LOW-VOLTAGE AND LOW-POWER FIELD-IONIZATION GAS SENSOR BASED ON MICRO-GAP BETWEEN SUSPENDED SILVER NANOWIRES ELECTRODES FOR TOLUENE DETECTION

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ABSTRACT

We have demonstrated field-ionization gas sensor using suspended silver nanowires as electrodes. The tight gap of 1.5 μm between two facing sets of suspended in-plane nanowires on top of silicon microelectrodes, as well as the sharp protrusion of nanowires, allows the generation of high and non-uniform electric field. This produces field emission of electrons that result in ionization of gas molecules at a very low voltage applied. The fabricated sensor could detect toluene at 1.5 V of operational voltage, which is 10 times lower than the existing ionization gas sensors. Resultantly, extremely low power consumption of 75 nW for toluene sensing is also achieved, which implies the proposed field-ionization gas sensor could be a strong candidate for mobile device application.

INTRODUCTION

Recently, with advances in micro- and nanotechnology, high-performance gas sensors have been extensively studied for use in various applications such as mobile devices and distributed environmental monitoring systems for internet of things [1-3]. Low-power consumption is one of the essential requirements for such applications, since the power sources for mobile- and/or miniaturized devices are limited. Most common gas sensors which utilize chemisorption of gas molecules onto the surface of metal oxide semiconductor (MOS) at high temperature (250–500°C) [4] need an additional heater for activating it [5-8]. On the other hands, gas ionization sensors basically measure the amount of electrical charges of ionized gas molecules at room temperature and thus are suitable for gas sensor application with low-power consumption. In addition, compared to MOS-based gas sensors, the gas ionization sensors show better sensing selectivity for different gas species because they operate based on distinguishing the ionization characteristics according to the difference in ionization energy and electrical dipole moment of each gas species. However, conventional gas ionization sensors based on Townsend discharge were not suitable for portable devices due to their extremely high applied voltages [9]. The first reported miniaturized gas ionization sensor consists of vertically aligned carbon nanotubes [10]. Here the breakdown voltage was significantly reduced as compared with conventional electrodes, although the value was still in the range of hundreds of volts. In some other researches, experimental results showed that the operation voltage could be further reduced by adopting metallic nanowires [11, 12], decreasing the gap size [11-17] and measuring the pre-breakdown current. [15] Moreover, the pre-breakdown current measurement approach improved the stability issues of gas ionization sensor that arise from low current. However, the operation voltage is still in the order of tens of volts.

In this paper, a field-ionization gas sensor that utilizes silver nanowire as electrodes is presented. To form the tight gap spacing between two facing set of suspended nanowires, we used focused ion beam (FIB) process which has been widely used to fabricate micro- and nanopatterns for its high resolution, controllability, and reproducibility. The fabricated sensor could detect various concentrations of toluene ranging from 1000 down to 200 ppm at 1.5 V of applied voltage. The maximum current remains below 50 nA and the corresponding power consumption is as low as 75 nW.

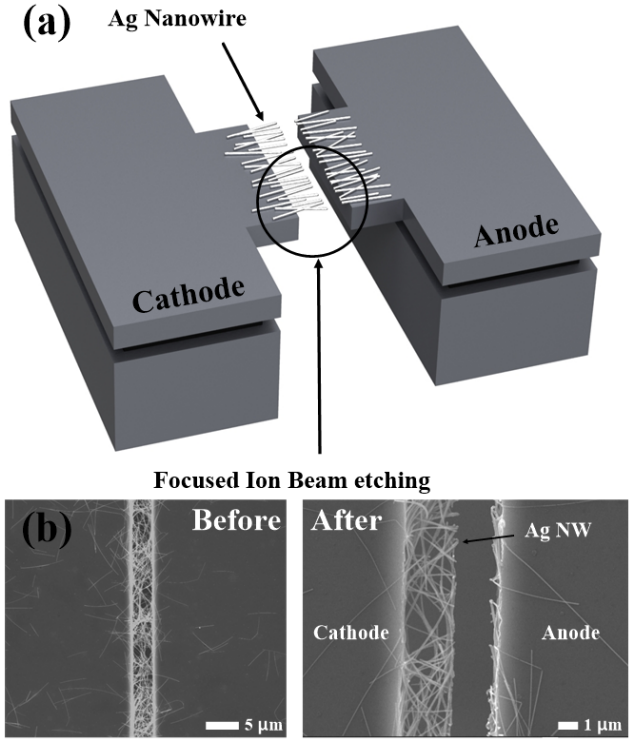

Figure 1: (a) A schematic of the proposed field-ionization gas sensor. (b) SEM images of Ag nanowires before and after cut to form tight spacing using focused ion beam process(FIB).

