A nature of low-temperature resistivity minimum in ceramic manganites

E. Rozenberg\textsuperscript{1}, M. Auslander\textsuperscript{2}, I. Felner\textsuperscript{3} and G. Gorodetsky\textsuperscript{1}

\textsuperscript{1}Department of Physics Ben-Gurion University of the Negev
POB 653, 84105 Beer-Sheva, Israel

\textsuperscript{2}Department of Electrical and Computer Engineering Ben-Gurion
University of the Negev
POB 653, Beer-Sheva 84105, Israel

\textsuperscript{3}Racah Institute of Physics The Hebrew University
Jerusalem 91904, Israel
(today)

Measurements of magnetoresistance and magnetization were carried out on ceramic samples of \( \text{La}_{0.5}\text{Pb}_{0.5}\text{MnO}_3 \) and \( \text{La}_{0.5}\text{Pb}_{0.5}\text{MnO}_3 \), containing 10 at. % Ag in a dispersed form. The results obtained for the resistivity at zero applied magnetic field exhibit a shallow minimum at the temperature \( T \approx 25 \div 30 \text{ K} \) which shifts towards lower temperatures upon applying a magnetic field and disappears at a certain field \( H_c \). Also the resistivity at helium temperature decreases upon applying magnetic fields. It is shown that the model of charge carriers tunneling between antiferromagnetically coupled grains may account for the results observed.

PACS numbers: 71.28.+d, 71.30.+h, 72.15.Rn, 72.20.-i

I. INTRODUCTION

As with any material, the transport properties of doped manganites \( \text{La}_{1-x}\text{A}_x\text{MnO}_3 \) (A is a divalent ion such as Cu, Sr, Ba, etc.) differ markedly whether they are in single-crystalline or polycrystalline form (see Chapters 1 and 5 in Ref.\textsuperscript{1}). There exists experimental evidence that the presence of grains and grain boundaries (GB) modifies drastically the type of the temperature and magnetic field dependence of the resistivity \( \rho(T,H) \) in ceramic manganites as compared to single-crystalline samples.\textsuperscript{2,3} In single crystals (at \( 0.2 < x < 0.5 \)) a strong peak of \( \rho(T,0) \) is observed near the Curie temperature \( T_c \) - a metal-insulator transition occurs. In contrast, the resistivity of a polycrystalline samples exhibits a wide maximum at a temperature \( T_{\max} \) well below \( T_c \). At sufficiently small grain size no peak is seen near \( T_c \), but as the grain size increases the peaks at both \( T_{\max} \) and \( T_c \) become coexistent.\textsuperscript{4,5} In good polycrystalline samples the former peak at \( T_{\max} \) degenerates to a "shoulder" at \( T < T_c \) and only a sharp maximum of \( \rho(T,0) \) is observed near \( T_c \). The magnetoresistance (MR) in the single crystals and polycrystalline samples also behave very differently. E.g., the single crystals have colossal MR (CMR) in a vicinity of \( T_c \) and small enough MR apart it.\textsuperscript{6,7} On the other hand, the ceramics have an appreciable MR throughout the ferromagnetic region and often manifest the largest MR at low temperatures.\textsuperscript{8} This low-temperature MR is characterized by enhanced low-field response \( \Delta \rho / \Delta H \). In addition to such low-field low-temperature MR, the prominent feature that distinguishes the polycrystalline from single-crystalline \( \text{La}_{1-x}\text{A}_x\text{MnO}_3 \) is a shallow minimum of \( \rho(T,0) \), which occurs at a temperature \( T_{\min} \) well below \( T_{\max} \).

Two approaches have been used to explain the phenomena specific for polycrystalline manganites. Intergrain tunneling concept has been applied to model the low- and high-field MR at low \( T \) as well as the temperature and grain-size dependencies of the resistivity.\textsuperscript{9}\textsuperscript{10,11} MR at intermediate \( T \) (around \( T_{\max} \)) and the low-temperature minimum of \( \rho(T,0) \) have not been examined within this model. The latter phenomenon, however, has been considered using the second approach, namely, bulk-scattering concept.\textsuperscript{12} It has been suggested that the minimum (and the resistivity upturn at lower \( T \)) arises from the competition of two contributions - one, usual, increasing and other, decreasing with the increase of the temperature. The origin of such an unusual contribution has been attributed to Coulomb interaction (CI) between carriers strongly enhanced by disorder.\textsuperscript{13} However, to the best of our knowledge, no attempt was done to describe within CI model the flattening and vanishing of the minimum under rather small external magnetic fields observed in very different polycrystalline manganites.\textsuperscript{14,15}

