Microwave absorption studies of Mn-based perovskites

S. M. BHAGAT AND S. E. LOFLAND

Dept. of Physics, University of Maryland, College Park, MD 20742-4111 USA

S. D. TYAGI

Dept. of Physics and Atmospheric Sciences, Drexel University, Philadelphia, PA 19128 USA

M. A. MANHEIMER

Lab for Physical Sciences, College Park, MD 20742 USA

We review recent studies of microwave absorption in a few prototypical manganites which exhibit colossal magnetoresistance. Ferromagnetic resonance measurements show that most bulk samples are far from homogeneous. Careful control of deposition parameters yields thin films with greatly improved homogeneity. The best films were used to observe spin wave resonances and obtain the spin wave stiffness parameter. Surface impedance measurements in zero field and applied fields show quite unexpected cross-overs from normal (ReZ $\propto \sqrt{\rho}$ or ρ) to inverted (ReZ $\propto 1/\sqrt{\rho}$ or ρ) behavior. The magnetoresistance at 10 GHz is even larger than that in the dc studies. Ferromagnetic antiresonance signals are used to get colossal magnetoimpedance (60% in 60 mT) as well as demonstrate that the ferromagnetic transition is continuous (second order).

Key words: magnetoresistance, microwave absorption, Mn-perosvkites.

Estudios de Absorción en Microondas en Perovskitas basadas en Mn.

Se revisan los estudios recientes de absorción en microondas de algunas manganitas que presentan efecto de magneto resistencia gigante. Las medidas de resmancia ferromagnética muestran que la mayoría de las muestras masivas están lejos de ser homogéneas. Un cuidadoso control de los parámetros de deposición de películas delgadas permite su obtención con una gran homogeneidad. Las mejores películas fueron utilizadas para observar la resonancia de la onda de spin y obtener los parámetros de dureza de la onda de spin. Las medidas de impedancia en superficie a campo cero y bajo campo aplicado muestran un inesperado cruce desde la conducta normal (ReZ $\propto \sqrt{\rho}$ or ρ) hacia la invertida (ReZ $\propto 1/\sqrt{\rho}$ or ρ). La magnetoresistencia a 10 GHz es aún mayor que en los estudios de cc. Las señales de antirresonancia ferromagnética son usadas para obtener magnetoimpedancia gigante (60% in 60 mT) así como demostrar que la transición ferromagnética es continua (segundo orden).

Palabras clave: magnetoresistencia, absorción en microondas, magnanitas.

1. INTRODUCTION

The Mn perovskites $R_{1-x}D_xMnO_3$, where R is a trivalent rare earth such as La, Y, or Nd and D a divalent alkaline earth such as Sr, Ca, or Ba, although known for a long time, (1) have become the focus of very intense studies in the recent past. (2) Much of the excitement is driven by the observation of very large changes in the dc resistivity on application of a magnetic field of ~ 5 T. Further, for $0.2 < x < 0.4$, the materials exhibit a transition to the ferromagnetic state when the temperature T is lowered, and this is often accompanied by a large drop in the dc resistivity ρ_{dc}. This observation led Zener (3) to propose a novel exchange mechanism, the so-called double exchange (DE), which fundamentally ties spin alignment to enhanced conductivity. That is, in order for an electron to get de-localized it is essential to have parallel spins at the two sites between which the hopping takes place. Although DE is quite successful in explaining some of the transport phenomena, it is clear that it is not the whole story, especially since in the paramagnetic state, the resistivity often appears to be activated (4) and polaronic, and one must invoke Jahn-Teller and other lattice effects to complete the picture.(5)

A vast majority of the research on the manganites is concentrated on dc magnetotransport studies using polycrystalline and thin-film samples. The Maryland group has done its share of such researches.(6) However, realizing that in a doped material the local chemistry is difficult to control but can be rather important in determining the properties of interest, we initiated studies on the magnetic resonance in the ferromagnetic phase of the perovskite manganites. Ferromagnetic resonance (FMR) is very demanding of magnetic homogeneity and uniformity since both the position and width of the resonance are strongly influenced by the fields «seen» by the spins. That is, any variations in the internal fields caused by departure from perfection would be directly revealed by FMR even if other structural studies suggested that the sample was of «high quality.» As we shall see, by combining FMR data with other investigations, our group has managed to produce some of the most uniform thin films available at this time. Starting with large values such as ~ 0.1 T, the FMR linewidths have been reduced to 2 mT.(7) In turn, this has allowed us to observe spin wave resonances (SWR) and effect the first determination of the spin wave stiffness in these systems.(8) The FMR technique also enables one to explore the effects of strains consequent upon mismatch with the substrate (9) as well as those arising from differential thermal expansion.(10) We have obtained

Bol. Soc. Esp. Cerám. Vidrio, 36 [2-3] 93-99 (1997)

93

direct signatures of the distribution of Curie temperatures in the specimen and by using a microwave «microscope» scanned a sample for gross inhomogeneity.

It was also felt that measurements of the surface impedance at high frequencies, both in zero field and applied magnetic fields, would shed further light on the transport mechanisms as well as demonstrate the utility of these materials for possible microwave device construction. These investigations have led to several novel results.(11) First we studied the conduction electron response. That is, the absorption of microwaves controlled by the resistivity. As we shall see, (i) in thin films, the surface resistance (R_s) changes from the normal ρ/t (t film thickness) form to an inverted $1/\rho$ dependence if $\rho > 1$ mΩ-cm; (ii) in thick samples also R_s exhibits both normal ($\sqrt{\rho}$) and inverted ($1/\sqrt{\rho}$) behavior depending on the sample thickness and ρ_{dc}. Finally, in bulk $Nd_{0.7}Sr_{0.3}MnO_3$ (NSMO) we have found a microwave giant magnetoresistance at 1 T which is nearly twice as large as the corresponding dc value.(12)

Next we focused on the microwave absorption arising from the dynamic permeability μ, well away from the FMR regime. In bulk, this gives $R_s \propto R_e\sqrt{i\mu}$, and with a judicious choice of ω/γ (ω being the angular frequency of the microwaves and γ the gyromagnetic ratio) we were able (13) to trace out the ferromagnetic antiresonance (FMAR) (sharp dip in absorption when $\omega/\gamma = \mu_0 M(T)$ where M is the magnetization) by varying T in the neighborhood of the Curie temperature T_C. This effect has been exploited to yield a colossal low-field magneto-impedance (50% for $\mu_0 H \sim 30$ mT) as well as to show that the ferromagnetic transition in single crystal $La_{0.7}Sr_{0.3}MnO_3$ (LSMO) is indeed second order.

