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Single-chirality multi-walled carbon nanotubes.

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Multi-walled carbon nanotubes (MWNTs) have, until now, been regarded as the 'ugly sister' of their single-walled counterparts as far as well-define electronic properties and potential applications in nanoscale devices were concerned, because each of the concentrically arranged walls of MWNTs exhibited an individual chirality, different to that of adjacent layers. The electron transport properties of individual MWNTs therefore generally corresponded to the enveloping conductivity of all walls, while SWNTs have been advocated as ballistic electron conductors or tuneable semiconductors for nanotechnology devices.

We demonstrate the synthesis and characterisation of large MWNTs (70 – 90 walls), which exhibit unprecedented degrees of internal order: not only is each tubular layer of the same chirality, but adjacent nanotube walls also appear to be in crystallographic register with one another, resulting in an ABAB-stacking sequence of the layers and a *c*-spacing, more typical for graphite than for the turbostratic layers usually observed in multi-walled carbon nanotubes [1]. The single-chirality MWNTs, shown in Figure 1, were synthesised using a modified chemical vapour deposition (CVD) technique, in which a small amount of the nitrogen (up to 3%) was added to the mixture of catalyst and carbon feedstock [1]. Several samples of MWNTs, produced by nitrogen-assisted CVD, were thoroughly characterised using a large range of advanced electron microscopy techniques, including scanning electron microscopy (SEM), (high-resolution) transmission electron microscopy ((HR)TEM), scanning transmission electron microscopy (STEM), electron diffraction (ED), energy-filtered TEM (EFTEM), electron tomography and digital restoration approaches of HRTEM through focal series. Figures 2 and 3 display a small selection of images and results obtained during the manifold analysis of these new forms of MWNTs. In general, electron diffraction techniques yield the discrete spot pattern of one of the two non-chiral structures, known as armchair and zigzag, throughout any given tube in the samples (see Figure 2).

The relation between any tubular layer and its chirality is given by $n\boldsymbol{r}=\pi d$, where n is an integer, $\boldsymbol{r}$ is any lattice vector (u,v) within the graphene sheet, and d is the diameter of the resulting cylinder. In the case of MWNTs, an additional geometric constraint is posed by the fact that the circumference of each successive layer increases by the discrete amount of $2\pi d_{002}$, where d_{002} is the *c*-spacing between adjacent graphene cylinders. For a commensurate structure, this amount must be equal to an integral multiple of a lattice vector, $n\boldsymbol{r}_{uv0}$ [2].

References

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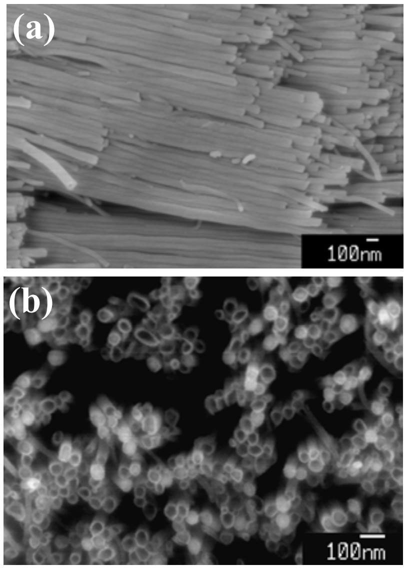

Fig. 1. SEM image of an MWNT carpet grown with feedstock containing nitrogen; view onto (a) the side and (b) the top of the carpet.