The present paper focuses on the study of the low-temperature minimum of resistivity in ceramic manganites. In Section 2 we present the experimental results on the temperature dependence of the resistivity in zero and an increased magnetic field. The data obtained are analyzed in Section 3 using a bulk-scattering model (A) and a model of carrier tunneling between antiferromagnetically (AFM) coupled ferromagnetic (FM) grains (B). The results of the consideration are concluded in Section 4.
II. EXPERIMENTAL RESULTS

Samples of La$_{0.5}$Pb$_{0.5}$MnO$_3$ (LPMO) and LPMO containing 10 at. % of dispersed Ag were prepared by a standard ceramic technology. It was noted in that Ag doping leads to the formation of Ag agglomerates within the sample that, in turn, decrease the resultant resistivity of LPMO (see Fig. 1) but have no pronounced effect on the magnetic and MR properties. Measurements of $\rho$ vs. $T$ at zero magnetic field and at $H$ up to 1.5 Tesla were carried out in the temperature range 4.2 – 360 K, and the results obtained are presented in Figs. 1 and 2.

FIG. 1. (a) temperature dependence of the resistivity of La$_{0.5}$Pb$_{0.5}$MnO$_3$ (curve 1) and La$_{0.5}$Pb$_{0.5}$MnO$_3$ containing 10 at. % of Ag in a dispersed form (curve 2); (b) - the temperature dependence at low-temperature extended scale

As it is shown in Fig. 1b the minimum of $\rho(T, H)$ is observed at $T_{\text{min}} \sim 25$ – 30 K. This result is similar to that obtained on self-doped (with cation vacancies on La and Mn-sites), Ca-, Sr-, and Ba-doped ceramic manganites, as well as on Ca-doped polycrystalline films. Moreover, artificially created single grain boundary induces the appearance of similar minimum for an epitaxial bicrystal La$_{0.67}$Ca$_{0.33}$MnO$_3$ film. It seems that the existence of the above low-temperature minimum is not sensitive to the nature of La-site dopant and to the presence of additional impurities; its position is almost sample-independent and is close to the above mentioned values of $T_{\text{min}}$. High level La-site doping of the LPMO ceramic do not suppress the above noted wide maximum of $\rho(T, 0)$ as well (see Fig.1).
FIG. 2. Experimental temperature dependence of the resistivity of La$_{0.5}$Pb$_{0.5}$MnO$_3$ containing 10 at. % of Ag measured at various magnetic fields.

The measurements of the magnetization $M$ vs. $T$ at a low $H$ were reported previously. For the benefit of the present discussion, the low-temperature data are displayed here in an extended scale, see Fig. 3.

FIG. 3. Magnetization vs. temperature measured at low magnetic field. The results are presented at temperatures up to 150 K; the magnetization vs. temperature measured at a wider temperature region is given in the inset.

The MR and magnetic properties of the LPMO ceramic are similar to those of other ceramic manganites. In particular, $T_{\text{max}}$ is significantly lower than $T_c$, the largest MR effect occurs at lowest $T$, and, except only a small peak near $T_c$, MR gradually decreases with increasing temperature. Note that the resistivity upturn at $T < T_{\text{min}}$ could not be attributed to the effect of charge ordering since, similarly to that observed in other ceramic manganites, it appears to be weak (<1%). So, the LPMO is an appropriate system for studying effects, which are peculiar for the La-based manganite ceramics.
A. Bulk-scattering model including quantum corrections to conductivity

Let us first analyze $\rho(T, H)$ at low temperatures under an assumption that bulk scattering dominates the conduction. It seems reasonable in the ceramics with large contacting grains that may form a percolation cluster. Generally, the resistivity can be represented as

$$\rho = \rho_{\text{el}} + \rho_{\text{in}}$$

(1)

where $\rho_{\text{el}}$ and $\rho_{\text{in}}$ are the contributions due elastic (electron-impurity interaction and CI) and inelastic (e.g. electron-phonon interaction) processes. Normally, the part $\rho_{\text{in}}$ increases with increasing the temperature due to a power law $\rho_{\text{in}} = b T^p$ in which the coefficient $b$ does not depend on $H$. In good conductors the part $\rho_{\text{el}} = 1/\sigma_{\text{el}}$ doesn’t depend on $T$ and $H$ being equal to the residual resistivity $\rho_0$, but at rather strong disorder both temperature and magnetic-field dependence appears in $\sigma_{\text{el}}$ due to CI and decoherence effects.

