Magnetic imaging of spin waves and magnetic phase transitions with nitrogen-vacancy centers in diamond

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Summary

The elementary excitations of magnets are called *spin waves*, and their corresponding quasi-particles are known as *magnons*. The rapidly growing field of *Magnonics* aims at using them as information carriers in a new generation of electronic devices, (almost) free of electric currents. Encoding information in the amplitude and/or phase of these coherent waves could lead to a drastic decrease in dissipated power, typically related to the motion of electrons ("Joule" or "Ohmic" heating).

This dissertation describes the development and use of a new technique to study spin waves. This technique uses the electronic spins associated with nitrogen-vacancy (NV) centers as magnetic field sensors. An NV center is a light-emitting defect in the crystal lattice of diamond. Remarkably, the brightness of its emission depends on its spin state, sensitive to magnetic fields. This way, magnetic information can be investigated optically.

The aforementioned field of *magnonics* is described in Chapter 1, where we discuss its large potential for technological innovation, that in turn leads to several research directions and the development of magnetic imaging techniques. In Chapter 2 we present the structural, electronic and optical properties of NV centers and introduce the NV-based experimental techniques that are used throughout this thesis to sense static and oscillating magnetic fields.

In Chapter 3, we present a theoretical treatment of spin waves that encompasses deriving their dispersion from the equations of magnetization dynamics (Landau-Lifshitz-Gilbert equation). We then show the equations that govern the inductive excitation of spin waves (relevant to chapter 4-5), and the stray magnetic fields they generate, stepping stone for understanding the NV-based measurements of spin waves.

In Chapter 4 we establish a technique for imaging coherent spin waves via their magnetic stray field with phase sensitivity. This relies on the interference between the spin-wave field and the homogeneous field of an additional antenna, which are of the same frequency and phase-locked, such that their interference is stationary. This way, we can image the amplitude of spin waves resonant with the NV spin. Having knowledge of the auxiliary field allows to reconstruct the spin-wave field, such that in model configurations we can measure the spin-wave amplitude quantitatively.

Using the developed technique and its "see-through" capability, in Chapter 5 we image spin waves propagating underneath metallic electrodes and quantify the additional damping these cause. This phenomenon is relevant for devices in which spin-wave excitation, control and detection are achieved via metallic gates. We reveal a 100-fold in-

crease in spin-wave damping and show that this matches the effective damping calculated by including the eddy currents field into the LLG equations self-consistently.

In Chapter 6 we focus on thermally-excited spin waves and characterize the spectrum of the magnetic noise they generate via NV relaxometry - which involves preparing the NV spin in a determined state and measuring its decoherence over time. Such noise is related to the excitations of the system via the fluctuation-dissipation theorem. The results are well matched by a theoretical model based on the chiral coupling between spin-wave fields and NV spin. However, we find surprising discrepancies at the ferromagnetic resonance frequency, which suggest the presence of inhomogeneities in the system.

NV centers are excellent local probes of magnetic fields. One challenge related to the *locality* of the results is how to effectively quantify properties that are inherently *global*, such as the temperature of a phase transition. In Chapter 7 we show that a possible answer to this challenge is provided by the use of statistical analyses to quantify spatial correlations. We employ these methods to study the temperature-driven metamagnetic (i.e. from antiferromagnetic to ferromagnetic) phase transition of the metallic alloy FeRh. We image the nucleation, growth, and coalescence of magnetic domains, and find evidence that suggests the presence of a domain reorientation across the phase transition.