



Micromechanical Instruments for Ferromagnetic
Measurements

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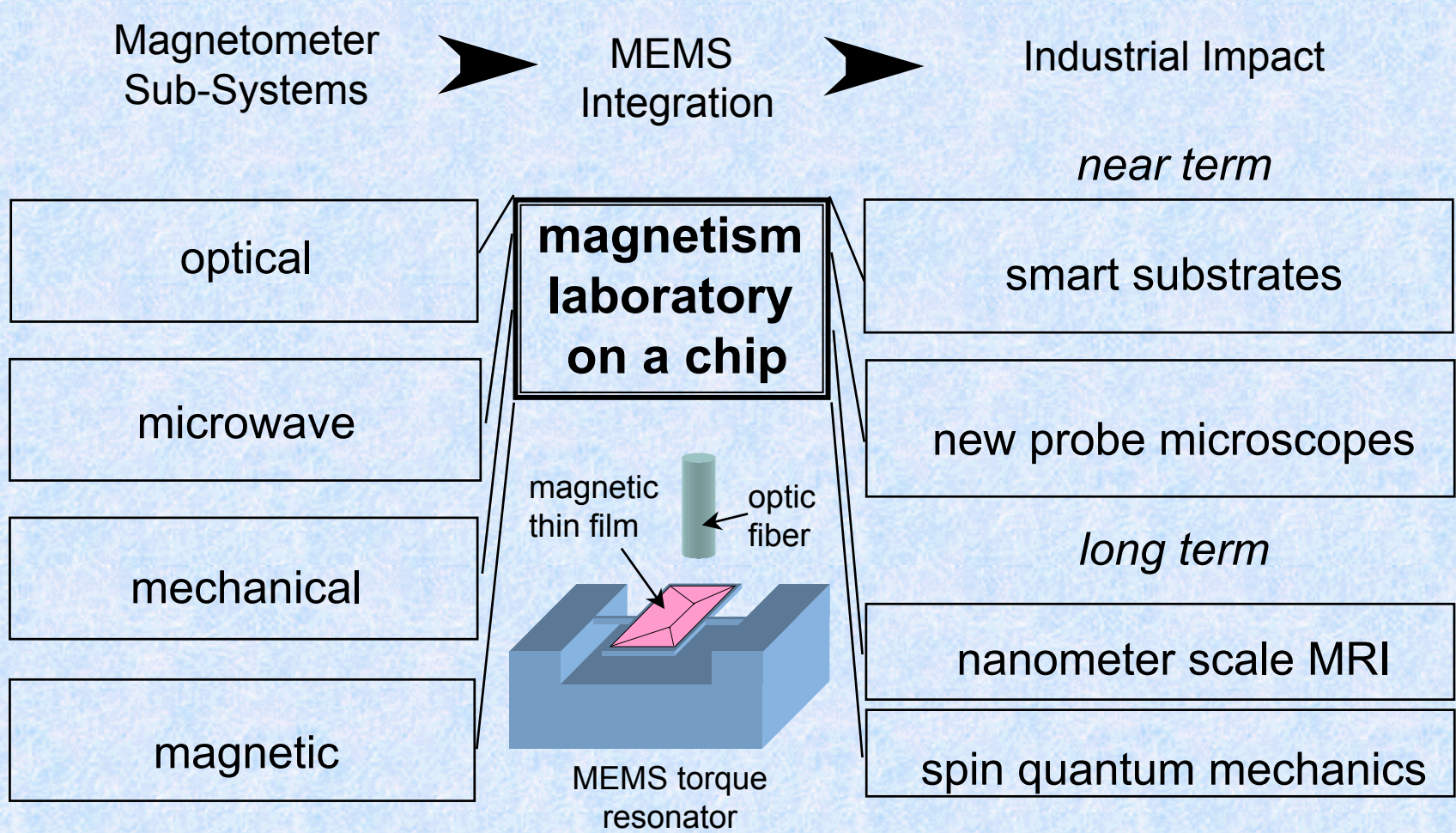
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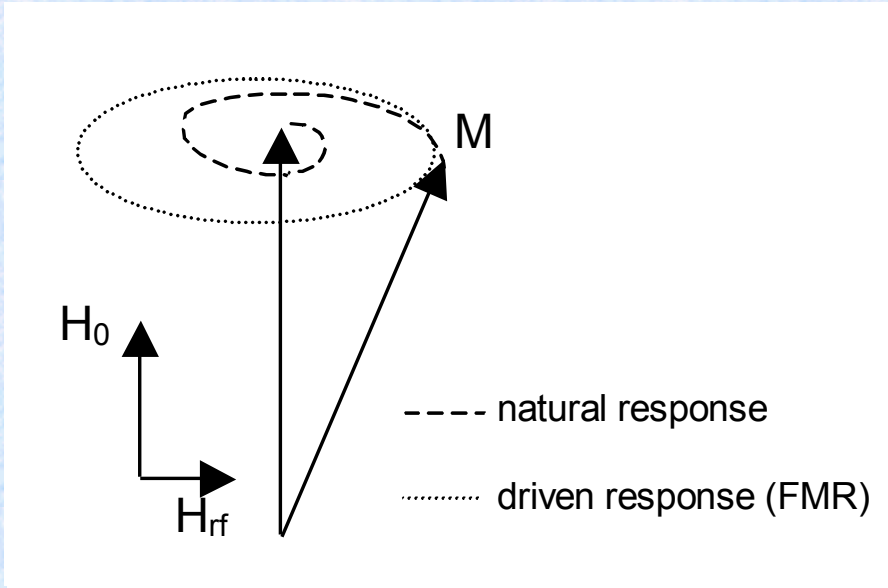
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MEMS Integration of Electromagnetic Systems: Impact on the Next Generation of Magnetometers.

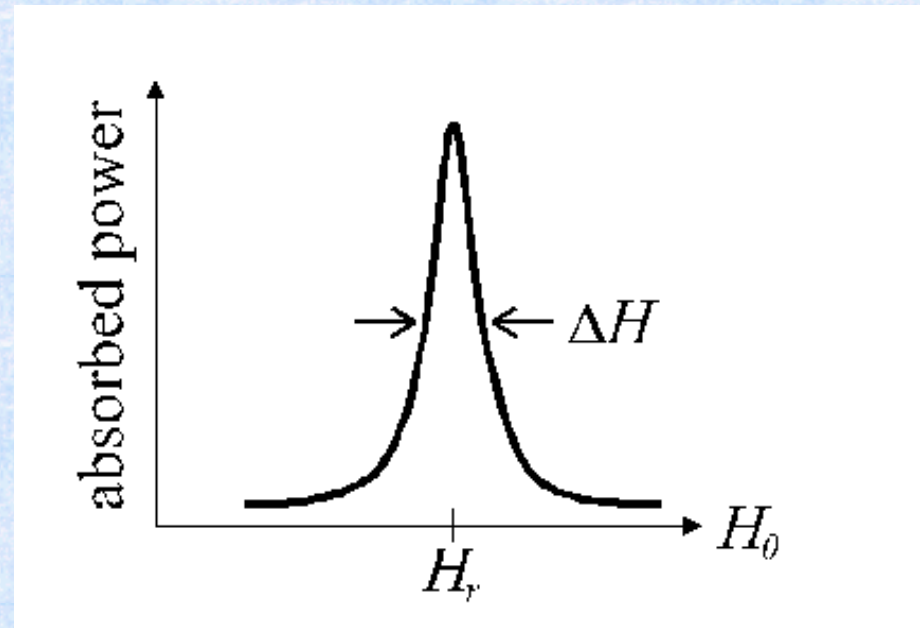


Ferromagnetic resonance (FMR).