DESIGN AND WORKING PRINCIPLES

Figure 1(a) depicts a schematic of the proposed field-ionization gas sensor. In order to reduce the operating voltage, we designed nanowire electrodes with micro-gap such that the nanowires are disposed in the same plane instead of typical design with vertical nanowires aligned out of the plane [10-17]. The field-emission scanning electron microscope images of silver nanowires on the

silicon structure before (left) and after (right) cut to form tight spacing is shown in Figure 1(b). The protrusive silver nanowires and the opposite silicon covered with residual silver nanowires serve as the cathode and anode, respectively.

The mechanism for toluene detection is described in figure 2. The electric field around the tip of silver nanowires is relatively higher than that at the flat surface of electrodes, thereby creating non-uniform electric field. According to Fowler-Nordheim tunneling theory, the electric field would deform the surface potential barrier and induce electron tunneling at low applied voltage [18]. Consequently, the electron impact ionization is triggered by field-emitted electrons via protrusive silver nanowires. When toluene molecules are introduced, the emitted electrons will collide with them, and the molecules are ionized depending upon the voltage applied. The electrons would be absorbed on the anode and the ions would move to the cathode under the electric field applied, leading to the changes in current between two electrodes.

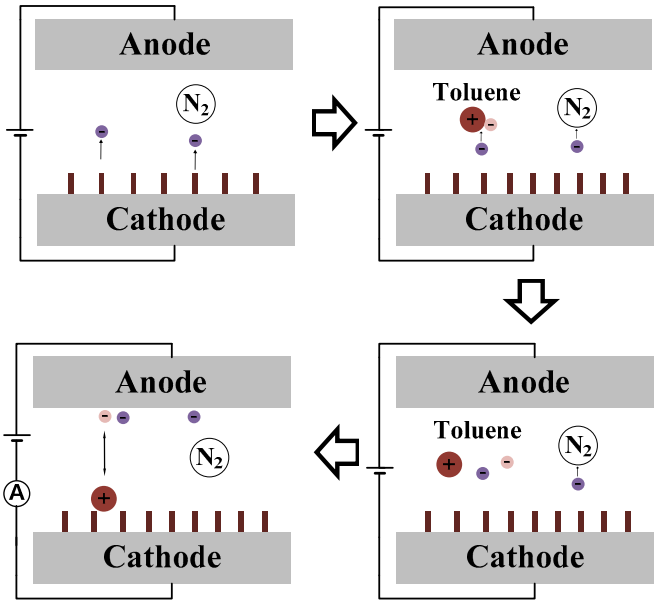

Figure 2: Selective sensing mechanism of toluene in air: (1) Electron emission via Ag nanowires. (2) collision with gas molecules. (3) Selective electron impact ionization of toluene. (4) Ionized electrons and toluene ions move to anode and cathode respectively.

FABRICATION AND EXPERIMENTS

The fabrication process is illustrated in Figure 3. An aluminum is deposited on both side of silicon-on-insulator (SOI) wafer (device layer thickness: 20 µm) by sputtering. In order to fabricate silicon microelectrodes with a gap spacing of 4 µm, an aluminum mask is patterned and then the device- and handle layers are etched using deep reactive ion etching. Next, the oxide layer is etched to release the electrodes and then aluminum is also removed. Subsequently, silver nanowires (Silver nanowires Prod. No. 739421, Sigma-Aldrich) are integrated across two MEMS electrodes by drop casting. Finally, well-controlled, fine cut is made across the suspended nanowires by FIB process, leaving a uniform gap of 1.5 µm.

