# Fully integrable magnetic field sensor based on delta-E effect

B. Gojdka,[1] R. Jahns,[2] K. Meurisch,[1] H. Greve,[3] R. Adelung,[4] E. Quandt,[3] R. Knöchel,[2] and F. Faupel[1,a)]

[1]*Institute for Materials Science–Multicomponent Materials, Faculty of Engineering, Christian-Albrechts-University of Kiel, Kaiserstraße 2, D-24143 Kiel, Germany*
[2]*Institute of Electrical and Information Engineering–Microwave Laboratory, Faculty of Engineering, Christian-Albrechts-University of Kiel, Kaiserstraße 2, D-24143 Kiel, Germany*
[3]*Institute for Materials Science–Inorganic Functional Materials, Faculty of Engineering, Christian-Albrechts-University of Kiel, Kaiserstraße 2, D-24143 Kiel, Germany*
[4]*Institute for Materials Science–Functional Nanomaterials, Faculty of Engineering, Christian-Albrechts-University of Kiel, Kaiserstraße 2, D-24143 Kiel, Germany*

(Received 11 October 2011; accepted 2 November 2011; published online 28 November 2011)

A fully integrable magnetic field sensor based on magnetic microelectromechanical systems is presented. The approach yields high application potential since it is compatible with standard micromachining techniques, operates at room-temperature, and provides high bandwidth and vector field capability. The demonstrator presented in this work consists of a tipless commercial atomic force microscope cantilever which is coated with an amorphous thin film layer of $(Fe_{90}Co_{10})_{78}Si_{12}B_{10}$. Amplitude and frequency of magnetic fields are measured via the modulation of the oscillation of the microcantilever via the delta-E effect of the FeCoSiB coating. © *2011 American Institute of Physics*. [doi:10.1063/1.3664135]

Microelectromechanical systems (MEMS) incorporating magnetic components (MagMEMS) have received great attention in recent years as they are highly interesting for various applications in sensors.[1] Amongst them, mechanically oscillating magnetic field sensors based on Lorentz-force[2] and the delta-E effect[3,4] have been demonstrated.

The design proposed by Osiander *et al.* features a MEMS cantilever coated with a layer of Terfenol-D.[3] The oscillation of the cantilever is excited by an external magnetic AC-field. In their work, the frequency shift of the oscillation is exploited to determine the field strength of static (DC) magnetic fields. However, this approach is not fully integrable due to the need for an external alternating (AC) magnetic field for the excitation of the oscillation. In addition, the external excitation field would likely introduce crosstalk in a sensor array for vector field measurements.

Greve *et al.* demonstrated a sensitivity of $7.1\mathrm{pT}/\sqrt{\mathrm{Hz}}$ with a macroscopic magnetoelectric resonator which is excited by the measured field itself.[5,6] While achieving high sensitivity, this scheme is restricted to very narrow bandwidth and the lowest detectable frequency is limited by the mechanical resonance frequency of the cantilever. Unfortunately, especially low frequency fields in the range of 0.1-100 Hz are interesting, for example, in biomedical applications[7] or for positioning devices.[8]

The approach presented in this work is sensitive to low frequency fields and is potentially fully integrable as there is no need for an external magnetic driving field. In addition, the concept works at room temperature, offers high bandwidth, and possesses vector field capability.

The decrease of Young's modulus of a magnetostrictive material in the small strain regime is called the delta-E effect with $\Delta E = E_M - E_H$, where $E_M$ is Young's modulus for purely elastic strain at fixed magnetization and $E_H$ the decreased modulus due to a magnetostrictive contribution to strain in a magnetic field $H$.[9] The resonance frequency of a cantilever is given by $f_0 = 1/(2\pi)\sqrt{k/m} \propto \sqrt{E_{eff}}$, with $E_{eff}$ the effective Young's modulus of the coated cantilever. Thus, upon application of an alternating magnetic field $H_{ac}(t)$ the delta-E effect results in a shift of resonance frequency $\Delta f(t) = f_0(E_{eff,M}) - f_0\left(E_{eff,H}(t)\right)$. Considering an excitation $X = A_{exc}\sin(2\pi f_{exc} t)$ of the cantilever with $A_{exc}, f_{exc} = const.$, $\Delta f(t)$ will result in a change of oscillation amplitude $\Delta A(t) = A(t) - A_0$, where $A_0$ is the oscillation amplitude at $H = 0$.