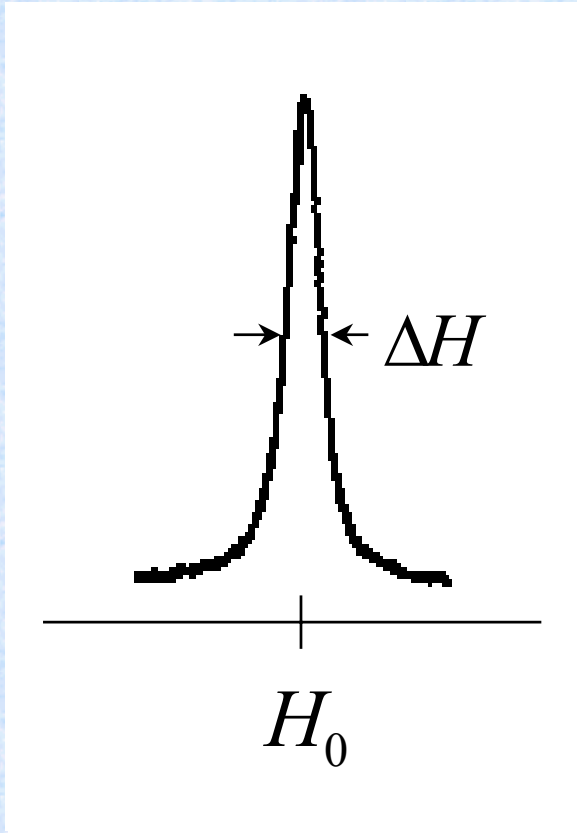


← Precession and relaxation of \mathbf{M} in response to an applied field \mathbf{H} .

Lorentzian absorption line typical of FMR showing microwave power absorption as a function of swept bias field. →



Quick review of FMR parameters.

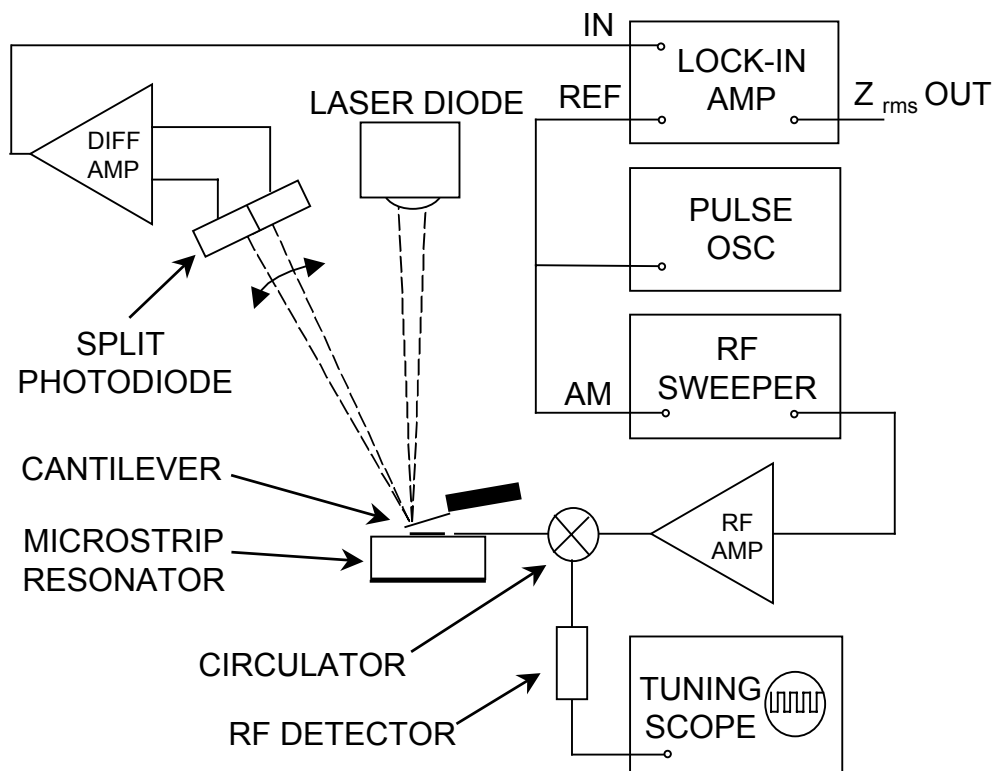


$$M_s = \frac{1}{H_0} \left(\frac{\omega^2}{\gamma^2} - H_0^2 \right)$$

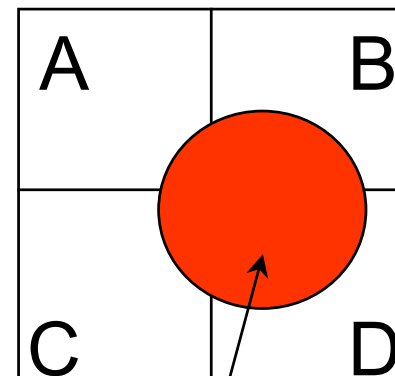
$$\alpha = \frac{\gamma}{2\omega} \Delta H$$

$$\chi'' = \frac{M_s}{\alpha} \frac{\gamma}{\omega} \left(\frac{M_s + H_0}{M_s + 2H_0} \right)$$

Instrumentation.



