Damping of micromechanical structures by paramagnetic relaxation

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We find that the damping of micromechanical cantilevers is sensitive to the relaxation dynamics of paramagnetic ions contained within the levers. We measure cantilevers containing paramagnetic Mn ions as a function of temperature, magnetic field, and the vibrational mode of the lever and find that the levers' damping is strongly enhanced by the interplay between the motion of the lever, the ions' magnetic anisotropy, and the ratio of the ions' longitudinal relaxation rate to the resonance frequency of the cantilever. This enhancement can improve the levers' ability to probe the relaxation behavior of paramagnetic or superparamagnetic systems; it may also represent a previously unrecognized source of "intrinsic" dissipation in micromechanical structures. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1577385]

The damping of a micromechanical structure reflects the flow of energy from the structure's macroscopic motion into the microscopic degrees of freedom of its environment. This dissipation can provide quantitative information about the response of the environment to the motion of the structure. Electrostatic coupling,[1,2] magnetic domain wall motion,[3,4] thermoelastic effects,[5] and a number of other phenomena have been probed with exceptional sensitivity and/or spatial resolution by measuring their effect upon the dissipation of micromechanical structures. However, this dissipation also limits the ultimate sensitivity of measurements which use the narrow resonance of micromechanical structures to probe conservative forces (e.g., magnetic resonance force microscopy,[6] torsional magnetometry,[4] and some types of atomic force microscopy).[7] At present the dissipation mechanisms which limit such measurements are not well understood.

In this letter we demonstrate that a micromechanical cantilever's damping can provide a sensitive probe of the relaxation dynamics of paramagnetic ions contained within the lever. We measure the damping of cantilevers containing paramagnetic ions as a function of temperature, applied magnetic field, and the vibrational mode of the lever. We find that our results can be explained by a simple model in which energy from the macroscopic motion of the lever is coupled to the ions' magnetic anisotropy and then dissipated by their longitudinal relaxation. In addition to providing insight into the relaxation dynamics of small magnetic systems (of importance to their use in data storage or spintronic applications), the damping resulting from this effect may also play an important role in limiting the ultimate sensitivity of micromechanical oscillator measurements.

The paramagnetic ions studied here are Mn^{2+} in a $Zn_{0.87}Cd_{0.13}Se$ host. The spin-5/2 Mn ions are isoelectronic with their host material, and at the concentration of these samples ($\sim 1\%$) are known to be paramagnetic over the relevant temperature range.[8] The epilayers which form both the magnetic samples and the cantilevers are grown by molecular beam epitaxy (MBE) as a single hybrid III–V/II–VI heterostructure [Fig. 1(a)].

The heterostructure is patterned into free-standing 100-nm-thick GaAs cantilevers, each of which supports a mesa of the magnetic material. The fabrication of these integrated cantilever/sample structures has been described in detail previously.[9]

Figure 1(b) is a scanning electron microscopy (SEM) photo showing a cantilever of length $L=250$ μm supporting a 40 μm$\times$100 μm rectangular mesa of the paramagnetic II–VI material. The levers used in the measurements described here are nominally identical except that the sample mesas are 15 μm radius disks (containing $\sim 2\times 10^9$ Mn^{2+}

(a)

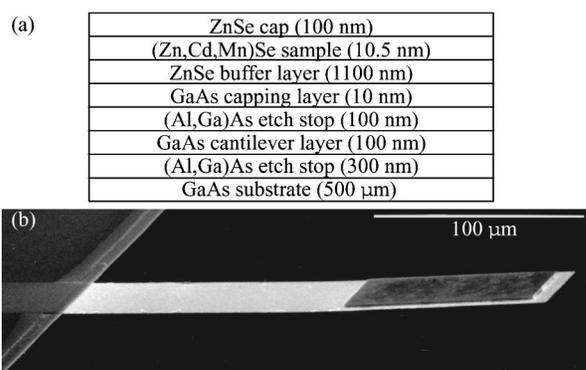| ZnSe cap (100 nm) |
|---|
| (Zn,Cd,Mn)Se sample (10.5 nm) |
| ZnSe buffer layer (1100 nm) |
| GaAs capping layer (10 nm) |
| (Al,Ga)As etch stop (100 nm) |
| GaAs cantilever layer (100 nm) |
| (Al,Ga)As etch stop (300 nm) |
| GaAs substrate (500 μm) |

