New horizons and challenges in the microscopic characterization of 2-D materials

Jannik Meyer

University of Vienna, Physics department, Boltzmanngasse 5, 1090 Vienna, Austria
Jannik.Meyer@univie.ac.at

The microscopic characterization of two-dimensional materials, and low-dimensional matter in general, poses unique challenges but also opens unique new avenues that are not available with 3-D bulk structures or on he surfaces of 3D crystals. In this talk, I will discuss these aspects in connection with high-resolution electron microscopic studies as well as scanning probe investigations.

The study of nano-carbons and other low-atomic number materials remains a particular challenge for high resolution transmission electron microscopy (HRTEM) owing to their intrinsically low contrast and high susceptibility to radiation damage [1]. However, the recent developments in aberration-corrected electron optics open a route to a atomically-resolved studies of these materials at reduced electron energies [2–9] below the knock-on threshold of carbon atoms in graphene [10,11]. I will present insights to this class of materials from electron microscopic studies with single-light-atom precision. Static deformations, topological defects, various vacancy configurations, the two-dimensional equivalent of dislocations, grain boundaries and substitutional dopants can be analyzed and exact atomic configurations are obtained.

At the same time, the electron microscope can be used to structure and modify graphene with highest resolution and with a direct feedback [12–14]. We analyzed the mechanisms behind beam-driven structural changes and demonstrate how a controlled modification, beyond the ejection of atoms, can be achieved [15]. An electron beam can be used to selectively suppress and enhance bond rotations and atom removal in graphene, which allows to turn graphene into a two-dimensional coherent amorphous membrane composed of sp2-hybridized carbon atoms [15,16]. In addition, substitutional doping of graphene can be obtained not only via a modified synthesis but also by electron irradiation effects [17]. The graphene substrate may further serve as an extreme thermal test platform, which then provides a means to study physisorbed carbon species under the influence of high temperatures and electron irradiation [18].

Nevertheless, for TEM imaging, beam-induced material modifications remain as a primary concern and limitation [19]. I will show a new approach on how to circumvent the radiation damage problem for imaging of material configurations based on a statistical treatment of large, noisy, low-dose data sets. This can reduce the required dose per area by several orders of magnitude, and will open a route to study beam-sensitive configurations that are currently not accessible. It will be of particular importance for TEM studies of low-dimensional materials, where every atom (rather than atomic column) is important for the analysis of the projected structure.

As a complementary tool of atomic-level analysis, scanning probe microscopy and in particular scanning tunneling microscopy (STM) has been extensively used for studying graphene and related materials. Very recently, free-standing membranes of graphene have been explored by STM [20–22]. In the free-standing case, the deformation of the graphene membrane induced by the STM tip is the predominant effect to the height profiles, meaning that the membrane follows the probe rather than vice versa. I will show initial results from a dual-probe STM setup where a free-standing graphene membrane is probed simultaneously from opposing sides. At the closest point, the two probes are separated only by the thickness of the graphene membrane. This allows us for the first time to directly measure the deformations induced by one STM probe on a free-standing membrane with an independent second probe [23].

References

[1] F. Banhart, Reports on Progress in Physics **62**, 1181 (1999).

[2] J. C. Meyer, C. Kisielowski, R. Erni, M. D. Rossell, M. F. Crommie, and A. Zettl, Nano Letters **8**, 3582 (2008).

[3] M. H. Gass, U. Bangert, A. L. Bleloch, P. Wang, R. R. Nair, and a K. Geim, Nature Nanotechnology **3**, 676 (2008).

[4] A. Chuvilin, J. C. Meyer, G. Algara-Siller, and U. Kaiser, New Journal of Physics **11**, 083019 (2009).

[5] O. L. Krivanek, N. Dellby, M. F. Murfitt, M. F. Chisholm, T. J. Pennycook, K. Suenaga, and V. Nicolosi, Ultramicroscopy **110**, 935 (2010).

[6] P. J. F. Harris, Z. Liu, and K. Suenaga, Journal of Physics: Condensed Matter **20**, 362201 (2008).

[7] U. Kaiser, J. Biskupek, J. C. Meyer, J. Leschner, L. Lechner, H. Rose, M. Stöger-Pollach, A. N. Khlobystov, P. Hartel, H. Müller, M. Haider, S. Eyhusen, and G. Benner, Ultramicroscopy **111**, 1239 (2011).

[8] K. Suenaga, K. Akiyama-Hasegawa, Y. Niimi, H. Kobayashi, M. Nakamura, Z. Liu, Y. Sato, M. Koshino, and S. Iijima, Journal of Electron Microscopy **61**, 285 (2012).

[9] J. H. Warner, E. R. Margine, M. Mukai, a. W. Robertson, F. Giustino, and a. I. Kirkland, Science **337**, 209 (2012).

[10] A. Zobelli, A. Gloter, C. Ewels, G. Seifert, and C. Colliex, Physical Review B **75**, 1 (2007).

[11] J. Meyer, F. Eder, S. Kurasch, V. Skakalova, J. Kotakoski, H. Park, S. Roth, A. Chuvilin, S. Eyhusen, G. Benner, A. Krasheninnikov, and U. Kaiser, Physical Review Letters **108**, 196102 (2012).

[12] J. C. Meyer, C. O. Girit, M. F. Crommie, and A. Zettl, Applied Physics Letters **92**, 123110 (2008).

[13] M. D. Fischbein and M. Drndic, Applied Physics Letters **93**, 113107 (2008).

[14] A. W. Robertson, C. S. Allen, Y. A. Wu, K. He, J. Olivier, J. Neethling, A. I. Kirkland, and J. H. Warner, Nature Communications **3**, 1144 (2012).

[15] J. Kotakoski, A. Krasheninnikov, U. Kaiser, and J. Meyer, Physical Review Letters **106**, 105505 (2011).

[16] J. Kotakoski, J. Meyer, S. Kurasch, D. Santos-Cottin, U. Kaiser, and A. Krasheninnikov, Physical Review B **83**, 245420 (2011).

[17] J. C. Meyer, S. Kurasch, H. J. Park, V. Skakalova, D. Künzel, A. Gross, A. Chuvilin, G. Algara-Siller, S. Roth, T. Iwasaki, U. Starke, J. H. Smet, and U. Kaiser, Nature Materials **10**, 209 (2011).

[18] B. Westenfelder, J. C. Meyer, J. Biskupek, S. Kurasch, F. Scholz, C. E. Krill, and U. Kaiser, Nano Letters **11**, 5123 (2011).

[19] R. F. Egerton, Microscopy Research and Technique **75**, 1550 (2012).

[20] R. Zan, C. Muryn, U. Bangert, P. Mattocks, P. Wincott, D. Vaughan, X. Li, L. Colombo, R. S. Ruoff, B. Hamilton, and K. S. Novoselov, Nanoscale **4**, 3065 (2012).

[21] N. N. Klimov, S. Jung, S. Zhu, T. Li, C. A. Wright, S. D. Solares, D. B. Newell, N. B. Zhitenev, and J. A. Stroscio, Science **336**, 1557 (2012).

[22] P. Xu, Y. Yang, S. Barber, M. Ackerman, J. Schoelz, D. Qi, I. Kornev, L. Dong, L. Bellaiche, S. Barraza-Lopez, and P. Thibado, Physical Review B **85**, 121406R (2012).

[23] F. Eder, J. Kotakoski, K. Holzweber, C. Mangler, V. Skakalova, and J. C. Meyer, Submitted (2012).