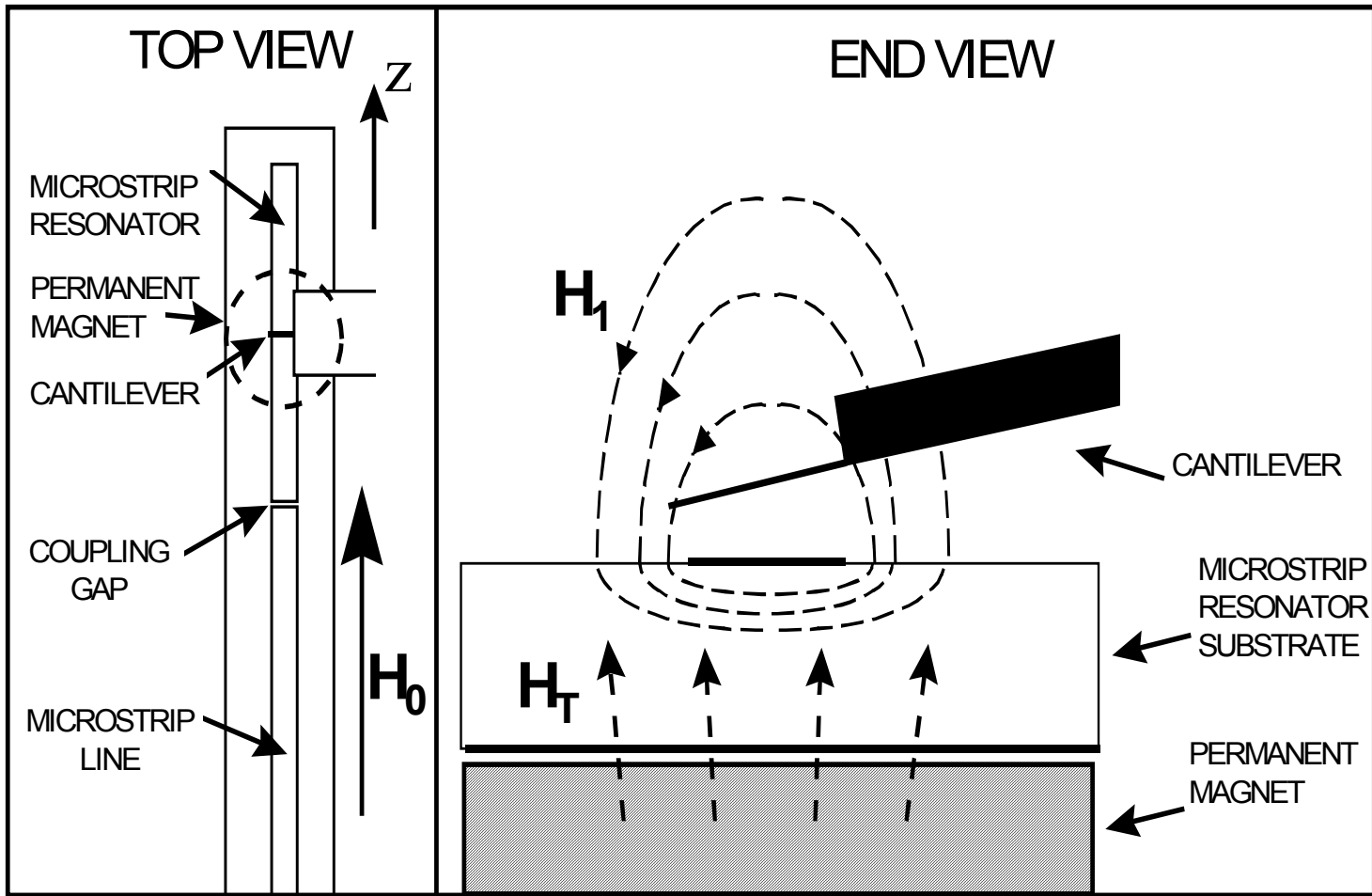
FOUR QUADRANT PHOTODIODE



LASER SPOT

Torsion mode $\frac{(A+C)-(B+D)}{A+B+C+D}$

Deflection mode $\frac{(A+B)-(C+D)}{A+B+C+D}$



Cantilever characteristics

Deflection

$$K_s = Ewt^3/4l^3$$

$$F_{noise}/\sqrt{Hz} = \sqrt{\frac{2K_s k_b T}{Q f_o}}$$

$$K_s = 0.2 \text{ N/m}$$

$$f_o = 15 \text{ kHz}$$

$$Q = 200$$

$$F_{noise} \approx 10^{-14} \text{ N}/\sqrt{Hz}$$

Torsion

$$K_s = \frac{E(wt^3)}{6(1+m)l}$$

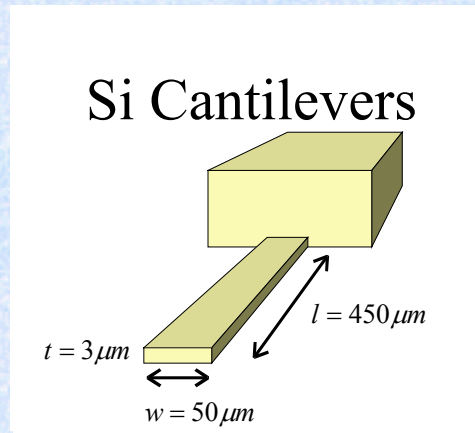
$$T_{noise}/\sqrt{Hz} = \sqrt{\frac{2K_s k_b T}{Q f_o}}$$

$$K_s = 3 \cdot 10^{-8} \text{ N}\cdot\text{m}/\text{rad}$$

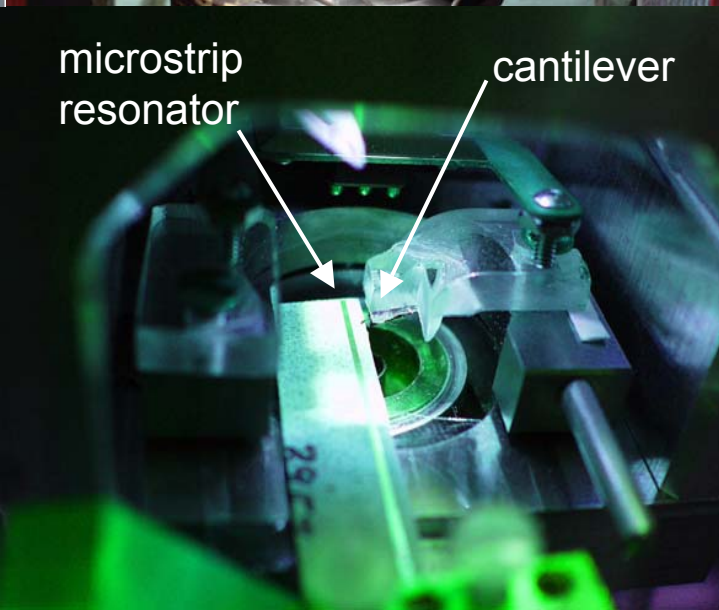
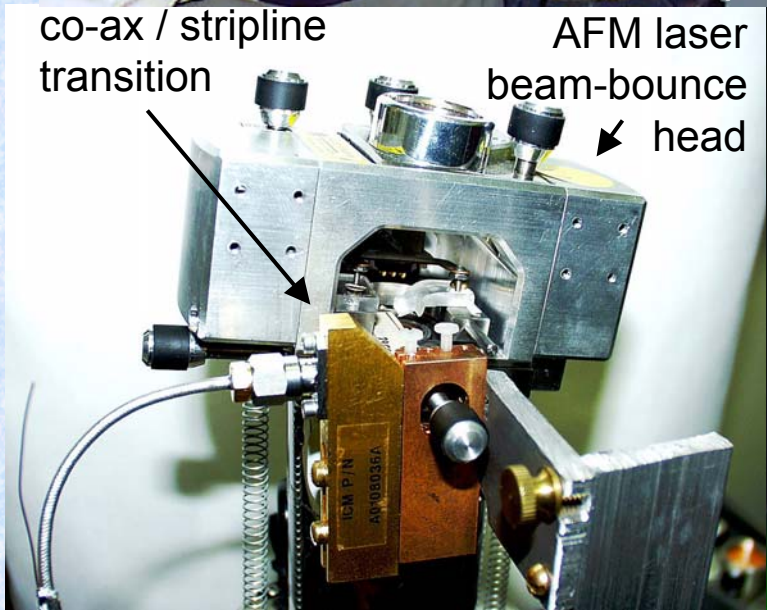
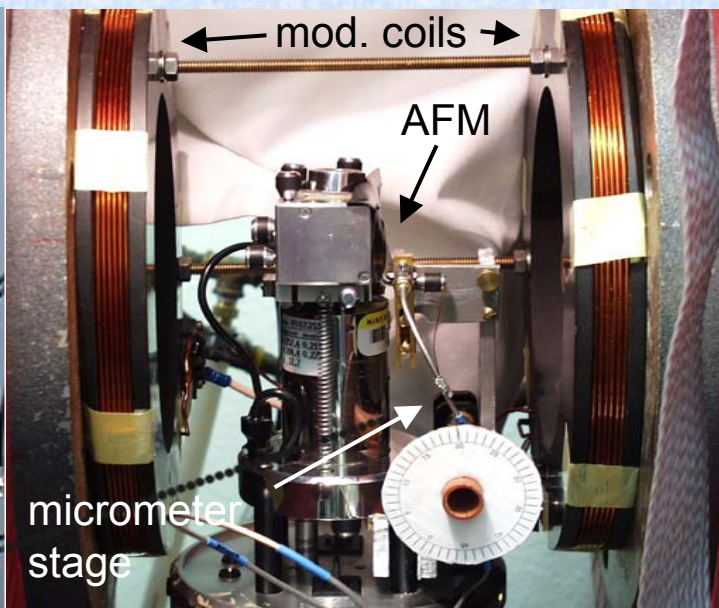
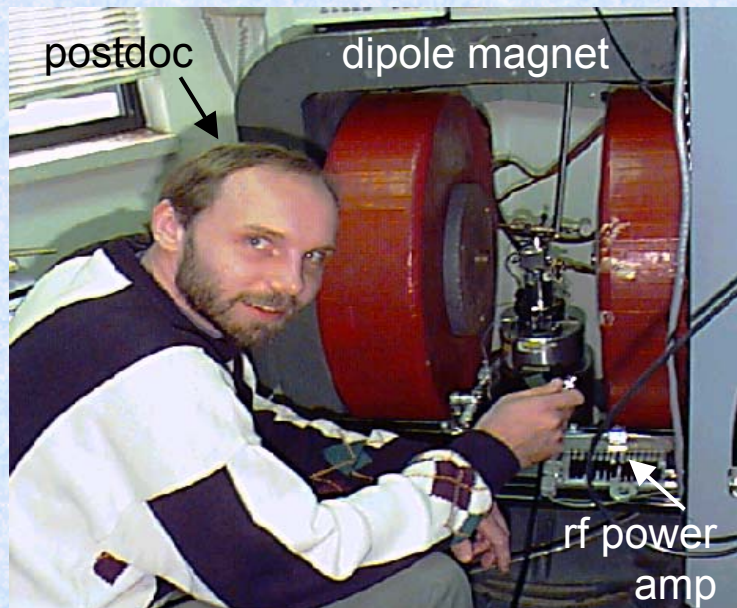
$$f_o = 250 \text{ kHz}$$

