Large magnetoresistance over a wide temperature range in Eu$_{0.99}$La$_{0.01}$TiO$_3$

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Abstract – We report the magnetization ($M$), electrical resistivity ($\rho$) and magnetoresistance ($MR$) in the electron-doped antiferromagnet Eu$_{0.99}$La$_{0.01}$TiO$_3$. While $M(T)$ measured upon cooling indicates the occurrence of a paramagnetic to antiferromagnetic transition at $T_N = 5.46$ K, zero field $\rho(T)$ goes through a broad maximum at $T = T_p = 65$ K $> T_N$. The application of an external magnetic field raises the value of $T_p$ and decreases the magnitude of $\rho$ at $T_p$ leading to a negative magnetoresistance ($MR$) effect. A large $MR$ of $-75\%$ for $\mu_0 H = 7$ T is observed at 2.5 K with a remarkable change occurring in sub-tesla magnetic fields ($MR = -42\%$ for $H = 0.6$ T). In addition, significant $MR$ prevails even up to 10 $T_N$ ($MR = -20\%$ at 50 K). While $MR$ over a wide field range for $T > T_N$ can be satisfactorily described by the equation $MR = -a^2 \ln(1 + b^2 H^2)$, $MR$ scales with $M$ below $T_N$. Unlike the resistivity, thermopower is insensitive to magnetic fields. Our results indicate that electrons doped into the Ti-3d conduction band are strongly coupled to localized 4$f^7$ spins of Eu$^{2+}$ ions via the $d$-$f$ exchange interaction. We suggest that the observed $MR$ is most likely caused by the field-induced suppression of 4$f$ spin fluctuations and the subsequent reduction of the scattering of 3d electrons. This is a unique example in perovskite oxides where the magnetoresistance of 3d electrons is controlled by spin fluctuations associated with 4$f$ localized electrons of a rare-earth ion.

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Introduction. – Although the perovskite rare-earth titanate EuTiO$_3$ having cubic structure at room temperature was synthesized and its magnetic properties were studied by neutron diffraction and magnetometry in the 1960s and 1970s [1–4], it hardly attracted attention until a recent report of the giant positive magnetocapacitance effect surfaced in 2001 [5–9]. While other RTiO$_3$ oxides, in general, have orthorhombic structure at 300 K and usually possess trivalent rare-earth (R$^{3+}$) and titanium (Ti$^{3+}$) ions, the Eu ion is divalent and the Ti ion is tetravalent in EuTiO$_3$. The presence of a magnetically active rare-earth ion (Eu$^{2+}$:4$f^7$ with spin $S = 7/2$) and “ferroelectric active” Ti$^{4+}$:3$d^0$ in EuTiO$_3$ makes it an attractive material for investigating the coupling between magnetism and electrical polarization. The 4$f^7$ spins on neighboring Eu$^{2+}$ ions order antiferromagnetically below $T_N = 5.4 \pm 0.1$ K [1]. Although EuTiO$_3$ fails to show ferroelectricity down to 2 K, it exhibits a strong magneto-electric coupling as revealed by a steep decrease of the static dielectric constant ($\varepsilon$) at $T_N$ in the absence of a magnetic field [5]. The dielectric anomaly is progressively eliminated upon increasing the strength of the magnetic field, leading to a positive magnetocapacitance effect ($\Delta \varepsilon/\varepsilon = +7\%$ for $\mu_0 H = 1.5$ T at 2 K). A strong spin-lattice coupling is considered to be the origin of the magnetocapacitance effect [10]. Goian et al. [11] suggest that the 4$f$ spin ordering at Eu sites influences the frequency of one of the transverse optical phonon modes (TO1) due to the Eu-O-Eu superexchange interaction causing the observed magnetocapacitance effect. EuTiO$_3$ also undergoes a cubic to tetragonal structural transition around 282 K which resembles the low-temperature structural transition at 110 K in the quantum paraelectric SrTiO$_3$ [12].