Here we will briefly review some of the highlights of our investigations while full details can be found in other publications from this laboratory.

2. SAMPLES AND EXPERIMENTAL METHODS

The thin film samples used in the present investigation were prepared at Maryland in the laboratories led by Profs. R. Ramesh and T. Venkatesan. The method employed is pulsed-laser deposition onto a variety of substrates. In order to obtain the most homogeneous films, it is necessary to control the deposition parameters very carefully. Complete details can be sought in Ref. 14. In addition to the investigations reported here, the films were characterized by x-ray diffraction, Rutherford back-scattering, ion-channeling, and atomic force microscopy.

The single crystal specimens come from Dr. Mukovskii's group in Moscow. For the FMR studies, they were cut to yield thin (~ 0.5 mm) slices and polished with diamond paste.

The target materials have been purchased from SSC where they were made by a proprietary process.

The FMR was studied using conventional microwave techniques.(7) Measurements were made with the applied field H in the sample plane (parallel geometry) or rotated out of the plane. The perpendicular geometry refers to H being normal to the sample surface. The ac susceptibility χ_{ac} was measured using a locally built two-secondary counterwound transformer(15) which allows for not only the measurement of χ_{ac} but also direct monitoring of the field derivative of the ferromagnetic hysteresis loop with maximal applied fields ≤ 5 mT. The microwave absorption studies were done using the cavity perturbation technique, (11) the sample being located at the site of

the maximum of the microwave magnetic field b which is parallel to the surface.

3. RESULTS AND DISCUSSION

3.1 Ferromagnetic Resonance

In a high quality ferromagnetic metal one should expect (12) to observe an FMR linewidth which is sensibly independent of T when $T < 0.9\ T_C$ but rises rapidly for $T > T_C$. Any deviation from such a dependence at low T is a direct indicator of magnetic inhomogeneity. Fig. 1 shows the observed temperature dependence of the parallel geometry FMR width $\Gamma_{||}$ in an as-grown film of $La_{0.67}Ba_{0.33}MnO_3$ (LBMO) as well as the same film after it had been heat treated for 3 days at 1000° C in an O_2-rich atmosphere. The reduction in the low T value of $\Gamma_{||}$ is truly dramatic. However, since g ~ 2 in these materials, it was felt that even this width was too large. A systematic study (17) involving variation of deposition temperature, oxygen pressure, etc. finally led to the perpendicular geometry linewidth $\Gamma_{\perp}$ variation shown in Fig. 2 for LBMO and LSMO films
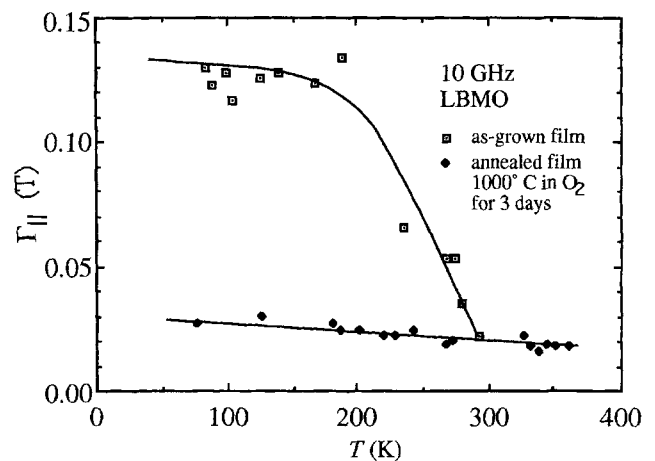

Fig. 1. *Parallel geometry FMR linewidth in LBMO films. Note the dramatic reduction on annealing.*
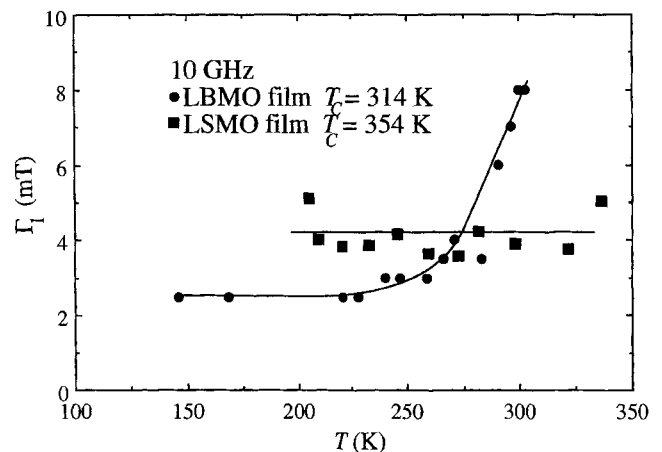

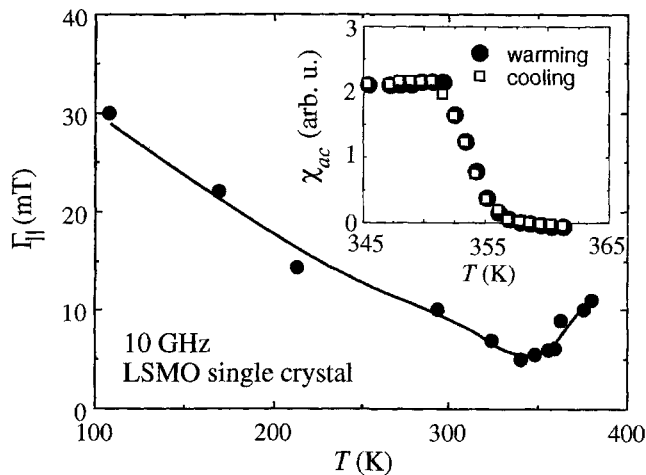Fig. 2. *T variation of the linewidth of the n = 1 SWR modes. Note $\Gamma_\perp$ is nearly independent of T below T_C.*

