Nanoparticle-induced strain and nanoscale rippling in graphene

Z. Osváth[1,3], G. Molnár[1], E. Gergely-Fülöp[1], A. Deák[1], N. Nagy[1], K. Kertész[1], P. Nemes-Incze[1,3], X. Jin[2,3], C. Hwang[2,3], and L. P. Biró[1,3]

[1]Institute of Technical Physics and Materials Science, MFA, Research Centre for Natural Sciences, P.O. Box 49, 1525 Budapest, Hungary (http://www.nanotechnology.hu)
[2]Center for Nano-metrology, Division of Industrial Metrology, Korea Research Institute of Standards and Science, Yuseong, Daejeon 305-340, Republic of Korea
[3]Korean-Hungarian Joint Laboratory for Nanosciences (KHJLN), P.O. Box 49, 1525 Budapest, Hungary
Osvath.Zoltan@ttk.mta.hu

Abstract

Atomically thin graphene membranes are intrinsically non-flat and have random or quasi-periodic corrugations at the nanometer scale [1, 2]. Since this is closely affecting the electronic properties, there is an increasing need for the realization of graphene sheets with controlled corrugation. Substrates play a crucial role, as the graphene–substrate interaction can impart an extrinsic rippling to graphene which differs from its intrinsic corrugation [3, 4]. Such rippling can contribute to the scattering of charge carriers [5, 6]. In order to preserve the high carrier mobility needed for nanoelectronic applications, atomically flat mica [7] and hexagonal boron nitride [8] substrates were introduced recently, which reduce charge inhomogeneity [9] and smooth out corrugations in graphene leading to ultra-flat morphology. On the other hand, corrugated graphene can be good candidate for sensor applications, as recent simulations [10, 11] predict enhanced chemical activity in rippled graphene. The crests and troughs of graphene ripples form active sites for the adsorption of different molecules. It was proposed – based on first-principles calculations [12] – that this can open a way for tunable, regio-selective functionalization of graphene. The extrinsic rippling can be induced for example by pre-prepared elastic substrates [13] or silica nanoparticles (NPs) [14], a possibility which has not been fully explored yet experimentally [15].

In this work we investigate by atomic force microscopy (AFM) the properties of CVD-grown graphene transferred onto a continuous layer of SiO_2 NPs with diameters of around 25 nm, prepared on Si substrate by Langmuir-Blodgett technique (Figure 1). We show that the extrinsic graphene rippling can be controlled by annealing at moderate temperatures (400 ^{o}C). Confocal Raman microscopy (*WITec*) revealed that annealing increases doping and introduces compressive strain into the atomically thin membrane (Figure 2).

Due to the high nanoparticle density, graphene membranes remain completely detached from the Si substrate. The membrane parts bridging the nanoparticles are suspended, as revealed by both AFM topographic and phase images, and can be reversibly lifted by the attractive forces between an atomic force microscope tip and graphene. Such dynamic control of the local graphene morphology can play an important role in the development of graphene based nanomechanical devices such as switches [16, 17]. Local indentation experiments were performed on the suspended parts in order to investigate the elastic properties of the graphene membrane.

References

[1] A. Fasolino, J.H. Los, M.I. Katsnelson, Nat. Mater. **6** (2007) 858.
[2] J.C. Meyer, A.K. Geim, M.I. Katsnelson, K.S. Novoselov, T.J. Booth, S. Roth, Nature **446** (2007) 60.
[3] M. Ishigami, J.H. Chen, W.G. Cullen, M.S. Fuhrer, E.D. Williams, Nano Lett. **7** (2007) 1643.
[4] V. Geringer, M. Liebmann, T. Echtermeyer, S. Runte, M. Schmidt, R. Rückamp, M.C. Lemme, M. Morgenstern, Phys. Rev. Lett. **102** (2009) 076102.
[5] M.I. Katsnelson, A.K. Geim, Phil. Trans. R. Soc. A **366** (2008) 195.
[6] G.-X. Ni, Y. Zheng, S. Bae, H.R. Kim, A. Pachoud, Y.S. Kim, C.-L. Tan, D. Im, J.-H. Ahn, B.H. Hong, B. Özyilmaz, ACS Nano **6** (2012) 1158.
[7] C. Lui, L. Liu, K. Mak, G. Flynn, T. Heinz, Nature **462** (2009) 339.
[8] C.R. Dean, A.F. Young, I. Meric, C. Lee, L. Wang, S. Sorgenfrei, K. Watanabe, T. Taniguchi, P. Kim, K.L. Shepard, J. Hone, Nat. Nanotechnol. **5** (2010) 722.
[9] R. Decker, Y. Wang, V.W. Brar, W. Regan, H.-Z. Tsai, Q. Wu, W. Gannett, A. Zettl, M.F. Crommie, Nano Lett. **11** (2011) 2291.
[10] D.W. Boukhvalov, M.I. Katsnelson, J. Phys. Chem. C **113** (2009) 14176.
[11] D.W. Boukhvalov, Surf. Sci. **604** (2010) 2190.
[12] X. Gao, Y. Wang, X. Liu, T.-L. Chan, S. Irle, Y. Zhao, S.B. Zhang, Phys. Chem. Chem. Phys. **13** (2011) 19449.

