

Carbon Nanotubes

Carbon nanotubes are small (micron length, nanometre diameter), single-molecule tubes comprised of carbon molecules. A common way of envisioning carbon nanotubes is that of a graphene sheet (carbon atoms bonded to three other atoms each, arranged in a hexagonal configuration) rolled up into a tube, and then capped at each end with half a fullerene (spherical 3-bond-carbon molecule).

The bonds formed between the carbon atoms are very strong, resulting in a colossal tensile strength for carbon nanotubes. IN addition, the bonding of each carbon atom to three others leave one unoccupied orbital remaining on each atom. The effect of this is making orbit (and any electrons inserted in it) delocalised across the whole nanotube. As a result, the carbon nanotube conducts in certain directions. In other directions, backscattering of electrons off of carbon atoms results in the nanotube behaving as an intrinsic semiconductor – with bulk-scale band gap theory apparently applicable.

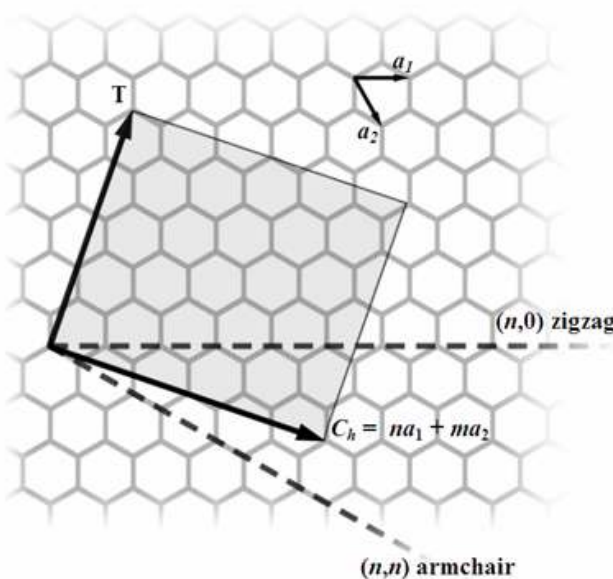
In each nanotube, there are several important properties. The physical dimensions – length and diameter effect the uses the tube can be put to, as well as some inherent properties (for example, diameter effects band-gap in semiconducting behaviour). There is also the *chirality* of the nanotube. Also known as the “wrapping factor”, this describes the arrangement of the graphene lattice with respect to the axis of the tube. As shown here, with the line T representing the direction of the tube’s axis, and the chiral vector, C going around the tube at 90° to the axis. The chiral vector is expressed by number

of steps made in the a_1 direction and the a_2 direction.

Tubes with only a_1 components of the chiral vector are known as “zigzag” due to the distinctive patten that would be seen on a clean-cut end. Where $a_1=a_2$ then the nanotube is known as an “armchair”

pattern. The chiral vector of a nanotube has significant effects on the electronic behaviour of the nanotube. If the chiral vector is $a_1 - a_2 = 3n$ where n is any vector, then the tube acts as a metallic conductor – this includes armchair tubes. Any other chirality leads to a semiconducting nanotube.

Conduction in so-called metallic nanotubes behaves somewhat differently to in conventional wires however. Because electrons travel along a path created by channels between the carbon atoms along the nanotube, they actually exhibit 1 dimensional conduction – the electrons cannot travel around or through the nanotube, merely along it. Again, as a result of the channelled path of the electrons, there is no scattering of electrons – instead, **all** inserted electrons leave the tube and with the same amount of energy as upon entering – a metallic nanotube exhibits no resistance,



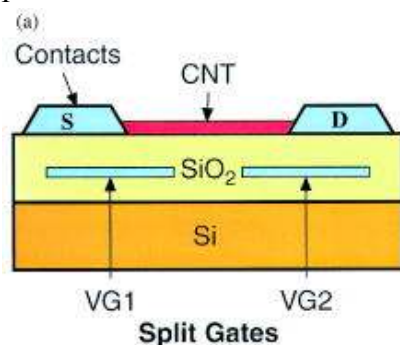
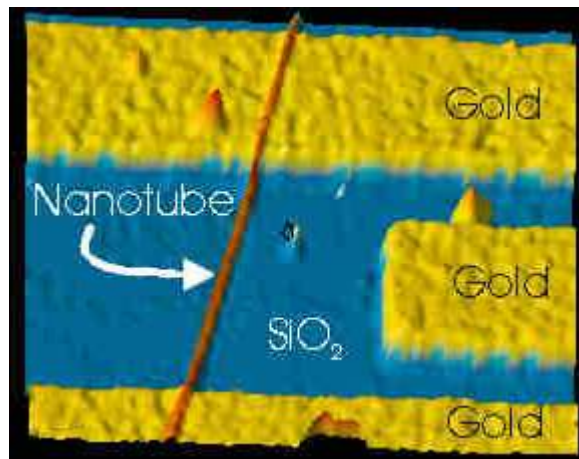
although the contact between a nanotube and another material may well have an inherent resistance.

