H-7-04 Extended Abstracts of the 2020 International Conference on Solid State Devices and Materials, VIRTUAL conference, 2020, pp559-560

Gate-Bias Assisted Humidity Sensor based on ReS_2 Field-Effect Transistors

Amir Zulkefli[1, 2], Bablu Mukherjee[1], Takuya Iwasaki[1, 3], Ryoma Hayakawa[1], Shu Nakaharai[1*] and Yutaka Wakayama[1, 2*]

[1] International Center for Materials Nanoarchitectonics (WPI-MANA), National Institute for Materials Science (NIMS)
[2] Department of Chemistry and Biochemistry, Faculty of Engineering, Kyushu University
[3] International Center for Young Scientists (ICYS), National Institute for Materials Science (NIMS)
1-1 Namiki, Tsukuba 305-0044, Japan
E-mail: WAKAYAMA.Yutaka@nims.go.jp, NAKAHARAI.Shu@nims.go.jp

Abstract

We report the performance of humidity sensors based on rhenium disulphide (ReS_2) field-effect transistors (FETs). The underlying mechanism includes electrons being transferred from water molecules and/or dissociated ions into the ReS_2 to induce variations in transistor behaviors. A negative gate biasing improved the sensing responsivity especially in the low humidity range. Meanwhile, the threshold voltage change was found to be a superior parameter with which to monitor humidity level in a wide range of 0-70% relative humidity (RH) at room temperature. Practical sensitivity of threshold voltage change of 0.45 V per 1%RH was achieved. These results outperform over reported research from literature, which can be utilized for future sensing device applications.

1. Introduction

Detecting humidity level is vital in a wide range of applications such as environmental and industrial monitoring. The increased demand of humidity sensing requires higher responsivity, sensitivity, and broader detection range [1]. Among the reported humidity sensor approach, resistive FET is becoming a promising approach because of relative simplicity in the sensor fabrication and measurements. Also, the current modulation from the gate electrode provides advantage in varied sensor performance.

Two-dimensional (2D) transition metal dichalcogenides (TMDCs) materials have attracted significant research interest in future electronic/optoelectronic device-based sensors. This is due to their unique electrical, optical, and physical properties. 2D van-der-Waals material, rhenium disulphide (ReS_2) has gained substantial interest due to its promising application of transistor, detectors, and sensors. Unlike other conventional TMDCs, ReS_2 1T crystal structure results in much weaker interlayer coupling property [2]. Inspired by this characteristic, many noteworthy research field has been investigated which extending from the material synthesis to transistors, photodetectors, and photo-induced gas sensors [3]. These promising results imply that ReS_2 is a favorable contender for future ultrathin nanoelectronics device applications.

Considerable work to improve the ReS_2 based gas sensor has been reported ranging from surface functionalization, heterostructure, intentional plasma induced defected material, and photo-assisted effect [4, 5]. However, the investigation of humidity sensing performance in terms of gate-bias-tunable effect, especially as regards to gas-solid interactions have not yet been explained. The details study in these matters are still lacking. In this regard, it would be interesting to investigate the ReS_2 FET-based humidity sensor under gate-bias assisted for further development of high-performance sensor.

Herein, we systematically investigate humidity sensing performance of ReS_2 FETs under different gate voltage operation. Consequently, high responsivity in low humidity range was achieved by utilizing negative gate voltage effect. Meanwhile, responsivity based on threshold voltage change was found to be a superior parameter for a wide humidity range with a practical sensitivity of threshold voltage change of 0.45 V per 1%RH. This study contributes to an in-depth understanding of the roles of gate biasing, leading to the development of a high-performance humidity sensor based on ReS_2 FET.

2. Experimental Parts

ReS_2 FET fabrication and humidity sensing measurement

Large-scale and crystalline ReS_2 flakes on a SiO_2/Si substrate were prepared by a gold-mediated exfoliation technique [6]. 8 nm (ca. 11 layers) thickness and high crystallinity of ReS_2 were confirmed by using atomic force microscopy (AFM) (Fig. 1a) and Raman spectroscopy (Fig. 1b) [7], respectively. Electron beam lithography and evaporator were used to fabricate the FET sensor with Cr (3nm) and Au (80nm) electrode (Fig. 1c). The home-made gas measurement setup was equipped with a mixing connector linked to mass flow controllers that made it possible to adjust the humidity level by changing the wet/dry air mixing ratio. The current-voltage (I-V) measurements were performed by the source-measurement unit (Keysight B2912A).

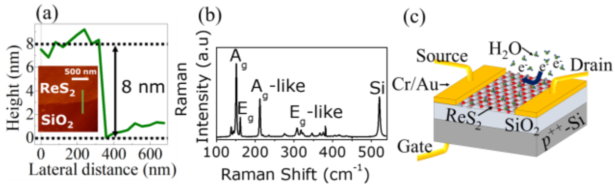

Fig. 1 (a) Height profile and its AFM image, and (b) Raman spectrum of the ReS_2 channel (ca. 11 layers). (c) Schematic illustration of a humidity sensor based on ReS_2 FET.

