Method for Assembling Nanosamples and a Cantilever for Dynamic Cantilever Magnetometry

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The use of ultrasoft cantilevers gives dynamic cantilever magnetometry (DCM) unique capabilities and sensitivity to probe magnetization processes in individual microscopic samples. However, to date, DCM has been applied mostly to wire-shaped samples, because no universal method is yet available for assembling nanosamples and a cantilever. Here we report a sample-transfer method that allows DCM to be applied to individual nanostructures without imposing any particular shape requirements. The method uses a dual-beam system of a focused ion beam and a scanning electron microscope and a nanomanipulator. We demonstrate the proposed method by measuring the magnetization process of a cobalt microdisk, a $CoFe_2O_4$ nanopyramid, and a nonmagnetic sample. The use of the proposed method allows the application of DCM to be extended to the study of the magnetic properties of individual nanosamples of arbitrary shape.

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I. INTRODUCTION

A fundamental need in nanomagnetism research is a practicable magnetic characterization technology [1]. Magnetic nanostructures are elemental components in many different areas, such as high-density magnetic recording [2,3], magnetic sensors [4,5], magnetic force detection [6–9], and biomedical sciences [10,11], and the measurement of the magnetic properties of individual nanostructures, such as magnetic anisotropy and saturation magnetization, is vital for these applications. Cantilever magnetometry has been shown to be a sensitive technique for studying the magnetization process of thin magnetic films [12–14] and individual nanotubes or nanowires [11,15–20]. Cantilever magnetometry as a typical mechanical detection method can be divided into cantilever torque magnetometry [12] and dynamic cantilever magnetometry (DCM) [14]. In cantilever torque magnetometry, one measures the static equilibrium deflection of the cantilever, whereas in DCM, one measures the magnetic-field-dependent resonance-frequency shifts of the cantilever, so DCM is also called "torque differential magnetometry" [21].

By use of ultrasoft cantilevers, dynamic cantilever magnetometry has achieved very high sensitivity for measuring the magnetization process of nanostructures, such as rings [22,23], nanotubes [15,18,20], and nanowires [11,16,19]. In such DCM studies of wire-shaped samples [11,15–20], the samples were transferred onto the tips of cantilevers by a micromanipulation system with the aid of a microscope, and were fixed by use of nonmagnetic materials. Therefore, only samples that are visible and that can be handled by micromanipulation systems can be prepared for DCM measurements. In other cases [12–14,22–24], the films or rings are fabricated together with the cantilevers. There is no general method for obtaining assemblies of a sample and a cantilever. To promote the application of dynamic cantilever magnetometry, it is thus essential to develop universal sample-preparation and sample-transfer techniques.

Magnetic measurements of a single nanosample are far beyond the capability of commercial magnetometers. To

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have sufficient signal, a large number of nanosamples, usually more than 1×10^6, are measured simultaneously. However, these nanosamples are usually diverse in size and shape, which makes their magnetic properties diverse as well. Experimental magnetic measurements of individual nanosamples are thus required for detailed investigations into the physics of nanomagnetism in individual nanosamples.

Few magnetic characterization methods exist that are capable of detecting individual nanosamples. Electric transport measurements, magneto-optical-Kerr-effect (MOKE) microscopy, and Lorentz microscopy are the methods used most often for studying the magnetism of individual nanosamples. However, only nanosamples with special shapes and properties can be measured by these methods. For example, for electric transport measurements, a nanosample must be conductive, and it is hard to use MOKE microscopy to measure a nanosample that is smaller than the relevant optical wavelength. The use of Lorentz microscopy requires a thin (less than a few hundred nanometers) nanosample with a regular shape so that electrons can be transmitted through the sample. In comparison with these methods, the working principle of DCM sets few requirements for the size, shape, and conductivity of nanosamples. For example, the sub-100-nm pyramid sample discussed herein cannot be measured by conventional electric-transport-measurement techniques, MOKE microscopy, or Lorentz microscopy. The challenges involved in using DCM to measure arbitrary individual nanosamples are mainly assembling the sample and the sensitivity of DCM.

