Gas Sensors Based on Atomically-Thin Field-Effect Transistors

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論　文　内　容　の　要　旨

Detection of organic vapors is necessary in many different fields such as emission control, military and public safety, industrial and agricultural production, environmental monitoring, and medical diagnosis. The conventional chromatography-mass spectroscopy and electronic nose are widely used for those purposes. However, these sensing approaches have drawbacks: device complexity, large size, and selectivity challenges in a gas mixture condition. Therefore, the selective and sensitive gas detection of specific target gas molecules using a simple and portable device is highly required.

The field-effect transistors (FET) with two-dimensional (2D) transition metal dichalcogenides (TMDC) have been developed for the gas sensors because the 2D films as transistor channels, such as molybdenum disulfide (MoS_2) and tungsten disulfide (WS_2) have intrinsic advantage, i.e., their high surface-area-to-volume ratio. Additionally, the 2D-TMDC FET technology is a promising approach for gas sensors because of the simple device structure, well-developed device fabrication process and measurement, and capability to integrate to an electrical circuit. However, the selective detection of the organic vapors is challenging, especially for sensors using a 2D material-based single device. Consequently, exploring appropriate sensing materials and sensing concept to address the challenge is critical.

Light illumination on the 2D-TMDC FETs could significantly enhance the gas sensing properties because of the increased photo-induced carriers that interact with gas molecules. Nevertheless, minimal research has been done to develop the light-assisted tunability based on the 2D-TMDC FETs because of the limited material selection. Among TMDCs, rhenium disulfide (ReS_2) is ideal because ReS_2 has a direct bandgap that matches with the visible light range regardless of thickness, unlike other TMDCs. Therefore, ReS_2 can overcomes the trade-off between the charge carrier density of the optical absorption (thick layer better) and the surface-area-to-volume ratio (thin layer better). It can be used to realize a single device operation to selectively and sensitively detect gas and organic vapors based on the effective response of ReS_2 to the light illumination.

This dissertation provides a device concept that focuses on the advantages of the effective drain current response of the ReS_2-FET to the light illumination to enhance the gas selectivity and sensitivity. The response of the drain current in the ReS_2-FET sensor is depending on the gas molecules, and such dependence is modulated by light illumination. Additionally, these differences for each gas molecules exhibit wavelength and carrier density dependence, with which the sensor will be able to distinguish the analyte gas molecules in the gas mixture, thus improving the selectivity. By focusing on the specific device concept of light illumination, these results will contribute to the development of new sensor technology to detect almost infinite number of molecules around us by enhancing the sensing data used in the machine learning technology.

This dissertation includes five chapters. Chapter 1 describes the general introduction, including background, problems, purposes, and approaches for this work.

In chapter 2, a gate biasing operation of the ReS_2-FET for humidity sensor was initially established. This chapter details the gate biasing operation to design the high-quality ReS_2-FET based humidity sensors. The sensing performance and underlying mechanism were discussed with respect to the gate bias operation. Negative gate biasing enhanced the sensing response by decreasing the charge transfer level of the ReS_2 FET, especially in the low humidity range. More importantly, the threshold voltage change was found to be the superior sensing parameter for a linearity, wide relative humidity (RH) range monitoring with high response and sensitivity. A practical sensitivity of 0.4 V per 1% RH was attained, surpassing the results reported in prior research. Moreover, long-term stability and reversibility operations actualized the utilization of the sensor in real-time applications with quick response and recovery time. The findings indicate that the gate-bias tunable humidity sensor based on the ReS_2 FET possesses the competency to promote more advanced sensor development towards adaptable and tunable humidity sensors.

Chapter 3 systematically investigates the oxygen gas sensor performance and mechanism of few-layer-thick ReS_2 FET under both light illumination and gate biasing. As a result, the combination of light illumination and positive gate voltage enhanced the device response by increasing the photogenerated carrier and charge transfer level of the ReS_2 FET sensor. A practical sensitivity of 0.01% ppm^{-1} was achieved, which outperformed the results from the previous reports on the oxygen gas sensing. The underlying mechanism was explained by the electron transfer from ReS_2 into oxygen gas molecules to stimulate changes in the transistor properties. The results imply that a light-assisted and gate-bias-tunable oxygen gas sensor based on a ReS_2 FET has the potential to allow further sensor development towards versatile tunable oxygen gas sensors. Future studies have yet to consider further understanding on oxygen gas sensing properties of ReS_2 FET, including the angle-dependent study of ReS_2 anisotropic crystal lattice structure on oxygen gas sensing performance.

Chapter 4 discusses the development of the detection of volatile organic compound (VOC) gases using a single device of 2D ReS_2 FET with an enhanced selectivity by light illumination. Here, the advantages of the effective response of ReS_2 to light illumination were capitalized to enhance the selectivity of gas sensing performance of a ReS_2 FET device. The response of drain current in a ReS_2 FET to the adsorbed molecules was modulated by light illumination, and the sensing behavior differed depending on the gas species, such as acetone, ethanol, and methanol. Furthermore, such differences in the light-modulated sensing behaviors for each chemical also exhibited dependence on wavelength and carrier density. By utilizing the differences caused by the light illumination, the device would be able to identify gases concentration in a mixture of VOC, enhancing the selectivity of the sensor device. These results cast a new light on the sensing technology, realizing a large-scale sensor network in the era of Internet-of-things (IoT).

Chapter 5 summarizes this dissertation.