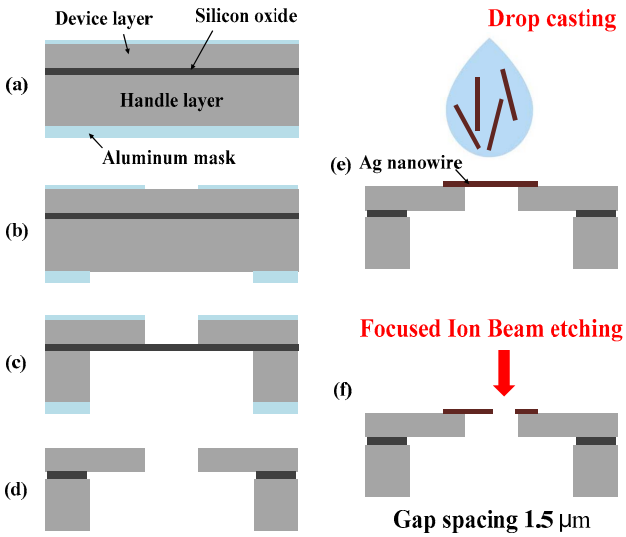

Figure 3: Fabrication process for the field-ionization gas sensor based on micro-gap between Ag nanowires electrodes. (a) Deposition of Al as an etch mask. (b) Patterning of Al etch mask. (c) Etching of device- and handle layers by DRIE. (d) Oxide etching to release the electrodes. (e) Ag nanowires were integrated across two MEMS electrodes by drop casting. (f) fine cut was made across the suspended Ag nanowires by FIB etching process, leaving a uniform gap of 1.5 µm.

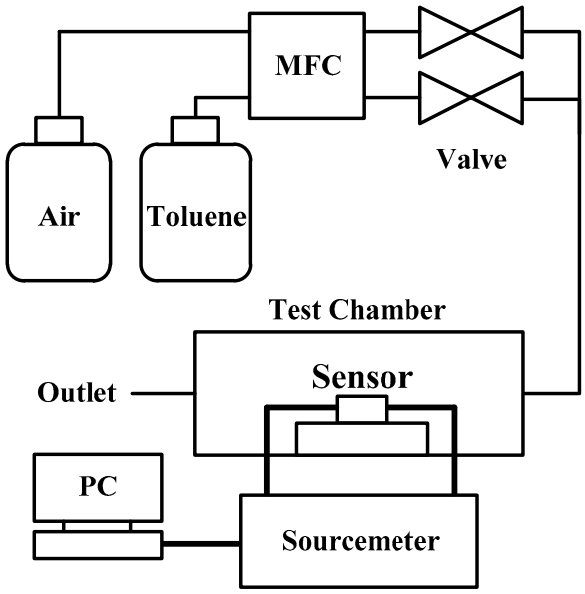

Figure 4: Schematic illustration of the experimental setup. Gases are flown into the chamber via mass flow controller. Pre-breakdown current is measured using a sourcemeter under the voltage applied.

The schematic of the experimental setup is shown in Figure 4. The fabricated sensor is first placed onto a chamber and the anode and cathode are connected to sourcemeter (SMU 2400, Keithley) which provides the bias voltage and also measure the current between them. The sensor is exposed to air for a few minutes for the stabilization of initial emission current, and then toluene diluted in air is introduced while the current is measured. The flow rates of both air and toluene are controlled by

mass flow controller unit.

RESULTS AND DISCUSSION

Figure 5 shows the changes in current of the sensor with respect to time at the exposure to toluene under an operation voltage of 1.5 V. When the toluene is introduced, the current of the sensor increases because the electrons and toluene ions generated by the electron impact ionization process move to the anode and cathode, respectively. As shown in Figure 5(a), the sensor exhibited repeatable and reliable response upon cyclic exposure to 1000 ppm toluene, indicating that nanowires are not damaged during the ionization process. The measured change in current was 0.7, 1.2, and 1.7 nA at the exposure to 200, 500, and 1000 ppm toluene, respectively (Figure 5(b)). The maximum current did not exceed 50 nA at an operation voltage (1.5 V), showing the extremely low power consumption of 75 nW.