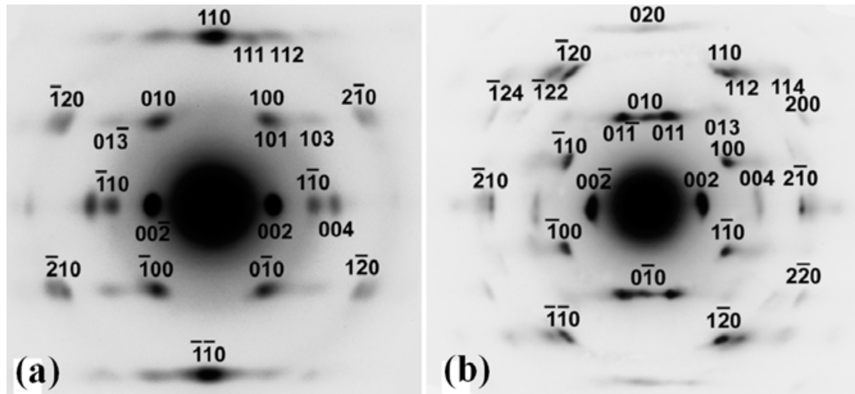

Fig. 2. Electron diffraction patterns of individual carbon nanotubes grown in the presence of nitrogen. In each case, the tube axis is vertical, and the patterns are index according to the primitive hexagonal unit cell (three-index system). (a) ED pattern, typically observed for about 20% of the MWNTs. The pattern indicates that all the nested tubular components of the nanotube share the same armchair chirality. (b) Diffraction pattern typical of about 30% of the MWNTs; like (a) the pattern is indicative of constant chirality layers, but in this case, they are all in the zigzag orientation.

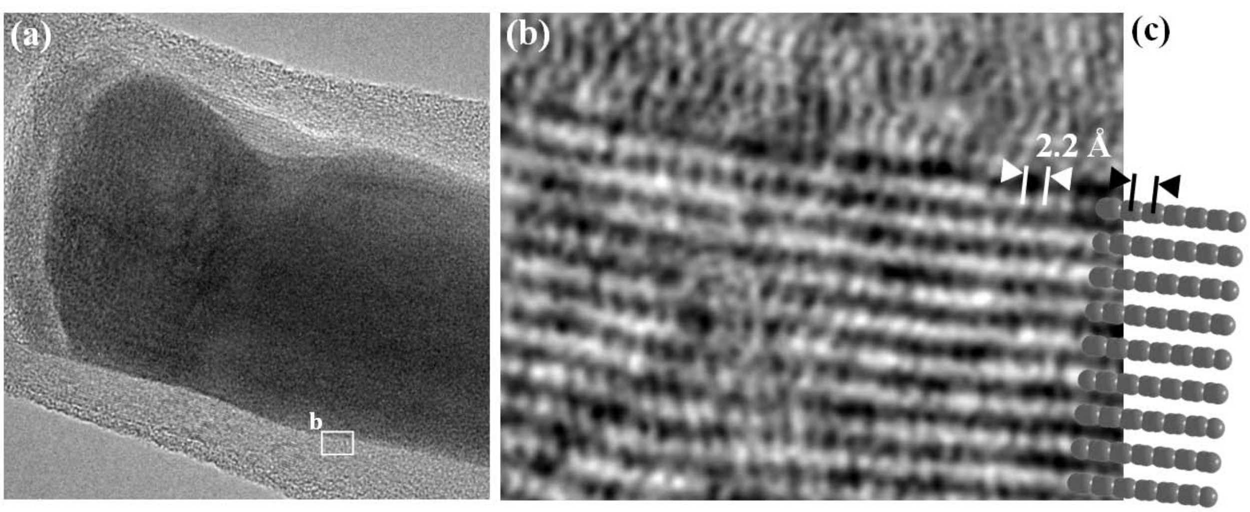

Fig. 3. Composite picture showing (a) a single-axial TEM image of an iron carbide catalyst particle on the top end of a single-chirality MWNT, (b) the restored phase of an enlarged area of (a) (indicated by the white frame in (a)), and (c) a model of graphite, viewed along $[1\,\bar{2}\,0]$. The alignment of (b) and (c) illustrates both the uniform chirality in each layer and the regular ABAB-stacking pattern of adjacent layers; the resolved distance of 2.2 Å between adjacent spots in each layer indicates that the MWNT consists of nested graphene cylinders with zigzag chirality [3,4].

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