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DSE3T (Nano Materials and Applications)

Topic – Applications (Part – 2)

We have already discussed part 1 of this e-report.

Now let us continue part 2 of it.

Carbon Nanotube (CNT) based Transistors:

The feasibility of designing field-effect transistors (FETs), the switching components of computers based on semiconducting carbon nanotubes (CNTs) connecting two gold electrodes, has been demonstrated. An illustration of the device is shown in Fig. 1. When a small voltage is applied to the gate, the silicon substrate, current flows through the nanotube between the source and the drain. The device is switched on when current is flowing, and off when it is not. It has been found that a small voltage applied to the gate can change the conductivity of the nanotube by a factor $> 1 \times 10^6$, which is comparable to silicon field-effect transistors. It has been estimated that the switching time of these devices will be very fast, allowing clock speeds of a terahertz, which is 10^4 times faster than present processors. The gold sources and drains are deposited by lithographic methods, and the connecting nanotube wire is less than one nanometer in diameter. This small size should allow more switches to be packed on a chip. It should be emphasized that these devices have been built in the laboratory one at a time and methods to produce them cheaply in large scale on a chip will have to be developed before they can be used in applications such as computers. A major objective of computer developers is to increase the number of switches on a chip. The approach to this is to use smaller-diameter interconnecting wires and smaller switches, and to pack then more tightly on the chip. However, there are some difficulties in doing this with present metal interconnect wire and available switches. As the cross section of a metal wire (such as copper) decreases, the resistance increases and the heat generated by current flowing in the wire increases. The heat can reach such a value that it can melt or vaporize the wire. However, carbon nanotubes with

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diameters of 2 nm have extremely low resistance, and thus can carry large currents without heating, so they could be used as interconnects. Their very high thermal conductivity means that they can also serve as heat sinks, allowing heat to be rapidly transferred away from the chip.

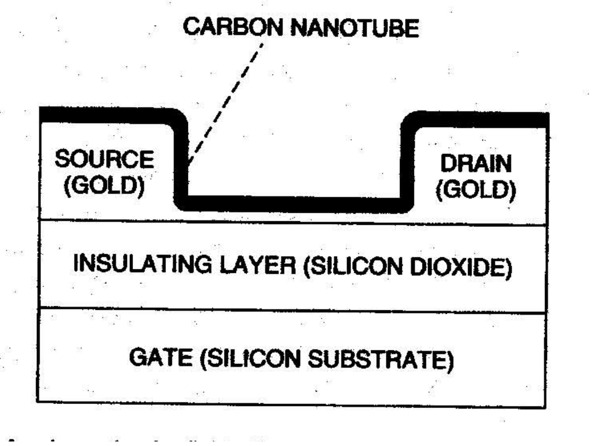

Fig. 1

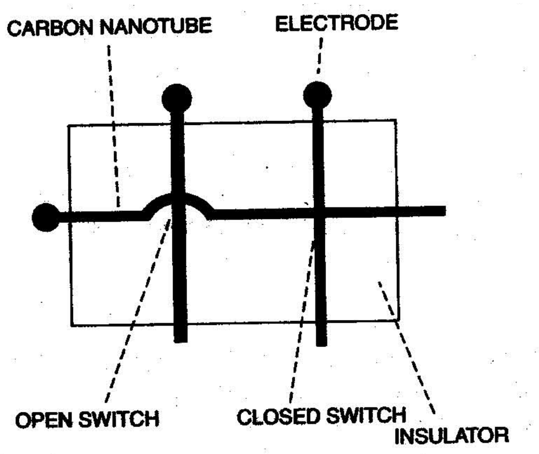

Fig. 2

Another idea that is being pursued is to make a computer out of carbon nanotubes. The computer would be an array of parallel nanotubes on a substrate. Above this, but not touching the lower array and having a small separation from them, are carbon nanotubes oriented perpendicular to the tubes on the substrate. Each tube would be connected to a metal electrode. Fig. 2 illustrates the concept. The crossing points would represent the switches of the computer. When the tubes are not touching at the crossing points, the switch is off because

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the resistance is high. In the ON state the tubes are in contact and have a low resistance. The ON and OFF configurations can be controlled by the flow of current in the tubes. The researchers estimate that 10^{12} switches could fit on a square cm chip. Present Pentium chips have about 10^{8} switches on them. The switching rate of such devices is estimated to be about 100 times faster than that of the present generation of Intel chips. Ideally one would like to have semiconducting nanotubes on the bottom and metallic nanotubes on the top. Then, when contact is made, there would be a metal-semiconductor junction that allows current to flow in only one direction; thus the junction is a rectifier.

