Journal of Theoretical Physics

Founded and Edited by M. Apostol **88** (2003)

ISSN 1453-4428

Advanced Materials

M. Apostol
Department of Theoretical Physics, Institute of Atomic Physics,
Magurele-Bucharest MG-6, POBox MG-35, Romania
email: apoma@theory.nipne.ro

Materials Science is immense, so it is vaguely defined. However, it is the greatest practical output of the Condensed Matter, *i.e.* of the Quantal Mechanics plus Statistical Physics. As regards materials, we are interested in their mechanical, electric, thermal, optical and magnetic properties mainly. All these originate in the atomic structure of the materials and in their electronic structure. The full understanding of the basic properties of the materials comes from first principles, *i.e.* from the aggregation of their atomic constituents. Though we know for a long time the general principles of matter aggregation and chemical bonding, we are still far away from a complete knowledge of building up materials from atoms and molecules. The atomic clusters and nanostructures of today demand ever more such a basic knowledge, and the newly raising Nanoscience opens new routes toward achieving it. I might say that our age will see soon such an achievement.

During the classical age of the Condensed Matter, which extends until, say, the middle of the 20th century, we acquired a fair knowledge of a few basic materials, like some simple metals and insulators. At the same time, it is worth noting that during the same period we got more knowledge about some particular quantal fluids, like superfluids, superconductors or the electron liquid, than about more common substances or materials like very real gases, complex fluids or electric plasmas. This lack of knowledge still lasts today.

The modern age of the Condensed Matter began in 1948 with the discovery of the transistor. This discovery was also the birth of the new Materials Science. The transistor made three main points, at least. First, it drew attention to the semiconducting materials, like Ge and Si, which made possible computers and modern telecommunication. The present-day electronics is dominated by compound semiconductors like GaAs, SiGe or GaN, of which integrated circuits, solid-state lasers and light-emitting diodes are made. Second, the transistor opened the way toward miniaturization, a race which is in full progress today, and whose end is forecast in a near future. And third, the transistor brought forth material structures with a special geometry, sandwich or low-dimensional structures like layered materials or quasi-one-dimensional conductors, either man-made, artificially fabricated, or naturally synthesized. We learnt a lot of basic physics from low-dimensional materials, which dominate, silently, the modern Condensed Matter.

The usefulness of the new semiconducting materials pushed people to look by extension for other chemical combinations, with new atomic and electronic structures. One of the first topics in the modern age was the glass, and the glassy state, and, in general, the amorphous materials. On this occasion, we learnt about electron localization, disorder, solid-liquid transition, and coloured glasses were optically doped for various practical purposes. SiO_2 is a glass of which high-capacity and transmission high-speed optical fibers are made. Ceramics followed soon, combinations of metals and non-metals, hard, brittle and good insulators, as well as composites, designed mainly for improving the mechanical properties of the original components, like those reinforced with carbon fibres, for instance. Superalloys of Ni with small amounts of Al, Ti, Cr, etc, possess a high strength needed in turbines blades and jet engines. Magnetoresistive thin films of Ni-Fe are reading heads of stored magnetic data, while Nd-Fe-B is an efficient permanent magnet. The microstructure is of utmost importance here, and grains, dendrites, cracks, faults, fracture, friction remain still to be understood. The usual non-equilibrium synthesis was mastered on this occasion in order to get control over desired properties. Chemistry was definitely enrolled by now as the underlying background of the Materials Science.

Materials Science continued with organics. Chemistry was put seriously at work for synthesizing new, large super-molecules, with special properties and self-assembling propensities. Liquid crystals came first along this route. Their molecules allign themselves under low electric fields, being able to switch on and off the passing of the polarized light. Flat panel displays like those of the laptops are made of liquid crystals. Plastics and polymers made then epoch. They come either as soft materials, neither liquids nor solids, with great applications as biomaterials for prosthetic replacements, or strong materials. Soft mater has a complex behaviour, largely not yet understood. The usual compact disks are made of polymers, with small atomic inprints read by a semiconducting laser. Polymers can also be very strong, like Kevlar, a polymer twice stronger than steel, which the bulletproof vests are made of. Around 1970 a breakthrough took place by making organic polymers, like polyacetilene chains, conducting by doping, with iodine, for instance. Electric properties were joined this way with the lightweight and flexibility of plastics, opening way to many potential applications in organic electronics.

