing is achieved by the chemical reaction between the surface ions of the annealed nanowire and water molecules. The amount of free electrons inside the nanowire decreases as a result of adsorption of water molecules and therefore the DC resistance of the annealed nanowire increases.

2. Experimental

2.1. Synthesis of single nanowire on microelectrodes

A suspended single tungsten nanowire is formed on batch-fabricated silicon microelectrodes by focused ion beam (FIB)-chemical vapor deposition (CVD), as shown in Fig. 1. The nanowire was formed by the FIB-CVD system (SMI3050, SII Nano Technology, Inc.), which uses tungsten hexacarbonyl [$W(CO)_6$] as a precursor gas to fabricate conductive nanostructures. Ga^+ ion beam current of 11.7 pA is irradiated at 30 kV of acceleration voltage, and maintained at the targeted point. During the ion beam irradiation, the precursor gas is introduced into the FIB-CVD chamber via the gas nozzle, as the chamber is maintained at the constant pressure of 1×10^{-3} Pa. Then the solid tungsten nanowire containing W, C, O, and Ga atoms is formed by the decomposition of the tungsten hexacarbonyl precursor gas. FIB has been used to form various nanostructures [34,35] since FIB is capable of both etching and deposition up to, respectively, 10 nm minimum depths and thickness. The electrical and mechanical properties of the fabricated structures have also been subsequently explored [36–38]. For the fabrication of nanostructures, the FIB-CVD is advantageous for its good controllability of shape, dimensions and location of the nanostructure, as well as its easy and fast fabrication process in comparison with other high-temperature CVD methods.

The deposition rate, shape, length and diameter of the nanowire were controlled by adjusting the deposition conditions of the FIB-CVD process such as the scan area of the ion beam, field of view (F.O.V.) and ion dose. As shown in Fig. 1(b–d), the long and tilted part of the nanowire was formed, and then the short and vertical part of the nanowire was deposited afterwards. Two parts were then bonded together to form a single tungsten nanowire under a scan beam mode of FIB-CVD. One side of the inclined nanowire was adhered to the sidewall of one microelectrode and the other side of the vertical nanowire was attached to the top of the counter microelectrode. The inclined part of the nanowire was angled at 30° with respect to the substrate surface.

2.2. Fabricated device

A scanning ion microscope (SIM) image of the fabricated sensor and an enlarged view of the suspended nanowire bridge is shown in Fig. 2. A pair of batch-fabricated microelectrodes is connected

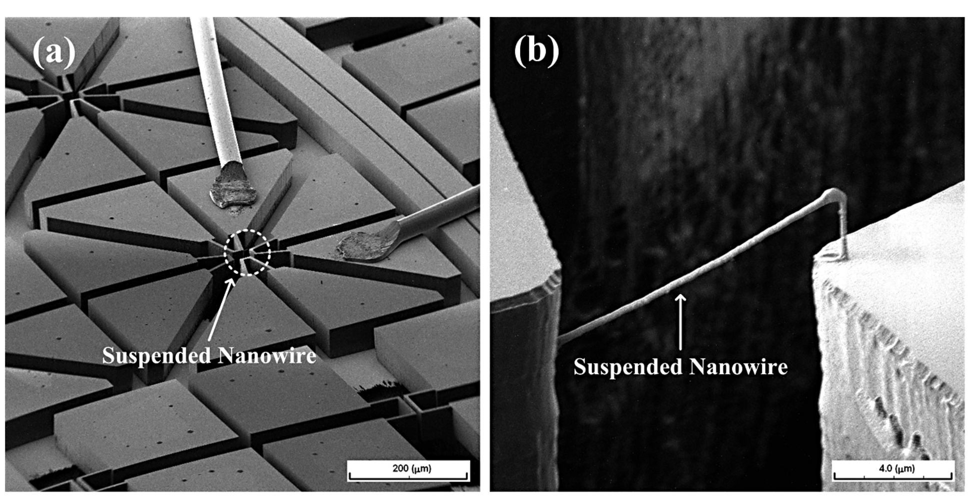

Fig. 2. SIM image of FIB-induced single tungsten nanowire for humidity sensor. (a) Microelectrodes with suspended tungsten nanowire. (b) Enlarged view of suspended single tungsten nanowire between two electrodes.