Microelectromechanical Systems (MEMS):

Although microelectromechanical systems do not technically fall under the subject of nanotechnology, it is useful to briefly discuss them because they represent a more mature technology, and many of the differences in behaviour observed in the micromechanical world could well apply to the nano-regime, thereby providing a basis for the design of nanomachines. The extensive fabrication infrastructure developed for the manufacture of silicon integrated circuits has made possible the development of machines and devices having components of micrometer dimensions. Lithographic techniques combined with metal deposition processes, are used to make MEMS devices. Microelectromechanical systems involve a mechanical response to an applied electrical signal, or an electrical response resulting from a mechanical deformation.

The major advantages of MEMS devices are miniaturization, multiplicity and the ability to directly integrate the devices into microelectronics. Multiplicity refers to the large number of devices and designs that can be rapidly manufactured, lowering the price per unit item. For example, miniaturization has enabled the development of micrometer-sized accelerometers for activating airbags in cars. Presently used accelerometers based on MEMS devices are the size of a dime, and cost only a few dollars. The size of MEMS devices, which is comparable to electronic chips, allows their integration directly on the chip. In the following, we present an illustration of a MEMS device and describe how it works.

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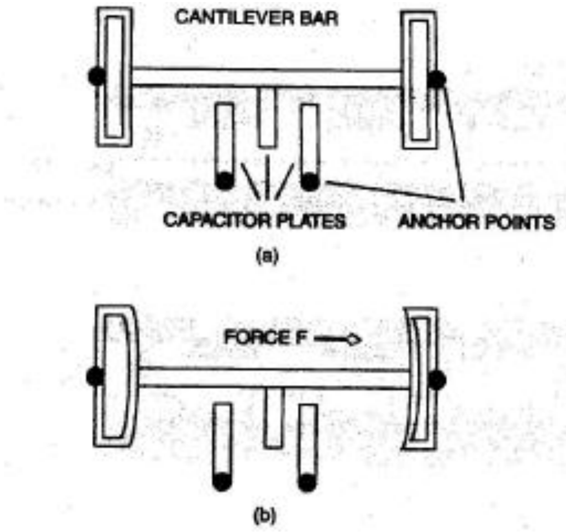

Fig. 3

Fig. 3 illustrates the principle behind a MEMS accelerometer used to activate airbags in automobiles. The figure a shows the device, which consists of a horizontal bar of silicon a few micrometers in length attached to two vertical hollow bars, having flexible inner surfaces. The automobile is moving from left to right in the figure. When the car suddenly comes to a halt because of impact, the horizontal bar is accelerated to the right in the figure, which causes a change in the separation between the plates of the capacitor, as shown in Fig. 3(b). This changes the value of the electrical capacitance of the capacitor, which in turn electronically triggers a pulse of current through a heating coil embedded in sodium azide, NaN_3. The instantaneous heating causes a rapid decomposition of the azide material, thereby, producing nitrogen gas N_2 through the reaction $2NaN_3 = 2Na + 3N_2$, which inflates the airbag.

Nanoelectromechanical Systems (NEMS):

Nanoelectromechanical machines and devices are in the early stages of development, and may are still in conceptual stages. Numerous computer simulations of possibilities and ideas have been proposed. It turns out that nature is far ahead of us in its ability to produce nanosized machines. Nanomotors exist in biological systems such as the flagella motor of bacteria. Flagellae are long, thin, blade-like structures that extend from the bacteria. The motion of these flagellae propel the bacteria through water. These whip-like

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structures are made to move by a biological nanomotor consisting of a highly structured conglomerate of protein molecules anchored in the membrane of the bacterium. The motor has a shaft and a structure about the shaft resembling an armature. However, the motor is not driven by electromagnetic forces, but rather by the breakdown of adenosine triphosphate (ATP) energy-rich molecules, which causes a change in the shape of the molecules. Applying the energy gained from ATP to a molecular ratchet enables the protein shaft to rotate. Perhaps the study of biological nanomachines will provide insights that will enable us to improve the design of mechanical nanomachines. Here we present an example of a NEMS device, called *actuator* and its working principle.