$$Q = 250$$

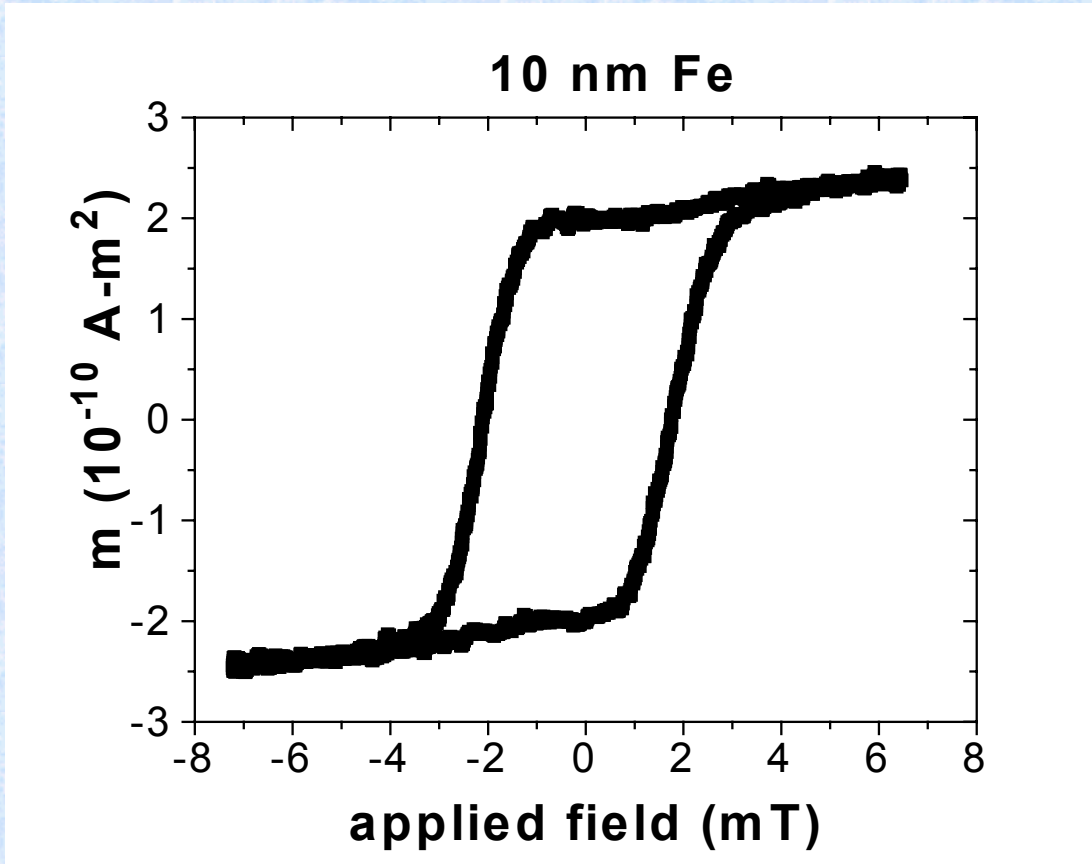
$$T_{noise} \approx 10^{-17} \text{ N}\cdot\text{m}/\sqrt{Hz}$$



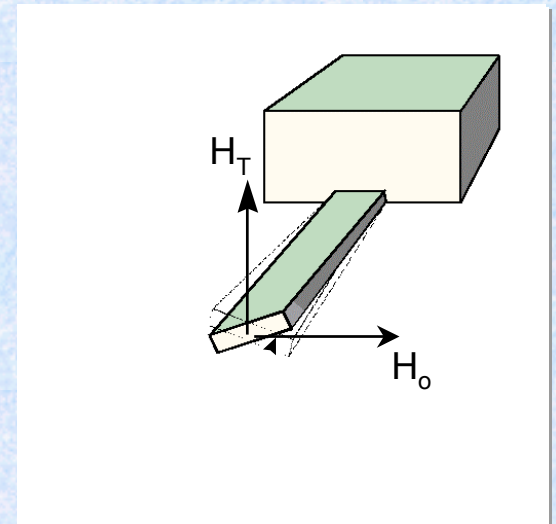
Apparatus for micromechanical detection of FMR



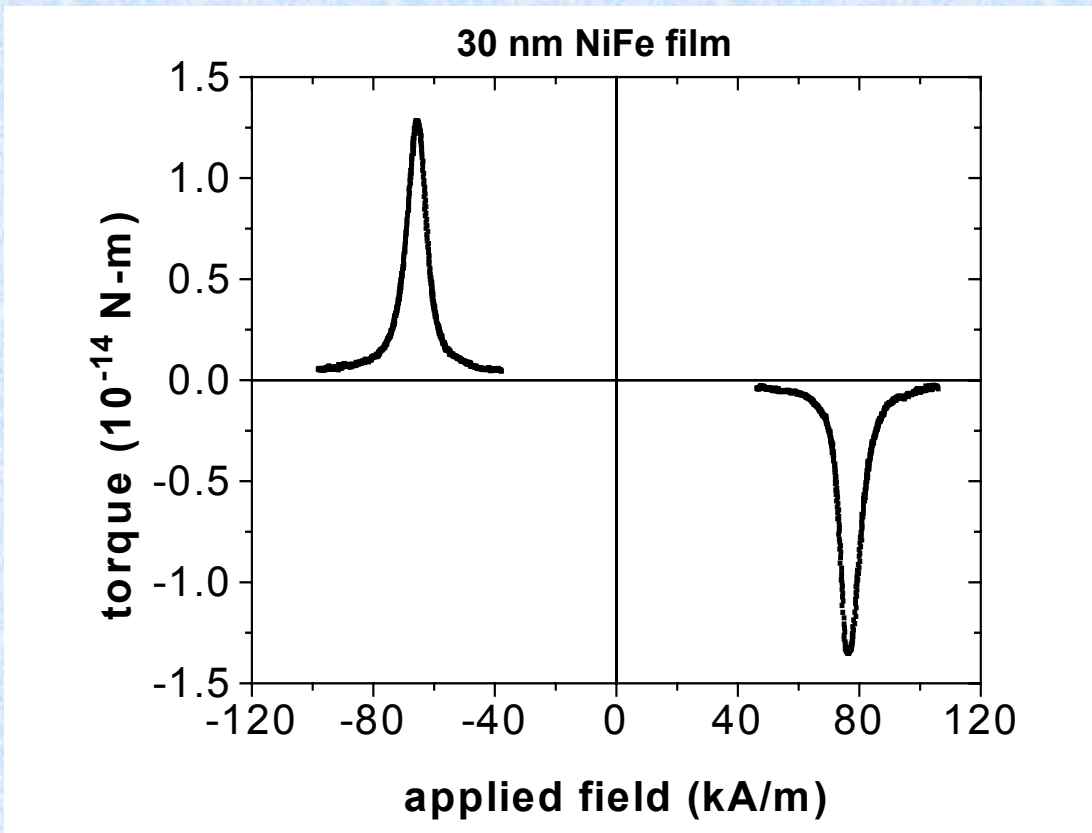
Micro torque magnetometer.



