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Flicker Noise in Bilayer ReS_2 Transistors on HfO_2 and its Application for pH Sensing

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Abstract

In this report, bilayer rhenium disulfide (ReS_2) field effect transistors (FETs) are demonstrated on 20 nm-thick HfO_2/Si substrate. A small threshold voltage of -0.25 V, high on/off current ratio of up to ~10^7, small subthreshold swing of 116 mV/dec, and electron carrier mobility of 6.02 $cm^2/V\cdot s$ are obtained. Low frequency noise characteristics in ReS_2 FETs are analyzed and it is found that the carrier number fluctuation mechanism well describes the flicker (1/*f*) noise of bilayer ReS_2 FETs. pH sensing using bilayer ReS_2 FET with HfO_2 as sensing oxide is then demonstrated with a voltage sensitivity of 54.8 mV/pH and a current sensitivity of 126. The noise characteristics of the ReS_2 FET based pH sensors are also examined and a corresponding detection limit of 0.0132 pH is obtained. Our studies suggest the high potential of layered ReS_2 for future low-power nanoelectronics and biosensor applications.

1. Introduction

Two-dimensional (2D) transition metal dichalcogenides (TMDs) have emerged as potential candidate materials for future digital electronics, optoelectronics and sensing applications.[1] Very recently, rhenium disulfide (ReS_2), as a new member of TMDs, has gained considerable attention owing to its promising applications for logic circuits, anisotropic electronics and sensors.[2-5] However, in most demonstrations, FETs were fabricated on a thick SiO_2 coated on highly doped Si which results in poor gate controllability with subthreshold swings (SS) of the FETs usually larger than 1 V/dec. Introducing a thin high-*k* dielectric, such as HfO_2 and Al_2O_3, to replace the thick SiO_2 is conducive to the scaling down of the gate dielectric thickness and is a promising solution for small SS and low voltage operation. In addition, low frequency noise (LFN) is another key limiting factor to the performance of nanoelectronics and this becomes more pronounced in miniaturized devices operated under low voltages.[6-7] In this report, bilayer ReS_2 FET fabricated on 20 nm-thick HfO_2 is demonstrated and its dc and noise performances, in dry and pH sensing wet environment, are both characterized.

2. Device Structure and Fabrication

As shown in **Fig. 1a**, layered ReS_2 flakes were obtained by micromechanical exfoliation of ReS_2 bulk crystal and subsequently transferred onto the 20 nm-thick HfO_2 coated Si. The source/drain regions were patterned by standard electron beam lithography. Cr/Au (3 nm/55 nm) were deposited by thermal evaporation which was then followed by a lift-off step. 20 nm Al_2O_3 was deposited by ALD to passivate the ReS_2 FETs.

3. Results and Discussion

As shown in **Figs. 1b,1c**, the thickness of the ReS_2 flake measured by AFM is about 1.4 nm, corresponding to two atomic layers. Two characteristic Raman peaks located at 150 and 210.5 cm^{-1} corresponding to the in-plane (E_{2g}) and mostly out-of-plane (A_{1g}) vibrational modes of ReS_2, respectively are observed (**Fig. 1d**). Output curves and transfer characteristics for the bilayer ReS_2 FET are depicted in **Fig. 2b-2e**. A typical n-type transport for ReS_2 FETs is observed. From the transfer curves in **Figs. 2b,2c**, a small threshold voltage (V_{th}) of -0.25 V, high current on/off ratio of ~ 10^7 and a low *SS* of 116 mV/dec are observed at V_{DS}= 0.5 V, which demonstrate the good gate controllability with 20 nm-thick HfO_2 dielectric. Besides, the bilayer ReS_2 FET exhibits nearly hysteresis free characteristics, which is mainly related to the reduction of surface adsorption of oxygen and water due to the passivation layer. The linear and symmetric drain current *vs* drain voltage (I_{DS}-V_{DS}) curves at low drain voltage from -0.2 to 0.2 V presented in **Fig. 2d** indicate an ohmic contact between Cr/Au and ReS_2 channel. Based on the derived *k* value (15.4) of the HfO_2 (**Fig. 2a**), an electron mobility of 6.02 $cm^2/V\cdot s$ is obtained for the bilayer ReS_2 FET at V_{DS} = 0.1 V. The typical power spectral densities (PSDs) of the current fluctuations (S_I) in the bilayer ReS_2 FET versus frequency (*f*) at different V_{BG} with constant V_{DS} = 0.1 V are shown in **Fig. 2g**. The S_I increases with increasing V_{BG} due to an increase of I_{DS}. As shown in **Fig. 2h**, the normalized S_I/I_{DS}^2 follows the same trend of $(g_m/I_{DS})^2$, where g_m is the transconductance of the transistor, which suggests the current noise behavior can be modeled by the carrier number fluctuation (CNF) model.

