Available online at www.sciencedirect.com
SCIENCE DIRECT®
Journal of Magnetism and Magnetic Materials 286 (2005) 320–323
Journal of magnetism and magnetic materials
www.elsevier.com/locate/jmmm

Microwave power imaging with ferromagnetic calorimeter probes on bimaterial cantilevers ☆

T.M. Wallis*, J. Moreland, B. Riddle, P. Kabos

National Institute of Standards and Technology, Electromagnetic Division (818), NIST m/s 818.01, 325 Broadway, Boulder, CO 80305-3328, USA

Available online 4 November 2004

Abstract

We report a near-field microscope technique that uses a ferromagnetic film deposited onto a bimaterial cantilever for imaging of microwave power distributions. The bimaterial cantilever absorbs microwave power via the induction of eddy currents and, additionally, in the presence of a biasing magnetic field, via ferromagnetic resonance. The resultant heating of the cantilever leads to deflection that is detected by a laser beam-bounce method. Comparison of images of a microstrip resonator acquired with and without a biasing field indicates that eddy currents induced by the tangential component of the magnetic field play a significant role in cantilever heating.
© 2004 Elsevier B.V. All rights reserved.

PACS: 07.79.Pk; 75.70.−i; 76.50.+g

Keywords: Fe alloys; Ferromagnetic resonance (FMR); Magnetic resonance force microscopy; Microwaves

1. Introduction

Spatially resolved, near-field microwave measurements are highly desirable due to potential applications in characterizing integrated circuits and in investigating electromagnetic properties of structures with lateral dimensions of micrometers or less. Among scanning near-field microwave microscopy techniques that have been demonstrated [1], those that integrate the microwave probe into micromachined cantilevers have several advantages. Well-established scanning probe microscopy techniques for precise probe positioning, detection of cantilever deflection, and feedback control of probe-sample separation can be readily adapted to incorporate microwave probes integrated into micromachined cantilevers. Additionally, modification of the cantilever fabrication process permits customization of the physical properties of the cantilevers. Such customization allows a reduction in the size of the probe and in

☆Contribution of the National Institute of Standards and Technology, not subject to US copyright.

*Corresponding author. Tel.: +303 497 5089; fax: +303 497 3970.
E-mail address: mwallis@boulder.nist.gov (T.M. Wallis).

0304-8853/$ - see front matter © 2004 Elsevier B.V. All rights reserved.
doi:10.1016/j.jmmm.2004.09.087

turn, improves the sensitivity and spatial resolution of the measurements. The work reported here expands on a previously reported technique for calorimetric detection of ferromagnetic resonance (FMR) with bimaterial cantilevers [2–4]. Two imaging modes, with and without a biasing magnetic field are described and demonstrated. We refer to these modes as ‘‘bias field-’’ and ‘‘eddy current-’’ imaging modes, respectively. Comparing images of selected segments of a microstrip resonator acquired using the two imaging modes indicates that the tangential component of the magnetic field generated by the resonator contributes significantly to eddy currents induced in the bimaterial cantilever.

2. Experiments

A schematic of the experimental setup is shown in Fig. 1. A 30 nm NiFe alloy film was deposited on one side of a commercial silicon cantilever to produce a bimaterial cantilever. The cantilever is placed above a source of high-frequency (4–20 GHz) electromagnetic radiation such that the tip of the cantilever is about 200 μm above the

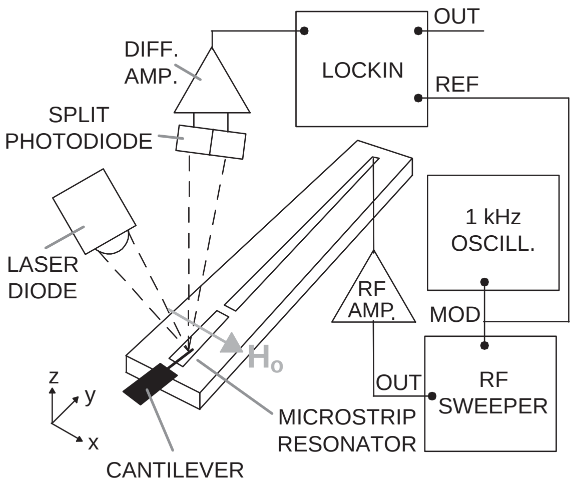

Fig. 1. A schematic of the experimental apparatus. The length of the cantilever is parallel to the resonator (y-direction). The bias field H_0 is applied perpendicular to the resonator (x-direction).

