Magnetic Resonance Force Microscopy using a Commercially Available SPM Unit

S. Won[*] and J. Heo

[*]Materials Characterization Research Group, Korea Institute of Materials Science, Changwon 641-831,
Republic of Korea, wsh@kims.re.kr

ABSTRACT

Magnetic resonance force microscopy (MRFM) is considered another as a novel scanning probe microscope (SPM) combined with conventional SPM and magnetic resonance imaging (MRI). Originally, MRFM is proposed as a means to improve detection sensitivity to the single-proton level. However, MRFM has not become a commercialized technology up to now, in contrast with atomic force microscope (AFM). All MRFMs working currently, including our MRFM, are home-made systems manufactured in unique ways. Therefore, there is still room for improvement in each of the components making up an MRFM device, and this kind of improvement is a very important right now, necessary for true application of this device in the field of nanotechnology. Also, assigning reliability to hardware is very important in the process of development of new technology. In this study, we propose a MRFM using a commercially available SPM unit. Also, we introduce a module for correcting the optical fiber-to-cantilever alignment.

Keywords: mrfm, force detection, magnetic resonance, scanning probe microscope, electron spin resonance

1 INTRODUCTION

Conventional MRI has been persistently used due to its prominent spatial resolution and nondestructive method. Nevertheless, this inductive method using pick-up coils cannot resolve objects smaller than several microns. Recently, researchers at the IBM Almaden Research Center demonstrated MRI to the nanoscale level by using MRFM [1-3]. MRFM has been proposed as a new technique that could improve the sensitivity and spatial resolution of magnetic resonance to the single spin level [4-6]. MRFM is based on the detection of the magnetic force between a ferromagnetic magnet and spins in a sample. To detect a force by magnetic resonance, MRFM uses a microfabricated cantilever as a mechanical oscillator and the oscillation of the cantilever is detected using a high-sensitive fiber-optic interferometer [7-8] based on the optical interference. Two detection methods have been developed to detect the motion of a micromechanical cantilever: amplitude detection for measuring the oscillation of the cantilever and frequency detection for the cantilever resonance frequency shift. In this paper, we present a MRFM using a commercially available SPM unit. Also, we introduce a module for correcting the optical fiber-to-cantilever alignment.

2 EXPERIMENTAL DETAILS

The experiments were accomplished for electron spins in diphenylpicrylhydrazyl (DPPH) at T = 292 K in a vacuum of P = 10 μtorr. It is known that the spin density of DPPH is 2.3×10^{21} spins/cm^3. Our present MRFM is a “sample on cantilever” setup [9]. We applied the amplitude modulation (AM) of the microwave field as a spin modulation technique to manipulate the sample magnetization at the cantilever eigenfrequency. A flat iron needle with a radius of 35 μm was used as a magnetic field gradient source and served to generate magnetic force on the sample. The MRFM head is located in a small vacuum chamber with a solenoid coil to generate an external polarizing magnetic field.

3 RESULTS AND DISCUSSION

The basic principles of the MRFM can be explained with Fig. 1. The micron-sized sample is attached to a sensitive micromechanical cantilever, and the ferromagnetic magnet produces an extremely inhomogeneous magnetic field $\mathbf{B}_{\mathrm{mag}}(\mathrm{r})$ at a nearby sample. It defines the spatial regions of a sample where the magnetic resonance condition is met. The resonance condition is written as follows:

