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Thermal Management of SnO_2 Nanowire Sensor utilizing "Microsecond Thermal Relaxation Time" and "Reduced Thermal Conductivity"

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Abstract

Here we report the thermal management of oxide nanowire sensor in both spatial and time domains by utilizing unique thermal properties of nanowires, which are (1) the reduced thermal conductivity and (2) the short thermal re-laxation time down to several microseconds. Our method utilizes a pulsed self-Joule-heating of suspended SnO_2 nanowire device, which enables not only the gigantic reduction of energy consumption down to ~ 10^2 pJ/s, but also enhancing the sensitivity for electrical sensing of NO_2 (100 ppb). Thus, this proposed thermal management concept of nanowires in both spatial and time domains offers a strategy for exploring novel functionalities of nanowire-based devices.

1. Introduction

Electrical sensing of volatile molecule species in envi-ronments and/or from our body by using mobile elec-tronics is an important issue for future electronics. This is because these sensor electronics will give an im-pact on our daily life and health via collecting and ana-lysing numerous big data. However, conventional gas sensors including semiconductor oxide sensors have been difficult to be integrated into CMOS electronics and wearable electronics due to the relatively high ener-gy consumption (~ J/s) to ensure a rapid and reversible sensing operation via programming the temperature of sensor between ~ 470 and 670 K. For example, most of conventional metal oxide gas sensors are typically oper-ated at the temperature range ~ 510 K by using an exter-nal heater with 835 mJ/s. The major reason why the conventional semiconductor gas sensors require rela-tively high energy consumption is that the external heater must heat up large volume (typically ~10^7 μm^3) of sensors via the solid heat conductions by competing with the heat dissipation into surroundings. Thus, the thermal management is an important issue for design-ing sensor electronics.

Various concepts have been proposed to manage the thermal properties of sensors. Among them, micro electro mechanical systems (MEMS) sensors with mi-cro-hotplate integrated on Si_3N_4 membrane have recent-ly emerged by utilizing advanced lithographic technology. The state-of-the-art membrane MEMS sensors have proved the feasibility to reduce the energy con-sumption down to ~ 20 mJ/s at 520 K via controlling the spatial temperature distribution on the membrane. The fundamental design concepts include (1) to reduce the heat dissipation, (2) to decrease the sensor volume, and (3) to decrease the distance between the external heater and the sensing part. A suspended nanowire sen-sor with self-Joule-heating is an ideal sensing platform, which satisfies all above requirements. This is because (1) the volume of nanowire is extremely small (~ 10^{-3} μm^3), (2) the suspended nanowire structure substantial-ly suppresses the heat dissipation into surroundings and (3) the self-Joule-heating method ultimately decreases the distance between the heater and the sensor. Here we propose the thermal management of oxide nanowire sensors in both spatial and time domains, which enables not only the reduction of energy con-sumption of volatile molecule sensors down to ~ 10^2 pJ/s but also the sensitivity higher than conventional con-tinuous heating method. Our method focuses on the short thermal relaxation time (~ μs) of suspended SnO_2 nanowire device, which is defined as a time required for heating up/ or cooling down to a desired temperature.

2. Results and Discussion

We examine the feasibility of our thermally managed nanowire devices for volatile molecule sensors. The device configuration (L = 1850 nm, D = 57 nm) is designed based on numerical study. NO_2 gas (100 ppb) was employed for the present sensing experiments. Figure1 shows the comparison between different heating methods, including (a) external heating, (b) self-Joule-heating and (c) pulsed self-Joule-heating, on the resistance change of suspended nanowire devices when introducing NO_2 gas (100 ppb). For all heating systems, introducing NO_2 gas increased the resistance of SnO_2 nanowire, as reported elsewhere. In external heating system, increasing the temperature from 300 K to 520 K significantly enhanced the sensitivity via promoting the chemisorption on the oxide surface. Similar trend on the sensitivity was also observed when increasing the current value for self-Joule-heating system. For pulsed self-Joule-heating system, there was the pulse width dependence on the sensitivity. Increasing the pulse width enhanced the sensitivity. However, the sensitivity change was not significant when considering the fact that the pulse width decreased down to less than 1/100. For example, in the case of the pulse width (1 ms), the sensitivity was almost 60 % of the continuous heating data, although the nanowire was heated up during just 0.03 % of total time. Thus, the present results high-light that the suspended nanowire sensor does not re-quire the continuous heating condition for the electrical sensing. Table 1 shows the comparison between the three heating methods on the consumed energy value to reach the sensitivity of 200 %. As clearly seen, the pre-sent pulsed self-Joule-heating method in suspended nanowire device can lower the energy consumption down to 0.6 nJ/s, which is much lower than the other two methods. The substantial reduction of energy consumption can be ascribed

to the thermal management of suspended nanowire in both spatial and time domains based on the unique thermal properties of nanowires, such as the low thermal conductivity and the short thermal relaxation time. Suspended nanowire can be heated up to a higher temperature within a short electrical pulse to activate the charge exchange between absorbed molecules and nanowire surface even without continuous heating. Thus, the thermal management in both spatial and time domains significantly enhances the sensing properties of nanowire sensor.