FIG. 1. (a) Schematic of the MBE-grown heterostructure. The 10.5-nm-thick magnetic layer is grown as a digital alloy (seven iterations of: 1/16th monolayer of MnSe followed by 4 15/16th monolayer of $Zn_{0.87}Cd_{0.13}$Se). The etch stop layers are grown as a random alloy ($Al_{0.7}Ga_{0.3}$As). (b) SEM photo of a 100-nm-thick, 250 μm long cantilever supporting a rectangular mesa of paramagnetic (Zn,Cd,Mn)Se.

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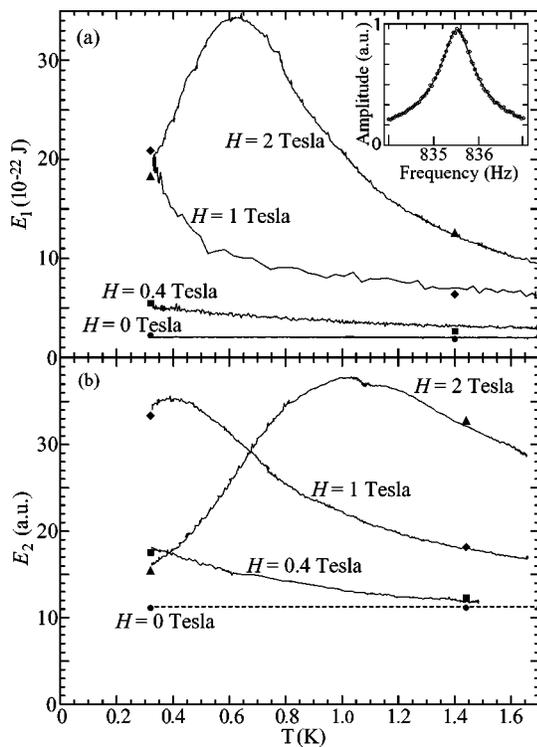
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FIG. 2. (a) ΔE_1 as a function of temperature for various values of the applied magnetic field. Inset: resonance curve of the lever at $T=0.32$ K, $B=2$ T (open points) and fit to a damped simple harmonic oscillator (solid line). (b) ΔE_2 as a function of temperature for various values of the applied magnetic field. In both plots the solid lines are taken as the temperature of the cryostat is slowly changed. The solid points ($\bullet$ $H=0$ T; $\blacksquare$ $H=0.4$ T; $\blacklozenge$ $H=1$ T; $\blacktriangle$ $H=2$ T) are from fits of the cantilever resonance taken at fixed temperature. The dashed line in (b) is a guide for the eye.

ions). Measurements were performed with the cantilevers mounted in a sorption-pumped ^{3}He cryostat[10] over a range of temperature 0.32 K$<T<$10 K. A magnetic field H was applied normal ($\pm\sim3°$) to the plane of the sample. A piezoelectric crystal was used to drive the cantilever with an amplitude x, which was measured by an optical fiber interferometer. The interferometer used a 1310 nm laser with $<$30 nW of power to minimize unintentional heating of the sample. For $T<10$ K, the lowest flexural resonance of the cantilever was $\omega_1/2\pi=835$ Hz. Similar structures were used in earlier work to measure the equilibrium magnetization M of integrated samples.[9,11] Here we focus exclusively on the damping of the cantilever.

The damping of the cantilever is characterized by the energy it dissipates in each period of its motion, $\Delta E_1 = \pi k_1 x^2/Q_1$. Here k_1 is the spring constant of the lever's lowest flexural mode (calculated from the dimensions of the lever to be 7×10^{-5} N/m) and Q_1 is the quality factor of the lowest flexural mode. We use two methods to determine ΔE_1: in the first we drive the cantilever at ω_1 using a phase-locked loop and vary the strength of the drive to maintain constant x (~100 nm). This drive is proportional to ΔE_1, but does not provide an absolute value. In the second method we measure the resonance curve of the cantilever and fit the data to extract Q_1. This approach is more time consuming, but provides an absolute value of ΔE_1.

