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Research Progress on Colossal Anisotropic Magnetoresistive Effect

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Perovskite manganites show exotic functionalities due to the coupling between spin, charge, orbital and lattice, such as metal-insulator transition, colossal magnetoresistance (CMR), charge-orbital order and phase separation. Recently, an extraordinary anisotropic magnetoresistance (AMR) has been observed in perovskite manganite single crystals. The AMR value is about 2 orders larger than that of the conventional 3d transition metals and alloys, which is attributed to tunable metal-insulator transition temperature modulated by the magnetic field. This result provides a new route for exploring novel AMR materials and their applications.

Key words perovskite manganite, metal-insulator transition, AMR

The correlated electron materials show many interesting physical properties due to the coupling between spin, charge, orbital and lattice. In doped perovskite manganite $Ln_{1-x}A_xMnO_3$ where Ln and A are rare- and alkaline-earth cations, respectively, prominent change of the physical properties can be got due to the subtle variation of the coupling between spin, charge, orbital and lattice by doping, strain effect and external field, etc. Recently, Run-Wei Li's group in Ningbo Institute of Materials Technology and Engineering, Chinese Academy of Sciences, has found colossal Anisotropic Mametoresistance (AMR) in the $La_{0.69}Ca_{0.31}MnO_3$ single crystals, which has been published on Proceedings of the National Academy of Sciences (*PNAS*). 106, 142224(2009).[1]

In 1857, W. Thomson found AMR effect, i.e. the resistivity changing with the orientation of the external magnetic field. AMR effect is found universally in 3*d* magnetic materials and has been applied in various magnetic read-out heads and magnetic sensors. The AMR value in the conventional 3*d* magnetic materials is usually very small compared to giant magnetoresistance (GMR), tunneling magnetoresistance (TMR) and colossal magnetoresistance (CMR). For example, the AMR value in the permalloy, the most widely used AMR material, is only about 1%—2% at the room temperature. Due to the lower sensitivity of the AMR devices compared to the GMR and TMR devices, the AMR devices are being replaced gradually by the GMR and TMR devices. However, the research results in Li's group indicate that even a weak crystalline anisotropy can induce a colossal AMR effect in perovskite manganites, the AMR value can even be larger than GMR and TMR.

$La_{0.69}Ca_{0.31}MnO_3$ single crystals are orthorhombic, deviating from the cubic perovskite structure via two dissimilar Jahn-Teller (*J*-*T*) distortions—in-plane (i. e., in *ab*-plane) rotation and out-of-plane (**c**-axis) tilt of the MnO_6 octahedron. The metal-insulator transition coincides with a ferromagnetic-to-paramagnetic transition at $T_{MI} \approx$ 220 K, characterized by the *T*-dependence of magnetization $M(T)$ and the resistivity $\rho(T)$ shown in Fig. 1 A and B, respectively. The measured $\rho(T)$ vs. **H** curve demonstrates a typical negative magnetoresistance behavior. However, the observed MR shows a strong dependence on the field orientation, leading to a remarkable AMR effect.

In conventional 3*d* transition metals or alloys, AMR depends monotonically on temperature or magnetic field and saturate at the high field, but in the perovskite manganite, the situation is different. The temperature- and field dependence of AMR and their correlation with the field dependent metal-insulator transition were systematically investigated. The results are shown in Fig. 2. T_{MI} increases almost linearly with field (see Fig. 2A). A key discovery here is that the measured R_ρ peak follows almost exactly the field dependence of T_{MI}, as shown in Fig. 2B. Large AMR emerges only near T_{MI} (Fig. 2C), whereas no prominent AMR appears in either the pure ferromagnetic-metallic state at $T \leqslant T_{MI}$ or the pure paramagnetic-insulating state at $T \geqslant T_{MI}$. We can define the value of AMR as $R_\rho = \frac{R_{0^\circ} - R_{90^\circ}}{R_{0^\circ}}$ or $R_\rho = \frac{R_{0^\circ} - R_{90^\circ}}{R_{90^\circ}}$, where R_{0° and R_{90° is corresponding