Fig. 3. T dependence of the FMR linewidth in LSMO single crystal. The inset shows a sharp transition, but the low-T increase in $\Gamma_{||}$ is symptomatic of residual inhomogeneity.
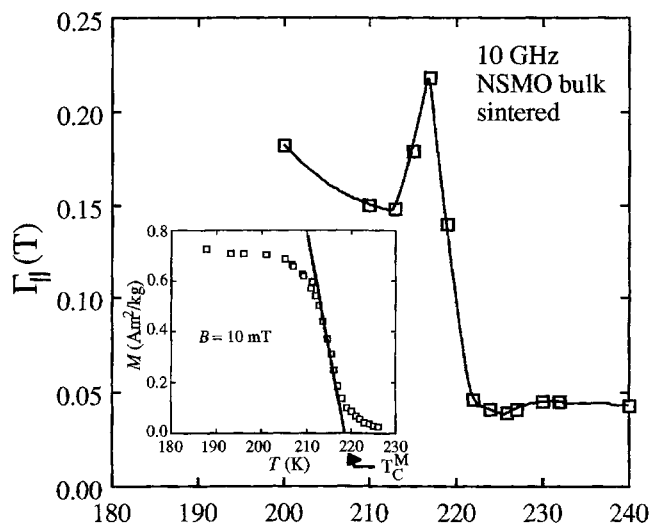

Fig. 4. FMR linewidth in bulk NSMO at T close to T_C. The peak [18] arises because the sample does not have a single T_C value.

on $LaAlO_3$. As we shall see, in this geometry one observed SWR, and Γ_1 refers to the width of the lowest order spin wave mode. The intrinsic FMR width at 10 GHz is therefore only a few mT, and one should be very suspicious of detailed models which have been proposed to account for the large observed FMR widths.

Fig. 3 shows the T variation of $\Gamma_{||}$ in a single crystal of LSMO. From the inset it can be noted that the ferromagnetic transition is quite sharp. However, the slow increase with lowering T again suggests that the single crystal is far from perfect even though x-ray and other structural studies may suggest otherwise.

Variation in local chemistry can easily lead to a macroscopic sample having a distribution of T_C values. The FMR linewidth again is a very good tool for revealing this.(18) An example is the case of a sintered cuboid of NSMO shown in Fig. 4. Whereas the low-field dc magnetization exhibits a sharp transition, $\Gamma_{||}$ shows a peak characteristic of a material with a T_C spread of ± 10 K. To summarize, it is our experience that,

barring single crystals, all bulk samples of manganites have quite sizable widths in their T_C distribution. Quite often, attempts are made to identify «T_C» with the temperature at which the zero-field resistivity has a peak. Such identification must be treated with care.

3.2. Spin wave resonance

Once the FMR in the perpendicular geometry became sufficiently narrow, it became possible to resolve several SWR modes.(8) In a perfect ferromagnetic thin film of thickness t with identical spin pinning on both surfaces one should expect to observe a series of SWR modes whose field positions H_n satisfy

$$\mu_0 H_n = \frac{\omega}{\gamma} + \mu_0 M - \frac{D}{\gamma \hbar}\left(\frac{n\pi}{t}\right)^2 \qquad [1]$$

with n, the mode number, being only odd. In most films, however, slight deviations from homogeneity and/or asymmetric spin pinning yield SWR spectra in which both odd and even modes occur. This is indeed the case in the present LSMO-on-Si and LBMO films (Figs. 5 a,b). The slope of the lines give a spin wave stiffness D around 100 meV-$Å^2$ at room temperature. In the LBMO case one could follow the SWR over a wide range of T and check that the T dependence of D was in accord with conventional theory (Fig. 5c). Unfortunately, the behavior of the LSMO film was strongly influenced (10) by the large difference in the thermal expansion coefficients of LSMO and Si. The SWR was measurable only for 280 < T < 310 K.

3.3 Zero-field surface resistance

The surface impedance Z of a sample of thickness t and resistivity ρ immersed in a rf b field should be written as

$$Z = \alpha^2 k\rho \coth kt + (1 - \alpha)k\rho \tanh(kt / 2) \qquad [2]$$

where $k = (-i\mu_0\mu\omega/\rho)^{1/2}$ and α is a measure of the difference between the b field at the two surfaces. α = 0 implies symmetric excitation while for α = 1, the b field is non-zero at only one surface. It has been shown severally (19) that for studying the contribution from the conduction electrons (i.e. μ = 1, dependence of Z on ρ) one should neglect the symmetric term. One then gets for the real part of the surface impedance

$$R_s = (\mu_0\omega\rho)^{1/2} \qquad [3]$$

for bulk samples, i.e. $t \gg \delta = (2\rho/\mu_0\omega)^{1/2}$ the electromagnetic skin depth, and

