doi:10.1017/S1431927617007863
Microsc. Microanal. 23 (Suppl 1), 2017

Cross-sectional STEM Imaging and Spectroscopy of Devices with Embedded 2D Materials

Ryan J. Wu, Danielle Reifsnyder Hickey, K. Andre Mkhoyan

Department of Chemical Engineering and Materials Science, University of Minnesota, MN, USA

Two-dimensional (2D) systems have been demonstrated to be excellent materials for charge [1] and spin transport [2] in devices. Their exceptional performance in these devices is afforded by their unique electronic structure in their single- or few-layer states. As such, it would be advantageous to characterize how their atomic and electronic structures change while embedded in actual devices, as compared to in their free-standing states. Although simulations have modeled 2D materials embedded within a solar cell or field effect transistor in order to predict the material's performance [3], experimental results to corroborate these theoretical predictions that show the structure of the 2D material or the interface it shares with the substrate or contacts in the device remain scarce. This region, together with its interface, is as thick as the embedded 2D material in the device, which is often only a few atomic layers, making access inherently difficult.

In this work, we present a method to study 2D materials fabricated in a device, as well as their surrounding interfaces by (1) preparing ultra-thin cross-sectional TEM samples using a focused ion beam (FIB) and (2) measuring the atomic and electronic structure using analytical transmission electron microscopy (TEM). 2D material devices are first thinned using an FEI Helios G4 in order to minimize the ion beam damage incurred during TEM sample preparation. Subsequently, analytical TEM is performed on an aberration-corrected FEI Titan G2 60-300 S/TEM.

Scanning TEM (STEM) is used simultaneously with energy dispersive X-ray spectroscopy (EDX) at lower magnification to map the chemical structure of the device (example shown in Figure 1). Subsequently, atomic resolution STEM images are recorded to observe the uniformity, or lack thereof, of the interfaces surrounding the 2D material (example shown in Figure 2). At this magnification, electron energy loss (EELS) spectra are then recorded to reveal the electronic structure as a function of position across the 2D material and its surrounding interfaces. Because the embedded 2D material is only a few atomic layers, STEM images and EELS results will likely reveal a continuous change in the atomic and electronic structure across the 2D material. These measurements will then be compared to theoretical models to improve our understanding of the role of 2D materials in devices [6].

[1] M. Chhowalla, D. Jena and H. Zhang, *Nature Reviews: Materials* **1**, (2016) 16052
[2] W. Han *et al*, *Nature Nanotechnology* **9**, (2014), p. 704
[3] X. Qian *et al*, *2D Materials* **2**, (2015), 2003
[4] H. Wang *et al*, *Physical Review Letters* **117**, (2016) 076601
[5] J.S. Lee *et al*, *Physical Review B* **92**, (2015), 155312
[6] The authors gratefully acknowledge funding provided by C-SPIN, one of six centers of STARnet, a Semiconductor Research Corporation program, sponsored by MARCO and DARPA.