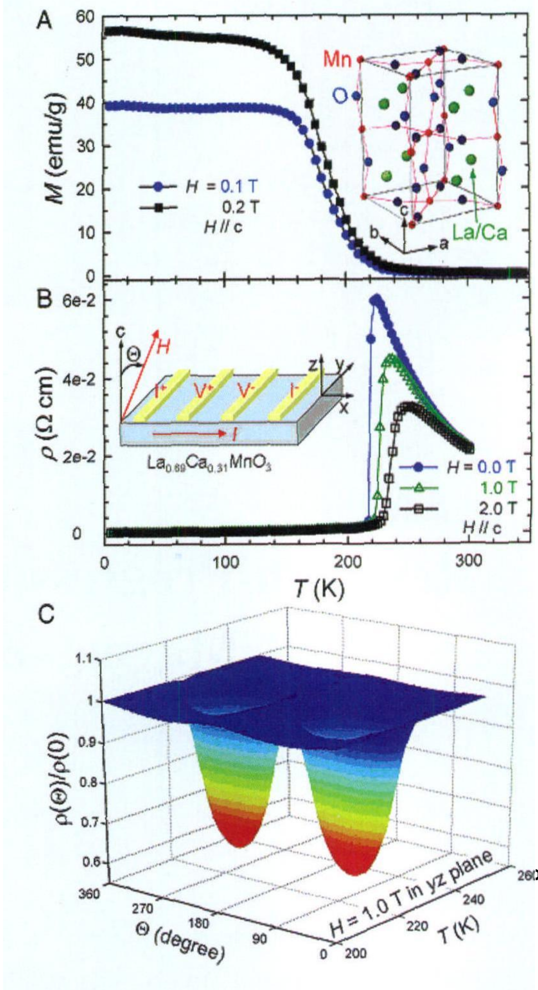

Fig. 1 ***M*(*T*) and *ρ* (*T*, *θ*) of $La_{0.69}Ca_{0.31}MnO_3$ single crustal**

to the resistance when $H /\!/ \mathbf{c}$ axis and $H \perp \mathbf{c}$ axis respectively. The nonmonotonic field-dependence of R_ρ at a given *T* close to T_{MI} is evident in Fig. 2D, such that R_ρ(*H* and *T*) exhibits very similar line shapes for varying field or temperature. Under 220 K and 0.2 T, if adopting the former definition of R_ρ, R_ρ reaches 90%, and if the latter definition is adopted, R_ρ can be over 600%. This result breaks undoubtedly the conventional impression that the AMR value is smaller than that of GMR and TMR.

In order to study the mechanism of the anomalous AMR effect, the dependence of the resistivity and T_{MI} on the magnetic field was investigated in detail. Fig. 3 presents the measured field-dependence of both the normalized resistivity and T_{MI} for the field along three different sample orientations. The measured $\rho(\mathbf{H})$ has similar values for the

$\boldsymbol{H} /\!/ x$ and $\boldsymbol{H} /\!/ y$ directions but quite different values for the $\boldsymbol{H} /\!/ z$ direction (see Fig. 3A). A small difference in $\rho(\boldsymbol{H})$ between the $\boldsymbol{H} /\!/ x$ and $\boldsymbol{H} /\!/ y$ directions can mainly be attributed to the Lorentzian MR, whereas the large difference between the $\boldsymbol{H} /\!/ z$ and $\boldsymbol{H} /\!/ x(y)$ directions gives rise to the observed giant AMR. Also shown in the Inset of Fig. 3B, a small but clear shift of $\rho(T)$ is evident by orienting $\boldsymbol{H} /\!/ z$- from $\boldsymbol{H} /\!/ x(y)$-direction, thus indicating an anisotropic field-dependent metal-insulator transition. As presented in Fig. 3B, the $T_{MI}(\boldsymbol{H})$ curve for the $\boldsymbol{H} /\!/ z$ direction deviates from that for the $\boldsymbol{H} /\!/ x(y)$ direction. The crystalline **c**-axis (i. e. , the z direction), which is perpendicular to the sample plane, is the hard axis for the field-dependent metal-insulator transition. The correlation between AMR and metal-insulator transition displayed in Fig. 2 and Fig. 3, especially the gap of the two $T_{MI}(\boldsymbol{H})$ curves shown in Fig. 3B, provide a crucial key for understanding the anisotropic magneto-transport properties. The difference in T_{MI} due to field orientations ($\boldsymbol{H} /\!/ \boldsymbol{c}$- or **H**_**c**-axis) leads to the observed unusual AMR effect. At a given field strength (vertical cut and between the two T_{MI} curves in Fig. 3B), the sample becomes insulating when $\boldsymbol{H} /\!/ \boldsymbol{c}$-axis while remaining metallic when **H**_**c**-axis—creating the R_ρ peak as shown in Fig. 2C. On the other hand, at a