$$R_s = \rho/t \qquad [4]$$

for thin films. We designate Eqs. [3] and [4] as indications of normal behavior. In our systematic studies of the zero-field surface resistance of perovskite thin films and bulk manganite samples, we find, to our surprise, that Eqs. [3] and [4] do not
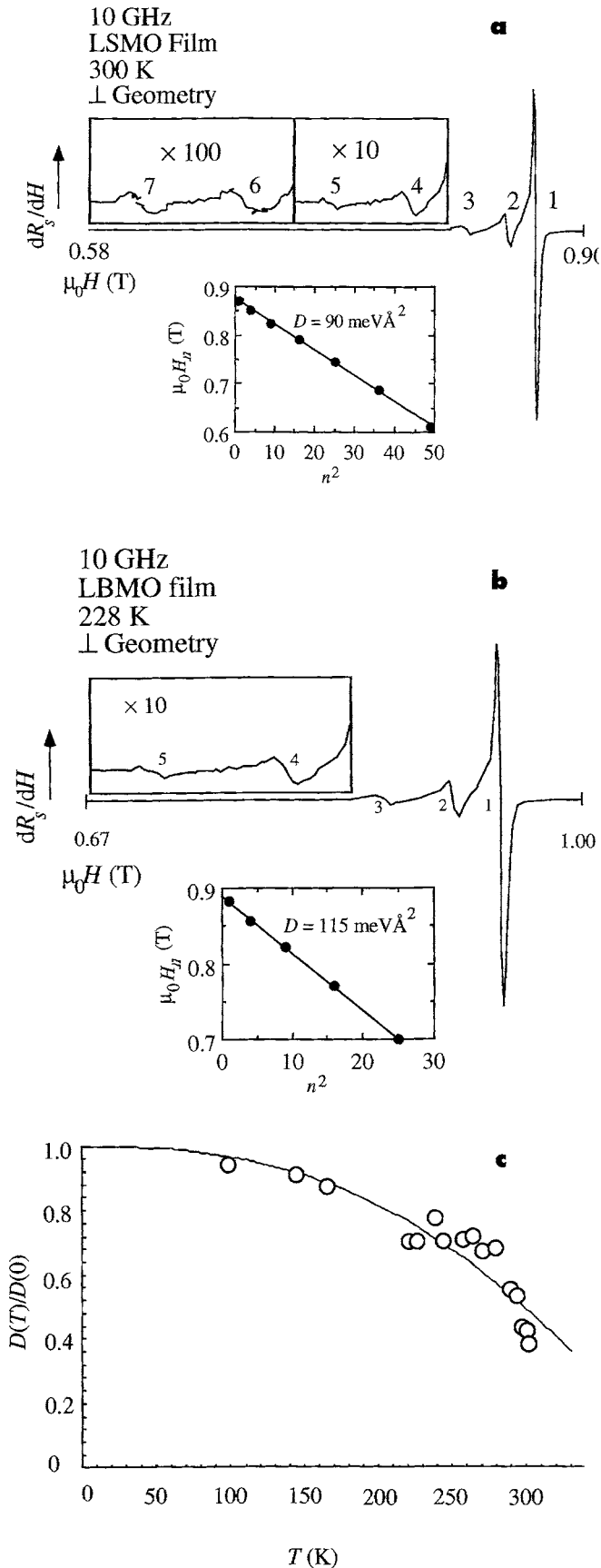
95

Fig. 5. *a. SWR in LSMO film. Inset shows n^2 dependence, Eq. [1]. The slope yields the indicated D value. b. Same as a. but for LBMO film. c. T variation of the spin wave stiffness. The full line represents $T^{5/2}$ as expected from spin wave theory.*
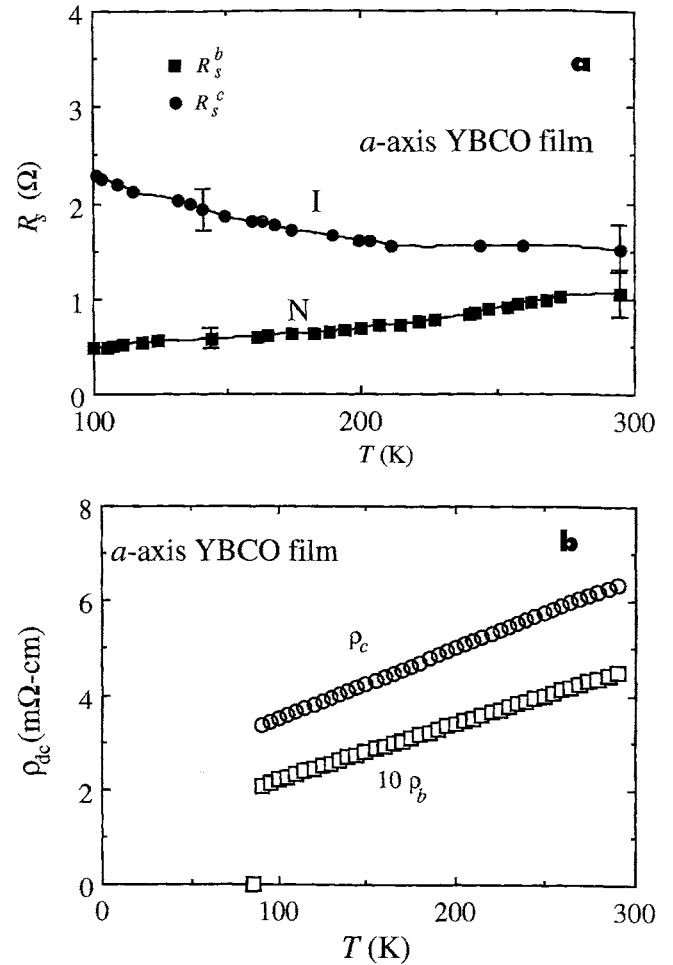

Fig. 6. *a. Temperature dependence of the surface resistance in an a-axis-oriented YBCO film. b. dc resistivity of an a-axis-oriented YBCO film. Note that $R^b{}_c$ is normal ($\propto \rho$), designated N, while $R^c{}_s$ is inverted ($\propto \rho^{-1}$) and marked I.*

hold in all cases. Figs. 6 through 8 show the effect in a straightforward manner. Figs. 6 a,b show the observed R_s and the corresponding ρ_{dc} for an *a*-axis-oriented film of $YBa_2Cu_3O_7$ (YBCO). Note that R_s^b (rf currents flowing along the *b* axis) scales with $\rho^b{}_{dc}$ while R_s^c varies as $\rho^c{}_{dc}{}^{-1}$. This phenomenon occurs when the sample is rotated in situ so that the only change is with the direction of the microwave currents. Figs. 7 a-c compare the R_s vs. *T* behavior of $La_{0.7}Sr_{0.3}CoO_3$ (LSCO) and NSMO with the dependences exhibited by the respective ρ_{dc}s. Again, LSCO is normal ($R_s \propto \rho_{dc}$) while NSMO is inverted ($R_s \propto \rho_{dc}^{-1}$). Systematic studies lead us to suggest that the crossover occurs at $\rho_{dc} \sim 0.1$ Ω-m. This was totally unanticipated. However, the surprise becomes even more dramatic when one compares the R_s of a high-density (~80%) NSMO 1-mm-thick sintered sample (max ρ_{dc} = 220 mΩ-cm) with that of a low-density (50%) NSMO target (max ρ_{dc} = 2.5 Ω-cm) slice of thickness 0.5 mm. Whereas the former is normal the latter is inverted (Fig 8 a,b). In fact, Fig. 8b shows the microwave resistivity $\rho_{\mu w}$ using $R_s \propto 1/\sqrt{\rho_{dc}}$ Once $\rho_{\mu w}$ is scaled to ρ_{dc} at 300 K the *T* dependences are identical except below T_C (~ 215 K) when the microwave resistivity is strongly suppressed. This is most probably a consequence of the granularity and poor connectivity of a low-density specimen.

