Properties and Applications of hBN-encapsulated Graphene

J. Hone[1]

[1] Department of Mechanical Engineering, Columbia University, New York NY USA

Graphene and other 2D materials offer novel physics and exceptional performance in multiple application areas. However, all 2D materials are highly sensitive to environmental effects, and are not well matched to conventional 3D dielectric insulators. We have pioneered the use of hexagonal boron nitride (BN) as an ideal dielectric material for graphene and other 2D materials, and have developed techniques for clean 'stacking' of these materials into vertical heterostructures in which the device layer is fully encapsulated [1]. Figure 1A shows the van der Waals transfer technique used to assemble BN/G/BN stacks, and achieve electrical contact to the encapsulated graphene from an exposed edge. These devices can be essentially contamination-free over large areas (Fig. 1B), and show room-temperature electrical transport behavior at the intrinsic limit (Fig. 1C), corresponding to mobility of 40,000 – 140,000 cm^2/Vs, depending on carrier density.

Figure 2 highlights some of the physical phenomena that can be observed and studied in these large, clean devices. They show magnetic focusing at fields below .05 T, evidence of ballistic electron transport; and quantum oscillations at higher fields that can be used to characterize small-angle scattering (Fig. 2A). For graphene crystallographically aligned to one of the BN layers, Hofstader Butterfly physics emerges. In these ultraclean samples, we observe both the 'Butterfly' he fractional quantum Hall effect, as well as new states attributable to neither phenomenon alone (Fig. 2B)[2]. Finally, in bilayer graphene, a clean electronic gap can be achieved up to ~ 200 meV upon application of a vertical displacement field (Fig. 2C).

Figures 3 and 4 shows applications in electronics and optoelectronics. We have demonstrated BN-encapsulated GFETs on flexible substrates with frequencies (f_{max}) above 10 GHz and strain limits above 1% (Fig. 3). This combination of strain and operation frequency is not achieved in conventional materials. A waveguide-integrated graphene photodetector is shown in Fig. 4A. This device operates up to 43 GHz, with sensitivity 10× that of similar devices using SiO_2 dielectrics. A modulator device is shown in Fig. 4B. This device incorporates two graphene layers in a BN/G/BN/G/BN stack, and is integrated with a photonic crystal cavity to improve coupling to light at the resonance frequency of cavity. Applying a voltage between the two layers modulates the optical absorption in the graphene, and hence the quality factor of the cavity. We find modulation depth above 10 dB, and maximum frequency above 1 GHz.

References

[1] C.R. Dean *et al.*, *Nature Nanotechnology* **5**, 722 (2010); L. Wang *et al.*, *Science* **342**, 614 (2013).

[2] L. Wang *et al.*, arXiv:1505.07180

[3] R. Shuie *et al.*, submitted (2015).

[4] Y.D. Gao *et al.*, *Nano Letters* **15**, 2001 (2015)

[5] This research was supported by the US Office of Naval Research N00014-13-1-0662

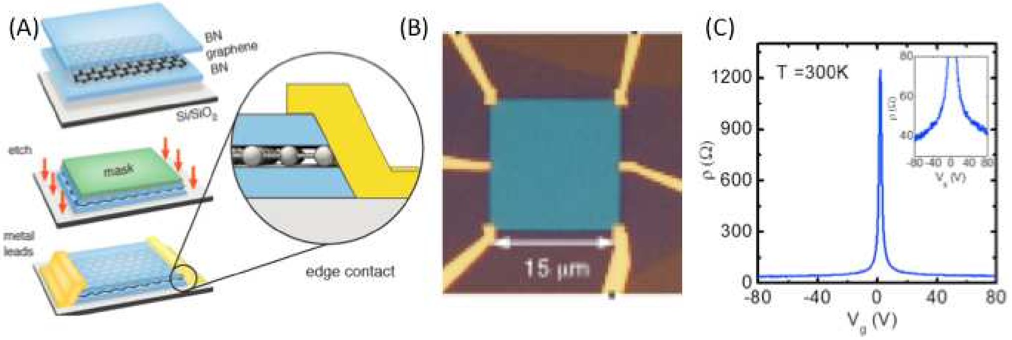

Figure 1: Fabrication and properties of BN/G/BN stacks. (A) van der Waals assembly and edge contacts. (B) Large contamination-free device. (C) Room-T electrical transport.

