Sodium Chloride Concentration Measurement by Using Doping/Un-doping Poly-silicon Nanowire Device

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Abstract: This work fabricates doping/un-doping poly-Si nanowire sensor with various lengths by using top-down technique for measuring salt concentration. Experimental results indicate that the resolution is proportional to the nanowire length and dopant concentration. But the sensitivity is inversely proportional to the length nanowire length. Moreover, the proposed sensor demonstrates 10 applications with similar current-time response and shows good repeatability.

Keywords: Sodium chloride concentration, nanowire device, n-type dopant, reusable.

1. Introduction

Numerous risk factors for developing cardiovascular disease (CVD) include age, family history of hypertension and genetic, high blood cholesterol and blood pressure, and bad healthy behaviours. American Heart Association (AHA) developed methodology to project future costs of care for CVD and their study pointed out the costs will be increased about 60% by 2030. They also indicated that 44% of the US population would be attacked by CVD around 2030 [1], [2]. The leading risk factor for death in US is suboptimal diet quality, which is related to excess intakes of sodium. AHA reported an estimated 1.65 million annual CVD deaths were attributable to sodium intake > 2 g/day. Lowering daily dietary sodium intake to 100 mmol may reduce high blood pressure in over 10 million individuals and save nearly $US 20 billion in health care-related costs annually [1], [2].

Many methods [3]-[5] have been developed and pointed out the possibility to measure the sodium chloride concentration in blood by using a nanowire structure sensor. This work fabricates doping/un-doping poly-Si nanowire sensor with top-down method for measuring salt concentration. Nanowire width is trimmed down to 130 nm in size with two different nanowire lengths (3.5 μm and 5.3 μm) by using a re-oxidation procedure. The p-type (boron) dopant was selected and the concentration was controlled at 5×10^{17} cm^{-3}. According to experimental results, the resolution is proportional to length and dopant concentration of the nanowire. Moreover, the smallest threshold voltage, the best resolution, and the best sensitivity were 1.3 V, 0.06 μM, and 0.51 μA/M, respectively. The proposed sensor shows more sensitivity than resistance method [5] for determining the sodium ions concentration and 10^{-6} M concentration variation can be observed by p-type nanowire sensors with various lengths. Furthermore, the proposed sensor demonstrated 10 applications while retaining an acceptable performance and exhibited high repeatability. Based on these findings we successful demonstrated the p-type poly-Si nanowire sensor is applicable to bio-chemical detection with appropriate surface modification of the nanowire.

2. Fabrication Procedure of the Proposed Method

The proposed nanowire sensor was fabricated by a top-down method [3] with I-line lithography for the nanopatterning of silicon nanowire feature. A 35 nm thick oxide layer was grown at 900 °C with thermal oxidation and, then a 30 nm thick Si_3N_4 was deposited at 780 °C with low pressure chemical vapor deposition method (LPCVD). Next, an approximately 2 nm thick layer was grown by thermal oxidation at 900 °C on the Si substrate as the bottom dielectric layer. A 60 nm thick poly-Si layer was deposited for the channel with LPCVD at 550 °C. There after, I-line lithography was performed along with the photoresistor trimming process, followed by Si etching. The source/drain pad regions were on the bottom dielectric layer with n-type dopant (concentration of 5×10^{15} cm^{-2}) by ion-implantation method. To trim the dimension of poly-Si nanowire, a 30 nm thick thermal oxidation was carried out at 900 °C followed by oxide removal. The lengths of the nanowire were controlled at 3.5 and 5.3 μm. The n-type dopant was selected and the implanted concentration was controlled at 5×10^{17} cm^{-2}. Fig. 1 shows the measurement setup which is similar to Bergveld's method [6].

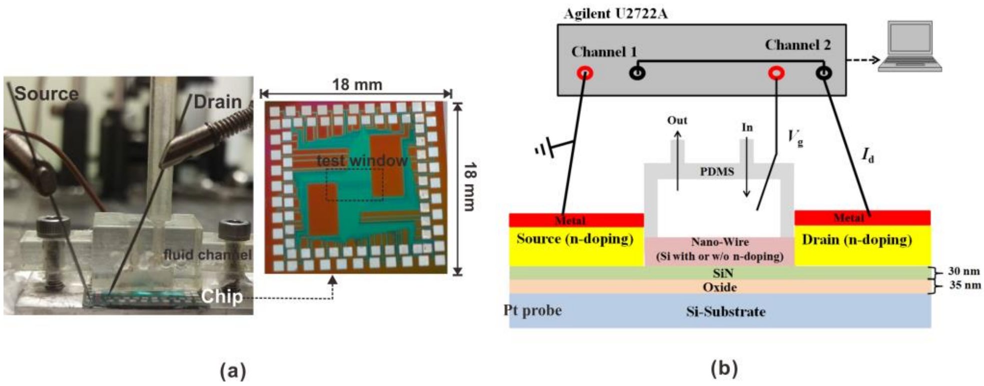

Fig. 1. Measurement setup of the proposed method. (a) Photograph of the measurement configuration and device; (b) diagram of the setup and structure of device.