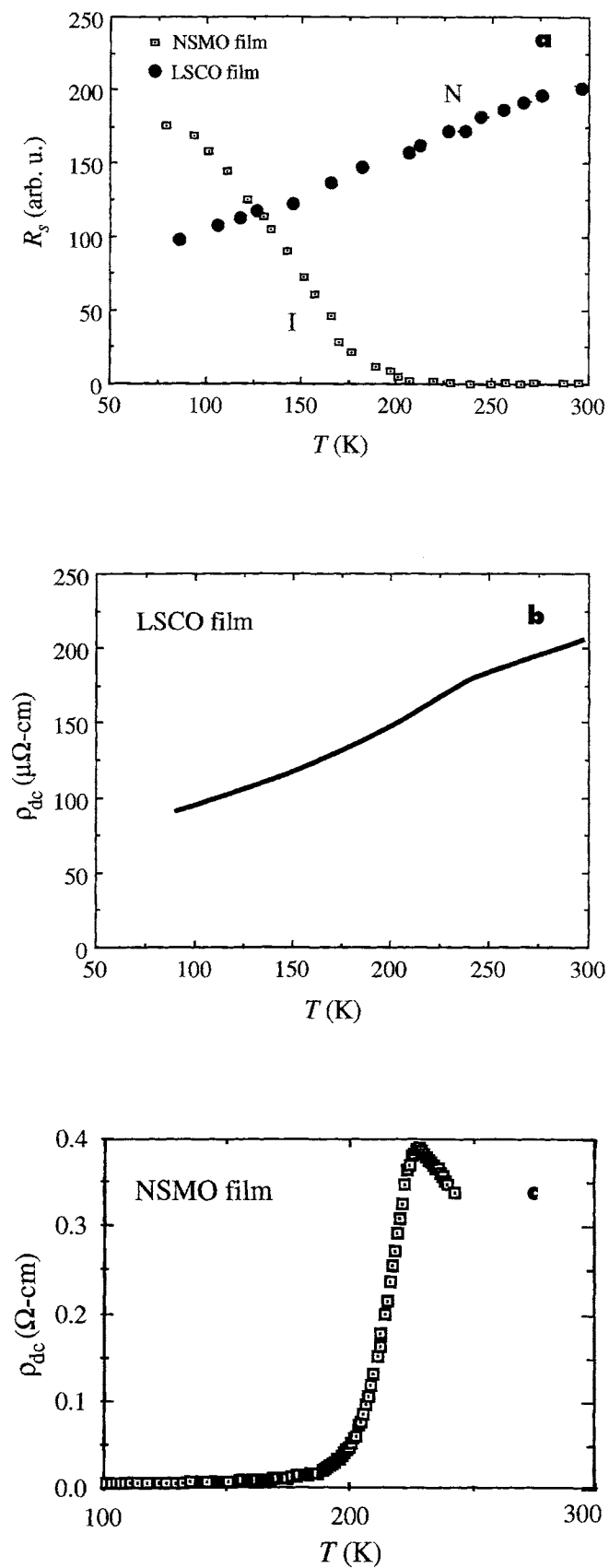It should be noted that the switch over from normal to inver-

Fig. 7. *T-dependence of a. the surface resistance in LSCO and NSMO films, b. the dc resistivity of LSCO film, and c. the dc resistivity of NSMO film. The surface resistance of the LSCO film is normal ($\alpha\,\rho$), while that of the NSMO film is inverted ($\alpha\,\rho^{-1}$).*
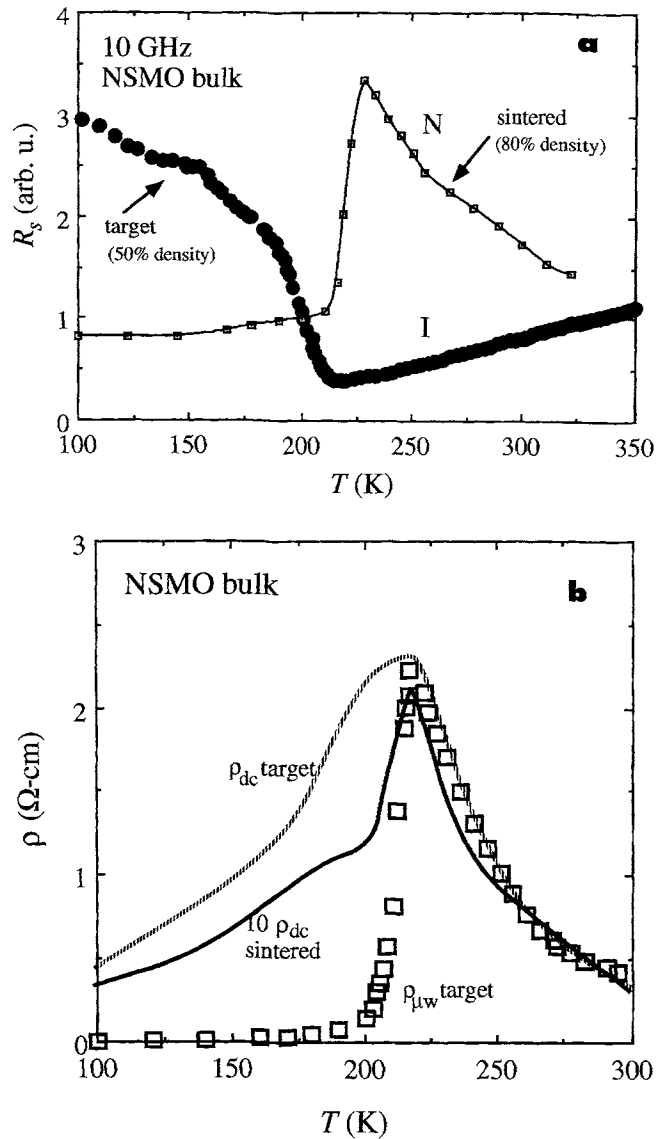

Fig. 8. *T-dependence of a. the surface resistance b. dc resistivity in two NSMO bulk samples. Here the sintered sample shows normal response ($R_s \propto \sqrt{\rho dc}$) while the target has $R_s \propto 1/\sqrt{\rho dc}$. It is to be noted that for the target $\rho_{\mu w}$ at low T is much smaller than ρ_{dc}.*

ted behavior is far from understood but received its most convincing support from the recent observations on a 0.2 mm thick single crystal of the layered material (20) $La_{1.2}Sr_{1.8}Mn_2O_7$ (Fig. 9 a,b). In this case, R_s exhibits inverted behavior from 300 K to about 110 K. At lower T, R_s is proportional to $\sqrt{\rho_{dc}}$. Again the crossover seems to be driven by some characteristic value of ρ_{dc} for a fixed t. Considerable systematic work will be necessary to fully settle the parameter values, but we have found that if the layered sample is ~ 1 mm thick there is no inversion at any T.