There are a variety of techniques used for fabricating carbon nanotubes (and some that create nanotubes, but aren't used as a fabrication technique, for example burning a candle). The most commonly used are arc discharge through a gas (used in early experiments, less frequent now), chemical vapour deposition (CVD) using a light hydrocarbon gas and metal catalysts and laser ablation of a carbon target. CVD is the most popular of the techniques in most experiments, especially as using a substrate patterned with catalyst can induce the nanotubes to grow in desired locations. Experiments using this have been reported to create a nanotube "brush".

The high effectiveness of carbon nanotubes as both conductor and semiconductor leads to the concept of making extremely small scale circuits comprised of nanotubes. Current patterning techniques are not capable of creating complex or predictable structures, but simple examples of nanotube-based electronic devices have been developed.

Placing a metallic nanotube between two or more metal contacts has been achieved – through a variety of techniques. Tests done by applying a potential between the two electrodes have shown ohmic behaviour, and as contact quality has been developed, total resistances in the region of $6k\Omega$ – although poor contacts lead to much higher resistances. This shows that metal nanotubes could make very effective small scale "wires".

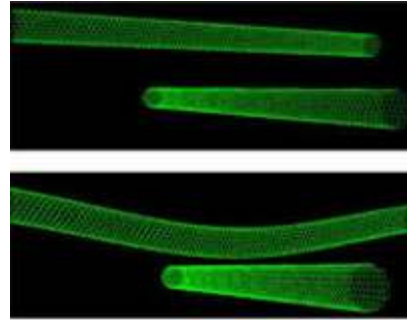
Perhaps more interestingly, placing a semiconducting nanotube between two metal contacts, with an insulating layer below and then a gate layer than that produces extremely useful results. In this case, the nanotube acts as a FET (Field Effect Transistor). When sufficient bias is applied to the gate, the semiconductor nanotube becomes conducting, hence acting as an effective electronic switch. Thinner layers of silica have been shown to increase the effectiveness of the carbon nanotube FETs somewhat. The entire device, with the lithographically produced metal contacts is however still quite large compared to the nanotube and placing the correct type of nanotube in the correct location, for all these electronic applications is proving a rather fiddly and unscalable process.



Steps have also been made in synthesising carbon nanotube diodes, forming a p-n junction. These have exhibited rectifier behaviour of very high quality (at least under low bias, breakdown voltage is an issue). The developers hypothesise that these CNT diodes could also be used a LEDs and light-sensitive devices as well.

Work has been done on developing nanotube-based electronic memory as well. There are two notably different ways in which utilising nanotubes as a storage medium has been achieved.

Using a combination of both metallic and semiconducting nanotubes can be used to create a form of physical memory. When a charge is applied, the metallic tube (top one in the image to the right) deflects towards the semiconducting nanotube, to the point that the resistance between the two tubes is substantially decreased. The tubes remain like this until another charge is applied to separate them again. The very high resistance/low resistance provides a digital switch and hence a form of storage for binary data.



Carbon Nanotubes can also be used as single-electron traps and hence act as memory in this way too. Electron present/absent provides the two states, and reading determines the presence otherwise of an electron. Writing involves either placing or removing an electron. The use of a single electron means that the state the memory is in is unambiguous – either 1 electron of charge or not. The nanotube single electron trap is based on a carbon nanotube FET with a single scattering defect in the tube used to detect the electron which is stored in a silicon based single electron charge trap.

Effectively nanotubes can be seen as here as having the potential to replace all conventional electronic components. They have been demonstrated to perform as transistors, diodes and memory, although their nature as ballistic conductors means they are unlikely to be effective resistors (although perhaps controlled levels of defects could achieve this).

There are however, considerable issues with creating “nanotube circuits” however. At the very least, all the devices here, while having small nanotubes as an important component, feature far larger, typically lithographically formed structures in the form of gates, contacts and surfaces. So the size of components that can be achieved is still far larger than perhaps what the promise of nanotubes offers.

A greater problem however is the actual creation and use of the nanotubes. While metal-catalyst based CVD nanotube synthesis produced high quality nanotubes effectively, it offers very little control in terms of the properties of the nanotubes involved (chirality, size, single walled/multi walled). Moreover, while placing catalyst on the substrate allows growth of nanotubes directly on the component, inability to control direction, type or size of nanotube growth means there is no real option for large-scale nanotube production as would be necessary for carbon nanotubes to become commercially viable in the electronics industry.

Locating the nanotubes is also a fiddly process. Typically it involves fiddly physical manipulation of the nanotube, often with AFM tips, or simple bulk direction of nanotubes at the device, hoping some will reside in correct positions. Techniques have been developed, so that in devices with many nanotubes, metallic nanotubes can be destroyed and only the semiconducting parts of the bundle remaining.

Overall, carbon nanotubes have present a whole variety of ways in which they can imitate and enhance conventional semiconductor and metal based devices. Their relative ease of production and profusion of research based upon them means that applications will continue to be developed and it can be expected that more commercial applications of nanotube technology will arise and be marketed. There is

certainly a hope for smaller-scale electronics (if not single-molecule based) to be developed based on the nanotubes.