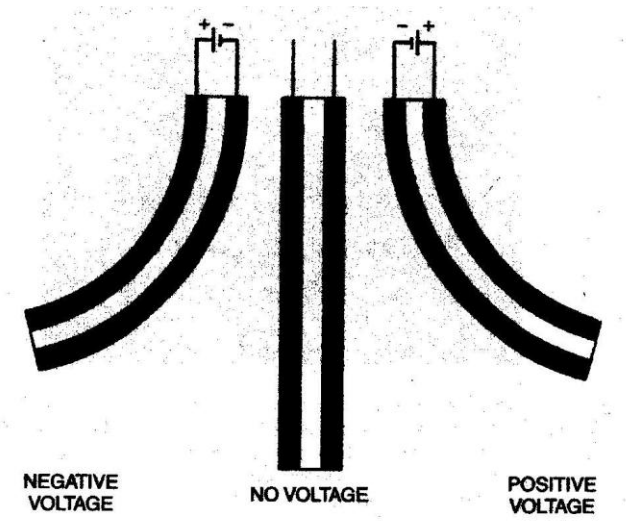

Fig. 4

Actuators are devices that convert electrical energy to mechanical energy, or vice versa. It is known that single-walled carbon nanotubes deform when they are electrically charged. An actuator based on this property has been demonstrated using single-walled carbon nanotube paper. Nanotube paper consists of bundles of nanotubes having their long axis lying in the plane of the paper, but randomly oriented in the plane. The actuator consisted of 3×20-mm strips of nanopaper $25 - 50$ μm thick. The two strips are bonded to each other in the manner shown in Fig. 4 by double-stick Scotch tape. An insulating plastic clamp at the upper end supports the paper and holds the electrical contacts in

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place. The sheets were placed in a one molar NaCl electrolytic solution. Application of a few volts produced a deflection if up to a centimeter, and could be reversed by changing the polarity of the voltage, as shown in Fig. 4. Application of an AC voltage produced an oscillation of the cantilever. This kind of actuator is called a *bimorph cantilever actuator* because the device response depends on the expansion of opposite electrodes. It works because of the effect of charging on the individual carbon nanotubes, and indicates that nanosized actuators employing three single-walled carbon nanotubes are possible. Such a device might consist of three fibers aligned with their axes parallel and in contact. The outer two tubes would be metallic and the inner tube insulating. Although electron-beam lithography can be used to fabricate silicon structures less than 10 nm in size, nanomachines have not been produced to any large extent. A number of difficulties must be overcome before significant progress can be made. The first is the problem of communicating with and sensing the motion of the nanoscale devices. The second obstacle is that little is known or understood about the mechanical behaviour of objects, which have up to 10% of their atoms on or near the surface.

Now a cantilever beam having a length of 10 nm and thickness 1 nm will have a resonant frequency 10^5 times greater, of the order of $20-30$ GHz (which means $2-3\times10^{10}$ cycles per second). As the frequency increases, the amplitude vibration decreases, and in this range of frequencies the displacements of the beam can range from a picometer (10^{-12} m) to a femtometer (10^{-15} m). These high frequencies and small displacements are very difficult, if not impossible, to detect. Optical reflection methods such as those used in the micrometer range on the cantilever tips of scanning tunnelling microscopes (STMs) are not applicable because of the diffraction limit. This occurs when the size of the object from which light is reflected becomes smaller than the wavelength of the light. Transducers are generally used in MEMS devices to detect motion. The MEMS accelerometer shown in Fig. 3 is an example of the detection of motion using a transducer. In the accelerometer mechanical motion is detected by a change in capacitance, which can be measured by an electrical circuit. It is not clear that such a transducer sensor can be built that can detect displacements as small as 10^{-15} to 10^{-12} m, and do so

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at frequencies up to 30 GHz. These issues present significant obstacles to the development of NEMS devices.

