challenge of trying to understand the complex record produced 4.56 billion years ago by processes many of which may have no terrestrial analog. At the workshop, these different models were vigorously debated, and several lines of evidence to support both models were presented. It would be inaccurate to say that the differences between the different protagonists were completely resolved and everyone went home happy. However, the workshop was highly successful in highlighting future areas of research that may help resolve some of these key issues, perhaps involving collaborations between scientists with highly divergent views. The challenge now is to try to reconcile many apparently contradictory observations into some sort of coherent model. Whatever the outcome, this process will undoubtedly lead to revelations about a meteorite that has already stimulated and intrigued many planetary scientists for the last 25 years.

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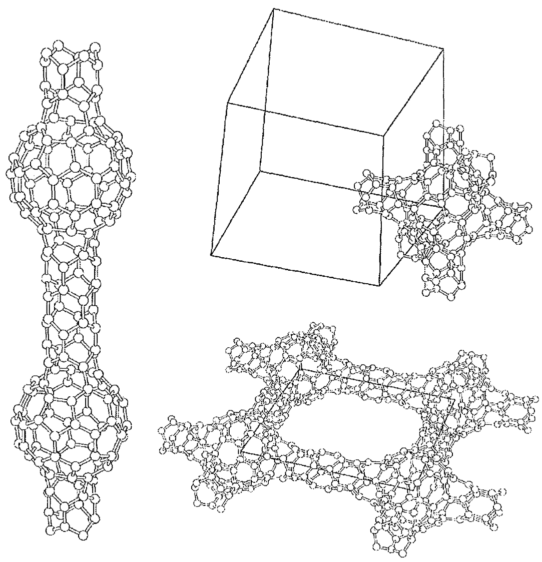
APPLIED PHYSICS

# Carbon Nanotubes for Next-Generation Electronics Devices


Susumu Saito


The age of semiconductor technology started in 1947, just a half century ago, when the first semiconductor device, a germanium-based transistor, was invented at Bell Telephone Laboratories. Since then, the miniaturization of devices has been continuous, and computers have become faster and smaller. Meanwhile, silicon has become the most popular device material, owing to its geological abundance and suitable physical properties. Nowadays, the size of the typical device is halved every 3 years. But how far can we go along this road? Although the present devices consist of tiny material domains and junctions between them, each domain is designed to behave in the same way as its macroscopic counterpart. Hence, the present path should end when we go from the present micrometer (~10 μm) world to the nanometer (~10 nm) world where materials are known to behave quite differently because of quantum effects.



**Nanotubes and fullerenes** may be useful as constituent units of carbon nanoelectronics device. [Adapted from Hamada (*5*)]

At the present pace of miniaturization, we will reach this end within a decade. In order to overcome this technological limit, several types of devices are being investigated that make use of quantum effects rather than trying to overcome them. For this reason, the nanometer-scale carbon materials, namely the fullerenes and nanotubes (see figure), have attracted great interest not only in the scientific fields but also in the field of semiconductor technology. Solid $C_{60}$ is semiconducting (*1*), whereas nanotubes are predicted to be semiconducting or metallic, depending on their network topology (*2*), and several device structures have been theoretically proposed (*3*). On page 100 of this issue, Collins *et al.* report an experimentally functioning carbon nanodevice based on nanotubes (*4*).

In general, there are two kinds of elemental device structures: two-terminal and three-terminal devices. The transistor is a three-terminal device with a variety of structures, materials, and basic functional mechanisms. A typical two-terminal device is the diode, having also a variety of structures and applications, such as switching, rectification, and solar cells. The "nanotube nanodevice" reported by Collins *et al.* is a kind of nanodiode.

