# Helium-Ion-Beam Etched Encapsulated Graphene Nanoribbons

Gaurav Nanda, Gregor Hlawacek*, Srijit Goswami, and Paul Alkemade

Kavli Institute of Nanosciece, Delft University of Technology, Delft, The Netherlands
*Helmholtz-Zentrum Dresden-Rossendorf, Germany
mail: p.f.a.alkemade@tudelft.nl

Graphene nanoribbons (GNRs) have been studied extensively since the realization that narrow graphene ribbons have a band-gap [1]. However, much of the predicted novel physics in GNR devices eluded experiments. The methods of fabrication were the bottleneck, being either too complex or not flexible, or introducing contaminations or lattice imperfections. In the last two years one sees a resurgence of this field, mainly driven by the ability to encapsulate graphene, thus greatly reducing the risk of contamination during or after fabrication.

One of the fabrication methods is etching with a subnanometer helium focused ion beam (He-FIB) [2-5]. So far lattice damage and/or contamination precluded reliable electrical measurements in ion-beam etched graphene devices. In the present work we avoided contamination by encapsulating graphene in boron nitride layers. Subsequently we have conducted extensive electrical measurements.

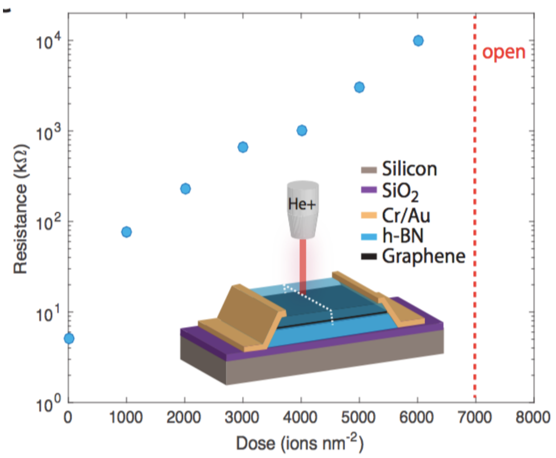


Fig. 1. Creation of an insulating barrier in encapsulated graphene with a $He^+$ FIB. The resistance between the Cr/Au leads increases with dose until an open circuit is reached at 7000 ions nm$^{-2}$.

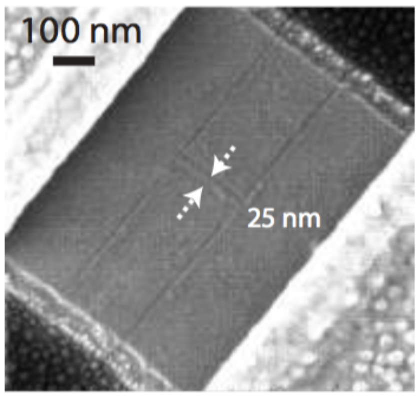


Fig. 2. He-ion microscope image of a 200-nm long and 25-nm wide GNR, etched into a BN-Gr-BN stack. Upper left and lower right are Cr/Au electrodes. The two etched U-shaped barriers are 10 nm wide.

We used a He-FIB to etch encapsulated graphene into ribbons of varying width. First, we made a sandwich of a boron nitride bottom layer, single-layer graphene, and a 15-nm top boron nitride layer. In the stacks we fabricated using e-beam lithography [6,7] rectangular (10 x 1 um$^2$) strips, connected to multiple Cr/Au electrodes. Next, we determined using in-situ electric probes the required 30-keV $He^+$ dose to make a 10-nm wide insulating barrier in the graphene between the electrodes, see Fig. 1; it was 7000 ions nm$^{-2}$ (or 110 nC cm$^{-1}$), about ten times higher than for $SiO_2$ supported graphene [2-5]. In the final fabrication step, we etched the actual GNR devices; they are 200 nm long and 10 to 90 nm wide, see an example in Fig. 2.

