THE SEMICONDUCTOR NANOSTRUCTURES BASED ON TWO-DIMENSIONAL MOLYBDENUM DITELLURIDE (MOTE2)

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Abstract. In the world, the advancement of the electronics industry worldwide, together with the expansion of green energy priorities, has highlighted the increasing significance of renewable and smart materials in addressing global energy challenges. In this context, semiconductor materials based on two-dimensional (2D) transition metal dichalcogenides (TMDs), particularly $MoTe_2$ structures, have attracted considerable attention from leading scientific research centers due to their high functional performance and the relatively less demanding experimental conditions required for their fabrication. The semiconducting nature, excellent chemical stability, and tunable electronic structure of $MoTe_2$ make it a highly promising candidate for the development of high-performance nanoelectronic and optoelectronic devices. At present, numerous approaches have been established for fabricating $MoTe_2$-based semiconductor nanotransistors under high-vacuum conditions, regulating electrical transport characteristics through ionic liquids, and enhancing optoelectronic performance to develop efficient functional devices.

Keywords: *MoTe2/h-BN field-effect transistor, transconductance, charge transfer.*

Introduction

The introduction outlines the relevance and necessity of the dissertation topic, clearly defining the research objectives and tasks. It identifies the object, subject, and methods of the study, and highlights its alignment with the priority areas for scientific and technological development in the Republic of Uzbekistan. The current state of research on the problem is discussed, and the scientific innovation and practical outcomes of the study are presented. Additionally, the scientific and practical significance of the results is emphasized, along with their reliability.

Low-dimensional materials have exhibited remarkable physical properties, with TMDs such as MoS_2, $MoSe_2$, $MoTe_2$, WS_2, WSe_2, WTe_2, and $PdSe_2$ attracting significant attention as potential candidates for the post-silicon era. Single layers of these 2D TMD nanomaterials have demonstrated high efficiency in light absorption, resulting in enhanced photodetector responsivity. [1-5] TMDs possess a characteristic MX_2 structure, where M represents a hexagonally arranged sheet of atoms, sandwiched between two layers of X atoms. These crystals are held together by weak van der Waals forces, enabling their exfoliation into single 2D flakes from bulk crystals. The absence of covalent bonds between adjacent layers minimizes dangling bonds, contributing to their chemical stability and reduced carrier scattering. These features, along with high anisotropy in their electrical properties, make semiconducting TMDs excellent candidates for next-generation electronic and optoelectronic devices, such as FETs, light-emitting diodes, and Van der Waals heterostructure devices. Additionally, the 2H phase of $MoTe_2$ has been extensively researched for applications in spin transport electronics and solar cells. $MoTe_2$ FETs, in particular, display both unipolar and ambipolar charge transport characteristics, with their polarity easily tunable via the contact electrode. [6-8]