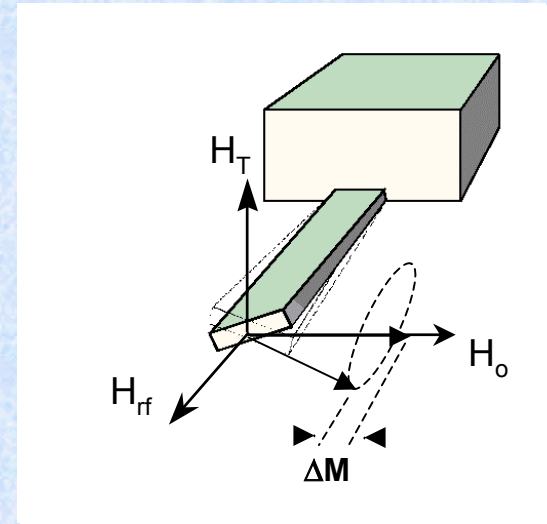
$$T = \mu_0 M H_T V$$



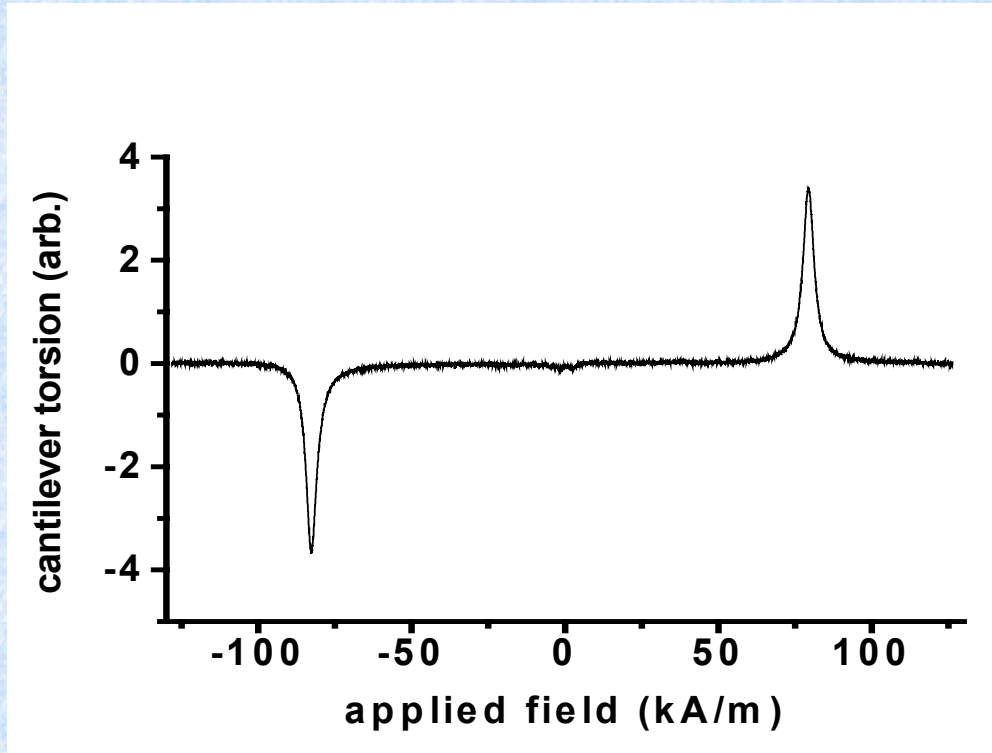
FMR with a micro resonating torque magnetometer: magnetic moment modulation.



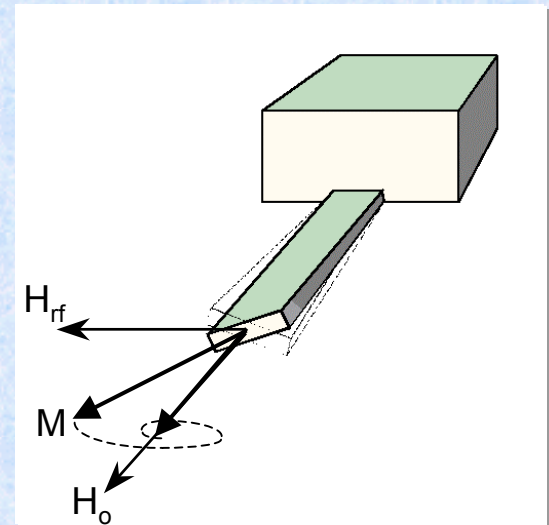
$$\Delta T_{quasi-static} = \mu_0 \Delta M H_T V$$



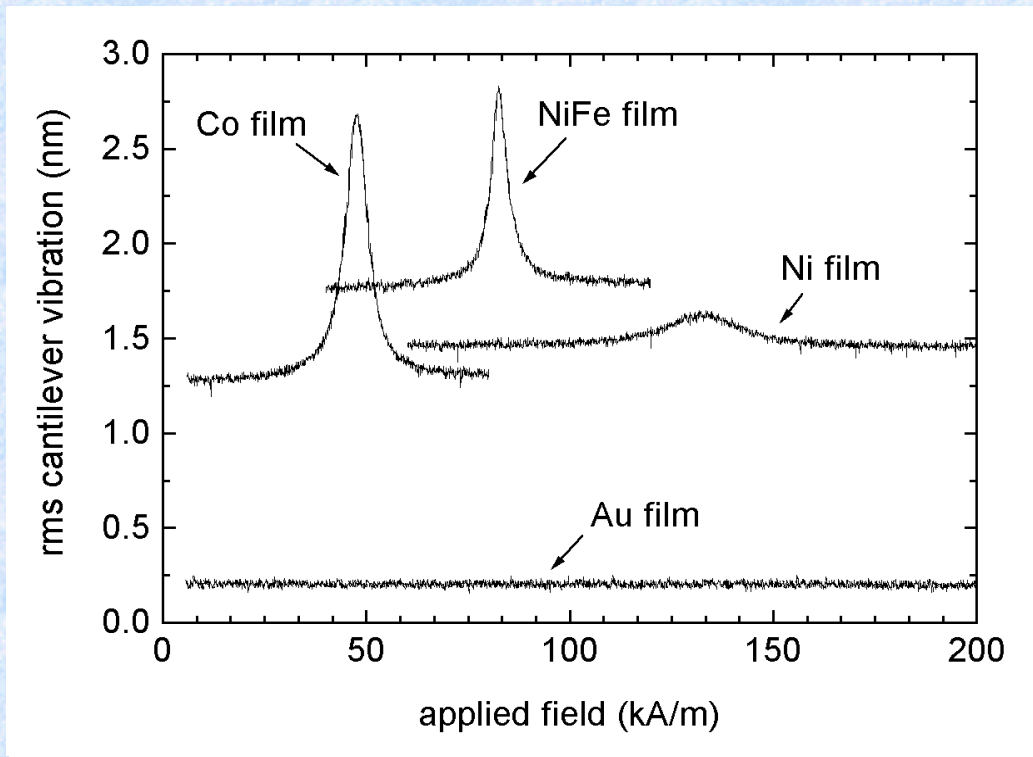
FMR with a micro resonating torque magnetometer: spin angular momentum damping.



