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ENHANCED OPTO-ELECTRICAL CHARACTERISTICS OF THE SYNTHESIZED TWO-DIMENSIONAL MoTe2 FIELD-EFFECT-TRANSISTOR

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Abstract. We have successfully manufactured nanometer-sized FETs using a few-layer Molybdenum Ditelluride (MoTe2) and conducted a detailed examination of their optoelectronic properties. Specifically, our investigation delves into the mechanisms governing photocurrent generation in MoTe2 FETs through gate and bias-dependent measurements. The findings highlight distinct photocurrent signals at MoTe2-electrode junctions, indicating the presence of a gain photoconductor effect in both off- and on-states. This stands in contrast to conventional MoTe2 field-effect non-volatile transistors, which exhibit a continuous increase in photocurrent unaffected by the back-gate voltage.

Keywords: $MoTe_2$; field-effect transistor; photocurrent; back-gate sweep.

Улучшенные оптически-электрические характеристики синтезированного двумерного полевого транзистора MoTe2

Аннотация. В данной работе представлены результаты исследования оптоэлектронных свойств полевых транзисторов нанометрового размера с использованием многослойного молибдена дителлурида (MoTe2). В частности, наше исследование углубляется в механизмы, управляющие генерацией фототока в полевых транзисторах MoTe2 посредством измерений, зависящих от затвора и смещения. Результаты подчеркивают отчетливые сигналы фототока на соединениях MoTe2-электрод, что указывает на наличие эффекта усиления фотопроводника как в выключенном, так и включенном состоянии. Это контрастирует с обычными полевым энергонезависимыми транзисторами MoTe2, которые демонстрируют постоянное увеличение фототока, не зависящее от напряжения обратного затвора.

Ключевые слова: MoTe2; полевой транзистор; фототок; зачистка задних затвор.

Sintezlangan ikki o‘lchamli MoTe2 maydoniy effektli tranzistorining optik-elektrik xususiyatlari

Annotatsiya. Ushbu ishda, ko‘p qatlamli ikki xalkogenli molibden tellurid (MoTe2) nanometr o‘lchamdagi materialdan foydalangan holda maydoniy effektli tranzistor natijalari taqdim etilgan va unig optoelektronik xususiyatlari batafsil o‘rganilgan. Xususan, bizning tadqiqotimiz zatvor va qarama-qarshilikka bog‘liq bo‘lgan o‘lchovlar orqali MoTe2 MYaT larda fotooqim hosil bo‘lishini nazorat qiluvchi mexanizmlarni o‘rganadi. Natijalar MoTe2-elektrod birikmalarida aniq fotooqim signallarini ta’kidlaydi, bu ham yopiq, ham yoqilgan holatda fotoo‘tkazgichni kuchaytirish effekti mavjudligini ko‘rsatadi. Bu an’anaviy MoTe2 MYaT lardan farqli o‘laroq, teskari eshik kuchlanishidan qat’iy nazar fototokning doimiy o‘sishini namoyish etadi.

Kalit so‘zlar: MoTe2; maydoniy effektli tranzistor; fototok; orqa zatvor.

Introduction.

Low-dimensional materials are renowned for showcasing unique physical properties, and among these, layered semiconducting transition-metal dichalcogenides (TMDs) like MoS2, MoSe2, MoTe2, WS2, WSe2, WTe2, and PdSe2 have emerged as promising candidates for the post-Silicon era. These 2D TMD nanomaterials, composed of single layers, demonstrate efficient light absorption, resulting in high responsivity in photodetectors. Typically, TMDs adopt the MX2 form, where M represents a hexagonally arranged sheet of atoms positioned between two layers of X atoms. The weak van der Waals forces between the three layers facilitate the separation of bulk crystals into single 2D flakes. The absence of covalent bonds between adjacent triple layers ensures chemical stability and low carrier scattering on the surfaces of 2D TMD flakes. These layered TMD structures maintain high anisotropy in their electrical properties throughout the process. Such characteristics make semiconducting TMDs excellent platforms for next-generation electronic and optoelectronic devices, including Field-effect transistors (FETs), light-emitting diodes, and Van der Waals heterostructure devices. Furthermore, 2H-MoTe2 has been extensively studied for applications in spin transport electronics and solar cells. Notably, single-layer and a-few-layer MoTe2 FETs exhibit both unipolar and ambipolar charge transport characteristics, easily tunable by employing contact electrodes. External heat energy applied to the metal electrode induces thermionic emission on its surface, influencing the tunneling process responsible for current flow through the channel. Ambipolar transfer characteristics in I_{DS}-V_{BG} for normal edge contact TMDs near the charge transfer region are observed due to differences in Fermi levels between the metal and semiconductors[1-3].

