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HR-TEM of Carbon Network, Towards Individual C-C Bond Imaging

K. Suenaga, Y. Sato, Z. Liu, M. Koshino and C. Jin

Nanotube Research Center, National Institute of Advanced Industrial Science and Technology, AIST Central 5, Tsukuba 305-8565, Japan

The diversified properties of carbon nano-structures (nanotubes, fullerenes and their derivatives) are related to their polymorphic arrangement of carbon atoms. Therefore the direct observation of carbon network, such as defects or chirality, is of great consequence in both scientific and technological viewpoints in order to predict the physical and chemical properties of carbon nano-structures. In order to identify the local configuration of pentagons and hexagons in carbon nanostructures, an electron microscope with higher spatial resolution and higher sensitivity is definitively required. Since the spatial resolution of the conventional TEM is limited by the spherical aberration coefficient (Cs) of its objective lens and the wave length (λ) of incident electron beam, the Cs must be minimized to achieve the best performance because the reduction of the λ is detrimental to the high sensitivity to visualize individual carbon atoms. A high-resolution transmission electron microscope (HR-TEM, JEOL-2010F) equipped with an image Cs corrector (CEOS) was operated at a moderate accelerating voltage (120kV). The Cs was set to 0.5 ~ 10 μm in this work. The HR-TEM images were digitally recorded under a slightly under-focus condition (Δf = -2 to -7 nm) where the point resolution of 0.14 nm was achieved at 120kV. The spatial resolution of 0.14 nm (a typical C-C bond length) obtained at a moderate accelerating voltage provides us a great advantage because we can realize the visualization of carbon atomic arrangement without massive electron irradiation damage.

Here we show some examples for atomic-level characterization of carbon nanostructures. The C_{60} and C_{80} fullerene molecule has been successfully identified its structure and orientation at a single-molecular basis [1, 2]. Also the active topological defects have been eventually caught red-handed [3, 4]. The technique can be widely applicable to visualize a biological activity, at an atomic level, for which any conformation change of the C-C bonds is responsible. The cis-/trans-isomerization of retinal molecules have been successfully visualized [5]. Some recent progress for *in situ* observation of carbon nanotube/fullerene growth [6, 7] and defect dynamics [8] will be also presented.

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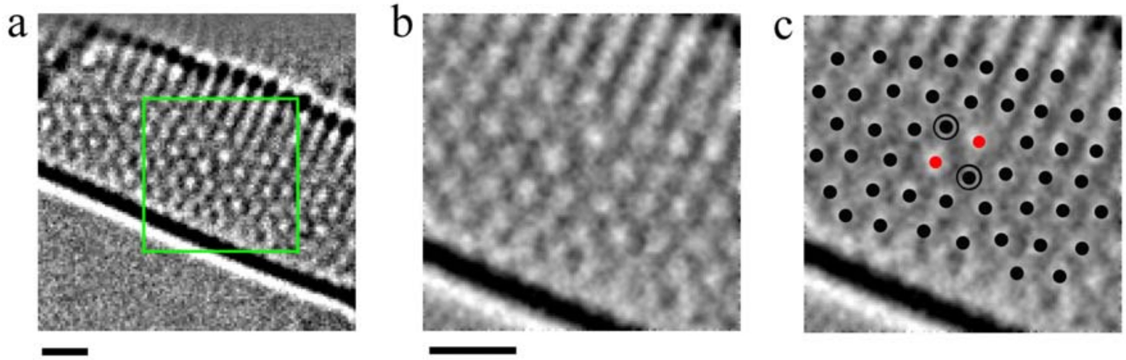

FIG. 1. A pentagon-heptagon pair defect after found on a single wall carbon nanotube after a heat treatment at 2000K. The defect is a proof of the Stone-Wales transformation due to the C-C bond rotation [3]. Scale bar = 0.5 nm.

