High-Frequency Performance of MoS_2 Transistors at Cryogenic Temperatures

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Abstract

Recently, due to its potential in high-speed flexible electronics, radio-frequency transistors based on two-dimensional MoS_2 has attracted the interest of researchers. However, for the moment, little is known on the RF performance of MoS_2 transistors at cryogenic temperatures, which is important for evaluating performance limits of high-frequency MoS_2 devices. In this work, we report the RF performance of MoS_2 transistors at cryogenic temperatures based on chemical vapor deposited bilayer MoS_2 for the first time. As the temperature reduces, the higher cut-off frequency was achieved. At the liquid helium temperature, extrinsic and intrinsic f_T of 5.7 and 12.7 GHz for the transistor with 300 nm gate-length were achieved. Furthermore, saturation velocity and intrinsic f_{max} of 2.4×10^6 cm/s and 24 GHz were obtained at 4.3 K, respectively. The revealed high-frequency performances of MoS_2 transistors at cryogenic temperatures are helpful to the advancement of MoS_2 high-frequency electronics.

1. Introduction

Recently, the radio-frequency performance of two-dimensional molybdenum disulfide has attracted extensive attention due to it is important for future ubiquitous electronics, such as novel flexible rectenna, amplifier, and mixer [1-3]. Exfoliated MoS_2 radio-frequency (RF) transistors with extrinsic f_T/f_{max} of 10.2/14.5 GHz, and CVD MoS_2 RF transistors with extrinsic f_T/f_{max} of 7.2/23 GHz have been demonstrated by different groups [1, 4]. Zhang *et al.* presented a flexible and multifunction Wi-Fi-band rectenna based on MoS_2 Schottky diodes with a well-designed source and drain contact electrodes [3]. In modern society, many interesting physics phenomena were observed at low temperatures and a number of applications require cryogenic operation. However, no MoS_2 RF transistors have been operated and studied at cryogenic temperatures [5].

In this work, we carried out the first study of MoS_2 RF transistors down to liquid helium temperatures. The transconductance was obviously improved with the temperature reducing from 250 K down to 4.3 K. As the temperature reduced to 4.3 K, extrinsic cut-off frequency f_T increased from 3.2 GHz to 5.7 GHz and intrinsic f_T increased from 5.7 to 12.9 GHz for the transistor with gate length of 300 nm, and a maximum $f_T \cdot L_g$ of 3.87 GHz·μm was achieved.

(a) (b)

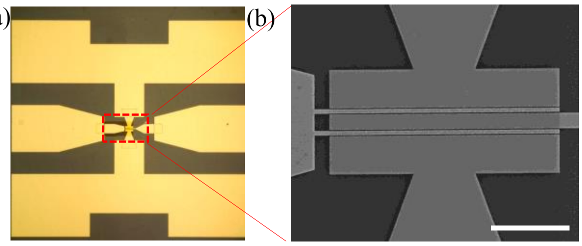

Figure 1. (a) Optical microscopy of the fabricated MoS_2 RF transistor. (b) SEM image of the two-finger top-gated MoS_2 RF transistor with 300 nm gate length. Scale bar 5 μm.

2. Experimental

Chemical vapor deposited bilayer MoS_2 was grown on molten glass at about 830 °C. Using PMMA as a protective layer, the MoS_2 film was transferred onto high-resistance silicon substrate with atomic layer deposited HfLaO. Excess MoS_2 outside the channel and contacts was etched using O_2/Ar plasma. Then, the source and drain S/D contacts consist of 20 nm Ni flim and 60 nm Au film was fabricated using electron-beam lithography (EBL) and electron-beam evaporation (EBE). The top gate dielectric layer is composed of 6 nm naturally oxidized Al_2O_3 and 11 nm atomic layer deposited HfO_2. At last, top-gate electrodes were formed as the same process as S/D electrodes with 20/60 nm Ni/Au. Here, a two-finger top gate structure with an

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underlap arrangement was adopted to improve the current transport as well as to reduce parasitic capacitances between top-gate and S/D electrodes [6]. Figure 1a shows an optical microscope of the fabricated MoS_2 RF transistor with the ground-signal-ground (GSG) configuration. The standard GSG pads were designed to transmit the high-frequency signal from microwave coaxial cables to the MoS_2 RF transistor with coplanar waveguide electrodes. Figure 1b displays the SEM image of the two-finger top-gated MoS_2 transistor with L_g = 300 nm, and the distance between gate and S/D electrodes are about 75 nm.

