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From Stonehenge to Nanohinge

Functional materials are materials that have physical and/or chemical properties that can be exploited to perform specific functions. The prime modern example of such a functional material is the semiconductor, which is put to use in every conceivable electronic device in use today. It is a type of material that has completely reshaped today's world as we know it. However, it is far from the only type of functional material we have. Magnetic, ferroelectric, optically active, metallic, insulating, superconducting, and thermally insulating materials are some important examples. Materials have always played an important role in the history of modern man, from the Stone Age via the Iron and Bronze ages, up to the Semiconductor Age in which we may say we live today. Changes in the way materials have been used, and in which materials have been used, have historically given rise to changes in technology and thus in civilizations.

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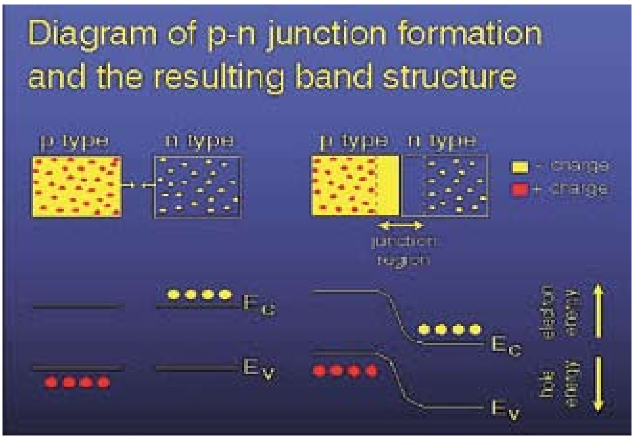
Agriculture and hence stable non-nomadic societies developed in the Younger Stone Age about 4000 years ago on the basis of three materials: stone, wood and animal bones. The making of clothes and shelters, the keeping of livestock and the cultivation of the soil were largely contingent on these three materials for several thousand years. About 4000 years ago, man discovered how to extract minerals and make metals and metal alloys, such as iron, bronze and brass, in areas such as Egypt. However, it took another 2000 years before this knowledge spread to northern Europe, for example. The Stone Age was followed by the Bronze Age (1800–500 B.C.), which in turn was followed by the Iron Age (500 B.C.–1000 A.D.). Compared with stone, wood and bones, metals have the novel property of being ductile, i.e. one can make them in practically any shape without breaking them. This makes them suitable for manufacturing tools and weapons, which was their original novel functionality. In addition, many of them are excellent conductors of electrical current. As such, they are extremely important modern functional materials. Functional materials have been of such importance in the history of human beings that entire eras have been named after them. Among the most prominent and lasting, not to mention pleasing uses of materials are in art and architecture. Without a doubt, the most famous structure remaining from the Stone Age is the




enigmatic Stonehenge on the Salisbury plain in the UK. It is made of huge vertically positioned blocks of solid rock in a regular pattern of concentric circles, topped by even larger horizontally positioned blocks of rock. The fact that Stonehenge has remained largely intact for more than 4000 years bears witness to its expert construction.

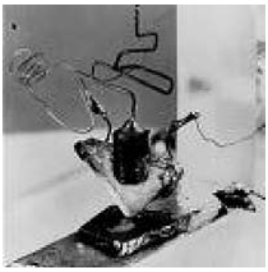
By far the most important single functional material of the 20th century is silicon, designated by the chemical symbol Si. One might quite reasonably assert that we are currently living in the Silicon Age. Si is the cornerstone and workhorse of most semiconductor devices, although GaAs (gallium arsenide) is often used also. A semiconductor is only able to conduct electrical current with great difficulty, and only if sufficiently large voltages are applied. The reason for this is that crystalline materials only allow certain bands of energy for the electronic states of the material. A semiconductor is a material where all such bands up to a certain energy level are precisely filled, while the next available energy band is entirely void of charge carriers. A metal, on the other hand, is a material where the next available band is only partially filled. For a semiconductor to be able to carry an electrical current, an electron in the uppermost entirely filled band must be transferred up to the next available band where it can enter a state in which it can conduct electrical current without the associated current being compensated for by the motion of an electron in the opposite direction. This requires an energy transfer across the energy band gap of the semiconductor, and this in turn requires a minimum bias voltage to produce a measurably large current.



