Research Article

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Single flake homo p–n diode of MoTe2 enabled by oxygen plasma doping

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Abstract: Two-dimensional (2D) materials play a crucial role as fundamental electrical components in modern electronics and optoelectronics next-generation artificial intelligent devices. This study presents a methodology for creating a laterally uniform p–n junction by using a partial oxygen plasma-mediated strategy to introduce p-type doping in single channel MoTe2 device. The MoTe2 field effect transistors (FETs) show high electron mobility of about $23.54 \text{cm}^2 \text{V}^{-1} \text{s}^{-1}$ and a current ON/OFF ratio of $10^6$ while p-type FETs show hole mobility of about $9.25 \text{cm}^2 \text{V}^{-1} \text{s}^{-1}$ and current ON/OFF ratio $10^5$ along with artificially created lateral MoTe2 p–n junction, exhibited a rectification ratio of $\sim 10^2$ and ideality factor of $\sim 1.7$ which is proximity to ideal-like diode. Thus, our study showed a diversity in the development of low-power nanoelectronics of next-generation integrated circuits.

Keywords: TMDs, field effect transistor, MoTe2 homojunction diode

1 Introduction

The emergence of the artificial intelligence revolution is propelled by notable progress in the fields of the Internet of Things, terahertz communications, and thermoelectrics [1]. Consequently, there is a growing need for a new hardware infrastructure that can effectively tackle the substantial obstacles inherent in conventional and neuromorphic computing systems [2–5]. The transition metal dichalcogenides layered structure grants remarkable flexibility, facilitating easy customization of physical properties for diverse nanodevices [6–8]. This capability has significant potential for the development of forthcoming applications. As a result, there has been a notable surge in the attention received by these materials in the realm of sensors, electrical, and optoelectronic applications [9–11].

Considerable research has been undertaken on the use of TMD diodes, which include the stacking of p- and n-type materials, for various purposes [12–14]. These diodes function as memory-switching devices [3,15–17], artificial devices [18,19], and self-powered sensors [20,21] by generating depletion regions that facilitate the rectification of unidirectional current [22]. One of the noteworthy materials in this group is the 2H phase semiconducting molybdenum ditelluride (MoTe2), which stands out due to its very small bandgap [4,14,23]. Specifically, it has a direct optical bandgap of 1.02 eV when in the form of a monolayer. On the other hand, the multi-layered flake of the material demonstrates an indirect bandgap of 0.85 eV, which renders it appropriate for a wider range of spectral responses [24–26].
Moreover, MoTe$_2$ can efficiently capture light throughout the visible and near-infrared regions, making it a very promising material for photoresponsive phenomena [27]. At present, there is a need to improve the dependability of the transfer process for 2D materials due to its propensity to generate novel interface states and potentially cause material damage during the transfer [28]. The acquisition of a stable, efficient, and controlled doping process is a critical factor in the p–n homojunction devices [29,30]. Recently, prevalent doping approaches including plasma doping, chemical doping [31], and surface charge transfer have been accomplished to modulate the carrier’s polarity [13,29,32]. The conventional technique of surface charge-transfer doping involves the transfer of charges at the interface between the dopant and the material to modulate the performance of carrier transfer [26,33,34]. However, this approach leads to doping effects that are irreversible and lack of control. The conventional technique of ion implantation offers a precise means of controlling the doping effects in materials [35]. However, it is important to note that this method may also result in lattice damage [36]. Consequently, a subsequent high-temperature annealing process is required to repair the lattice and activate the doped atoms [37–39]. However, the regulation of in situ doping during development is sometimes problematic.

This study demonstrates the selective doping technique with oxygen plasma, which has advantages such as little damage and precise control. The prevailing focus in contemporary research on p–n junction diodes is heterojunction diodes, which are mostly fabricated using two distinct channel materials. Nevertheless, the existing body of research on homojunction p–n diodes is limited, despite its advantages in terms of ease of fabrication and compatibility with conventional diode production techniques. However, the utilization of chemical doping and surface charge-transfer techniques diminishes the reliability of the device, rendering it exceedingly susceptible to the presence of moisture and oxygen in the surrounding atmosphere. The present investigation used a manufacturing methodology that included the utilization of a metal mask and oxygen plasma region-selective doping technology to successfully produce a homojunction p–n diode composed of MoTe$_2$. This approach yields no physical harm while providing exceptional stability and manageability.

