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ABSTRACT

Semiconducting molybdenum disulfide (MoS$_2$) has drawn a lot of attention for its exceptional electronic and optoelectronic properties. Despite the potential advantages, the large contact resistance at the metal–MoS$_2$ interfaces has been one of the biggest obstacles for the realization of ideal MoS$_2$ transistors. One solution to improve the metal–MoS$_2$ interfaces is to use the graphene electrodes. Here, we provide a selective etching method for fabricating graphene-contacted MoS$_2$ transistors. It has been proved that the graphene could be totally etched with Ar$^+$ plasma treatment, and the multilayer MoS$_2$ flake can also be reduced layer by layer with Ar$^+$ plasma treatment. By etching graphene selectively in graphene–MoS$_2$ heterostructures, one can obtain graphene-contacted MoS$_2$ transistors successfully. The transistor reported in this paper shows an on–off ratio about 10$^6$ and a carrier mobility about 42 cm$^2$ V$^{-1}$ s$^{-1}$. This selective etching method would be beneficial for some other graphene-contacted electronic devices.

I. INTRODUCTION

Two-dimensional (2D) layered materials have drawn a lot of attention in recent research. Graphene has shown exceptional electric properties and is promising for various future nanoelectronics applications.$^{1-5}$ However, the zero-gap band structure of graphene seriously restricts its applications in electronic devices, which leads to the development of 2D layered semiconductors.$^{6-8}$ Thus, the family of transition metal dichalcogenides (TMDs) stands out and is widely studied by many research groups.$^{6,7}$ Semiconducting molybdenum disulfide (MoS$_2$) was first found in the TMD family.$^{9}$ Bulk MoS$_2$ shows an indirect bandgap of 1.2 eV, while single-layer MoS$_2$ changes into a direct semiconductor with a bandgap of 1.8 eV.$^{10,11}$ The on–off ratio of single-layer MoS$_2$ field effect transistors (FETs) could reach 10$^6$.$^{12}$ More importantly, layered MoS$_2$ FETs could overcome short channel effects, making it a promising channel material for post-silicon nanoelectronics.$^{12}$ Moreover, the proper bandgap of MoS$_2$ ensures that it is useful for energy-harvesting applications.$^1$ Despite such potential advantages, the ideal performances of the layered MoS$_2$ FETs have not been realized so far due to the large resistance at their metal contact interfaces.$^{13-15}$ The large resistance at the metal contact interfaces can be mainly attributed to the Fermi level pinning, which locates close to the conduction band edge of MoS$_2$. The large resistance at the metal contact interfaces can be mainly attributed to the Fermi level pinning, which locates close to the conduction band edge of MoS$_2$. To improve the contact property in the metal–2D material interface, one conventional approach is annealing at 150–400 °C under an inert gas with 2%–10% content of H$_2$ for 0.5–3 h.$^{16}$ Besides, one of the promising methods is surface molecular adopting on 2D materials due to its easy operation without defect generation; however, the stability of the device needs a more profound study.$^{17}$ Some researchers have proved that graphene is an excellent electrical contact for MoS$_2$ devices since the electron is enhanced to inject into the conduction band of MoS$_2$, resulting in reduced contact
resistance.\textsuperscript{15,18,19} Particularly, the dangling-free bonds of graphene make it widely employed for van der Waals (vdW) heterojunction fabrication.\textsuperscript{9} Leong et al.\textsuperscript{9} have shown that the contact resistance in MoS\textsubscript{2} transistors with nickel-etched-graphene electrodes can be as low as 200 \( \Omega \mu \text{m} \).