Collins *et al.* took a novel approach in using a scanning tunneling microscope (STM) as nanotube manipulator. The tip is first used to pick up and retract the nanotube rope, and then it is used as a sliding local probe to measure the electrical conductivity between the tip and substrate, connected by means of retracted tubes. They found an abrupt change in the current flow from that in a graphite wire to that in a device upon sliding the tip in one direction. Beyond certain well-localized positions, the current can flow only in one direction, which is called rectification, the fundamental function of the two-terminal diode device.

In semiconducting materials, a small amount of impurity added as a dopant can make electron-excess *n*-type or electron-deficient *p*-type semiconductors. A junction between *p*- and *n*-type semiconductors works as a diode. A rectifying junction can also be formed between a semiconductor and a metal. In the case of carbon nanotubes, they can be either metallic or semiconducting, depending on the topology. Hence, experimentally observed diode properties can be explained by the presence of the junction between two topologically or electronically different nanotubes.

Such junctions can be designed by introducing pentagon-heptagon pair defects into otherwise hexagonal nanotube networks (*3*). Fullerenes are also known to work as junction units for nanotubes (*5*). Therefore, the next milestone toward fullerene-nanotube electronics would be the construction of topologically designed two- and three-terminal nanostructures.

Carbon is also one of the geologically most abundant elements. Moreover, it can take a variety of forms, as has already been shown in fullerene and nanotube geometries.


The author is in the Department of Physics, Tokyo Institute of Technology, Oh-okayama, Meguro-ku, Tokyo 152, Japan. E-mail: saito@stat.phys.titech.ac.jp

Not only $C_{60}$ but also many kinds of large fullerenes (6) and endohedral metallofullerenes (7) have been produced in a macroscopic amount, and macroscopic production of size-controlled nanotubes is now in progress (8). The technology for manipulation of these nanostructural units and the quantum-mechanical material design will be the keys to realizing carbon-nanostructure electronics in the next century.

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RNA SYNTHESIS

# MutT Prevents Leakiness

Bryn A. Bridges

In 1994, DNA repair enzymes were nominated as *Science*'s "molecule of the year." This celebrity status not only reflected the great explosion of knowledge about how organisms ensure the fidelity and integrity of their DNA, but also paid tribute to the ubiquity of these repair mechanisms from bacteria to humans. Now, a report by Taddei *et al.* (*1*) on page 128 of this issue turns the spotlight to the fidelity of cellular RNA synthesis and raises hitherto neglected questions about the consequences of RNA infidelity in nondividing cells

As the cell replicates its DNA to make a second set of genetic material to donate to its offspring, it can make various mistakes, resulting in mutations. Spontaneous mutations can also be caused by endogenous DNA-damaging agents, which become relatively more important when DNA replication is restricted (as is so often the case in nature) (*2*). The chief DNA-damaging culprits are active oxygen species, and their most significant lesion in DNA appears to be 8-oxo-7,8-dihydroguanine, a base that is able to form Watson-Crick pairs with both cytosine and adenine with roughly equal facility (*3, 4*) and can thus give rise to transversions from G:C to T:A (*5, 6*).

Other cellular components besides DNA are also at risk from active oxygen species. One is the nucleotide precursor pool in which 8-oxo-deoxyguanosine triphosphate (8-oxo-dGTP) is continually being formed and is liable to be incorporated into DNA as the complement of adenine, giving rise to transversion mutations from T:A to G:C. Cells deal with this problem by means of a hydrolase that removes 8-oxo-dGTP from the pool. In bacteria this hydrolase is the product of *mutT* (*3*), a gene that also has homologs in several mammalian species.