Magnetic Nanostructures, Magnetic Data Storage:

Nanotechnology is one of the hottest research fields in the science and engineering arena. Of the many potential applications of nanotechnology, one of the most promising ones is in data storage, particularly the hard disk drives (magnetic data). This is because the physical size of the recording bits of hard disk drives is already in the nanometer regime, and continues shrinking due to the ever-increasing demand for higher recording densities. If the pace of areal density increase is maintained at the current level for about ten years, the dimension of the recording bit will reach the sub-10 nm regime. At this level, both the writing and reading processes will become extremely challenging, if not impossible. The rapid shrinkage of bit size poses formidable challenges to the read sensors. This is because the sensor must be made smaller or at least comparable to the bit size, and at the same time, its sensitivity must be improved continuously so as to compensate the loss in signal-to-noise ratio due to the decrease in the bit size. The former has to rely heavily on the advance of nanotechnology, and the latter on an emerging field called *Spintronics*. The combination of these two fields has played an important role in advancing the areal density of magnetic recording from a few Gbits/inch^2 to the current level of more than 100 Gbits/inch^2. In addition to hard disk drives, the technologies developed have also been applied to magnetic random access memories (MRAMs). Further advance in the two fields is the key to realizing terabits/inch^2 hard disk drives and gigabit non-volatile memories within this decade.

Among the magnetic storage devices, the hard disk drive (HDD) is the dominant secondary mass storage device for computers, and very likely also for home electronic products in the near future. The HDD is an integration of many key technologies, including head, medium, head-disk interface (HDI), servo, channel coding/decoding, and electromechanical and electromagnetic devices. Among them, the read head is the only component that has experienced the most changes, including some revolutionary ones in terms of both the operating

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principle and the structural design and fabrication processes during the last decade. The ever-increasing demand for higher areal densities has driven the read head evolving from a thin-film inductive head to an *anisotropic magnetoresistive* (AMR) head, and recently, the *giant magnetoresistive spin-valve* (GMR SV) head. There are two different forms of GMR SVs, depending on whether the sense current flows in the film plane (CIP) or perpendicular to the film plane (CPP). Currently, CIP SVs are dominant, but CPP SVs are more promising for future extremely high-areal-density heads. In addition to CPP spin valves, a *magnetic tunnel junction* (MTJ) with low junction resistance is also one of the potential candidates for future read sensors. The MTJ is particularly useful for MRAM applications. As is with the case of read sensors, the MRAM started from the ferrite core design to AMR, GMR pseudospin valve, and the current MTJ cell design. However, it is only after the introduction of MTJ that the MRAM taken off, and is expected to be in mass production in a few years' time. The GMR and MTJ sensors are generally called magnetoelectronic or metal-based spintronic devices. The metal-based spintronic devices are based primarily on the spatial modulation of electron spins through using layered structures of magnetic and nonmagnetic materials. The lack of capability in charge modulation in these types of structures may eventually limit their ultimate performances in terms of both the magnetoresistance and other functionalities. To address this issue, recently, a great deal of effort has been devoted to the development of magnetic semiconductors which allow the modulation of both the spins and charges. The advance in this field may eventually lead to spintronic devices with performances superior to their metal-based counterparts. In addition to pure metal-based or semiconductor-based spintronic devices, hybrid devices making use of both technologies also have been explored actively in recent years.

The thin-film medium for a hard disk drive is a stack of multiple layer thin films formed on either an NiP-coated aluminium alloy or a glass substrate. Among the multiple layers of thin films, the early hard disk media only employed a single magnetic layer as the recording layer, which is usually a polycrystalline alloy of Co, Cr, and Pt with additional elements such as Ta or B to improve the magnetic properties. The latest magnetic media, however, employ more than

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one magnetic layer as the recording layer, such as the antiferromagnetically coupled (AFC) media to improve the thermal stability of the information bits recorded on the hard disk. When recording the information onto the disk, a writer which can generate a sufficiently high magnetic field is used to switch the magnetization of a localized area of the media to one of two fixed directions, with one of them representing digit "1" and the other representing digit "0". Each of the localized areas can be considered as one bit. Each bit consists of a number of partially exchange-coupled magnetic grains. A typical spin valve nanostructure is shown in Fig. 5.

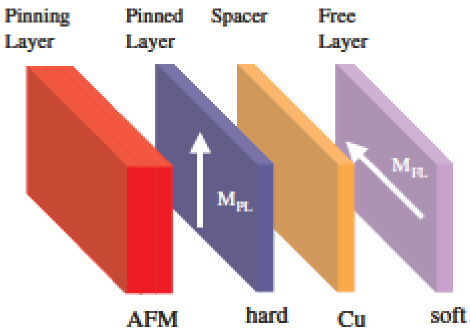

Fig. 5

Reference(s):

Introduction to Nanotechnology, Poole Jr. & Owens, Willey

Nano Spintronics for Data Storage, Yihong Wu, Encyclopedia of Nanoscience and Nanotechnology

(All the figures have been collected from the above mentioned references)