We further performed the pH sensing measurements of the ReS_2 FETs on HfO_2/Si. As shown in **Fig. 3a**, 20 nm HfO_2 as the sensing layer is deposited by ALD on highly doped Si, which is wired to the back gate of ReS_2 FET. **Fig. 3b** shows I_{DS} *vs* the liquid gate (V_{LG}) at different pH values. The transfer curves shift positively with an increase in the pH value, which can be explained that a higher pH value in the solution causes more negative charge on the HfO_2 surface. **Fig. 3c** compares the current sensitivity in the pH range from 4.22 to 5.26 in subthreshold, saturation and linear regions. A current sensitivity ($S_{pH\text{-}I}$= $(I_{pH1}$-$I_{pH2})/I_{pH2}\times100$) of 126 in the subthreshold region is significantly higher than those of 34.8 and 14.5 in the saturation and linear regions, respectively, which is due to the exponential dependence of I_{DS} on the gate voltage in the subthreshold regime. This sensitivity of 126 is significantly higher than that of 6.6 in graphene FET biosensor and comparable to recently reported values of 196, 130, and 100 in MoS_2, Si nanowire, and In_2O_3 based FET biosensors, respectively.[8,9] The shift of V_{th} with different pH value ($S_{pH\text{-}V}$) is estimated to be 54.8 mV/pH (**Fig. 3d**), a value close to the Nernstian limit of 59.2 mV/pH at room temperature. **Fig. 3e** shows the I_{DS} as a function of time. The I_{DS} increases stepwise with discrete changes in pH value and quickly goes to a stable value in each pH value.

Fig. 4a shows the typical current PSD (S_I) as a function of frequency (*f*) in pH= 5.26 solution. Normalized PSD (S_I/I_{DS}^2) is dependent on the transconductance to drain current ratio squared $(g_m/I_{DS})^2$ (**Fig. 4b**), suggesting that the LFN in ReS_2 FET under pH sensing follows the CNF model, which is similar with that in dry environment. As shown in **Fig. 4c**, the gate referred voltage PSD ($S_{VG}=S_I/g_m^2$) shows no evident dependence with pH values. Further, the pH resolution ($\Delta pH_{Min}=3\times S_{VG}^{1/2}/S_{pH\text{-}V}$), which determines the smallest pH value a sensor can respond, is measured, and the limit of detection is calculated to be 0.0132 pH at a typical sampling rate of 10 Hz with V_{DS}= 0.1 V and V_{LG}= 1 V, which is comparable with the value of 0.01 pH in Si nanoribbons ion-sensitive field effect transistor (ISFET).[10]

4. Conclusions

Bilayer ReS_2 FETs on 20 nm-thick high-*k* HfO_2 were fabricated and studied. A small threshold voltage of -0.25 V, high on/off current ratio of ~10^7, low *SS* of 116 mV/dec and electron mobility of 6.02 cm^2/Vs are obtained. Current fluctuation in ReS_2 FETs is comprehensively analyzed for the first time. It is found that the CNF model dominates in the current flicker (1/*f*) noise. pH sensing based on ReS_2 FETs are demonstrated with HfO_2 sensing layer, exhibiting a sensitivity of 54.8 mV/pH and a detection limit of 0.0132 pH. The dc, noise and pH sensing characteristics of ReS_2 transistor on high-*k* dielectric presented here could pave the way for nanoelectronic devices and sensing applications.

References [1] K. Novoselov *et al*. Science **306** (2004) 666. [2] E. Liu *et al*. Nat. Commun. **6** (2015) 6991. [3] D. Chenet *et al*. Nano Lett. **15** (2015) 5667. [4] E. Liu *et al*. Adv. Funct. Mater. **26** (2016) 1938. [5] R. He *et al*. Nano Lett. **16** (2016) 1404. [6] J. Shim *et al*. Adv. Mater. **28** (2016) 6985. [7] A. Balandin, Nat. Nanotechnol. **8** (2013) 549. [8] H. Chen *et al*. ACS Nano **11** (2017) 4710. [9] D. Sarkar *et al*. ACS Nano **8** (2014) 3992. [10] N. Rajan *et al*. Appl. Phys. Lett. **104** (2014) 084106.