The bulk EuTiO$_3$ is an insulating antiferromagnet at low temperatures but transforms into a ferromagnetic metal upon carrier doping (electron doping in the Ti-3d
conduction band) by partial replacement of the divalent Eu cation by the trivalent La cation [13]. The ferromagnetic Curie temperature ($T_C$) of the single-crystalline Eu$_{1-x}$La$_x$TiO$_3$ series increases initially with increasing La content, goes through a maximum value for $x = 0.1$ ($T_C = 8$ K) before decreasing with a further increase in the La content [13]. Eu$_{0.9}$La$_{0.1}$TiO$_3$ single crystal is metallic below 300 K and $\rho(T, H = 0)$ exhibits a peak at $T_C$. The application of an external magnetic field diminishes the amplitude of the resistivity peak resulting in $-24\%$ magnetoresistance at $T_C$ in a field of 7 T [13]. In contrast to the widely studied magnetoresistive manganites or cobaltites where the 3d band is the source of both magnetism and electrical conduction [14], the magnetism in EuTiO$_3$ is dominated by the localized 4f electrons of Eu$^{3+}$, whereas the electrical transport is governed by the dynamics of charge carriers doped into the Ti-3d band. An interesting scenario is the magnetic interaction of low-density electrons in the 3d band with the localized 4f spins on the magnetoresistance. However, there is no report of magnetotransport so far either in pure EuTiO$_3$ or Eu$_{1-x}$La$_x$TiO$_3$ for $x < 0.05$. Here, we report the occurrence of a giant negative magnetoresistance ($\sim 75\%$ at 2.5 K for $\mu_0 H = 7$ T) in Eu$_{0.99}$La$_{0.01}$TiO$_3$. Surprisingly, magnetoresistance prevails for temperatures up to ten times $T_N$. Thus, lightly doped EuTiO$_3$ is a new addition to the family of colossal magnetoresistive oxides.

**Experimental details.** – Polycrystalline Eu$_{1-x}$La$_x$TiO$_3$ ($x = 0.0, 0.01$) samples were synthesized by the solid-state reaction method starting from the stoichiometric mixture of Eu$_2$O$_3$, La$_2$O$_3$ and TiO$_2$ powder. La$_2$O$_3$ was preheated at 900°C for 8 hours to remove hydroxides and carbonates prior to mixing. After mixing and grinding, the powder was calcined at 1200°C for 24 hours in reducing atmosphere (95% Ar and 5% H$_2$) which converts Eu$^{3+}$ into Eu$^{2+}$. Later, the powder was pressed into a pellet and sintered at 1300°C for 24 hours in the same atmosphere. The structural, magnetic and magnetocaloric properties of these compounds were reported by us in earlier publications [15]. Both samples are in single phase and have a cubic structure (phase group $Pm3m$) with the lattice constants $a = 3.0951$ Å (EuTiO$_3$) and $a = 3.9056$ Å (Eu$_{0.99}$La$_{0.01}$TiO$_3$) at room temperature. Four-probe dc resistivity and magnetization were measured using a Physical Property Measurement System (PPMS) and a vibrating sample magnetometer probe (VSM) attached to the PPMS. The seebeck coefficient (thermopower) under zero and 7 T magnetic fields was also measured in the PPMS using the thermal transport option.

