The weird world of the nanoscale

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The existence of atoms was proposed by Democritus in 430 BC but their properties and behaviour were largely ignored until the pioneering studies of John Dalton circa 1800. Since then of course, the behaviour of individual atoms and molecules, and of macroscopic aggregates of them, has been the subject of intense study. However, one area that was neglected until about 1990 was the behaviour of non-molecular structures constructed or synthesized from several dozens of atoms. This was despite the now famously prescient speculations of Richard Feynman on nanoscale devices in 1959 [1]. The reason for this omission was that the common tools of chemistry, such as the analytical balance, spectroscopy and X-ray diffraction, are not hugely useful when attempting to study the behaviour of matter arranged in structures with characteristic dimensions of the order of a few nanometers to a hundred nanometers. It is only recently that microscopy has routinely provided the means to characterize such objects. A particularly significant enabling technology has been the scanning probe microscope, the first example of which was only invented in 1981 by Gerd Binnig and Heinrich Rohrer [2].

Objects or structures which have at least one important dimension in the range 0.5 to perhaps 20 nm may be considered to be in the nano-scale domain. These sizes lie far below the 800 nm or so that can be resolved with an optical microscope, and are closer in size to the 0.3 nm diameter of individual atoms. Nanotechnology, which is the study and exploitation of these tiny structures, is attracting keen interest at present. The excitement is motivated by the observation that control of matter at the nanoscale holds the promise of offering faster computing, better medicines, and smarter materials. This optimism is based not only on a consideration of the tremendous miniaturization that can be implemented at this scale (the point which Feynman emphasized) but also, and perhaps more significantly, on the observation that matter at the nanoscale has quite different and interesting physical and chemical properties.

As far as metallic nanostructures and devices are concerned, these interesting phenomena may be most readily studied and exploited by making them out of gold. [3] This is because almost all other metallic elements will readily oxidize, which would normally destroy the operation of any metallic nano-scale device. Serendipitously, gold also has the advantage that it is readily fabricated into nanoscale structures with, for example, the techniques of both physical evaporation and aqueous chemistry being suitable.

In the bulk form, gold is a bright yellow metal, with the face centred crystal structure and a melting point of 1068°C. However, not one of these 'facts' necessarily applies at the nanoscale! First of all, light interacts rather differently with nano-scale metallic conductors, and gold nano-particles are not yellow, but instead have a colour varying from red to purple, depending on size. This is due to the phenomenon of plasmon resonance. In addition, gold nano-particles are not necessarily face centred cubic either, and in many cases adopt the non-crystalline icosahedral or decahedral structures [4].

These forms (Figure 1) have five-fold symmetry and are non-crystalline in the sense that they cannot be packed together to make macroscopic crystals.

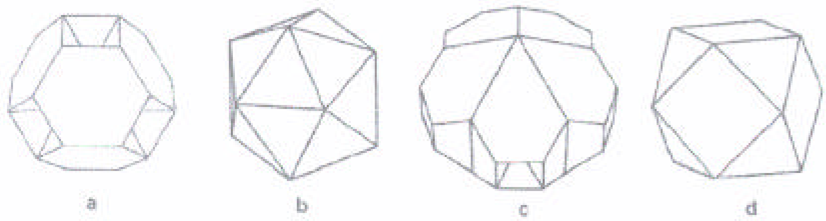

Figure 1. Some shapes of gold nano-particles, (a) truncated octahedron, (b) icosahedron, (c) Marks decahedron and (d) cuboctahedron.

Furthermore, the melting point of gold nano-particles is depressed from that of the bulk material, to such an extent that the melting point of particles of 2 nm diameter is only about 200°C [5] (Figure 2). Finally, gold structures at the bottom end of the nanoscale may, depending on shape and substrate, be semi-conductors with a significant band gap [6]. So, at the nanoscale, gold can be semi-conducting, purple, non-crystalline and perhaps even molten.

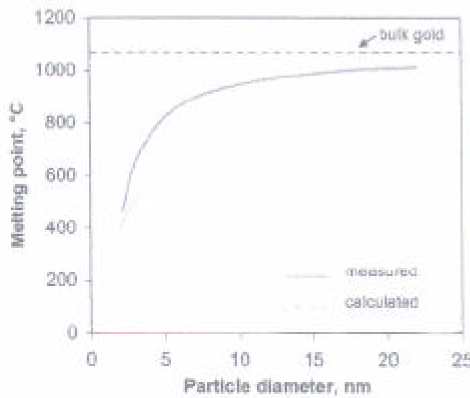

Figure 2. Melting point of gold nano-particles as a function of particle diameter.

These observations, which run somewhat contrary to everyday experience, are mirrored in the nanoscale properties of other diverse materials and devices. So aluminum can become magnetic [7] and the charge in electronic devices can tunnel from one part to another. It is these new properties and phenomena that the practitioners of this young field of nanotechnology seek to exploit.

References

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