

# Structural Metrology of SWCNTs by Electron Diffraction

Hua Jiang<sup>1</sup>, Albert G. Nasibulin<sup>2</sup>, David P. Brown<sup>2</sup>, Delphine Chassaing<sup>2</sup>, Esko I. Kauppinen<sup>1,2</sup>

<sup>1</sup> VTT Technical Research Center of Finland, P.O. Box 1000, FIN-02044 VTT, Finland

<sup>2</sup> NanoMaterials Group, Laboratory of Physics and Centre for New Materials, Helsinki University of Technology, Finland

*Hua.Jiang@vtt.fi*

Among various metrologies for carbon nanotubes, transmission electron microscopy (TEM) is the one by which carbon nanotubes were discovered [1], and it remains one of the most powerful techniques in characterizing carbon nanotubes. In addition to its capability for high-resolution imaging, TEM enables electron diffraction analysis of objects such as nanotubes with nano-scale electron beam. The electron diffraction pattern (EDP) is a representative of the object in crystallographic reciprocal space. From an EDP of an individual single-walled carbon nanotube (SWCNT), one can determine the tube diameter  $D_0$  and the chiral angle  $\alpha$ , which are equivalent to the chiral indices ( $n$ ,  $m$ ) in terms of defining the atomic structure of the nanotube [2, 3]. In order to determine chiral indices  $n$  and  $m$  unambiguously, both  $D_0$  and  $\alpha$  must be evaluated with high accuracy. However, with traditional methods the evaluation of the tube diameter  $D_0$  from an EDP depends on the correct calibration of the diffraction patterns. This calibration is sensitive to the tube inclination with respect to the incident electron beam [4], unless the diffraction pattern could be intrinsically calibrated with standard materials, which are typically unavailable in the measurement.

In this contribution, we present a new method for direct ( $n$ ,  $m$ ) determination of the carbon nanotubes from their electron diffraction patterns. The unique method is based on a novel concept of the nondimensional “*intrinsic layer-line spacing*” which we introduced [5] with an intention to establish a measurement standard for electron diffraction analysis of SWCNTs. The method is absolutely calibration-free. Uniquely, errors due to the nanotube inclination are specified and tilt angles of nanotubes with respect to the electron beam are simultaneously calculated so that the tilt effect on the ( $n$ ,  $m$ ) determination is eliminated. Moreover, the introduced method enables several effective procedures to cross-check the results by using the abundant information contained in the diffraction patterns. Due to the fact that only the layer-line distances and the interval between the zeros along the equatorial line are involved in the measurement, this method has no significant limitations, and has proven to be an easy, fast and trustworthy method for ( $n$ ,  $m$ ) determination of SWCNTs. The method can be extended to structural analysis of other nanotubes having structures similar to carbon nanotubes, such as boron nitride nanotubes.

## Reference

- [1] S Iijima: *Nature* **354** (1991), 56.
- [2] S Iijima and T Ichihashi: *Nature* **363** (1993), 603.
- [3] M Gao, J M Zuo, R D Twisten, I Petrov, L A Nagahara and R Zhang: *Appl. Phys. Lett.* **82** (2003), 2703.
- [4] H Jiang, D P Brown, A G Nasibulin and E I Kauppinen: *Phys. Rev. B* **74** (2006) 035427.
- [5] H Jiang, A G Nasibulin, D P Brown and E I Kauppinen: *Carbon* **45** (2007) 662.