**Results.** – The main panel of fig. 1(a) compares the temperature dependence of magnetization, $M(T)$, of Eu$_{1-x}$La$_x$TiO$_3$ ($x = 0.0$ and 0.01) measured while cooling the samples in a magnetic field of $H = 100$ Oe. For clarity, we show only the low-temperature behavior. The sharp peak in $M(T)$ at $T = 5.54$ K for $x = 0.0$ signals the onset of the antiferromagnetic transition ($T_N$). The Néel temperature decreases only a little upon 1% La-substitution ($T_N = 5.46$ K for $x = 0.01$) but the low-field magnetization is enhanced over the parent compound below $T_N$. The inset compares $M$ vs. $H$ isotherms of both compounds at 2.5 K. As the field is increased from 0 T, $M(H)$ of $x = 0.0$ increases nearly linearly up to $\mu_0 H = 0.1$ T followed by a weak field dependence above 1 T. While the $M(H)$ curve of $x = 0.01$ is overall similar to the parent compound, it shows enhanced $M$ values for fields lower than 1 T and the value of magnetization at the highest field reaches 6.65 $\mu_B$/f.u. which is slightly lower than 7 $\mu_B$/Eu atom expected for the saturation of Eu$^{2+}$:4f$^7$ moments. The substitution of nonmagnetic La$^{3+}$ for magnetic Eu$^{2+}$ in EuTiO$_3$ introduces electrons into the Ti:3d(t$_{2g}$) band. The doped electron ($d^1, S = 1/2$) weakens the antiferromagnetic coupling between localized 4f spins and promotes the ferromagnetic interaction. The interaction between the localized 4f and 3d conduction electrons is likely to be of RKKY type.

Figure 1(b) shows the temperature dependence of the four-probe dc resistivity, $\rho(T)$, for $x = 0.0$ and 0.01 in zero external magnetic field. The $\rho(T)$ of the parent compound increases monotonically with decreasing temperature and exceeds 70 kΩ cm at 50 K. Since the two-probe
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resistance of the sample exceeds 5 MΩ below 40 K, it is not possible to reliably measure the four-probe resistivity with the PPMS. In contrast, the four-probe resistivity of the $x = 0.01$ sample is measurable down to 2.5 K. It is obvious from the graph, although the resistivity values of both the samples are comparable at room temperature, the resistivity of the 1% La-doped sample is lower than that of the parent compound below 100 K and it is about 4 kΩ cm at 2.5 K. The inset of fig. 1(b) depicts $\ln(\rho(T))$ vs. $1/T$ for $x = 0.01$. In the high-temperature region ($T > 350$ K), $\rho(T)$ follows a thermally activated behavior with $\rho(T) = \rho(0)e^{-E_a/k_B T}$, where $E_a$ is the activation energy for hopping to the next-nearest neighbor and it is 285 meV for $x = 0.01$. However, $\rho(T)$ below 350 K could not be fitted over a wide temperature either with the polaronic or the variable range hopping mechanism.

In fig. 2, we show (a) $M(T)$ and (b) $\rho(T)$ of $x = 0.01$ for different values of the external magnetic field ($H$) in an enlarged temperature scale. The peak in $M(T)$ seen at $T_N$ disappears as the field strength increases above 0.6 T. The zero field $\rho(T)$ shows a broad maximum at $T_p = 63$ K ($\gg T_N$) and the value of resistivity ($\rho_{peak}$) at $T_p$ decreases upon the application of a magnetic field. The $T_p$ is obtained from the zero crossing point of the $d\rho/dT$ curve. With increasing value of $H$, $T_p$ shifts up and the amplitude of $\rho_{peak}$ decreases. The inset of fig. 2(b) shows the magnetic-field dependence of $T_p$ and $\rho_{peak}$. It is noted that $\rho(T = 2.5$ K) is extremely sensitive to sub-tesla magnetic fields, e.g., $\rho(H)/\rho(0) = 0.58$ for $H = 6$ kOe. Magnetoresistance ($MR$) is estimated using the standard definition $MR(\%) = (\rho(H)−\rho(0))/\rho(0) × 100$, where $\rho(H)$ and $\rho(0)$ are the resistivity values in a magnetic field $H$ and $H = 0$ tesla, respectively. Figure 2(c) shows the temperature dependence of $MR$ for different values of $H$. The magnitude of negative $MR$ at 2.5 K increases from $\sim 3\%$ for $H = 1$ kOe to 42% for $H = 6$ kOe and then to 73% for $H = 2$ T. However, $MR$ increases only marginally as $H$ increases from 2 T to 7 T. The magnitude of $MR$ decreases rapidly between 2.5 K and 20 K when $H < 1$ T but the decrease is gradual for $\mu_0 H \geq 2$ T. Surprisingly, a large $MR$ prevails for $T > T_N$. For example, at $T = 50$ K ($\approx 10 T_N$), magnetoresistance in our polycrystalline sample is $\sim 20\%$ for $\mu_0 H = 7$ T which is comparable to the maximum $MR$ of $\sim 24\%$ seen in single-crystalline Eu$_{0.9}La_{0.1}$TiO$_3$ at $T_C (= 8$ K) [10]. The $MR$ decreases to $\sim 6\%$ at 70 K and becomes negligibly small above 90 K.