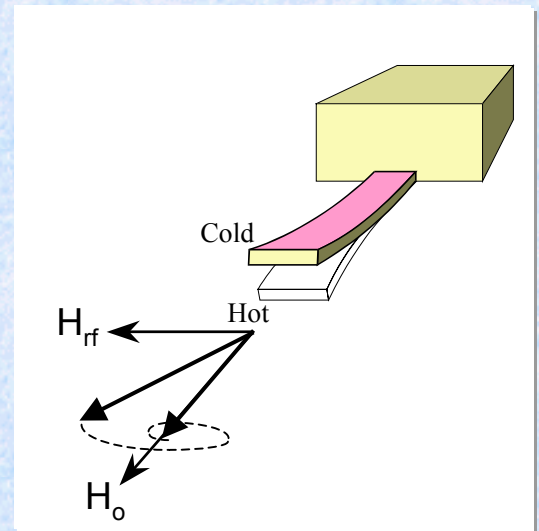
$$T_{dynamic} = \frac{\mu_0 M_s}{2\alpha(2H_r + M_s)} H_{rf}^2 V$$



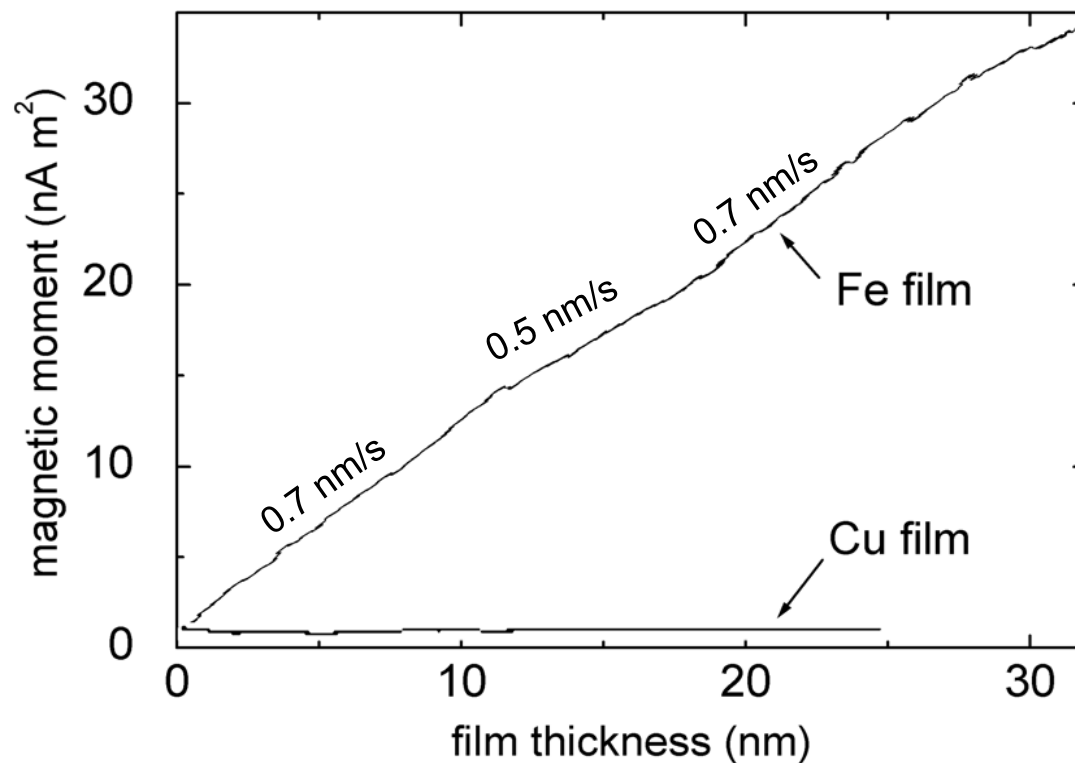
FMR with a micromechanical calorimeter sensor.



$$P = \frac{\mu_0 M_s \gamma (H_r + M_s)}{2\alpha(2H_r + M_s)} H_{rf}^2 V$$

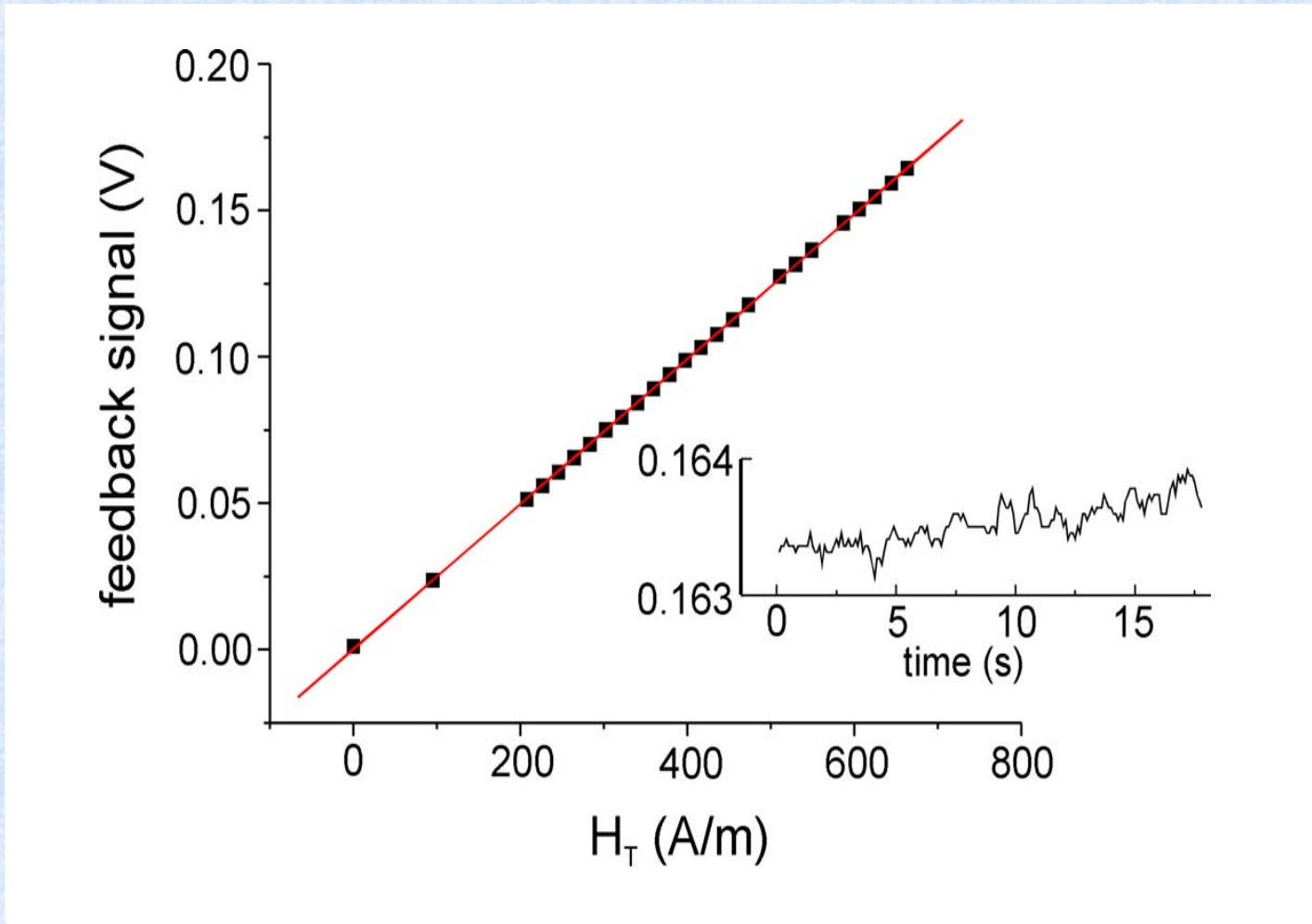


in situ monitoring during thin-film deposition.



