Enabling Electronic Applications of Two-Dimensional Materials

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Two-dimensional (2D) materials can have intrinsic properties that make them ideal for electronic applications such as transistors, sensors, photodetectors, and flexible electronics. As an example, due to electrostatic considerations, it is envisioned that atomically thin 2D channels will enable the shortest possible transistors for high-performance integrated circuits. There is widespread precompetitive research in academia and industry to determine the most promising materials and device structures for 2D electronics.

New and improved measurements are needed to drive the discovery of scientific phenomena and enable commercial applications of 2D materials. While the need for cutting edge measurements and precise fabrication process monitoring techniques is clear, fulfilling that need is challenging. It is important to measure the intrinsic properties of 2D materials, to determine integration and interaction aspects, [1] and to correlate the properties obtained from material characterization directly with the electrical performance of completed devices. The advanced electronics industry looks to the research community for the results of these measurements to enable them to determine the most promising materials and devices in which to invest for future products. To reach that goal, the semiconductor industry needs research results presented so they can make direct comparisons between the performance of 2D materials and structures. Uniform benchmarking and reporting approaches are required.[2]

While innovative measurements drive new technologies and discoveries, the opposite is also true. Discoveries can enable new metrology. For instance, the quantum anomalous hall effect (QAHE) is a recently discovered quantum transport behavior associated with 2D topological materials. In a QAHE device, the Hall resistance is quantized to the von Klitzing constant, R_K (25,812.8074...**Ω**) at 0 T. Such devices could be combined with Josephson voltage standards in a single cryostat to create a system that would realize the three fundamental units of electricity: volt, amp, and ohm.

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[1] Zhihui Cheng, Huairuo Zhang, Son T. Le, et al., Are 2D Interfaces Really Flat? ACS Nano, **16**, 5316-5324 (2022).

[2] Zhihui Cheng, C.S. Pang, P. Wang, et al., How to report and benchmark emerging field-effect transistors, Nat Electron, **5**, 416–423 (2022).

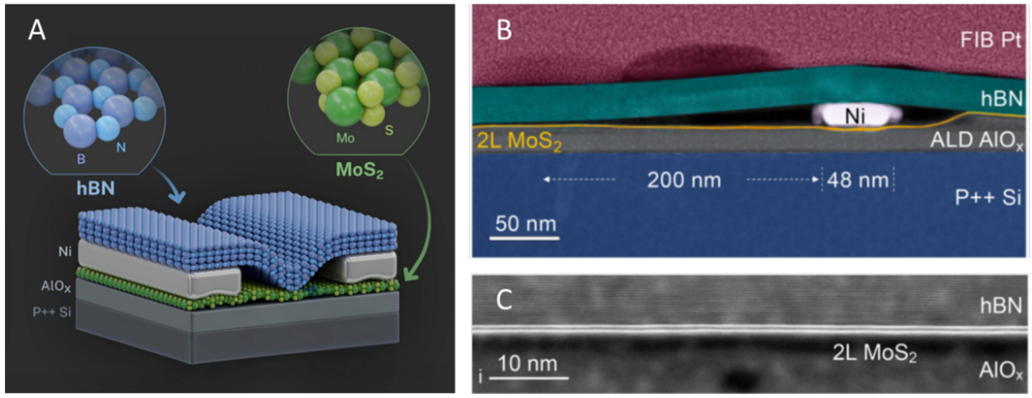

Figure 1: The reality of 2D transistors: While it is envisioned that emerging transistors fabricated with 2D crystals will have perfectly flat 2D-2D and 2D-3D interfaces, obvious bending and nanogaps are observed in real structures.
(A) Illustration of a 2D FET with gaps, nanogaps, and contact regions (B) False-colored HAADF-STEM image of a contact region showing a large gap at a 3D metal-3D semiconductor contact. (C) STEM image of hBN-MoS_2 and MoS_2-AlO_x interfaces in a FET channel region where the interfaces are ideal: flat and intimate (after [1]).

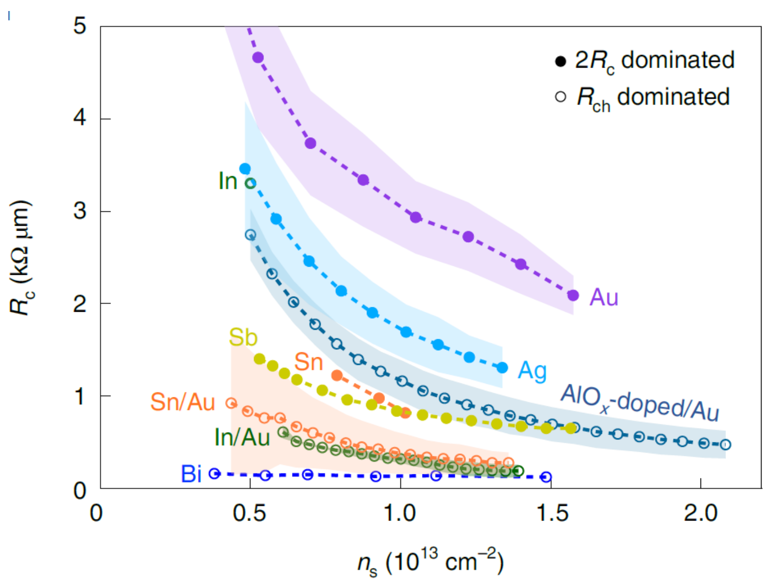

Figure 2: Example of benchmarking device performance of monolayer MoS_2 FETs. Contact Resistance, R_c, versus carrier concentration, n_S, in a few representative reports. The shaded regions represent uncertainties reported in the respective studies (from [2]).