Standing Spin Wave Resonances in Manganite Films

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Doped manganites, such as La$_{0.66}$Ba$_{0.33}$MnO$_3$, have recently evoked great interest because they exhibit a giant magnetoresistance [1]. It is also clear that the electronic transport in these materials is strongly influenced by the spin ordering consequent upon the transition to the ferromagnetic state. Thus, it is of fundamental interest [2] to establish the characteristics of the low-lying excitations in the spin system. Provided that one can obtain a suitable thin film sample, the spin wave resonance technique furnishes the most direct method for accessing the spin wave stiffness $D$ in the dispersion relation, $\varepsilon = Dq^2$. In this note we report the first observation of several well-resolved modes in 100 nm thick films of La$_{0.66}$Ba$_{0.33}$MnO$_3$. Since the modes follow the quadratic dependence envisaged by Kittel [3], this provides a straightforward determination of $D$.

Films of La$_{0.66}$Ba$_{0.33}$MnO$_3$ (LBMO) were prepared by a pulsed-laser deposition technique [4]. For successful observation of standing spin wave resonances (SWR) over a wide temperature range, it was necessary to use carefully controlled deposition parameters. Full details will be presented elsewhere. In brief, starting with a (100) single crystal LaAlO$_3$ substrate, we first put down a 160 nm thick SrTiO$_3$ buffer layer, followed it with the LBMO film and eventually deposited a SrTiO$_3$ cap layer. This multilayer deposition was performed in situ using a multi-target holder, the deposition temperature being 700$^\circ$ C. The oxygen pressure was kept at 400 mTorr during deposition, and the sample was cooled to room temperature in 300 Torr of oxygen.

The thickness of the LBMO film was estimated to be 110 nm using Rutherford backscattering with a 1.5 MeV He beam obtained from a 1.7 MV tandem accelerator. A computer fitting program was used to iteratively adjust the thickness until the theoretical curve matched the experimental plot. The accuracy is about 10%.

Spin wave resonance (SWR) measurements were performed at 10 and 36 GHz for temperatures ranging from 100 to 300 K using conventional cavity techniques and field modulation [5].

Below 300 K, we observed 3 or more narrow ($\leq$ 100 Oe) lines. For example, Fig. 1 shows the observed spectrum at 10 GHz and 228 K, and one can clearly discern 5 modes. The effective wavelengths lie between about 60 $a$ and 550 $a$ where $a$ is the lattice parameter; i.e., the excitations are very close to the zone center. For a uniform ferromagnetic film whose spins are pinned at the film surfaces, simple SWR theory [3] predicts that in the perpendicular
geometry used here, resonances occur at fields $H_n$ such that

$$H_n = \frac{\omega}{\gamma} + 4\pi M - \frac{D}{\gamma h} \left( \frac{n}{\pi L} \right)^2$$  \hspace{1cm} (1)$$

where $\omega$ is the angular frequency, $\gamma$ the gyromagnetic ratio, $M$ the magnetization, $n$ the mode number and $L$ the film thickness. Shown in Fig. 2 is a plot of $H_n$ vs. $n^2$. The agreement with Eq. (1) is very good. As predicted by Kittel [3] the line intensities vary roughly as $1/n^2$. As a further check, it was confirmed that, at a fixed temperature, $(H_{n-2} - H_n)$ is the same for both 10 and 36 GHz. In Fig. 3, we display the normalized temperature dependence of $D$. Spin-wave theory [6] suggests that

$$D(T)/D(0) = \left( 1 - \alpha T^{5/2} \right)$$  \hspace{1cm} (2)$$

The full line in Fig. 3 represents Eq. (2) with $\alpha = 2.9 \pm 0.3 \times 10^{-7}$ K$^{-5/2}$, a reasonable value [7]. From the data we compute that the zero-kelvin value is $D(0) = 47 \pm 8 \text{ meV}\AA^2$. This result is at least a factor of seven smaller than the value estimated by Millis et al. [2] from the measurements of the zone-boundary magnon frequency (See Ref. 8 of [2]) in La-Pb manganite. The magnon energy is also much lower than would be implied by the band-theory results quoted by Millis et al.[2] Since the present experiments measure the magnon energies at the zone center, they are clearly more reliable to fix the value of $D$. The only source of error in $D$ arises from the determination of the film thickness which, as noted above, is accurate to 10%. Finally, one should note (Fig. 1) that the lines broaden as the mode number is increased. A thickness variation of $\Delta L$ will give an additional contribution to the linewidth $\Delta H_n$ given by

$$\Delta H_n = \frac{2D}{\gamma h} \left( \frac{n}{\pi L} \right)^2 \frac{\Delta L}{L}$$  \hspace{1cm} (3)$$

A 3% variation in the film thickness is sufficient to account for the line broadening seen in Fig. 1. It also accounts for our inability to observe higher order resonances. In conclusion, we report measurement of spin wave resonances in a thin film of the GMR manganite La$_{0.66}$Ba$_{0.33}$MnO$_3$. The zero-kelvin stiffness coefficient $D(0)$ is rather small, $47 \pm 8 \text{ meV}\AA^2$. The $T$ dependence of $D$ is consistent with simple spin-wave theory. It is expected that with an accurate value of $D$ becoming available, it will be possible to achieve a more meaningful development of theoretical models.
**References**

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Figure Captions

Fig. 1. SWR spectrum at 10 GHz and 228 K. Note that the field span is 6700 to 9950 Oe. One can clearly distinguish 5 distinct modes.

Fig. 2. $H_n$ vs. $n^2$ for 10 GHz and 228 K. The linearity, as expected for Kittel modes, is quite satisfactory. Notice that the ordinate begins at 6000 Oe.

Fig. 3. Temperature dependence of the normalized spin wave stiffness. The full curve represents $(1 - 2.9 \times 10^{-7} K^{-5/2} T^{5/2})$. 