3. Results and Discussion

First, we investigated the humidity sensing behavior of a two-terminal ReS_2 device without gate voltage. Fig. 2a shows the output curves, which were measured in a 0% to 70% relative humidity (RH) range. These curves were observed to have linear characteristics even under humid conditions. This indicates no impact on the ohmic contact of the source-drain electrodes and the ReS_2 channel. This fact proved that the Schottky barrier [8] underwent no change in the RHs range employed in this work. The device responsivity (S_R) was calculated with the following equation,

$$S_R = \left[\frac{R_{dry} - R_{H2O}}{R_{dry}} \times 100\right]\% \qquad (1)$$

where R_{dry} and R_{H2O} are the channel resistance in dry air and humid vapor, respectively. S_R increased monotonically with increasing RH as shown in Fig. 2b (black line). Importantly, S_R changes greatly from 0 to 40% in the low RH range (0-20%). Meanwhile, it showed a relatively small changes from 56 to 60% in the high RH range (50-70%). The reason is probably related to the coverage of the water molecules on ReS_2 surface. This tendency was enhanced by applying a negative gate voltage (red line), which reduced the drain current (I_D). Thus, S_R was enhanced from 0 to 83% at 10%RH. However, high negative gate bias also had an impact on humidity sensing; S_R was saturated above 30%RH as seen in Fig. 2b. As a result, the ReS_2 channel surface was fully covered immediately even at a low RH, and further electron transfer was suppressed at a high RH.

On the other hand, a positive gate voltage (V_G = +40V) prevented the variation in S_R (blue line). When a positive gate voltage was applied, the electrons accumulated at the ReS_2-SiO_2 interface, which led to reduction of R_{dry}. Therefore, S_R was decreased. Meanwhile, the negative gate biasing depleted the electrons and increased the R_{dry}. Hence, S_R was enhanced, which contributed to the small amount detection of water molecules. These results demonstrate the tunability of humidity sensing by controlling the gate biasing. Specifically, a negative gate biasing is advantageous for detecting very low-level humidity. However, the non-linearity of the S_R-RH curves is disadvantageous for wide range sensing.

In contrast, we found that the threshold voltage showed a continuous variation against RH over a wide range operation. Figure 2c shows the transfer characteristics at different RH values. Initially, a typical n-type operation of ReS_2 FET was observed; electrons were majority carrier. Also, consecutive shifts toward a negative gate voltage were observed with increasing RH. The variations in threshold voltage (ΔV_{th}) are plotted as a function of RH as shown in Fig. 2d. Here, ΔV_{th} is the difference between the threshold voltage at 0%RH ($V_{th,dry}$) and those obtained at a range of humidity values ($V_{th,humid}$). The ΔV_{th} varied from 0 V to 32 V as RH was increased to 70%, in which a practical sensitivity of 0.45 V per 1%RH was achieved. These above results outperform the results from the previous report [9]. It should be noted that the ΔV_{th}-RH curve in Fig. 2d shows a similar tendency to the S_R-RH curves; the variation rate decreased with increasing RH. This could be considered to indicate that the ReS_2 active channel surface decreased with increasing water molecule/ions coverage, leading to a decrease in the adsorption rate of the water molecules/ions.

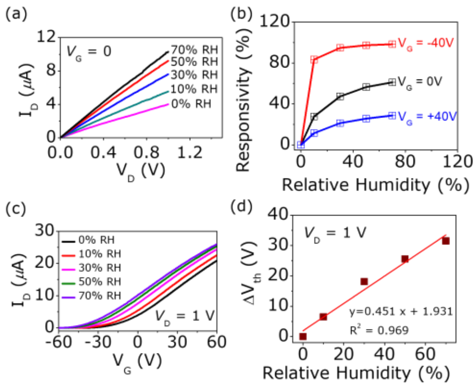

Fig. 2 (a) Output characteristics of ReS_2 FETs under different RH values without a gate voltage (V_G = 0). (b) S_R-RH curves of the ReS_2 FET with a wide gate voltage range of –40 V to +40 V (c) Transfer characteristics of the ReS_2 FET with different RH values. (d) Responsivity in terms of threshold voltage change ($\Delta V_{th} = V_{th,dry} - V_{th,humid}$) dependence on relative humidity.

3. Conclusions

In conclusion, we studied the humidity sensing properties of an ReS_2 FET. The tunable sensing performance was systematically discussed under different gate biasing. The negative gate voltage improved humidity responsivity especially in the low humidity range. Here, the coverage of water molecules/ions on ReS_2 surface play an important role. Meanwhile, variation of ΔV_{th} was found to be a superior performance parameter for wide humidity range monitoring. A practical sensitivity of 0.45 V per 1%RH was achieved. Our fabricated sensor outperformed over reported sensor. Thus, it reveals that a gate-bias-tunable humidity sensor based on an ReS_2 FET has the potential for allowing further sensor development towards versatile tunable humidity sensors.

Acknowledgements

This research was supported by the World Premier International Center (WPI) for Materials Nanoarchitectonics (MANA) of the National Institute for Materials Science (NIMS), Tsukuba, Japan. A part of this study was supported by JSPS KAKENHI Grant No./Project/Area No.17F17360, and the NIMS NF & MMS Platform sponsored by the Ministry of Education, Culture, Sports, Science, and Technology (MEXT), Japan.

References

[1] Y. T. Huang *et al.* Jpn. J. Appl. Phys. **58** (2019) SD.
[2] J. M Urban *et al.* 2D Materials **6** (2019) 1.
[3] M. Rahman *et al.* Adv. Func. Mater. **27** (2017) 10.
[4] B. Martin-Garcia *et al.* Small **15** (2019) 52.
[5] S. Yang *et al.* Adv. Mater. Interfaces **3** (2016) 6.
[6] S. B. Desai *et al.* Adv. Mater. **28** (2016) 21.
[7] B. Mukherjee *et al.* ACS Photonics **6** (2019) 9.
[8] D. J. Late *et al.* ACS Nano **6** (2012) 6.
[9] A. Yang *et al.* 2D Materials **3** (2016) 4.