Here, we present a facile method for fabricating graphene-contacted MoS\textsubscript{2} transistors by selectively etching graphene in graphene–MoS\textsubscript{2} heterostructures. First, we proved that the etching thickness of graphene could be precisely controlled by tuning the treatment time of Ar\textsuperscript{+} plasma, and the MoS\textsubscript{2} flake could be reduced layer by layer with Ar\textsuperscript{+} plasma. Then, the graphene–MoS\textsubscript{2} heterostructures were achieved by employing a vdW mechanical transfer method followed by a standard electron beam lithography (EBL) process. With PMMA spin coating on the heterostructure for protecting the un-etched graphene part, a desired graphene-contacted MoS\textsubscript{2} transistor was fabricated by selectively etching graphene in the graphene–MoS\textsubscript{2} heterostructures. This selective etching method makes the fabrication process more convenient, avoiding damages from the multi-transfer steps or transfer again after etching. The channel length of the graphene-contacted transistors could be easily designed into nanometers with this method.\textsuperscript{12} Moreover, the layer by layer reducing of MoS\textsubscript{2} would be beneficial for fabricating precise layer numbers of MoS\textsubscript{2} transistors with graphene electrodes.\textsuperscript{7–9}

II. EXPERIMENTAL DETAILS

Monolayer and multilayer graphene and MoS\textsubscript{2} flakes were mechanically exfoliated from their bulk crystals with 3M Scotch tape. Then, we transferred the flakes onto a piece of 300 nm SiO\textsubscript{2} capped highly p-doped Si substrate. The thicknesses of the flakes are characterized by their Raman and Photoluminescence (PL) spectra. The Raman and PL spectra are extracted from the flakes on a Witec Alpha Raman system with an excitation laser at 532 nm. Ar\textsuperscript{+} plasma in Plasma System Q 235 (power of 50 W and Argon flow of 100 sccm) was used to etch the sample.

The graphene–MoS\textsubscript{2} heterostructures were prepared using a vdW adhesion technique to assemble monolayer graphene on multilayer MoS\textsubscript{2} flakes (for more details please, see Ref. 23). Then, a standard lift-off process was used for fabricating Ti/Au (2 nm/50 nm) metal electrodes onto the flakes by using an electron beam lithography (EBL) system and an electron beam evaporating (EBM) system. For the fabrication of graphene-contacted MoS\textsubscript{2} transistors, a thin PMMA film is employed for protecting the un-etched part of graphene in the graphene–MoS\textsubscript{2} heterostructures. After the selected graphene was etched with Ar\textsuperscript{+} plasma, the thin PMMA film was removed with acetone and then the electrodes of the graphene-contacted MoS\textsubscript{2} transistors were bonded to a custom socket with gold wires. Under ambient atmosphere at room temperature, a Keithley 2636B digital Source-Meter was used for the electrical characterization.

III. RESULTS AND DISCUSSION

This study was designed in two phases. In the first phase, the precise etching conditions of layer by layer reducing for graphene and MoS\textsubscript{2} prepared by mechanical exfoliation were studied under Ar\textsuperscript{+} plasma treatment. A graphene flake with different layers is shown in Fig. 1(a). The thickness of the graphene flake is characterized by its Raman spectra. The Raman spectra in Fig. 1(b) correspond to the graphene in Fig. 1(a) with the edge marked with a red dashed line, and its intensity of the 2D band is nearly one time larger than that of the G band, indicating that the area marked with the red dashed line corresponds to single-layer graphene.\textsuperscript{26–28} The Raman spectra in Fig. 1(c) correspond to the graphene in Fig. 1(a) with the edge marked with a black dashed line, and the intensity of the 2D band is much smaller than that of the G band. The inset in Fig. 1(c) shows that the full width at half maximum (FWHM) of the 2D band of the black dashed area is about 56 cm\textsuperscript{-1}, indicating that the graphene area marked with the black dashed line corresponds to three-layer graphene.\textsuperscript{26–28}

