Current-driven magnetization decrease in single crystalline ferromagnetic manganese oxide

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The electrical and magnetic response to a bias current has been investigated in a single-crystalline ferromagnetic manganese oxide Pr_{0.8}Ca_{0.2}MnO_3. A significant decrease of the magnetization is observed at the same threshold current where a non-linearity of V-I characteristics appears. Such a behavior cannot be understood in the framework of the filamentary picture usually invoked for the non-linearity of the other manganese oxides. Instead, an analogy with spintronic features might be useful and experimental signatures seem to be in agreement with excitations of spin waves by an electric current. This provides an example of a bulk system in which the spin polarized current induces a macroscopic change in the magnetization.

75.10.-b, 75.25.+z

The physics of the phase transition from a charge-ordered antiferromagnet (CO-AF) to a charge delocalized ferromagnet (CD-FM) in bulk manganese oxides has recently been under very active investigation. This CO destabilization is of great interest because this feature can be achieved under a wide variety of external perturbations. For instance, numerous experimental results have shown that application of a moderate electric field leads to a metal-insulator (MI) transition associated with a strong non-linearity of V-I characteristics. This MI transition is not believed to affect the entire bulk of the sample: conducting filaments along the current path, stabilized by FM correlations (due to DE mechanism), may occur instead, and a gradual melting of the CO-AF phase would follow. This scenario increases considerably the technological potential of the AF-CO manganese oxides in the form of thin films, since nanoscale production of heterostructure geometry is a key requirement in all technologies. Recently, we have observed the same kind of feature in a non charge-ordered ferromagnetic insulator bulk crystal, i.e. a strong drop in resistance under application of a moderate electric field concomitant with non-linearity in V-I characteristics. However, the physics at work here are quite different than those in the former case, because the CO ground state can not be invoked as a key ingredient for the understanding of this feature.

Among various manganites, the Pr_{1−x}Ca_{x}MnO_3 system (PCMO) is unique since it shows insulating behavior over the whole composition range due to the narrow bandwidth of the e_g electrons. Within the doping range 0.3 ≤ x ≤ 0.5, the ground state of the PCMO system is a CO-AF insulator; the real space ordering of 1:1 Mn^{3+}/Mn^{4+} ions occurs at 270K, and the local spin moments order at 170K. At lower doping levels (x ≤ 0.25), this system exhibits a non trivial FM insulator ground state. In this letter, we address the specific question of the current-induced excitation of the magnetic state of an insulating ferromagnet and its connection with the non-linearity of the electric response. To do so, we have examined simultaneously the electrical and magnetic response to a bias current of a non charge-ordered bulk crystal (Pr_{0.8}Ca_{0.2}MnO_3). In order to put our results in perspective, data obtained for a CO compound (Pr_{0.63}Ca_{0.37}MnO_3) are also presented.

For this study, single crystals of Pr_{0.8}Ca_{0.2}MnO_3 and Pr_{0.63}Ca_{0.37}MnO_3 were grown using the floating zone method in an image furnace. Experimental details are presented elsewhere, including electron diffraction and spectroscopic analysis. The V-I characteristics and magnetization versus current curves were measured simultaneously by means of a SQUID magnetometer and an external current - voltage source (Keithley 236).

Figure 1 shows the V-I characteristics for Pr_{0.8}Ca_{0.2}MnO_3 (Fig. 1b) and Pr_{0.63}Ca_{0.37}MnO_3 (Fig. 1a) crystals. Non-linear effects are observed for both compounds with the occurrence of negative differential resistance when the bias current attains a current threshold (J_{th}). In both cases, the V-I characteristics are not hysteretic. These two materials, whose electrical ground state is insulating, are thus driven to become conducting when a sufficient bias current is attained. Such a result is now well-established for the CO-AF ground state and its occurrence for low-doped FM insulator manganites suggests that this feature is not linked to this specific ground state. One may speculate that the current induced delocalization of carriers may follow a different process for the FM and CO-AF compounds. We have carefully determined that the Joule heating does not account for this current-induced effect. The temperature rise of the sample with respect to the sample holder (∆T) was measured by attaching a thermometer to the top of the sample itself. In this low temperature range, the power dissipation level where the voltage drop sets in leads to ∆T ≈ 3K.
For higher temperatures, $\Delta T$ becomes negligible. Moreover, the same non-linear effects are produced when keeping the current in the sample constant and reducing the cross-sectional area of the sample by a factor of ten, thus increasing the current density, which is the controlling factor of such behavior.