A few decades ago several major breakthroughs heralded the contemporary age of Condensed Matter and Materials Science. First, there came up optical and electron litography, molecular beam epitaxy and scanning probe microscope. The first two took the microelectronics toward its own limits. Microfabricated electronic structures reach today about 1500 Å in linear size. The scanning probe microscopy however is able to manipulate even individual atoms, so it only remains to build up molecules, super-molecules, atomic quantum dots, nanostructures and nano-objects of a few tens of angstroms, with functionalities, in a bottom-up approach starting from chemistry and atomic constituents. This is the new Nanoscience. At the same time there were discovered the fractional quantal Hall effect, the high-temperature superconductivity, the fullerene and nanotubes, atomic clusters were synthesized and Bose-Einstein condensation was obtained in droplets of atoms.

At the interface of Al-GaAs and GaAs a two-dimensional electron liquid forms up, with a variable density. Such an interface is called a heterostructure. In two dimensions electrons behave quite distinctly from three dimensions. They form a highly correlated liquid, feeling one another much more than in three dimensions. For very low densities they even organize themselves in a crystal, called the Wigner crystal, under the action of the Coulomb interaction. Of course, such correlations are effective at very low temperatures and in high purity samples. When a high magnetic field is applied upon such a highly-corelated two-dimensional electron liquid the electrons behave as if each would have a fractional charge; which can be seen in the Hall conductivity. This is the fractional quantal Hall effect, a rather strange phenomenon in basic physics. It was made possible by having semiconducting interfaces of good quality. The integral quantal Hall effect was previously seen in other types of two-dimensional electron liquids, formed at the interface between a metal oxide and a semiconductor (MOS), like metal-oxide-silicon, where disorder leads to localization and the Coulomb interaction is pretty ineffective.

Superconducting materials are widely used for obtaining powerful magnets. High magnetic fields are needed in nuclear magnetic resonance, a powerful method of imaging the structure of matter. The superconductivity occurs usually at very low temperature, which is expensive, but the discovery of the high-temperature superconductors made the superconductivity available at liquid nitrogen temperature (˜70K), which is much less expensive. The new high-temperature sueprconductors are ceramics, of typical composition YBaCuO, or BiSrCuO, for instance. The charge carriers interact rather strongly with the neighbouring atoms, leading to an overall Cooper pairing responsible for the high superconducting temperature. The phenomenon is accompanied by many complex details, whose control might improve upon the quality of these valuable new materials.

Fullerene is a new molecule, and a new form of carbon, made of 60 carbon atoms arranged regularly. Such a giant symmetric molecule contributed much toward the definite interest in nanostructures. Its solid state, like alkali fulerides, is superconducting, and has many other interesting properties. Atomic carbon sheets roll upon themselves to form carbon nanotubes, with cca 6 Å diameter. They would be ideal nanowires for electric nanocircuits.

Then, it has been observed that pretty many atoms may get together, in laser furnaces, for instance, and form atomic clusters of, say, 10-100-1000 atoms. This raised the question of matter aggregation, on one hand, and how to make use of the new properties of such objects, on the other. The main objective, for instance, would be to add active molecular agents to such clusters, which would be used as pharmaceutical vectors; they are more effective as they go everywhere in the body, and are eliminated easily. Then, electronic properties of such small nano-objects would open the access to a new, immense scale of nano-miniaturization. In general, functional nanostructures are very effective, because they allow us to control phenomena at atomic scale.

Atoms can be confined to small region of space, by laser cooling and magnetic traps. The temperature of such atomic droplets can thus be made very low, so that the quantal delocalization begins to be effective. If their spin happens to be integral, such atomic droplets get superfluid, by Bose-Einsetin condensation. The wavefunction of the condensate is entangled and non-local, and the teleportation and the non-local communication predicted by Quantal Mechanics would have a chance to be tested on these new materials at atomic scale.

Finally, we must note the large experimental facilities that are making possible the investigation of materials structure, namely the nuclear reactor for neutron physics and the synchrotron radiation of the accelerators.