Quantum confined electronic states in atomically well-defined graphene nanostructures

P. Liljeroth[1], S.K. Hämäläinen[1], Z. Sun[2], M.P. Boneschanscher[2], J. van der Lit[2], A. Uppstu[1], M. Ias[1], A. Harju[1], D. Vanmaekelbergh[2]

[1]*Department of Applied Physics, Aalto University, FI-00076 Aalto, Finland*
[2]*Condensed Matter and Interfaces, Debye Institute for Nanomaterials Science, University of Utrecht, 3508 TA Utrecht, the Netherlands*

Despite the availability of good quality, large scale graphene layers, the realization of both the room-temperature graphene transistor as well as the more advanced theoretical ideas require well-defined samples, in particular in terms of the graphene edge structure. This level of control is currently not available through conventional lithographic techniques and there is a lack of experimental data on atomically well-defined graphene nanostructures. For example, opening a sufficient gap for room-temperature operation through quantum confinement requires structures in the size range of 10 nm. Furthermore, the electronic structure of graphene nanostructures is sensitive to the structure of the edges (e.g. zig-zag vs. armchair) [1]. There is a possibility of edge reconstructions and attachment of various functional groups, which further complicate the comparison between theory and experiment [2].

We use chemical vapor deposition (CVD) to grow small graphene flakes and on-surface polymerization from molecular precursors to form narrow graphene nanoribbons (GNRs) with well-defined edge structures [3 – 6]. Graphene interacts only weakly with the underlying Ir(111) or Au(111) substrates and retains the electronic structure of isolated graphene. We explore the size-dependent electronic properties of the atomically well-defined graphene nanostructures using low-temperature scanning tunneling microscopy (STM). The CVD growth yields a relatively broad distribution of different GQD sizes and shapes ranging from a couple of nanometers up to ca. 20 nm with a roughly hexagonal shape. All the flakes have edges in the zig-zag direction with a very small roughness (we see steps with a height of a single atomic row at the flake edges). On the contrary, the on-surface polymerization yields very narrow GNRs with arm-chair edge structure. We can readily access individual GQDs and GNRs and measure their atomic structure using STM. The local electronic properties can be probed by scanning tunneling spectroscopy (STS), which shows the presence of quantum confined states with different envelope wavefunction symmetries. We are able to reproduce the experimental results using tight-binding calculations of free-standing GQDs and GNRs with the experimentally determined atomic structure. Our measurements provide the necessary experimental input on the electronic properties of atomically well-defined graphene nanostructures for future electronic devices.

[1] A.H. Castro Neto et al., Rev. Mod. Phys. 81, (2009) 109.
[2] P. Koskinen, S. Malola, H. Häkkinen, Phys. Rev. Lett. 101, (2008) 115502.
[3] J. Coraux et al., New J. Phys. 11, (2009) 023006.
[4] S.K. Hämäläinen et al., Phys. Rev. Lett. 107, (2011) 236803.
[5] J. Cai et al., Nature 466, (2010) 470.