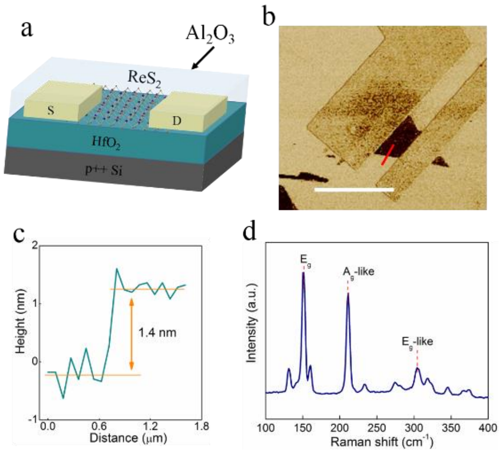

Figure 1. (a) Sketch of the ReS_2 FET on 20 nm HfO_2/Si substrate. A layer of 20 nm Al_2O_3 on top of the device is used as the passivation layer. (b) An optical image of a pair of Cr/Au electrodes deposited on bilayer ReS_2 flake. The length and width of the ReS_2 channel is 1.72 μm, and 3.01 μm, respectively. The scale bar is 10 μm. (c) AFM image of the bilayer ReS_2 FETs on HfO_2. (d) Measured height at the flake edge of ReS_2 flake. (e) Raman spectrum of the bilayer ReS_2 flake. Two main Raman peaks located at 150 and 210.5 cm^{-1} are observed, which correspond to the in-plane (E_{2g}) and mostly out-of plane (A_{1g}) vibrational modes of ReS_2, respectively.

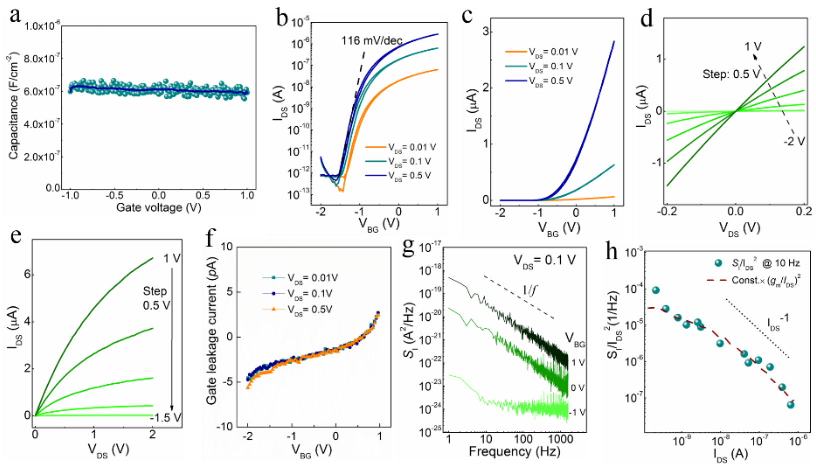

Figure 2. (a) The C-V curve of a metal-HfO_2-p++ Si capacitor as a function of gate voltage at 1 MHz. The capacitance density of 20 nm-thick HfO_2 was determined to be 6.7×10^{-7} F/cm^2 and a dielectric constant (k) of 15.4 was extracted. (b) I_{DS} versus V_{BG} with fixed V_{DS} at 0.01, 0.1 and 0.5 V plotted in logarithmic scale. (c) I_{DS} versus V_{BG} with fixed V_{DS} at 0.01, 0.1 and 0.5 V plotted in linear scale.(d) I_{DS} as a function of V_{DS} ranging from -0.2 to 0.2 V with the V_{BG} varying from -2 to 1 V in steps of 0.5 V. (e) I_{DS} as a function of V_{DS} ranging from 0 to 2 V with V_{BG} varying from -2 to 1 V in steps of 0.5 V, showing the linear and saturation region. (f) The gate leakage as a function of the V_{BG} with V_{DS} at 0.01, 0.1 and 0.5 V. The total contact pad area is 6×10^4 μm^2. Note that the gate leakage current is less than 6 pA in the V_{BG} range of -2 to +1 V. (g) Typical S_I as a function of frequency with different V_{BG}. The value of V_{DS} is kept at 0.1 V. The dashed line indicates the slope of $1/f$. (h) Normalized PSD (S_I/I_{DS}^2) and a constant $\times(g_m/I_{DS})^2$ as a function of I_{DS}. The dotted line indicates the slope of $1/I_{DS}$.