$$\omega_{\mathrm{mw}} = \gamma|\mathbf{B}_{\mathrm{sum}}(\mathrm{r})| \tag{1}$$

where γ is the gyromagnetic ratio and $\mathbf{B}_{\mathrm{sum}}(\mathrm{r})$ is the resonance magnetic field. The resonance magnetic field $\mathbf{B}_{\mathrm{sum}}(\mathrm{r})$ at position *r* in the sample can be expressed as $\mathbf{B}_{\mathrm{sum}}(\mathrm{r}) = \mathbf{B}_{\mathrm{ext}} + \mathbf{B}_{\mathrm{mag}}(\mathrm{r})$, where $\mathbf{B}_{\mathrm{ext}}$ is the externally-applied magnetic field. The thickness of the spatial regions, Δz, determines the spatial resolution of MRFM, known as a “resonance slice”, and is given by $\Delta B/|\nabla B_{\mathrm{mag}}|$, where ΔB is the magnetic resonance linewidth and the strength of the gradient field ∇B_{mag} produced by the ferromagnetic magnet. This field partially polarizes the spins in the sample, creating a small magnetization $\mathbf{M}(\mathrm{r},\mathrm{t})$. Because the magnetic field is spatially inhomogeneous, the spins in the sample experience a force given by [10]

$$\mathbf{F}(\mathrm{r},\mathrm{t}) = [\mathbf{M}(\mathrm{r},\mathrm{t}) \cdot \boldsymbol{\nabla}]\mathbf{B}_{\mathrm{mag}}(\mathrm{r}) \tag{2}$$

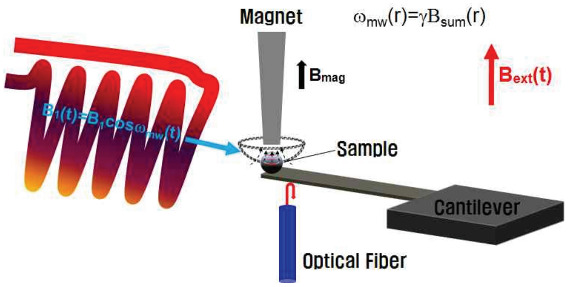

Figure 1: Schematic of a basic MRFM experiment.

Our MRFM with a commercially available SPM unit proposed in this study is composed of a probe[1] and cryostat[2], as shown in Fig. 2. And, the notable point here is the configuration of each component. First, considering the distance between the iron needle magnet and the DPPH sample, the iron needle magnet should be brought close enough to the sample to obtain a resonance. The thickness of the resonance slice also depends on the magnet size. In our case, the distance between the iron needle magnet and the DPPH sample is shorter than 40 μm and, in addition, should be located on a straight line. The situation is not significantly different in the optical fiber and the cantilever, because the optical fiber is located just below the cantilever. All of these are integrated in the block (probehead), which is 50 mm in diameter. After the setup, with the aid of an optical microscope, is completed, the probehead is located in the vacuum chamber. In the whole process, the setup should be perfectly maintained in the initial state; however, it is difficult to verify this result. Therefore, we need a tool to check the result and have adopted the CCD camera in the probehead.

We conducted the MRFM-ESR experiment on the DPPH sample in order to verify the performance of our MRFM. The coupling between the cantilever and the microwave magnetization dynamics is purely static. Therefore we applied the amplitude modulation of the microwave field as a spin modulation technique. The typical ESR resonance signals we measured are shown in Fig. 3. By retracting the iron needle magnet away from the DPPH sample, the resonance signal moves towards outside. According to the distance variation between the iron needle magnet and the DPPH sample, the shift in position of the resonance signal reflects the corollary of the MRFM principle, as stated above.

4 CONCLUSIONS

We adopt a commercially available SPM unit in MRFM apparatus and report our experimental results on detecting isolated electron spins in a DPPH sample. All the apparatus of magnetic resonance is home built and we are well optimized with our equipment. Also, we describe a system capable of correction for fiber-to-cantilever alignment. Easy alignment system utilizes a commercially available CCD unit.