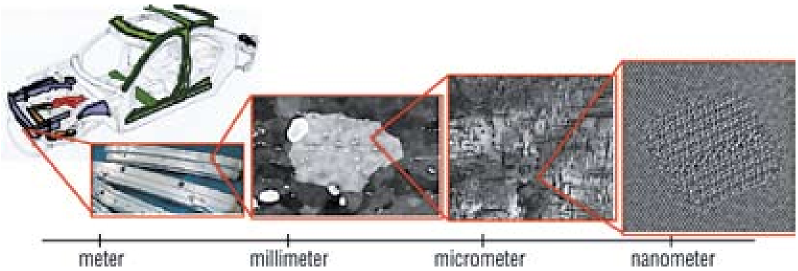
One may, however, improve the conducting properties of such semiconductors either by removing electrons from the top of the uppermost filled band or by adding electrons to the bottom of the next available energy band using atomic substitutions. The former is called hole-doping (giving a p-type semiconductor), the latter electron doping (giving an n-type semiconductor). Making a sandwich of a p-type and an n-type semiconductor will result in the principal structure of the transistor, which is nothing but a current valve. This principal is illustrated in the figure above.

The world's first operational transistor was made by John Bardeen, William Shockley and Walter Brattain at AT&T Bell Laboratories on 23 December 1947 (see illustration below). It was originally intended as a solid state amplifier, but today its role is almost exclusively as a current valve in Very Large Scale Integrated Circuits, where tens millions of transistors are etched by photolithography onto a few square millimetres on the Central Processing Unit of any personal computer. This is a very far cry from the current valves which were used in the first generation of electronic numerical integrators right after WWII (the number crunchers of that era). These early computers used bulky radio tubes as current valves.

The ENIAC at Princeton had a punching power many orders of magnitude less than any relatively ordinary PC today. It took up three full stories in an entire building, and consumed so much electrical power during the runs that the electrical power to households in the greater Princeton area had to be temporarily suspended. No wonder the market analysts at IBM estimated the worldwide need for such computers to be about five (5) at that time. *In short, the transistor is without a doubt the single most important invention of the 20th century.*



Among the metals, we must mention iron, copper and aluminium. From iron one obtained, perhaps entirely by accident, steel. Steel is an alloy of iron and carbon. Its carbon content ranges from a fraction of a per cent to a few per cent, depending on the grade of the steel. It has a history of 3000 years of development, and is the main material used in structures where tensile strength is of prime importance. Due to its low electrical resistivity and relatively low price, copper has been the mainstay material in current-carrying wires for years. In contrast to iron and copper, aluminium is a light metal and has become the material of choice in the automotive industry. The material has been refined to an extreme degree, an effort where Norway has been a pioneering country due to cheap hydroelectric power. As the picture below illustrates, material defects and impurities on a vast range of length scales ultimately determine the usefulness and strength of the material.



A novel class of materials currently emerging on the scene, and which will be of great importance in the future are the so-called bio-compatible functional materials. These can be a sort of substitute artificial body parts, as illustrated in the picture of the 'Bionic Man' to the left. He moves artificial limbs simply by thinking about moving them. In this context, bio-compatible nano-structures are also envisaged used in replacement or regrowth of teeth, ligaments, blood vessels, replacement heart valves and artificial kidneys, to mention a few examples.

Finally, to close the circle on our journey through time from

Stonehenge to present-day material technology, reference is made to Nanoelectromechanical Systems (NEMS). They can potentially improve our ability to measure small displacements and forces at the molecular scale, and of being used in intelligent nanoscale mechanical devices, such as nanoscale door hinges (nanohinges) that have actually been manufactured in Japan. The ability to make virtually any sort of moving mechanical device almost on the molecular scale, clearly opens new vistas in the human endeavour of making good use of Mother Nature.

References

Schulz, M. J., Kelkar, A. D. & M. J. Sundaresan (eds.): *Nanoengineering of Structural, Functional and Smart Materials,* Taylor & Francis (Boca Raton), 2006.