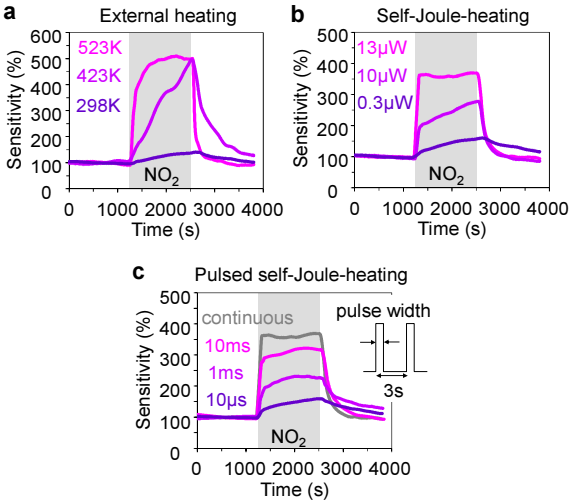

Figure 1. Sensing data of suspended nanowire device when introducing NO_2 (100 ppb). (a) Sensing data of external heating mode using an external heater, (b) Sensing data of continuous self-Joule-heating mode, and (c) Sensing data of pulsed self-Joule-heating mode.

	External heating	Self-Joule-heating	Pulsed self-Joule-heating
Energy consumption	0.6 J/s	1.6 μJ/s	0.6 nJ/s

Table 1. Comparison between three methods (External heating, Self-Joule-heating, and Pulsed self-Joule-heating) on the energy consumption to reach the sensitivity of 200 % for NO_2.

Next, we question why the thermally managed nanowire sensor using a pulse heating exhibited relatively good sensitivity in spite of the fact that the cumulative heating time for pulse heating is less than 1 % of continuous heating method. To answer this, we have per-formed transient measurements when applying a pulse heating, as shown in Figure 2. As can be seen, the resistance increased when the nanowire was heated up during the pulse. The modulated resistance change was maintained until next pulse heating. This indicates that the chemisorbed molecules onto the nanowire surface might be frozen between two pulses at lower temperature, as illustrated in Figure 2. This can be understood by considering the fact that an energy barrier exists for desorption from the chemisorbed state. These "frozen" chemisorbed molecules on the nanowire sur-face are mainly responsible for relatively high sensitivity of pulse heating method. However, even for constant cumulative heating time, there is a difference between the pulse heating method and the continuous heating method on the sensitivity. The pulse heating method exhibits the sensitivity higher than that of continuous heating method. Although it is difficult to obtain the direct experimental evidences, it is considered that the physisorption of molecules was promoted at lower temperatures during cooling time, which increases the molecule concentration near the nanowire surface for chemisorption of molecules during pulse heating. The other interesting feature of the thermal management in both spatial and time domains is the enhancement of sensitivity via reading the electrical resistance at lower temperature during pulses. As shown in Figure 2, the sensitivity was significantly enhanced when decreasing the reading voltage between pulse heating. For example, the sensitivity increased 3 times higher than the continuous heating method. This sensitivity enhancement can be interpreted in terms of different temperature coefficient of resistance (TCR), as illustrated in Figure 2. In principle, the temperature dependence of semiconductors tends to be stronger as carrier concentration decreases. When oxidizing for n-type SnO_2 nanowires by NO_2, the carrier concentration of SnO_2 nanowires de-creases. Thus, the sensitivity, defined as the resistance difference between pristine SnO_2 nanowire and SnO_2 nanowire oxidized by NO_2, can be enhanced by reading the resistance values at the lower temperature, as illustrated. To the best of our knowledge, such sensitivity enhancement concept has not been reported, probably due to relative long thermal relaxation time of external heating for other existing sensors.

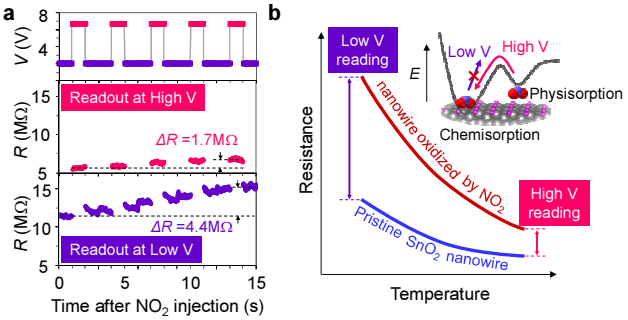

Figure 2. Enhanced sensitivity of pulse measurement and the underlying mechanism. (a) Transient response of suspended SnO_2 nanowire device for sensing NO_2 (100ppb). (b) Mechanism to explain the enhancement of sensitivity of pulse measurement.

3. Conclusions

In summary, we demonstrated the impact of thermal management of oxide nanowire sensors on the sensing characteristics. The thermal management of nanowires was performed in both spatial and time domains by utilizing unique thermal properties of nanowires, which are (1) the reduced thermal conductivity and (2) the short thermal relaxation time down to several micro-seconds. This method enables not only the reduction of energy consumption down to ~ 10^2 pJ/s, but also the enhancement of sensitivity for electrical sensing of NO_2 (100ppb).

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