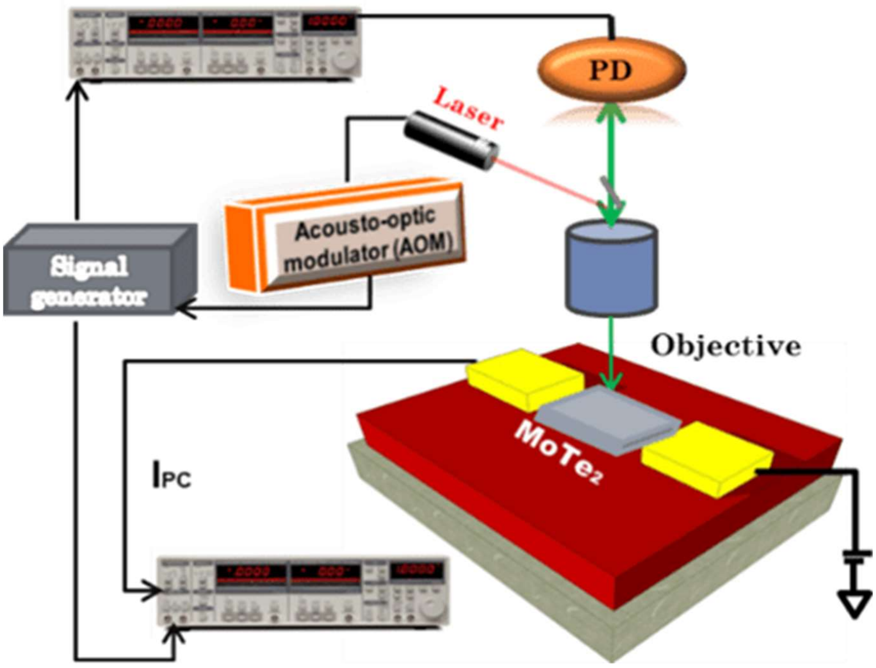

Figure 1. The schematic circuit diagram of the experimental setup and device. The $MoTe_2$ phototransistor was fabricated using the dry-transfer method

First, a few layers of $MoTe_2$ flakes were exfoliated from commercially available bulk material using the mechanical exfoliation technique and placed on a Si wafer. Polyvinyl alcohol (PVA) was then used to transfer the $MoTe_2$ flakes onto a pure Si/SiO_2 (300 nm) substrate. The flakes were identified using an optical microscope and characterized with electrical measurements. A spin coater applied a layer of polymethyl methacrylate (PMMA) on top of the $MoTe_2$. The PVA was dissolved in water, leaving the $MoTe_2$ flakes settled on the PMMA sheet. Cr/Au electrodes were patterned using electron-beam evaporation, with 5 nm of Cr and 50 nm of Au deposited after a standard lift-off process. [9-11]

Output and transfer measurements were conducted using a two-channel model, with gate voltage applied. AC photocurrent measurements were taken using a low-noise current preamplifier (SR 570), and the photocurrent and electrical measurements were performed inside a Close Cycle Refrigerator (CCR) chamber maintained at a pressure of 1×10^{-7} Torr. A green laser (532 nm) was directed through a quartz window into the CCR to focus on the sample, and a chopper controller (Model SR540) provided a reference signal for the lock-in amplifier (SR 830) to measure the photoresponse with high sensitivity. [12]

A novel optoelectronic device structure for ambipolar FETs based on few-layer and monolayer TMD materials was proposed. The optoelectronic properties of $MoTe_2$ p-n diodes were examined using scanning photocurrent microscopy (see, Figure 1). Experimental measurements focused on p-type SiO_2 $MoTe_2$ FET devices, with p- and n-type parameters determined by current-voltage (I-V) measurements using a six-probe station and Keithley 4200-SCS Source Measure Units (SMUs). It was observed that a lower gate voltage increased the Schottky barrier height between the metal and the channel. [13]

Characterizing nanoscale systems is essential for understanding their potential, and Raman spectroscopy is a powerful tool for analyzing the vibrational properties of two-dimensional materials. This technique enables quick identification of chemical species and polymorphs by examining the unique vibrational characteristics of the elements involved. The Raman effect occurs when light interacts with a material, resulting in either Rayleigh scattering (no energy change) or Raman scattering, where energy is shifted due to the creation or absorption of phonons. These shifts, known as Raman shifts, provide insights into the material's vibrational states. [14]

A novel optoelectronic device structure for ambipolar field-effect transistors based on multilayer OMD materials and the optoelectronic properties of $MoTe_2$ p-n diodes were investigated using a scanning photocurrent microscope (see Fig. 1). Experimental measurements were focused on p-type SiO_2 $MoTe_2$ MT devices, and the p- and n-type parameters were determined using a six-needle probe station (Vacuum Probe Station) and a Keithley 4200-SCS source measurement unit (SMU) using VAX (I-V) measurements. It was noted that the back gate voltage increased the height of the Schottky barrier between the metal and the channel. [15]

It is important to characterize and understand the capabilities of nanoscale systems. Raman spectroscopy is an effective method for analyzing the vibrational phases of two-dimensional materials. This technique helps to quickly identify chemical species and polymorphs based on their unique vibrational properties. When light interacts with a material, Rayleigh or Raman scattering occurs, in which the energy is changed by phonons. The photocurrent map of the 15-layer $MoTe_2$ MT revealed a trap density of approximately 6×10^{12} cm^{-2} with a uniform overall distribution. The back gate-dependent photocurrent is consistent with previous studies, and we have obtained similar results using CCR devices, including a small AC photocurrent (~7 nA) map (Fig. 2).