We characterized the exposed graphene and the GNRs by Raman spectroscopy, atomic force microscopy, and most importantly by electrical (*I-V*) measurements. The electrical measurements revealed the presence of 8-nm wide inactive strips at the edges of the GNRs, consistent with previous e-beam lithography and He- FIB etching results [1,5]. Conductance measurements at 4 K showed an energy gap, that was largest for the narrowest ribbons. Furthermore, we observed that the low-temperature *I-V* measurements are characterized by power-law scaling, see Fig. 3. This scaling behavior demonstrates [8] that the electrical transport in the encapsulated GNRs is governed is governed by Coulomb blockade and charge hopping between islands and localized states. The Coulomb blockade points to beam-induced disorder in the GNRs.

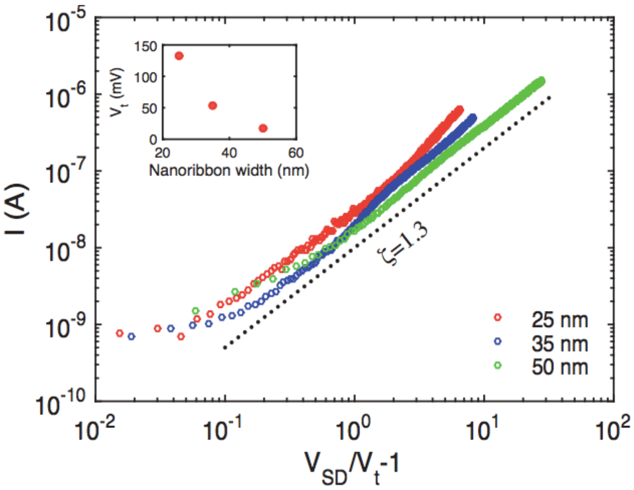


Fig. 3. Current *I* as a function of the source-drain voltage $V_{SD}$, relative to the threshold voltage $V_t$. The power-law scaling with an exponent of 1.3 points to Coulomb blockade.

We attribute the almost complete disappearance of conductance in previous studies [2-5] to surface contamination that is aggravated by beam-induced disorder. Our study provides insight into the role of beam-induced disorder in graphene and it opens a new avenue for the controlled structuring of graphene and other 2-D materials, essential for *e.g.* bandgap engineering, fabrication of *p-n* junctions, and DNA translocation studies.


[1] M. Y. Han, B. Özyilmaz, Y. Zhang, and P. Kim. *Energy band-gap engineering of graphene nanoribbons*. Phys. Rev. Lett. **98**, 206805, 2007

[2] D. C. Bell, M. C. Lemme, L. A. Stern, J. R. Williams, and C. M. Marcus. *Precision cutting and patterning of graphene with helium ions*. Nanotechnology **20**, 455301, 2009

[3] S. Nakaharai, T. Iijima, S. Ogawa, S. Suzuki, S. L. Li, K. Tsukagoshi, S. Sato, and N. Yokoyama. *Conduction tuning of graphene based on defect-induced localization*. ACS Nano **7**, 5694, 2013

[4] N. Kalhor, S. A. Boden, and H. Mizuta. *Sub-10 nm patterning by focused He-ion beam milling for fabrication of downscaled graphene nano devices*. Microelectronic Eng. **114**, 77, 2014

[5] A. N. Abbas, G. Liu, B. Liu, L. Zhang, H. Liu, D. Ohlberg, W. Wu, and C. Zhou. *Patterning, characterization, and chemical sensing applications of graphene nanoribbon arrays down to 5 nm using helium ion beam lithography*. ACS Nano **8**, 15381546, 2014

[6] C. R. Dean, A. F. Young, I. Meric, C. Lee, L. Wang, S. Sorgenfrei, K. Watanabe, T. Taniguchi, P. Kim, K. L. Shepard, and J. Hone. *Boron nitride substrates for high quality graphene electronics*. Nature Nanotechnology **5**, 722, 2010

[7] G. Nanda, S. Goswami, K. Watanabe, T. Taniguchi, and P. F. A. Alkemade. *Defect control and n-doping of encapsulated graphene by helium-ion-beam irradiation*. Nano Lett. **15**, 4006, 2015

[8] A. A. Middleton and N. S. Wingreen. *Collective transport in arrays of small metallic dots*. Phys. Rev. Lett. **71**, 3198, 1993