For investigating the layer by layer reducing conditions, the graphene flake was irradiated by Ar\textsuperscript{+} plasma, and the Raman spectra for graphene with different layers were collected every 5 s treatment. The Raman spectra of single-layer and three-layer graphene with different time Ar\textsuperscript{+} plasma treatment are shown in Figs. 1(d) and 1(e), respectively. As shown in Fig. 1(d), the D band of single-layer graphene appeared after 5 s Ar\textsuperscript{+} plasma treatment, indicating that defects were induced by Ar\textsuperscript{+} plasma treatment.\textsuperscript{26–28} With an increase in Ar\textsuperscript{+} plasma treatment time, both the intensity of the 2D band and D band of the single-layer graphene gradually decrease. All Raman modes of graphene completely disappeared after 40 s Ar\textsuperscript{+} plasma treatment, implying that the single-layer graphene was totally etched.\textsuperscript{26–28} In Fig. 1(e), the change of Raman spectra of the three-layer graphene had a similar trend as that of the single-layer graphene under the Ar\textsuperscript{+} plasma treatment. After 120 s Ar\textsuperscript{+} plasma treatment, all Raman modes of three-layer graphene disappeared, implying that the three-layer graphene was totally etched with Ar\textsuperscript{+} plasma treatment. We noted that it took approximately three times as long to etch three layers of graphene as it does to etch a single-layer graphene, which means that the etching rate was almost constant what we could take the advantage to precisely control the layer number of graphene by setting the treatment time of Ar\textsuperscript{+} plasma.\textsuperscript{26–28}

A similar work for different layers of MoS\textsubscript{2} flakes was carried out for investigating the MoS\textsubscript{2} etching properties. The layer number of the flake is also characterized by its Raman and PL spectra. Figure 2 displays the spectrum of the single-layer and three-layer MoS\textsubscript{2} flakes with different time Ar\textsuperscript{+} plasma treatment. The ~385 cm\textsuperscript{-1} Raman peak in Fig. 2(a) corresponds to the E\textsubscript{2g} (1) mode of MoS\textsubscript{2} with in-plane vibration. The ~404 cm\textsuperscript{-1} Raman peak in Fig. 2(a) corresponds to the A\textsubscript{1g} mode of MoS\textsubscript{2} with out-of-plane vibration.\textsuperscript{9,10} The two Raman peaks both became weak and broadened after 5–15 s treatment, implying that the atomic structure of the MoS\textsubscript{2} flake became disordered.\textsuperscript{21} After 20 s, the two Raman peaks both disappeared, suggesting that the monolayer MoS\textsubscript{2} flake was finally etched with Ar\textsuperscript{+} plasma treatment.\textsuperscript{9}\textsuperscript{10,21} As the etching time increased from 5 s to 15 s, the intensity of PL spectra in Fig. 2(b) also became much weaker. After 20 s, the PL spectra disappeared, which confirmed that the single-layer MoS\textsubscript{2} flake could finally be etched with Ar\textsuperscript{+} plasma treatment.\textsuperscript{9}\textsuperscript{10,21} For the three-layer MoS\textsubscript{2} flake, as shown in Figs. 2(c) and 2(d), the results were quite different. The Raman peak
position of the E_{2g}^{1} mode of the three-layer MoS_{2} flake moved to higher frequency with the increase in treatment time, and this can be attributed to the effect of the Coulomb interaction in the few-layer MoS_{2} flake.21 After 40 s Ar⁺ plasma treatment, the frequency difference between the two Raman peaks of the MoS_{2} flake decreased from 23.4 cm⁻¹ to 19.2 cm⁻¹, which rightly corresponds to that of monolayer MoS_{2}, indicating that the top two layer MoS_{2} was etched by Ar⁺ plasma treatment.21,22,29 In addition, the PL spectra shown in Fig. 2(d) could also display clear evidence for the thickness variation. The intensity of PL spectra of the three-layer MoS_{2} flake decreased with the increasing etching time from 5 s to 35 s. However, there is a giant enhancement of PL intensity of the flake after 40 s Ar⁺ plasma treatment, indicating that the top two layer MoS_{2} was etched by Ar⁺ plasma.21,22,29

In the second phase, the graphene-contacted MoS_{2} transistors by selectively etching graphene were fabricated and the electron transport properties of the devices were measured. Since the etching thickness of graphene and MoS_{2} could be precisely controlled by tuning the treatment time of Ar⁺ plasma, a selective etching method could be employed for fabricating graphene-contacted MoS_{2} transistors. The scheme diagram for fabricating the device is shown in Fig. 3(a). First, the single-layer graphene was transferred onto the few-layer MoS_{2} flake; then, the lift-off and Ar⁺ plasma etching processes were employed to fabricate the graphene electrodes. Finally, the electric properties of the devices were measured after metal wire bonding. The device structure of the graphene–MoS_{2} heterostructure and the graphene-contacted MoS_{2} transistor is illustrated in Figs. 3(b) and 3(c), respectively. The experimental details in Sec. II will give much information on the fabrication process.

