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# Low-voltage electric-double-layer $MoS_2$ transistor gated via water solution

Junjie Guo, Jie Jiang*, Bingchu Yang*

*Hunan Key Laboratory of Super Microstructure and Ultrafast Process, School of Physics and Electronics, Central South University, Changsha, Hunan 410083, PR China*

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ABSTRACT

Two-dimensional (2D) molybdenum disulfide ($MoS_2$) has attracted growing interests due to its intriguing electrical, optical, and scalable properties. Exploring 2D $MoS_2$-based electronic devices which are compatible with the biological systems are of great significance. Herein, a proof-of-concept water-gated multilayer $MoS_2$ transistor is successfully demonstrated by using a side-gated device architecture. Electric-double-layer (EDL) effect is observed in such water-gated multilayer $MoS_2$ transistor. The device exhibits a good performance with a high current on/off ratio of $4 \times 10^3$, a small subthreshold swing of 0.27 V/dec, and a low operation voltage of ~1.5 V, respectively. Furthermore, an ion-contributed quasi-EDL model can be further confirmed by the frequency-dependent capacitance and phase angle measurements. Such merits of water-containing systems coupled with $MoS_2$ opens new opportunities to harness the excellent physical and electrical properties of 2D $MoS_2$ for the potential bioelectronic devices integrated in biological systems for monitoring, diagnostic, and medical applications.

## 1. Introduction

Field effect transistors (FETs) are regarded as the basic building blocks in many state-of-the-art electronics devices. In recent years, two-dimensional (2D) transition metal dichalcogenides (TMD) as a series of new materials have aroused widespread concerns due to their special electrical and optical properties [1–12]. Among the different TMD, one of the most promising materials is molybdenum disulphide ($MoS_2$) [13–20]. It has an indirect bandgap of 1.2 eV for bulk forms, and increase to 1.8 eV with a direct bandgap for the monolayer $MoS_2$ [18,19]. Due to this intriguing electric structure, 2D $MoS_2$ transistors based on bottom-gated silicon oxide substrates have been fabricated and exhibit reasonable performances [14]. Presently, $MoS_2$-based FETs have attracted increasing attentions in many applications, such as the gas detectors [21], photo-electricity detectors [22] and logic circuit [23], etc.

At the same time, biocompatible wearable and implantable medical bioelectronics have attracted growing interests [24–26]. Exploring the 2D $MoS_2$-based electronic devices which are compatible with the biological systems is of great importance [13,14]. Toward this end, employing water as the gate dielectric for $MoS_2$ gating would be ideal since water is the basic and natural insulating electrolyte in biological systems. Water accounts for 70% weight of human body, which plays an utmost role in transforming nutrients, oxygen and metabolic waste in many physiological activities. Furthermore, it is also abundant, inexpensive, and environmentally friendly. In this contribution, a proof-of-concept water-gated 2D $MoS_2$ transistor is successfully demonstrated by using a side-gated device architecture. Electric-double-layer (EDL) effect is observed in such water-gated $MoS_2$ transistor. This device exhibits a good performance. Furthermore, ion-contributed quasi-EDL model is proposed to understand the device operation mechanism, which can be further confirmed by the frequency-dependent capacitance and phase angle measurements. Comparing with the work of Yuan Huang, etc [27], the novelties in our paper can be summarized as follows: (i) Water is demonstrated in our device as an efficient gate dielectric with large low-frequency capacitance, and we find that it is due to the strong electric-double-layer effect which is proposed as the underlying mechanism; (ii) The electrochemical window in the water-gated $MoS_2$ transistor is experimentally measured through the *I-V* tests. The prototype demonstration of water-gated $MoS_2$ transistor represents a great step for 2D $MoS_2$-based electronics towards many potentially bioelectronic applications.