2 Experimental section

Before commencing the oxygen plasma doping procedure, a photoresist shielding layer was coated onto the sample using photolithography techniques. The prepared sample was coated with a layer of photoresist, namely AZ5214, using a spin-coating technique. This process resulted in a uniform thickness of 1.5 μm. Subsequently, the device was subjected to a temperature of 110°C on a hot plate for 2 min. Following the completion of alignment, exposure, development, and drying procedures, a distinct portion of the sample was shielded and safeguarded by the photoresist, whilst the remaining portion was subjected to exposure. During the doping procedure, a flow rate of 60 standard cubic centimeters per minute (sccm) of oxygen was delivered into the vacuum chamber. The pressure inside the chamber reached a stable state at about 10 mtorr, while a radio frequency power source operating at a frequency of 1 MHz was used. The power output of the power source was modified to induce ionization of the oxygen present inside the chamber, resulting in the emission of a luminous glow. This glow was sustained at a constant power level of 5 W for a period of 60 s in inductively coupled plasma mode. During this experiment, oxygen plasma was applied to the uncovered surface of the MoTe$_2$ film, to achieve p-type doping of the material. Following the doping procedure, any residual photoresist was eliminated using acetone. In a prior investigation, the MoTe$_2$ film underwent characterization using Atomic Force Microscopy (AFM) before the doping procedure.

A lithography method was used to generate an electrode pattern, on the device channel. Following this, the device was introduced into a vacuum chamber for electron beam evaporation specifically designed for metal electrode deposition. The pressure inside the chamber was further decreased to a level below 10$^{-5}$ mtorr. The thickness of metal electrodes was kept at 10/30 nm. The device is put in acetone to lift off, resulting in the attainment of the ultimate homojunction p–n diode. Furthermore, the MoTe$_2$ was subjected to Raman characterization under ambient settings, using a laser with a wavelength of 532 nm. The objective of this investigation was to assess the quality and surface properties of the MoTe$_2$ flakes. The MoTe$_2$ device underwent electrical transport studies in a vacuum environment with a Keithley 4200-SCS parameter analyzer.

3 Results and discussion

Figure 1 illustrates the schematic diagram of the device fabrication process of MoTe$_2$ field effect transistors (FETs) corresponding to the optical image. First, 1×1 cm$^2$ SiO$_2$/Si substrate was cleaned in acetone and isopropyl alcohol. Using the scotch-tape technique, mechanically exfoliated few layers of MoTe$_2$ flake were chosen by optical
Figure 1: Schematic diagram of the MoTe$_2$ device fabrication process.

Figure 2: Schematic and characterization of MoTe$_2$ device: (a) schematic diagram of the MoTe$_2$ FETs device, (b) optical image of the device showing intrinsic and extrinsic electrodes, (c) Raman spectrum of MoTe$_2$, and (d) AFM image and line scan (green line) of the MoTe$_2$ flake.
microscope and then transferred onto SiO$_2$/Si substrate using a polydimethylsiloxane (PDMS) dry transfer process. In the next step, the photoresist/PMMA was spin-coated, and using UV/e-beam patterning, the electrode pattern was drawn, and the sample was developed before metallization. Finally, the device was put in acetone to lift off and measure the electrical characteristics of the MoTe$_2$ device.

Figure 2a illustrates the schematic diagram of MoTe$_2$ FETs, while Figure 2b presents an optical view of the device. In this device, Pd electrodes with a high work function are positioned at the plasma-doped region, while electrodes with a low work function are placed on top of the multi-layered MoTe$_2$ material in its intrinsic region. The choice of Pd was motivated by its inherent stability in atmospheric conditions and favorability to p-type materials. To fabricate the device, we used a mechanical exfoliation technique on multi-layered flakes of MoTe$_2$ obtained from bulk crystals. These flakes were then transferred onto pre-patterned outer electrodes using a dry transfer approach facilitated by a PDMS stamp. Subsequently, electrodes were fabricated on the upper surface of the MoTe$_2$ multi-layered channel. To get Raman spectra of the n-type MoTe$_2$ flake, we used a 532-nm excitation laser in an ambient atmosphere at standard room temperature. Figure 2c displays the Raman spectrum of MoTe$_2$, revealing the presence of three distinct peaks [24]. The first peak corresponds to the A$_{1g}$ mode and exhibits a peak value of 170 cm$^{-1}$. The second peak corresponds to the E$_{2g}^1$ mode and has a peak value of 234 cm$^{-1}$. Lastly, the third peak corresponds to the B$_{1g}$ mode and has a peak value of 289 cm$^{-1}$.

The use of AFM was employed to validate the layer thickness, or the quantity of layers present in the MoTe$_2$ flake, as shown in Figure 2d. The MoTe$_2$ flake exhibited a layer thickness of $\sim$5.4 nm, indicating that it consisted of roughly six layers, as visually shown by a green line [40].