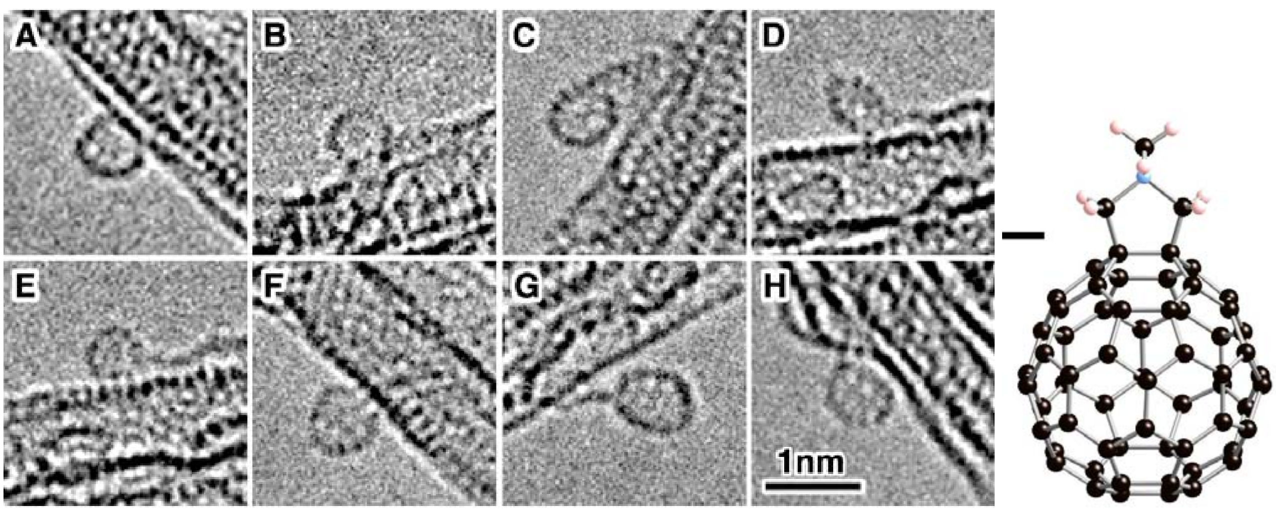

FIG. 2. HR-TEM images of C_{60} functionalized fullerenes. The functional groups are attached to the surface of single-wall carbon nanotubes. The atomic arrangement of the molecules can be clearly seen inside the ball [1].

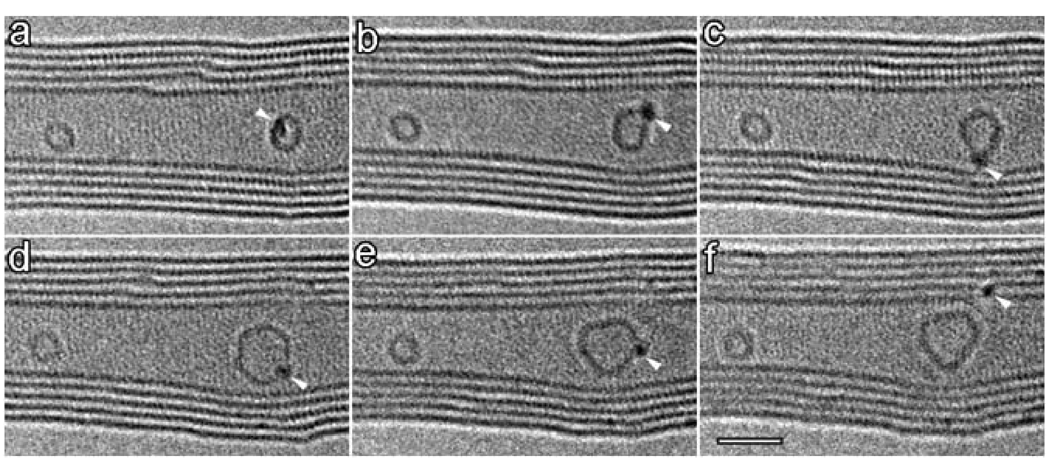

FIG. 3. In situ HR-TEM images of fullerene growth at high temperatures. W clusters act as catalyst (indicated by arrows) [8].

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