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Surface Modified Poly-crystalline Silicon Nanowires Field Effect Transistor for Ammonia Gas Sensor

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Abstract

The surface modified by fluoro-functional groups containing organic compound on poly-crystalline silicon nano-wires field effect transistor (poly-Si NWs FET) possesses higher sensitivity of ammonia. The sensitivity of 0.5 ppm ammonia of modified NWs is 1.06, better than 1.02 of bare NWs at 40% Rh. The sensitivity of modified NWs is able to reach 1.30 of 0.5 ppm ammonia at 25% Rh., which is 23% higher than the sensitivity at 40% Rh. Our results also suggested that the water molecules may compete with ammonia in the sensing mechanism.

1. Introduction

The strong ammonia odor in breath can be directly linked to the hepatic injury and some kidney diseases [1]. Breath ammonia concentration is found at 0.278±0.011 ppm in the healthy people, but may rise to 0.558±0.067 ppm in the liver cirrhosis patients or 0.977±0.159 ppm in acute cases [2]. Field effect transistor based gas sensors has been reported to distinguish sub-ppm level gas molecules [3]. They have attractive properties, such as miniature size, label free, and low cost. Moreover, the nano-scale FET can provide the high sensitivity due to their large surface to volume ratio [4, 5]. The humidity in exhaled breath may critically disturb ammonia signal. Researcher used desiccating agent or freezer to reduce moisture before examination [5]. The ammonia sensing in poly-Si NWs FET also interfere with moisture. In this study, poly-Si NWs FET surface modification by fluorine-containing material was proved to enhance the sensitivity of ammonia in moister present condition.

2. Experiment

A n-type poly-Si NWs FET consists of ten poly-Si NW channels with the width of 80 nm and length of 2 μm, which is fabricated based on the literature [6]. Silicon substrate served as the bottom gate during device characterization. In order to enhancing the sensitivity to NH_3, we applied 1, 2, 3, 4, 5, 6, 7, 8 - Octafluoro - 9, 10,-bis [4-(trifluoromethyl) phenyl] anthracene (F8-TFMPA) with strong polar attraction of fluorine-containing functional groups to modify the surface of the poly-Si NWs FET. The chemical structure of F8-TFMPA, purchased from Sigma-Aldrich, is shown in Fig. 1 (b). The 0.005 wt. % of the F8-TFMPA in tetrahydrofuran (THF) solution was prepared for spin coating process. The residual solvent was removed by hotplate at 70°C for 5 min. The thickness of F8-TFMPA was controlled at 3~5 nm, confirmed by Atomic Force Microscope (AFM-D3100).

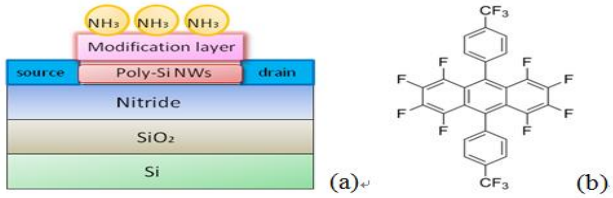
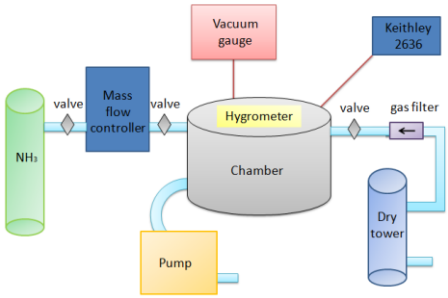


Fig. 1 (a) The schematic structure of the Poly-Si NWs FET. (b) The chemical structure of F8-TFMPA.



Scheme 1. The test chamber system

The ammonia test chamber system is schematically illustrated in Scheme 1. Current-voltage characteristics of devices were measured with a Keithley 2636 chip analyzer. The test device was placed in a chamber equipped with vacuum pumps. A high-purity N_2 (99.999%) piping with a manual valve to control the N_2 flow was connected to the chamber. NH_3 gas was injected into the chamber by the mass flow controller (MFC) (Brooks Instrument, Model 5850E). The moist was introduced by humidifier.

In this study, we observed the drain current when the poly-Si NWs exposed under various NH_3 concentrations and different relative humanities at 500 torr nitrogen. The electrical characteristic I_D-V_G curve variation were measured with constant bias voltage 0.5V, and the gate voltage -1~10V. The sensitivity is defined as in Eq.1:

$$\text{Sensitivity} \equiv \left.\frac{I_{D(NH3)}}{I_{D(Base)}}\right|_{V_G(max)} \quad (1)$$

where $I_{D(NH3)}$ is the saturation current of each device at specific concentration. $I_{D\,(Base)}$ is the saturation current of each

device at specific concentration. $V_{G\ (max)}$ is the saturation voltage.