FETs play a crucial role in various photodetector devices used extensively in both research and daily life. Photodetectors capture photons, converting them into electrical signals for further processing by standard electronics. Their applications range from spectral imaging and sensors to fiber-optic communications. Semiconducting 2D materials significantly contribute to enhancing photodetector functionality due to their transparency, high flexibility, and tunable bandgaps dependent on layer thickness[4].

Upon exposure to light, photon absorption leads to the generation of electron-hole pairs. Applying voltage (drain-source) separates these pairs. Photogenerated electrons and holes move in opposite directions along the metal, resulting in increased current. Photogenerated electrons traverse channels faster than holes due to the slow mobility of holes compared to electrons. This discrepancy facilitates the participation of many electrons in the photocurrent, leading to photoconductive gain characterized by the ratio of photogenerated carrier lifetime to transit time. Moreover, a single photon can generate multiple electrons, enhancing quantum efficiency. While previous studies mainly focused on the photoresponsivity of FETs based on transition metal dichalcogenides (TMDs), the results were limited to the present back gate sweep. To improve photoresponsivity, synthesizing monolayer materials with higher charge transfer properties becomes crucial. Thus, many electrons can participate in the photocurrent originating the photoconductive gain which is characterized by the photogenerated carrier lifetime divided by the transit time. Moreover, these electrons can be derived from a single photon, resulting in increased quantum efficiency. In previous studies, mainly the photoresponsivity of TMDs based FETs have been investigated. However, these results were obtained only for the of presents backgate sweep. In order to achieve better photoresponsivity, it is important to synthesize monolayer material that demonstrates higher charge transfer properties.

In this study, we present comprehensive experimental results on the photoresponsivity of MoTe2 using Cr/Au metals as electrodes, shedding light on the impact of Schottky barriers on the carrier transport characteristics of FETs.

Experiment and Materials.

The $MoTe_2$ phototransistor was fabricated using the dry-transfer method. Initially, bulk material which is commercially available was used to extract a few layers i.e., of $MoTe_2$ flake. The flake was formed by means of the mechanical exfoliating method and further used to place on Si

wafer. Next, in order to transfer the $MoTe_2$ flake from the Si wafer into the pure Si/SiO_2 (280 nm) substrate the polyvinyl alcohol (PVA) was utilized. The exfoliated flakes were spotted/ detected using an optical microscope and characterized with an electrical measurement. The spin coater was used to coat the polymethyl methacrylate (PMMA) on top of $MoTe_2$. Thereafter, PVA was fully dissolved in water, while the $MoTe_2$ flake settled on the PMMA sheet. The Cr/Au electrodes were patterned using electron-beam evaporation of 5 nm Cr and 30 nm Au following the norm lift-off process. The output and transfer measurements were performed by employing two-channel models where we applied the gate voltage. [5] The AC photocurrent measurements are used to detect small photocurrents with a low-noise current preamplifier (SR 570). The photocurrent and electrical measurements were taken inside a Close Cycle Refrigerator (CCR) chamber. The chamber pressure inside was maintained at 2×10^{-6} Torr. Moreover, the chamber was equipped with a quartz window which the applied laser could pass through and focus onto the sample. The green laser with 532 nm wavelength was then directed to CCR which focused onto the sample which is a partially suspended in the region. The chopper controller (Model SR540) provides a reference signal for the lock-in amplifier (SR 830) and detects simple voltages in a certain frequency of the modified light that stands a very sensitive measure number of active traps of the photoresponse of these FET[6]. We mainly concentrated on the p-type SiO_2 $MoTe_2$ FET devices in our experimental measurements. P - and n-type parameters of MoTe2 FET devices can be determined by current-voltage (I-V) measurements of FET. The I-V characteristics were measured using the six probe station and Keithly 4200-SCS's Source Measure Units (SMUs) was employed as a source and a unit of measurement of both current and voltage. The lower gate voltage can lead to a higher Schottky barrier height between metal and channel. The metal contacts play an important role in the performance of devices. In our devices, Cr (5 nm) and Au (50 nm) have been selected for electron (hole) conduction and minimize the Schottky barrier in metal-semiconductor (MS) contacts. The photocurrent variations near MoTe2/Cr/Au Schottky barrier junctions are not investigated[7].