Figure 2(a) shows ΔE_1 as a function of T for different values of H. The data shown as lines were taken using the first of these methods. The absolute scale of each curve in

Fig. 2(a) was then determined by measuring the resonance curve of the lever at several different values of H and T, shown as solid points in Fig. 2(a). One such resonance curve and its fit are shown in the inset of Fig. 2(a).

The data show a strong temperature dependence down to 0.32 K, indicating that thermal contact is maintained between the cantilever and cryostat. At temperatures below 2 K, the presence of a magnetic field produces a dramatic increase in ΔE_1. For $H=2$ T, ΔE_1 is peaked near $T=0.6$ K. This is in marked contrast to the data for $H=0$ T, in which ΔE_1 varies by only $\sim2\%$ over the same temperature range.

The data for $H=0$ T are similar to those from cantilevers which do not contain paramagnetic ions, and correspond to the lever's intrinsic (nonmagnetic) mechanical dissipation. The increase of ΔE_1 for $H>0$ T is only observed in levers containing paramagnetic ions. In order to understand the origin of this additional damping, we note that paramagnets in an oscillating magnetic field produce dissipation when their longitudinal relaxation rate $1/T_1$ and the frequency of the oscillating field are comparable. For Mn^{2+} in II–VI host materials, T_1 increases dramatically with decreasing T, and data[12] for $T>2$ K suggest that in the temperature range shown in Fig. 2(a), $1/T_1$ should approach ω_1, thereby making it possible for the motion of the lever to produce dissipation via the paramagnetic ions.

The oscillation of the lever in the static, uniform magnetic field H is equivalent to an oscillating magnetic field because of the nonzero (but weak)[13] magnetic anisotropy of the Mn^{2+} ions. This can be understood as follows: in a static applied field H the six Zeeman levels of the Mn^{2+} ion are each split by $E_z\approx g\mu_B H$, where g is the Landé g factor for Mn^{2+} and μ_B is the Bohr magneton. However, the presence of any magnetic anisotropy in the sample will cause E_z to depend also upon the angle θ between H and the sample.[14] Thus as the sample rotates with each oscillation of the lever,[15] the splitting of the Zeeman levels will change by an amount $\Delta E_z\approx\theta_1\partial E_z/\partial\theta$, where $\theta_1=1.377\,x/L$ is the amplitude of the sample rotation. This is formally equivalent to an oscillating magnetic field parallel to H of magnitude $H_{ac}^{eff}=\Delta E_z/g\mu_B$.

In order to compare this model with the data in Fig. 2(a) we note that for weakly anisotropic paramagnetic ions with a single relaxation time T_1 in an oscillating magnetic field H_{ac} of frequency ω superposed on a parallel static field H, the energy dissipated per period of the oscillating field is given by[16]

$$\Delta E = \pi H_{ac}^2 \chi_{dc} \frac{\omega T_1}{1+\omega^2 T_1^2}. \tag{1}$$

Previous measurements have shown that in these materials the dc magnetic susceptibility is given by $\chi_{dc}=\partial M/\partial H \propto \partial B_{5/2}(y)/\partial H$ where $B_{5/2}$ is the spin-5/2 Brillouin function, $y=5g\mu_B H/2k_B T_{eff}$, and the effective temperature $T_{eff}(T)$ is somewhat higher than the physical temperature and reflects the weak interactions between Mn ions.[17] If as a first approximation we make the assumption that χ_{dc} is the only quantity in Eq. (1) which varies appreciably with T or H, then the temperature dependence of each curve in Fig. 2(a) is simply that of χ_{dc}. In this case the $H=0.4$ T and $H=1.0$ T data can be understood as reflecting the condition $y\lesssim1$.
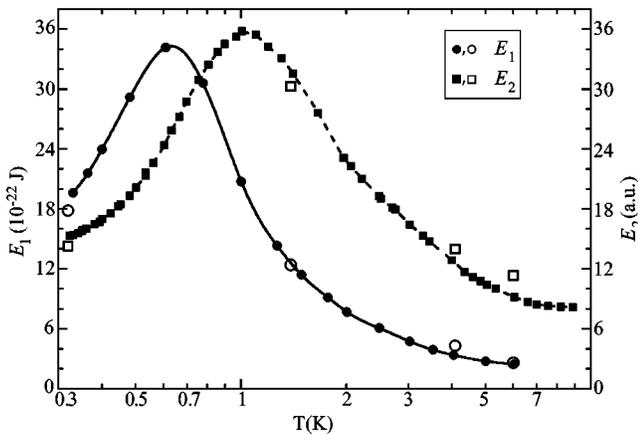
FIG. 3. ΔE_1 and ΔE_2 as a function of temperature at $H=2$ T. Each data point is acquired with the temperature of the cryostat held constant. Solid symbols are measurements of the drive amplitude required to maintain constant cantilever amplitude; hollow symbols are from fits of the cantilever resonance curve. The lines are guides for the eye.

