Negative differential resistance in multilayer $MoTe_2$ FET

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***Abstract*—Recently, NDR and hysteresis in TMDCs devices have been reported for logic applications. Here, we demonstrated a NDR multilayer $MoTe_2$ device with a high peak current density of 37 mA/mm^2 and a high PVR of 2. © 2023 The Author(s)**

***Keywords*—negative differential resistance, hysteresis, transition metal dichalcogenides, logic application.**

I. Introduction

Negative differential resistance (NDR) due to the electron transfer mechanism based on transition-metal dichalcogenides (TMDCs) has attracted a lot of interest recently [1-3]. The phenomena of NDR and hysteresis has been applied for realizing logic applications [4-6]. However, the reported peak-to-valley ratio were around 1 and the peak current density were low at room temperature, which limits the practical applications. Multilayer Molybdenum ditelluride ($MoTe_2$), has relatively small energy difference between Γ valley and K valley and higher mobility than monolayer [7,8]. These make it a good candidate for electron transfer and electrical injection. In this report, we demonstrated a NDR device based on the hot-electron transfer in few layer $MoTe_2$. Peak current density ranges from 27 mA/mm^2 to 37 mA/mm^2 under different scan rates and a peak-to-valley ratio of 2 have been realized.

II. Materials And Methods

The schematic and optical image of the hBN/$MoTe_2$/Graphite heterostructure NDR device are shown in Figs.1a and 1b, respectively. All 2d materials are mechanically exfoliated from bulk materials and transferred onto gold electrode regions by a homemade micromanipulator. Gold electrodes were defined and deposited by the conventional photolithography process and thermal evaporation method. The hBN layer was used as an insulator layer and the graphite on top of $MoTe_2$ was used for carrier injection. V_S and V_D are voltages applied to source and drain (The two electrodes on the bottom of Fig.1b). V_{gs} and V_{gd} are voltages applied to gate on the side of source and drain.

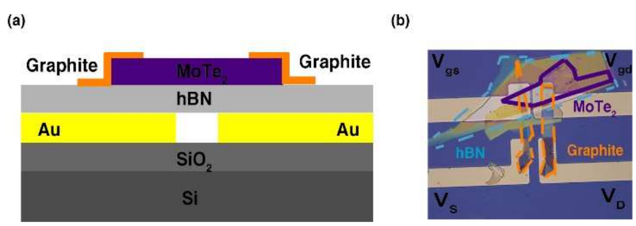

Fig. 1. The structure of multilayer $MoTe_2$ device. (a) Schematic of the hBN/$MoTe_2$/Graphite heterostructure NDR device. (b) Optical image of the NDR device. The outline of the hBN, $MoTe_2$ and graphite are marked by the dotted blue, purple and orange lines, respectively.

III. Ndr And Hysteresis

Fig.2a shows the source-drain current-voltage (I_{ds}-V_{ds}) curves under various scan rate from 2 V/s to 0.2 V/s. It is clearly seen that peak current density decreases from 37 mA/mm^2 to 27 mA/mm^2. As scan rate decreases, the speed of carrier injection gets slower, which hinders the electron transfer process and leads to reduction in current. However, the measured lowest peak current is still larger than that in monolayer TMDCs FETs [1] due to the higher mobility in multilayer TMDCs [9]. In addition, the current I_{ds} increases with the increasing voltage when V_{ds}< 10 V and follows the relationship of MOSFET ($I \sim V^2$) [10]. Further increases in voltage cause decreases in the current due to the electron transfer and scattering process [11].

Fig.2b shows I_{ds}-V_{ds} curves measured with sweeping from 0 V to 50 V (red dots) and sweeping back from 50 V to 0 V (black dots), respectively. The hysteresis is clearly shown in the current. It significantly reduced when sweeping the voltage down from a large value. The peak to valley ratio is 2, which is higher than previous work and calculated results in other TMDCs materials [1-3]. The improvement of PVR is attributed to bandgap of $MoTe_2$, as energy separation of K valley and Γ valley in bulk $MoTe_2$ is smaller than that in other TMDCs materials [12]. The small energy separation provides convenience for electron transfer and results in higher PVR of the device.

