High-Performance MoS2 Field-Effect Transistors Enabled by Chloride Doping: Record Low Contact Resistance (0.5 kΩ·μm) and Record High Drain Current (460 μA/μm)

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Abstract

In this paper, we report a novel chemical doping technique to reduce the contact resistance (Rc) of transition metal dichalcogenides (TMDs) – eliminating two major roadblocks (namely, doping and high R) towards demonstration of high-performance TMDs field-effect transistors (FETs). By using 1.2 dichloroethane (DCE) as the doping reagent, we demonstrate an active n-type doping density > 2×10^{15} cm^{-2} in a few-layer MoS2 film. This enabled us to reduce the Rc value to a record low number of 0.5 kΩ·μm, which is ∼10×lower than the control sample without doping. The corresponding specific contact resistivity (ρc) is found to decrease by two orders of magnitude. With such low Rc, we demonstrate 100 nm channel length (Lc) MoS2 FET with a drain current (Ids) of 460 μA/μm at Vds = 1.6 V, which is twice the best value reported so far on MoS2 FETs.

Introduction

Semiconducting TMDs possess unique electrical and optical properties due to their d-electron orbitals and 2D nature [1,2]. Among TMDs, MoS2 has attracted the most attention for its potential applications in low-power electronics [3,4]. However, high Rc value limits the device performance of MoS2 FETs significantly and the realization of ohmic contacts for MoS2 remains a challenge so far [5]. There were several attempts to reduce Rc including use of low workfunction metal [6] and employing edge contact concept [7]. One of the keys to resolve this issue is to dope the MoS2 film, however doping the atomically thin film is nontrivial and requires a simple and reliable process technique [8-10]. In this work, we demonstrate such a doping technique enabling high-performance MoS2 FETs.

Fabrication and Physical Characterization

Fig. 1(a) schematically shows the MoS2 back-gate FET fabricated in this work. Few-layer MoS2 flakes were mechanically exfoliated from bulk MoS2 on a 90 nm SiO2/p+ Si substrate and then soaked in DCE. Acetone and isopropanol rinses were used to remove the residue of the chemical. After e-beam lithography, Ni (30 nm)/Au (60 nm) were deposited to form S/D contacts. The thickness of the MoS2 flake was identified by the optical image (Fig. 2(a)) and measured by the AFM (Fig. 2(b)). The flake thickness was ∼4 nm, corresponding to about 6 monolayers. Fig. 2(c) shows a SEM image of a fabricated TLM structure. The presence of Cl in DCE treated MoS2 film was confirmed by XPS and SIMS, as shown in Fig. 3 (a) and (b). In Fig. 4, we observe a relative blue shift in the binding energies of the core level peaks of the MoS2 sample that was treated with DCE, which results from an upward shift in the Fermi level, and hence can be attributed to an n-type doping of the sample. However, we note that Cl, when acts as an adatom dopant, results in p-type doping in MoS2 film [11]. Thus, such n-type doping can be attributed to the donation of extra electron when substitution of S2− by Cl takes place, particularly at the sites of sulfur vacancies in the MoS2 film.

Contact Resistance Reduction

The TLM resistances of MoS2 FETs at 50 V back-gate-bias (Vbg) with and without the Cl doping are plotted as a function of contact separations in Fig. 5(a). The extracted Rc is significantly reduced from 5.4 kΩ·μm to 0.5 kΩ·μm after the Cl doping. Such an improvement in Rc is attributed to the doping induced thinning of tunneling barrier width. In Fig. 6, we observe that the extracted Rc is a weak function of temperature (although the sheet resistance changes by a factor of 2), indicating the dominance of tunneling component of the current over thermionic component at the contact interface. In order to determine the ρc, the transfer lengths (Lch) of Ni-MoS2 junctions are extracted by the TLM and are determined to be 60 nm and 590 nm for the contacts with and without the Cl doping, respectively. Compared with the control sample without the Cl doping, the ρc is reduced from 3×10^-7 Ω·cm to 3×10^-9 Ω·cm when the DCE treatment time is 36 hours, as shown in Fig. 7. The n-type doping concentration (N) by chloride is ~2×10^{15} cm^{-2} extracted from the slope of the TLM fitting when Vgs is 0 V. Fig. 8 shows the channel resistance and the Rc as a function of Vgs for a 1 μm device. Usually in back-gated MoS2 FETs, Rc strongly depends on Vgs because Vgs would electrostatically dope the semiconductor underneath the contact, thus reducing the Rc. In this work, the Rc shows very weak dependence on Vgs when Vgs is larger than -30 V, indicating heavily doped S/D regions are realized. Since back gate is not necessary for achieving the low Rc any more, it paves the way to realize three-terminal top-gate low-R MoS2 FETs. The present Cl doping technique with DCE treatment is also valid for the other TMD materials such as WS2, whose Eπ is pinned near the middle of the bandgap.