Figure 4 mainly shows the electric properties of the device. As a comparison, the electric properties of the graphene–MoS_{2} heterostructure before and after Ar⁺ plasma treatment are characterized. Moreover, the electric properties of the MoS_{2} transistor with metal electrodes are also extracted as a reference. Figure 4(a) displays the scheme structures of the graphene-contacted MoS_{2} transistor. Figure 4(b) gives the optical image of the device with a graphene-contacted MoS_{2} transistor and a MoS_{2} transistor with a metal electrode on the same flake. The metal electrode of the graphene-contacted MoS_{2} transistor is labeled 1 and 2 and that of the pristine MoS_{2} transistor is labeled 3 and 4. It is clearly observed that the graphene in the channel of the graphene-contacted MoS_{2} transistor has been completely etched out. This conclusion could be further confirmed by the Raman mapping result [Fig. 4(b), inset], the edge of graphene etched by Ar⁺ plasma is sharp, and the channel width is about 2 μm, almost the same with the pristine sample. The I–V characteristics of the comparisons are shown in Fig. 4(c). The I–V property of the graphene-contacted MoS_{2} transistor before Ar⁺ plasma
etching shows a linear behavior, and the resistance of the device is about $5 \times 10^2 \Omega$. The resistance of the device has an increase in three orders of magnitude, i.e., $8 \times 10^5 \Omega$, after the graphene in the channel was etched out by Ar$^+$ plasma completely. Much smaller contact resistance could be obtained by using graphene electrodes, referring to the pristine MoS$_2$ transistor. The large resistance change in the heterostructure after Ar$^+$ plasma treatment indicates that the selected graphene has been completely etched, implying that the device is a graphene-contacted MoS$_2$ transistor. The transfer characteristics of the specimen are also extracted. The transfer
FIG. 4. Atomic sectional drawing (a) of a MoS$_2$ transistor with graphene electrodes. Optical image (b) of the devices with graphene electrodes and normal metal electrodes on the same MoS$_2$ sheet. Raman mapping [(b), inset] of the transistor with graphene electrodes extracted at the 2D band of graphene (at 2695 cm$^{-1}$ with width 20 cm$^{-1}$). The channel width of the transistor is 2 $\mu$m. I–V (c) and transfer characteristics (d) of the MoS$_2$ transistor with metal electrodes and the graphene–MoS$_2$ heterostructure before and after graphene etching.

Characteristics of the device before etching in Fig. 4(d) show a similar behavior of the graphene FET with a p-type behavior due to a combination of O$_2$, H$_2$O, and the bottom MoS$_2$. The transfer characteristics of the device after etching in Fig. 4(d) show the behavior of the MoS$_2$ FET, and it is further proved that the selected graphene is etched out completely. For analyzing the performance of the device, some parameters of the transistor are extracted from the transfer curve. The on–off current ratio of the graphene-contacted MoS$_2$ transistor (the red curve in left scale) is about 10$^6$ larger about one order than that of pristine one. The calculation of carrier mobility could use the equation as follows:

$$\mu = \frac{\partial I_d}{\partial V_g} \left( \frac{L}{WC_i V_{ds}} \right),$$

where $L$ and $W$ correspond to the channel length and width, respectively. $C_i$ is the insulating layer capacitance between the gate electrode and the conducting channel. It is calculated using the equation $C_i = \varepsilon_0 \varepsilon_r d$, ($8.85 \times 10^{-12}$ F/m), and $\varepsilon_r$ (3.9) is vacuum dielectric constant. The thickness of SiO$_2$ ($d$) is 300 nm. The mobilities of the graphene-contacted MoS$_2$ transistor are about 42 cm$^2$ V$^{-1}$ s$^{-1}$ calculated according to Eq. (1), which has been increased by 55% than the pristine MoS$_2$ FET with the same channel width. The improvement for the graphene-contacted MoS$_2$ transistor can attribute to the following reasons. The graphene-contacted MoS$_2$ transistor does not have the residue and the damage of the MoS$_2$ flake in the fabrication process, compared to the pristine MoS$_2$ transistor. Furthermore, the graphene is inert and stable, which does not react with MoS$_2$ and does not have any diffusion.

