Perforation of 2D heterostructures

J. Schwestka[1], A. Niggas[1], H. Inani[2], S. Creutzburg[3], J. Kotakoski[2],
R.A. Wilhelm[1,3] and F. Aumayr[1]

[1]TU Wien, Institute of Applied Physics, 1040 Vienna, Austria
[2]University of Vienna, Faculty of Physics, Boltzmanngasse 5, 1190 Wien, Austria
[3]Helmholtz-Zentrum Dresden-Rossendorf, Institute of Ion Beam Physics and Materials Research, 01328 Dresden, Germany

Two-dimensional materials such as graphene and transition metal dichalcogenide monolayers open a wide range of potential applications including biological sensors, electronic devices, DNA sequencing, water desalination and purification. Especially for the latter, it is essential to consider that the efficiency for separation is limited by the transmission speed of the particles and by the selectivity. Therefore, 2D materials as sieving membranes and sophisticated ways to perforate them are highly requested [1]. Using high-energy electrons, ion beam lithography or focussed ion beams for hole drilling results either in creation of single or double vacancies only or high fluencies are necessary for the required results, which is not suitable for mass production [2]. Slow highly charged ions (HCIs) on the other hand, carry high potential energy initially stored in their production process. They are favoured for surface-only modifications, i.e. 2D membranes, as they enable deposition of large fractions of their ionization energy within a very shallow area. Once the potential energy exceeds a certain threshold perforation with pores of tunable sizes becomes feasible, depending on the applied ion charge state [3].
Figure 1 shows the successful perforation of a 1nm thick carbon nanomembrane (CNM) after irradiation with 176 keV Xe^{40+} ions.

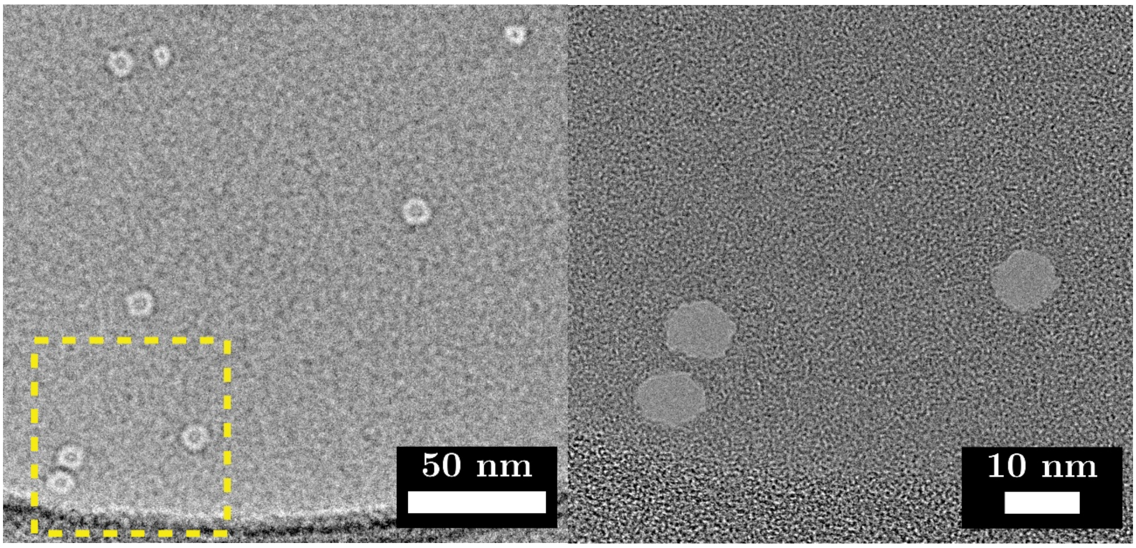

Figure 1 - TEM images of observed pore formation in 1nm thick carbon nanomembrane after irradiation with 176 keV Xe^{40+} ions. The right image shows zoom of yellow marked area in left image. Taken from [3].

Further, it was recently shown that such holes with an adjustable radius of 0.3-3 nm can also be drilled not only in supported molybdenum disulfide (MoS_2) but also in the free-standing monolayer [2] via slow HCI impact. The nature for damage creation is very likely the same for both materials, the release of energy due to the neutralization and deexcitation of the HCI. However, bombarding a single layer of graphene (SLG) under the same experimental conditions, has not shown any evidence for efficiently drilling of pores into the membrane so far. We therefore assume the high electron mobility within the semimetal graphene sheet as the reason for prevention of perforation. The missing charge, created through the fast charge exchange with the ion, is promptly resupplied leading therefore to suppression of Coulomb explosion [4].

In current experiments, we irradiate heterostructured 2D samples consisting of a monolayer MoS_2 on top of SLG and vice versa with slow HCIs. Large areas of the sample consist of regimes covered by the MoS_2-SLG structure while small areas with either SLG or MoS_2 only remain. In earlier studies, stacks of CNMs were irradiated with HCIs and pore formation was observed in all stacks even tough with decreasing efficiency for higher stack number [3]. However, our results on the irradiation of the heterostructures again indicate no pore formation when SLG faces the ion beam and covers the MoS_2. Further, when reversing the order of layers, i.e. the MoS_2 faces the ion beam, nano-sized damages in the monolayer are observed. Possible mechanism for SLG protecting the MoS_2 from pore formation will be discussed.

Support by the TU-D doctoral collage of the TU Wien is gratefully acknowledged.

[1] K. Celebi, J. Buchheim, R.M. Wyss, A. Droudian, P. Gasser, I. Shorubalko, J.-I. Kye, C. Lee, H.G. Park, Science 344, 289–292 (2014)

[2] R. Kozubek, M. Tripathi, M. Ghorbani-Asl, S. Kretschmer, L. Madauß, E. Pollmann, M. O'Brien, N. McEvoy, U. Ludacka, T. Susi, G.S. Duesberg, R.A. Wilhelm, A. V Krasheninnikov, J. Kotakoski, M.Y. Schleberger, J. Phys. Chem. Lett. 10, 904–910 (2019)

[3] R.A. Wilhelm, E. Gruber, R. Ritter, R. Heller, A. Beyer, A. Turchanin, N. Klingner, R. Hübner, M. Stöger-Pollach, H. Vieker, G. Hlawacek, A. Gölzhäuser, S. Facsko, F. Aumayr, 2D Mater. 2, 35009 (2015)

[4] E. Gruber, R.A. Wilhelm, R. Petuya, V. Smejkal, R. Kozubek, A. Hierzenberger, B.C. Bayer, I. Aldazabal, A.K. Kazansky, F. Libisch, A. V Krasheninnikov, M. Schleberger, S. Facsko, A.G. Borisov, A. Arnau, F. Aumayr, Nat. Commun. 7, 13948 (2016)