3. Result and Discussion

The results of various ammonia sensing under different environment were shown in **Fig. 2 (a), (b), (c),** and **(d)**. The sensitivity results at various humidity's are summarized in **Table I**. The I_D of bare poly-Si NWs FET was chosen to be the model for comparing various conditions in **Fig. 2 (a)**. The I_D current increased slightly as rising NH_3 concentration. This may attribute to the ammonia gas molecule serving as donor molecule on the surface grain boundaries of poly-Si NWs. The carrier-like electron promotes the electrical property of n-type NWs. The NH_3 sensitivity, however, is too small to be detected effectively. On the other hand, the sensitivity of the surface modified with F8-TFMPA has significant improvement at same humidity level, as shown in **Fig. 2 (c)**. The fluoro-functional groups of modification layer possess strong polar attraction to the ammonia. Comparing the ammonia sensitivity ratio of bare and F8-TFMPA modified pSi-NWs at 0.5 ppm and 4 ppm, the F8-TFMPA modified pSi-NWs has slightly better sensitivity. When comparing the humidity effect on the F8-TFMPA modified pSi-NWs, the sensitivity is much higher at 25% Rh than 55% Rh. The higher relative humidity, the I_D current increases and ammonia sensitivity decreases. The result suggested that the relative humidity also affects the sensitivity of modified poly-Si NWs FET. In particular, there is no sensitivity for F8-TFMPA modified pSi-NWs at 55% Rh. Apparently, water molecules compete with ammonia when contacted with the fluoro-functional groups surface.

Table I The sensitivity of bare poly-Si NWs FET, F8-TFMPA modified poly-Si NWs FET in various humidity.

Current(μ A)/sensitivity	0.0 ppm	0.5 ppm	1.0 ppm	2.0 ppm	4.0 ppm
Bare NWs in 40% Rh.	6.64/ -	6.77/1.02	7.03/1.06	7.10/1.07	7.25/1.10
Modified NWs in 25% Rh.	2.68/ -	3.48/1.30	3.84/1.43	4.45/1.66	4.95/1.85
Modified NWs in 40% Rh.	3.98/ -	4.21/1.06	4.51/1.13	4.74/1.19	5.05/1.27
Modified NWs in 55% Rh.	11.76/ -	11.96/1.02	12.01/1.02	12.09/1.03	12.36/1.05

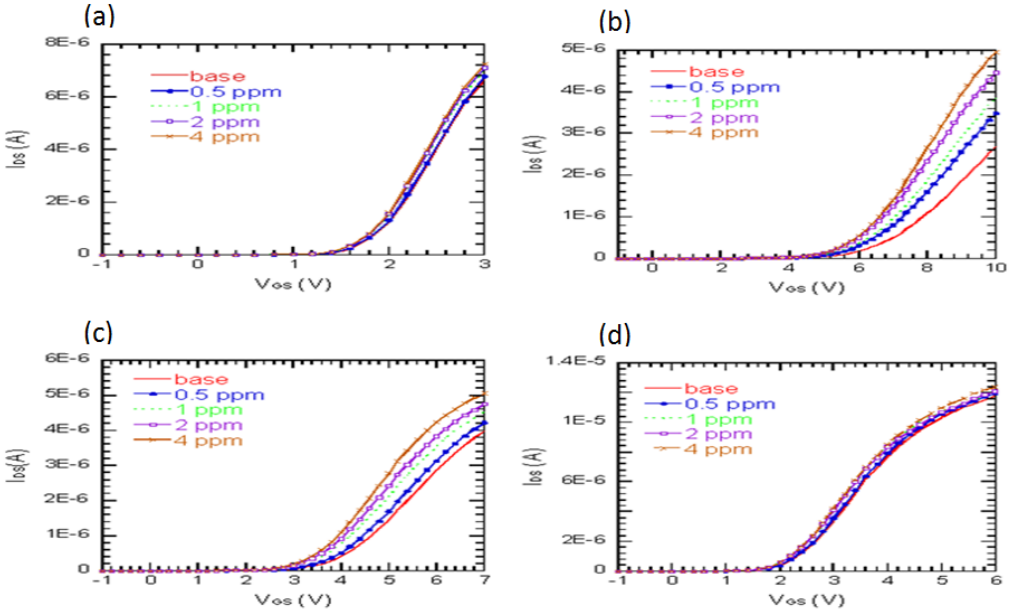


Fig. 2 The I_D-V_G characteristics of various ammonia concentrations gas sensing: **(a)** the bare Poly-Si NWs FET at 40% Rh.; the F8-TFMPA modified poly-Si NWs FET at **(b)** 25%**, (c)** 40%**,** and **(d)** 55% Rh.

4. Conclusion

In this study, we have improved the poly-Si NWs FET's sensitivity by surface modified F8-TFMPA. The detection level can be as low as 0.5 ppm under 40% relative humidity. We also observe that the sensitivity of modified poly-Si NWs FET will decreases as the relative humidity increases.

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