Ludwig and Quandt reported a delta-E effect of up to 50 GPa for field-annealed FeCoSiB thin films.[10] Accordingly, commercial tipless Si-cantilevers with $f_0 \approx 320$ kHz (Nanosensors, TL-NCH) were coated with 500 nm of amorphous $(Fe_{90}Co_{10})_{78}Si_{12}B_{10}$ by rf-magnetron sputtering (200 W, $2 \times 10^{-1}$ Pa Ar) in a commercial sputtering system (Von Ardenne CS 730 S). Subsequently, the probes were annealed (550 K, $10^{-3}$ Pa, 60 min) to relax film stress. During the annealing a magnetic field ($\mu_0 H = 0.2$ T) was applied to induce an in-plane anisotropy parallel to the long axis of the cantilever.[5]

The probes were imaged via scanning electron microscopy (SEM), (FEI, Helios NanoLab Dualbeam), in order to assess possible distortion of the cantilevers due to film stress. The coated cantilevers were mounted in a commercial AFM system (Aist-NT, SmartSPM 1000) (Fig. 1(a)). A pair of Helmholtz coils was arranged within the AFM head around the cantilever to provide the magnetic test field. Optionally, a magnetic DC-field could be applied for biasing. The cantilevers were excited mechanically by a constant excitation amplitude via piezoelectric actuation of the AFM system. Thus, without an applied magnetic field the cantilever oscillates at constant amplitude $A_0$. The oscillation was monitored with the laser beam deflection system of the AFM. An excitation frequency $f_{exc} = 324.8$ kHz was chosen 600 Hz above $f_0 = 324.2$ kHz to exploit the slope of the resonance curve.

a)Electronic mail: ff@tf.uni-kiel.de.

 

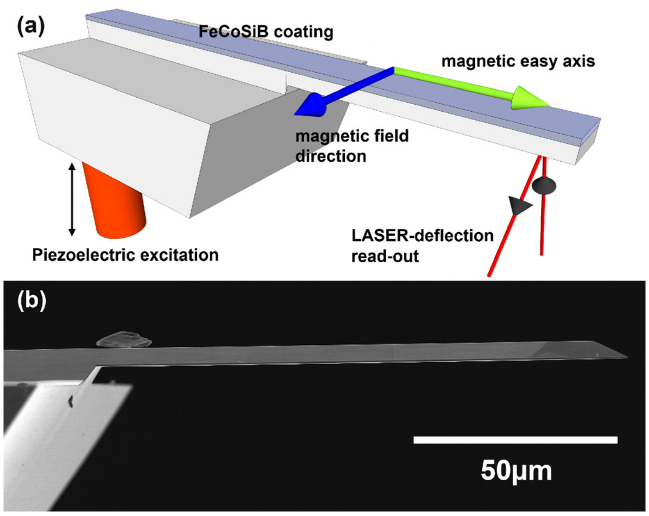


FIG. 1. (Color online) (a) Experimental setup comprising a FeCoSiB-coated tipless cantilever placed in a commercial AFM unit. The oscillation is read out via the LASER deflection method. (b) SEM image of tipless Si-cantilever coated with 500 nm FeCoSiB.

SEM images (Fig. 1(b)) of the coated cantilevers confirm relaxed FeCoSiB films after the post-annealing process. After the deposition the oscillators still exhibit one sharp resonance peak around 324 kHz (depending on the individual probe) with a quality factor $Q \approx 230$.

Upon application of an external magnetic field, the oscillation amplitude of the cantilever is being modulated as shown in the inset of Fig. 2 for a field $\mu_0 H_{ac} = 100\,\mu\text{T}$ and $f_H = 15\,\text{Hz}$. The rms of the oscillation modulation is used as a measure for the magnetic field amplitude (Fig. 2) and recorded for 5 s for every datapoint. To demonstrate the linear and hysteresis-free operation of the sensor, the field amplitude $H_{ac}$ is first decreased from 100 $\mu$T to 400 nT and subsequently increased again. The sensor reaches maximum sensitivity when it operates at $\partial E_H/\partial H = \text{max}$. According to $\Delta E(H)$ of FeCoSiB reported by Ludwig and Quandt[10] maximum $\partial E_H/\partial H$ should be reached at a magnetic field of some 100 $\mu$T. In good agreement, a magnetic DC-field $\mu_0 H_{dc} = 353\mu\text{T}$ enhances the sensitivity by up to one order of magnitude. However, it should be noted that this bias field is

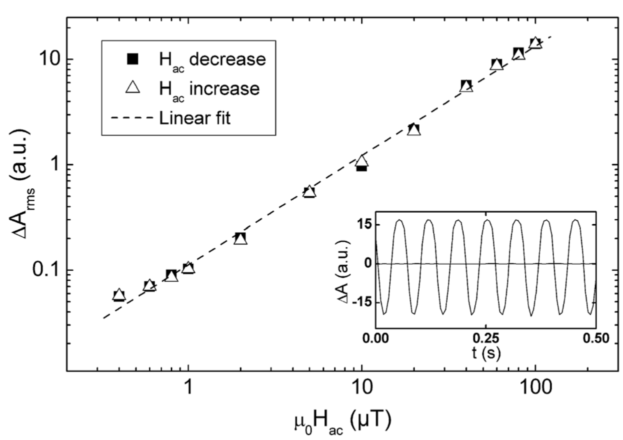


FIG. 2. rms of the modulation of the oscillation amplitude with respect to an AC magnetic field $H_{ac}$ ($f_H = 15\text{Hz}$). Inset: modulated amplitude of the cantilever oscillation without external field and with $\mu_0 H_{ac} = 100\,\mu\text{T}$, respectively. A biasing magnetic DC-field $\mu_0 H_{dc} = 353\,\mu\text{T}$ is applied during the measurement.