A theory of CI correction to the residual conductivity at $H = 0$ was originally developed by Altshuler and Aronov,\cite{A91} yielding the following expression

$$\sigma_{\text{el}}(T, 0) = \sigma_0 + \delta \sigma_{\text{CI}}(T, 0), \quad \delta \sigma_{\text{CI}}(T, 0) = 0.0309 \frac{e^2}{\hbar L_T},$$

(2)

where $L_T^{-1} = \sqrt{k_F^2 T / D} = A \sqrt{T}$ and $D$ is the carriers diffusion constant. Thus, with the use of Eq. (2) and assumed form of $\rho_{\text{in}}$, Eq. (1) takes the form

$$\rho(T, 0) = \rho_0 - a T^{1/2} + b T^p$$

(3)

where $a = 0.0309 A \rho_0^2 e^2 h^{-1}$. The interplay of the increasing and decreasing temperature-dependent terms in Eq. (3) gives rise to the minimum of $\rho(T, 0)$. Such an explanation was suggested in Refs. \cite{A91, A91}. It appears that our experimental curves $\rho(T, 0)$ at low temperatures are fitted fairly well by Eq. (3) with the same $p = 2$ as was taken in Refs. \cite{A91, A91}. Though, this explanation is plausible, it must be verified by an additional evidence. In this connection the influence of external magnetic field on the minimum is a crucial test for the model. Very recently, the calculation of the total quantum correction to $\sigma_0$ that could shed light on our problem, has been accurately recast by Aleiner et al.\cite{A91} It gives

$$\sigma_{\text{el}}(T, H) = \sigma_0 + \delta \sigma_{\text{CI}}(T, H) + \delta \sigma_{\text{DP}}(T, H)$$

(4)

where $\delta \sigma_{\text{CI}}(T, H)$ is the CI contribution in a non-zero magnetic field, and $\delta \sigma_{\text{DP}}(T, H)$ is the contribution of dephasing caused by both magnetic field and CI. Asymptotic formulas of Refs. \cite{A91, A91} suitable mostly for 1D and 2D cases, contain the terms divergent in 3D. To get finite results such terms have been recalculated. For the CI correction we have

$$\frac{\delta \sigma_{\text{CI}}(T, H)}{\delta \sigma_{\text{CI}}(T, 0)} - 1 = \frac{0.7510}{k_F^2 l_H}$$

(5)

where $k_F$ is the Fermi wave-number, $l$ is the mean free path and $l_H = \sqrt{e H / c}$ is the magnetic length. The condition $l_H \gg L_T$ under which the calculation was done, holds for $H$ up to tens Tesla. Formally Eq. (5) predicts a reduction of the CI correction but actually this effect is negligibly small. For example, at typical carrier density $\sim 10^{22}$ cm$^{-3}$, $k_F l > 1$, the right-hand side of Eq. (5) is smaller than 1\% up to $H = 10$ T. The term $\delta \sigma_{\text{DP}}(T, H)$ has been obtained assuming domination of the magnetic-field contribution to this correction.\cite{A91} The result may be treated as first two terms of expansion of the weak-localization expression

$$\delta \sigma_{\text{DP}}(T, H) = \frac{e^2}{(2\pi)^2} \hbar \sqrt{4 L_T^2 + L_{\phi}^2}$$

(6)

with respect to small $l_H / L_{\phi}$,\cite{A91, A91, A91} where $L_{\phi}$ is the length of dephasing due to CI given by

$$L_{\phi}^2 = \frac{14.7336}{k_F^2 l_H} \left( 1 - 1.2794 \frac{2 L_T}{l_H} \ln \frac{l_H}{2 l_T} \right)$$

(7)

The numerical factors in Eqs. (3), (5) and (6) stem from the assumed parabolic spectrum and full spin polarization of the carriers. Eq. (5) may serve as a reliable extrapolation of $\delta \sigma_{\text{DP}}(T, H)$ to all $H$. It follows from Eq. (6) that
parametrically $L_T << L_\varphi$, and so $\delta \sigma_{DP}(T, H) << \delta \sigma_{C1}(T, H)$ (for realistic parameters these inequalities may not hold in the strong form).