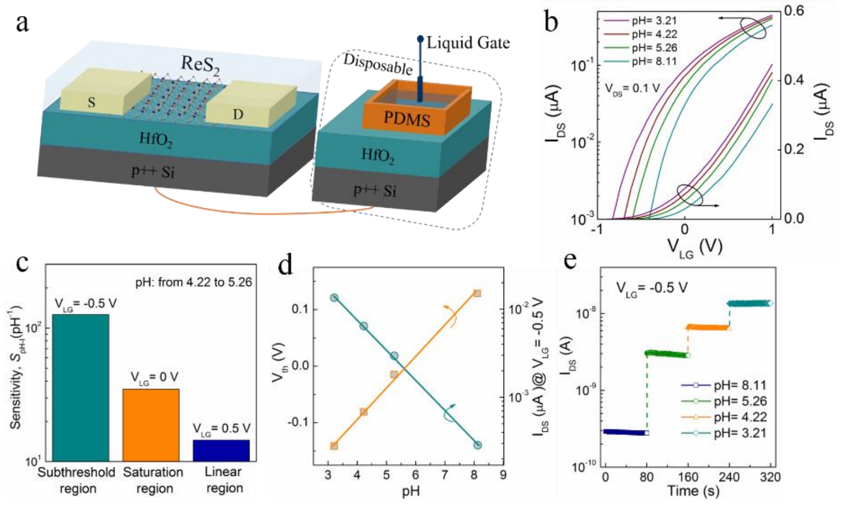

Figure 3. (a) A schematic diagram of a ReS_2 FET for pH sensing. A Ag/AgCl electrode is used as the liquid gate. A poly(dimethylsiloxane) (PDMS) reservoir with size of 0.6×0.4×0.4 mm (Length × Width × Height) is glued onto the HfO_2 by epoxy to hold the PBS solutions. (b) Transfer curves (I_{DS}-V_{LG}) at different pH values (3.21, 4.22, 5.26 and 8.11) in both logarithmic and linear scale. The V_{DS} is kept at 0.1 V. (c) Sensitivity (S_{pH-I}) in subthreshold, saturation and linear regions for a pH change from 4.22 to 5.26 calculated from the transfer curves shown in (b). (d) The shift of the V_{th} and change of the I_{DS} of ReS_2 FET as a function pH value. The linearity of the V_{th} shift over the pH range from 3.21 to 8.11 is calculated to be 99.81%. (e) Response curve for pH sensing with V_{DS}= 0.1 V and V_{LG}= -0.5 V at room temperature.

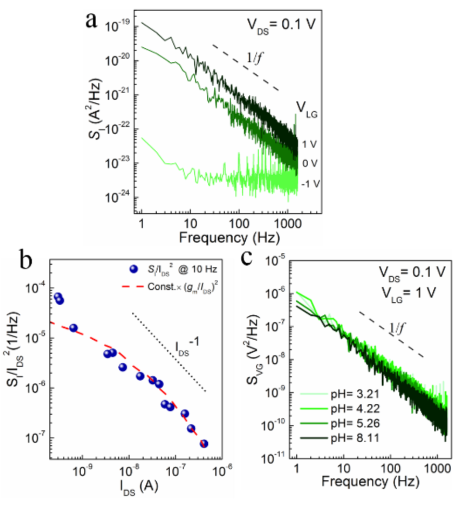

Figure 4. (a) The typical S_I as a function of frequency (f) in pH= 5.26 PBS solution with different ligquid voltage V_{LG}. The V_{DS} is kept at 0.1 V. (b) S_I/I_{DS}^2 and a constant $\times(g_m/I_{DS})^2$ as a function of I_{DS} (in pH= 5.26 solution). The dotted line indicates the slope of $1/I_{DS}$. (c) Voltage PSD (S_{VG}) as a function of frequency (f) in PBS solution with different pH values at V_{LG}= 1V and V_{DS}= 0.1 V.

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