3.4. Microwave giant magnetoresistance (MGMR)

Our laboratory was the first to report a giant magnetoresistance at microwave frequencies.(12) As an example, Fig. 10 shows the observation of MGMR = $[\rho_{\mu w}(0) - \rho_{\mu w}(H)]/\rho_{\mu w}(0)$
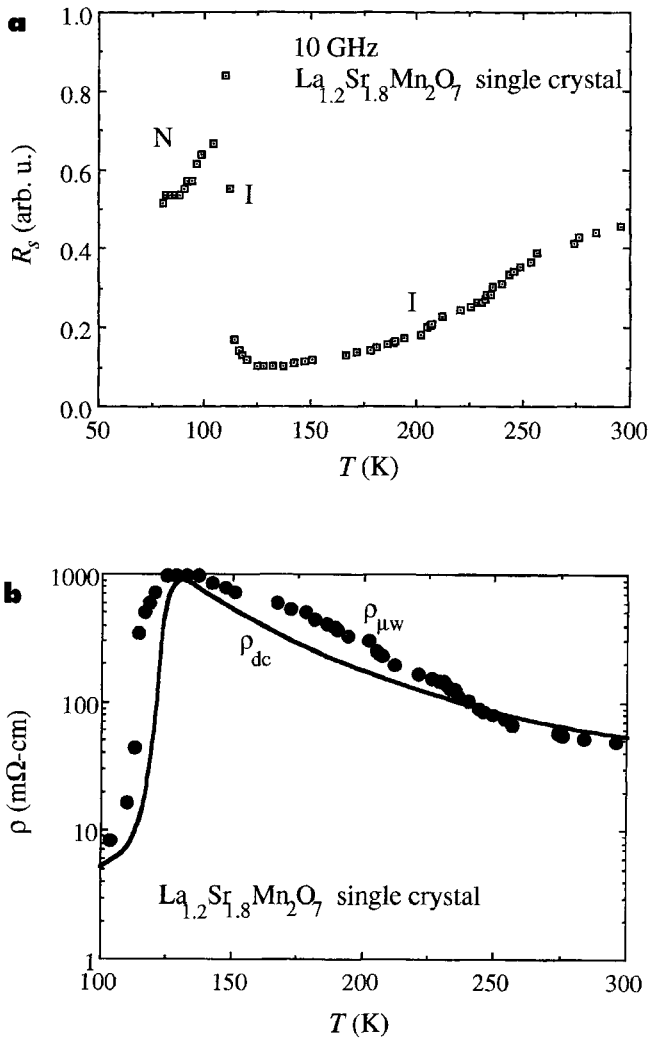
Boletín de la Sociedad Española de Cerámica y Vidrio. Vol. 36 Núms. 2-3 Marzo-Junio 1997

97

Fig. 9. *T variation of a. surface resistance, b. dc resistivity of layered perovskite. Here the cross-over from normal (N) to inverted (I) behavior occurs as a function of T.*
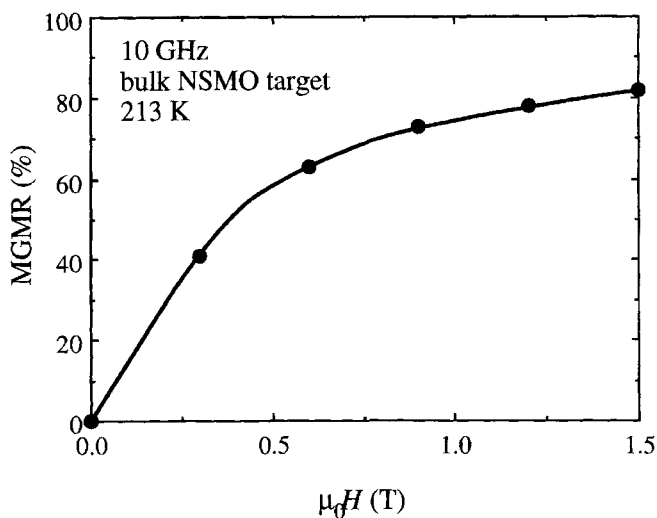

Fig. 10. *Microwave GMR in bulk NSMO. Note that this is among the largest effects seen so far.*

just below T_C, on the bulk NSMO target slice. A 70% effect at 1 T is among the largest reported so far. The initial slope is much higher so that the low-field GMR yields $(\partial \ln \rho_{\mu w}/\partial B) = 1.5$ T^{-1}.

3.5. Low-field giant magneto-impedance (13)

Here we consider the field dependence of R_S arising form the field variation of the dynamic permeability μ far from the FMR regime. For a bulk disk-shaped sample, in the parallel geometry, it has been known for a long time that R_S being proportional to $R_e \sqrt{i\mu}$ one should observe a sharp dip in R_S when

$$\frac{\omega}{\gamma} = \mu_0 (H + M).$$ [5]

Technically, this is the so-called ferromagnetic antiresonance (FMAR). From Eq. [5] it is clear that for $H = 0$ and ω fixed one could «tune» the system by varying M. This is most conveniently accomplished by varying T in the neighborhood of T_C because in that regime M varies rapidly with T. Fig. 11a shows R_S vs. T for three microwave frequencies. Indeed one observes a clear minimum whose position is fixed by $\omega/\gamma = \mu_0 M$. Alternately, one can keep ω fixed, apply a field H and trace out the FMAR dip as a function of T. This is shown in Fig. 11b. Such data were used recently to show that in an LSMO single crystal M varies as $(T_C - T)^\beta$ with $\beta = 0.45 \pm 0.05$.