In this paper, we introduce a sample-preparation and sample-transfer method that allows dynamic cantilever magnetometry to be used to measure individual nanostructures with no particular shape requirements. We use a dual-beam system consisting of a focused ion beam and a scanning electron microscope (SEM), on which is installed a nanomanipulator. To illustrate the proposed method, we demonstrate DCM measurements of a cobalt disk 0.1-μm thick and 2.2 μm in diameter, a $CoFe_2O_4$ nanopyramid with a base size of about 90 nm, and a nonmagnetic sample. The sample-preparation and sample-transfer processes for the nanopyramid are described in detail to explain the method. The saturation field, saturation moment, and magnetic anisotropy are then measured for both the cobalt disk and the nanopyramid. As a benchmark, a nonmagnetic sample (i.e., the $SrTiO_3$ substrate of the nanopyramid; without any nanopyramids) is measured by DCM with the exact same sample-preparation and sample-transfer processes as for the $CoFe_2O_4$ nanopyramid sample. This comparison shows that the proposed sample-preparation and sample-transfer method introduces negligible magnetic signal into the DCM measurements.

II. SETUP OF DYNAMIC CANTILEVER MAGNETOMETRY AND THE SAMPLE-PREPARATION AND SAMPLE-TRANSFER METHOD

DCM probes the magnetization process of a sample by measuring the change in the frequency of the cantilever in an externally applied magnetic field with the sample fixed to the tip of the cantilever. The interaction between the sample and the applied magnetic field produces a torque on the cantilever, which is then measured by DCM as a change in the frequency of the cantilever oscillations. To achieve high sensitivity to torque (i.e., highly sensitive magnetic detection), ultrasoft cantilevers are often used [11,15–18,20,23,24]. The typical spring constant of cantilevers used in DCM is less than 1 mN/m. In comparison, the typical spring constant of cantilevers used in atomic force microscopy is on the order of 1 N/m, and the typical spring constant of tuning forks used in DCM experiments [25] is on the order of 1 kN/m. The typical dimensions of such ultrasoft cantilevers are a thickness of 100 nm, a width of a few micrometers, and a length of several-hundred micrometers. It is highly nontrivial to transfer a sample onto such small, soft cantilevers while maintaining their mechanical quality.

In our DCM experiments, we use ultrasoft, single-crystal-silicon cantilevers with parameter values as listed in Table I. The cantilever frequencies are measured by a homebuilt microlens optical fiber interferometer system that uses a 1550-nm laser with incident power less than 1 μW. The microlens is held by a three-dimensional positioner that maintains the laser focus on the cantilever. A piezoelectric actuator is fixed to the cantilever holder to drive it. The cantilever, microlens optical

TABLE I. Parameters of samples and cantilevers in DCM experiments.

	Sample 1	Sample 2	Sample 3
Main material	Cobalt	$CoFe_2O_4$	Pt plus $SrTiO_3$
Shape	Disk	Pyramid	Irregular
Volume (m^3)	$(3.8 \pm 0.2) \times 10^{-19}$	$(1.6 \pm 0.2) \times 10^{-22}$	Pt, $(4.0 \pm 1.5) \times 10^{-19}$ $SrTiO_3$, $(8.8 \pm 0.7) \times 10^{-18}$
	Cantilever 1	Cantilever 2	Cantilever 3
l_0 (μm)	163	102	87
t_0 (μm)	0.9	0.1	0.1
α	1.3	1.4	1.4
f_0 (Hz)	23 965	3938	4857
k_0 (mN/m)	44	0.13	0.21
Q	12 000	15 000	13 000
Temperature (K)	16	10	10

fiber interferometer, three-axis positioner, and supporting mechanical structure are all installed in a high-vacuum chamber to maintain the high Q factor of the cantilever. The vacuum chamber incorporates a variable-temperature insert with which the temperature of the sample and the cantilever can be tuned from 1.5 to 300 K. Finally, we use a superconducting vector magnet to produce a magnetic field of up to 9 T along the z axis and 1 T along the x and y axes.

The idea of DCM is to convert the magnetic energy of a tiny sample in a magnetic field into tiny forces that deflect the cantilever. When a cantilever with a magnetic sample fixed to its free end oscillates in a magnetic field, the Zeeman energy and the effective anisotropy energy of the magnetic sample together with the cantilever energy determine the motion of the cantilever. In some cases, the magnetic energy of the magnetic sample in a magnetic field modifies the dynamics of the cantilever by adding an effective magnetic spring constant to the cantilever. This effective magnetic spring constant depends on the applied magnetic field and is determined by the magnetic moment and magnetic anisotropy of the sample. Therefore, measuring the change in frequency (i.e., the magnetic spring constant) of the cantilever as a function of applied magnetic field makes it possible to deduce the magnetic state (change) of the sample as a function of applied magnetic field.

