The Role of Nanoradios and Nanosensors in Scientific Observation

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1. Introduction

We have decided to diverge from the structure of scientific articles in the presentation of this work, voting for an in medias res approach on practical research which might better serve the needs of the reader. Focusing on the benefits of nanotechnology in delivering scientific measurements, we attempt to give an overview on nanosensors and nanoradios, their role in observation and future potential applications. We shall introduce the fundamentals of nanoscience to allow readers a deeper understanding of the topic. In this article, we define nanosensors as devices, capable of measuring at least one parameter, with a size not exceeding 100 nm, although some authors also include any equipment beyond this size limit that can be used to measure properties on this scale.

Nanosensors are not necessarily devices merely reduced in size to a few nanometres, but devices that make use of the unique properties of nanomaterials to detect and measure new types of events and entities in the nanoscale. Owing to their size, they have numerous advantages over similar microscale mechanisms such as a low response time or high sensitivity. These result in more accurate measurements, even enabling single molecule detections. Small size requires low power consumption and less sample. It also makes devices lighter and easily portable. Finally, they need less material resulting in lower cost and disposability [1].

2. Nanosensors

We distinguish three main types of nanosensors: physical, chemical, and biological. In this article we mainly deal with physical nanosensors. A great variety of different properties can be measured using these including mass, displacement, acceleration, force, temperature, fluid flow and many others. Based on their working mechanism, nanosensors can be ordered into four main groups.

2.1. Mechanical nanosensors

Nanosensors using electron tunnelling turn the distance between the sensor and the sample into an electrical signal. They do so with the help of a sharp tip and quantum tunnelling. The smaller the distance is between the tip and the sample, the greater the electrical current flowing through the tip. The current is then measured to deduce the distance. A change in the position of the sample relative to the sensor hence results in a change in the electric signal. To calculate the tunnel current, one can use the following expression [1]

$$i = \rho_s(E_F)Ve^{-(2\kappa d)} \qquad (1)$$

where V is the DC bias voltage, d is the gap between the sensor and the test mass, $\rho_s(E_F)$ is the local density of electronic states in the sample, κ is the decay constant of the electron wave function within the gap and $\kappa = \sqrt{2m_e\phi}/\hbar$ where m_e is the mass of electron, ϕ is the approximate work function of the metal and ħ has it usual meaning. Alternative methods also exist using Michelson or other interferometry. As a comparison, LIGO similarly utilizes Michelson interferometry to detect gravitational waves. Yet here the phase shift is due to the displacement of the sample instead of gravitational waves. Single-Electron Transistors are also a regular element of nanosensors, as they are great electrometers. Similarly, Coulomb blockade electrometers are used along with cantilevers. Cantilevers come in a great variety of shapes (rectangular, triangular, etc). They are thin plates with well-defined fundamental frequencies. This changes when a force is applied to them. From the change of their oscillating frequency the magnitude of the force can be deduced.

2.2. Thermal nanosensors

Measuring temperature is usually done by obtaining a value for the change of a well-known property of an object such as volume or electrical conductivity. Tracking the electrical resistivity of a single Sb_2Se_3 nanowire was reported to be a way of acquiring values for nanoscale temperatures. Between a temperature range from 300 K to 525 K the resistivity of the nanowire was measured at several voltages. The thermal activation energy was found to be 0.234 eV. Resistivity for the nanorod is given by [5]

$$R = R_0 e^{\frac{E_a}{2KT}} \qquad (2)$$

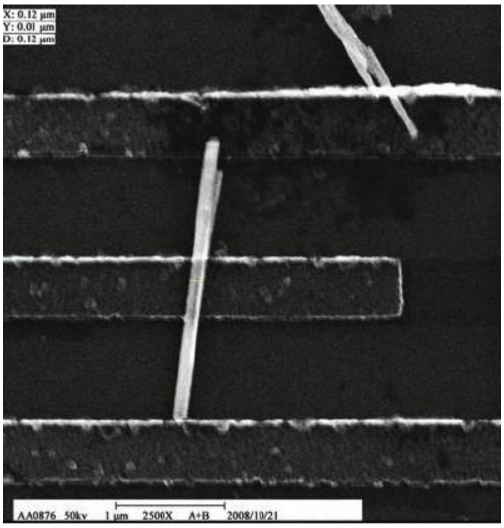

Figure 1. Sb_2Se_3 nanowires across inter-digitated electrodes [4].

where T is temperature, R_0 is the resistance as $T \rightarrow \infty$ and E_a is the thermal activation energy for conduction. This example indicates the basic concept of temperature measurements on the nanoscale. Yet other methods may use different materials and setups. Airflow or vacuum pressure can be similarly measured by monitoring the temperature change of a nano-sized object.

