H-10-01 (Invited) Extended Abstracts of the 2020 International Conference on Solid State Devices and Materials, VIRTUAL conference, 2020, pp581-582

Two-dimensional Materials and Devices: Promising Concepts for Emerging IT Applications

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Abstract

Scientists continue to report new highlights in graphene and two-dimensional materials and device research on a daily basis. Despite these intensive research efforts, there are no clearly "2D driven" end-customer microelectronics products on the market today. The bottleneck for 2D electronic products is a lack of reliable and scalable manufacturing technology, which prevents realizing the outstanding performance in electronics, optoelectronics or sensing.

1. Introduction

Transition metal dichalcogenides (TMDs) make up a large part of the family of two-dimensional (2D) layered materials. They consist of a transition metal such as molybdenum (Mo), tungsten (W), niobium (Nb) etc., and a chalcogen like sulfur (S), selenium (Se), or tellurium (Te). Molybdenum disulfide (MoS_2) is a semiconducting TMD with a band gap between 1.3 eV in bulk and 1.88 eV as a monoatomic layer. The material is a potential candidate for applications in nanoelectronics, optoelectronics and neuromorphic computing [1]–[5]. Noble metal dichalcogenides like platinum diselenide ($PtSe_2$) are another branch of the 2D family. They can be grown at temperatures below the 400° C back-end-of-line temperature limit [6], [7]. Here, several promising device concepts based on these materials will be discussed.

2. Ion-based Plasticity in MoS_2

Vertical heterostructures of silicon (Si), MoS_2 and metal electrodes have been fabricated with conventional process technology, including thermally assisted conversion of MoS_2 [8]. Vertical transport across the structures is dominated by thermionic emission when the 2D MoS_2 layers are aligned with the silicon surface [9]. However, when the MoS_2 layers are oriented perpendicular to the Si surface, the device characteristics show the signature of ionic transport [10] (Fig. 1a). Extensive analyses suggest hydroxyl ions, possibly formed by catalytic splitting of adsorbed water molecules through the MoS_2 (Fig. 1b). This can be exploited as non-volatile resistive switching to form memristors with nanocrystalline MoS_2 as the active material [5] (Fig. 1c). The switching process is forming-free with stable retention for at least 2500 seconds. The device fabrication process is scalable and offers an opportunity to integrate such memristors into Si technology for future neuromorphic applications.

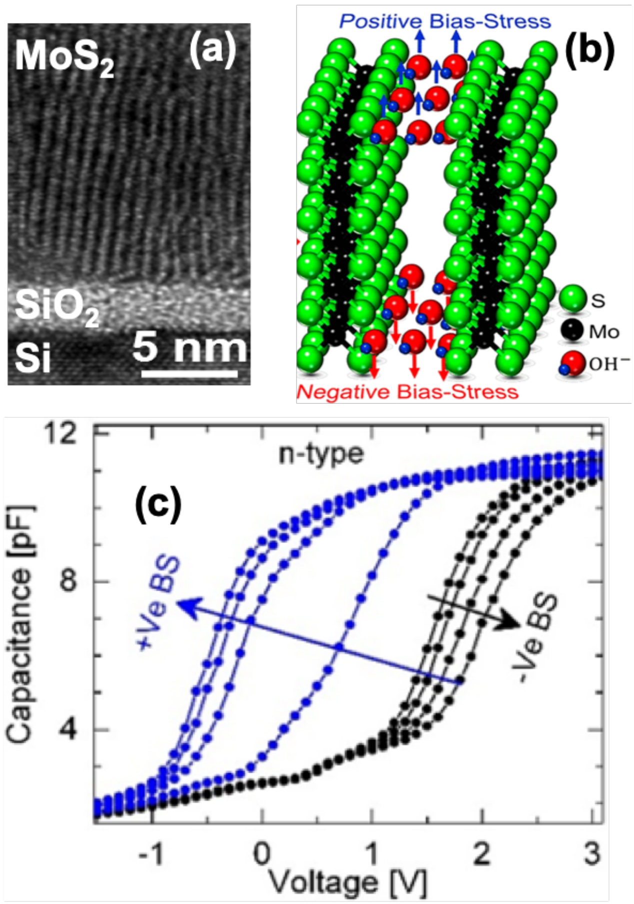

Fig. 1: Transmission electron micrograph of a vertical MoS_2 film (a). Schematic of two MoS_2 layers with mobile inter-layer hydroxyl ions (b). Capacitance-Voltage measurement with bias-dependent, non-volatile flatband voltage shifts (c).