FETs containing MoTe$_2$ were fabricated both before and after enduring oxygen plasma doping. The output curves corresponding to the n-type MoTe$_2$ FET are shown in Figure 3a which illustrates the output characteristics of In-In contacts on MoTe$_2$ at different gate biases. It

![Figure 3](image-url)

Figure 3: $I-V$ electrical characteristics at $T = 300$ K: (a) $I_d-V_d$ characteristics of pristine n-type MoTe$_2$ FETs, (b) $I_d-V_G$ characteristics and its logarithmic scale of pristine n-type MoTe$_2$ FETs at $V_D = 0.1$ V, (c) $I_d-V_G$ characteristics of pristine n-type MoTe$_2$ FETs as function of drain voltage, (d) $I_d-V_G$ characteristics in logarithmic scale of pristine n-type MoTe$_2$ FETs as function of drain voltage.
demonstrates a junction with ohmic-like behavior, characterized by a low resistance, as shown by the linear output characteristics. When an n-type semiconductor meets a low-work function metal, there is a phenomenon of Fermi-level alignment, leading to the movement of electrons from the semiconductor to the metal. This electron transfer occurs because the work function of the semiconductor is lower than that of the metal, resulting in the formation of an ohmic contact. The transfer curve at drain voltage \( V_D = 0.1 \) V with its logarithmic scale is shown in Figure 3b, which shows the type of intrinsic nature of the channel material. Furthermore, the transfer characteristics as a function of drain voltages and respective logarithmic scale curves are illustrated in Figure 3c and d, which demonstrate homogeneous pristine n-type MoTe\(_2\) characteristics. Figure 4a illustrates the oxygen plasma-doped output curves as a function of gate voltages. The transfer curve and its logarithmic scale of oxygen plasma-doped FETs (at \( V_D = 0.1 \) V) are shown in Figure 4b, where it shows hole dominant charge transport behavior. Furthermore, the transfer characteristics as a function of drain voltages and respective logarithmic scale curves are illustrated in Figure 4c and d, which demonstrate p-type MoTe\(_2\) characteristics. Upon the interaction between the O\(^{2-}\) species inside the oxygen plasma and the MoTe\(_2\) lattice, a resultant effect will be the creation of an acceptor impurity level. Simultaneously, the process will facilitate the extraction of electrons from the MoTe\(_2\) lattice, therefore inducing a p-type doping phenomenon. The vacancies of tellurium atoms by oxygen ions in MoTe\(_2\) induce a p-type doping effect, as seen by the shift of the Fermi level towards the valence band. The field-effect mobility \( \mu_{FE} \) of MoTe\(_2\) device with electrons and holes is calculated by using equation [41].

\[
\mu_{FE} = g_m \times \left( \frac{L}{W C_{ox} V_{DS}} \right),
\]

where \( g_m = \frac{dI_D}{dV_G} \) is the transconductance, \( L \) is the channel length, \( W \) is the width, \( C_{ox} \) is the capacitance of

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**Figure 4:** I–V electrical characteristics at \( T = 300 \) K: (a) \( I_D-V_D \) characteristics of p-type MoTe\(_2\) FETs after oxygen plasma doping. (b) \( I_D-V_G \) characteristics and its logarithmic scale of pristine MoTe\(_2\) FETs after oxygen plasma doping at \( V_D = 0.1 \) V. (c) \( I_D-V_G \) characteristics of p-type MoTe\(_2\) FETs as a function of drain voltage. (d) The \( I_D-V_G \) characteristics in logarithmic scale of p-type MoTe\(_2\) FETs as a function of drain voltage.
285 nm thick SiO₂. \( I_D \) is the source–drain current, \( V_D \) represents the drain voltage, and \( V_G \) is the gate voltage. The lateral structure for the n-type region exhibits an electron mobility of 23.54 cm² V⁻¹ s⁻¹ at room temperature, accompanied by a current on/off ratio of \( 10^6 \) at a voltage of 0.1 V. In contrast, the hole mobility in O₂ plasma-doped FET is 9.25 cm² V⁻¹ s⁻¹, along with a current on/off ratio of \( 10^5 \). The on/off ratios related to lateral structures are calculated from the logarithmic scale of transfer characteristics curves. The metal–semiconductor interface is characterized by the presence of a barrier that impedes the movement of charge carriers. This barrier is associated with a primary carrier transport process, which is elucidated by the thermionic emission theory. Figure 5a presents the oxygen plasma doping process mechanism and particle interaction with the material. The oxygen plasma was generated with low power such that oxygen concentration can be gently implanted into MoTe₂. To provide further validation of the p-type doping effect produced by oxygen plasma on MoTe₂, we proceeded to fabricate a horizontally uniform p–n junction on MoTe₂. The schematic representation of the corresponding device design is shown in Figure 5b, while Figure 5c illustrates diode behavior at \( V_G = 0 \) V and its logarithmic curve, which exhibits a rectification ratio of \( \sim 10^2 \). Furthermore, rectification curves are illustrated in Figure 5d as a function of gate voltages, (inset: logarithmic scale). The evaluation of the ideality factor \( (\eta) \) may provide an estimation of the rectifying performance of the diode and can be determined by using the Shockley diode equation [42,43].

