Transfer-Printing of Prepatterned Semiconducting Few-Layer-Molybdenum Disulfide Structures for Electronic Applications

Hongsuk Nam, Sungjin Wi, and Xiaogan Liang*

Mechanical Engineering, University of Michigan, Ann Arbor, MI 48109

Molybdenum disulfide (MoS_2), previously widely used as a lubricant material, recently attracts a great deal of attention because of its attractive electronic, optoelectronic, and mechanical properties.[1-3] Especially, monolayer and few-layer MoS_2 films have a large direct bandgap that is suitable for semiconductor-related applications such as thin-film transistors (TFTs)[1], chemical sensors[4], and light emission devices[2]. Such atomically layered films also exhibit a high mechanical flexibility and can be used for making flexible electronic products with high performance.[3] The current methods for producing few-layer MoS_2 flakes include scotch tape exfoliation,[5] chemical vapor deposition (CVD),[6] and laser-thinning process[7] *etc*. These methods still suffer from specific disadvantages and cannot create ordered, pristine MoS_2 device arrays over large areas that are required for large-area applications. Therefore, novel low-cost, upscalable nanofabrication methods are needed for addressing such manufacturing-related issues and enabling the future scale-up applications of MoS_2 in electronics and optoelectronics. In this work, we systematically studied transfer-printing approaches for creating orderly arranged MoS_2 micro- and nanostructures over large (cm^2-scale) areas and demonstrated working field-effect transistors (FETs) made from printed MoS_2 flakes with excellent transistor performance. This research also identified the key processing conditions affecting the printing uniformity over large areas, morphologies of printed MoS_2 structures, and ultimate transport properties of MoS_2-based FETs.

In our processes, the device patterns are firstly pre-structured onto a bulk MoS_2 disc by using photolithography followed with plasma etching. This MoS_2 disc is then used as a relief template for exfoliating prepatterned MoS_2 flake arrays over large areas *via* various printing processes, including direct mechanical printing[8], plasma-assisted printing, and electrostatic printing[9]. All of these printing processes can produce ordered MoS_2 arrays over large areas, but different printing processes can result in different morphologies of individual MoS_2 flakes, as demonstrated in Fig. 1. In addition, the MoS_2 flakes created by various transfer-printing processes exhibit different transport properties. For example, Figs. 2a and 2b show I_{DS}-V_{DS} and I_{DS}-V_G characteristic curves, respectively, of a MoS_2 FET produced by using electrostatic printing, which exhibit N-type conduction. Figure 2c shows the I_{DS}-V_G characteristic curve of another MoS_2 FET made by plasma-assisted printing, which exhibits P-type conduction.

Our work demonstrated the printing of high-quality, well-defined MoS_2 flakes over large areas and working MoS_2-based FETs with excellent performance. The fundamental knowledge achieved in this work could also be used for optimizing the printing-based manufacturing routes for producing other atomically layered materials and devices.

[1] B.Radisavljevic, A.Radenovic, J.Brivio, V.Giacometti, and A.Kis, Nature Nanotechnology **6**, 147 (2011)
[2] K. F. Mak, C. Lee, J. Hone, J. Shan, and T. F. Heinz, Phys. Rev. Lett. **105**, 136805 (2010)
[3] J. Pu, Y. Yomogida, K. K. Liu, L. J. Li, Y. Iwasa, and T. Takenobu, Nano Letters **12**, 4013 (2012)
[4] Q. He, Z. Zeng, Z. Yin, H. Li, S. Wu, X. Huang, H. Zhang, Small **8**, 2994 (2012)
[5] K. S. Novoselove, A. K. Geim, S. V. Morozov, D. Jiang, Y. Zhang, S. V. Dubonos, I. V. Grigorieva, and A. A. Firsov, Science **306**, 666 (2004)
[6] Y. Lee et al., Advanced Materials **24**, 2320 (2012)
[7] A. Castellanos-Gomez, M. Barkelid, A. M. Goossens, V. E. Calado, H. S. J. van der Zant, and G. A. Steele, Nano Letters **12**, 3187 (2012)
[8] X. Liang, Z. Fu, and S. Chou, Nano Lett. **7**, 3774-3780 (2007)
[9] X. Liang, et al., Nano Lett. **9**, 467-472 (2009)