A general analysis of DCM is available in Ref. [21], in which a theoretical model is presented for the general configuration of the sample, the cantilever, and the applied field. When the angles between the sample, the cantilever, and the applied field are set at some special values, the analysis of the change in frequency is greatly simplified [15]. For example, in a typical configuration in which the magnetic field is along the longitudinal axis of the cantilever (z direction), as shown in Fig. 1, DCM measures the magnetization process of the sample along the z axis. Therefore, depending on the magnetization behavior of interest in certain orientations of the sample, the sample is to be fixed onto the tip of the cantilever with its orientation aligned with the cantilever. For example, consider a disk sample: to measure its out-of-plane magnetization process, the disk should be fixed onto the cantilever such that the normal vector of the disk is parallel to the z axis, as shown in Fig. 1(a). However, to measure its in-plane magnetization process, the disk should be fixed parallel to the z axis, as shown in Fig. 1(b). Therefore, a reliable and practical method of sample preparation and transfer is very important for measuring the magnetization process of an arbitrary sample along a desired direction by DCM.

In the following, we describe our method of preparing and transferring individual samples onto an ultrasoft cantilever for DCM experiments. We start with nanosamples already on the surface of a nonmagnetic substrate, such as silicon or silicon dioxide. The nanosamples may

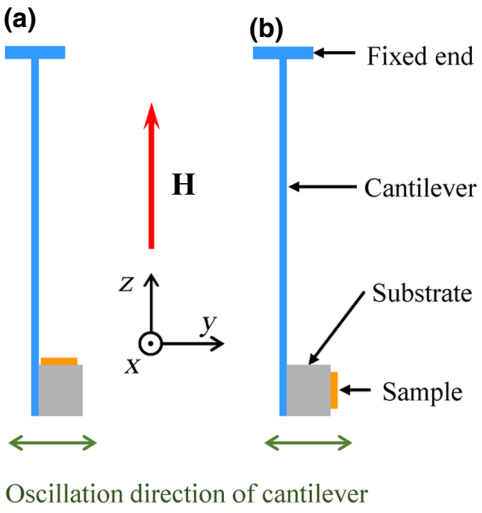

FIG. 1. Two typical DCM configurations for measuring the magnetization process of a disk sample. The disk sample (in orange, side view) together with the nonmagnetic substrate (in gray) is attached to the tip of the cantilever (in blue). A magnetic field is applied along the length of the cantilever (z direction) and the cantilever oscillates in the y direction. (a) The normal vector of the disk is parallel to the z direction, so the out-of-plane magnetization process of the disk is measured. (b) The disk is parallel to the z direction, so the in-plane magnetization process of the disk is measured.

be directly grown on the substrate by molecular-beam epitaxy, chemical vapor deposition, pulsed-laser deposition, or any other growing method. The nanosamples may also be transferred onto substrate surfaces by use of any possible method, such as spin coating with a liquid containing suspended nanosamples. As long as the nanosamples are on a nonmagnetic substrate, the proposed method may be applied. In this work, we apply this sample-preparation and sample-transfer method to three samples to demonstrate the process and explain the principles behind it. The first sample is a 100-nm-thick cobalt disk, 2.2 μm in diameter and cut from a 100-nm-thick cobalt film sputtered onto a silicon wafer. The second sample is a $CoFe_2O_4$ nanopyramid with a bottom width of about 90 nm and grown on a Nb-doped $SrTiO_3$ substrate. The third sample is Nb-doped $SrTiO_3$, which is expected to have essentially zero magnetic signal.

The processes involved in the proposed method are summarized below. Figure 2 shows snapshots of some key points in the preparation and transfer of the nanopyramid sample for DCM measurements. Each step is accomplished by use of an FEI Helios NanoLab™ 600i DualBeam (focused ion beam/SEM) system and a nanomanipulator (Omni probe 200) installed on the DualBeam system.

