

Chapter 1. Impact 3.1

Impact ... ON NANOSCIENCE: I3.1 Quantum dots

The future economic impact of nanotechnology could be 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 current fabrication technologies. As the ability to process data increases with the number of components in a chip, it follows that soon chips and the devices that use them will have to become bigger if processing power is to increase indefinitely. 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 easily excited into closely lying empty energy levels. By ignoring all the electrostatic interactions, we can treat the electrons as occupying the energy levels characteristic of independent particles in a three-dimensional box. Because the box has macroscopic dimensions, we know from eqn 9.12 that the separation between neighbouring levels is so small that they form a virtual continuum. Consequently, we are justified in neglecting energy quantization on the properties of the material. However, in a *nanocrystal*, a small cluster of atoms with dimensions in the nanometre scale, eqn 9.12 predicts that quantization of energy is significant and affects the properties of the sample. This quantum mechanical effect can be observed in ‘boxes’ of any shape. For example, the energy levels corresponding to spherically symmetrical wavefunctions of an electron in a spherical cavity of radius R are given by ¹

$$E_n = \frac{n^2 h^2}{8m_e R^2}$$

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 (see Topic 39 for a more detailed discussion). Three-dimensional nanocrystals of semiconducting materials containing 10 to 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.

First, we see that 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. Second, 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 indeed observed in suspensions of CdSe quantum dots of different sizes.

Because quantum dots are semiconductors with tunable electrical properties, there are many uses for these materials in the manufacture of transistors. 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 visual representation 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.

¹ This expression does not apply to solutions that are not spherically symmetrical; see our *Molecular Quantum Mechanics* (2011).

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