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What is Nanoscale Science and Nanotechnology?

A Scientific Revolution

In the 1940s, the world witnessed a scientific revolution. For the first time, humans had harnessed the immense energy stored within an atom to build the first nuclear weapons, producing a level of destruction never seen before. Just over a decade later, man penetrated the outermost boundaries of the Earth, enabling exploration of outer space, unlocking the final frontier. The next great scientific revolution would be the computer revolution of the 70s and 80s, stemming from the invention of the first integrated circuit. Presently, we are witnessing yet another scientific revolution, continuing the pattern of decades past.

On December 29, 1959, Richard Feynman asked the American Physical Society at an annual meeting, "Why cannot we write the entire 24 volumes of the Encyclopedia Britannica on the head of a pin?" Now, his hopeful proposition has not only become a reality, but has motivated scientists to solve the world's largest problems on the smallest scale. "Atoms on a small scale behave like *nothing* on a large scale, for they satisfy the laws of quantum mechanics. So, as we go down and fiddle around with the atoms down there, we are working with different laws, and we can expect to do different things."

"Another thing we will notice is that, if we go down far enough, all of our devices can be mass produced so that they are absolutely perfect copies of one another. We cannot build two large machines so that the dimensions are exactly the same. But if your machine is only 100 atoms high, you only have to get it correct to one-half of one percent to make sure the other machine is exactly the same size---namely, 100 atoms high! The principles of physics, as far as I can see, do not speak against the possibility of maneuvering things atom by atom. It is not an attempt to violate any laws; it is something, in principle, that can be done."

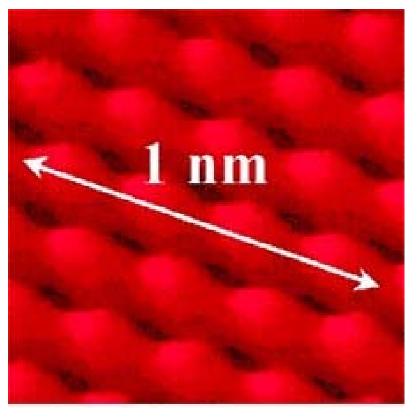

Fig. 1: One nanometer spans 3-4 atoms in diameter

A New Word for Small

Feynman was speaking of a technology that we now call nanotechnology. The root *nano* specifically refers to a nanometer, which is a length exactly one billionth (10^{-9}) of a meter. It is about 50,000 times smaller than the diameter of a human hair, a distance spanned by three to four atoms end-to-end.

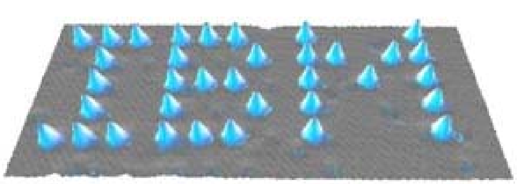

Fig. 2: Don Eigler used a STM in 1989 to write the letters "I-B-M" in Xenon atoms

What is nanotechnology, then? By definition, nanotechnology refers to the fabrication of materials and devices on atomic and molecular scales. Because the laws of quantum mechanics (very small scale) are vastly different than the laws of classical mechanics (very large scale), nanoscale materials and devices exhibit unique and often superior properties and performance. As a result, the scientific community has poured billions of dollars of

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funding into the research of such technology, and nanotechnology had an economic worth of hundreds of billions of US dollars today.

One of the first major advancements in nanotechnology occurred on September 28, 1989, when Don Eigler of IBM successfully wrote the letters I-B-M by manipulating individual Xenon atoms using a scanning tunneling microscope (IBM). Soon afterward, Eigler's group began making quantum corrals, or rings of atoms on a substrate. In figure 3, a quantum corral can be seen with surface state electrons confined to a region within the ring. Eventually, more intricate designs were created in the same method, and shapes and figures ranging from simple geometric objects to Chinese characters were fabricated (Figure 4).