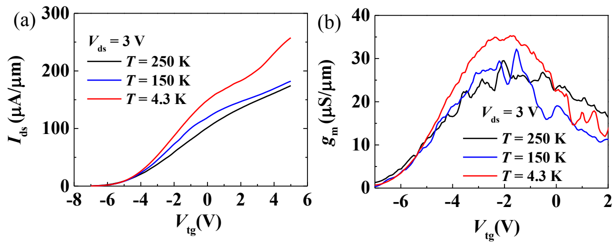

Figure 2. (a) Transfer characteristics (I_{ds}–V_{tg}) of the MoS_2 device at cryogenic temperatures. (b) The corresponding transconductance g_m of the device.

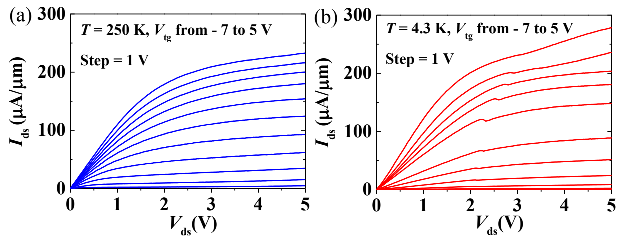

Figure 3. Output characteristics (I_{ds}–V_{ds}) of the same MoS_2 device at 250 K(a) and 4.3 K(b).

3. Results and Discussion

Using the Lakeshore probe station and the Agilent B1500A semiconductor parameter analyzer, the DC characterization of the MoS_2 transistors at cryogenic temperatures was performed. Figure 2a shows the transfer characteristics (I_{ds}-V_{gs}) of the 300-nm MoS_2 RF transistors at high drain bias of 3 V from 250 K to 4.3 K. The on-current at V_{gs} = 5 V increases from 174 μA/μm to 257 μA/μm with temperature reduced from 250 to 4.3 K. The corresponding transconductance dependence on gate voltage was shown in Figure 2b, and the highest transconductance of 35 μS/μm at 4.3 K was achieved. These improvements in on-current and transconductance could be attributed to the reduced phonon scattering from the underlying substrate with temperature reduction [7]. Figures 3a and 3b show the I_{ds}-V_{ds} curves at 250 K and 4.3 K at different gate voltages of the 300-nm MoS_2 RF transistors, respectively. A clear current density improvement in 4.3 K could be observed, which is consistent with the transfer characteristics.

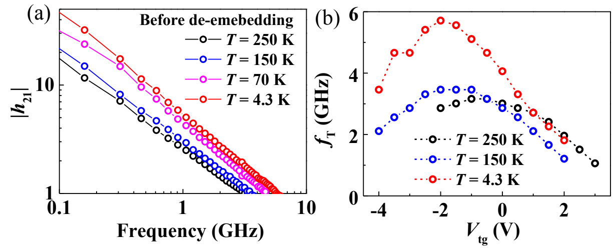

Figure 4. (a) Measured current gain $|h_{21}|$ of the MoS_2 RF transistor at cryogenic temperatures. (b) The dependence of cut-off frequency f_T with gate voltage V_{tg} at different temperatures.

In order to characterize the RF performance of MoS_2 transistors at low temperatures, we used Lakeshore cryogenic probe stations and Agilent N5225A vector network analyzers to perform standard on-chip S-parameter measurements. Before S-parameter measurements, standard short-open-load-through (SOLT) calibration method was adopted to calibrate-out the response of the network analyzer, cables, and probes. Then, cut-off frequency f_T of the MoS_2 RF transistors at cryogenic temperatures can be obtained. Cut-off frequency corresponds to the maximum frequency with current gain, and which is an important quality factor to evaluate the high-frequency performance of RF transistors. Mathematically, it can be expressed as

$$|h_{21}(f = f_T)| = 1 \quad (1)$$

where $|h_{21}(f)|$ represents the relationship between the current gain and frequency. And $|h_{21}(f)|$ can be obtained from the measured Y-parameters of the transistors.