Step (a). Select a sample on the substrate. Record its location with respect to nearby features; for example, take

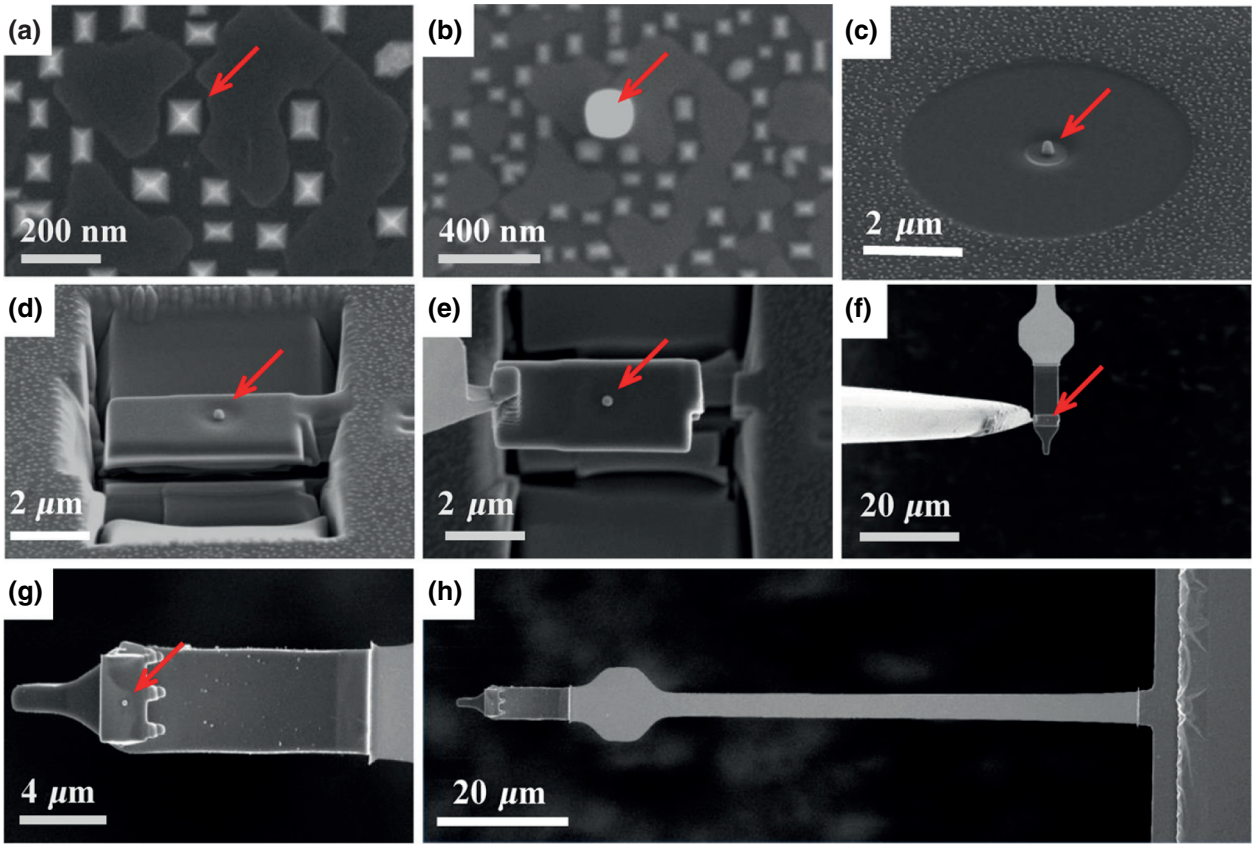

FIG. 2. Preparing and transferring an individual sample onto an ultrasoft cantilever for DCM experiments. The sample or its location is highlighted by the red arrows in the panels. (a) Choose a sample on the substrate. (b) Protect the sample from damage caused by the ion beam in subsequent processing by covering the sample with nonmagnetic material. Here 100 nm of platinum is deposited over the sample. (c) Remove all samples in the neighborhood of the selected sample by using the ion beam. (d) Use the ion beam to cut off the small piece of the substrate to which the selected sample is fixed. (e) Lift the small piece of the substrate with the selected sample by using the Omni probe. (f) Preset the orientation of the cantilever and align with the cantilever the selected sample fixed on the small piece of the substrate. (g) Fix the small piece of the substrate together with the selected sample onto the cantilever with platinum. (h) Final assembly of the selected sample and the cantilever.

a SEM image of the selected sample and its neighborhood [Fig. 2(a)].