Electrical Performance of MoS2 FET

Fig. 9 shows the output characteristics of 100 nm Lc MoS2 FETs with and without the Cl doping. The reduced Rc helps to boost the Ic from ~ 110 μA/μm to 460 μA/μm at Vgs = 1.6 V, which is twice of the best reported value so far on MoS2 FETs at the same Lc [6]. Fig. 10 shows the components of total resistance (Rtotal) indicating mitigation of the adverse dominance of high Schottky S/D contact resistance (Rc) at 100 nm Lc. Such reduction in Rc also results in excellent current saturation, as observed in Fig. 9. The transfer characteristics of the two devices are shown in Fig. 11. Due to its relatively large bandgap and ultra-thin channel, we achieved an excellent I/Lc of ~6.3×10^{4}. Considering the thick gate oxide (90 nm) used in this work, the Ic/Lc ratio can be further improved by EOT scaling down. As shown in Fig. 12, the intrinsic long channel field-effect motility (μFE) as a function of gate electric field is calculated for different Lc by approximately eliminating the Rc effect with a peak μFE of 50-60 cm²/Vs. Fig. 13 benchmarks the Ic/Vgs = 1.6 V and the Rc for MoS2 FETs in literature [5-7, 12-13]. Due to the significant reduction of Rc, the present work shows superior performance at various Lc compared with existing literature. These results indicate that the Cl doping by the DCE treatment is an effective way to realize low contact resistance MoS2 FETs. Table 1 summarizes the electrical performance of the presented devices.

Conclusion

For the first time, a record low Rc of 0.5 kΩ·μm is achieved on the MoS2 FET with Cl doping technique. As a result, the ρc significantly decreases from 3×10^{-7} Ω·cm to 3×10^{-9} Ω·cm. The 100 nm Lc MoS2 FETs show a record high Ic of 460 μA/μm at Vgs = 1.6 V, which is twice of the best reported Ic on any TMD FETs. As a result, this technique is promising for realizing high-performance top-gate low-R MoS2 FETs as well as other TMD based electronic devices.

References

The gate dielectric is 90 nm SiO₂. The S/D contact metal is Ni (30 nm)/Au (60 nm). (b) Process flow for the MoS₂ back-gate FETs with the exfoliated MoS₂ flakes.

Fig. 1 (a) Schematic of the MoS₂ back-gate FET fabricated in this work. The energy of the core levels w/ and w/o the Cl doping. A blue shift of 0.76 eV is observed. (b) Binding energy of the core levels w/ and w/o the Cl doping. Mo 3d (a) XPS spectra of MoS₂ back-gate FETs w/ and w/o the Cl doping at 5.4 kΩ·µm to 0.5 kΩ·µm (b) Band diagram w/ and w/o the Cl doping. R_contact and R_channel vs. Vbg for the 1 µm device. The R_contact shows very weak dependence on the Vbg when Vbg > -30 V indicating heavily doped contact regions.

Fig. 2 (a) Optical image of the few-layer MoS₂ FET fabricated in this work. (b) Process flow for the MoS₂ back-gate FETs with the exfoliated MoS₂ flakes.

Fig. 3 Cl signal from MoS₂ after the doping confirmed by (a) XPS and (b) SIMS.

Fig. 4 (a) XPS spectra of Mo 3d w/ and w/o the Cl doping. A blue shift of 0.76 eV is observed. (b) Binding energy of the core levels w/ and w/o the Cl doping.

Fig. 5 (a) TLM resistances of MoS₂ FETs w/ and w/o the Cl doping at Vbg = 50 V. The R_contact is reduced from 5.4 kΩ·µm to 0.5 kΩ·µm (b) Band diagram of the metal-MoS₂ contacts w/ and w/o the Cl doping. R_contact is reduced due to the doping induced thinning of tunneling barrier width.

Fig. 6 TLM resistances of MoS₂ FETs at 25, 75, and 125 ºC. The extracted R_contact remains similar from 25 ºC to 125 ºC, indicating the current is dominated by tunneling.

Fig. 7 DCE dip time dependence of ρ_C and N_i with the DCE treatment. The ρ_C is reduced by 100 after a 36 hours DCE treatment. N-type doping density of 2×10¹⁷ cm⁻³ is

Fig. 8 R_contact and R_channel vs. Vbg for the 1 µm device. The R_contact shows very weak dependence on the Vbg when Vbg > -30 V indicating heavily doped contact regions.

Fig. 9 Output characteristics of the 100 nm Lch MoS₂ FETs w/ and w/o the Cl doping. A record high I_on of 460 µA/µm is obtained.

Fig. 10 Component of Vbg vs. Vbg for the two devices. The R_contact of 100 nm Lch MoS₂ FET is reduced from 11.7 kΩ·µm to 1.85 kΩ·µm due to the Cl doping.

Fig. 11 Transfer characteristic curves of the 100 nm Lch MoS₂ FETs w/ and w/o the Cl doping. The I_on/Vgs ratio is 6.3×10⁸ at Vgs = 1.2 V.

Fig. 12 Calculated intrinsic field-effect mobilities as a function of the gate field for the MoS₂ FET with various Lch.

Fig. 13 Benchmarking of the I_on/Vgs = 1.6 V and the R_contact in the reported MoS₂ back-gate FETs.

Table 1 Summary of the electrical performance of the MoS₂ FETs in this work.

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