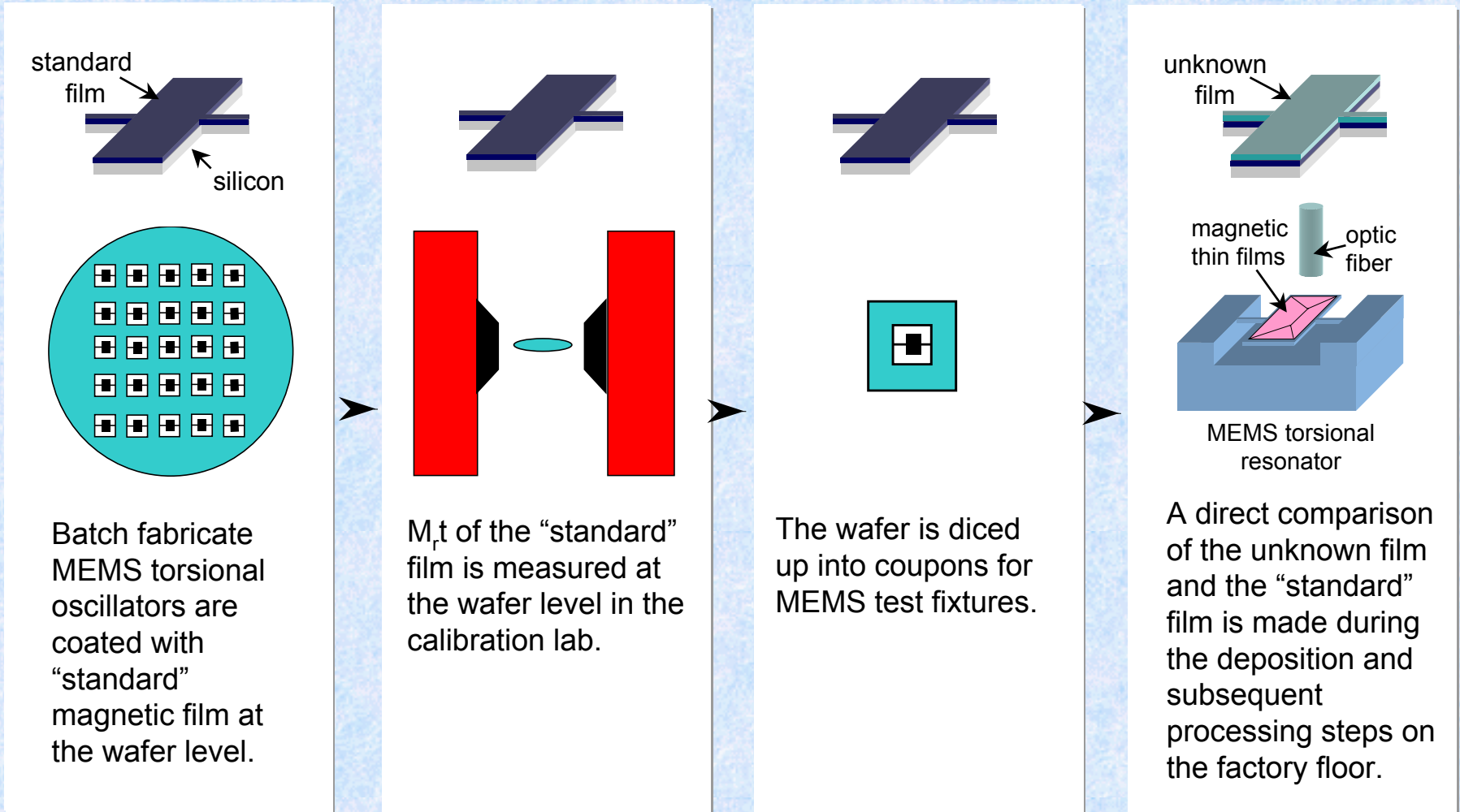
Magnetic moment measured with a resonating torque microbalance versus film thickness measured with a quartz crystal microbalance.

in situ monitoring during thin-film deposition.

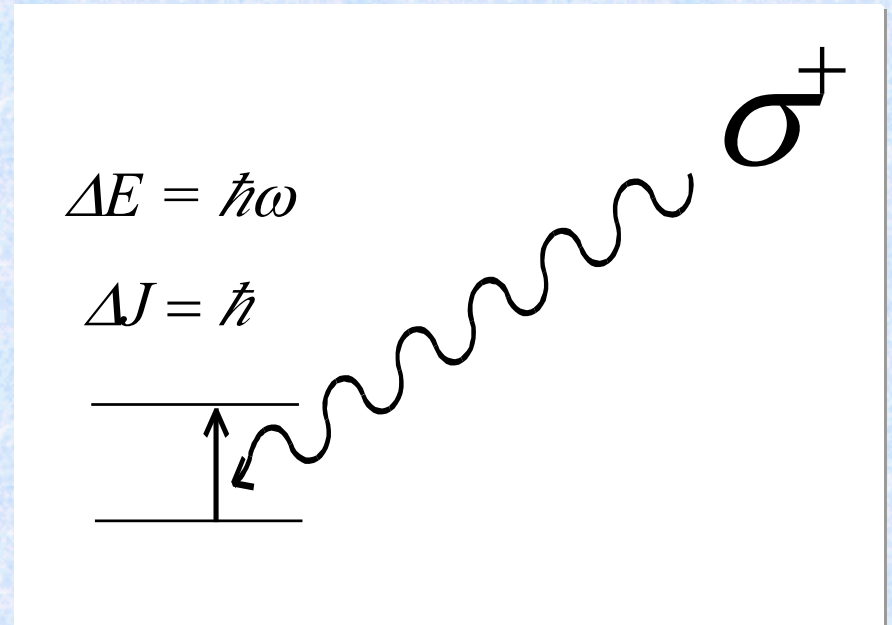
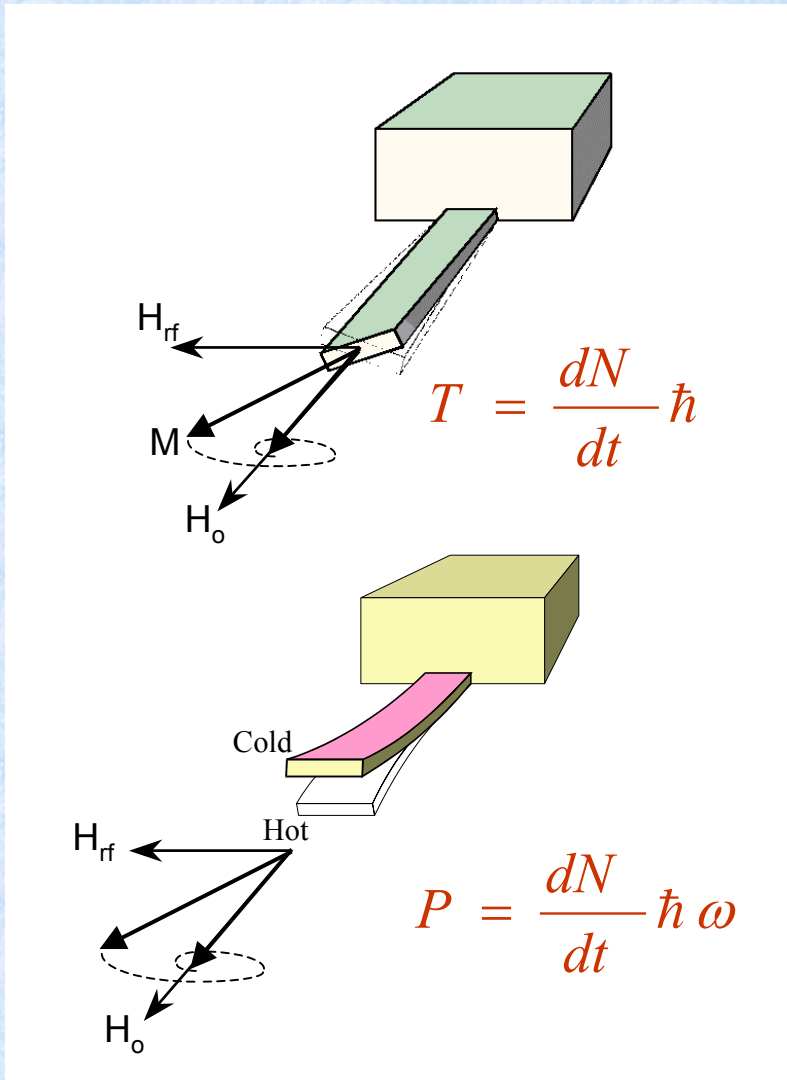


Active damping feedback signal versus torque field for a 30 nm thick permalloy film.