Step (b). Protect the selected sample by depositing platinum on top of it. Depending on the sample, carbon or platinum may be chosen as the protective material. The protective material is deposited first by electron-beam deposition and then by ion-beam deposition to minimize any effect on the selected sample [Fig. 2(b)]. One could also protect the sample by covering it with a thin layer of poly(methyl methacrylate) or some other type of photoresist.

Step (c). Isolate the selected sample by removing any nearby samples or magnetic material. If any other magnetic samples are near the selected sample, remove them by using the ion beam. The ion-beam milling process is optimized for introduction of the least amount of magnetic material on top of the selected sample and in its near neighborhood. At the end of this step, we obtain the selected individual sample on the magnetic-free substrate [Fig. 2(c)].

Step (d). Cut off the selected sample together with a small piece of the substrate by using the ion beam. Leave a weak link between the small piece of the substrate and the main substrate to hold the selected sample in place [Fig. 2(d)]. Avoid introducing any magnetic material onto the small piece of the substrate and the selected sample.

Step (e). Pick up the selected sample by using the nanomanipulator. Fix the small piece of the substrate with the selected sample to the nanomanipulator by depositing platinum or carbon and cut the small piece of the substrate completely off the main substrate. Then pick up the selected sample, which is ready for transfer onto the tip of the cantilever [Fig. 2(e)].

Step (f). Preset the orientation of the cantilever and then align the selected sample and the small piece of the substrate with the cantilever. Depending on which orientation of the selected sample is to be measured, properly orient the cantilever by using the cantilever holder, and then place the small piece of the substrate with the selected sample

on top of the cantilever tip by using the nanomanipulator. In this work, we measure the magnetization process of the nanopyramid along one of the edges of its base plane, so we align the base plane of the pyramid with the cantilever surface and align an edge of the base parallel to the longitudinal axis of the cantilever [Fig. 2(f)].

Step (g). Fix the small piece of the substrate together with the selected sample onto the cantilever. This is done by depositing platinum or carbon over the cantilever and the small piece of the substrate, and then cutting the small piece of the substrate fully off the nanomanipulator. This completes the sample-preparation and sample-transfer processes, and the cantilever with the selected individual sample is ready to be put into the DCM system. Figure 2(g) shows the assembled cantilever and sample.

All three samples studied in this work are manipulated in accordance with this process. Note that the 2.2-μm-diameter cobalt disk is defined in step (c) when we draw a 2.2-μm-diameter circle on the cobalt film and remove all cobalt outside the circle by use of the ion beam.

III. DYNAMIC-CANTILEVER-MAGNETOMETRY EXPERIMENTS

To validate the proposed method for preparing and transferring samples and to determine how it influences the samples and the ultrasoft cantilevers, we use it to assemble three samples with cantilevers (see the parameter values in Table I) and perform DCM measurements with the resulting assemblies. The first two samples are made of ferromagnetic materials. The third sample is nonmagnetic and is used to benchmark the DCM measurements to verify the performance of the DCM system and determine how the ultrasoft cantilever is affected by having the sample fixed to it by the proposed method.

A. Sample 1: cobalt disk

The cobalt disk is made from 100-nm-thick cobalt film that is deposited on a thermally oxidized silicon wafer at room temperature by use of multisource magnetron sputtering. A 5-nm SiO_2 capping layer is deposited over the cobalt disk to protect it from oxidation. The cantilever used in this experiment is made from a commercial AFM cantilever (NanoWorld^{TM}) that is 0.9-μm thick. The base pressure of the sputtering system is less than 1×10^{-6} mbar and the working argon pressure is 5×10^{-3} mbar. The cobalt disk and cantilever are assembled by use of the method described in Sec. II.

We measure both the out-of-plane and the in-plane magnetization processes of the cobalt disk by using DCM (see Fig. 3). The experiments are done at 16 K. Transforming the change in the frequency of the cantilever into the magnetic momentum of an individual nanosample involves the details of the microscopic magnetic states of the sample, which may be obtained in certain situations [15]. For an individual sample with only one magnetic domain and uniaxial magnetic anisotropy, the frequency change of the cantilever can be quantitatively transformed into its magnetic moment and anisotropy [15]. In particular, at sufficiently high magnetic field, the sample is always magnetized at the saturation level, so it can be treated as a single-domain object whose magnetization is nearly aligned with the applied magnetic field. Thus, for samples with uniaxial anisotropy at large applied magnetic fields, the frequency change $\Delta f = f - f_0$ of the cantilever can be written as [15]