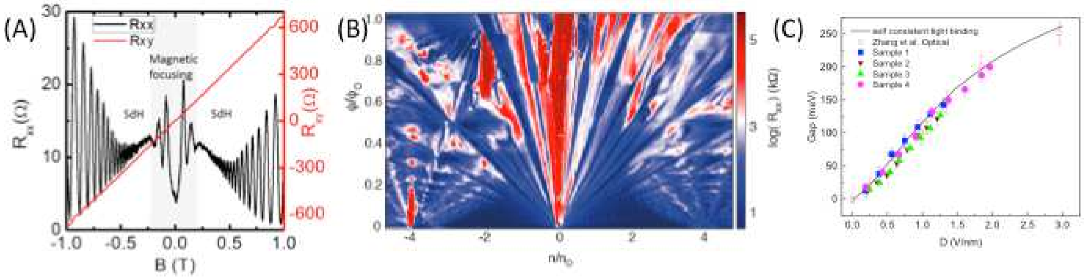

Figure 2: Low-T properties. (A) Magnetic focusing and quantum oscillations. (B) Coexistence of fractional quantum Hall effect and Hofstader Butterfly. (C) Clean transport gaps up to 200 meV in bilayer graphene.

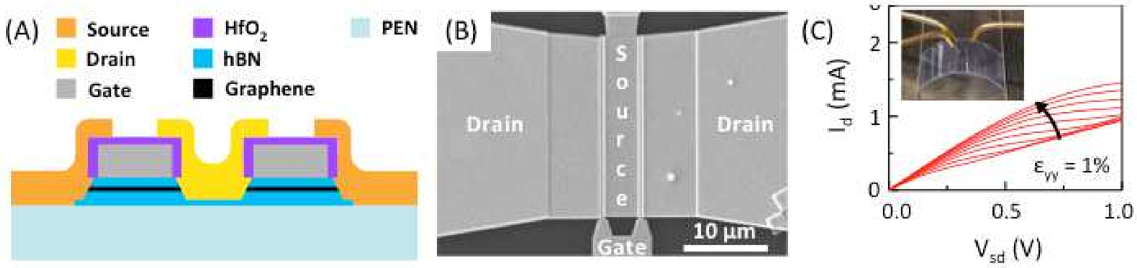

Figure 3: Flexible RF-FETs. (A) Schematic cross-section. (B) SEM image of device. (C) DC characterization under large strain.

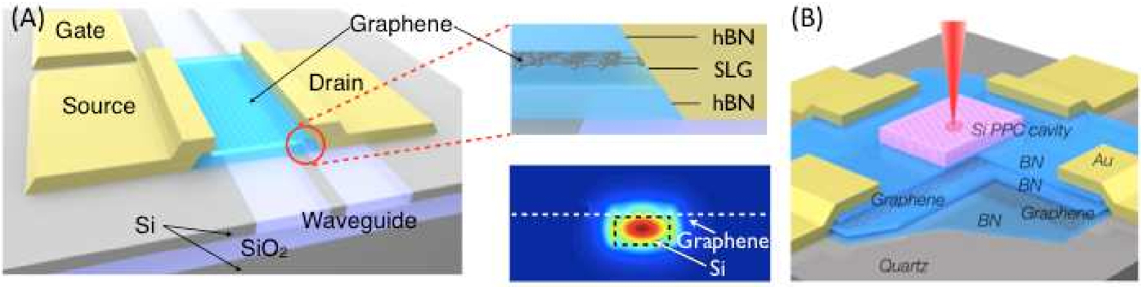

Figure 4: Optoelectronic devices. (A) Ultrafast waveguide-integrated photodetector. (B) Photonic crystal-integrated modulator.