

Chapter 1

Introduction

Recent remarkable progress in magnetic resonance imaging (MRI) naturally raises the question about the ultimate possibility for atomic scale MRI resolution (single spin detection). However, the MRI techniques are based on the phenomenon of electromagnetic induction, which implies the detection of a macroscopic number of spins. The minimum number of nuclear spins detected by MRI techniques is about 10^{12} [1], and the minimum number of electron spins detected using electron spin resonance (ESR) techniques is about 10^7 [2]. To resolve the problem of a single spin detection Sidles [3, 4] suggested using the force detection techniques like those used in atomic force microscopy (AFM). However, the magnetic force is much smaller than the electric force detected in AFM. In order to overcome this difference Sidles proposed a combination of magnetic resonance techniques for a single spin with the mechanical resonance of an ultrasensitive cantilever.

According to this idea, a ferromagnetic particle attached to the cantilever tip (CT) will experience a magnetic force produced by a single spin. If the frequency of the spin oscillations matches the resonant frequency of the cantilever vibrations, the spin force will amplify the cantilever vibrations, which can be detected, for example, by optical methods. This method of a single spin detection was labeled magnetic resonance force microscopy (MRFM).

The idea of MRFM quickly attracted the attention of experimentalists.

Soon, the MRFM techniques were implemented by Rugar *et al.* in ESR [5] and nuclear magnetic resonance (NMR) [6], and by Zhang *et al.* in ferromagnetic resonance (FMR) [7]. Finally, in 2004, 13 years after the proposal of MRFM, Rugar *et al.* [8] announced the first detection of a single electron spin below the surface of a non-transparent material (vitreous silica), using a modified MRFM technique.

The authors of this book believe that MRFM will find many important applications in physics, chemistry, biology and medicine. Consequently we decided to write this book to explain the basic ideas of MRFM and some theoretical approaches used to describe the MRFM techniques for readers with a variety of backgrounds. We were fortunate to take part in the development of the MRFM theory, and our book is based mainly on research in which we directly participated.

The book is organized as follows. In Chapters 2–4, we give the basic information about the classical and quantum description of magnetic resonance and quantum theory of a simple harmonic motion. These chapters are written for a reader who is not familiar with magnetic resonance or coherent states in quantum mechanics but who wants to understand the theoretical approaches used in MRFM. In Chapters 5 and 6, we consider the detection of a single spin using magnetic force microscopy (MFM) without magnetic resonance. The experimental implementation of a single spin MFM is beyond current experimental capability. However, from the theoretical point of view MFM is much simpler than MRFM. In particular MFM allows us to obtain the exact analytical solution for the master equation which is impossible for MRFM. Thus, the theory of a single-spin MFM allows one to understand the spin-cantilever system. In Chapter 7, we describe one of the simplest MRFM techniques which could be used for a single-spin measurement. In this technique a periodic sequence of the *rf* π -pulses drives periodic spin reversals, which, in turn, drive the cantilever vibrations. In Chapter 8, we describe a more sophisticated technique, in which cyclic adiabatic spin reversals are driven by a frequency modulated *rf* field. This technique has been widely used in MRFM experiments with macroscopic ensembles of elec-

tron and nuclear spins. Chapters 9, 10 and 11 are devoted to the oscillating cantilever driven adiabatic reversals (OSCAR) technique, which was used in [8] for single-spin detection. In this technique spin cyclic adiabatic reversals are driven by the cantilever vibrations in the presence of an rf field. In turn, spin reversals cause a frequency shift of the cantilever vibrations, which can be detected with high precision. In Chapter 11, Section 4, we propose a new experiment for measuring the characteristic time-scale for the collapse of the spin-cantilever wave function. In Chapter 12, we discuss possible applications of MRFM to the measurement of spin entangled states and to quantum computation. In Chapter 13, we consider the application of highly nonuniform magnetic fields used in MRFM techniques for the suppression of the spin diffusion and relaxation.

Our book has a multi-level structure. Even a reader who is not familiar with magnetic resonance and quantum mechanics can understand the basic principles of the MRFM if he or she will read Chapter 2 (the quasiclassical theory of the magnetic resonance) and skip all “quantum sections” of the book. The next level includes the readers who are familiar with magnetic resonance but not familiar with quantum mechanics. They may skip Chapter 2 and all “quantum sections” of the book. The readers who are not familiar with the master equation may skip the corresponding sections but still understand the quantum theory of MRFM.

We would like to mention that in addition to MRFM there are other approaches to the single-spin measurement in condensed matter. One of them relies on the optical detection of magnetic resonance. (See, for example, the review by Köhler [9] and the recent paper of Jelezko *et al.* [10].) As an example in the fluorescence-detected magnetic resonance (FDMR) technique a single molecule is excited with a laser to a metastable paramagnetic state. The magnetic resonance in the metastable state under the action of the rf field is detected via a change in the fluorescence intensity. Another approach utilizes the scanned tunneling microscopy (STM). As an example, Manassen *et al.* [11] reported modulation of the tunneling current with the Larmor frequency of the localized spin of an individual iron atom in silicon in the

presence of a small permanent magnetic field. Recently, Elzerman *et al.* [12] demonstrated the electrical measurement of the spin state of an individual electron spin in a semiconductor quantum dot. They used spin-to-charge conversion of a single electron in a dot, and detected a single-electron charge using a quantum point contact. Xiao *et al.* [13] reported the electrical detection of magnetic resonance under the action of an *rf* field for a structural single electron paramagnetic defect near the *Si/SiO₂* interface. They also used spin-to-charge conversion. The electric charge was measured using a silicon field-effect transistor.

We do not intend here to give the full list of articles. All of the single-spin measurement approaches may find (or may already have found) important applications in science and technology. However, so far, MRFM is the only approach which has the potential to detect a single spin and to measure the state of the spin localized below the surface of a non-transparent material.