RESEARCH: QUANTUM DOTS

The Evidence of Small Things

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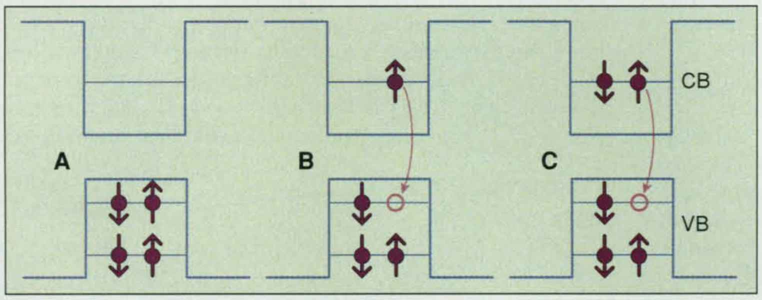
Semiconductor quantum dots are often described as solid state atoms: These objects are so small (10^3 to 10^6 nuclei) that, like atoms, their energy spectrum is discrete [see figure, panel (A)] (*1*). Unfortunately, size fluctuations in ensembles of quantum dots lead to fluctuations in energy and to broadened spectral lines. In response to this ubiquitous problem, researchers have developed techniques to selectively study individual quantum dots. As reported on page 262 of this issue, Landin *et al.* (*2*) accomplished this by reducing the density of quantum dots with special growth techniques to the point at which they could be individually probed with a microscope.



On the dot. Discrete energy levels derived from the valence (VB) and conduction bands (CB). The arrows denote spin. (**A**) Ground state: analogous to the ground state of a beryllium atom. (**B**) Radiative recombination of a single electron-hole pair: analogous to recombination from an atomic excited state. (**C**) Electron-hole pair recombination in the presence of an additional electron: analogous to a charged atom.

Other groups have used other combinations of sample preparation techniques and high spatial and spectral resolution to selectively probe individual quantum dots (*3*–*5*). Individual quantum dots have spectral linewidths that are reduced by orders of magnitude below those measured from inhomogeneously broadened ensembles. As a result of this remarkable improvement in spectral resolution, it is possible to measure directly phenomena that were previously hidden in the inhomogeneous linewidth. Effects such as fine structure splittings and hyperfine shifts due to the spin of the electron and the nuclei (*5*) as well as Zeeman splittings and Stark shifts due to magnetic (*4*–*6*) and electric fields (*7*) make striking analogs with atomic spectroscopy. The atom analogy has been broadened with demonstrations of quantum dot molecules (*8*), chains (*9*), and solids (*10*). The improvement in quality of optically active quantum dots and the capability to study individual quantum dots have brought the study of optically excited quantum dots up to a level comparable to that of quantum dots defined by electrostatic fields and studied through transport (*11*) and to that of individual molecular impurities in solids (*12*).

In a quantum dot, it is possible to excite optically many electrons and holes. The behavior of each of these excitations depends on all the others, and therefore the overall response of the quantum dot is modified in interesting and possibly useful ways. By probing individual quantum dots, Landin *et al.* took advantage of the narrow spectral lines and simplified spectra to study the power dependence of individual quantum dots (*2*). Starting in the low laser power regime where they measured the recombination of a single isolated electron-hole pair [averaged over many excitation-recombination events; see figure, panel (B)], they recorded the development of new spectral features very close in energy as the laser power was increased. The authors argue that these new spectral lines arise from complexes of electrons and holes in which a single electron-hole pair recombines, leaving behind various combinations of other electrons and holes [figure, panel (C)]. The spectral features are shifted in energy because of the change in interactions induced by these additional electrons and holes. The physics of such interactions is being studied in many quantum dot systems, and it will be an interesting challenge to understand the relationship between all these exciting new results (*3*, *13*).

The growth and spectroscopy studies of Landin *et al.* (*2*) and others on quantum dots provide the data we need to continue to develop our understanding, our techniques, and ultimately our predictive powers. Many research groups are looking into the possibility that quantum dots may offer advantages over other material systems as lasers, memories, and other useful devices. However, quantum dot technology is still in an embryonic state. The single biggest problem is the current difficulty in producing large numbers of quantum dots with precise sizes and positions. As materials are improved and optical techniques are further developed, spectroscopy of quantum dots will eventually compare in elegance with that obtained with atoms.

A provocative example is suggested by the sharpness of the spectral lines obtained from single quantum dots. Small homogeneous linewidths arise from long phase coherence times (*14*), which imply that it is feasible to manipulate optically not only the population of a single quantum dot state but also its phase. The optical control of the complete quantum mechanical wave functions of arbitrary combinations of individual electronic excitations in a quantum dot such as those measured by Landin *et al.* (*2*) would open up new possibilities in semiconductor physics and technology, including quantum logic (*15*). In general, with the improving quality of materials and the ability to probe optically individual quantum dots, if it can be done on atoms, perhaps it can be done on quantum dots, and we are led to envision what one could do with a highly controllable and flexible artificial quantum dot atom or more complex quantum dot structure.

References

1. *MRS Bull.* **23** (1998); U. Woggon, *Optical Properties of Semiconductor Quantum Dots* (Springer-Verlag, Berlin, 1997).
2. L. Landin *et al.*, *Science* **280**, 262 (1998).
3. K. Brunner *et al.*, *Phys. Rev. Lett.* **73**, 1138 (1994).
4. H. F. Hess, E. Betzig, T. D. Harris, Z. N. Pfeiffer, K. W. West, *Science* **264**, 1740 (1994); J.-Y Marzin *et al.*, *Phys. Rev. Lett.* **73**, 716 (1994); A. Zrenner *et al.*, *ibid.* **72**, 3382 (1994); M. Grundmann *et al.*, *ibid.* **74**, 4043 (1995).
5. D. Gammon *et al.*, *Science* **277**, 85 (1997), and references therein.
6. W. Heller and U. Bockelmann, *Phys. Rev. B* **55**, R4871 (1997).
7. S. A. Empedocles and M. G. Bawendi, *Science* **278**, 2114 (1997).
8. G. Schedelbeck *et al.*, *ibid.*, p. 1792.
9. Q. Xie *et al.*, *Phys Rev. Lett.* **75**, 2542 (1995); G. S. Solomon *et al.*, *ibid.* **76**, 952 (1996).
10. C. B. Murray *et al.*, *Science* **270**, 1335 (1995).
11. D. R. Stewart, D. Sprinzak, C. M. Marcus, C. I. Duruöz, J. S. Harris Jr., *ibid.* **278**, 1784 (1997); L. P. Kouwenhoven *et al.*, *ibid.*, p. 1788.
12. M. Orrit *et al.*, *Progress in Optics XXXV*, E. Wolf, Ed. (Elsevier, Amsterdam, 1996), p. 61.
13. R. J. Warburton *et al.*, *Phys. Rev. Lett.* **79**, 5282 (1997); M. Ikezawa *et al.*, *ibid.*, p. 3522; L. Efros and M. Rosen, *ibid.* **78**, 1110 (1997); M. Nirmal *et al.*, *Nature* **383**, 802 (1996).
14. D. Gammon, E. S. Snow, B. V. Shanabrook, D. S. Katzer, D. Park, *Science* **273**, 87 (1996).
15. A. Ekert and R. Jozsa, *Rev. Mod. Phys.* **68**, 733 (1996).

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