IMPACT 12 …ON NANOSCIENCE: Quantum dots

Over the past few decades, *nanotechnology* has become a major area of research and technological development. Broadly speaking we can define this area as involving materials with dimensions in the range of up to 100 nm that can serve as building blocks for devices with unique physical properties. The economic impact of nanotechnology is already very significant. For example, increased demand for very small digital electronic devices has driven the design of ever smaller and more powerful microprocessors. However, there is an upper limit on the density of electronic circuits that can be incorporated into silicon-based chips with conventional fabrication technologies. As the ability to process data increases with the number of components on a chip, it follows that such chips and the devices that use them would have to become bigger if processing power were to increase further. One way to circumvent this problem is to fabricate devices from nanometre-sized components.

Ordinary bulk metals conduct electricity because, in the presence of an electric field, electrons become mobile when they are excited into closely lying empty energy levels. By ignoring all the electrostatic interactions, the electrons can be treated as occupying the energy levels characteristic of independent particles in a three-dimensional box. Because the box has macroscopic dimensions, eqn 7D.10 ($E_{n+1} - E_n = (2n+1)h^2/8mL^2$) implies that the separation between neighbouring levels is so small that they form a virtual continuum. Consequently, it is justified to neglect the effects of energy quantization on the properties of the material. However, in a *nanocrystal*, a small cluster of atoms with dimensions in the nanometre scale, eqn 7D.10 predicts that quantization of energy is significant and will affect the properties of the sample.

The quantization of energy in nanocrystals has important technological implications when the material is a semiconductor, in which electrical conductivity increases with increasing temperature or upon excitation by light. That is, transfer of energy to a semiconductor increases the mobility of electrons in the material. Three-dimensional nanocrystals of semiconducting materials containing 10–10^5 atoms are called **quantum dots**. They can be made in solution or by depositing atoms on a surface, with the size of the nanocrystal being determined by the details of the synthesis.

The energy required to induce electronic transitions from lower to higher energy levels, thereby increasing the mobility of electrons and inducing electrical conductivity, depends on the size of the quantum dot. The electrical properties of large, macroscopic samples of semiconductors cannot be tuned in this way. In many quantum dots, such as the nearly spherical nanocrystals of cadmium selenide (CdSe), mobile electrons can be generated by absorption of visible light and as the radius of the quantum dot decreases, the excitation wavelength decreases. That is, as the size of the quantum dot varies, so does the colour of the material. This phenomenon is observed in suspensions of CdSe quantum dots of different sizes.

The special optical properties of quantum dots can also be exploited. Just as the generation of an electron–hole pair requires absorption of light of a specific wavelength, so does recombination of the pair result in the emission of light of a specific wavelength. This property forms the basis for the use of quantum dots in the visualization of biological cells at work. For example, a CdSe quantum dot can be modified by covalent attachment of an organic spacer to its surface. When the other end of the spacer reacts specifically with a cellular component, such as a protein, nucleic acid, or membrane, the cell becomes labelled with a light-emitting quantum dot. The spatial distribution of emission intensity and, consequently, of the labelled molecule can then be measured with a microscope. Though this technique has been used extensively with organic molecules as labels, quantum dots are more stable and are stronger emitters of light.