$$\Delta f = \begin{cases} \dfrac{f_0}{2k_0\frac{l_0^2}{\alpha^2}}\left(\dfrac{2HKV}{H+\dfrac{2K}{M_S}}\right) & \text{for } H > -\dfrac{2K}{M_S}, \\ \dfrac{f_0}{2k_0\frac{l_0^2}{\alpha^2}}\left(\dfrac{2HKV}{H-\dfrac{2K}{M_S}}\right) & \text{for } H < \dfrac{2K}{M_S}, \end{cases} \tag{1}$$

where f is the measured resonance frequency of the cantilever, f_0 and k_0 are the resonance frequency and the spring constant, respectively, of the cantilever with the sample on its tip and in an external magnetic field $H = 0$ T, l_0 is the length of the cantilever, α is a coefficient that translates the magnetic torque on the sample in the magnetic field into the force on the cantilever (α is related to the profile of the resonance mode of the cantilever and to the location where the magnetic sample is fixed to the cantilever), V is the volume of the sample, K is its anisotropy in the plane of the cantilever oscillation, and M_S is the saturation magnetization. On the basis of Eq. (1), reasonable estimates of the magnetic moment and magnetic anisotropy of the sample can be calculated from the change in the frequency of the cantilever. These magnetic parameters of nanomagnets are very useful in nanomagnetism research. Recall that Eq. (1) holds strictly only when a single-domain sample with a uniaxial magnetic anisotropy (such as a nanowire or a nanodisk) is magnetized to its saturation point and its magnetic moment is aligned with the applied magnetic field at sufficiently high magnetic field.

By fitting to Eq. (1) the frequency change as a function of H at high magnetic field (where the positive and negative sweeps overlap each other) for the configurations shown in Figs. 3(c) and 3(e), we obtain the saturation magnetization and magnetic anisotropy of the cobalt disk for in-plane magnetization and anisotropy as $M_S = 1150 \pm 150$ kA/m and $K = 650 \pm 50$ kJ/m^3, respectively. For out-of-plane magnetization and anisotropy, we obtain $M_S = 1400 \pm 50$ kA/m and $K = -700 \mp 40$ kJ/m^3, respectively. The derived values for the saturation magnetization are, within the error of the measurement, comparable to the value for bulk cobalt (1440 kJ/m^3) and are mainly

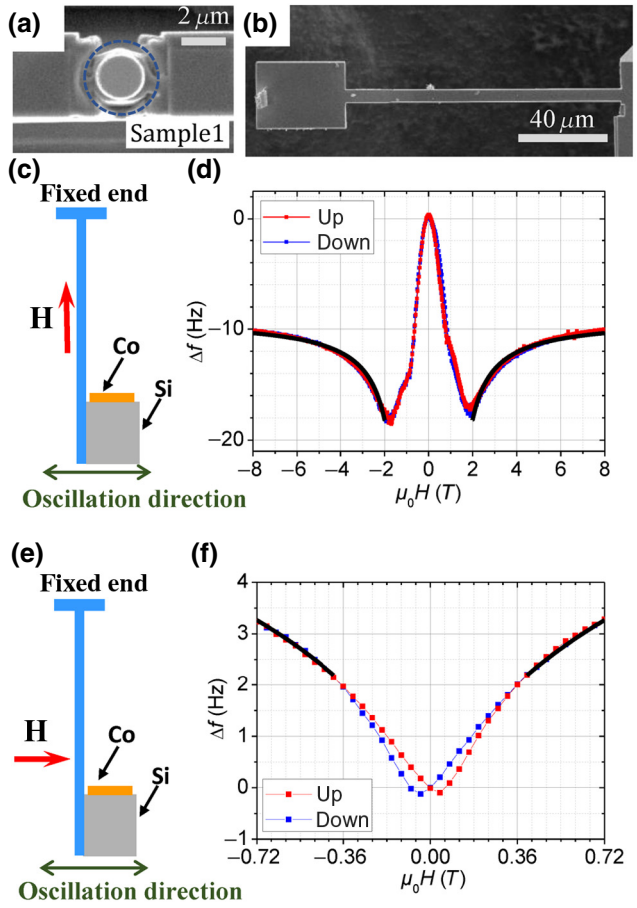

FIG. 3. Magnetization process of an individual cobalt disk probed by dynamic cantilever magnetometry. (a) The cobalt-disk sample is patterned by use of a focused ion beam. The disk is buried inside the pillar (in the blue circle). (b) Assembly of cobalt-disk sample and cantilever. The normal vector of the disk is parallel to the longitudinal axis of the cantilever. (c),(e) The DCM configurations. The disk is in orange in a side view. (d),(f) The change in the frequency of the cantilever with the magnetic field applied normal to the disk and parallel to the disk, respectively. The black curves are fits to Eq. (1).

