MoS$_2$ Field-Effect Transistors With Graphene/Metal Heterocontacts

Yuchen Du, Lingming Yang, Jingyun Zhang, Han Liu, Kausik Majumdar, Paul D. Kirsch, and Peide D. Ye, Fellow, IEEE

Abstract—For the first time, n-type few-layer MoS$_2$ field-effect transistors (FETs) with graphene/Ti as the heterocontacts have been fabricated, showing more than 160-mA/mm drain current at 1-µm gate length with an ON-OFF current ratio of $10^7$. The enhanced electrical characteristic is confirmed in a nearly 2.1 times improvement in ON-resistance and a 3.3 times improvement in contact resistance with heterocontacts compared with the MoS$_2$ FETs without graphene contact layer. Temperature-dependent study on MoS$_2$/graphene heterocontacts has been also performed, still unveiling its Schottky contact nature. Transfer length method and a devised $I$–$V$ method have been introduced to study the contact resistance and Schottky barrier height in MoS$_2$/graphene/metal heterocontacts structure.

Index Terms—MoS$_2$, graphene, heterocontacts, MOSFET, Schottky barrier height.

I. INTRODUCTION

GRAPHENE and other two-dimensional (2D) materials are the rapidly rising stars on the horizon of materials science, condensed-matter physics, and solid state devices. They stand for a brand new family of materials that are one or few atomic layer thick, and offer many new research directions towards nanoscience and nanotechnology. However, the gapless nature of monolayer graphene has restrained its wide electronic device applications, in particular for logic circuits [1]. Transition metal dichalcogenides (TMDs), another type of 2D materials, recently attracted wide attentions due to their appropriate bandgap and reasonable mobility. Owing to its unique structural and electronic properties, TMDs provide us novel material systems to explore interesting phenomena, such as 2D interfaces, which might be not available to be investigated in the traditional Si and III-V semiconductors. As one of the most studied TMDs, MoS$_2$ has a bandgap between 1.3-1.8 eV, depending on the number of layers, and reasonable mobility [2], [3]. The on-state performance of the MoS$_2$ FETs is mainly limited by the large contact resistance at MoS$_2$/metal interfaces [4]–[9]. Recent attempts to improve MoS$_2$ contacts had been concentrated on the following areas using: (1) low work function contact metal [10], (2) gas doping of MoS$_2$ flakes [11], and (3) molecular or solid doping on MoS$_2$ films [12], [13]. However, the fundamental reason for the large contact resistance is the result of Fermi level pinning on MoS$_2$ near conduction band edge due to S-vacancy defect level and charge neutral level location [14], [15]. All above experiments have just partially touched the issue and barely resolved the issue completely. Graphene contacts on MoS$_2$ [9], which has a 2D to 2D interface, might provide a new angle to solve this technical challenge. In this letter, graphene is used in between metal contact and n-type few-layer MoS$_2$ film to enhance the electronic coupling between metal and MoS$_2$ and boost the electron injection into MoS$_2$. For the first time, well-performed graphene/metal hetero-contacts MoS$_2$ FETs were fabricated. The feasibility using graphene/metal hetero-contacts to reduce contact resistance ($R_c$) and improve on-resistance ($R_{on}$) of the devices is demonstrated.

II. EXPERIMENT

MoS$_2$ flakes with 5-6nm thickness were mechanically exfoliated from bulk ingot (SI Supplies) by standard scotch tape technique, and then transferred to a heavily p-doped silicon substrate with a 90 nm SiO$_2$ capping layer. Monolayer CVD graphene grown on Cu foil (Graphene Supermarket Inc.) was transferred onto the MoS$_2$/SiO$_2$/Si wafer with the PMMA method: A 500 nm PMMA (10% in Anisole) layer was first spin-coated on graphene/Cu. The copper substrate was etched using 1M FeCl$_3$ solution. After rinsing in DI water for several times, the PMMA/graphene layer was transferred onto the target substrate. The sample was dried in N$_2$ ambient for 12 hours, and then PMMA was removed by rinsing in acetone bath. An additional H$_2$/N$_2$ annealing at 450 °C was used to remove the PMMA residues. After the graphene film transfer onto the MoS$_2$/SiO$_2$/Si substrate, electron beam lithography was used to pattern the source and drain contacts, combining with low power oxygen etch to isolate the source/drain, and the different devices. Graphene is fully etched from the channel. Metallization was performed by electron-beam evaporation of 20 nm/60 nm Ti/Au with the size 50 nm smaller at each side than graphene contacts as illustrated in Fig. 1. In order to


This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.
have accurate comparison, similar device without monolayer graphene were also fabricated on few-layer MoS$_2$ with a similar thickness and the same channel length. Electrical measurements were carried out with Keithley 4200 semiconductor parameter analyzer and probe station in ambient atmosphere.