So, in the considered model at all actual $H$ the resistivity minimum persists and is weakly affected by the magnetic field. It is worth to note that such a resistivity minimum is observed in a single-crystalline bilayered manganite. At the same time the behavior noted above fully disagrees with the experimental data for ceramic manganites (see Sections 1 and 2). Magnetic-field dependence of $\delta \sigma_{DP}(T, H)$ leads to a negative MR, but it is too small to account for the observed MR. At $l_H << L_\varphi$ $\delta \sigma_{DP}(T, H)/\sigma_0 \approx 3(k_B^2 l_H)^{-1}$ and hence, as follows from the above estimation, the model MR in rather strong fields achieves percents at best. In comparison, measured MR is $\sim 36\%$ at $T = 4.2$ K, and $H$ of only $1.5$ T causes the minimum to disappear (see Fig. 2).

Thus, the bulk-scattering model with quantum corrections to conductivity predicting a resistivity minimum at zero magnetic field, strongly disagrees with the experiment on ceramic manganites as concerns the behavior of the minimum in finite magnetic fields.

### B. Intergrain tunneling model

Let us treat the problem using an approach, which is quite opposite to that examined previously. Namely, we will assume that in the discussed materials much of the grains are isolated from each other. In this model the tunneling between grains brings dominating contribution to the conduction. This is consistent with the low-temperature conductivity weakly dependent on $T$, but being smaller than the minimal metallic conductivity. Several groups (see e.g. Ref.[4]) attributed the low-temperature MR to spin-polarized intergrain tunneling. Our purpose is to describe the low-temperature resistivity minimum also using this concept.

Regular theory of tunneling conduction through FM metal - non-magnetic insulator - FM metal junction exists only for the planar geometry. For the tunneling resistance between two FM grains, say $i$ and $j$, we will use phenomenological expression of Ref.[22]

$$R_{ij} = \frac{r_{ij}}{1 + \varepsilon \cos \vartheta_{ij}},$$  \hspace{1cm} (8)

Here $\vartheta_{ij}$ is the angle between the magnetization directions $\mathbf{n}_i$ and $\mathbf{n}_j$ of the grains $i$ and $j$, respectively ($\mathbf{n}_i^2 = 1$), $\varepsilon = P^2$ is the spin-valve coefficient,[23,24] where $P$ is the degree of spin polarization of current carriers in each grain

$$P = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\down\uparrow},$$  \hspace{1cm} (9)

$N_\uparrow$ and $N_\down\uparrow$ being the densities of states for spin-up and spin-down carriers, respectively, and $r_{ij}$ is a factor independent on the magnetization orientations, which cannot be determined in phenomenological approach. By analogy with the case of planar-junction tunneling,[22] it has been proposed[25] to use the expression

$$r_{ij} = r_0 \exp(2\kappa d_{ij}), \hspace{0.5cm} \kappa = \sqrt{2mU/h}$$  \hspace{1cm} (10)

where $d_{ij}$ is the distance between the grains and $U$ is the tunneling barrier height. Though Eq.(10) holds only at large $d_{ij}$ and/or $U$, it may be used for qualitative description.

Eqs.(8) and (10) define a random resistor network, which has to be solved in order to obtain the sample resistivity. As it stands, the problem cannot be solved unless the statistics of the configurations $\{\mathbf{n}_i\}$ is defined. At equilibrium the configuration energy $E$ and temperature $T$ defines the statistical distribution $\mathbf{P}$ of the contributions to $E$ is the energy of the grain moments ($\mathbf{m}_i = 2\mu_i\mathbf{n}_i$) in the magnetic field $\mathbf{H}$. Slonczewski[26] showed that carriers tunneling via the planar junction mediate an exchange interaction between FM electrodes, which proves to become of AFM type for sufficiently high barrier. As in that case we will assume each two grains $i, j$ to be coupled by an AFM exchange $J_{ij} = J_0 \exp(-2\kappa d_{ij})$, with $J_0 < 0$. So the energy will take the form