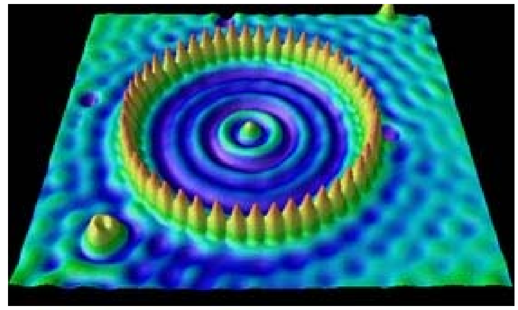

Fig. 3: Don Eigler's group also invented the quantum corral

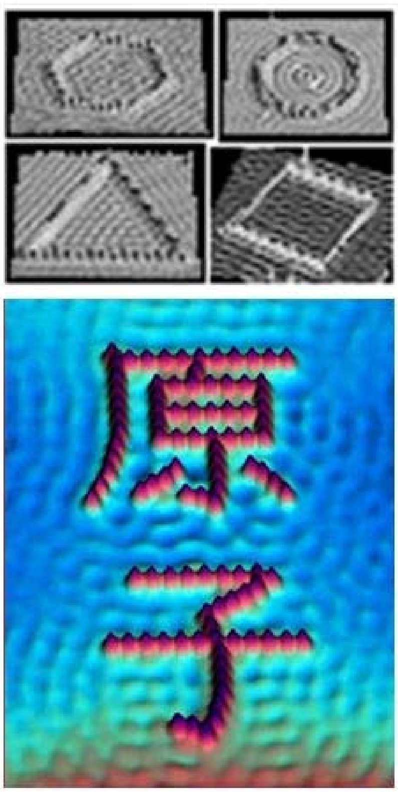

Fig. 4: More interesting shapes were created with the STM

Tools of the Trade

The device which made this all possible was the scanning tunneling microscope (STM), invented in 1981 by Gerd Binnig and Heinrich Rohrer of IBM. The STM allowed scientists to view materials at a resolution of less than one nanometer, finally enabling people to "see" the atoms they had become so familiar with over the past century. With this new lens in hand, the possibility of developing technologies at the atomic scale became true.

Other technologies soon emerged in the following decades, and a diverse collection of tools for manipulating atoms and molecules were created in the 80s and 90s. Among these, the most significant were ion beam lithography, optical lithography, and electron beam lithography. These technologies use beams of particles to "carve" out features on certain materials to a very high degree of accuracy. Figure 5 shows a picture of Gordon Gee, then chancellor of Vanderbilt University, carved in silicon using ion beam lithoraphy.

Fig. 5: A portrait of Gordon Gee measuring 8 x 6 microns

Thin Films Open New Doors

One branch of nanotechnology that has become quite active in recent years is the study and application of thin films. Thin films are just what they sound like: very thin layers of a certain material deposited onto a substrate. Micro Magnetics, Inc. is one of the key players in modern magnetic thin film development and utilization, and our focus is on the magnetoresistive properties of ferromagnetic thin film-based devices.

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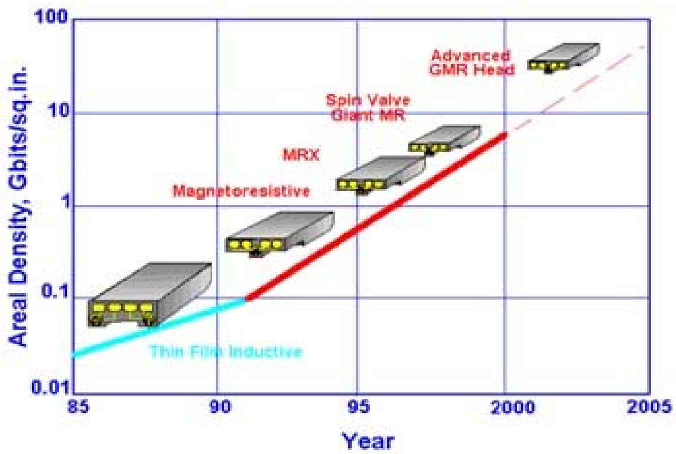

Fig. 6: Areal density of data capacity has increased exponentially since the early 90s

One of the key applications of magnetic thin film devices is magnetic data storage. In every modern hard disk drive, there are multiple spinning plates coated with a magnetic thin flim. This film contains trillions of tiny magnets (bits) which can point in one of two directions, corresponding to the 0s and 1s of computer language. The density of these bits has increased exponentially over the past two decades, and the most advanced hard drives pack over 200 Gigabits (10^9) per square inch.

Fig. 7: Data storage devices are continually getting smaller

Another magnetic thin film device used for reading the data stored in hard drives is the giant magnetoresistance (GMR) read head. GMR is the property that the resistivity, or current carrying capacity, of a material changes with the strength of an applied magnetic field. GMR devices respond to extremely small changes in magnetic field, which make them ideal for hard drive reading applications. As the data density increases to astounding levels, the increasing need for extremely sensitive magnetic sensors to detect the tiny bits of data becomes present. Current research is devoted to a new type of magnetoresistive magnetic sensor device, known as a magnetic tunneling junction (MTJ). Micro Magnetics, Inc. currently produces some of the worlds most sensitive magnetic tunneling junctions. For a further explanation of Micro Magnetics' MTJ devices, click here.

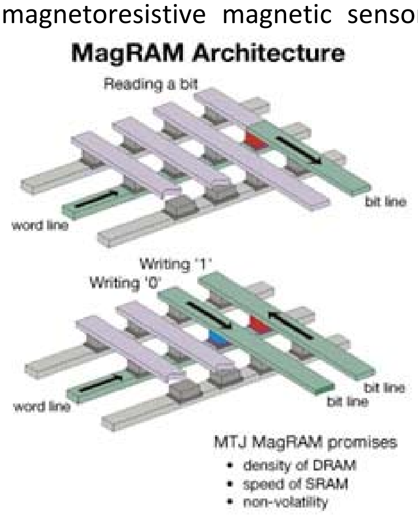

Fig. 8: Magnetic RAM is a nonvolatile solution to present RAM technology

Other applications for MTJ magnetic sensors are far and plenty. Micro Magnetics, Inc. provides failure analysis services for intregrated circuits which rely exclusively on MTJ sensing technology (more detail).