The magnetic signature of the current-driven MI transition is of great interest to understand the nature of the interaction between the current and the local magnetic moments. Concerning the CO-AF system and within the framework of the CO phase destabilization, there should be a magnetic signature of the transition in terms of an enhanced magnetic moment. This is confirmed in Fig. 1a where a significant rise in magnetization is observed at the same current threshold as the voltage drops. We obtain a 17% rise in magnetization which seems to fit the filamentary picture. However, although the electrical response is identical for the FM and CO-AF ground states, the magnetic signatures at the transition strongly differ. This is illustrated in Fig. 1b in which the FM compound shows a dramatic decrease in magnetization as the transition is crossed (80% of the value without biasing).

This huge current driven effect can, by no means, be ascribed to a local magnetic and/or electrical transition as proposed by the filamentary picture. It seems that, in the case of the FM ground state, the nature of the interaction between current and moment is much more complex. The experimental observations strongly resemble spintronic features, a kind of spin-valve effect acting in the reverse. An analogy with spin transfer effect, governed by local exchange, as in magnetic multilayer devices, can provide an interesting clue to account for experimental data in our ferromagnetic crystal. A large number of experiments on magnetic elements and multilayers indicate that the spin of the conduction electrons influences the magnetization of the elements. In addition, theoretical studies indicate that spin-polarized current affects the magnetic state of ferromagnetic conductors via the transfer of angular momentum between the carriers spins and the conductor magnetic moment. Such interaction would create a so-called "spin transfer" torque. Most of the experimental and theoretical works have treated this issue by considering microdevices having well-controlled geometry. This facilitates a quantitative study of the spin-transfer effect and allows the testing of the theoretical models that describe this phenomenon. It is not clear how a nanomagnetic model can account for experimental data in a bulk ferromagnet, since the magnetization that we measure in our experiment is the average moment of the entire sample along the direction of the applied field (See Fig. 2). To be more precise, the "spintronic effects" exist when the mean free path of the polarized electrons is larger than the size of the magnetic domains. The mean free path being in the range of 100 nm, this gives an upper limit for the typical size of the domains in Fig. 2. In absence of current in such samples, neutron diffraction experiments have shown that the domain size is larger than 200 nm in Pr$_{0.8}$Ca$_{0.2}$MnO$_3$. This suggests that the current itself would create the nanostructure necessary for the occurrence of the current-induced magnetization decrease.

Bazayil et al. [1] have generalized the Landau-Lifshitz equation for a continuously changing magnetization in the presence of a spin polarized current. This situation is more likely what happens in bulk ferromagnets where the local moments of adjacent domains (separated by Bloch walls) have different orientations (provided the applied magnetic field is well below the saturation field). One reason that the spin-polarized transport effect should be significant in the perovskite manganites is the high degree of spin-polarization in these materials; this constitutes the basis for the double exchange mechanism governing their magnetic ordering. In the manganese oxide perovskites, the conduction bandwidth of the 3$d$ electrons is likely to be smaller than the Hund coupling energy $2\Delta$; hence, the carriers in the ferromagnetic ground state are almost spin polarized, in contrast to the case of the itinerant ferromagnets.

By considering the time-dependent solutions to their general approach, Bazayil et al. [1] predict a spin wave instability. Other papers have predicted and observed such a current-induced spin wave generation. To be excited, spin waves must overcome anisotropy, exchange and damping effects; it is found that the current alters the energy gap of the spin waves for large enough current. In a recent paper dealing with the same ferromagnetic compound, the amplitude of the spin waves was studied. In the latter paper, the amplitude of the spin waves is controlled by a nonlocal current and not by a stream of charge particles. However, the soft nature of the spin waves in Pr$_{0.8}$Ca$_{0.2}$MnO$_3$ is found to be a general trend in the low doped region of the PCMO system ($D \approx 15\pm 3$ meV $\AA^2$). Since generation of spin waves in a conducting ferromagnet requires a decrease of magnetization, the experimental observation in the FM Pr$_{0.8}$Ca$_{0.2}$MnO$_3$ might be understood by considering the excitation of spin-waves through the spin transfer framework. Moreover, it appears that this would cause the same observed voltage-current anomalies. As observed in Fig. 3, the magnetization versus current curves are nonhysteretic and symmetric. According to Myers et al. [22], nonhysteretic features are also consistent with spin waves excitations induced by spin transfer. It should be noted that the spin transfer theory predicts that the current necessary to generate spin-wave excitations should increase with field. We only observe a slight shift of the current threshold with field, which is not consistent with the expected field dependence. This suggests that the current necessary to trigger spin wave instability would be rather independent of the...
applied magnetic field. One might imagine that the applied magnetic field can eventually re-orient the domains within each other but fails to make stiffer the spin system inside a domain. Although all the details of the understanding are not sorted out, the manganese oxides seem to be of great interest since the magnetic and electric states are easily tunable by changing the bias current.

