Single spin detection by magnetic resonance force microscopy

D. Rugar, R. Budakian, H.J. Mamin & B.W. Chui. 2004. Nature

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Objective

Previous Achievements

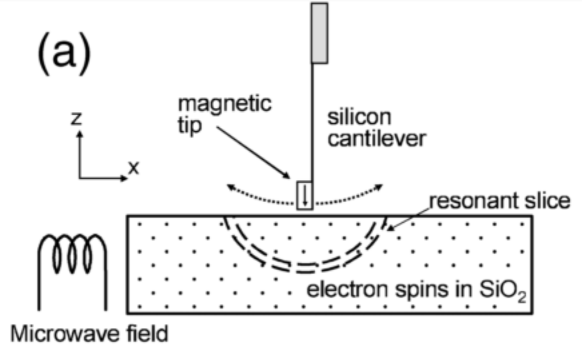
- ➔ MRI: 10^{12} nuclear spins per volume
- ➔ ESR: 10^{7} electron spins per volume

Why detect Single Spin?

- ➔ 3D imaging of macromolecules with atomic resolution
- ➔ Qubit readout device for spin based quantum computer

Problem: Exceedingly small magnetic force from single spin

Experimental Setup



- ➔ Mass Loaded Silicon Cantilever suppresses thermal motion
- ➔ Co^{60} Gamma rays producing low concentration of bonds
- ➔ Low temperature minimizes force noise and relaxation rate
- ➔ Resonance: $B_0 = \vec{B}_{tip} + \vec{z}B_{ext}$

H.J. Mamim and *et. al.*. *Detection and Manipulation of Statistical Polarization in Small Spin Ensembles*. 2003. *PRL*

Working Principle

interrupted Oscillation Cantilever Resonance Frequency (iOSCAR)

Positive feedback loop to automatically vary the vibration frequency of the cantilever in response to tip-sample interactions

Cantilever Frequency Shift

- ➔ Vibration of the cantilever tip forms resonant slice
- ➔ If sweep through the location of a spin, spin cyclically gets inverted in sync with the cantilever motion: *adiabatic rapid passage*
- ➔ Inversion creates alternating magnetic force on the cantilever that mimics a change in cantilever stiffness
- ➔ Shift in Cantilever Frequency

Working Principle

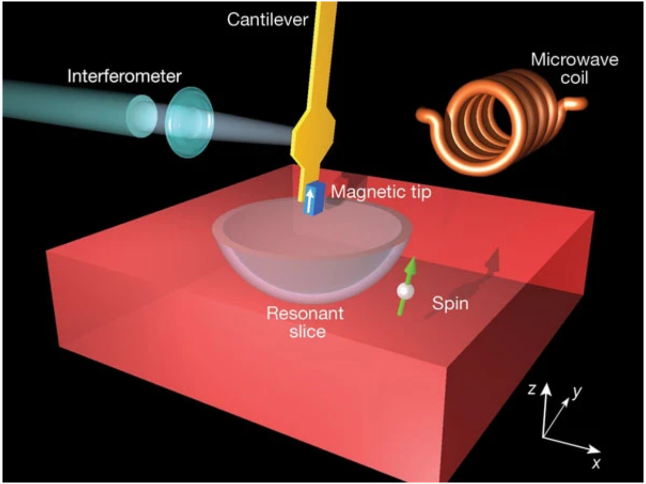
Shift in Cantilever Frequency

$$\delta f_c = \pm \frac{2 f_c G \mu_B}{\pi k x_{peak}} \quad \text{with} \quad G \equiv \frac{\partial B_0}{\partial x}$$

where,

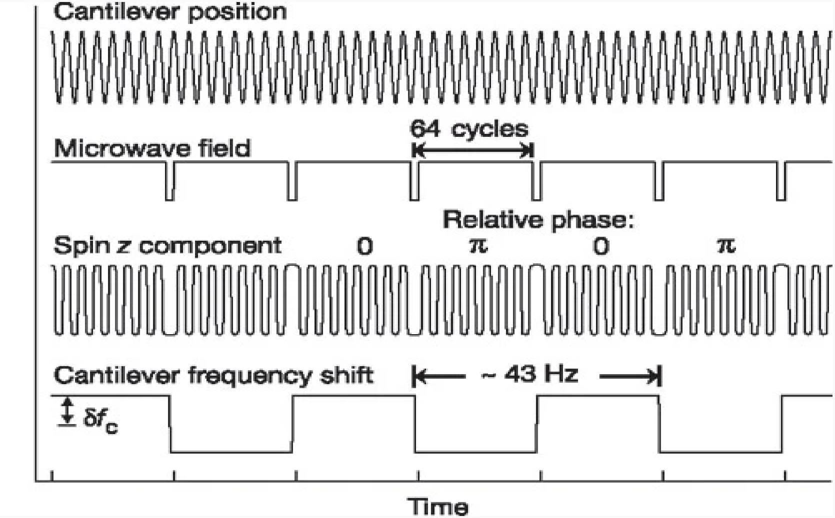
$$\begin{aligned} f_c &= \text{cantilever frequency} \\ G &= \text{lateral field gradient} \\ \mu_B &= \text{magnetic moment of the electron} \\ k &= \text{cantilever spring constant} \\ x_{peak} &= \text{peak vibration amplitude of the cantilever} \end{aligned}$$