A possible reason for the existence of $MR$ over a wide temperature above $T_N$ could be the presence of short-range ferromagnetic clusters in the paramagnetic background. The inverse susceptibility ($\chi^−1 = H/M$) in many colossal magnetoresistive manganites [16] starts to deviate from the Curie-Weiss linear fit from a temperature much above $T_C$, typically $T \sim 1.2$–1.4$T_C$, and its origin was suggested due to the presence of nano-size ferromagnetic clusters (“magnetic polaron”) in the paramagnetic state. To check such a possibility in our sample, we plot $\chi^−1(T) = H/M$ for different values of $H$ in the inset of fig. 2(a). Although $\chi^−1(T)$ curves for different $H$ values show visible deviations from each other for temperatures below $\sim 35$ K, the difference is negligible at higher temperature. No anomaly appears in $\chi^−1(T)$ for $\mu_0 H = 7$ T at $T = 80$ K where $\rho(T)$ shows a maximum. Hence, the existence of magnetic polarons in the paramagnetic state of our sample is doubtful.

Our attempt to measure the carrier concentration by the Hall effect experiment was not successful due to the high resistivity of the sample. Resistivity and thermopower data can be utilized to deduce the Fermi level as well as the charge carrier concentration and mobility [17,18]. We performed the thermopower experiment
as a function of temperature under zero and 7 T magnetic fields for Eu0.99La0.01TiO3. The inset of fig. 2(d) shows a temperature dependence of the thermopower, $S(T)$, measured under zero field over a wide temperature range (5 K $\leq T \leq$ 400 K), while the main panel compares $S(T)$ for zero and 7 T fields in the low-temperature regime (5 K $\leq T \leq$ 120 K). The negative sign of $S$ over the entire temperature range suggests that electrons are the majority charge carriers in this sample. The zero field $S$ shows a linear temperature dependence for $T > 100$ K, but a non-linear behavior below 100 K. Although Heike’s formula ($S = \frac{k_B}{e} \{ \ln(\frac{1}{r}) \}$), where $c = n/V$ is the carrier concentration per unit cell, was generalized for a temperature independent thermopower [19], it can be also used to get a rough estimate of the charge carrier density at room temperature [18]. The $n$ value at room temperature estimated from Heike’s formula is 4.7 $\times$ 10$^{20}$ cm$^{-3}$, corresponding to the $S$ value of $\sim$308 $\mu$V/K. We noticed that the estimated $n$ value for the Eu0.99La0.01TiO3 sample is almost the same as the value for the $x = 0.02$ sample of the Sr$_{1-x}$La$_x$TiO$_3$ series, which was obtained from the Hall effect experiment [20]. Further, the charge carrier mobility and effective mass ($m^*$) can be estimated using eqs. (1) and (2), respectively:

$$\sigma = ne\mu, \quad (1)$$

$$S = \frac{8\pi^2k_B^2}{3eh^2} (Tm^*) \left( \frac{\pi}{3m} \right)^{2/3} (1 + r), \quad (2)$$