Figure Captions

Figure 1: a V-I characteristic and magnetization versus current density at 100K under 100G for the CO-AF compound.

b: V-I characteristic and magnetization versus current density at 100K under 100G for the FM compound.

Figure 2: A current spin polarized J will exert a torque on the domain moments ($m_1$, $m_2$, $m_3$, ... $m_i$). For $J > J_{th}$, the interaction of the spin-polarized electrons with the local moments leads to a deflection of magnetization. As emphasized in the text, the measured magnetization ($M_{data}$) is the projection of the average moment of the sample in the direction of the applied field. The hatched area represents the interface between domains.

Figure 3: Magnetization versus current density at 100K under 100G for increasing / decreasing current and for different signs of current bias.

[1] For a review, see Colossal Magnetoresistance, Charge Ordering and Related Properties of Manganese Oxides, edited by C. N. R. Rao and B. Raveau (World Scientific, Singapore, 1998) and Colossal Magnetoresistive Oxides, edited by Y. Tokura (Gordon and Breach Science, New York, 1999).

[2] M. R. Lees et al., Phys. Rev. B. 52, R14 303 (1995).
[3] V. Kiryukhin et al., Nature (London) 386, 813 (1997).
[4] K. Ogawa et al., Phys. Rev. B 57, R15033 (1998).
[5] A. Asamitsu et al., Nature 388, 50 (1997).
[6] J. Stankiewicz et al., Phys. Rev. B 61, 11 236 (2000).
[7] A. Guha et al., Phys. Rev. B 62, 5320 (2000); A. Guha et al., ibid B 62, R11941 (2000)
[8] C. N. R. Rao et al., Phys. Rev. B 61, 594 (2000)
[9] S. Mercone et al., Phys. Rev. B 65 (2002)
[10] C. Martin et al., Phys. Rev. B 60, 12 191 (1999).
[11] Z. Jirák et al., J. Magn. Magn. Mater. 53, 153 (1985).
[12] V. Hardy et al., Phys. Rev. B 63, 224403 (2001)
[13] A. Wahl et al., Eur. Phys. J. B 26, 135 (2002)
[14] L. Berger et al., Phys. Rev. B 54, 9353 (1996)
[15] J. Slonczewski et al., J. Magn. Magn. Mater. 159, L1 (1996)
[16] J. Slonczewski et al., J. Magn. Magn. Mater. 195, L261 (1999)
[17] Ya. B. Bazaliy et al., Phys. Rev. B 57, R3213 (1998)
[18] C. Heide et al., Phys. Rev. Lett. 87, 197201 (2001)
[19] M. Tsoi et al., Phys. Rev. Lett. 80, 4281 (1998)
[20] J. Z. Sun et al., J. Magn. Magn. Mater. 202, 157 (1999)
[21] J. A. Katine et al., Phys. Rev. Lett. 84, 3149 (2000)
[22] E. B. Myers et al., J. Appl. Phys. 87, 5502 (2000)
[23] Ch. Simon et al., submitted to Phys. Rev. Lett.
[24] J. M. D. Coey et al, Phys. Rev. Lett. 75, 3910 (1995).
[25] H. Y. Hwang et al., Phys. Rev. Lett. 77, 2041 (1996)
[26] S. M. Rezende et al, Phys. Rev. Lett. 84, 4212 (2000)
Figure 1a
A. Wahl et al.
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Figure 1b
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\[ M_{\text{average}} \]

\[ M_{\text{data}}(J=0) \]

\[ M_{\text{data}}(J > J_{th}) \]

\[ B_z = 100 \text{G} \]

\[ J \]

\[ S \]

\[ m_i \]

\[ m_1 \]

\[ m_2 \]

\[ m_3 \]

\[ \rightarrow : m(J=0) \]

\[ \rightarrow : m(J > J_{th}) \]
Figure 3
A. Wahl et al.
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