Record high current density and low contact resistance in MoS_2 FETs by ion doping

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Abstract

Record high current density of 300 μA/μm with low contact resistance of 200 Ω μm and a channel length of 0.8 μm at a drain-source bias of 1.6 V has been achieved for the first time in MoS_2 field-effect transistors (FETs) grown by chemical vapor transport. The low contact resistance is achieved using a polyethylene-oxide cesium-perchlorate solid polymer ion conductor formed by drop casting. The charged ions are placed into position over the channel by the application of a bias to a side gate and then locked into place by lowering the temperature. A weak temperature dependence of the drain current after ion doping indicates that transport in the Schottky contacts is dominated by tunneling.

Introduction

Transition metal dichalcogenides (TMDs) are of interest as a channel material for FETs and tunnel FETs[1]. This is due to their unique properties such as atomically thin bodies, dielectric mediated mobilities, and absence of surface dangling bonds[2]. However, TMD FETs usually suffer from the large contact resistance of the Schottky contacts, which hinders the characterization of the intrinsic channel characteristics. Several techniques have been used to improve the contact resistance including contact metal engineering[3], molecular doping[4], substitutional doping[5], and electrostatic doping[6,7]. In this paper we explore for the first time the use of polyethylene-oxide (PEO) cesium-perchlorate ($CsClO_4$) solid polymer electrolyte to dope MoS_2 flakes and ribbons.

Fabrication

The MoS_2 nanostructures were grown by chemical vapor transport (CVT) from MoS_2 powder, using an iodine transport agent in an evacuated silica ampoule. This method enables the vapor-phase growth of nanostructures with a slow growth rate[8]. The device process consisted of e-beam evaporation of Ti/Au (5/100 nm) on the back of a p^+ Si wafer. The nanostructures were then transferred by tape from the CVT source onto a 27 nm Al_2O_3 oxide formed by atomic layer deposition on the wafer top surface. The nanostructures were patterned for source, drain and side gate contacts using electron beam lithography followed by metal evaporation of Ti/Au (0.8/140 nm). The PEO and $CsClO_4$ were dissolved in acetonitrile and drop-cast to cover the entire surface of the wafer, follow by a 3 minute anneal at 90°C in an Ar glove box. Measurements were carried out in a vacuum probe station at 1.2 x 10^{-6} Torr.

Results and Discussion

The $CsClO_4$ dissociates into Cs^+ and ClO_4^- in the insulating PEO at room temperature. By applying a potential on a side gate formed in the same metallization step as the source/drain contact, a lateral electric field is established which, depending on the polarity of the side gate, moves either the positive or negative ions into place at the MoS_2 surface. At room temperature the ions are mobile and their position can be changed by the active transistor biases at the source, drain and back-gate contacts. To lock the ions into place, the device is cooled below the glass transition of the PEO:$CsClO_4$ (240 K). Below this temperature the ions are immobile and the transistor doping is fixed.

Using Cs^+ ions to induce electrons in the MoS_2 channel, the drain current increases by over two orders of magnitude with zero back-gate bias. After Cs^+ ion doping, the back-gate can still be used to modulate the conductivity; however, the ion doping is so large that the back-gate has only a minor effect. The weak temperature dependence of the drain current is consistent with tunneling through the Schottky barriers. This is an indication of the effectiveness of the ion doping technique in thinning the Schottky barrier. This behavior is demonstrated in both multilayer flakes and ribbons of MoS_2. While *n*-doping of MoS_2 using the Cs^+ is achieved, hole doping using the perchlorate counter ion was not observed.

Measurements of contact resistance were made using 4-contact FET structures after ion doping yielding a contact resistance of 200 Ω μm comparable to the report of 180 Ω μm by Rai[9]. The two transistors shown here reach record current densities of 230 μA/μm in the MoS_2 ribbon FET and 300 μA/μm in the MoS_2 flake FET at channel lengths of 1.4 and 0.8 μm, respectively.

Conclusions

For the first time, ion doping of MoS_2 flakes and ribbons grown by CVT was demonstrated using the solid polymer electrolyte, PEO:$CsClO_4$. Record low contact resistance with record high ON current density was achieved at a channel length of 0.8 μm. The transfer characteristics after ion doping are substantially independent of temperature consistent with tunneling and showing a weak negative temperature coefficient.

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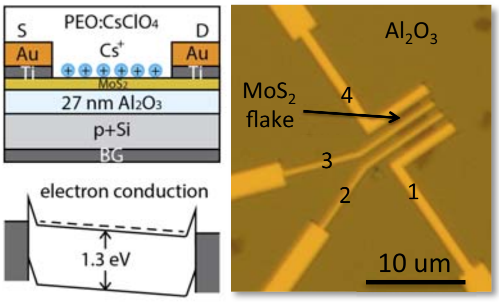
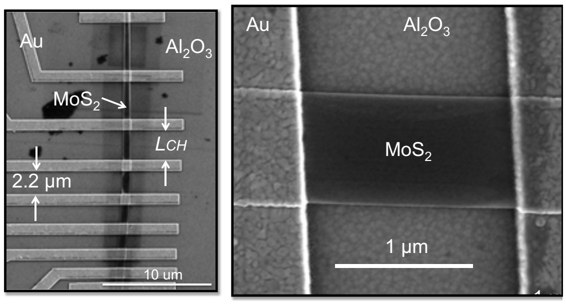