Smart Substrates for Calibrated Magnetometry of Ultra Thin Magnetic Films



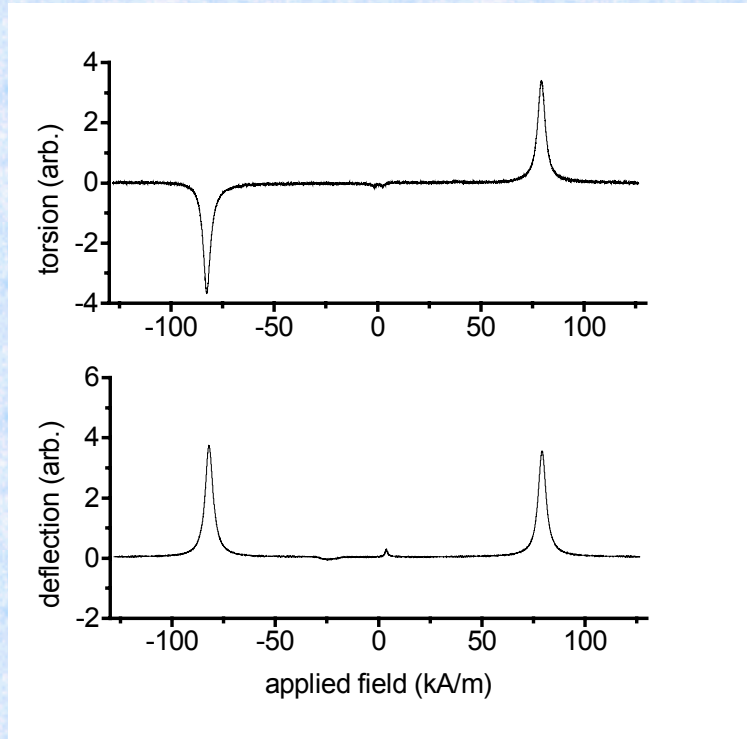
FMR absorption of photon energy and angular momentum.



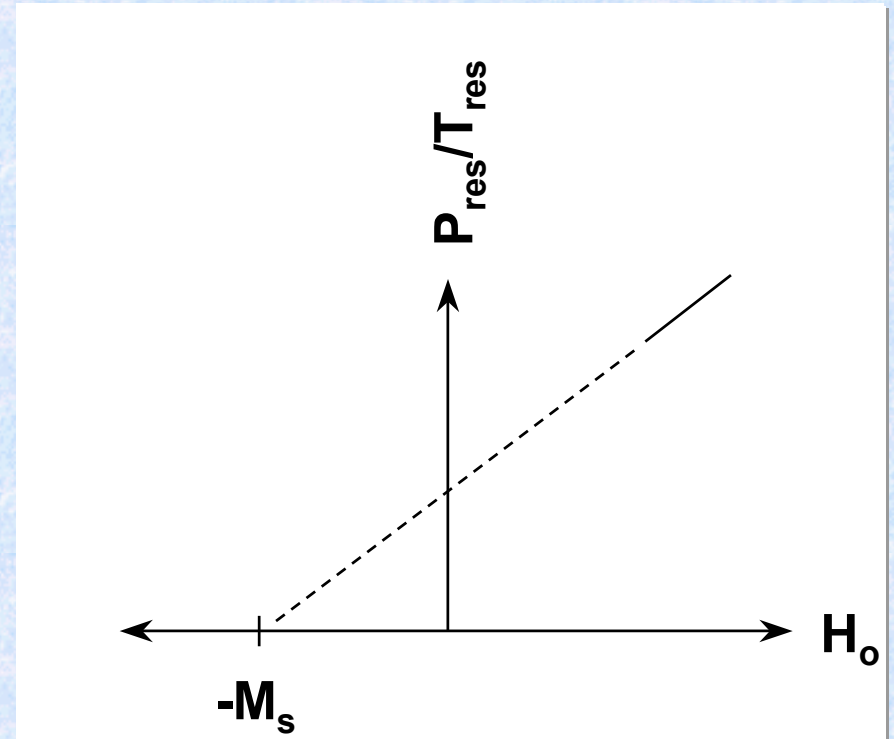
$$P/T = \omega$$

Combining cantilever torque and deflection (power) measurements of the same sample:

$$P_{res} = \gamma(H_0 + M_s)T_{res}$$

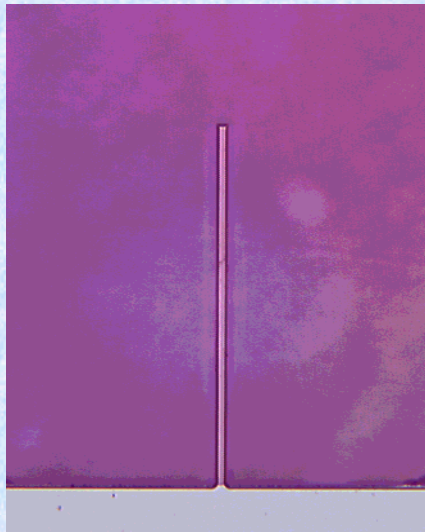


Deflection and torque measurements taken with the same experimental configuration.

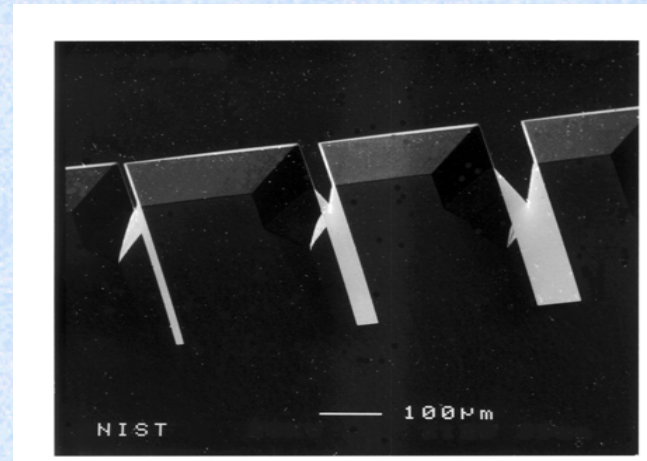


New way to measure M_s or, alternatively, the ratio of γ 's of different spin systems.

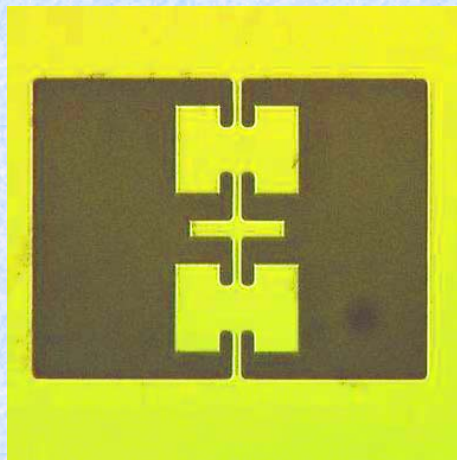
MEMS Magnetometer Projects at NIST-Boulder.



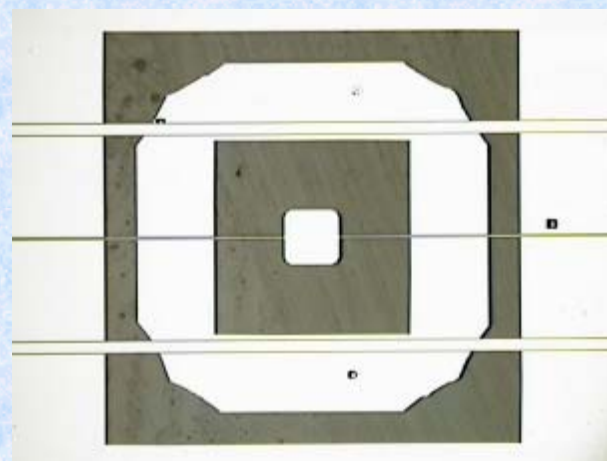
Dielectric bimaterial
cantilever



Ultra thin cantilevers



Triple torsional oscillator



High Q torsional oscillators

Magnetic moment sensitivity comparisons ($A \cdot m^2$)