2.3. Optical nanosensors

Apart from the miniaturization of fibre-optic sensors, there are several approaches for optical detection. Because these fibre-optic sensors fall into the field of chemistry, we will not discuss them in detail. To mention some,

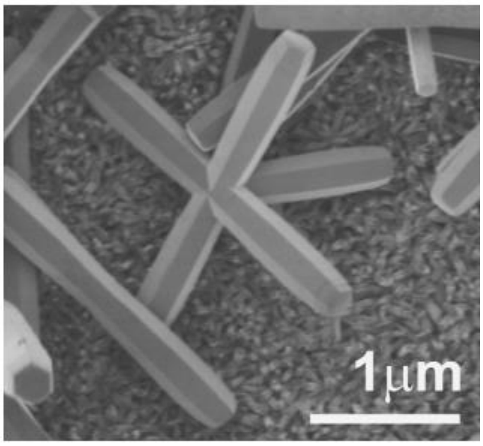

Figure 2. Self-assembly crossed ZnO nanorods [5].

the use of quantum dots, multi-functional magnetic beads, core-shell systems, or noble metals is common. However, we present an ultraviolet nanosensor as this may have numerous applications in physics as well as in other fields. Ultraviolet photosensing was achieved using ZnO nanorods [4]. The working principle of the self-assembled crossed nanorods is as follows. When they are not exposed to direct light, oxygen molecules extract free electrons from the surface of the ZnO nanorods leading to a low conductivity layer there. When there is UV light the holes recombine with electrons from absorbed oxygen ions releasing oxygen atoms from the surface. This whole process results in an increase in conductivity.

2.4. Magnetic nanosensors

Magnetic nanosensors convert magnetic field into an electrical signal. Magnetoresistance represents the change in the electrical resistance as an effect of an external magnetic field. Giant magnetoresistance sensors use the change in magnetic field arising from the spin-dependent scattering of conduction electrons. These are mainly used in computers for data storage. There are also spin-dependent tunnelling sensors and magnetic nanoparticles as proximity sensors. Nanowires that are magnetoresistive can be used to monitor the position of a magnetic object or to find the direction of a magnetic field. Magnetic nanosensors can therefore be divided into two groups. One uses the principle of giant magnetoresistance while the other functions as proximity switches.

3. Nanoradios

The size of processors has greatly decreased over the last few decades, however, there are limits which make tasks involving ordinary computation for nanomachinery impossible. Instead of computing on-site, we can transmit the information to a computer then send the orders back to the nanodevice. For this, we use nanotube radios.

Nanoradios use nanotubes to transmit or receive electromagnetic waves. The charged nanotube with one end fixed starts oscillating when incoming electromagnetic waves are received. The amplitude of this oscillation is the

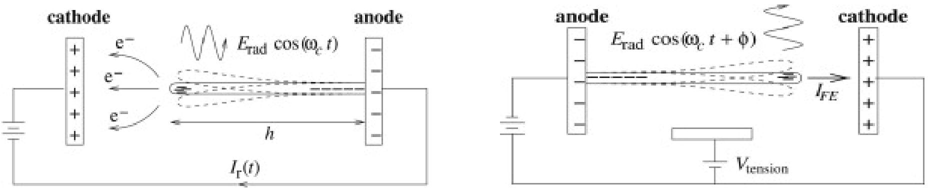

Figure 3. Nanotube radio receiver (left) and transmitter (right) [2].

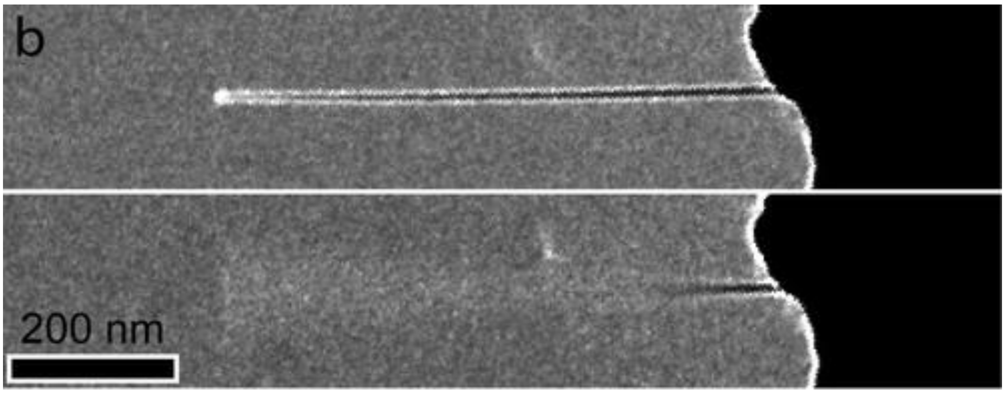

Figure 4. Nanotube radio antenna off and on resonance during a radio transmission [7].