3. 2D Membrane-based Nanoelectromechanical Sensors

Membrane-based sensors benefit from the ultimate thinness of 2D materials, and a wide variety of 2D material-based sensors have been proposed [11]. Pressure sensors from single and bilayer graphene membranes show very high sensitivity, despite a graphene gauge factor of less than ten [12], [13] (Fig. 2a, b). Platinum diselenide ($PtSe_2$) shows even higher sensitivity, mainly driven by a much larger piezoresistive gauge factor [14], [15] (Fig. 2c). Attaching silicon proof masses to graphene membranes result in highly sensitive accelerometers [16], [17]. Graphene membranes can also be used as sensitive Hall sensors and microphones that are resonance-free for frequencies up to 700 kHz, which is an advantage over conventional MEMS microphones [18].

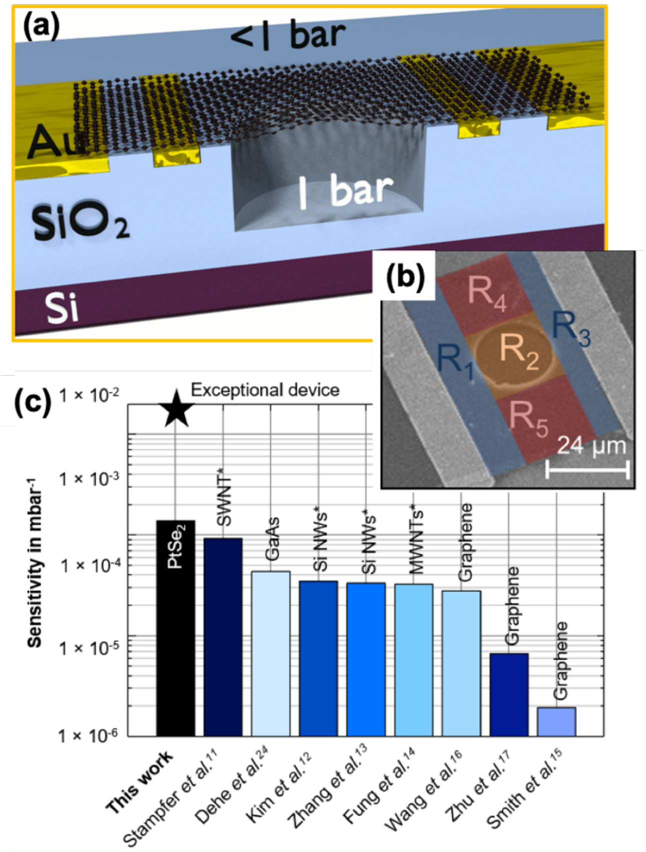

Fig. 2: Schematic of a 2D membrane-based pressure sensor (a). Color enhanced scanning electron micrograph of a graphene membrane (R2, yellow area) (b). Schematic of two MoS_2 layers with mobile inter-layer hydroxyl ions (b). Performance comparison of 2D membrane-based pressure sensors with other technology options (c).

4. 2D Material Integration with Silicon Technology

Scalable, reproducible and reliable process technology is a key requirement for 2D materials to be successful, independent of the target application. Hence, the Graphene Flagship has taken a generic approach to address open issues in its 2D Experimental Pilot Line project. This is in line with recent publications highlighting the need for higher quality material, in particular improving growth and transfer [19], [20], low contact resistances [21] and high quality and uniform encapsulation [22], e.g. for hysteresis free transistor or sensor operation. The 2D Experimental Pilot Line will be introduced in the talk.

3. Conclusions

Although many very promising 2D device concepts exist, the path towards integrated 2D electronics is currently blocked by the lack of manufacturing tools and processes. The upcoming European 2D Experimental Pilot Line aims to address these generic challenges over the course of the next years.

Acknowledgements

Funding from the European Union Horizon 2020 programme under grant agreements 829035 (QUEFORMAL), 825272 (ULISSES) and 881603 (Graphene Flagship Core 3), the German BMBF projects 03XP0210 (GIMMIK), 16ES1121 (NobleNEMS) and 16ES1134 (NeuroTec), and the German Research Foundation (UltiMOS2, MOSTFLEX) is gratefully acknowledged.

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Appendix

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