[13] S. Scharfenberg, D.Z. Rocklin, C. Chialvo, R.L. Weaver, P.M. Goldbart, N. Mason, Appl. Phys. Lett. **98** (2011) 091908.
[14] M. Yamamoto, O. Pierre-Louis, J. Huang, M.S. Fuhrer, T.L. Einstein, W.G. Cullen, Phys. Rev. X. **2** (2012) 041018.
[15] T. Li, Modelling Simul. Mater. Sci. Eng. 19 (2011) 054005.
[16] J.S. Bunch, A.M. van der Zande, S.S. Verbridge, I.W. Frank, D.M. Tanenbaum, J.M. Parpia, H.G. Craighead, P.L. McEuen, Science **315** (2007) 490.
[17] P. Li, Z. You, G. Haugstad, T. Cui, Appl. Phys. Lett. 98 (2011) 253105.

Figures

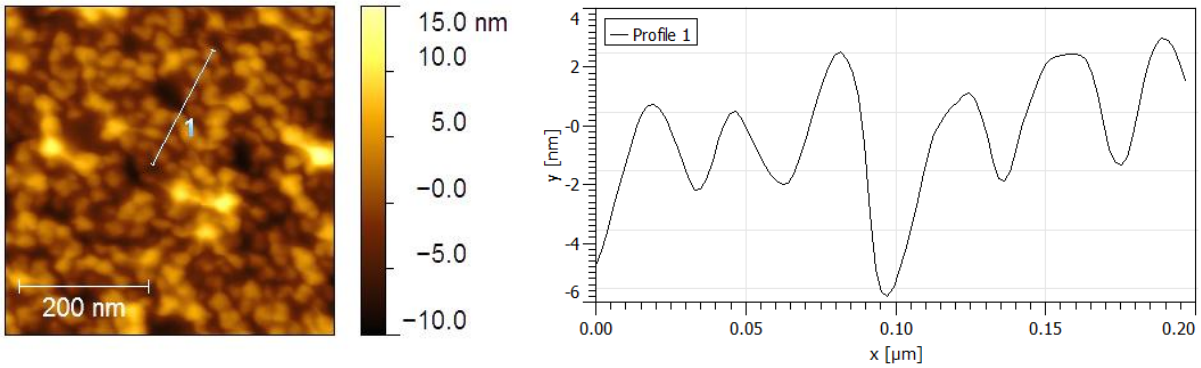

Figure 1. Induced (extrinsic) rippling in graphene transferred onto SiO_2 nanoparticles: AFM image performed after annealing at 400 ^{o}C.

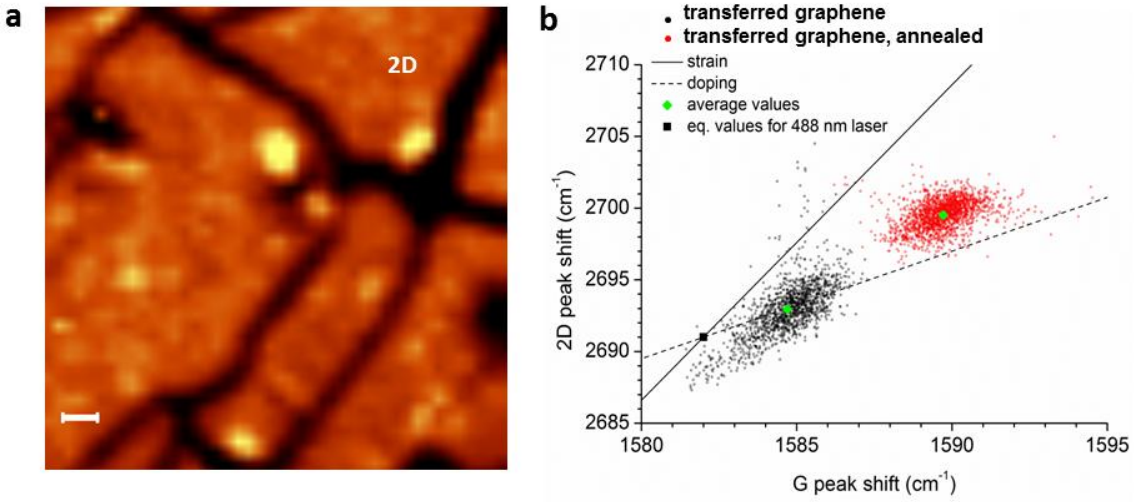

Figure 2. (a) Confocal Raman 2D peak map of graphene transferred onto SiO_2 NPs. Scale bar is 500 nm. The dark lines correspond to the substrate not covered with graphene. (b) (ω_G, ω_{2D}) correlation plot before (black dots) and after annealing (red dots). The corresponding average peak positions are marked with green diamonds. The equilibrium values for 488 nm laser are shown with a black square.