where $\sigma$ is the electrical conductivity, $m^*$ is the effective mass, $h$ is the Planck constant and $r$ is the scattering parameter ($r = 0.5$ for ionic solids). The room-temperature mobility of charge carriers is $4 \times 10^{-5}$ cm$^2$V$^{-1}$s$^{-1}$, which is 4 orders lower compared to similar oxides [20,21]. Such a small value of mobility suggests a strong localization of charge carriers in the present system. The deduced effective mass of carriers at room temperature is $m^* = 4.68m_0$, which is close to that for the La-doped SrTiO$_3$ system [22]. As can be seen from the main panel of fig. 2(d), $S(T)$ for zero and 7 T fields match each other perfectly until the lowest temperature 5 K, whereas the value of resistivity decreases dramatically under 7 T. Hence, the absence of magnetothermopower implies that the charge carrier density probably remains constant but mobility and hence the relaxation time increase with increasing magnetic field. A similar conclusion was reached for the antiferromagnetic europium chalcogenide EuTe [23], where the carrier density and the mobility were obtained from the combined Hall voltage and resistivity data.

In order to seek a connection between the magnetic and electrical properties, we measured the field dependence of magnetization and magnetoresistance at selected temperatures and these isotherms are shown in figs. 3(a) and (b), respectively. While $M$ increases linearly with $H$ for $T \geq 28$ K, a non-linearity develops at lower temperatures. At 2.5 K, $M$ shows a rapid increase for $\mu_0H \leq 1$ T and a tendency to saturate at higher magnetic fields. The magnitude of $MR$, in concomitance with the field dependence of $M$, increases smoothly with increasing $H$ for $T \geq 28$ K, but the $MR$ shows a steep increase for lower fields for $T < T_N$. This is vividly illustrated by the field dependence of $MR$ at 2.5 K: $MR$ increases as much as 63% for a field of 1 T but the increase is only incremental for $\mu_0H \geq 2$ T. Thus, the field dependence of $MR$ at 2.5 K seems to closely follow the field dependence of magnetization.

**Discussion.** – This is the first time that negative $MR$ of magnitude comparable to that of manganites is found in a rare-earth titanate. $MR$ in undoped RTiO$_3$ oxides was rarely investigated in the past because the majority of the RTiO$_3$ (R = La, Gd, Nd etc.) oxides, despite having one electron per Ti ion, are highly insulating at 4.2 K due to the strong on-site Coulomb repulsion among charge carriers [24,25]. It is only recently reported an unusual positive $MR$ in non-stoichiometric RTiO$_3$ (R = Pr, Ce) [26] and its origin was attributed to the Zeeman splitting of the Ti-3d conduction band. In contrast to PrTiO$_3$, $MR$ is negative.

![Fig. 3](Image)

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in our sample. What could be the origin of the negative MR in the La-substituted EuTiO$_3$?

