Ultimate limits in force detection

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The magnetic resonance force microscopy (MRFM) provides a new tool to achieve magnetic resonance with extremely high spatial resolution. Here, we present, a comparison of the sensitivity with a standard NMR, detailed analysis of the interaction between the magnetic tip and the scanned sample, and a discussion about the ultrahigh vacuum (UHV), low temperature set-up and first force sensitivity measurements.

Calculations and experiments demonstrate that the force detection of paramagnetic resonance phenomena is more sensitive than the inductive detection for dimension smaller than 1mm sample.
To perform this calculation, all geometry parameters are scaled except the cross-sectional area of the coil wire and the thickness of the cantilever, which are fixed since they can not be scaled arbitrarily in a micro fabrication process. An additional assumption in MRFM is that the quality factor and the resonance frequency of the cantilever are also fixed. We obtain the following scaling law:
$S_{INMR} \propto L^{-3/2}$ and $S_{MRFM} \propto L^{-5/2}$. In the case of NMR first experiments report a sensitivity of 10^{13} spins at room temperature and in a field of 2.4 T which represents a substantial improvement over the standard coil detection sensitivity.

To calculate the interaction between the magnetic tip and the sample, we assume that the magnetic tip is much smaller that the dimension of the sample. This assumption leads to a complex interaction caused by the inhomogeneous and high field generated by the magnetic tip. In order to analytically calculate the interaction we will derive the formula of the local field and we will derive the spatial volume where the resonance condition is met.

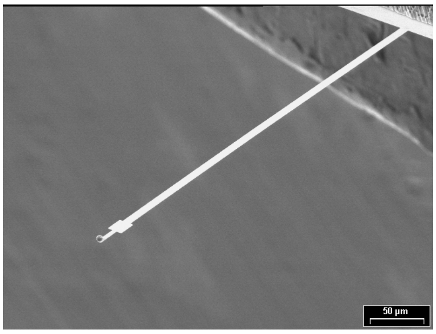

Figure 1: The Figure show a MRFM detector, consisting in a ultra sharp cantilever 454 um long, 4 um large and 0.2 um thick. The spring constant is around 0.0001 N/m and the quality factor 1 million. In the end a small magnetic particle of NbFeB is mounted as a tip.

The external magnetic field gradient is produced by a permanent magnetic tip close to the sample with smaller spatial dimensions. In order to determine the resonance response of the mechanical resonator, we calculate the magnetisation generate by the superposition of the different magnetic fields $B_{tot}=B_{tip}+B_0+B_1$ multiplied by the intrinsic magnetic resonance lineshape of the sample $m(r,t)=m_0*L(r,t)$. In the presence of a gradient magnetic field (generated by the tip) the magnetisation generates a force that can be calculated by integration over the full sample. A full expansion analytical function is calculated.

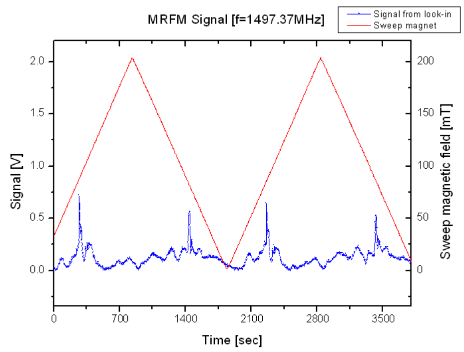

Figure 2: The Figure show a simple CW MRFM signal at room temperature. The magnetic field is sweep with amplitude of 100mt and a period of 2800 s. The sample consists of a spherical DPPH particle with a radius of 20um mounted on a commercial Nanosensor cantilever of 10KHz. The signal is detected by using a lock-in amplifier with a sensitivity of 20mV and 100ms as a time constant.

or smaller, the UHV conditions are recommended. So the microscope is mounted in a superconducting split pair magnet system with a maximal field strength of 7 T, mechanical decoupled from the external noise excitation. Moreover the low temperature insert allows to vary temperature from 1.8 K to 400 K. By lowering the cantilever temperature to 4.2 K the stochastic movement of the cantilever can be lowered as long as the sensor is well decoupled form the surrounding. Beyond the tremendous change of quality factor between 300 K and 4 K other intrinsic properties of the cantilever material occur which can take part in the dissipation process. It can be shown that the cantilever movement governs to the theoretically predicted movement. . In this wide temperature range interesting phenomena such as phase transitions, transport and dissipation effects can be observed. The maximum sensitivity achieved with our microscope is 10^{-18} N/Hz$^{0.5}$.
Local electron and nuclear spin resonance experiments can be performed and 3d images generated.