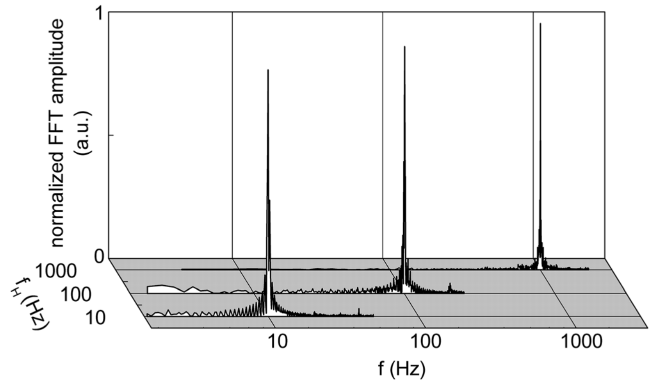


FIG. 3. Fourier transforms of the modulated amplitude $A(t)$ with magnetic test fields of $\mu_0 H_{ac} = 20\,\mu\text{T}$ and $10\,\text{Hz} \leq f_H \leq 1000\,\text{Hz}$.

optional and is not a prerequisite for the functionality of the concept. In addition, an advanced design of the sensor could be based on a self-biased magnetoelectric sensing layer, with maximum sensitivity at zero bias field.[11,12]

Fourier transformation of the mechanical oscillation provides a frequency analysis of the magnetic field. Fig. 3 depicts the Fourier transforms of magnetic fields between 10 and 1000 Hz. The system allows for easy frequency analysis even of complex magnetic fields since virtually no higher order harmonics are present.

Considering $Q \approx 230$ for the cantilevers in air, the sensitivity of the scheme can likely be increased by two orders of magnitude by driving the resonator in vacuum, where typical $Q$ are in the order of 10 000.[13] In future designs the detection of the oscillation can be implemented piezoelectrically to allow for full integration of the sensor and read-out. For example, a piezo- or ferroelectric layer could be added to the system. This layer would produce an electric voltage corresponding to the oscillation of the cantilever due to the piezoelectric effect. Subsequently, the voltage can be measured in order to detect the mechanical oscillation, as has already been used in various sensors.[5,14]

The functionality of a fully integrable MagMEMS magnetic field sensor concept based on the delta-E effect has been demonstrated. Measurements of amplitude and frequency of magnetic AC-fields confirmed a linear sensor response without hysteresis. The absence of higher order harmonics enables direct frequency analysis of magnetic fields. Due to the presented characteristics, the sensor concept yields application potential whenever magnetic fields with frequencies from quasi-static up to some kHz have to be measured under the consideration of costs, space and compatibility with established micromachining techniques.

This project was funded by the German Research Foundation (DFG) as part of the Collaborative Research Center 855–Magnetoelectric Composites–Future Biomagnetic Interfaces (SFB 855 subprojects A1, A2, A5, and C3). The authors would like to thank H. Kohlstedt from SFB 855 subproject A4 for the kind permission to use the group's AFM system and B. Henkel for the SEM image.

[1] M. R. J. Gibbs, J. Magn. Magn. Mater. **290–291**, 1298 (2005).
[2] Z. Kádár, A. Bossche, P. M. Sarro, and J. R. Mollinger, Sens. Actuators, A **70**, 225 (1998).

[3]R. Osiander, S. A. Ecelberger, R. B. Givens, D. K. Wickenden, J. C. Murphy, and T. J. Kistenmacher, Appl. Phys. Lett. **69**, 2930 (1996).
[4]N. Yoshizawa, I. Yamamoto, and Y. Shimada, IEEE Trans. Magn. **41**, 4359 (2005).
[5]H. Greve, E. Woltermann, H.-J. Quenzer, B. Wagner, and E. Quandt, Appl. Phys. Lett. **96**, 182501 (2010).
[6]R. Jahns, H. Greve, E. Woltermann, E. Lage, E. Quandt, and R. Knöchel, in Medical Measurements and Applications Proceedings, Bari (Italy), 107, 30–31 May 2011.
[7]S. Baillet, J. C. Mosher, and R. M. Leahy, IEEE Signal Process. Mag. **18**, 14 (2001).
[8]F. H. Raab, E. B. Blood, T. O. Steiner, and H. R. Jones, IEEE Trans. Aerosp. Electron. Syst. **15**, 709 (1979).
[9]R. C. O'Handley, *Modern Magnetic Materials: Principles and Applications* (Wiley, New York, 2000), pp. 240–244.
[10]A. Ludwig and E. Quandt, IEEE Trans. Magn. **38**, 2829 (2002).
[11]S. K. Mandal, G. Sreenivasulu, V. M. Petrov, and G. Srinivasan, Appl. Phys. Lett. **96**, 192502 (2010).
[12]S. M. Wu, S. A. Cybart, P. Yu, M. D. Rossell, J. X. Zhang, R. Ramesh, and R. C. Dynes, Nat. Mater. **9**, 756 (2010).
[13]F. J. Giessibl, Rev. Mod. Phys. **75**, 949 (2003).
[14]B. Rogers, L. Manning, T. Sulchek, and J. D. Adams, Ultramicroscopy **100**, 267 (2004).