Selective Deposition of High-k Capping Layer on MoS$_2$ Field Effect Transistors by Using Graphene Electrodes

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Abstract

It is demonstrated that capping high-k layer on MoS$_2$ FETs can strongly dampen the Coulombic scattering of charge carriers due to the dielectric constant mismatch between nanoscale channel material and the high-k dielectric$^1$. Meanwhile, high-k materials deposited by Atomic Layer Deposition (ALD) exhibit the best electronic properties. However, the photoresist used in lithography process could seriously contaminate the MoS$_2$ channel during the patterning of high-k material. Moreover, it is also impossible to use common shadow mask to prevent high-k material from depositing on the metallic electrodes in the ALD process owing to its growing mechanism. In this work, we demonstrated a new method in which graphene was chosen as the electrode material, where ALD materials were difficult to deposit on top.

Figure 1 illustrates the schematic flow of the fabrication process of our devices. Few-layer MoS$_2$ flakes were mechanically exfoliated by the classical scotch-tape technique and transferred to a heavily doped silicon substrate capped with 300 nm SiO$_2$. We used the heavily doped silicon substrate as the bottom gate. The best candidate of flakes was chosen by optical microscopy (Fig. 2a) and its thickness was checked by AFM (Fig. 2b). A layer thickness in the range of 6–12 nm would be ideal. Then, two few-layer graphene flakes serving as source and drain were transferred to the target position on top of the MoS$_2$ by PDMS stamping, which is an all-dry method. After the transfer process, two-step annealing was conducted. First, the devices were annealed at 200°C in an Ar atmosphere for 2h (100 sccm) to remove residue. Secondly, the devices were annealed at 120 °C for up to 20 h in high vacuum (∼10$^{-7}$ torr) before measurement. It is believed that in situ vacuum annealing can dope devices and significantly reduce Schottky barrier height and contact resistance$^4$. High-k materials are difficult to deposit on pristine graphene by ALD because of its perfect symmetry and strong global π bond$^5$. On the contrary, there is a small window to deposit high-k material on MoS$_2$ by ALD if we select appropriate growth temperature, purge time, and pause time$^6$. Therefore, a 20 nm ALD-Al$_2$O$_3$ layer was deposited on MoS$_2$ surface at 200 °C without any resist. The graphene electrodes wouldn’t be capped by Al$_2$O$_3$ thanks to its selectivity.

The transfer (I$_b$-V$_g$) and output I-V characteristics (I$_d$-V$_d$) of the device are shown in Fig. 3. It is fairly clear that the graphene is not capped by Al$_2$O$_3$. The device shows n-type conduction. The field effect mobility and I$_{on}$/I$_{off}$ of the device before ALD deposition are about 1.81 cm$^2$/V⋅s$^{-1}$ and 10$^{3.5}$ (Fig. 3a), respectively. After Al$_2$O$_3$ deposition, the field effect mobility and I$_{on}$/I$_{off}$ of the device are enhanced to 13 cm$^2$/V⋅s$^{-1}$ and 10$^5$ (Fig. 3b). This significant enhancement of device performance can be attributed to the dielectric engineering of Al$_2$O$_3$, which helps screening the Coulombic scattering of carriers. Also, the optimized thickness helps striking the balance between Thomas-Fermi charge screening and interlayer coupling according to the resist network model$^7$, so that this mobility value is three times higher than the MoS$_2$ FETs with graphene electrodes in previous literatures$^8$. In addition, the output I-V characteristics (Fig. 3d) display linear and saturation regions in low and high V$_d$ ranges, respectively. The linear part is attributed to the quasi-ohmic contact between MoS$_2$ and graphene, while the saturation arises from the channel pinch-off.

In conclusion, MoS$_2$ FETs using graphene as electrodes shows excellent electronic properties: current on/off ratio (∼10$^5$) and a field effect mobility of ∼13 cm$^2$/V⋅s$^{-1}$. ALD-Al$_2$O$_3$ capping can not only enhance the mobility but offer relatively dense passivation. Besides, water molecules adsorbed on the surface of MoS$_2$ before passivation can be removed since water is the precursor in the growth process of ALD. More importantly, with graphene as the electrodes, the selective growth of ALD-Al$_2$O$_3$ between MoS$_2$ and graphene provides a resist-free passivation process, which can eliminate the possibility of contamination from resist.

References

Figures

Fig. 1 Schematic fabrication process of MoS$_2$ FET with graphene electrode.

Fig. 2 (a) The OM image of MoS$_2$ FET device. (b) AFM line profile of MoS$_2$

Fig. 3 (a)(c) Transfer and Output characteristics of MoS$_2$ FET before ALD deposition (b)(d) Transfer and Output characteristics of MoS$_2$ FET after ALD deposition