Quantum Sensors: Magnetic Resonance at the Nano-Scale

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Quantum mechanics governs physical phenomena. Yet, classical laws describe objects and devices we use in everyday life. Where does the practical boundary between quantum and classical world lie? More importantly, what benefits would we obtain if we could push it closer to the scales of human devices? Improving the control over quantum systems while understanding the mechanisms that destroy their quantumness holds the keys to answering these questions. My research efforts aim at exploring the limits of quantum control. The goal is to build quantum devices, such as computers and simulators, that can outperform their classical counterparts.

A particularly promising application area for quantum devices is in precision sensing. Solid-state quantum sensors may enable unprecedented combination of sensitivity and spatial resolution due to the availability of nano-scale devices.

A major breakthrough has been our proposal to use Nitrogen-Vacancy (NV) centers in diamond [1] as magnetic field sensors [2]. The NV center consists of a single electronic spin that can be polarized and read out optically and controlled by magnetic resonance techniques. NV centers can be used for magnetic field imaging in ensembles, as magnetic scanning tips or even as fluorescent bio-markers in-vivo, sensitive to local magnetic fields.

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**Diamond-based magnetometer for in-vivo detection of neuronal activity.** Center image: schematic of the NV-magnetometer. A neuronal network is grown on a diamond slab, thanks to its bio-compatibility. NV color centers (red dots) are implanted in the diamond. When illuminated by green laser, the NV centers fluoresce in the red. Light from one (or few) NV is collected in individual pixels of a CCD camera (not pictured). The light intensity carries information about the NV spin state, which in turns is determined by the magnetic field produced by the neurons. The magnetic field is measured with high sensitivity, thus performing a nano-scale functional MRI of the neuronal network. 

**A:** confocal image of a single NV, showing high photoluminescence (PL) counts at the NV location.  
**B:** optically detected magnetic resonance of a single NV, showing transitions to the $m_s=1$ levels. The energy difference between the two levels $m_s=1$ is set by the external magnetic field one wishes to measure. By varying a microwave excitation field frequency it is possible to monitor the energy splitting and thus the magnetic field. The energy levels involved in the magnetometry scheme are shown in **D**, while panel **C** shows the sensitivity achievable by a single-NV magnetometer for constant (DC) or AC magnetic field. Quantum control techniques (CPMG) we proposed considerably improve the sensitivity.
A NV-based magnetometer could sense individual electronic and nuclear spins in biological specimens and allow unraveling molecular structure and functionality at the single bio-molecule level. Moreover, NV ensembles could detect magnetic fields generated by ionic activity in neurons. Real-time monitoring of functional activity in complex neuronal networks could lead to breakthroughs in understanding how microscopic connectivity affects macroscopic, whole brain functions. After the first proof-of-principle experiment [3], I am currently working to address major challenges that hinder these quantum sensors from reaching their full potential: the fragility of entangled states [4-6], decoherence [7-9] and low fidelity of readout [10].

References


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