Fabrication and Characterization of the 2D Tungsten Disulfide (WS_2) Field Effect Transistor

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by

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CHAPTER 6

Conclusions and Future Direction of Research

Contents:

Chapter 6: Conclusions and Future Direction of Research

6.1. Summary of the Thesis:

This research presents a detailed analysis of 2D WS_2 nanosheets and their application in semiconductor devices, particularly in field-effect transistors. In this study, WS_2 nanosheets are employed as the semiconducting channel material in back-gated FETs. Prior to device fabrication, the WS_2 nanosheets are prepared specifically for the intended application, as tailoring their layer count is key to optimizing their electrical and optical properties. Modulating the number of layers allows for tunable scalability, adapting the material's characteristics as needed. The atomic and physical properties of WS_2 nanosheets are influenced by adjusting the energy bandgap, which can exhibit both direct and indirect bandgap transitions distinct advantages over traditional semiconductors.

In this work, the synthesis of WS_2 nanosheets is accomplished through liquid-phase exfoliation, utilizing a surfactant-assisted exfoliation technique that is both scalable and environmentally friendly. Exfoliation was performed under ambient conditions using sonication-assisted methods. Following exfoliation, thin nanosheets were deposited onto the targeted substrate and the atomic and structural characteristics of the material were optimized through spectroscopic analysis to ensure high-quality performance for semiconductor applications. To identify the layer number and thickness of the WS_2 nanosheets, spectroscopic techniques including Raman spectroscopy, AFM, UV-Vis spectroscopy, and photoluminescence were employed. Later, the structural morphology, surface property, and crystalline nature of the exfoliated WS_2 nanosheets were analyzed using AFM, FESEM, HRTEM, and XRD techniques. The estimated layer thickness of the nanosheets, derived from the A-exciton peak in the UV-Vis spectra, is approximately <10 nm, confirming that the resulting nanosheets are few-layer structures with an indirect bandgap characteristic of 2H-phase WS_2. The results from these complementary methods consistently confirm the formation of WS_2 nanosheets comprising a few layers of nanosheets in between ~3 nm to ~10 nm. The morphological data revealed the formation of highly crystalline, hexagonal WS_2 flakes. These flakes exhibit a uniform distribution with lateral sizes ranging from a few nanometers to several micrometers.

The exfoliation process and environmental factors can lead to the degradation of WS_2 nanosheets, often through the formation of atomic vacancies, surface defects, or the presence of impurities. These structural imperfections impair charge carrier transport and conductivity, resulting in contact resistance, a high Schottky barrier height at the Metal-

Semiconductor interface, and other limitations in device applications. To mitigate these issues and improve the conductivity of WS_2 nanosheets, n-type doping has been employed, introducing dopant atoms through surface absorption to enhance electrical charge transport. This doping process helps correct atomic defects and reduce impurities on the nanosheet surface. Density Functional Theory calculations have been used to study the energy band structure of WS_2, with and without Cl doping. The results show that a single Cl atom in the WS_2 lattice shifts the conduction band toward the Fermi level, confirming Cl as an n-type dopant. This band shift boosts the n-type characteristics of WS_2, making Cl-doped WS_2 superior to pristine or defected WS_2 in electronic applications.

Spectroscopic analysis confirmed that Cl atoms were successfully incorporated into the WS_2 lattice, achieving effective doping without altering the nanosheet's surface morphology. This doping improved the stoichiometry and reduced defect states and vacancies. The electrical measurements of the two-terminal WS_2 devices with Ag contacts revealed non-ohmic characteristics, attributed to contact resistance and a high Schottky barrier height at the metal-WS_2 interface, which hindered charge transport by increasing the width of the depletion layer. The widened depletion layer at this interface further limits current flow through the junction, resulting in reduced device conductivity. However, after doping, a steady increase in current conductivity was observed with a longer doping duration, indicating enhanced n-type conductivity. Additionally, the R_C and SBH at the Metal-WS_2 junction significantly decreased from 0.35 to 0.15 kΩ and from 0.75 eV to 0.65 eV, respectively, facilitating carrier transport. These findings provide valuable insights for optimizing the performance of high-quality, 2D-TMD semiconductor devices like WS_2.

Later, the exfoliated and doped WS_2 nanosheets were used in back-gated FET application. The integration of 2D WS_2 as the semiconducting channel in the fabrication and electrical characterization of FETs was optimized. However, the WS_2 in FET application also faces some difficulties like low carrier mobility, current on/off ratio, SS, etc. The FET device was fabricated on SiO_2 acting as a back gate dielectric and Si was used as a back gate. The fabrication of the FL-WS_2 based back-gated FET device was done by the lithography process. However, the Cr metal contact with the WS_2 nanosheet displayed non-linear characteristics due to high contact resistance, arising from the difference between the metal's work function and the semiconductor's electron affinity.

The field-effect mobility of the FL-WS_2 FET was found to be 25 $cm^2/V{\cdot}s$ with a Ti contact and 14.3 $cm^2/V{\cdot}s$ with a Cr contact, measured for a channel length of 2 μm. The highest mobility, around 102.7 $cm^2/V{\cdot}s$ and ~189.5 $cm^2/V{\cdot}s$, was achieved after doping with a channel length of ~2 μm with Cr and Ti metal contact. The contact resistance of the WS_2 FET decreased from 91.7 kΩ·μm to 44.82 kΩ·μm with n-type doping and to 63.34 kΩ·μm without doping with Ti contacts reduce to 23.39 kΩ·μm after doping. The fabricated FET with Ti contact demonstrates superior operational performance compared to Cr contact-based FETs. This includes a higher carrier concentration, lower threshold voltage and subthreshold swing, higher field-effect mobility, and reduced contact resistance. Despite these differences, all the fabricated FETs exhibit n-type characteristics, with the Ti-contact FET achieving a maximum carrier concentration of 10^{10} cm^{-2}. These findings highlight the potential of WS_2 as a promising material for future electronic applications, although further optimization is needed to address the challenges in device performance.