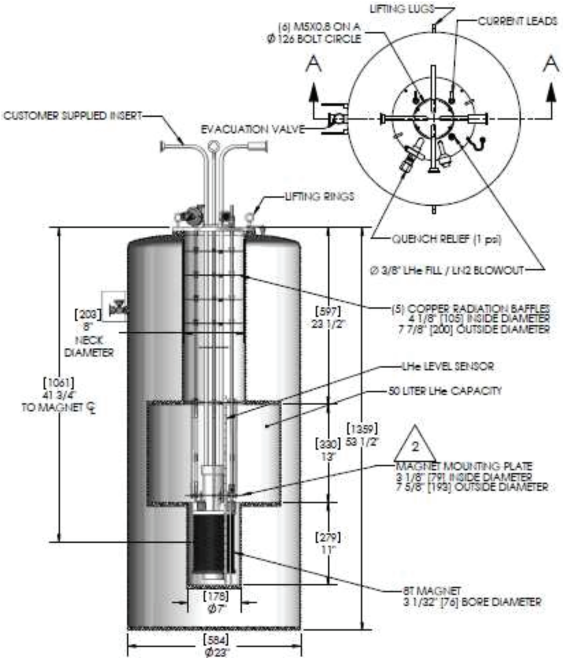

Figure 2: Details of the cryostat with MRFM support assembly.

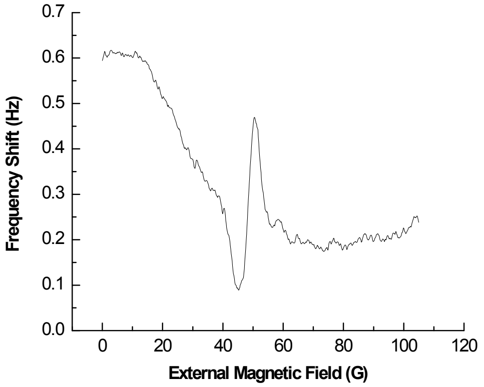

Figure 3: MRFM spectrum measured in a DPPH sample.

REFERENCES

[1] H. J. Mamin, M. Poggio, C. L. Degen, D. Rugar, Nuclear magnetic resonance imaging with 90-nm resolution, Nature Nanotechnology 2, 301, 2007.

---

[1] Attocube Systems AG, Königinstrasse 11a RGB 80539 München, Germany (http://www.attocube.com), Model: ANPz101/RES & ANPx101/RES.

[2] American Magnetics Inc., 112 Flint Rd Oak Ridge TN 37830, USA (http://www.americanmagnetics.com), SN: 13505

[2] C. L. Degen, M. Poggio, H. J. Mamin, C. T. Rettner, D. Rugar, Nanoscale magnetic resonance imaging, Proceeding of the National Academy of Sciences of the United States of America 106, 1313, 2009.

[3] H. J. Mamin, T. H. Oosterkamp, M. Poggio, C. L. Degen, C. T. Rettner, D. Rugar, Isotope-selective detection and imaging of organic nanolayers, Nano Letters 9, 3020, 2009.

[4] J. A. Sidles, Noninductive detection of single-proton magnetic resonance, Applied Physics Letters 58, 2854, 1991.

[5] J. A. Sidles, Folded Stern-Gerlach experiment as a means for detecting nuclear magnetic resonance in individual nuclei, Physical Review Letters 68, 1124, 1992.

[6] J. A. Sidles, J. L. Garbini, K. J. Bruland, D. Rugar, O. Züger, S. Hoen, C. S. Yannoni, Magnetic resonance force microscopy, Review of Modern Physics 67, 249, 1995.

[7] D. Rugar, H. J. Mamin, P. Guethner, Improved fiber-optic interferometer for atomic force microscopy, Applied Physics Letters 55, 2588, 1989.

[8] K. J. Bruland, J. L. Garbini, W. M. Dougherty, S. H. Chao, S. E. Jensen, J. A. Sidles, Thermal tuning of a fiber-optic interferometer for maximum sensitivity, Review of Scientific Instruments 70, 3542, 1999.

[9] A. Suter, The magnetic resonance force microscope, Progress in Nuclear Magnetic Resonance Spectroscopy 45, 239, 2004.

[10] J. D. Jackson, Classical Electrodynamics, 3rd ed., John Wiley & Sons, Inc., New York, pp. 188, 1999.