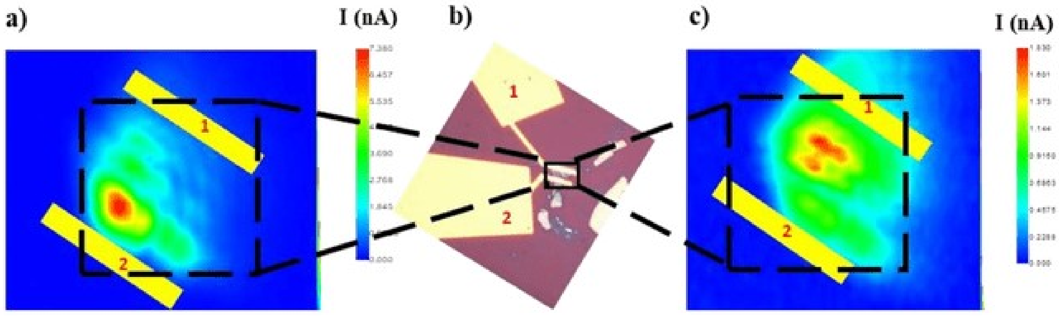

Figure 2. (a) Photocurrent map of the transistor at Vsd = 1V and Vbg = 0V with a laser power of 9.5 µW/µm2, the black dashed line marks the MoTe2 region. (b) Optical image of the MoTe2 MT and (c) photocurrent map of the transistor at Vsd = 1V and Vbg = 60V with the same laser power

The photocurrent map showed a decay of the signal near the drain region. Temperature-dependent measurements confirmed the current decay characteristic of semiconductors at low temperatures. However, at 280 K, the output characteristics remained linear at different gate voltages, suggesting the presence of an ohmic connection between the $MoTe_2$ and the Cr/Au contacts. A secondary frequency νm is observed if a phonon (vibrational state transition) is created or absorbed, leading to a shift in energy. If a phonon is created, the frequency is defined as $\nu phonon = \nu 0 - \nu m$ (Stokes mode); if a phonon is absorbed, it is $\nu phonon = \nu 0 + \nu m$ (Anti-Stokes mode). Raman spectroscopy measures these frequency shifts relative to the excitation source, which is why it is also referred to as Raman shift. [16]

To determine the epitaxial relationship in 3D thin films, X-ray diffraction pole figure measurements are commonly used due to their non-destructive nature and minimal sample preparation, yielding results quickly. However, for 2D materials, the lack of out-of-plane continuity makes this method ineffective. Instead, (0001) plane periodicity allows techniques like RHEED, LEED, and TEM to assess in-plane crystallographic orientation. Lab-scale X-ray diffraction can determine in-plane epitaxial relationships for TMDs by aligning the X-ray incidence nearly parallel to the surface.

The transfer characteristics of $MoTe_2$/h-BN FETs are crucial for analyzing their electronic performance. Here, $MoTe_2$ acts as the semiconducting channel, while h-BN serves as a dielectric layer that improves interface quality, reduces impurities, and enhances electronic properties like mobility and threshold voltage. Evaluating the drain current (Id) versus gate voltage (Vg) helps determine key metrics such as on/off ratio, subthreshold swing, and mobility. This high-quality interface minimizes charge trapping and dielectric losses, yielding superior stability and performance, making $MoTe_2$/h-BN FETs promising for future nanoelectronic applications. The h-BN and MoTe2 nanoflakes were fabricated using adhesive tape-assisted mechanical exfoliation, followed by a dry transfer method to create the h-BN/MoTe2 heterostructures, which illustrates the transfer and output characteristics of the resulting FET, as depicted in Figure 3. The gate voltage values are chosen to be close to the flatband condition as determined from the transfer characteristics measured in back-gate configuration. The electron and hole conduction threshold voltages progressively shifted to higher voltages from gate to MoTe2. The average values of the threshold voltage Vth versus the MoTe2 work function. The effect of gate-induced stress for devices on SiO2 is reduced by choosing a h-BN flake as gate dielectric that provides a more stable dielectric environment.