3. Experiment Results and Discussion

Fig. 2(a) shows that the I_d-V_g curves of doping/un-doping nanowire devices with the lengths of 3.5 μm and 5.3 μm. The curves A (3.5 μm) and B (5.3 μm) indicated that the nanowire devices with n-dopant and the curves C (3.5 μm) and D (5.3 μm) indicated nanowire devices were un-doping, respectively. According to those results, the variation of I_d increases with an increasing V_g. Based on Garnet *et al.*'s work [7], threshold voltage V_{th}, which can be determined and threshold voltages of those nanowire sensors are approximated of 1.3 V (curve A), 1.25 V (curve B), 1.43 V (curve C), and 1.67 V (curve D), respectively. The. Fig. 2(b) shows that the I_d-V_d curves of the doping/un-doping nanowire sensors and the gate voltage controlled at 2 V. The results show the V_d should be within 0.75 V to maintain the device operated in linear region.

Fig. 3(a) indicated that the drain current increases with an increasing sodium chloride concentration. It obvious that the current-time response curves of the doping nanowire sensors are notable increasing as the concentration of salt solution increasing. By comparison, especially in lower sodium chloride concentration measurement results, un-doping nanowire devices exhibited less sensitivity of current-time response. Repeatability of the proposed sensor was verified by taking ten successive measurements of the sodium chloride concentration of 10^{-1} M, in which sensors A and C were selected for comparison, as shown in Fig.

3(b). Obviously, Fig. 3(b) shows that the current-time response exhibited highly similarity within 10 applications for each sensor.

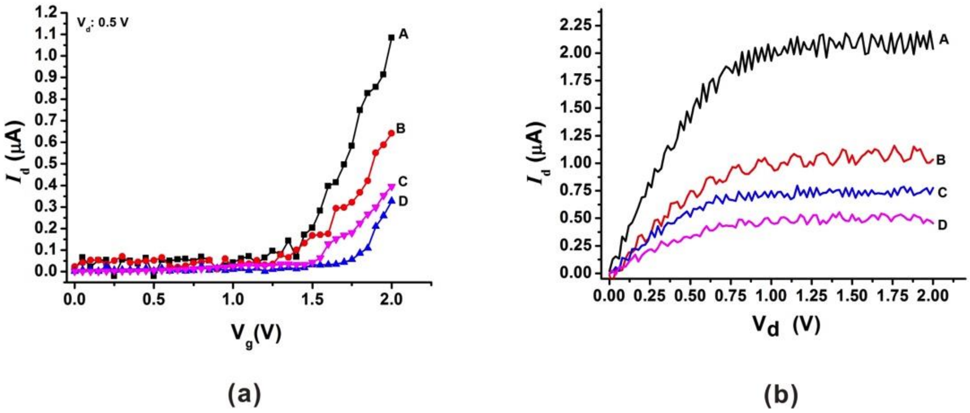

Fig. 2. Electronics properties of the proposed sensor. (a) I_d-V_g measurement; (b) I_d-V_d measurement.

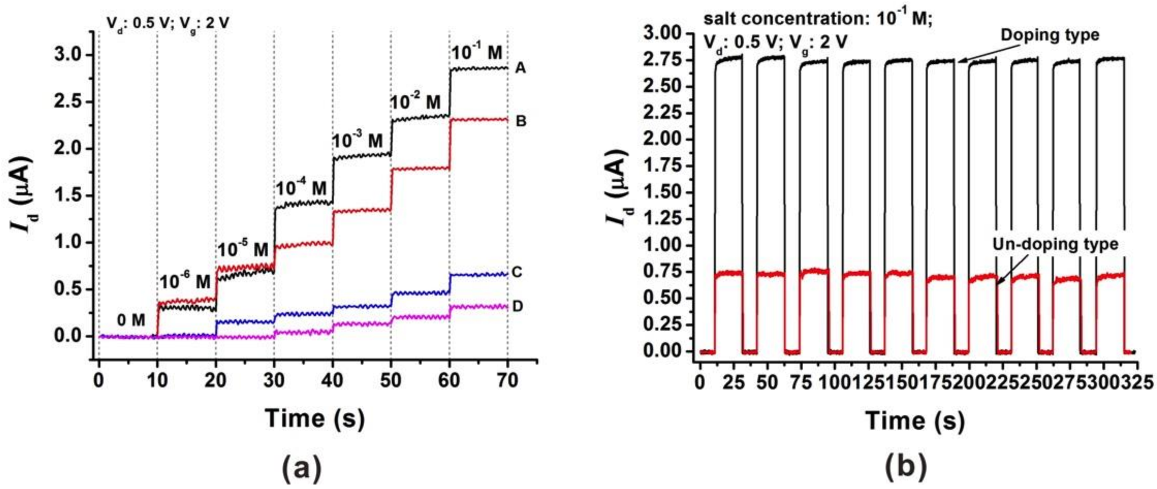

Fig. 3. Current-time response curves of the proposed sensor. (a) drain current variation with various sodium chloride concentrations; (b) repeatability demonstration.