To verify the mechanism of ionization of toluene, the *I-V* characteristics were measured in air (the inset of Figure 6). Flower-Nordheim plot (ln (I V^{-2}) against V^{-1}) of the sensor is reconstituted in Figure 6, showing the negative slope. This indicates that the field emission electrons are the dominant source for ionization [18, 19]. The turn-on voltage is estimated to be around 1.42 V, which corresponds to the operation voltage (1.5 V).

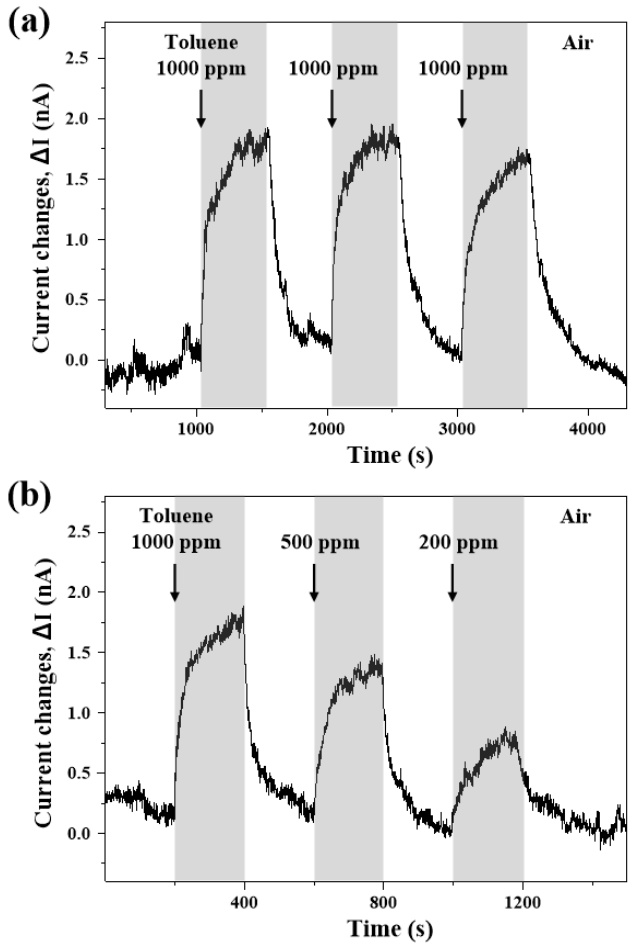

Figure 5: Dynamic response of the air-toluene mixture at 1.5 V operation voltage. (a) Air and toluene 1000 ppm, (b) Air and toluene 200, 500, 1000 ppm in a constant flow rate.

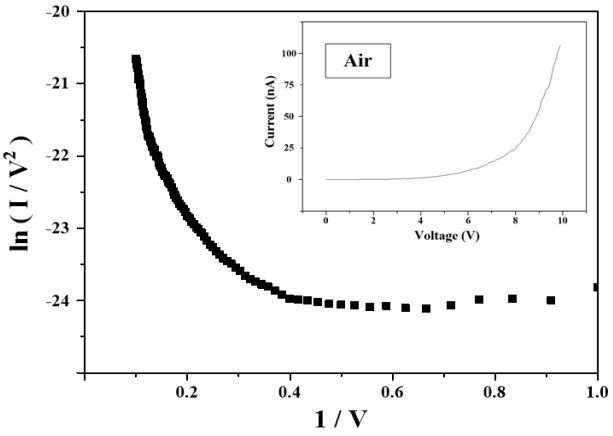

Figure 6: Fowler-Nordheim plot of the tested sensor. The turn-on voltage is estimated to be around 1.42 V. (inset: Corresponding I-V characteristic in air)

CONCLUSIONS

In summary, we developed a field-ionization gas sensor using two facing sets of suspended silver nanowires with micro-gap as electrodes. The fabricated sensor exhibited reliable responses without noticeable degradation at the periodic exposure to various concentrations of toluene. We could also achieve the comparable result at much lower applied voltage (1.5 V) than that of the existing ionization gas sensors (20~130 V). Notably, extremely low power consumption (75 nW) for toluene sensing is highly advantageous for applications such as portable devices and distributed environmental monitoring systems.

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