When this condition holds $\chi_{dc}(T)$ and, hence, $\Delta E_1(T)$ exhibit Curie-like behavior (i.e., both increase roughly as $1/T$), as seen in the data of Fig. 2(a). For $H=2$ T, this condition is violated and as T decreases $\chi_{dc}(T)$ and hence $\Delta E_1(T)$ reach a maximum and then fall off, reflecting the saturation of the paramagnetic spins as $y \gg 1$.

We can refine this model by making use of the known trend of $T_1(T)$.[12,18] In order to do this we drive the cantilever at its second flexural resonance $\omega_2/2\pi=7625$ Hz and measure ΔE_2, the energy dissipated per period of the cantilever's second flexural mode. In this data [shown in Fig. 2(b)] the peak in ΔE_2 for $H=2$ T is shifted to nearly twice the temperature of the peak in the ΔE_1 data. Additionally, a peak emerges in the $H=1$ T data for ΔE_2, whereas no peak was observed in ΔE_1 for $H=1$ T down to 0.32 K [Fig. 2(a)].

This dependence of $\Delta E(T)$ upon ω results from the Drude-like term in Eq. (1). This term depends only upon the quantity $\omega T_1(T)$; because $T_1(T)$ decreases with increasing T, an increase in ω means that a given value of $\omega T_1(T)$ occurs at higher T. This shifts the overall curve of $\Delta E(T)$ to higher T when ω is increased from ω_1 to ω_2, as is observed in Figs. 2(a) and 2(b). Figure 3 illustrates this effect over a broader range of temperature for $H=2$ T.[19]

From this analysis we can conclude that in general the dissipation effects studied here are strongest when the following conditions hold: ωT_1 is of order unity, χ_{dc} is large, and the anisotropy (and, hence, H_{ac}^{eff}) is also large. In our measurements, the long relaxation time of the Mn^{2+} ions ensures that the first condition is approached at low temperature. However, χ_{dc} in these ions is merely typical for paramagnets, and their anisotropy is notably weak.[13] Given the dramatic impact upon the lever's dissipation observed here, the presence of even a small number of paramagnetic moments in a micromechanical structure (arising from unintentional impurities, broken bonds, or nuclear spins) may be a dominant source of dissipation. We note that the strong magnetic field and temperature dependence observed[4,20] in the dissipation of nominally nonmagnetic cantilevers may arise from these effects.

The ultimate sensitivity of a cantilever as a detector of paramagnetic relaxation is set by the minimum resolvable dissipation. In our current setup, the intrinsic (nonmagnetic) dissipation of the levers is typically $\Delta E_1(H=0) \sim 2 \times 10^{-22}$ J [Figs. 2(a) and 3] with changes of 1% resolvable in a 1 s measurement, corresponding to a sensitivity of 2×10^{-24} J. The present sample produces a maximum signal roughly 10^3 times larger than this [Figs. 2(a) and 3], implying a sensitivity to $\sim 2 \times 10^6$ Mn^{2+} ions. Because ΔE scales as the square of the magnetic anisotropy, a suitable choice of ion and host material may improve this sensitivity substantially. This enhancement may also allow this technique to be applied to the study of the relaxation of single magnetic nanoparticles or magnetic molecules, many of which satisfy the requirement of strong anisotropy, and whose relaxation rate is directly related to their crossover to superparamagnetic and quantum tunneling regimes.[21]

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