2D Materials for Gas Sensing

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Outline

• Background
• Structures of 2D Material for Gas Sensing
• TMDS Material
• Examples of 2D material for gas sensing and Results
• Conclusion and Future Work
• Acknowledgement
Background

• Recently 2D materials have been used for gas sensing because of the atomic-thin layered structure, large surface-to-volume ratio, and large adsorbing capacity of gas molecules and strong surface activities.

• Recently layered inorganic material analogues of graphene, such as Transition Metal Dichalcogenides (TMDs) were developed.

• These material include MoS$_2$, WS$_2$, MoSe$_2$, WSe$_2$, ReS$_2$, and ReSe$_2$, as well as layered metal oxides (MoO$_3$ and SnO$_2$).

• Unlike graphene, TMDs monolayers have the potential to exist in more than one possible crystal structure. This implies:
  
  • Semiconducting (2H) phase
  • Semi-metal (1T’) phase
  • Tunable Band gap, high sensitivity for varieties of chemicals.
  • Thickness dependent Physical and Chemical properties.
Gas Sensing Mechanism

• The Gas sensing mechanism is based on transfer of charges, in which the sensing material acts as absorber or donors of charges.

• The charge transfer between the gas molecules and the sensing material will cause changes in the sensing material properties.
Semiconductor gas sensing mechanism

<table>
<thead>
<tr>
<th>Classification</th>
<th>Oxidising Gases</th>
<th>Reducing Gases</th>
</tr>
</thead>
<tbody>
<tr>
<td>N-type</td>
<td>R increase</td>
<td>R decrease</td>
</tr>
<tr>
<td>P-type</td>
<td>R decrease</td>
<td>R increase</td>
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Gas Sensing Device (FET) structure

- The gas sensor works by bridging the two electrodes (source and drain) with sensing materials and passing current through them.

- Gas detection can be realized by monitoring the current change upon exposure to the target gas environment under a constant voltage.

- For conductance type gas sensor, both high sensitivity and fast recovery rate are desirable.
Various Types of 2D Gas Sensing devices

- There are several structures of 2D material Gas sensing devices, examples of such devices are:
  - Chemiresistor Sensors
  - Field Effect Transistors FETs
  - Schottky diodes
  - Conductometric sensors
  - Surface Acoustic Wave (SAW) sensors
Performance Parameters

• The performance parameters for gas sensing are characterized by:
  – Sensor Response Time
  – Selectivity
  – Sensitivity
  – Stability
  – Recovery Time
Performance Parameters Factors

- The Gas sensor Performance is influenced by several parameters:
  - The sensing material type and dimension
  - Humidity
  - Temperature
  - Gas flow rate

There are several approaches to improve the performances of the sensor such as using programming temperature, the use of UV light into the sensor, and the use Nano Particles as catalyst to improve absorption and thus improve selectivity.
Our Group Research on Gas Sensing

• We are studying gas sensing properties for two TMDs materials:
  – MoSe\(_2\)
  – MoTe\(_2\)
Gas sensors using MoSe$_2$

- Molybdenum diselenide (MOSe$_2$)
- An inorganic compound, its structure is similar to MoS$_2$
- Single Crystal layers of MoSe$_2$ and flakes are exfoliated from bulk Crystal
- Electron mobility of 2D MoSe$_2$ is higher than MoS$_2$
- It has direct band gap
Transfer material
Gold Assisted Exfoliated

Flakes Transferred

Optical image of transferred flake
MoSe$_2$ Characterization using Raman and PL

Raman Spectra

PL
Mask and Optical image of the device

Contact Pad

Etched channel
FET characteristics (n-type)

Transfer Characteristic

Output Characteristic
Gas sensing set up Structure
Gas response (20ppm NO$_2$)

In comparison, MoSe$_2$ always have large recovery time which we need to find a way to improve. Our device can reach 20% response for 20ppm NO$_2$ and shows great sensitivity.
Challenges with the measured Data

• Large recovery time 400s

• How to improve the sensitivity in the range of 100ppb - 10ppm

• How to improve the selectivity
Work we are doing to improve the results

1. Heat assist to help recovery
2. FET structure/UV assist to help improve sensitivity
3. Metal nanoparticles decoration to help improve selectivity
MoTe$_2$

- Molybdenum ditelluride (MoTe$_2$) is an especially attractive 2D material because it exists in two stable polymorphs.

1. Semiconducting hexagonal (2H) and
2. Semi-metallic monoclinic (1T’)

Two phases can be reversibly transformed by altering MoTe$_2$ crystal growth conditions or by a post-growth thermal treatment.
MoTe$_2$ 2-D Material

Material Characterization of 2H-MoTe$_2$

- Cooling rate defines a crystal structure of MoTe$_2$ single crystals, regardless of the initial crystal phase of the poly-MoTe$_2$.

- X-Ray diffraction patterns were obtained using milled MoTe$_2$ powders and platelets.
Material Characterization of 2H-MoTe$_2$

- Raman spectra were acquired from the 2H-MoTe$_2$ flakes exfoliated onto SiO$_2$/Si substrates. The spectra for the 2H flakes, exhibit an out-of-plane A$_g$ mode around 170 cm$^{-1}$, an in-plane E$_{2g}$ mode around 235 cm$^{-1}$ and an out-of-plane B$_{2g}$ mode at 289 cm$^{-1}$.

- All lines are in excellent agreement with Raman studies reported in the literature [14, 15], which confirms the phase and quality of the flakes.
Electrical Characterization

Annealing was done at 350 °C
Electrical Characterization

Output Characteristic

Transfer Characteristic

P-type
Packaging of MoTe$_2$ For gas sensor

Three different thickness MoTe$_2$ FET are packaged on above chip-career for gas-sensing measurement.
Approaches to improve the Gas-sensing performance

1. Incorporation of UV light into gas sensors.
2. High sensitivity can be achieved by good Schottky barrier modulation of 2D material and metal electrode junction.
3. Surface functionalization of the 2D channel between source and drain electrodes.
   Example: Pt nanoparticles on MoS$_2$ thin films.
4. Decoration of 2D material with metal oxides.
   Example: MoS$_2$/SnO$_2$ channel between source and drain electrode.
5. Annealing the 2D sensing material at proper temperature.
Summary

• It is an important to develop Very sensitive and Very selective gas sensing device for many applications such as health, food, agriculture, …

• Two dimensional (2D) material is showing great potential in gas sensing with high sensitivity due to their high surface-to-volume ratio and promising semiconductor properties.

• Our Goal is to develop portable wearable gas sensing device
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➢ Dr. R. Debnath : Electrical Characterization
➢ Irian Kalish : X-Ray Diffraction