Spin coherence in a semiconductor quantum dot

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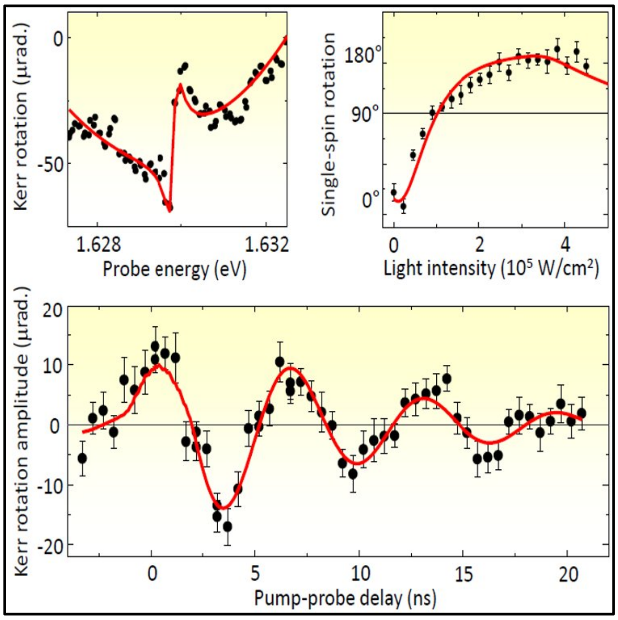
The promise of spintronics to enabe super-fast quantum computers and truly secure communication is tantalizing – yet far away. Recent advances allowing an individual electron spin to be manipulated ultrafast using optical pulses brings this dream one step closer to reality.

For spin-based electronics, information is carried by the electron spin instead of the electron charge like in standard electronics. The spin degree of freedom has the advantage of being a quantum property so that, in addition to the states “up” and “down” (corresponding to “0” and “1” in traditional electronics), it may be in any superposition of the two. This means such a bit could store a vast amount of information, and is referred to as a “quantum bit” or “qubit.” For these spin-states to be useful for applications, one must be able to set it to a desired value (initialization) as well as detect and change this value. Furthermore, all of this must be possible at a very fast time scale before the spin-information is lost due to interactions with its surroundings (coherence time). With a recent set of experiments we have demonstrated how a promising qubit candidate – a single electron spin confined in a semiconductor quantum dot – can be initialized, manipulated and detected at ultrafast time scales.



Single electron spin dynamics. (a) Characteristic Kerr rotation feature indicating a single spin-polarized electron. (b) Single spin precession in a magnetic field. Kerr rotation amplitude refers to the height of the feature in (a). (c) Single electron spin rotation as a function of intensity of the control pulse. Adapted from Ref. [1]-[3].

In these experiments, circularly polarized light we used to excite a spin-up electron. In an applied magnetic field the spin rotates between spin-up and spin-down (precession) at a speed proportional to the strength of the magnetic field. The oriented spin causes a tiny effective local birefringence, meaning right and left circularly polarized light propagates at slightly different speeds in the material. This can be detected as a rotation of the polarization of linearly polarized light upon reflection off the sample and is the main principle of Kerr rotation. Remarkably, we have extended this technique to detect the polarization of an individual spin, using first a time-averaged method (Fig. 1a), and later a time-resolved (Fig.1b) version, directly revealing the spin dynamics [1,2].

The challenge of performing a large number of qubit operations within the observed 10ns spin coherence time was addressed using short optical pulses that induce spin rotations. The effect at the heart of the action is the optical Stark effect. Here, an intense optical pulse with energy below, but very close, to an optical transition, actually alters the energy of this transition – a level repulsion of sorts. Due to optical selection rules, circularly polarized light only alters the energy level of one of the spin states. The resulting difference in energy levels of the two spin states equals a large effective magnetic field up to ~10 tesla. The electron spin was observed to make a full 180 degree rotation despite the fact that the field was only present for 30 ps – the duration of the optical pulse. The spin rotation was reliably controlled by varying the intensity of the optical pulse, see Fig. 1c, [3]. This technique can readily be extended to use shorter and more intense optical pulses, allowing for ~10,000 operations within the coherence time as required for implementations of error-correction schemes.

These studies provide both valuable insights into the fundamental dynamics of single spin behavior and are a crucial step towards all-optical spin-based qubits integrated into advanced solid state and photonic networks.

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[3] J. Berezovsky, M. H. Mikkelsen, N. G. Stoltz, L. A. Coldren & D. D. Awschalom. *Picosecond Coherent Optical Manipulation of a Single Electron Spin in a Quantum Dot.* Science **320**, 349 (2008).

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