The band structure of EuTiO$_3$ is characterized by the presence of a narrow 4$f$ band of Eu$^{2+}$ ions at about $\sim$0.8 eV below the Ti-conduction band edge [27]. The conduction band is composed of hybridized Ti-3$d$ and Eu-5$d$ states with a conduction band edge being dominated by Ti-3$d$(t$_{2g}$) states. The top of the valence band is dominated by O-2$p$ states. The Fermi level ($E_F$) is just on the top of the Eu-4$f$ band [27]. There are no free carriers in the Ti-3$d$ conduction band of stoichiometric EuTiO$_3$ since Ti$^{4+}$ is a $d^0$ ion. The introduction of La$^{3+}(4f^0)$ ions at the Eu$^{2+}(4f^7)$ site donates electrons. The donated electrons will be bound to the La$^{3+}$ impurity for a small concentration of the doped cations (typically $x \sim$ 10$^{-3}$) but impurity levels merge to form an impurity band which will spread to overlap with the Ti-3$d$ conduction band edge with increasing content of La ion. A doped electron (Ti$^{3+}$:$d^1$) having spin $S_{3d} = 1/2$ can interact with the localized 4$f$ moment of Eu$^{2+}$ having a much larger spin ($S_{4f} = 7/2$) via $d$-$f$ exchange interaction. As the donor electron is exchange coupled to Eu-4$f$ moments, it experiences spin-disorder scattering due to 4$f$ spin fluctuations above $T_N$ in zero external magnetic field. As the external magnetic field is applied above $T_N$ and increased in strength, 4$f$ spin fluctuations decrease progressively which reduces the spin-disorder scattering experienced by 3$d$ electrons. The mobility of electrons increases and the resistivity decreases smoothly with increasing magnetic field. On the other hand, the application of a high magnetic field below $T_N$ destabilizes the antiferromagnetic ground state and induces a ferromagnetic state. The critical field ($H_{sf}$) for the spin-flop transition is very small ($\sim$2.1 kOe at 2.5 K) for EuTiO$_3$ due to the weak anisotropy associated with Eu$^{2+}$ ($L = 0$) ions [28]. The $H_{sf}$ value was estimated from the peak position in $dM/dH$ vs. $H$ curves (not shown here). At $T = 2.5$ K, $H_{sf} = 1.7$ kOe for Eu$_{0.995}$La$_{0.01}$TiO$_3$. A decrease in the $H_{sf}$ value with substitution of La$^{3+}$ is either due to the 4$f$-3$d$ exchange interaction or caused by the disorder introduced by the non-magnetic La$^{3+}$ in the 4$f$ sublattice, which need to be clarified by theoretical work and experimental studies on single-crystalline Eu$_{1-x}$La$_x$TiO$_3$ samples in the future. When $H = H_{sf}$ spins in adjacent layers flop perpendicularly to the anisotropy axis. As the field is increased above $H_{sf}$, flopped spins rotate (cant) towards the field direction. This is the region where $M$ increases linearly and MR shows the greatest change. As $H$ increases above 1 T, 4$f$ spins on neighboring Eu ions are nearly parallel to each other and hence electrons experience less scattering that leads to only an incremental increase in the MR value in this field-induced ferromagnetic state. The presence of appreciable MR at temperatures as high as 70 K ($\sim$12 $T_N$) suggests that 4$f$ spin fluctuations are non-negligible over a wide temperature range above $T_N$.

It was predicted that negative magnetoresistance due to the suppression of spin fluctuations in different magnetic materials scales with the square of the reduced magnetization, i.e., $\Delta \rho/\rho = C(M/M_s)^2$, where $M_s$ is the saturation magnetization and $C$ is the proportionality constant ($C = (2k_F\xi_0)^{-2} \times n^{-2/3}$) related to the bare correlation length ($\xi_0$) and carrier density ($n$) [29,30]. Thus, the lower the carrier density, the larger the magnitude of MR. Since $M \propto H$ for low fields, $\Delta \rho/\rho \propto H^2$ in the paramagnetic state. We could fit our data over the entire magnetic-field range ($\mu_0H = 0$ to 7 T) with the above quadratic relation for $T > 40$ K but the high field MR deviates from the $M^2$ behavior with temperature decreasing below 40 K. Khosla and Fischer [31] extended Kausya’s model of $s$-$d$ scattering to include a third-order correction in the $s$-$d$ interaction Hamiltonian and showed that MR over a wide field range can be described by the empirical relation

$$\Delta \rho/\rho = -a^2 \ln(1 + bH^2),$$

(3)

where

$$a^2 = A_1JD(E_F)[S(S + 1) - \langle M^2 \rangle],$$

(4)

$$b^2 = \left[1 + 4S^2\pi^{-2}(2JD(E_F)/g)^4\right]g^2\mu_B^4/(\alpha k_B T^2).$$

(5)