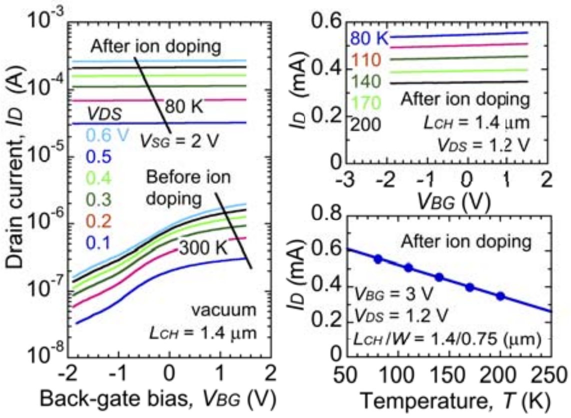
(a) (b)

Figure 1. Ion doping of MoS_2 nanostructures. (a) Applying a positive bias to the side gate contact (not shown), drives the Cs^+ ions onto the channel, inducing electrons in the channel and doping it *n*-type. (b) Optical top view micrograph of the four-contact Kelvin connection made on a multilayer MoS_2 flake grown by chemical vapor transport and exfoliated onto Al_2O_3.



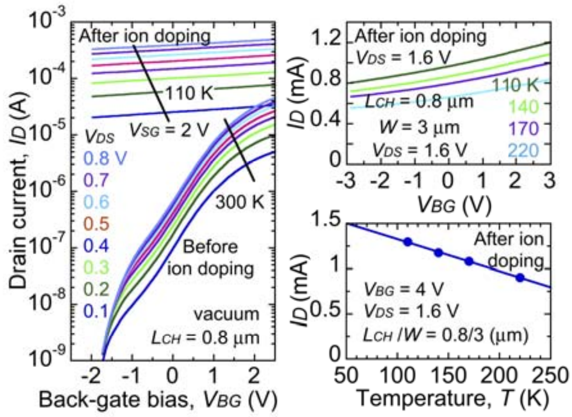
(a) (b)

Figure 2. SEM images of (a) patterned and metallized MoS_2 ribbon FET for different channel lengths. The channel lengths are 0.4, 0.8, 1.4, 1.8, 2.2, 2.8, 3.6, and 4.6 µm and the metal width is 1 µm. (b) Magnified image of the device with 1.4 µm contact spacing. Thickness of the ribbon is 173 nm as measured by AFM.



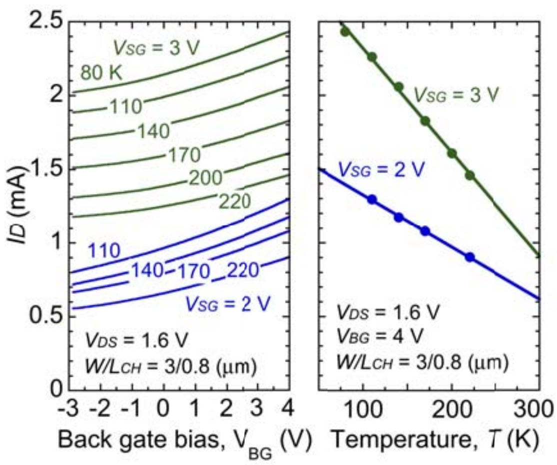
(a) (b)

Figure 3. (a) Transfer characteristics of a multilayer MoS_2 ribbon grown by chemical vapor transport and measured before and after ion doping with Cs^+. (b) Upper figure shows the temperature dependence of the drain current on a linear scale as a function of back-gate bias. The current is dominated by the electric double layer formed by the Cs^+ ion doping of the channel. Extrapolating the current (lower right figure) to 300 K gives 0.17 mA or 230 µA/µm.



(a) (b

Figure 4. (a) Transfer characteristics of a multilayer MoS_2 flake grown by chemical vapor transport and measured before and after ion doping with Cs^+. (b) Upper figure shows the temperature dependence of the drain current. The lower right figure shows the weak temperature dependence of the tunneling transport.



(a) (b)

Figure 5. (a) Transfer characteristics of the multilayer MoS_2 flake after increasing the side-gate bias to 3 V showing higher current achieved with higher side gate bias. (b) Extrapolating the drain current to 300 K shows a current of 0.9 mA or 300 µA/µm

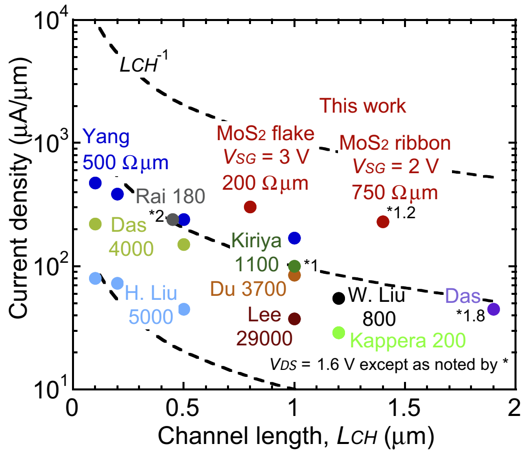


Figure 6. Benchmarking of current density and contact resistance in MoS_2 back gated FETs. References: L. Yang et al., *2014 VLSI*, pp. 192-193. R. Kappera et al., *Nat. Mater.* 13, 1128 (2014). D. Kiriya et al., *JACS* 136, 7853 (2014). S. Das et al., *APL* 106, 173506 (2015). J. Lee et al., *2013 IEDM*, pp. 491. Y. C. Du et al., EDL 35, 599 (2014). W. Liu, et al., *2013 IEDM*, pp. 400. S. Das et al., *Nano Lett.* 13, 3396 (2013). H. Liu et al., *ACS Nano* 8, 1031 (2012). A. Rai et al., *Nano Lett.* 15, 4329 (2015).