### III. RESULTS AND DISCUSSION

Output and transfer curves of a hetero-contacts FET are plotted in Fig. 2(a) and (b) to demonstrate its effectiveness to improve device performance by inserting monolayer graphene between metal and MoS$_2$ contacts. The output curves of a reference sample are also shown in Fig. 2(a) in black. For the device contact without graphene, shown in Fig. 2(a), on-current at $V_{ds} = 4$ V, and $V_{bg} = 30$ V is equal to 48.5 mA/mm. As the monolayer graphene applied in the hetero-contacts, on-current is improved to be 161.2 mA/mm at the same source/drain and gate bias. $R_{on}$ determined from linear region as shown in Fig. 2(a) as dashed lines are used to have a direct comparison. Comparing to $R_{on}$ of 42.8 $\Omega$·mm for the reference device, hetero-contacts device shows a much lower $R_{on}$ of 20.6 $\Omega$·mm. In order to have a more accurate comparison, metal contacts with and without graphene on the same flake have also been fabricated. Similar values of $R_{on}$ and similar amount of reduction in $R_{on}$ have been achieved. The results further verified the feasibility of using graphene/metal hetero-contacts to improve on-resistance of the devices. With similar channel resistance of two devices, the nearly 2.1 times dropping in $R_{on}$ is directly related to the reduction of $R_{on}$ by inserting monolayer of graphene into contact. In Fig. 2(b), the transfer curves of hetero-contacts FETs are plotted with source/drain biases of 0.2 V. The exhibiting hysteresis from forward and backward sweeps is due to the charge injection at the interface between MoS$_2$ and the substrate and the charge transfer from/to neighboring adsorbates [16]. The $10^7$ current on/off ratio is achieved on hetero-contacts devices. Extrinsic field-effect mobility of hetero-contacts FETs is calculated to be 32.3 $cm^2/Vs$, which is extracted from the forward I-V transfer curves by the relation,

$$
\mu = \frac{dI_{ds}}{d(V_{bg})} \times \frac{L}{W \times C_{ox} \times V_{ds}}
$$

where $\frac{dI_{ds}}{d(V_{bg})}$ is the transconductance, $L$ is the channel length, $W$ is the channel width, and $C_{ox}$ is the backgate capacitance per unit area. Using $R_{C}$ of hetero-contacts device $\sim 3.7$ $\Omega$·mm, intrinsic field-effect mobility of 50.4 $cm^2/Vs$ is obtained.

A devised I-V method has been used to quantitatively investigate the Schottky barrier height of hetero-contacts of MoS$_2$/graphene/metal [17]. The barrier height is calculated from the current $I_s$, determined by extrapolating the semilog $I_q$ versus $V_d$ curve to $V_d = 0$ V. Schottky barrier height $I_s$ is calculated from $I_s$ according to

$$
\phi_B = \frac{K_B T}{q} \ln\left(\frac{A \times A^* \times T^2}{I_s}\right)
$$

where $A$ is the area, $A^*$ is the Richardson constant, and $T$ is the temperature. Due to the uncertainty of $A^*$ [17], the effective Schottky barrier height cannot be accurately calculated directly, however, instead of calculating the exact value of Schottky barrier height, exponential function of barrier height can be readressed. Normalized exponential Schottky barrier height versus backgate voltage has been plotted in Fig. 3(a) to demonstrate the Schottky barrier deduction with graphene contact. Moreover, transfer length method (TLM) with separations of 0.5 $\mu$m, 1 $\mu$m, 1.5 $\mu$m, and 2 $\mu$m are used to accurately extract the contact resistance of MoS$_2$/graphene/metal hetero-contacts. Contact resistance without graphene has also been extracted by applying TLM structure on a similar thickness flake. In Fig. 3, both Schottky barrier and contact resistance show a strong gate bias dependent behavior. It is because (1) gate-tunable Schottky barrier width reduction due to the increment of backgate bias and (2) carrier concentration enhancement from backgate bias doping, where all lead to reduce the effective Schottky barrier height and generate more injected electrons from Fermi level at metal to conduction band of MoS$_2$. To exclude the large absolute errors, high bias regions are appropriate to have direct comparison in the contact resistance. Contact resistance with monolayer graphene is $3.7\pm0.3$ $\Omega$·mm at $V_{bg} = 30$ V, which decreased from a value of $12.1\pm1.2$ $\Omega$·mm at the same backgate voltage without the graphene layer. This nearly 3.3 times reduction in contact resistance may possibly be attributed to the gate-induced electron injection from graphene layer to MoS$_2$. At the hetero-contact structure, the positive back-gate bias not only electro-statically dopes MoS$_2$, but also could move the Fermi-level in Ti doped n-type graphene [18]–[21] further up beyond the Ti/MoS$_2$ pinning level, thus enhance the electron injection from metal into the conduction band of MoS$_2$ leading to a lower contact resistance. The key difference from previous devices is that the back-gate can modulate not only the Fermi-level of the channel but also the contact (graphene) as shown in the inset of Fig. 3(b) [19]. The total carrier density summed over graphene and MoS$_2$ hetero-contact exceeds the single MoS$_2$/metal contact, where the monolayer graphene can be deemed as a “charge pumping” layer. It seems that 2D graphene to MoS$_2$ interface is fundamentally different from metals to MoS$_2$ interfaces.

Temperature dependent measurements of graphene/metal contact on MoS$_2$ have been also performed. Substrate temperatures are changed from 300 K to 400 K, and the electrical transport properties are reported in Fig. 4. As the temperature goes up, thermal-assistant tunneling improves the electron injection efficiency from the hetero-contacts to MoS$_2$ channel through the Schottky barrier, thus lowering the
Graphene hetero-contacts effectively reduce the contact resistance from 12.1±1.2 Ω-mm to 3.7±0.3 Ω-mm, compared to the reference MoS2/metal contacts. The nearly 3.3 times improvement in $R_c$ is attributed to the gate-enhanced electron injection from metal doped n-type graphene into MoS2 conduction band, which provides a new route to engineer 2D contacts towards the realization of Ohmic contacts on MoS2 and other 2D materials.

IV. CONCLUSION

In summary, we have demonstrated the first MoS2 field-effect transistor with graphene-metal hetero-contacts.