COHERENT POPULATION TRAPPING

Quantum optics with dots

The ability to optically drive a single electron spin confined to a quantum dot from an absorbing state to a trapped coherent dark state could be the key to realizing optical switches and other quantum optical devices.

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Quantum dots are small semiconductor islands of nanometre size and are formed by tens to hundreds of thousands of atoms. Although this ‘atomic background’ represents a complex potential landscape to a conduction electron injected into a quantum dot, its behaviour can be described quite well by a simple particle-in-box model. Owing to their small size, the electronic structure of a quantum dot consists of discrete energy levels, similar to that of an atom. As such they are often referred to as artificial atoms. But unlike atoms, their behaviour can be tailored by changing their composition and physical shape. Much of the research of the last two decades into quantum dots has focused on better understanding the confined energy states of electrons and holes within them. But recently, attention has shifted to exploiting their quantum nature for practical applications. To end, on page 692 of this issue, Xu and colleagues demonstrate an inherently quantum mechanical effect known as coherent population trapping — seen in a few systems but not previously in quantum dots — that could help unlock such potential.

The demonstration by Xu et al. begins with an individual quantum dot charged with a single electron. The electron sits in the ground state of the conduction band after controlled injection through a diode structure. The state of the electron can be tested by optical absorption spectroscopy, in which the photon energy of a laser is scanned over a range such that it may excite an additional electron from the valence band ground state to that of the conduction band. The Pauli principle dictates that such excitation is only possible if the two electrons resulting from this absorption have antiparallel spins, forming a singlet state. This requires suitable polarization of the exciting laser light. The electron that is removed from the valence band leaves behind a missing negative charge, which can be described as a positively charged hole. The two electrons and the hole interact through Coulomb interactions and form a negatively charged ‘trion complex’.

Realizing coherent population trapping requires a system of three discrete energy levels. Such a structure is known as a lambda system, owing to the fact that its schematic representation is reminiscent of the Greek letter lambda (see Fig. 1). The two lower energy levels are obtained by splitting the electron spin state by an external magnetic field through the Zeeman effect, the spin orientation of the two resulting states being parallel and antiparallel, respectively, to the applied field. The spin relaxation between these two spin states is strongly suppressed, so that they are stable and long-lived. For the uppermost state of the lambda system, the researchers have chosen a trion state with a particular spin orientation of the hole that occupies it. This state decays on a timescale of a nanosecond by relaxation of one electron from the conduction band into the valence band, during which a photon of corresponding energy is released and one electron is left behind, just as in the initial state before excitation.

To manipulate this system, the authors use two different wavelength, continuous-wave laser fields whose polarizations have been chosen specifically for their particular lambda system (see Fig. 1). One laser (the so-called probe laser) is resonant with the transition from the electron with parallel spin-state to the trion state, the other
laser (the drive laser) is resonant with the transition from the antiparallel spin-state to the trion. If the electron is initially in the parallel spin-state and the probe laser is turned on, it will be excited to the trion state, from where it can subsequently decay to the antiparallel spin state. Consequently, after several pumping cycles, the electron should eventually transfer to this stable antiparallel spin-state.

At this point, if nothing else is done to the system, the electron should remain in the antiparallel state. But if the drive laser is then turned on, it should, simply speaking, be able to excite the electron back up to the trion state from where it can again relax back to the parallel state. More significantly, if both lasers are switched on and tuned so that their electric field strengths are about equal, and so that both are in exact resonance with their respective transitions, their effects can be made to exactly cancel each other; that is, the fields generate destructive interference of the two transitions so that no absorption of the probe laser is observed. This in turn puts the system into a quantum mechanical superposition of the parallel and antiparallel spin states. This state is referred to as a trapped dark state, as it cannot be accessed by the applied optical fields.

Moreover, by varying the strength of the two applied lasers, the weight of the two spin states in this superposition can be precisely controlled, enabling the electron spin to be prepared in a well-defined quantum state. This in turn enables the state to be reliably initialized, which is an important prerequisite for the use of such systems in quantum information processing. Indeed, owing to their long decoherence times, quantum dot electron spins are currently considered to be one of the most promising candidates for realizing qubits3,4.

The results by Xu et al. demonstrate that quantum dots loaded with a single electron spin may be a basic building block for high-quality quantum hardware, through which various quantum effects can be implemented in practical applications. Besides quantum information processing, the ability to realize coherent population trapping opens many other possibilities. It is an important step towards the demonstration of quantum optical phenomena such as Rabi-splitting of an electron spin. Coherent population trapping is also the basis for generating electromagnetically induced transparency5 for high-speed optical switching, or slow light6 phenomena for high fidelity and efficient data transmission — both of intense interest in the field of optical telecommunications.

References