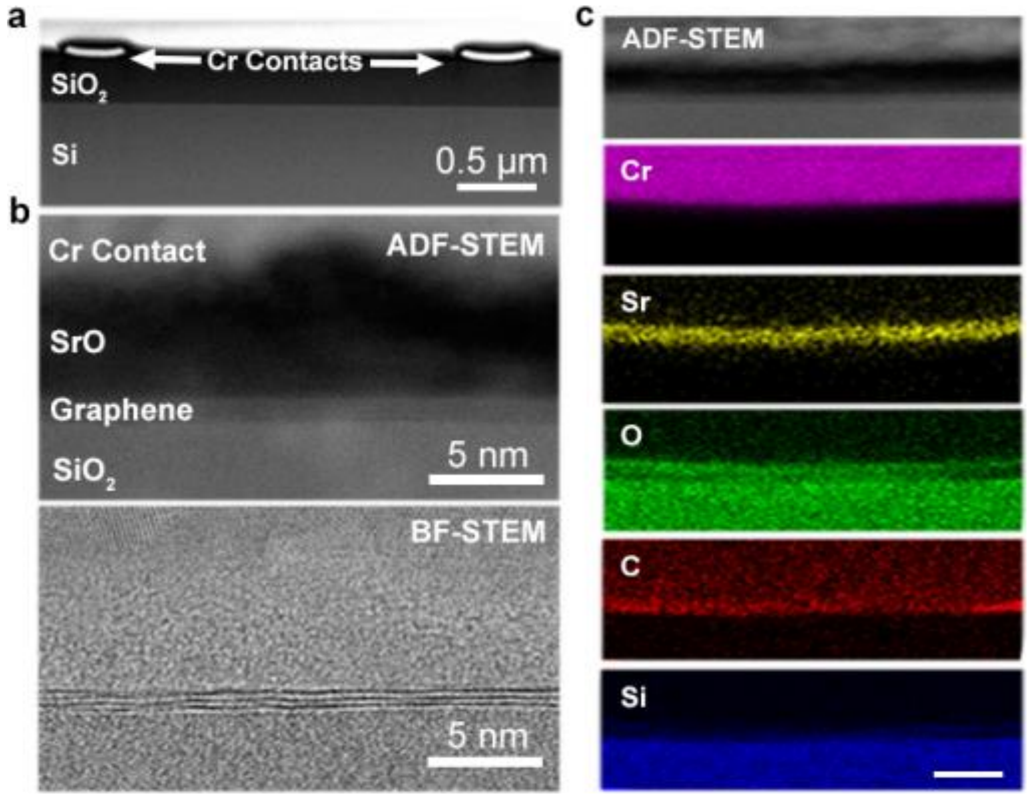

Figure 1: (a) Low-magnification image of a graphene spin valve device. The graphene interface is between the SiO_2 layer and Cr contacts. (b) High-magnification ADF-STEM and BF-STEM images showing a 4-layer graphene interface. (c) Energy dispersive X-ray spectroscopy (EDX) elemental maps acquired along the interface; scale bar is 5 nm.

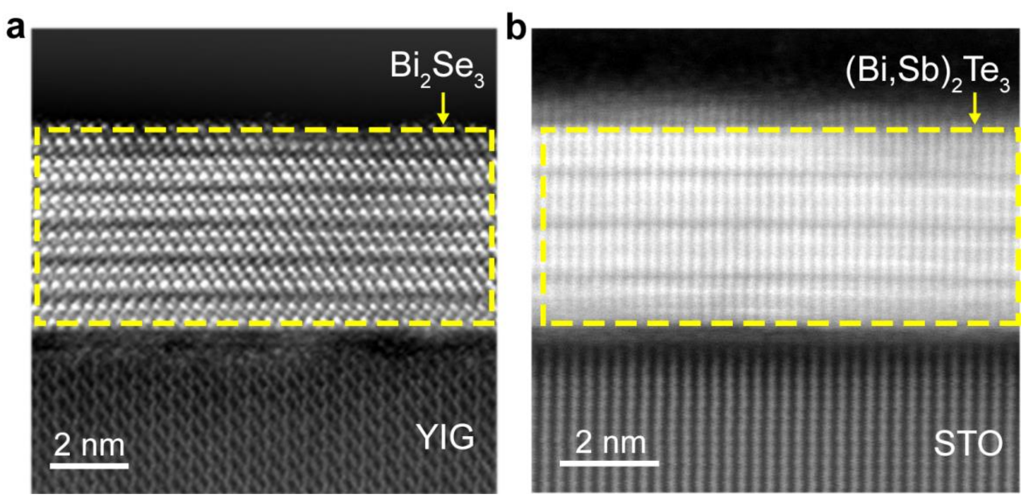

Figure 2: (a) Atomic resolution image of a thin Bi_2Se_3 layer grown on yttrium iron garnet (YIG). The 2D material is used to induce spin-charge conversion in a spintronic device, as discussed in [4]. (b) Atomic resolution image of a thin $(Bi,Sb)_2Te_3$ layer grown on strontium titanate (STO). $(Bi,Sb)_2Te_3$ is used as a spin channel below an Al_2O_3/Py magnetic tunnel junction, as discussed in [5].