Device fabrication with precisely placed carbon nanotubes of known chiral vector

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Abstract. The electrical properties of single walled carbon nanotubes are strongly dependent on their precise atomic configuration and as such it is of great importance to be able to fabricate devices containing individual carbon nanotubes of known structure. We have developed a novel technique that allows for the determination of the chiral indices of an individual carbon nanotube followed by the precise placement of the tube onto pre-patterned electrodes. Carbon nanotubes are grown by chemical vapour deposition onto perforated TEM grids. Electron diffraction is performed on individual carbon nanotubes, the analysis of which reveals their structure. The desired carbon nanotube is then manipulated inside a combined STM, SEM system and placed with high precision onto pre-patterned electrodes.

1. Introduction

A single walled carbon nanotube (SWCNT) is uniquely identified by reference to its chiral indices \( (n, m) \). These describe the translation vector around the circumference of the tube in terms of the unit vectors of the graphene sheet, which it can be considered to be made of. It is well known that of all possible tube structures one third satisfy the condition \( (n - m) = 3i \), where \( i \) is an integer, necessary for band structure calculations to describe them as metallic [1]. The other possible tube morphologies are semiconducting with band gaps approximately inversely proportional to the radius of the tube. In fact, due to the curvature of the tube there exists a small band gap in most “metallic” tubes, save those with \( i = 0 \) (i.e. \( m = n \)), which are commonly called armchair tubes [2].

Here we describe a technique that allows for the determination of the structure of carbon nanotubes via electron diffraction followed by the fabrication of electronic devices consisting of the desired tubes.

2. Carbon nanotube growth and characterisation

Carbon nanotubes were grown by chemical vapor deposition (CVD) on commercially available perforated silicon oxide transmission electron microscope (TEM) grids using a calcinated ferrotin catalyst. The TEM grid was placed inside a Phillips CM200 TEM operating at 80 kV, below the threshold for knock-on damage from carbon nanotubes [3]. Individual SWCNTs, individual double walled carbon nanotubes (DWCNTs) and ropes containing multiple tubes were located and their

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positions on the grid noted. High-resolution images were captured on a CCD camera and selected area
diffraction patterns recorded onto imaging plates from sections of approximately 200 nm length of
selected tubes. Once developed the diffraction patterns were digitally scanned at 2400 dpi resolution
to allow for subsequent analysis.

Figure 1 shows a diffraction pattern taken from an individual SWCNT spanning a hole in the TEM
grid. The diffraction pattern from a SWCNT takes the form of a series of layer lines corresponding to
the hexagonal reciprocal lattice of two graphene sheets, smeared in the radial direction due to
curvature of the tube.

![Figure 1](image1.png)

Figure 1. An electron diffraction pattern and real space CCD image (inset) of an individual
SWCNT. The equatorial line, Eq and the first four layer lines, L₁-L₄ are marked.

Figure 2. An electron diffraction pattern and real space CCD image (inset) of an
individual DWCNT.

To determine the chiral indices of the tube the axial distances of the layer lines (L₁-L₄) from
the equatorial line (Eq) are measured. The ratios of a combination of these distances are used to
determine the chiral angle and ratio of chiral indices [4][5]. This analysis is independent of the
 calibration of the diffraction pattern and tilt of the tube with respect to the incident electron beam. In
addition the intensity distribution along each layer line can be described by the square of a Bessel
function, the order of which is directly related to the chiral indices of the tube [6]. Once the structure
of the tube is confidently obtained from these complimentary analysis techniques, the diffraction
pattern can be accurately calibrated. The diameter of the tube can be obtained from a calibrated
diffraction pattern as it is related to the period of the oscillations of the Bessel function that describes
each of the layer lines and the equatorial line [7]. The SWCNT in figure 1 was determined to be a
(25,15) tube with a diameter of 2.7 nm and, as (n – m)=10, is a semiconducting tube.

The diffraction pattern from a DWCNT can be considered as the superposition of the diffraction
pattern from two SWCNTs. The diffraction pattern shown in figure 2 is from an individual DWCNT
and hence there are twice as many visible reflections in the same region of reciprocal space as in
figure 1. The inner tube was determined to have chiral indices (28,16) and the outer tube (30,25),
therefore written (28,16)@(30,25), with diameters of 3.0 and 3.7 nm respectively and an inter tube
separation of 0.35 nm, in agreement with other TEM studies of DWCNTs [7][8]. The inner tube, with
(n – m)=12 is a small band gap metal and the outer tube with (n – m)=5 is a semiconducting tube.