Results and discussion.

Electric transport measurements were conducted across a broad spectrum of source-drain voltage biases. The Si substrate served as a back-gate source, with a voltage bias spanning from +10 to -100 V. Figure 1 depicts a) the optical images of the created MoTe2 and b) the photo-optical response of the device junction featuring the few-layer film deposited on a 300 nm SiO2/Si substrate.

a) **b)**

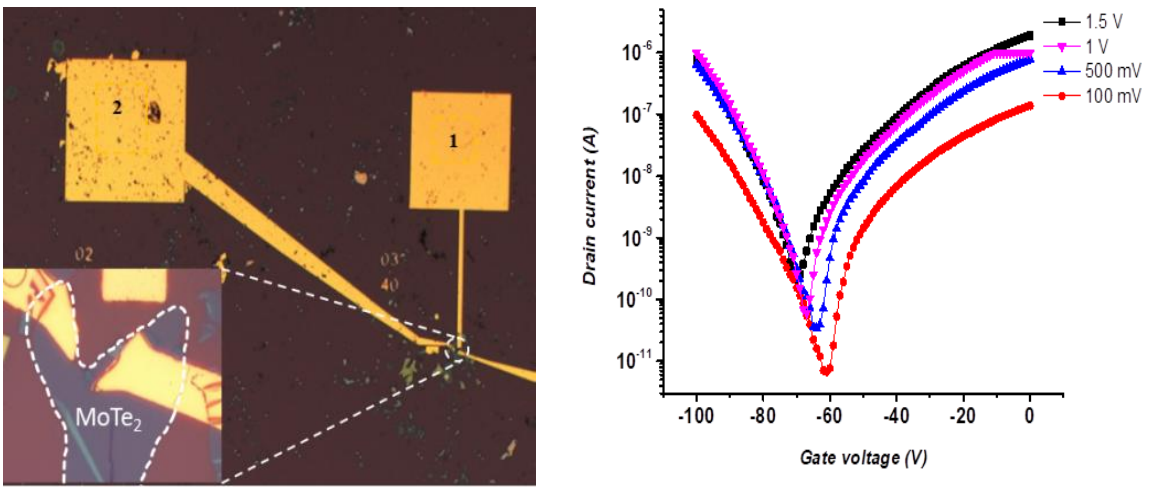


Figure 1. a) Optical image of the $MoTe_2$ FET, b) The current vs. gate voltage characteristics in the different drain source voltage.

The presented data in Fig. 1(b) indicates that our MoTe2 FET exhibits ambipolar conduction behavior. Ambipolar conduction was further elucidated using a theoretical model proposed in the literature. The AC photocurrent and overall electrical performance of FET devices are significantly influenced by the metal electrode junction. Employing the time-resolved photoresponse technique allowed us to assess trap states, and the introduction of air to the device induced surface trap states on MoTe2, attributed to its comparatively thicker sample size. Notably, the phototransistor is characterized by emitting photocurrent under zero gate bias conditions. Recent investigations confirm MoTe2 its nature as a phototransistor. To validate this characteristic, we mapped out the photocurrent spreading in the channel region of the 32-layered MoTe2 device. Additionally, trap states were estimated, with the maximum trap density calculated at about 5.2×10^{12} cm^{-2}. This calculation was based on the transient drain current measured at various V_{gs}, aligning with methodologies outlined in the literature. Importantly, the literature indicates no variation in the dependence of bandgap trap states on the thickness of MoTe2.

$$I_{ds}(t) = I_{ds,\ sat} - \frac{qW\mu_{FE}N_T V_{ds}}{L} e^{-t/\tau}$$

In the following equations, N_T represents the number of traps, V_{ds} denotes the bias voltage, τ signifies the decay coefficient, q represents the charge, μ_{FE} denotes the field effect mobility, while W and L correspond to the width and length of the MoTe2 channel, respectively. $I_{ds,\ sat}$ indicate the saturated drain current. The bandgap of MoTe2 remained unchanged. Although it is anticipated that there may be variations in trap density from point to point, the overall density remains consistent. The variation in photocurrent depending on the gate bias aligns with previous findings. [8, 9]