The determination of the ideality factor may be obtained by analyzing a graph illustrating the natural logarithm of the diode current as a function of the drain voltage and then calculating the slope of this plot which gives \( \frac{e}{\eta k_B T} \). The ideality factor of our device was determined to be 1.7 at room temperature, indicating near an ideal-like diode. The MoTe₂-fabricated device exhibits the characteristic transfer behavior associated with n-type conductivity and has a notably high electron concentration. The introduction of oxygen plasma as a dopant in MoTe₂ results in a gradual shift of the majority carriers from electrons to holes. Within the proximity of the interface between doped and undoped MoTe₂, the process of carrier diffusion facilitates the migration of electrons from the n-type MoTe₂ to the p-type MoTe₂. Similarly, holes diffuse from the p-type MoTe₂ to the n-type MoTe₂. Moreover, MoTe₂ exhibits the presence of an inherent electric field inside its structure. The electric field in question has a directionality that

![Figure 5](image_url)
originates from the n-type MoTe$_2$ and extends towards the p-type MoTe$_2$.

Consequently, this electric field induces the migration of carriers inside the MoTe$_2$ material. When the equilibrium is achieved between the diffusion motion and drift motion of carriers, the overall flow of carriers ceases. The application of an external voltage to the MoTe$_2$ horizontal homogeneous p–n junction disrupts the equilibrium between carrier diffusion and carrier drift. When the polarity of the applied voltage is opposite to that of the built-in electric field, the magnitude of the carrier diffusion current exceeds that of the drift current, resulting in the activation of the p–n junction and the generation of a forward current.

When the polarity of the applied voltage aligns with the direction of the built-in electric field, the magnitude of the carrier drift current surpasses that of the diffusion current, hence obtaining unidirectional conductivity. In addition, we address the tunneling behavior of our device as charge transport property. The primary mechanism for charge transfer across the barrier is attributed to tunneling behavior, which may manifest as either direct tunneling (DT) or Fowler–Nordheim tunneling (FNT). These tunneling phenomena are mathematically characterized by the following equations [22].

**DT**

\[
I = \frac{Aq^2V^2\sqrt{2m^*\varnothing_B}}{\hbar d} \exp \left( -\frac{4\pi d\sqrt{2m^*\varnothing_B}}{\hbar} \right). \tag{2}
\]

**FNT**

\[
I = \frac{Aq^2m_0V^2\sqrt{2m^*\varnothing_B}}{8\pi\hbar d^3 m^*} \exp \left( -\frac{8\pi d\sqrt{2m^*\varnothing_B^{3/2}}}{3\hbar V} \right). \tag{3}
\]

Here, $\varnothing_B$ is the tunneling barrier height, $m_0$ is the rest electron mass, $m^*$ (0.46 $m_0$) is the effective mass of electrons in the MoTe$_2$ flake, $q$ is an electronic charge, $h$ is Planck’s constant, and $d$ is the width of the interface barrier. The plot of $\ln(I/\mathcal{V}_D^2)$ versus $(I/\mathcal{V}_D)$, all curves shown in Figure 6a, illustrated at various gate voltages. The device has exponential behavior, suggesting that the major charge carrier mechanism is DT, whereas the presence of FNT was not detected.

### 4 Conclusion

In conclusion, we have demonstrated MoTe$_2$ FETs exhibiting high charge carrier’s mobility and formation of homojunction p–n diode using single-channel MoTe$_2$ flake after the n-channel conversion to p-type channel FETs subjected to oxygen plasma doping. This study examines the impact of varying oxygen plasma doping parameters on the operational efficiency of the MoTe$_2$ single-channel homojunction p–n diode. The observed value of ideality factor demonstrates an ideal diode-like response achieved in a simple single channel, irrespective of the complex
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References