## 2. Experimental details

Multilayer $MoS_2$ flakes were mechanically exfoliated by Scotch tape from a bulk crystal and subsequently transferred to a piece of heavily-doped silicon substrate with 300 nm $SiO_2$ capping layer. After proper $MoS_2$ flakes were selected under an optical microscope, Ni electrodes with a thickness of 30 nm were deposited by DC-sputtering and patterned using photolithography (lift-off process). The thickness of $MoS_2$

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* Corresponding authors.
*E-mail addresses:* jiangjie@csu.edu.cn (J. Jiang), bingchuyang@csu.edu.cn (B. Yang).

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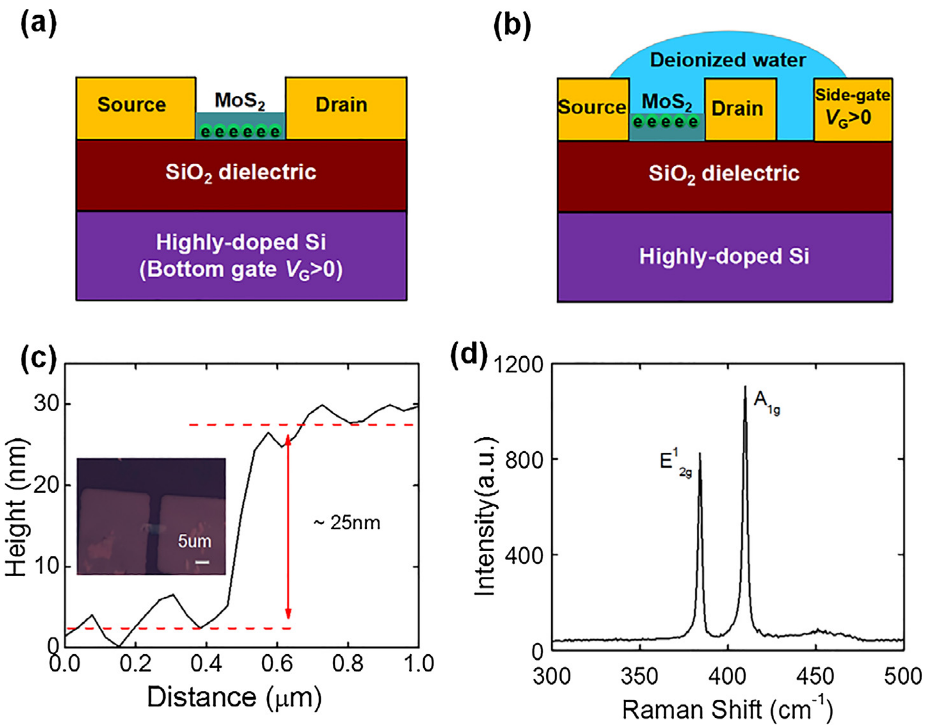

**Fig. 1.** (a) The schematic cross-section diagram of traditional bottom-gated $MoS_2$ transistor. (b) The schematic cross-section diagram of water-gated $MoS_2$ transistor. (c) AFM image at the $MoS_2$ flake edge. (d) The Raman spectroscopy for the $MoS_2$ flake.

flakes was measured by atomic force microscopy (AFM). Raman spectroscopy was used to evaluate the number of layers in $MoS_2$ besides the AFM measurement. The frequency-dependent capacitance and phase angle measurements are performed using the Hioki IM3539 LCR Meter. The I-V characteristics of the devices are measured with a Keithley 4200 semiconductor parameter analyzer at room temperature in dark. The model of photolithography device is URE-2000/35, produced by the Institute of Optics and Electronics, Chinese Academy of Sciences. DC-sputter device is produced by the Shenyang Science Instrument Co., Ltd., Chinese Academy of Sciences, having a factory number (1426112). And, the model of photoresist is PR1-2000A1.