Here, the parameter $A_1$ is the measure of the contribution of spin scattering to the total magnetoresistance, $J$ is the exchange interaction integral, $S$ is the spin of the localized moments, $g$ is the effective Landé $g$-factor, $D(E_F)$ is the density of states at the Fermi level, $\langle M^2 \rangle$ is the average magnetization squared and $\alpha$ is a numerical constant of the order of unity. For small magnetic fields, the above empirical relation also leads to $\Delta \rho/\rho \propto \langle M^2 \rangle$. We could fit the MR data over a wide field range with eq. (1) and the fits are shown by lines in fig. 3(b). While eq. (3) fits the field dependence of MR over the full field range for $T \geq 28$ K, deviations occur at lower temperatures. When the sample is in the antiferromagnetic state (see 5 and 2.5 K data), eq. (3) fits the data only for $\mu_0H < 1.5$ T. The temperature dependence of the $a$ and $b$ parameters is shown in the inset of fig. 3(c). Below 20 K, the parameter $a$ decreases rapidly whereas the parameter $b$ increases. The main panel of fig. 3(c) shows the field dependence of $-MR$ and $M$ at 2.5 K on the left and right y-axis, respectively. It is notable that $-MR$ vs. $H$ closely follows $M(H)$. Based on our unpublished data on oxygen-deficient single-crystalline EuTiO$_3$, we would like to mention that the observed magnetoresistance is intrinsic and not caused by spin-polarized tunneling of carriers across grain boundaries.

At this moment, it is worth recalling the magnetoresistance effect in EuO, which is a ferromagnetic semiconductor with $T_C = 69.8$ K. While the stoichiometric EuO is insulating down to 4.2 K, Eu-excess EuO and hence oxygen-deficient EuO shows an insulator-metal transition at $T_C$ and colossal magnetoresistance around $T_C$ [32]. The conduction band of EuO is made up of Eu-5$d$ and 6$s$ states and the valence band is made up
of a O-2p state, whereas the narrow 4f band lies close to the conduction band edge. Oxygen vacancy introduces shallow donor (impurity) states very close to the conduction band edge. A strong f-d exchange interaction between localized Eu:4f electrons and itinerant Eu:5d electrons causes the exchange splitting of the conduction band at $T_C$ when the temperature is approached from above. The spin-up 5d band moves down by 0.6 eV upon entering the ferromagnetic state from the paramagnetic state even in the absence of an external magnetic field [33].

The application of an external magnetic field close to $T_C$ causes a further lowering of the spin-up 5d conduction band edge which then starts to overlap with the impurity states. Those electrons localized in the shallow donor states are emptied into the spin-up 5d band and hence the resistivity decreases dramatically under external magnetic fields. A similar situation may also exist in our La-doped EuTiO$_3$. However, the bottom of the conduction band in EuTiO$_3$ is dominated by Ti-3d($t_{2g}$) states compared to the domination of Eu-5d states in EuO. First-principle calculations do predict the overlap of the Ti-3d and Eu-5d state and also the non-negligible overlap of the Ti-3d and Eu-4f states [27,34]. Hence, it is possible that the Ti-3d($t_{2g}$) band also spin splits with increasing strength of the magnetic field even above $T_N$ with the gap between spin-split bands proportional to the average magnetization of 4f spins, which could be a possible origin of the MR persisting over a wide temperature range above $T_N$. Hence, the suppression of 4f-spin fluctuations and the magnetic-field-induced shift of the spin-split Ti($t_{2g}$) band may work in tandem in our compound. However, we need theoretical and experimental supports to verify this possibility.

**Conclusion.** – In summary, it is found that the electrical resistivity of Eu$_{0.95}$La$_{0.05}$TiO$_3$ shows a non-metal to metal transition around 65 K upon decreasing temperature in the absence of an external magnetic field, whereas the antiferromagnetic transition occurs at a much lower temperature ($T_N = 5.43$ K). A large negative magnetoresistance is observed over a wide temperature range. The negative magnetoresistance for the 7 T field increases from $-6\%$ at 70 K to $-75\%$ at 2.5 K. We attribute the negative magnetoresistance to decrease in the spin-disorder scattering experienced by Ti-3d electrons following the suppression of Eu-4f spin fluctuations by the external magnetic field. Reports on the magnetoresistance in rare-earth titanates are still scarce. In view of our findings, it will be interesting to explore the impact of the d-f interaction on the magnetoresistance in other rare-earth titanates.

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