IV. CONCLUSIONS

In summary, we proved that the graphene flake could be totally etched with Ar$^+$ plasma, and the etching thickness of the flake could be precisely controlled by tuning the irradiation time of Ar$^+$ plasma. Moreover, the multilayer MoS$_2$ flake can also be reduced layer by layer with an increase in the etching time of Ar$^+$ plasma. Owing to the controlling of Ar$^+$ plasma, a selective etching method could be employed for fabricating the graphene-contacted MoS$_2$ transistors. A graphene-contacted MoS$_2$ transistor can be successfully fabricated by selectively etching graphene in the graphene–MoS$_2$ heterostructures. The transistor exhibits a high on–off ratio about 10$^6$ and a carrier mobility about 42 cm$^2$ V$^{-1}$ s$^{-1}$. This selective etching method would bring more convenience to the fabrication of graphene-contacted 2D devices.

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AUTHOR’S CONTRIBUTIONS

Z.S. and G.P. contributed equally to this work. W.L., G.P., and Z.L. supervised this study. Z.S. and W.L. fabricated the samples. Z.S., Z.B., and Y.W. performed the measurements. All authors discussed the data and wrote the manuscript.

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REFERENCES

1. K. S. Novoselov, A. K. Geim, S. V. Morozov, D. Jiang, Y. Zhang, S. V. Dubonos, I. V. Grigorieva, and A. A. Firsov, Science 306(5696), 666–669 (2004).
2. A. K. Geim and K. S. Novoselov, Nat. Mater. 6(3), 183–191 (2007).
3. Q. Bao and K. P. Loh, ACS Nano 6(5), 3677–3694 (2012).
4. B. Radisavljevic, A. Radenovic, J. Brivio, V. Giacometti, and A. Kis, Nat. Nanotechnol. 6(3), 147–150 (2011).
5. O. Lopez-Sanchez, D. Lembke, M. Kayci, A. Radenovic, and A. Kis, Nat. Nanotechnol. 8, 497 (2013).
6. N. Guo, S. Yang, Z. Wei, S.-S. Li, J.-B. Xia, and J. Li, Sci. Rep. 4, 5209 (2014).
7. G. R. Bhimanapati, Z. Lin, V. Meunier, Y. Jung, J. Cha, S. Das, D. Xiao, Y. Son, M. S. Strano, V. R. Cooper, L. Liang, S. G. Louie, E. Ringe, W. Zhou, S. S. Kim, R. R. Naik, B. G. Sumpter, H. Terrones, F. Xia, Y. Wang, J. Zhu, D. Akinwande, N. Alem, J. A. Schuller, R. E. Schaak, M. Terrones, and J. A. Robinson, ACS Nano 9(12), 11509–11539 (2015).
8. W. Zhang, M.-H. Chiu, C.-H. Chen, W. Chen, L.-J. Li, and A. T. S. Wee, ACS Nano 8(8), 8653–8661 (2014).
9. C. Lee, H. Yan, L. E. Brus, T. F. Heinz, J. Hone, and S. Ryu, ACS Nano 4(5), 2695–2700 (2010).
10. H. S. Lee, S.-W. Min, Y.-G. Chang, M. K. Park, T. Nam, H. Kim, J. H. Kim, S. Ryu, and S. Im, Nano Lett. 12(7), 3695–3700 (2012).