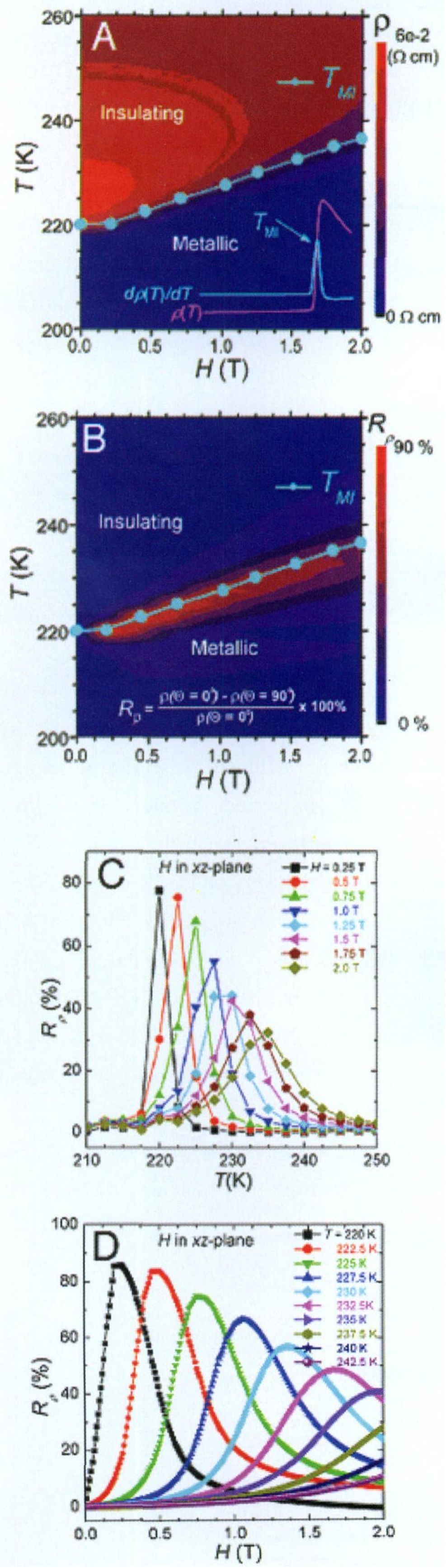

Fig. 2 The dependence of AMR on T and H

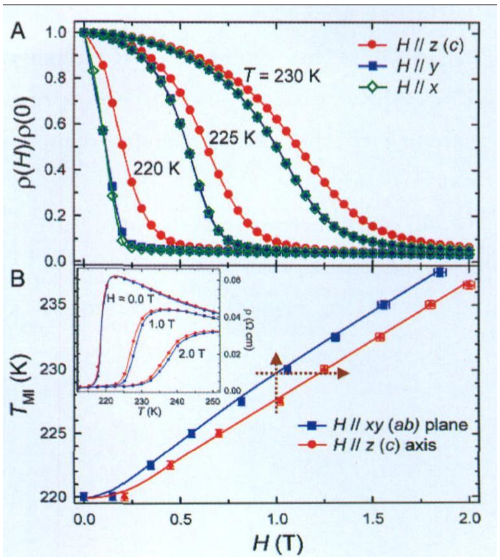

Fig. 3 The dependence of resistivity and T_{MI} on the direction of magnetic field

given T (horizontal cut in Fig. 3B), the sample becomes metallic as $\boldsymbol{H}\_\boldsymbol{c}$-axis but remains insulating as $\boldsymbol{H} // \boldsymbol{c}$-axis, thus resulting in the R_p peak as shown in Fig. 2D. When the system is far away from the gap region of the two $T_{MI}(\boldsymbol{H})$ curves, only conventional AMR with small amplitude should exist.

Jahn-Teller distortions and double-exchange (DE) interactions, which are intimately coupled in this class of doped perovskite oxides, play vital roles in both the transport and the magnetic properties. Simply speaking, Jahn-Teller (J-T) distortions tend to promote insulating phase to the system whereas DE interaction endorses ferromagnetic-metallic state, although the strength of DE interaction depends on the degrees of J-T distortions thus making a close coupling between them. Bending the Mn-O-Mn bond by enhancing J-T distortion reduces DE interaction so as bandwidth. The subtle competition between them causes the metal-insulator transition in these doped manganites. However, external field tends to disturb such a competition by facilitating the metallic state, evident by appearing *negative* CMR near the T_{MI} and tuning the metal-insulator transition. Owning to the strong correlation character in these materials, lattice also has its response to applied magnetic field by alter J-T distortions, depending on the detailed lattice structure and applied field orientation. Indeed, the giant AMR observed in $La_{0.69}Ca_{0.31}MnO_3$ reflects exactly the different lattice response to the external field, depending on the field direction.

If, in a cubic peroviskite structure, lattice should have identical response to external field in all high-symmetry crystalline directions, thus no AMR is generated by magneto-elastic coupling. However, in orthorhombic $La_{0.69}Ca_{0.31}MnO_3$, the structure has lower symmetry by bearing two distinct J-T distortions from a cubic perovskite. The lattice has larger response when the field is perpendicular to $\boldsymbol{c}$-axis than parallel to $\boldsymbol{c}$-axis, thus creating instinct effects on the transport properties including metal-insulator transition through different couplings with the DE interaction. This different response exactly makes $\boldsymbol{c}$-axis as the hard axis for the field-dependent metal-insulator transition, having a small but crucial anisotropy as clearly shown in the two field-dependent T_{MI} curves (see Fig. 3B). Consequently, the system exhibits a giant AMR effect near the metal-insulator transition region that is stimulated by the distinct lattice response to external field because of the asymmetric J-T distortions. Based upon the above scenario for the nature of intrinsic AMR, we are able to qualitatively explain the dissimilar magnitude of AMR effects observed in different manganite systems. Of course, in the imperfect crystal, the twinning effect can not be ignored.

The finding of the colossal AMR effect in perovskite manganite provides an alternative route for exploring novel AMR materials, and stimulates researchers to re-investigate the mechanism of the AMR effect. From the viewpoint of applications, the colossal AMR effect has applications in magnetic read-out heads, direction/angular sensors, etc.

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