Spin-based quantum information processing in Grenoble

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The use of spin degrees of freedom in solid-state devices is deemed to be one of the most promising options for a practical realization of quantum processors. All the basic quantum operations have been demonstrated in different semiconductors such as Si and GaAs (single-qubit and two-qubit gates), and Grover quantum algorithm has been solved using molecular spin qubits. In the case of Si, a clean spin environment could be obtained by using isotopically purified ^{28}Si. It results in extremely long relaxation and coherence times, compatible with fault tolerant quantum computation. The next effort now concentrates on how to integrate a large number of spin qubits and how to interface them with photons.

Grenoble research activity is well known for the investigation of magnetism since the early 50's. This research effort aggregates a wide community interested in the fundamental magnetic properties of smaller and smaller objects and their possible technological applications. It results in the acquisition of an important expertise and know-how on magnetic materials science, nanofabrication protocols, cryogenic techniques, optical and transport probing techniques, circuit designers, theoretical modelling. Grenoble gathers a recognized spintronics community with a start-up company (CROCUS) and hosts a strong expertise in Si-based microelectronic technology, with worldwide recognized actors like LETI and STMicroelectronics.

Important efforts in Grenoble are directed to investigating the quantum properties of spin based solid-state devices such as molecular-magnet systems (Fig. 1) and semiconductor quantum-dot spin qubits probed with both transport (Fig. 2 and 3) and optical techniques (Fig. 4). Several ground-breaking achievements make Grenoble a reference research pole in the quantum spintronics domain.

Spin-based quantum information processing in Grenoble addresses the following challenges:

1. **Optical interface in isotopically purified semiconducting material with direct band gap.** We want to use II-VI materials, where zero nuclear spin isotopes are accessible. A strong expertise already exists in Grenoble on this class of semiconducting materials.
2. **Fault tolerant scalable quantum architectures based on Si semiconducting spin qubits.** We will take advantage of a large consortium between academic research institutions and R&D laboratories to develop complex structures combining state-of-the-art microelectronics technology and quantum functionality.
3. **Chemically engineered molecular systems for spin-based quantum computing.** Grenoble is a world leader in the exploration of molecular systems for spin based quantum computing. The versatility of chemistry is an asset towards the engineering of the perfect environment for the spin. Their incorporation in more complex integrated circuits is the next important challenge.

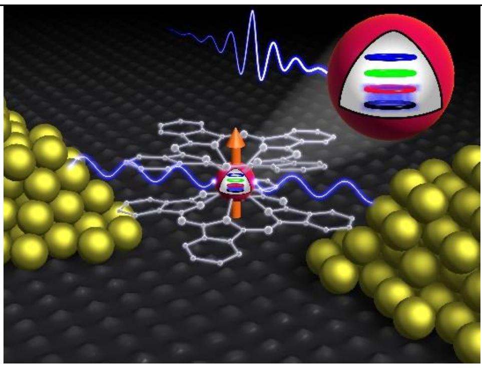

Fig. 1: **Coherent control of the individual nuclear spin of a molecular magnet.** The four anisotropic nuclear spin states of the Tb^{3+} can be tuned and manipulated with electric fields and detected via one-shot electronic read-out.[1]

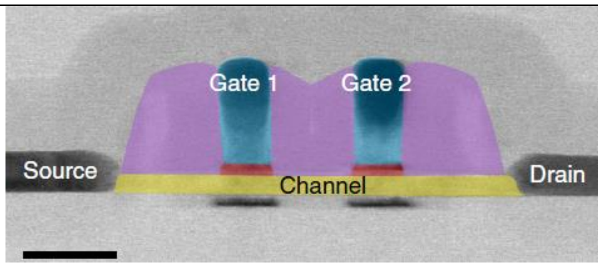

Fig. 2: **A spin qubit in a CMOS-Si-transistor** where individual electrons are trapped underneath each gate.[2] (scale bar=50 nm)

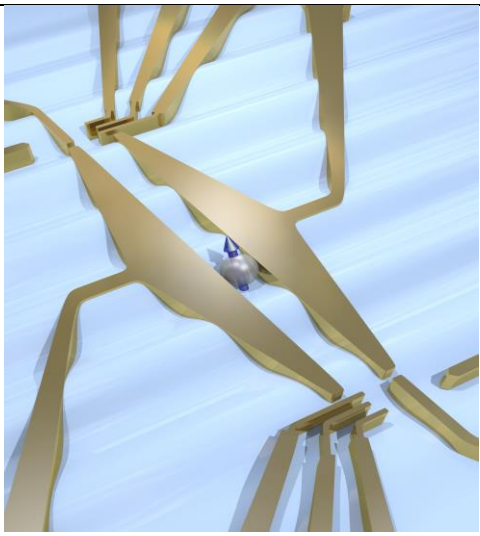

Fig. 3: **On-demand displacement of a single electron spin.** A single electron spin, trapped initially in the left quantum dot, is propelled by a sound wave towards the second quantum dot, at a distance of 4 microns.[3,4]

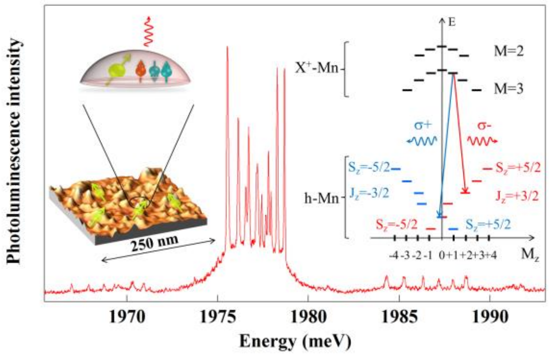

Fig. 4: **Optical control of an individual Mn atom in a semiconductor quantum dot.** The optical absorption and emission of the quantum dot are exploited to initialize and to read out the spin state of the magnetic atom.[5]

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[1] Electrically driven nuclear spin resonance in single-molecule magnets, S. Thiele, F. Balestro, R. Balou, S. Klyatskaya, M. Ruben and W. Wernsdorfer Science **344**, 1135 (2014).

[2] A CMOS silicon spin qubit, R. Maurand, X. Jehl, D. Kotekar Patil, A. Corna, H. Bohuslavskyi, R. Laviéville, L. Hutin, S. Barraud, M. Vinet, M. Sanquer, S. De Franceschi Nature Communications 7, Article number: 13575 (2016).

[3] Electrons surfing on a sound wave: an experimental platform for quantum optics with flying electrons, S. Hermelin, S. Takada, M. Yamamoto, S. Tarucha, A. D. Wieck, L. Saminadayar, C. Bauerle and T. Meunier, Nature (London) **447,** 435 (2011).

[4] Quantum manipulation of two-electron spin states in isolated double quantum dots, B. Bertrand, H. Flentje, S. Takada, M. Yamamoto, S. Tarucha, A. Ludwig, A. D. Wieck, C. Bauerle and T. Meunier, Phys. Rev. Lett. **115**, 096801 (2015).

[5] Resonant optical control of the spin of a single Cr atom in a quantum dot, A. Lafuente-Sampietro, H. Utsumi, H. Boukari, S. Kuroda, L. Besombes. Physical Review B **95**, 035303 (2017).