most significant for waves with a frequency identical to the nanotube's fundamental resonance frequency. Hence, nanoradios use mechanical parts to function, making them fundamentally different from traditional radios which operate solely electronically. Changing the nanotube's resonant frequency enables us to operate it on a frequency of our choice, similar to other radios. The vibration of the nanotube causes electron emission from the tip. Then, one can measure the induced current to acquire the message. Transmitting with nanoradios works similarly to receiving. This time we drive the oscillation with an electromagnetic field to create EM waves. The resonance frequency of the nanotube antenna can be calculated as follows [2]:

$$f_0 = \frac{0.56}{L^2}\sqrt{\frac{YI}{\rho A}} \tag{3}$$

where L is the length of the nanotube, ρ is the density, A is the cross-sectional area, Y is the Young's modulus, and I is the moment of inertia of a cylinder. Its usual value ranges between 10-100 MHz [2]. The amplitude of the oscillation is given by [7]

$$|Y_0| = \frac{\frac{qE_{rad}}{m_{eff}}}{4\pi^2\sqrt{\left(f^2 - {f_0}^2\right)^2 + \left(\frac{ff_0}{Q}\right)^2}} \tag{4}$$

Where q is the charge, E_{rad} is the electric field of the transmission, m_{eff} = 0.24m is the effective mass with m being the mass of the nanotube, f is the frequency of the transmission, and Q is the quality factor, with a value of approximately 500.

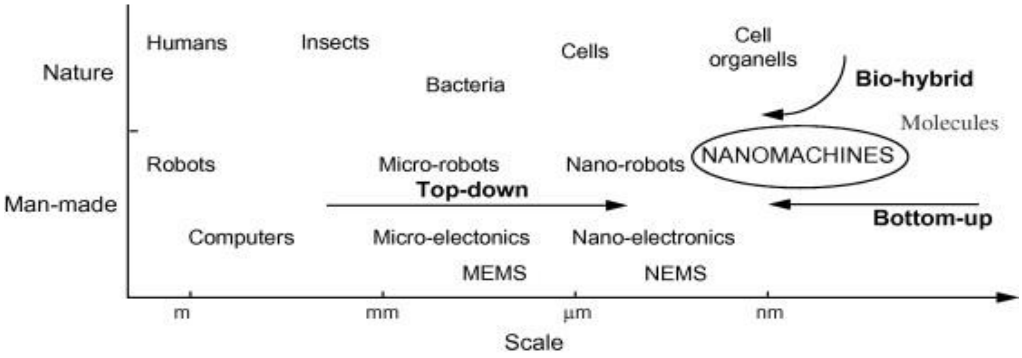

Figure 5. Approaches for the development of nano-machines [6].

4. Approaches to nanomachinery

The top-down approach tries to create nanomachinery by further reducing the size of existing microscale devices. To create such devices, they use advanced manufacturing techniques including beam lithography and micro-contact printing. This approach of course has its limitations. Certain designs are incompatible with such sizes due to scaling problems or quantum tunnelling. We discuss these phenomena in more detail later.

In the bottom-up method, nanodevices are built from individual molecules. This process is highly difficult and therefore it is still in its infancy stage. One popular technique is making use of self-assembly molecular properties.

The bio-hybrid approach proposes taking biological models as basis, and constructing devices based on these. Every living organism has biological nanosensors of one type or another. Understanding their basic properties and the way they function can have a crucial effect in developing our own nano-sized devices. A desired feature of a nanomachine in future is self-replication which can already be observed in living organisms [6,8,9].