The FMAR phenomenon also provides the possibility of appreciably varying R_S at low H. Fig. 12 shows $MI = [R_S(H_{||})$ $- R_S(H_\perp)]/R_S(H_{||})$ at $\mu_0 H = 60$ mT. Here $H_\perp$ and $H_{||}$ refer to the configuration wherein $\mathbf{H} \perp \mathbf{b}$ (coupling to spins) or $\mathbf{H} \ || \ \mathbf{b}$ (no coupling to spins), respectively. It is clear that one can get a truly giant effect at rather modest fields. R_S changes by nearly 70% while a 60 mT field is rotated from the parallel to the perpendicular geometry. The full line in Fig. 12 was derived from the μ obtained using the Landau-Gilbert equations. Further details are in Ref. 13.

To conclude, microwave absorption, especially magnetic resonance, measurements on a variety of bulk and thin film manganite samples show that most of the samples studied are far from being the uniform, homogeneous materials that are assumed for obtaining credible agreements with proposed models. Considerable systematic effort will be needed to obtain intrinsic results. In particular, generaliztions claimed in some recent reports on these systems should be treated with healthy skepticism. However, it is encouraging that by careful tuning of the parameters, one can expect to obtain highly field-senstive materials at ambient temperatures for use in the next generation of microwave devices.

ACKNOWLEDGEMENTS

98

Boletín de la Sociedad Española de Cerámica y Vidrio. Vol. 36 Núms. 2-3 Marzo-Junio 1997

a

b

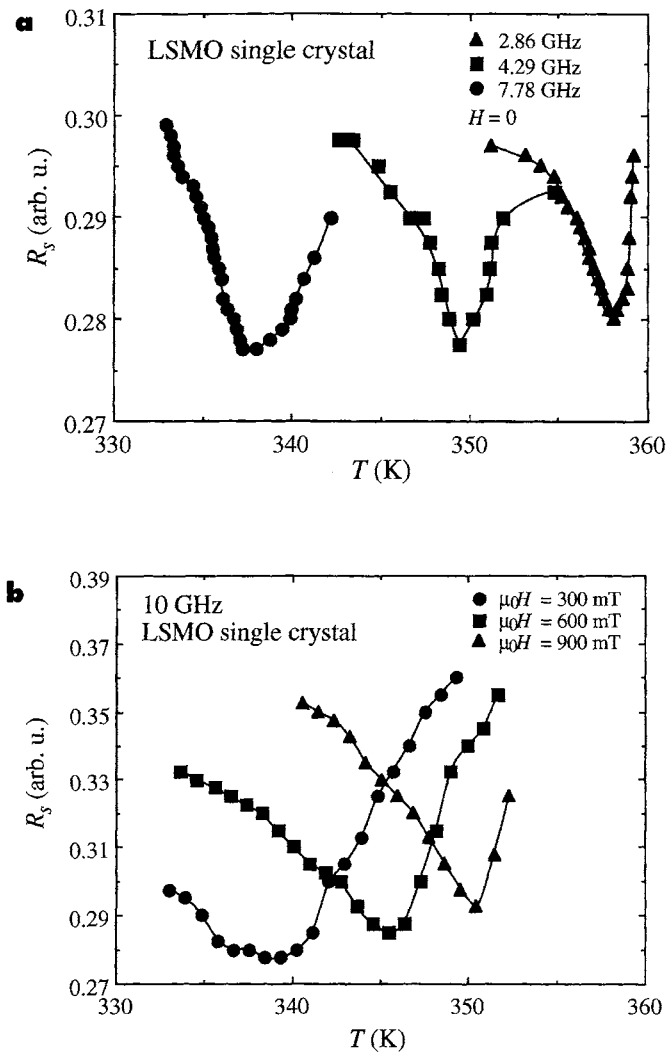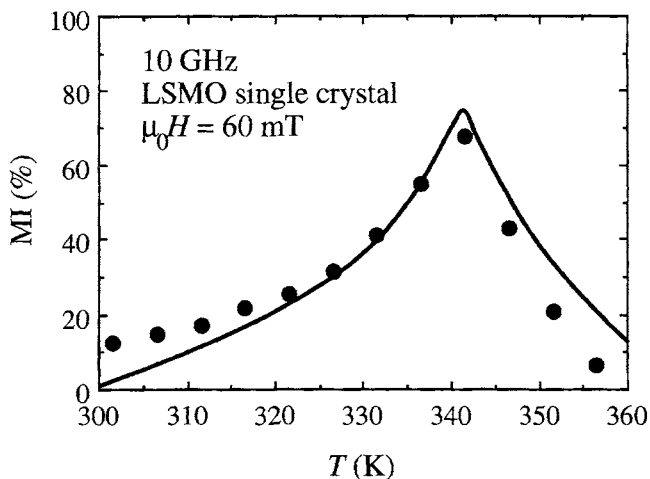*Fig. 11 Surface resistance vs. T showing FMAR at H = 0 and different frequencies.*

Fig. 12 Surface resistance vs. T showing FMAR at 10 GHz and indicated applied field values.

REFERENCES

1. G. H. Jonker and J. H. Van Santen, «Ferromagnetic compounds of manganese with perovksite structure,» Physica, Vol. 16, No. 3, pp. 337-349, (1950).

2. A. Urushibara, Y. Moritomo, T. Arima, A. Asamitsu, G. Kido, Y. Tokura, «Insulator-metal transition and giant magnetoresistance in $La_{1-x}Sr_xMnO_3$,» Phys. Rev. B, Vol. 51, No. 20, pp. 14103-14109, (1995).

3. C. Zener, «Interaction between the d-shells in the transition metals. II. Ferromagnetic compounds of manganese with perovskite structure,» Phys. Rev., Vol. 82, No. 3, pp. 403-405, 1951.

4. G. C. Xiong, S. M. Bhagat, Q. Li, M. Dominguez, H. L. Ju, R. L. Greene, T. Venkatesan, J. M. Byers, M. Rubinstein, «Anomalous magnetoconductivity of epitaxial $Nd_{0.7}Sr_{0.3}MnO_3$ and $Pr_{0.7}Sr_{0.3}MnO_3$ films,» Solid State Commun., Vol. 97, No. 7, pp. 599-604, 1996.

