QUANTUM COMPUTING

Fine lines from dots

Quantum dots are candidates for quantum computing applications, but the coherence time of their quantum states must be improved. Recent optical measurements on single quantum dots indicate that the local environment plays a large role.

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A quantum computer requires a quantum system that can be set in particular states, manipulated in controlled ways, and read out reliably — a simple enough idea, but hard to put into practice. Semiconductor quantum dots have been proposed as building blocks for quantum logic devices[1]. These dots are confined systems with discrete electronic states, and are therefore often referred to as 'artificial atoms'. Like atoms, quantum dots can be excited optically. But, unlike atoms, which can be completely isolated from their surroundings, quantum dots interact with their environment. The interactions result in a loss of coherence ('dephasing') of the optically excited states in the quantum dots, and can therefore lead to the erasure of any carefully prepared quantum information. For quantum-dot logic devices to be successful, it is crucial to determine the dephasing time and the factors influencing it. Reporting in *Applied Physics Letters* and *Physical Review B*, Kammerer *et al.* study the effect of the local environment on the dephasing time of the optical emission from a single InAs/GaAs quantum dot[2,3]. Their results show clear evidence for dot-to-dot variations of the dephasing times. Moreover, they were able to link the variations to the extent to which the quantum dots were energetically isolated from their environment.

Quantum dots are formed in regions of the semiconductor that have lower potential energy than their surroundings. This three-dimensional quantum confinement results in a series of discrete electronic states for both electrons and holes. Kammerer and co-workers studied 'self-assembled' InGaAs/GaAs dots, which arise from the reduction of strain energy during growth of an epitaxial InGaAs layer that is not lattice-matched to the GaAs crystal below. The growing layer clumps into many dots of reasonably uniform size sitting in a residual 'wetting layer'. This wetting layer permits free motion of the charge carriers in the regions between the dots (Fig. 1a). Another type of dot arises in narrow quantum wells. During growth, steps form at the quantum well interfaces, leading to the formation of large, flat quantum dots (Fig. 1b). An important point is that, in each of these systems, the quantum dot electronic states are in the presence of a background of two-dimensional states in the wetting layer or quantum well.

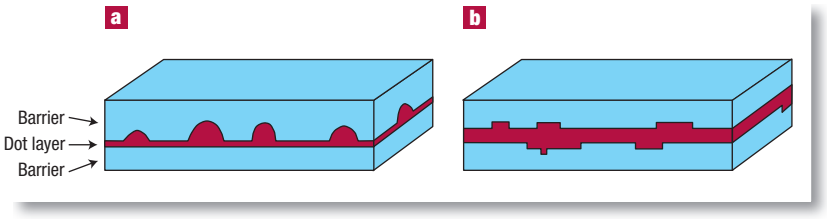
Although it is possible to measure directly the dephasing time T_2 of excitons (correlated electron–hole pairs) in these dots, it is often easier to determine the dephasing time through measurement of its spectral equivalent, the homogeneous linewidth ($\Gamma = 2\hbar/T_2$). But measuring this linewidth is not without complications of its own. For a start, the measurements require optical excitation of just a few dots ('micro-photoluminescence') in order to overcome the spectral broadening that results from variations in size of a large number of dots. Microphotoluminescence measurements are usually achieved by patterning the sample into submicrometre pillars containing just a few dots each. In addition, because the dephasing time cannot be greater than the time that it takes for the excitons to recombine radiatively (the 'radiative lifetime'), a relatively high spectral resolution is often required. For example, excitons in self-assembled dots have typical radiative lifetimes of ~1 ns, resulting in homogeneous linewidths down to ~1 μeV. Moreover, the presence of trapped charges in the material surrounding the quantum dot may temporarily shift its emission energy[4] — a phenomenon known as 'spectral diffusion'. If many such shifts occur over the time taken to record a spectrum, the quantum dot emission will be artificially broadened, resulting in a spectral linewidth that merely sets an upper limit[5] to the actual linewidth.

These problems have recently been overcome by the use of more complex nonlinear techniques, such as four-wave mixing[6]. Four-wave mixing experiments have revealed dephasing times of a few hundred picoseconds (equivalent to a linewidth of a few μeV) for an ensemble of self-assembled quantum dots at low (~6 K) temperature[5,7]. This dephasing time is close to the limit given by the radiative lifetime of the excitons. But difficulties arise when attempting to apply this

third-order nonlinear technique to single quantum dots. Four-wave mixing experiments have consequently only been conducted on dot ensembles, thereby averaging over the dephasing times of a large number of dots.

Kammerer *et al.* have addressed these issues by using an interferometric technique, combined with a standard microphotoluminescence set-up. In their experiments, photoluminescence collected from a few self-assembled quantum dots was passed through a Michelson interferometer and a spectrometer centred on the luminescence line of a single dot. By interfering the luminescence of the single dot with itself, they obtained a direct measure of the coherence of the emitted light, and therefore of the excited state of the dot. Using this technique, the researchers were able to determine the dephasing times of several single self-assembled quantum dots contained on a submicrometre-sized pillar[2]. They demonstrate that the dephasing time in self-assembled quantum dots is strongly influenced by interactions between carriers in the dots with states in their local environment.

In general, the most important interaction that can upset the coherence of the quantum system is scattering involving low-energy lattice vibrations (termed 'acoustic phonons'). The discrete electronic spectrum of the quantum dots should ensure that only a very small fraction of the acoustic phonons can interact with the electronic states. This acoustic phonon scattering is therefore expected to be much less efficient for quantum dots than for quantum wells or bulk material[8]. Kammerer *et al.* found that, for those quantum dots that were well isolated from the wetting layer, acoustic-phonon scattering was indeed strongly suppressed. But dots with electronic states that lay close in energy to the wetting layer states were much more affected by phonon scattering. It seems that the presence of the wetting layer states provides an efficient pathway for acoustic-phonon scattering, and adversely affects the dephasing time in quantum dots.



These findings should lead to a greater understanding of how to tailor the growth parameters to achieve long dephasing times in semiconductor quantum dots. As an example, the authors showed that increasing the indium content in an $In_xGa_{1-x}As$ dot layer results in a reduction of acoustic-phonon scattering because of the formation of a thinner wetting layer, whose states are energetically well-separated from those of the dots[3].

Although these results may lead to a sufficient suppression of dephasing at low temperature, one substantial obstacle remains. At temperatures greater than a few tens of kelvin, carriers inside a quantum dot may scatter into the higher-energy states by interacting with high-energy lattice vibrations known as optical phonons. This interaction leads to very fast exciton dephasing, thus making it impossible to store quantum information for significant lengths of time. Unless this fundamental problem can be overcome, any quantum computation scheme based on quantum dots will be limited to operation at cryogenic temperatures.

Figure 1 Two common types of semiconductor quantum dots. **a**, Stranski–Krastanow (self-assembled) dots, which form to reduce the strain energy during epitaxial growth of a layer that is not lattice-matched to the crystal below. The resulting dots are embedded in the residual 'wetting layer' (typically a few monolayers thick), in which carriers are confined to the plane of the layer. **b**, Narrow quantum wells (a few nanometres wide) show monolayer steps that may lead to localization of excitons in all three dimensions. Typical barrier/dot layer materials are $GaAs/In_xGa_{1-x}As$ for type **a** and $Al_xGa_{1-x}As/GaAs$ for type **b**. Advantages of self-assembled dots over those formed in narrow quantum wells are the higher dot densities and significantly longer exciton lifetimes.

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