source. In this configuration, the NiFe film absorbs microwave power through the generation of eddy currents in the film and, in the presence of a static biasing magnetic field H_0, through FMR. The resultant heating of the bimaterial cantilever leads to a deflection due to the different thermal expansion coefficients of the two constituent materials. The deflection of the cantilever was measured using a laser beam-bounce method in which focused light from a diode laser was reflected from the cantilever onto a split photodiode detector. The cantilever, laser diode, and photodiode detector were incorporated into a scanning head that was mounted on a commercial piezoelectric translation stage. A 0.5 mm × 6.0 mm microstrip resonator with a resonant frequency of 9.41 GHz was imaged [2]. During imaging, the cantilever was oriented parallel to the microstrip y-axis and was tilted a few degrees away from the x–y plane of the resonator. The distance between the tip of the cantilever and the microstrip resonator remained fixed at about 200 μm during imaging. The radio frequency sweep signal used to drive the resonator was amplitude modulated by a 1 kHz sine wave which was in turn used as the reference for the lock-in detection of the split photodiode difference signal. The apparatus was operated in air under ambient conditions.

Two modes of operation were used to acquire images. In the eddy current mode, no magnetic bias field was applied and the cantilever was heated exclusively via induced eddy currents. Eddy currents are induced in the quasi-stationary cantilever due to the oscillating magnetic flux. A similar technique, eddy current microscopy, was reported by Hoffmann and coworkers [5]. In their method, eddy currents are induced in a conducting probe that is vertically oscillated in close proximity to a magnetic sample. In the bias field mode, an appropriately chosen field of approximately 80 kA/m (1 kOe) was applied perpendicular to the resonator y-axis by a combination of permanent magnets and an electromagnet in order to induce FMR. In the bias field mode, both induced eddy currents and FMR caused the heating of the cantilever. The eddy current mode may be used to image samples over a wide band of microwave frequencies; we imaged the 60 μm × 40 mm center conductor of a coplanar waveguide (not reported here) at frequencies between 4 and 20 GHz without significant degradation to the cantilever response. Obviously, FMR enhances the cantilever heating in the bias field mode only when the resonance condition is met.

3. Results & discussion

An image of the edge of the resonator acquired in eddy current mode is shown in Fig. 2(A). The image shows a maximum in cantilever deflection over the edge of the resonator which is consistent with previous measurements [3] as well as the calculations described below. Noise in the deflection signal within the image is due to thermal and mechanical fluctuations, nonuniformity of the sample substrate, as well as small variations in the cantilever-sample distance due to sample tilt. Based on the contrast in Fig. 2(A) and on our ability to resolve the center conductor of a coplanar waveguide, the lateral spatial resolution of this imaging technique is found to be on the order of 10 μm. As with other scanning probe imaging techniques, the lateral spatial resolution is limited by the lateral dimensions of the detector. In this case, the detector is the ferromagnetic film and the spatial resolution reflects averaging due to the finite width of the film. Improvements in the spatial resolution can be made by decreasing the size of the ferromagnetic detector. However, a decrease in the size of the ferromagnetic detector will decrease the relative amount of microwave power absorbed and thus will require an increase in sensitivity. Optimization of the cantilever design and modulation of the high-frequency signal at the cantilever's resonant frequency offer promising opportunities for improvements in sensitivity.

Application of a biasing magnetic field led to an enhancement of the magnetic power absorption, as shown in Fig. 2(B) which depicts the cantilever deflection as a function of applied field (vertical axis) and the x-position (horizontal axis). At each position, a maximum in the cantilever deflection occurs around $H_0 = H_{res} = 76$ kA/m (950 Oe). After the resonant field H_{res} was determined, images were acquired in both bias field and eddy current imaging modes at several locations above the resonator. Comparison of the images acquired in the two modes revealed spatially dependent enhancement of the microwave power absorption. Figs. 2(C) and (D) show average profiles in the