Another computation application is in the development of Magnetic Random Access Memory (MRAM). By exploiting the spin degree of freedom of electrons, MRAM devices are a non-volatile, meaning they retain their information even when powered off. Current RAM devices are volatile, and recovering information after powering off is impossible without use of hard drives. If MRAM devices become mainstream, the computer industry would be

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completely revolutionized, as they would increase the speed and performance of computers many times over present levels since current hard drives operate at much slower speeds than modern RAM devices.

Biomagnetism is another branch of nanotechnology which embraces MTJ technology. Current research at Micro Magnetics, Inc. focuses on a new type of immunoassay involving the use of MTJs. For a more detailed explanation of this technology, click here. Future applications of MTJs include using wireless devices to conduct electroencephalograms (EEG) to detect brain waves, as well as wireless electrocardiograms (EKG) to monitor the heart. Also, using MTJ devices to detect brain waves could allow humans to interact with computers without moving a limb, relying purely on the MTJ device to detect what the user is thinking. Science fiction could soon become a reality.

Other Nanotechnology Applications

Thin film technology, as vast as it seems, is only a tiny branch of magnetic nanotechnology. There are many other nanotechnological applications that are curently being developed. For example, one promising technique that is in current development hopes to be a new treatment for cancer. Magnetic nanoparticles that are ferromagnetic below a critical temperature are introduced into tissue where a tumor is present. Since these particles are ferromagnetic below a certain temperature, they exhibit hysteresis effects in this regime. If they are exposed to an AC magnetic field, such as incident microwave radiation, they will convert the energy of the field to heat. Once enough heat is generated and their temperature surpasses the critical temperature, they no longer absorb any more radiation. Thus, they are self-regulating at the critical temperature, a temperature which is hot enough to kill the cancer, but safe for healthy tissues.

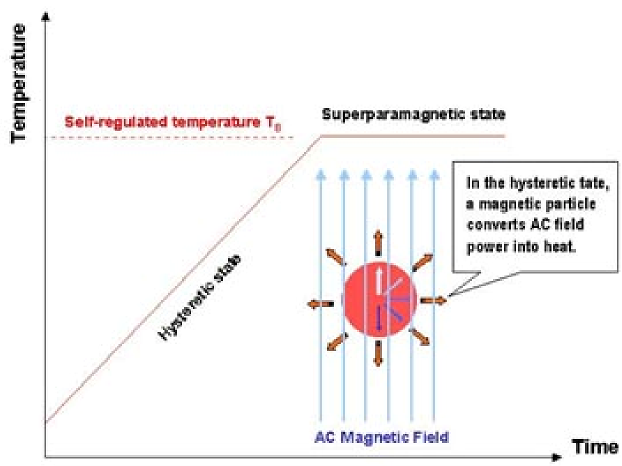

Fig. 9: Magnetic nanoparticles can be used as a possible treatment for cancer by converting microwave radiation into heat

Carbon nanotubes and buckyballs are other man-made nanomolecules that are hopeful candidates for future technologies. Currently, carbon nanotubes boast some of the highest tensile strengths of any present material. This means that they are very hard to break under pressure, and they are currently being investigated as a possible material to build the first elevator into space. They are also very good

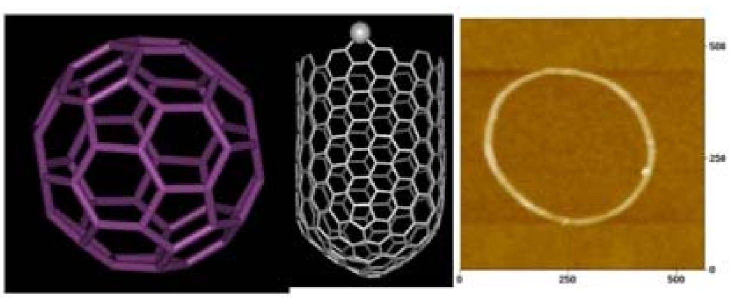

Fig. 10: Carbon nanotubes and buckyballs have very interesting tensile and electrical properties

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conductors, and have unique electrical properties, making them good candidates for nanoelectronics applications.

A New Age

There seems to be a trend in inventing new materials to solve the world's problems. Optical fibers have enabled broadband communication, revolutionizing the way we interact with one another. Silicon wafers have allowed for the creation of ultra-large scale integrated circuits, faciliating the the computer and data-storage revolution. Now, with the advent of nanotechnology, we are on the brim of yet another scientific revolution. Soon we will feel the effects and extraordinary benefits of nanotechnology, and a new era will begin.

http://www.almaden.ibm.com/almaden/media/eigler2.html