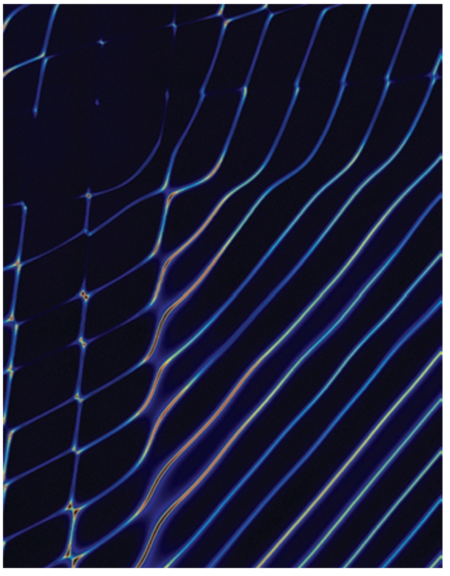
Join the dots

The properties of semiconductor quantum dots can now be controlled down to the level of single electrons and spins. These solid-state 'artificial atoms' have inspired scientists to look at them as possible building blocks for realizations of quantum computers, with unexpected consequences.

The development of scientific fields is notoriously hard to predict. However, few would argue against the notion that it is aided by the fruitful interplay between technological developments that make new experiments possible, and the new technologies that cutting-edge experiments inspire. The progress seen over the past decade or so in the study of semiconductor quantum dots is a case in point.

Widely studied since the 1990s because of their appealing electronic and photonic properties, quantum dots typically consist of several thousand atoms of a semiconducting material, such as gallium arsenide. The small size of these nanostructures results in a quantum confinement of the charge carriers (the electrons and the holes) that suppresses their motion in all three spatial directions. This gives rise to a quantization of the energy spectrum, with discrete energy levels reminiscent of the behaviour seen with electrons in atoms. Although the applications for these atom-like structures already range from diode lasers and light-emitting diodes to biomedical markers, the vision that has motivated much of the recent experimental and theoretical work on these systems is arguably more ambitious still, and places them as promising candidates for practical realizations of qubits for quantum information processing[1].

In this issue we explore the developments that have been made during the past 10 to 15 years regarding the materials, optical and transport properties of semiconductor quantum dots. As Richard Warburton notes in his Review[2], a quiet revolution has taken place. Breakthroughs in both fabrication and characterization techniques have made probing and manipulating the charge and spin states of individual electrons and holes in these structures routine. The level of precision and accuracy required to access and control single electrons and their spins is exquisite: the positioners and rotators developed by Attocube, an engineering company whose products are widely used by the quantum dots community, are accurate down to the nanometre and millidegree scales. To put this into context, the company is developing[3] similar mechanisms to help correct the laser-beam angles in the European Space Agency's New Gravitational wave Observatory (NGO, formerly known as the LISA mission)[4], which will consist of a giant laser interferometer with three measurement arms travelling between three spacecraft each at a distance of 5 million kilometres from each other.



Quantum dots allow a range of fundamental phenomena to be explored, such as the coupling of both the electron and the hole confined within a double dot, which can be controlled by applying suitable gate voltages[8]. Image reproduced from Gary Steele, Georg Gotz and Leo Kouwenhoven (cover image)[8], © 2009 NPG.

Although the initialization, manipulation and readout of individual electronic spins can now be carried out in a versatile and reproducible manner using optical techniques, a number of significant challenges remain if they are to be used as stable and reliable qubits. Perhaps the most significant of these is extending their coherence times. However, as Evgeny Chekhovich and colleagues make clear in their Review[5], achieving this requires a careful consideration of the interaction between the electronic spin and its surrounding environment consisting of several thousand nuclear spins, an issue known as the central spin problem. They survey the most significant effects of nuclear magnetism on the dynamics of a single electron or hole spin obtained through optical and transport experiments performed on single dots, as well as recent nuclear magnetic resonance experiments performed on small ensembles of nuclear spins.

The central spin problem also represents an opportunity for theoreticians to revisit an old issue from solid-state physics. As Hugo Ribeiro and Guido Burkard stress in their Commentary[6], the physics of the central spin problem is as rich as it is problematic, and researchers will need to find a way to tame and control the complex effects of nuclear spins. Of course, one way around this problem is to forego the presence of nuclear spins altogether and study so-called nuclear spin-free materials, such as carbon or silicon. This points to a materials science problem, in which the relative merits and shortcomings of different materials must be examined and understood to bring about further developments. Indeed, as Joaquín Fernández Rossier reports from the MRS Spring Meeting in San Francisco[7], it is clear that scientists now have the luxury of choosing between a wide range of material systems to study the dynamics of individual spins.

By addressing some of the most challenging problems in pure and applied physics in tandem, there is no doubt that the study of quantum dots has led to large strides in the fields of condensed-matter and mesoscopic physics more generally. The ultimate goal of the quantum computer remains elusive, but by giving scientists a taste for solid-state qubits, quantum dots will continue to inspire them as they attempt to realize their vision for the future. Joining the dots together will hopefully lead to something that will become a lot more than the sum of its parts. ❐

References

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