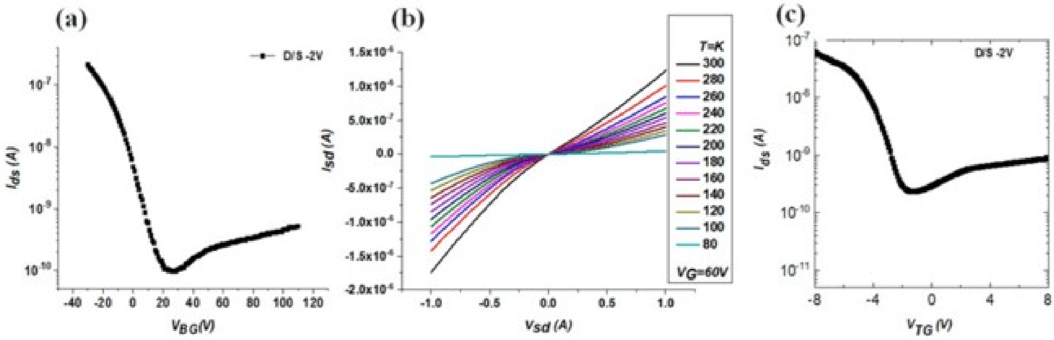

Figure 3. Transfer characteristic of the MoTe2/h-BN FET before dropping the ionic liquid (a) at back gate and (b) measured within three days after loading the sample in the vacuum setup at different temperatures; (c) transport measurements recorded at different a gate.

Figure 10 shows the transfer curves of the MoTe2/h-BN device obtained at different ambient temperatures on a SiO2 substrate with Cr/Au and Ti/Au metal contacts before the introduction of the ionic liquid. In particular, Figure 3.8 a,c display the transfer characteristics of the MoTe2/h-BN FET with the SiO2 back gate and Ti/Au top gate. The $MoTe_2$/h-BN FET exhibits temperature-dependent transfer characteristics, with a source-drain current that decreases as temperature rises from 80 K to 300 K, except for a slight increase near 200 K. This is attributed to reduced Schottky barriers and phase transitions. Mobility is highest at 80 K but decreases with temperature due to carrier-phonon scattering. At temperatures above 300 K, ion migration causes hysteresis and weakens the field effect.

Conclusion

The tunable band structure of TMDs enables tailored electronic, optical, magnetic, thermal, and mechanical properties for advanced applications in electronics, photonics, sensing, and energy systems. Volt–ampere and opto-electrical studies of 15-layered $MoTe_2$ crystals revealed a trap density of $\sim6\times10^{12}$ cm^{-2}, enhanced AC photocurrent, and high on/off ratios, demonstrating strong photocurrent generation potential.

$MoTe_2$/h-BN heterostructures were synthesized and characterized using Raman spectroscopy, XRD, and AFM, while dry transfer methods improved interface quality, mobility, and device stability. Transfer characteristics showed reduced impurities and promising nanoelectronic performance. Temperature-dependent measurements revealed peak mobility at 80 K, influenced by Schottky barriers, phase transitions, and carrier–phonon scattering.

Furthermore, an efficient BMIM-BF_4 ionic liquid encapsulation method was developed to enhance $MoTe_2$/h-BN FETs/MTs, enabling unipolar p-type behavior, high conductivity, excellent transconductance, improved hole and tunneling mobility, and enhanced electrical and optical stability, offering a practical route for functionalizing 2D materials.

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