Contact Email: xiaoganl@umich.edu

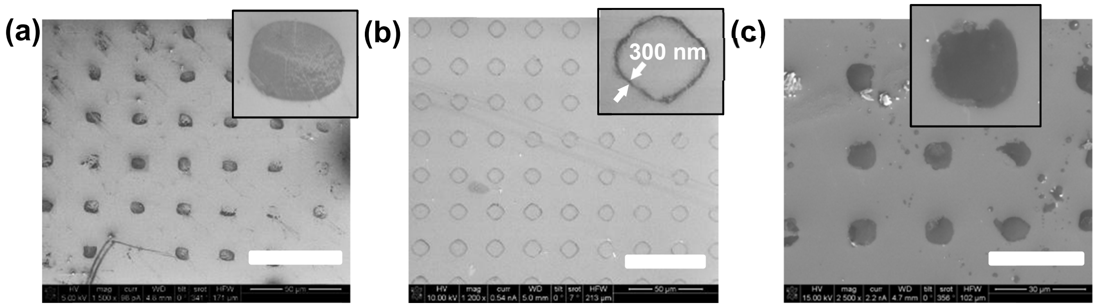

Fig. 1 SEMs of MoS_2 micro-/nanostructures produced by various transfer-printing processes: (a) microscale flakes with well-defined edges but broken central areas created by mechanical printing, (b) 300 nm wide rings with large-area uniformity created by plasma-assisted transfer-printing, and (c) microscale flakes with continuous MoS_2 films created by electrostatic printing. All the scale bars are 50 μm.

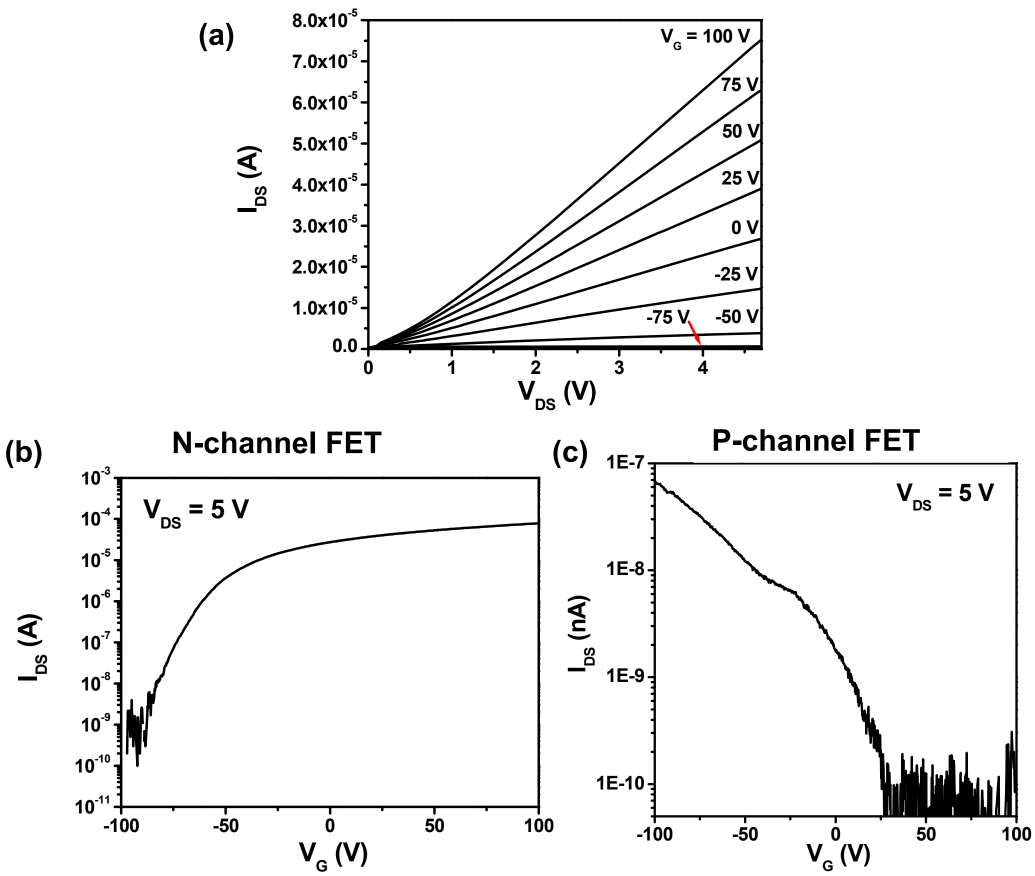

Fig. 2 Transport characteristics of MoS_2-based FETs made from transfer-printed MoS_2 flakes. (a) I_{DS}-V_{DS} and (b) I_{DS}-V_G characteristic curves of an N-channel MoS_2 FET; (c) I_{DS}-V_G characteristic curve of a P-channel MoS_2 FET made by using plasma-assisted transfer-printing.

Contact Email: xiaoganl@umich.edu