Fig. 4 indicates that the calibration curves measured by the doping/un-doping nanowire sensor. Slope of the calibration curve indicates the sensitivity of the proposed sensor and the shorter length of nanowire with n-type dopant device exhibited higher sensitivity. Resolution of these sensors depended on the sensitivity of current meter and the slope of the calibration curve which can be obtained from the Nernst equation [8] and the resolution and represented as

$$\Delta C = 10^{\left(\frac{\Delta I - K}{S}\right)} \tag{1}$$

Where K and S are the intersection and slope of the calibration curve; and ΔI and ΔC represent the resolution of the measured current and concentration. Furthermore, resolution of the measured current (depend on the current meter) will affect the resolution of the concentration.

The theoretical resolution can be indicated by consideration of the resolution of current meter, in which the resolution of measured current is 0.1 nA. Therefore, the resolution of these sensors can be calculated with Nernst equation and summarized in Table 1. Obviously, the doping nanowire sensor exhibited higher resolution than un-doping nanowire sensor and the resolution increased with decreasing nanowire length. The best resolution of the proposed sensor is higher than 0.06 μM, which can be achieved by using the n-type dopant sensor with a nanowire length of 3.5 μm.

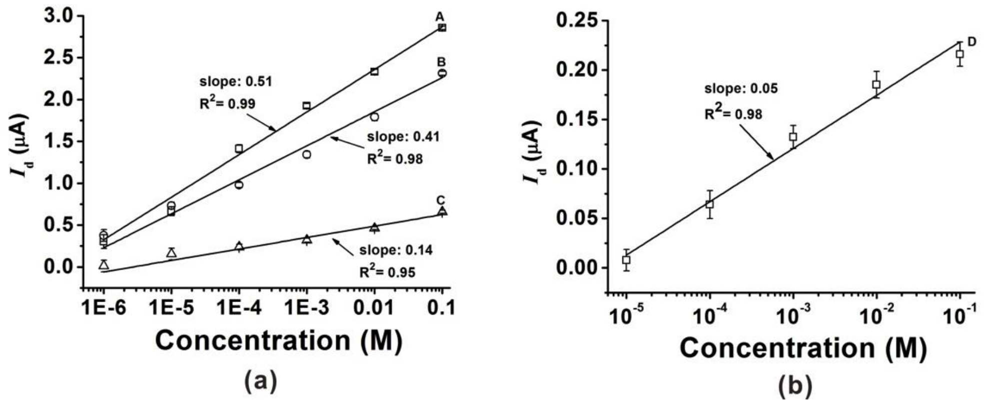

Fig. 4. Calibration curves of the proposed sensor. (a) sensors A~C; (b) sensor D.

Table 1. The Resolution of the Doping/Un-doping Poly-Si Nanowire Sensors

Item	Length (μm)	Doping concentration (cm^{-2})	Sensitivity (μA/M)	Resolution (μM)
A	3.5	5×10^{17}	0.51	0.06
B	5.3	5×10^{17}	0.41	0.123
C	3.5	0	0.14	1.11
D	5.3	0	0.05	3.11

4. Conclusion

This work demonstrates the feasibility of a doping/un-doping poly-Si nanowire sensor in measuring the concentration of sodium chloride. Experimental results indicate that the threshold voltage of the n-type doping sensor exhibited lower value than those of un-doping nanowire sensor. The smallest threshold voltage is around 1.3 V. Additionally, resolution of the proposed nanowire sensor is strongly related to the length and dopant property of the nanowire, indicating that the resolution increases with decreasing nanowire length and increasing dopant concentration. Moreover, the best resolution is approximately 0.06 μM and the smallest concentration variation can be determined is 10^{-6} M. This work further demonstrates the repeatability of the proposed sensor, indicating that the applications within 10 times can be sustained with an acceptable current-time response for doping/un-doping nanowire sensors.

Acknowledgement

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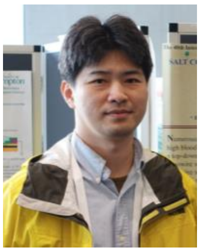

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