## 3. Results and discussion

The schematic diagram of $MoS_2$ device structure can be found in Fig. 1(a) (using bottom gate, $V_G > 0$), and the schematic diagram of water-gated $MoS_2$ transistor is shown in Fig. 1(b) (using top gate, $V_G > 0$), respectively. As shown in Fig. 1(c), the thickness of as-fabricated $MoS_2$ flake was estimated to be ~25 nm from profile line information of AFM image (performed by tapping mode of AFM equipment). Based on a 0.65 nm thickness per layer value, the number of layers in this $MoS_2$ flake should be about 38 layers [14]. A clear top-view optical image of as-fabricated device can be also found in the inset of Fig. 1(c), where two Ni electrodes bridged by a $MoS_2$ flake with a channel length of 4.3 μm and width of 3.2 μm, respectively. Fig. 1(d) shows the Raman spectra of the multilayer $MoS_2$ flake with bulk properties in air ambient environment. The $E^1_{2g}$ (384 $cm^{-1}$) and $A_{1g}$ (409 $cm^{-1}$) modes are still observed in the as-fabricated $MoS_2$ flake after the lift-off process. According to the previous report, vibration of the $E^1_{2g}$ mode involves the in-plane opposing motions of sulfur and molybdenum atoms in $MoS_2$ and that of $A_{1g}$ mode is the out-of-plane relative motions of sulfur atoms in $MoS_2$ [13,28]. These two sharp peaks and almost the same peak distance ($\Delta_{\text{peak shift}} \approx 25\ cm^{-1}$) and the absence of other peaks in Raman spectra indicate that our as-exfoliated $MoS_2$ flake after the lift-off process still has the typical $MoS_2$ characteristic peaks and minimal structural modifications after the device process [29]. What's more, there aren't any other new peaks in Raman spectra except the $MoS_2$ peaks, which indicates that there are no chemical residues on our as-exfoliated $MoS_2$ flake after the lift-off process. In other wards, if there are some chemical residues on the $MoS_2$ flake surface, some other new peaks should be observed in Raman spectra. Therefore, no chemical residues exist on $MoS_2$ surface after lift-off process.

Fig. 2(a) shows the output curves of traditional bottom-gate $MoS_2$ transistor by sweeping the value of $V_{DS}$ from 0 V to 5 V with a fixed $V_{GS}$ from −15 V to 20 V, with 5 V steps. The corresponding transfer curve (log to linear) is shown by sweeping the $V_{GS}$ from −15 V to 20 V with a fixed $V_{DS}$ bias of 0.1 V in Fig. 2(b). It clearly indicates that the $MoS_2$ device operated in a typical n-type depletion-mode. Current on/off ratio ($I_{on/off}$) and subthreshold swing ($S$) are observed to be 30 and 20.81 V/dec, respectively. The threshold voltage ($V_{th}$) is extracted to be 8.6 V by extrapolating the linear portion of $I_{DS}$-$V_{GS}$ curve to a zero drain current from the transfer curve. Finally, the field-effect mobility ($\mu$) can be extracted based on the equation [29–31]:

$$\mu = \frac{L}{W \times C_i \times V_{DS}} \times \frac{dI_{DS}}{dV_G} \tag{1}$$

where the $L$ is the channel length and $W$ is the channel width, and $C_i$ is the $SiO_2$ dielectric capacitance ($\varepsilon_o$ represents the dielectric constant of vacuum, $\varepsilon_r$ represents the relative dielectric constant of $SiO_2$ ($\varepsilon_r = 3.9$), and $d$ represents the thickness of the gate insulator ($d = 300$ nm), respectively). Therefore, according to the equation (1), the $\mu$ of the $MoS_2$ device is calculated to be 3.36 $cm^2/Vs$. There are two reasons to explain the such low mobility in our $MoS_2$ device: (i) The first reason is that the low mobility may be due to the Schottky-barrier contact issue. Since no post-annealing and specific interface engineering between the channel and source/drain electrodes were adopted in our device, the calculated field-effect mobility of ~3 $cm^2/Vs$ was quite reasonable [14]. (ii) The second reason is likely that the trap/impurity states exist at the $MoS_2$/water interface in the water-gated $MoS_2$ transistor, and the scattering from these charged impurities degrades the device mobility [31].

After a drop of deionized water (produced by machine (Molresearch