$$h_{21}(f) = \frac{Y_{21}(f)}{Y_{11}(f)} \quad (2)$$

Measured extrinsic $|h_{21}(f)|$ characteristics of the MoS_2 RF transistor at several cryogenic temperatures are shown in Figure 4a. The corresponding peak cut-off frequencies at 250 K, 150 K, 70 K, and 4.3 K are 3.2 GHz, 3.5 GHz, 4.7 GHz, and 5.7 GHz, respectively. There is approximately an 80% improvement in f_T at 4.3 K. This improvement can be attributed to the higher carrier mobility and saturation velocity at a lower temperature due to the reduced scattering from both surface phonons and interface traps [1, 8]. Figure 4(b) shows the plot of f_T versus gate voltage (V_{tg}) at different temperatures. It can be found that the high-frequency operation of the MoS_2 transistor at different temperatures is highly dependent on the dc bias condition. The f_T of a MoS_2 RF transistor can be expressed with

$$f_T = \frac{g_m}{2\pi[(C_{gs}+C_{gd})\bullet(1+(R_s+R_d)g_o)+C_{gd}\bullet g_m\bullet(R_s+R_d)]} \quad (3)$$

where R_s and R_d are the source and drain access resistances, g_o is the output conductance, g_m is the transconductance, C_{gs} and C_{gd} are the gate-source and gate-drain capacitances, respectively [9]. As shown in

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Figures 2b and 4b, a strong correlation between g_m and f_T can be observed, which is consistent with formula (3).

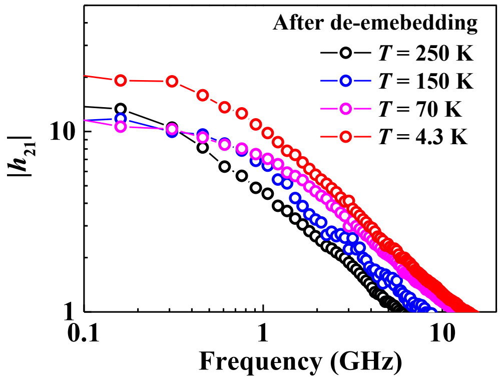

Figure 5. The short-circuit current gain $|h_{21}|$ after standard deembedding of the 300 nm MoS_2 RF transistor at cryogenic temperatures.

In order to obtain the intrinsic frequency performance of MoS_2 transistors, the standard de-embedding process was performed to minimize the parasitic effects on performance evaluation [10]. The short-circuit current gains of different temperatures after de-embedding are shown in Figure 5. The corresponding intrinsic f_T at 250 K, 150 K, 70 K, and 4.3 K are 5.7 GHz, 7.8 GHz, 11.8 GHz, and 12.9 GHz, respectively. Usually, f_T is inversely proportional to channel length, so the product of frequency and gate length ($f_T \cdot L_g$) is a useful metric to evaluate the high-frequency performance of RF transistor. From the maximum f_T obtained at 4.3 K, a $f_T \cdot L_g$ of 3.87 GHz·μm was demonstrated, which is among the highest range of MoS_2 high-frequency transistors [1]. Furthermore, using the expression $v_{sat} = 2\pi f_T L_g$, carrier saturation velocity of 2.4×10^6 cm/s is obtained. Maximum frequency of oscillation, f_{max}, is another important figure-of-merit for RF transistors. It is the frequency at which the power gain of an RF transistor equal to 1. For the 300-nm MoS_2 transistors, the extrinsic and intrinsic f_{max} extracted at 4.3 K are 16 and 24 GHz, respectively.

4. Summary

In this work, a study of the performance of a 300 nm gate-length MoS_2 transistor at cryogenic temperatures has been presented. Key figure-of-merit f_T has been studied systematically at various temperatures. As the temperature reduces, clear cut-off frequency improvement could be observed, and the highest extrinsic and intrinsic f_T of 5.7 and 12.9 GHz was achieved at 4.3 K. Meanwhile, intrinsic f_{max} of 24 GHz and high experimental saturation velocity of 2.4×10^6 cm/s were demonstrated at liquid-helium temperature. These results clearly demonstrated the potential of MoS_2 transistors in the applications of high-frequency electronics at cryogenic temperatures and are important to improve the high-frequency performance of MoS_2 transistors.

Acknowledgments

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