

## Raman Spectroscopy of Ultra-Narrow Graphene Nanoribbons

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### Abstract

Graphene shows many outstanding properties [1], which make it suitable for a wide range of applications [2]. However, the lack of a band gap strongly affects the development of graphene-based field effect transistors. A simple method to open a gap is to use quantum confinement, i.e. to cut graphene into small stripes, called graphene nanoribbons (GNRs).

The electronic properties of GNRs strongly depend on the width and on the atomic arrangement at the edges [3]. In particular, applications require ultra-narrow and well defined GNRs with perfect crystallographic edges. This is very difficult to achieve with the traditional top-down technology. Recent advances in bottom-up synthesis allowed production of GNRs of defined structure simply by sculpting the molecular precursor [4-6]. This opens a way to study narrow atomically-precise GNRs by optical means such as Raman spectroscopy.

In this work we present a detailed multi-wavelength Raman analysis of bottom-up synthesized ultra-narrow armchair GNRs (1-2nm in width) in powder. We also measured the precursors and the molecules synthesized from the original precursor during the GNRs synthesis.

The first-order Raman spectrum of GNRs is dominated by two prominent peaks, namely the D and G peak. The G peak is blue-shifted and broadened as compared to graphene, due to quantum confinement. The intense D peak is activated by confinement of  $\pi$ -electrons into a finite-size graphitic domain, similar to the band at around  $1300\text{ cm}^{-1}$  observed in Polycyclic Aromatic Hydrocarbons (PAHs) [7]. The D peak shows an interesting feature: depending on the excitation energy and power used, it splits into two components. Both the components follow the same vibration symmetry of the D peak.

The Raman spectrum of GNRs also shows low energy modes similar to the Radial-Breathing Modes (RBMs) of CNTs. The measured frequencies of those peaks depend on the widths of the GNRs in good agreement with theoretical predictions [8]. This makes Raman spectroscopy a powerful technique to characterize GNRs in analogy to CNTs.

### References

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