determined by the coefficient α of the cantilever and the exact volume of the cobalt disk.

In general, it is difficult to accurately calculate the magnetic properties of a sample from the change in the frequency of the cantilever. However, some magnetic parameters of the sample, such as the coercive magnetic field and the saturation magnetic field, may be inferred qualitatively from the change in the frequency as a function of the applied magnetic field. For example, in Fig. 3(f), on the basis of the shift in the change in frequency between the upward and downward sweeps of the applied magnetic field, one may deduce the presence of a coercive magnetic field of about 0.05 T for the in-plane magnetization process of the cobalt disk. In addition, the magnetic field at which the changes in frequency between the upward and downward sweeps of the applied magnetic field coincide gives an approximation of the saturation magnetic field of the in-plane magnetization process of the cobalt disk. On the basis of these qualitative observations, the sample may be classified as ferromagnetic or paramagnetic.

B. Sample 2: $CoFe_2O_4$ nanopyramid

Another individual nanosample we measured by DCM was a $CoFe_2O_4$ nanopyramid. $CoFe_2O_4$ nanopyramids are fabricated by combining nanoseeded ($CoFe_2O_4$ and $BiFeO_3$) layer growth and oxide self-assembly on a Nb-doped $SrTiO_3$ substrate [3]. The parameter values of the nanopyramid and cantilever are listed in Table I.

We measure the magnetization process of the nanopyramid along one of its base edges by DCM. To do this, we configure the DCM experiment as shown in Fig. 4. The

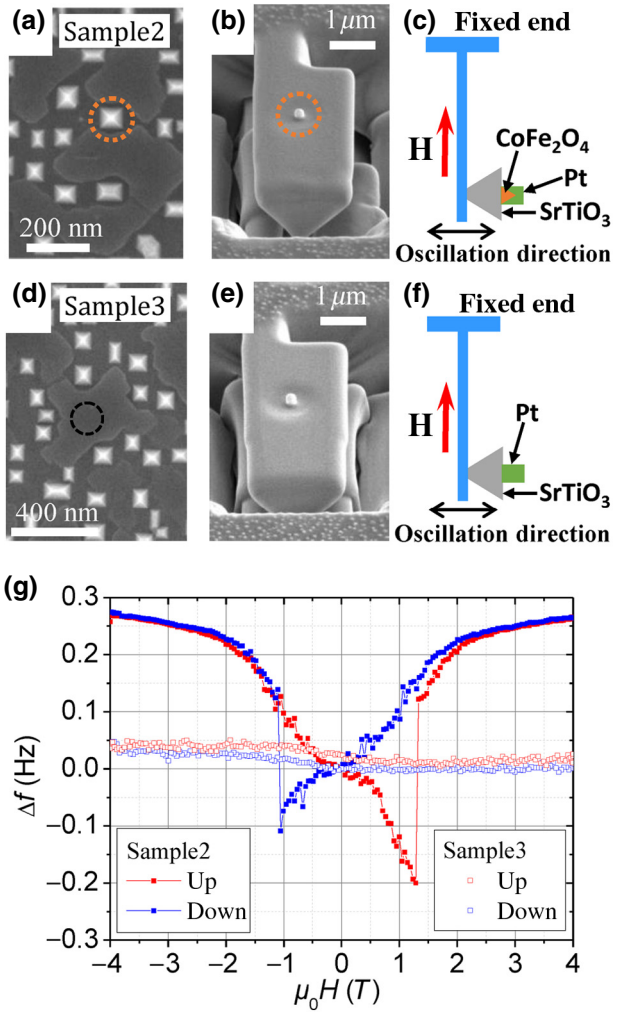

FIG. 4. Dynamic cantilever magnetometry of a magnetic nanopyramid and a nonmagnetic sample. (a),(d) The samples, (b),(e) the substrates, and (c),(f) the DCM configurations. (g) Change Δf in the frequency of the cantilever for the magnetic $CoFe_2O_4$ nanopyramid sample and the nonmagnetic $SrTiO_3$ sample.