11. R. Ganatra and Q. Zhang, ACS Nano 8(5), 4074–4099 (2014).
12. L. Xie, M. Xiao, S. Wang, H. Xu, L. Du, J. Tang, J. Zhao, J. Zhang, P. Chen, X. Lu, G. Wang, G. Xie, R. Yang, D. Shi, and G. Zhang, Adv. Mater. 29(37), 1702522 (2017).
13. J. Wang, Q. Yao, C.-W. Huang, X. Zou, L. Liao, S. Chen, Z. Fan, K. Zhang, W. Wu, X. Xiao, C. Jiang, and W.-W. Wu, Adv. Mater. 28(37), 8302–8308 (2016).
14. D. Liu, Y. Guo, L. Fang, and J. Robertson, Appl. Phys. Lett. 103(18), 183113 (2013).
15. W. S. Leong, X. Luo, Y. Li, K. H. Khoo, S. Y. Quek, and J. T. S. Thong, ACS Nano 9(11), 869–877 (2015).
16. Z. Wang, Q. Li, Y. Chen, B. Cui, Y. Li, F. Besenbacher, and M. Dong, NPG Asia Mater. 10(8), 703 (2018).
17. Z. Wang, J. Liu, X. Hao, Y. Wang, Y. Chen, P. Li, and M. Dong, New J. Chem. 43, 15275 (2019).
18. J. Yoon, W. Park, G.-Y. Bae, Y. Kim, H. S. Jang, Y. Hyun, S. K. Lim, Y. H. Kahng, W.-K. Hong, B. H. Lee, and H. C. Ko, Small 9(19), 3185 (2013).
19. T. Roy, M. Tosun, J. S. Kang, A. B. Sachid, S. B. Desai, M. Hettick, C. C. Hu, and A. Javey, ACS Nano 8(6), 6259–6264 (2014).
20. C.-H. Lee, G.-H. Lee, A. M. van der Zande, W. Chen, Y. Li, M. Han, X. Cui, G. Arefe, C. Nuckolls, T. F. Heinz, J. Guo, J. Hone, and P. Kim, Nat. Nanotechnol. 9, 676 (2014).
21. Y. Liu, H. Nan, X. Wu, W. Pan, W. Wang, J. Bai, W. Zhao, L. Sun, X. Wang, and Z. Ni, ACS Nano 7(5), 4202–4209 (2013).
22. X. Lu, M. I. B. Utama, J. Zhang, Y. Zhao, and Q. Xiong, Nanoscale 5(19), 8904–8908 (2013).
23. W. Luo, G. Peng, F. Wang, F. Miao, X.-A. Zhang, and S. Qin, Phys. Status Solidi A 214(9), 1700151 (2017).
24. A. C. Ferrari, J. C. Meyer, V. Scardaci, C. Casiraghi, M. Lazzeri, F. Mauri, S. Piscanec, D. Jiang, K. S. Novoselov, S. Roth, and A. K. Geim, Phys. Rev. Lett. 97(18), 187401 (2006).
25. Z. Ni, Y. Yang, T. Yu, and Z. Shen, Nano Res. 1(4), 273–291 (2008).
26. K. S. Hatra, J. Rafiee, M. A. Rafiee, A. Mathur, S. S. Roy, I. McLauhglin, N. Koratkar, and D. S. Misra, Nanotechnology 22(2), 025704 (2010).
27. X. Yang, S. Tang, G. Ding, X. Xie, M. Jiang, and F. Huang, Nanotechnology 23(2), 025704 (2011).
28. A. C. Ferrari and D. M. Basko, Nat. Nanotechnol. 8, 235 (2013).
29. S. Xiao, P. Xiao, X. Zhang, D. Yan, X. Gu, F. Qin, Z. Ni, Z. J. Han, and K. Ostrikov, Sci. Rep. 6, 19945 (2016).
30. S. McDonnell, R. Addou, C. Buie, R. M. Wallace, and C. L. Hinkle, ACS Nano 8(3), 2880–2888 (2014).
31. W. Mönch, Appl. Phys. Lett. 72(15), 1899–1901 (1998).
32. S. Das, H.-Y. Chen, A. V. Penumatcha, and J. Appenzeller, Nano Lett. 13(1), 100–105 (2013).