3. Device fabrication

With the analysis of the diffraction patterns complete the TEM grid was transferred to an Omicron
Nanoprobe system. This consists of four independently controllable tungsten scanning tunneling
microscope (STM) tips situated inside a high-resolution scanning electron microscope (SEM) all under
ultra high vacuum (~10⁻¹⁰ mbar). The desired tube was located under the SEM (figure 3 (a)) and two
opposing STM tips brought into close proximity. The tips were brought into contact with the tube at
either side of the hole and the length of tube lifted away from the TEM grid (figure 3(b)). The tips
were then moved away from each other until the tube became detached from one of the tips (figure 3 (c)).

![Figure 3. Removing the tube from the TEM grid. a) The tungsten tips are brought into close proximity to the desired tube. b) The tube is picked up, suspended between the tips and moved away from the surface of the TEM grid. c) The tips are moved apart leaving the tube dangling from one tip. The scale bars correspond to 200 nm.](image)

The TEM grid was then removed and replaced with electrodes patterned using standard electron beam lithography techniques. Using the STM feedback electronics the tube was brought into tunneling contact with one electrode. The tube was then moved away from the surface to the limits of the piezomotors, the STM electronics disconnected and the tips connected to external source sense electronics. A bias of 2V was applied between the tube and the electrode and, using the piezomotors and monitoring the current flow, the tube was brought into physical contact with the electrode. Using the SEM for guidance, the tube was then laid in the desired location (figure (4)). When the tip is retracted, the tube generally remains on the substrate due to the larger van der Waals force between the tube and the substrate, compared to that between the tube and the tip.

![Figure 4. Placing of a tube across pre fabricated electrodes. The scale bar represents one micron.](image)

4. Transport measurements

Figure 5 shows the current-voltage (I-V) characteristics through a SWCNT device measured immediately after fabrication, within the nanoprobe under UHV conditions. The device was fabricated using the technique described above from the semiconducting (25,15) SWCNT whose diffraction pattern is shown in figure 1. The tube was placed across pre-patterned palladium electrodes with electrode spacing of approximately 350 nm. The non-linear asymmetric I-V characteristics suggest barriers at the contacts dominate transport through the device. The choice of palladium, with its high work function, as the electrode material should limit the height of any Schottky barrier formed between the SWCNT and electrodes [9]. We therefore ascribe the asymmetric transport behaviour to the presence of poor quality tunnel barriers at the tube-electrode interfaces. We believe these barriers are formed by amorphous carbon buildup during SEM imaging, with the asymmetry due to different effective tunnel barrier thicknesses at the tube-source and tube-drain electrodes.
Figure 5. I-V through a (25,15) SWCNT performed at room temperature and under UHV.

Figure 6. I-V through a (28,16)@(30,25) DWCNT performed at room temperature and under UHV.

Figure 6 shows the I-V characteristics of a device fabricated using the (28,16)@(30,25) DWCNT whose diffraction pattern is shown in figure 2. The tube was placed across pre-patterned Pd electrodes with electrode spacing of approximately 1 micron. The I-V is again highly non-linear and asymmetric about 0 V. Despite the channel length being almost three times larger than in the case of the SWCNT the current through the DWCNT device at ± 2 V is over two orders of magnitude higher than the SWCNT device (note the different voltage ranges in figure 5 and figure 6). As barriers at the tube-electrode interfaces again dominate this device the increased conductance is due to the increase in contact area between tube and electrode as a result of larger diameter of the DWCNT.

We believe that patterning of electrodes on top of the carbon nanotubes will enable Ohmic contact to be achieved.

5. Summary
We have demonstrated a technique to allow for the controlled placement of carbon nanotubes with known structures across electrodes for device fabrication. The chiral indices of carbon nanotubes is determined via electron diffraction analysis and the desired tube is then manipulated with remote controlled STM tips and placed across pre-fabricated electrodes. Provided Ohmic contact can be achieved, this technique will allow for the investigation of the electrical properties of carbon nanotubes of various morphologies and also open up the possibility of fabrication of complex devices comprising multiple tubes of differing structures.

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