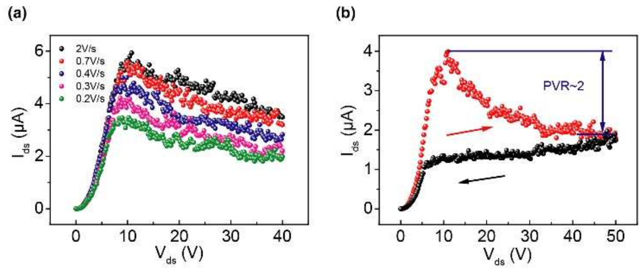

Fig. 2. Negative differential resistance and hysteresis in multilayer $MoTe_2$ based transistor. (a) Current density under different scan rate from 2 V/s to 0.2 V/s. The scan delay ranges from 100 ms to 900 ms. V_{gs} and V_{gd} are kept as 10V. (b) The hysteresis in I-V characteristics. The red and black dots represent measurements taken with the sweeping the source-drain voltage up from and down to zero, respectively. The scan rate is 700 ms and scan rate is 0.3 V/s. V_{gs} and V_{gd} are kept as 10 V.

IV. CONCLUSION

In summary, we have reported negative differential resistance in multilayer $MoTe_2$ FET based on electron transfer mechanism. The pronounced hysteresis with a PVR of 2 was realized in few layer $MoTe_2$. Simultaneously, the peak current density of the NDR device was increased up to 37 mA/mm^2 under fast scan rate. Our work has improved the NDR device performance and will promote the application for few layer TMDCs in logic and memory.

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REFERENCES

[1] G. He et al., "Negative Differential Conductance & Hot-Carrier Avalanching in Monolayer WS2 FETs," Scientific Reports, 7 (2017) 11256.

[2] C. Zhang, L. Cheng, Y. Liu, "Understanding high-field electron transport properties and strain effects of monolayer transition metal dichalcogenides," Physical Review B, 102 (2020).

[3] T. George, M.S. Islam, A.K. Dutta, A. Serov, V.E. Dorgan, A. Behnam, C.D. English, Z. Li, S. Islam, E. Pop, "High-field and thermal transport in 2D atomic layer devices," 9083 (2014) 908307.

[4] A. Nourbakhsh, A. Zubair, M.S. Dresselhaus, T. Palacios, "Transport Properties of a MoS2/WSe2 Heterojunction Transistor and Its Potential for Application," Nano Letters, 16 (2016) 1359-1366.

[5] J. Shim et al., "Phosphorene/rhenium disulfide heterojunction-based negative differential resistance device for multi-valued logic," Nature communications 7.1 (2016) 13413.

[6] C. Liu, H. Chen, X. Hou, H. Zhang, J. Han, Y.G. Jiang, X. Zeng, D.W. Zhang, P. Zhou, "Small footprint transistor architecture for photoswitching logic and in situ memory," Nat Nanotechnol, 14 (2019) 662-667.

[7] I.A. Rahman, A. Purqon, "First Principles Study of Molybdenum Disulfide Electronic Structure, " Journal of Physics: Conference Series, 877 (2017) 012026.

[8] Hyunjin Ji et al., "Thickness-dependent carrier mobility of ambipolar MoTe2: Interplay between interface trap and Coulomb scattering," Appl. Phys. Lett. 110, 183501 (2017).

[9] M.W. Lin, Kravchenko, II, J. Fowlkes, X. Li, A.A. Puretzky, C.M. Rouleau, D.B. Geohegan, K. Xiao, "Thickness-dependent charge transport in few-layer MoS2 field-effect transistors," Nanotechnology, 27 (2016) 165203.

[10] Sze, S. M., "Semiconductor Devices: Physics and Technology," Wiley,(1985).

[11] B.K. Ridley, "HOT-ELECTRONS IN SEMICONDUCTORS," Science Progress, 70 (1986) 425-459.

[12] T. Brumme, M. Calandra, F. Mauri, "First-principles theory of field-effect doping in transition-metal dichalcogenides: Structural properties, electronic structure, Hall coefficient, and electrical conductivity," Physical Review B, 91 (2015).