Experimental Procedure



D.Rugar and *et. al.* *Single spin detection by MRFM*. 2004. *Nat.* Supplementary information

Experimental Procedure



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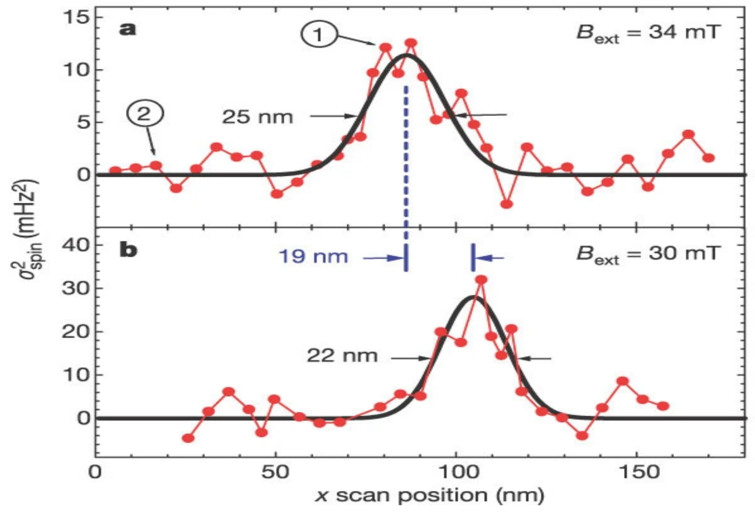
Results and Data Analysis

Spin Signal Amplitude

$\Delta f_1(t) \equiv \frac{4}{\pi}|\delta f_c|A(t)$ with $A(t) = \pm 1$

- Low modulated frequency compared to noise frequency of the cantilever
- Signal averaging to detect spin signal
- Frequency discriminator detects frequency modulation of the cantilever followed by digital lock-in amplifier
- Determination of energy of in-phase and quadrature components of the frequency shift signal
- Spin signal and measurement noise uncorrelated: $\sigma^2_{in-phase} = \sigma^2_{phase} + \sigma^2_{noise}$
- Quadrature variance contains only the measurement noise: $\sigma^2_{spin} = \sigma^2_I - \sigma^2_Q$

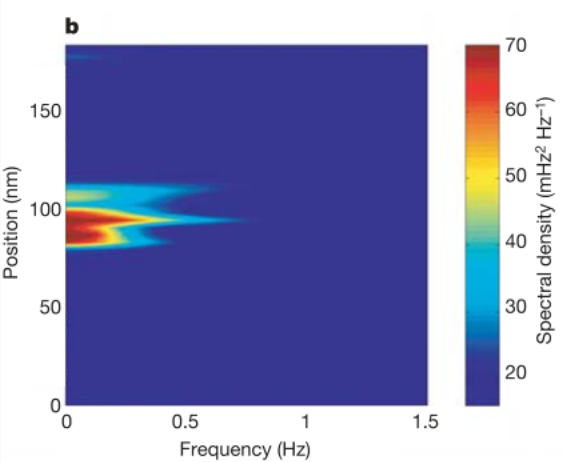
Results and Data Analysis



D.Rugar and *et. al. Single spin detection by MRFM*. 2004. *Nat*

Confirmation

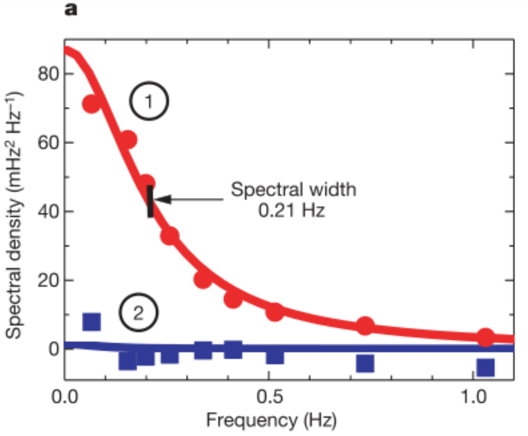
- ➔ Disappearance of signal when microwaves turned off or turned on continuously
- ➔ Timing of interruption
- ➔ Field Dependence



D.Rugar and *et. al. Single spin detection by MRFM*. 2004. *Nat*

Confirmation

- ➔ Sample with mean spacing $200 - 500\ nm$
- ➔ Cantilever Frequency Shift



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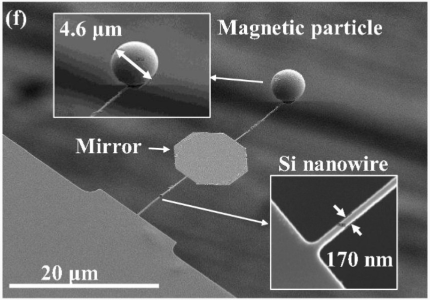
Conclusion and Applications

- ➔ Imaging below deep as 100 *nm*
- ➔ Useful for 2D & 3D imaging too (NMR, MRI)
- ➔ Quantum Computing



Masaya Toda, Takahito Ono. *Three-dimensional imaging*. 2021. *JMR*

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