5. A. J. Millis, P. B. Littlewood, and B. I. Shraiman, «Double Exchange alone does not explain the resistivity of La1-xSrxMnO3,» Phys. Rev. Lett. Vol. 74, No. 25, pp. 5144-5147, 1995.

6. G. C. Xiong, Q. Li, H. L. Ju, S. N. Mao, L. Senapati, X. X. Xi, R. L. Greene, and T. Venkatesan, «Giant magnetoresistance in epitaxial $Nd_{0.7}Sr_{0.3}MnO_{3-d}$ thin films,» Appl. Phys. Lett., Vol. 66, No. 11, pp. 1427-1429, (1995). G. C. Xiong, S. M. Bhagat, Q. Li, S. E. Lofland, H. L. Ju, R. L. Greene, and T. Venkatesan, «Giant magnetomemory effect of epitaxial $Nd_{0.7}Sr_{0.3}MnO_3$ Films,» Appl. Phys. Lett., Vol. 67, No. , pp. 3031-, 1995. S. D. Tyagi, S. E. Lofland, M. Dominguez, S. M. Bhagat, C. Kwon, M. C. Robson, R. Ramesh, and T. Venkatesan, «Low-field microwave magnetoabsorption in manganites,» Appl. Phys. Lett., Vol. 68, No. 20, pp. 2893-2895, 1996.

7. S. E. Lofland, S. M. Bhagat, H. L. Ju, G. C. Xiong, T. Venkatesan, and R. L. Greene, «Ferromagnetic resonance and homogeneity in GMR $La_{2/3}Ba_{1/3}MnO_3$,» Phys. Rev. B, Vol. 52, No. 21, pp. 15058-15061, 1995.

8. S. E. Lofland, S. M. Bhagat, C. Kwon, M. C. Robson, R. P. Sharma, R. Ramesh, and T. Venkatesan, «Standing spin wave resonances in manganite films,» Phys. Lett., Vol. 209, No. 3/4, pp. 246-248, 1995. S. E. Lofland and S. M. Bhagat, Technical Report, 1996, unpublished.

9. C. Kwon, K.C. Kim, M. C. Robson, M. Gomez, S. E. Lofland, S. M. Bhagat, T. Venkatesan, and R. Ramesh, «Stress-induced magnetic anisotropy in epitaxial $La_{0.7}Sr_{0.3}MnO_3$ films,» submitted to J. Magn. Magn. Mater.

10. S. E. Lofland, S. M. Bhagat, Z. Trajanovic, C. Kwon, R. Ramesh, T. Venkatesan, and D. Fork, «Strain effects in thin films of $La_{0.7}Sr_{0.3}MnO_3$,» 41st Annual Conference on Magnetism & Magnetic Materials, Atlanta, Georgia, November 12-15, 1996, paper HR-03, p. 131.

11. S. E. Lofland, M. Dominguez, S. D. Tyagi, S. M. Bhagat, M. C. Robson, C. Kwon, Z. Trajanovic, I. Takeuchi, R. Ramesh, and T. Venkatesan, «Surface resistance of thin perovskite films - high-temperature superconductors and giant magnetoresistance manganites,» Thin Solid Films, vol. 288, 256-261 (1996).

12. M. Dominguez, S. M. Bhagat, S. E. Lofland, J. S. Ramachandran, G. C. Xiong, T. Venkatesan, and R. L. Greene, «Giant magnetoresistance at microwave frequencies,» Europhys. Lett., Vol. 32, No. 4, pp. 349-353, 1995.

13. S. E. Lofland, S. M. Bhagat, S. D. Tyagi, Y. M. Mukovskii, S. G. Karabashev, and A. M. Balbashov, «Giant microwave magneto-impedance in a single crystal of $La_{0.7}Sr_{0.3}MnO_3$: the effect of ferromagnetic antiresonance,» J. Appl Phys., Vol. 80, No. 6, pp. 3592-3594, 1996.

14. T. Venkatesan, X. D. Wu, B. Dutta, A. Inam, M. S. Heagle, D. M. Hwang, C. C. Chang, L. Nazar, and B. J. Wilkens, «High-temperature superconductivity in ultra-thin films of $YBa_2Cu_3O_{7-d}$,» Appl. Phys. Lett., Vol. 54, No. 6, pp. 581-583, 1989.

15. J. A. Geohegan and S. M. Bhagat, «Magnetic phases of amorphous transition metal-metalloid alloys,» J. Magn. Magn. Mater., Vol. 25, No. 1, pp. 17-32, 1981.

16. S. M. Bhagat, «Resonance Methods - Magnetic Materials,» pp. 79-163, Techniques of Metal Research, edited by E. Passaglia (Interscience, New York, 1974).

17. M. C. Robson, C. Kwon, K. C. Kim, R. P. Sharma, T. Venkatesan, R. Ramesh, S. E. Lofland, M. Dominguez, S. D. Tyagi, and S. M. Bhagat, «Characterization of epitaxial $La_{0.7}Ba_{0.3}MnO_3$ structures using ferromagnetic resonance,» J. Appl. Phys., Vol. 80, No. 4, pp. 2334-2338, 1996.

18. M. Dominguez, S. E. Lofland, S. M. Bhagat, A. K. Raychaudhuri, H. L. Ju, T. Venkatesan, and R. L. Greene, «Are 'single phase' manganites homogeneous? a magnetic resonance study,» Solid State Commun., Vol. 97, No. 3, pp. 193-196, 1996.

19. M. X. Huang, S. M. Bhagat, A. T. Findikoglu, T. Venkatesan, M. A. Manheimer, S. Tyagi, «Fluxon dynamics and field-induced microwave absorption in c-axis oriented thin films of $YBa_2Cu_3O_7$,» Physica C, Vol. 193, No. 3/4, pp. 421-425, 1992.

20. This sample was kindly provided by J. F. Mitchell of Argonne National Laboratory, Argonne, Illinois, USA.

21. S. E. Lofland, V. Ray, P. Kim, S. M. Bhagat, M. A. Manheimer, and S. D. Tyagi, «Magnetic Phase Transitions in $La_{0.7}Sr_{0.3}MnO_3$: Microwave Absorption Studies,» to Phys. Rev. B 55, 2749-2751 (1997).