The author is at the Medical Research Council Cell Mutation Unit, University of Sussex, Falmer, Brighton BN1 9RR, UK. E-mail: b.a.bridges@sussex.ac.uk


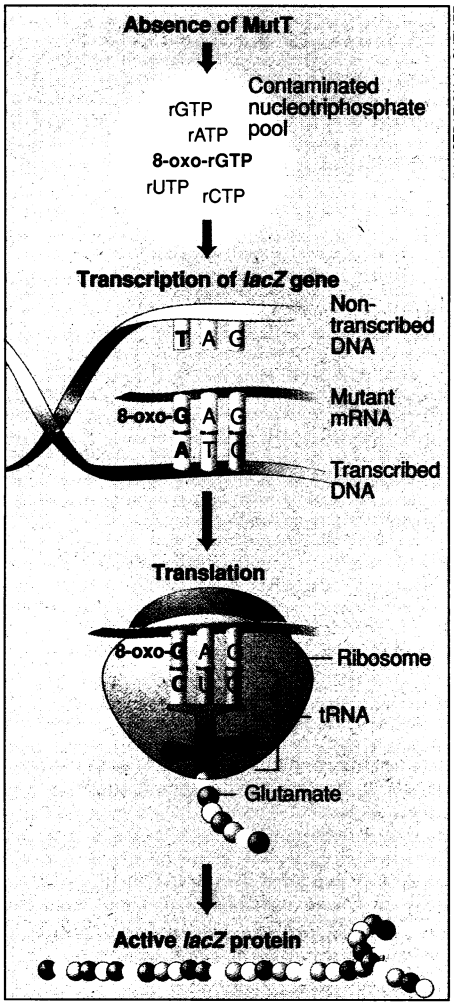


ILLUSTRATION: K. SUTLIFF

**Cleansing agent.** Active oxygen species generate 8-oxo-rGTP in the nucleotriphosphate precursor pool. Without the MutT protein, which normally cleanses the pool of this contaminant, the occasional 8-oxo-G can be erroneously inserted into RNA opposite an A of an ATC (amber) triplet (engineered into the *lacZ* gene). This causes "correction" of this artificial mutation during translation, resulting in a functional LacZ product. The amber mutation thus becomes leaky.

Now Taddei *et al.* show that oxidative damage to the RNA precursor pool is also significant and may have important consequences for transcription, whether the cells are dividing or not. It is already known that the MutT homolog in mammals can catalyze hydrolysis of 8-oxo-guanosine triphosphate (8-oxo-rGTP) in the precursor pool for RNA synthesis (*7*). Taddei *et al.* now show that purified bacterial MutT protein hydrolyzes 8-oxo-rGTP at least as well as 8-oxo-dGTP but that it has no effect on either rGTP or dGTP. They further demonstrate the incorporation of 8-oxo-rGTP into RNA by *Escherichia coli* RNA polymerase at one-tenth the rate of rGTP incorporation, opposite adenine on a poly(dA-dT) template.

To see whether 8-oxo-rGTP would be inserted opposite adenine during transcription in bacteria with defective MutT protein and give rise to "mutant" mRNA transcripts, Taddei *et al.* investigated a series of strains with different base change mutations in the *lacZ* gene. When (and only when) the mutation could be corrected by a T:A to G:C mutation, the presence of a *mutT* mutation increased 30-fold the activity of the LacZ gene product (β-galactosidase). This leakiness could not be accounted for by the small proportion of mutant bacteria in the population and is attributed to the incorporation of 8-oxo-G into RNA opposite adenine in the transcribed strand where there is an amber (stop codon) triplet. This would lead to a phenotypic reversion of the mutation in the protein (see the figure). I find this argument particularly persuasive since our laboratory has shown a similar *mutT lacZ* strain to be profoundly leaky for growth on lactose, even in the presence of scavenger bacteria (*8*).

If this sort of leakiness is a general phenomenon, it may have consequences for mutator activity over and above the production of T:A to G:C transversions by misincorporation of 8-oxo-dGTP into DNA. There will be the possibility of error-prone polymerases and other DNA-processing enzymes arising phenotypically from "mutant" RNA transcripts. Such transient mutator phenotypes may be responsible for only a small proportion of single mutations, but they are likely to be responsible for many multiple spontaneous mutations (*9, 10*). In the case of nondividing cells there may be other consequences. In