orientations of the nanopyramid, the cantilever, and the applied magnetic field are shown in Fig. 4(c). The nanopyramid is fixed to the tip of the cantilever such that the base edge in its base plane is parallel to the longitudinal axis of the cantilever (i.e., the z axis). Then the change Δf in the frequency of the cantilever is recorded while a magnetic field is swept along the z axis, as shown in Fig. 4(g). The nanopyramid DCM experiment is done at 10 K in a high vacuum.

In both the positive sweep and the negative sweep of the magnetic field, there is only one jump in the frequency change of the cantilever, suggesting that the nanopyramid sample has a single magnetic domain. The jump in the positive sweep happens at 1.3 T, whereas the jump in the negative sweep happens at -1.1 T. The reversible jump is likely from the inversion of the magnetic domain. In addition, the magnetic field at which the jump happens reveals the energy needed to invert the magnetic domain. This information could provide useful clues in picturing the magnetic states of the $CoFe_2O_4$ nanopyramid. A systematic magnetic characterization of $CoFe_2O_4$ nanopyramids, including more DCM measurements of $CoFe_2O_4$ nanopyramids, was done in other work [3] and shows that $CoFe_2O_4$ nanopyramids have a switchable single-domain state.

C. Sample 3: nonmagnetic material

Bare silicon levers give no DCM signal. To determine whether our sample-preparation and sample-transfer method introduces a DCM signal, we perform a DCM measurement of a nonmagnetic sample that is prepared and transferred onto the same type of cantilever and in the same way as is the $CoFe_2O_4$ nanopyramid. Thus, this benchmark sample has a shape similar to that of the $CoFe_2O_4$ nanopyramid with its substrate [Fig. 4(b)], except that there is no nanopyramid [Fig. 4(e)]. The main materials used to fabricate the benchmark sample are Nb-doped $SrTiO_3$ and platinum. To reduce exposure of the cantilevers to the electron beam, we do not take images of the samples once they are transferred onto the cantilevers. We measure the change in the frequency of the cantilever as a function of the magnetic field. The data are plotted in Fig. 4(g) as open squares.

The change in the frequency of the benchmark sample is relatively smooth, and the maximum change is less than 0.04 Hz. This change in the frequency of the benchmark sample, which should be nonmagnetic, is not fully understood. Possible reasons for this change in the frequency due to a changing magnetic field include temperature fluctuations, the magnetic effects of platinum, and small deformations of the structure onto which the cantilever is installed. While the frequency jumps in the data for the $CoFe_2O_4$ nanopyramid are 0.2–0.3 Hz, the frequency fluctuations of the cantilevers at $H = 0$ T are about 0.01 Hz for a measurement time of 1 s for the cantilever. Therefore, the jumps probed by the DCM measurements of the $CoFe_2O_4$ nanopyramid must come from the nanopyramid itself, and can come neither from the substrate nor from from the sample-assembly process.

IV. CONCLUSION

In this work, we propose and demonstrate a sample-preparation and sample-transfer method for application of DCM to micrometer- and nanometer-sized samples. The method uses commercial instruments. Provided the nanosamples to be studied by DCM are placed or fabricated on the surface of nonmagnetic substrates, the method proposed herein can be used. For a typical magnetization of $CoFe_2O_4$ nanosamples of 40 emu/g and a density of 5.3 g/cm^3, magnetic domain inversion in the nanosample with a minimum magnetic moment of about 1.7×10^{-15} emu can be detected by our DCM setup. This gives an idea of magnetic sensitivity for DCM measurements when the proposed sample-preparation and sample-transfer method is used. This sensitivity for measuring magnetic moments suffices to detect magnetic inversion processes in individual sub-100-nm ferromagnetic samples, which is 10^7 times smaller than the sensitivity of commercial magnetometers, such as the MPMS products from Quantum Design. Thus, these results demonstrate the feasibility of measuring individual, arbitrary-sized magnetic nanostructures by using DCM with ultrasoft cantilevers, which reveals the significant potential of dynamical cantilever magnetometry in nanomagnetism research.

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