5. Elements and properties used in nanotechnology

Carbon nanotubes are frequently used elements of nanomachines. They are made from graphene. The diameter of carbon nanotubes is a few nm while their length is well over 1 µm. Due to this high aspect ratio they are found to

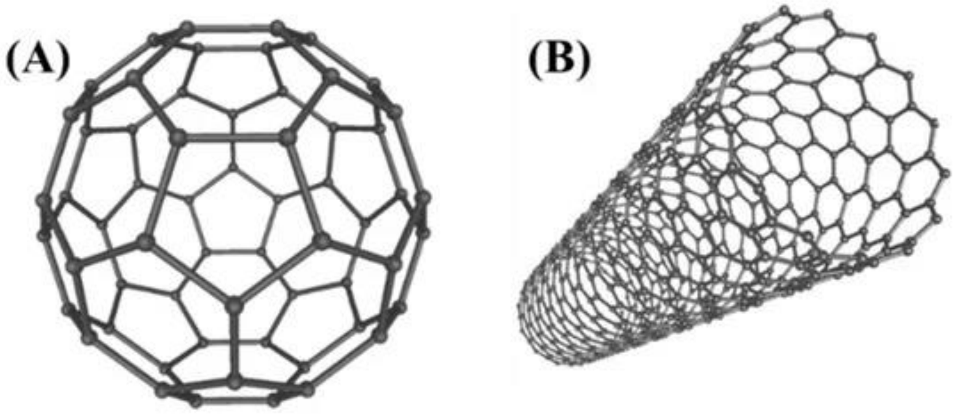

Figure 6. Schematic of a C60 Fullerene (A) and a carbon nanotube (B) [9].

be extremely useful as we will see later. Other carbon structures are similarly useful, however, they are not in direct connection to the topic of this article. Quantum tunnelling allows particles to penetrate potential barriers which classically would be impossible to penetrate. This phenomenon is only experienced over tiny distances.

Simply miniaturising existing designs is sometimes impossible owing to the scaling laws. When shrinking a body its volume changes drastically more than its surface area. Hence, properties connected to one will change differently compared to properties dependent on the other.

6. History of nanotechnology

In 1959, in his famous lecture “There’s Plenty of Room at the Bottom” Richard Feynman first introduced the concept of nanotechnology, describing his vision of using machines to create smaller machines and down to the nanoscale. The term nanotechnology was however first defined only in 1974 by Norio Taniguchi. A great leap for nanotechnology came when the Scanning Tunnelling Microscope was invented in 1981, which in its basic mechanism it is comparable to the electric tunnelling nanosensors. In 1985 carbon was found to possess the ability to exist as stable spheres. Six years later carbon nanotubes were first created. These are both fundamental elements of present nanotechnology. This was followed by the discovery of carbon dots in 2004. Their size is below 10 nm, and their low toxicity makes them highly useful in medicine. Nanotechnology has also been used to improve solar cells, hydrogen fuel cells and novel hydrogen storage systems [9].

7. The future of nanotechnology

There are new breakthroughs in nanotechnology every year. It is expected that nanotechnology will allow us to fight cancer better and identify tumours earlier. There is also a need to build more complicated nanoelectronics systems. It is desired that using molecules as building blocks will eventually become possible. Self-replication is an inevitable aspect of a future in vivo nanomachine. With the development of the manufacturing techniques, nanomachines are expected to have a competitive price, due to their low material requirements.

8. Applications

We have discussed in the introduction that nanosensors have several advantages over regular sized sensors including durability, disposability, and smaller material requirements. Today, nanosensors are mainly used in medicine, the food industry, IT, and security but due to their numerous benefits there are several theoretical future applications. Monitoring the structural integrity of bridges, tunnels and rails may be achieved using cost-effective nanosensors. Nanoradios may provide enhanced transportation infrastructure that can communicate with vehicles in real-time. In cases where weight is crucial, such as aeroplanes or spacecraft, a lightweight solution can save a great amount of fuel and hence lower the expenses [11]. In biology, a continuous observation of living cells could potentially simplify the understanding of complex mechanisms. Similarly in physics, the ability of real-time measurements of tiny structures has been desired for long decades.

9. Summary

Finding properties of objects in the nanoscale is a key aspect of today’s scientific observations. Nanosensors offer a superb solution to this. They also allow the utilisation of phenomena only present on tiny scales such as quantum tunnelling. We have presented the main forms of nanosensors with a detailed discussion of some particular examples including mechanical, thermal, optical, and magnetic nanosensors. These well represented the main ideas and problems in nanotechnology. Later, a description of a nanotube radio and its working mechanism was introduced including the way it allows communication between the sensors and the scientist. In the second part of the article, we discussed the three main approaches of nanomachinery, top-down, bottom-up and bio-hybrid. Then a short overview of the history of nanotechnology, its future properties and the main fields of application was given to deepen the understanding of the reader.

10. References

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