Structural analysis of strained quantum dots using nuclear magnetic resonance

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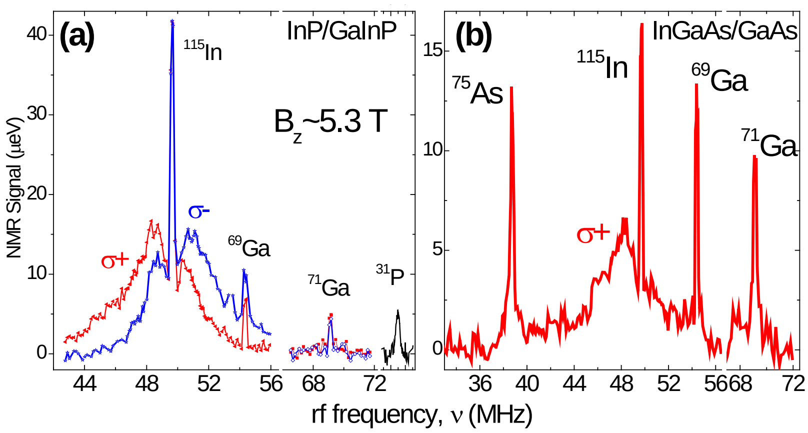
Strained semiconductor nanostructures can be used to make single photon sources, detectors and photovoltaic devices, and could potentially be used to create quantum logic devices. The development of such applications requires techniques capable of nanoscale structural analysis, but the microscopy methods typically used to analyse these materials are destructive. Nuclear magnetic resonance (NMR) techniques can provide non-invasive structural analysis, but have been restricted to strain-free semiconductor nanostructures due to significant strain-induced quadrupole broadening of the NMR spectra. In our work we show that optically-detected NMR spectroscopy can be used to analyze individual strained quantum dots. Our approach uses a continuous-wave broadband radio frequency excitation with a specially designed spectral pattern and can probe individual strained nanostructures containing only 10^5 quadrupole nuclear spins [1]. With the technique, we are able to measure the strain distribution and chemical composition of the quantum dots in the volume occupied by the single confined electron. In our method, all this information is obtained in a non-invasive fashion enabling direct link with the optical properties of the dot to be established.



Optically detected NMR spectra in single InP/GaIP (a) and InGaAs/GaAs (b) quantum dots.

Our optically detected nuclear magnetic resonance (ODNMR) technique is used to examine two different types of strained semiconductor nanostructures: self-assembled InP/GaInP and InGaAs/GaAs quantum dots grown at the EPSRC National Centre for III-V technologies. NMR spectra of strongly strained materials, as present in self-assembled QDs, normally extend to up to 20 MHz, leading to severe reduction in sensitivity of saturation NMR. In our work we develop a new method, so-called “inverse” NMR, leading to very major enhancement in the sensitivity of ODNMR. We use broad band excitation with a continuum spectrum containing a gap of width ω_{gap} defining the frequency resolution of our experiment. The figure above shows “inverse” ODNMR spectra measured on single InP (a) and InGaAs (b) quantum dots at $B_z \approx 5.3$ T. In the nominally InP dots grown in GaInP barriers, the "inverse" technique allows contributions from quadrupole nuclei ^{115}In, ^{69}Ga and ^{71}Ga to be resolved. Very strong In/Ga intermixing is also found in nominally InAs/GaAs QDs in (b). By reducing the gap width ω_{gap}, NMR features with widths below 10 kHz have been resolved.

The applications of these new techniques are not limited to single QDs only and also extend far beyond conducting the structural analysis of nano-structures. For example, in our recent studies selective rf excitation was used to carry out element-sensitive measurements of the hole hyperfine interaction [2], an important contributions to the fields of spintronics and quantum computing.

[1] E. A. Chekhovich, K. V. Kavokin, J. Puebla, A. B. Krysa, M. Hopkinson, A. D. Andreev, A. M. Sanchez, R. Beanland, M. S. Skolnick, A. I. Tartakovskii, Nature Nanotechnology **7**, 646 (2012).
[2] E. A. Chekhovich, M. M. Glazov, A. B. Krysa, M. Hopkinson, P. Senellart, A. Lemaître, M. S. Skolnick, A. I. Tartakovskii, Nature Physics **9**, 74 (2013).