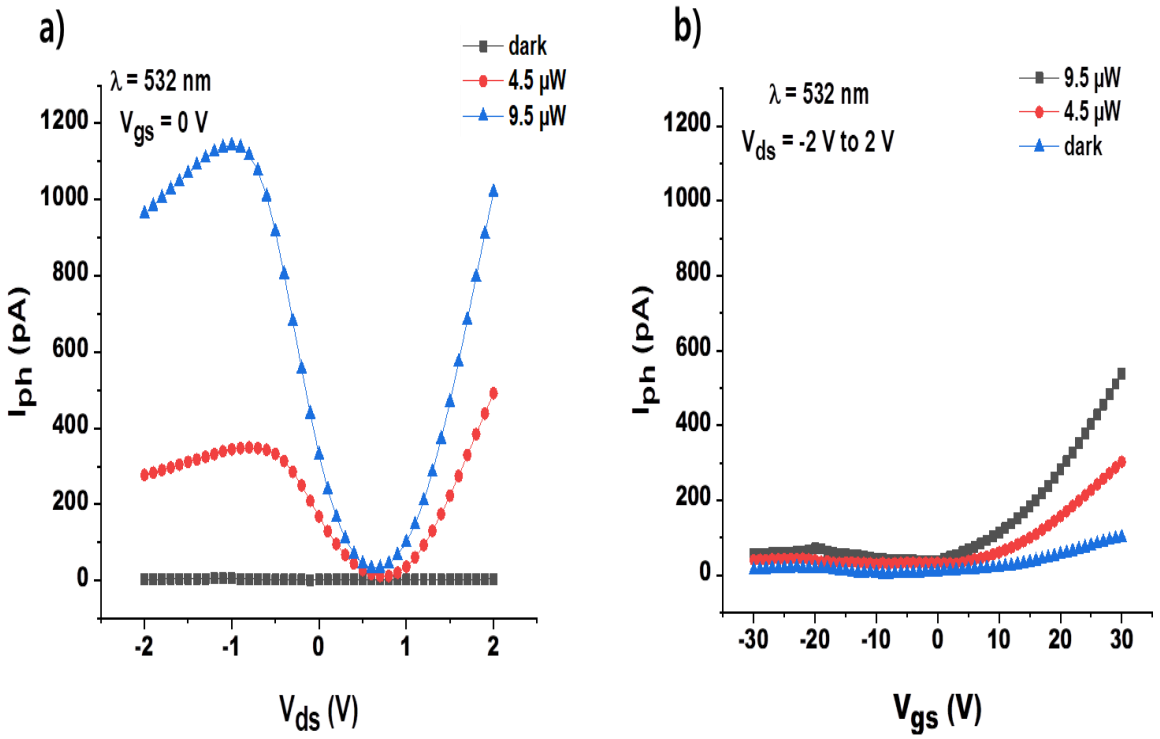


Figure 2. (a) Photocurrent at different laser power under zero back-gate and (b) under gate swipes.

We conducted several measurements of the photocurrent and trap states using CCR devices, yielding consistent results, including a small AC photocurrent of 12 nA.

The optoelectronic devices, specifically semiconductors mainly operate on the principle of direct electron-photon conversion which is a key process in the fields of photodetection and

photovoltaic. Thus, the semiconductor's energy gap directly defines the energy efficiency scale of the device's optical excitation which is crucial in the fabrication of FETs[10, 11].

Conclusions.

In this study, we performed optoelectrical measurements on freshly cleaved surfaces of MoTe2 crystals to evaluate their properties. Our analysis focused on estimating trap states for the 32-layered MoTe2, revealing a maximum trap density of approximately 5.2×10^{12} cm^{-2}. It's worth noting that our MoTe2 FET demonstrates superior AC photocurrent and on/off ratio compared to similar FETs, with the potential to increase the number of charges in photocurrent without gate sweeping. Furthermore, devices based on MoTe2 show promising stretchability with minimal electrical performance degradation, indicating their suitability for future applications in wearable and body-attachable electronics.

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