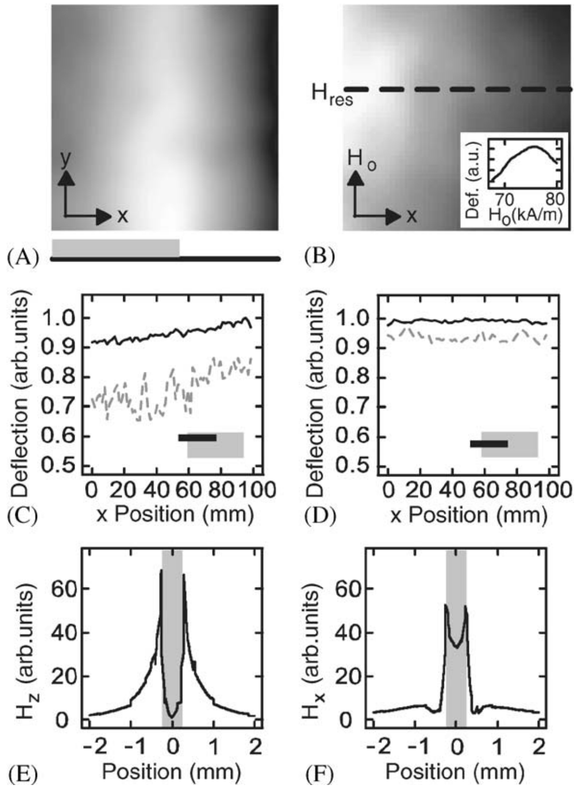

Fig. 2. (A) A microwave power image acquired in eddy current mode at the edge of the resonator. Image size is 100 μm × 100 μm. White corresponds to maximum power absorption as measured by cantilever deflection and black corresponds to minimum power absorption. Below the image, a schematic shows the location of the edge of the resonator. (B) Cantilever deflection as a function of applied field H_0 (vertical axis) and the x-position (horizontal axis). The field ranges from 68 to 80 kA/m (850 to 1000 Oe) and the position ranges over 100 μm. The ferromagnetic resonant field H_{res} is labeled. The inset in (B) shows an averaged cross section taken along H_0. (C) and (D) Profiles from microwave power images taken near the edge of the resonator (C) and near the center of the resonator (D) with the field on (black, solid line) and the field off (gray, dashed line). The position of the cantilever (black rectangle) relative to the resonator (gray rectangle) is shown. (E) and (F) Calculated values of the magnetic field amplitude for the components normal (E) and tangent (F) to the resonator plane. Gray strips correspond to the width of the resonator.

direction perpendicular to the y-axis of the resonator for four images: two images taken near the edge of the resonator and two images taken near its center, in both cases with and without a bias field. Near the edge of the resonator the application of the bias field led to an enhancement of the deflection by ~20%, while near the center of the resonator, the application of the bias field enhanced the deflection by ~5%. Additionally, the application of the bias field led to a significant reduction in noise, particularly near the edge of the resonator.

Given the relative orientations of the magnetic biasing field H_0, the cantilever, and the microstrip resonator in these experiments, only the normal component H_z of the magnetic field generated by the microstrip resonator will drive the FMR. Specifically, the average power absorbed via FMR will be proportional to the square of H_z [4]. Thus, the difference in the bias field and eddy current images should be most effectively enhanced where H_z is large. To confirm this, we calculated the amplitudes of the normal (H_z) and tangential (H_x) oscillating magnetic field components generated by the microstrip resonator using a commercial software package, as shown in Figs. 2(E) and (F). The fields were calculated at a distance of 100 μm above the resonator. H_z is sharply peaked at the edges of the resonator and drops near zero in the interior, in good agreement with the spatial dependence of the signal enhancement due to FMR. The nonzero (~5%) increase in the signal at the center of the resonator reflects spatial averaging of the signal due to the finite width of the cantilever.

Simple calculations show that the power absorbed via in-plane eddy currents in the NiFe film excited by the H_z field component is at least an order of magnitude greater than power absorbed in NiFe film via eddy currents excited by the H_x field component through the thickness of the cantilever and the film. However, despite the rapid fall off of H_z at the center of the resonator, a substantial deflection of the cantilever due to eddy current heating was measured. Thus, eddy currents induced by H_x, which is nonzero near the center of the resonator, appear to play a significant role in the Si/NiFe film bimaterial cantilever heating. In order to fully understand the roles of H_z and H_x in generation of eddy currents in these experiments, a detailed model that includes the frequency dependence of the permeability, the effect of H_0 on current density distributions, the eddy currents in the Si/NiFe film bimaterial cantilever, as well as the effects of FMR on eddy current induction, is required.

4. Conclusion

We have demonstrated an imaging technique based on calorimetric detection of microwave absorption by a ferromagnetic film deposited onto a bimaterial cantilever. The imaging technique operates in two modes: an eddy current mode ($H_0 = 0$) and a bias field mode ($H_0 = H_{res}$). The eddy current mode is effectively a broadband (4–20 GHz) technique while the bias field mode is a resonant, albeit tunable technique. The enhancement of the signal in the bias field mode compared to the eddy current mode is sensitive to the spatial variation of the normal component of the magnetic field, H_z. A significant signal in the eddy current mode at locations where H_z is very small indicates that H_x may make a significant contribution to the induced eddy currents.

References

[1] B.T. Rosner, D.W. van der Weide, Rev. Sci. Instrum. 73 (2002) 2505.
[2] J. Moreland, M. Lohndorf, P. Kabos, R.D. McMichael, Rev. Sci. Instrum. 71 (2000) 3099.
[3] A. Jander, J. Moreland, P. Kabos, J. Appl. Phys. 89 (2001) 7086.
[4] A. Jander, J. Moreland, P. Kabos, Appl. Phys. Lett. 78 (2001) 2348.
[5] B. Hoffman, R. Houbertz, U. Hartmann, Appl. Phys. A 66 (1998) S409.