$$E = - \sum_{i<j} \mathbf{n}_i \cdot \mathbf{J}_{ij} \cdot \mathbf{n}_j + 2 \sum_i \mu_i \mathbf{n}_i \cdot \mathbf{H}$$  \hspace{1cm} (11)

where a tensor $\mathbf{J}_{ij}$ includes both the dipolar and the above exchange interactions. At $T \to 0, H \to 0$ a system with the energy given by Eq.(11) will tend to magnetically frustrated state. Thus, to make AFM correlation between grains consistent with FM ground state, we have to attribute the moments contributing to $R_{ij}$ (Eq.(10)) to only a small
part of the grains, most probably to GB. Indeed, our magnetization measurements on LPMO show that at lowered temperature the magnetization curve bends only slightly below the expected saturation (see Fig.3).

In the subsequent discussion a simplified scheme is used. In accordance with Refs. [4,5] in which: (i) the exact conductance is replaced by an averaged inverse of Eq. (10) and (ii) the averaging over the spatial and magnetic variables is carried out independently. This gives for the resistivity

\[ \rho(T, H) = \frac{\rho_U}{1 + \varepsilon \langle \cos \vartheta_{ij} \rangle} \]  

(12)

where \( \rho_U \propto \langle r_{ij} \rangle \). Due to Eq. (10) the factor \( \rho_U \) is not expected to vary essentially at low \( T \) and \( H \); in this range the field dependence of the resistivity results from that of \( \langle \cos \vartheta_{ij} \rangle \). Thus, irrespective of the type of frustrated state at \( H = 0 \), Eq. (12) describes the cause of the low-field negative MR as being the rotation of the 'partial' grain moments to a unique direction along the magnetic field \( H \). For AFM correlation and sufficiently low \( H \), \( \langle \cos \vartheta_{ij} \rangle \) increases upon heating from a negative value at the ground state (note that authors of Ref. [4] estimated \( \langle \vartheta_{ij} \rangle \) from their data to equal \( \sim -0.8788 \)) to higher values. Therefore, the part of Eq. (12) depending on \( \langle \cos \vartheta_{ij} \rangle \) is a decreasing function of \( T \). At \( T = 0 \) such a behavior persists until \( \langle \cos \vartheta_{ij} \rangle \) changes its sign at \( H = H_{cr} \), while at \( H > H_{cr} \) it becomes an increasing function of \( T \). To describe full dependence of \( \rho(T, H) \) the modeling of \( \rho_U \) is required. Zhang et al. [4] obtained \( U \) as a function of the magnetization of the grain core and GB. Due to this model \( \rho_U \) is an increasing function of temperature at \( T < T_{max} \). Thus, in view of the above discussion concerning \( \langle \cos \vartheta_{ij} \rangle \), Eq. (12) predicts that a minimum of \( \rho(T, H) \) versus temperature should occur at a low \( T \) and \( H < H_{cr} \). This minimum will degrade upon increasing \( H \) and disappear at \( H \geq H_{cr} \), in qualitative agreement with our data shown in Fig. 2, for which \( H_{cr} \approx 1.5 \) T.

The quantitative use of Eq. (12) is possible only under some approximation to analytical calculation of \( \langle \cos \vartheta_{ij} \rangle \) and \( \rho_U \) (otherwise, many-body simulation method may be applied directly to the original network, so Eq. (12) becomes redundant). To illustrate the model we approximate \( \langle \cos \vartheta_{ij} \rangle \) by its value for a cluster of two grains with an AFM exchange \( J \) and equal moments \( \mu_i = \mu \). In addition, since the temperature dependence of the in-grain and GB magnetization is dominated by the spin wave \( T^3/2 \) terms at low well \( T \), we assume

\[ \rho_U = r_0 + r_1 T^{3/2} \]  

(13)

where \( r_0 \) and \( r_1 \) are the parameters independent on \( H \). The model parameters are then defined from the requirement that in the case \( H = 0 \) Eq. (12) fits the experimental data for \( \rho(T, H) \) in the range from 4.3 K to 50 K. In this fit Eq. (13) and the expression

\[ \langle \cos \vartheta_{ij} \rangle = -L (|J|/k_BT), \ H = 0, \]  

(14)

where \( L(x) = \coth(x) - 1/x \) is the Langevin function, are taken into account. This gives \( \varepsilon = 0.487 \) \((P \approx 0.697)\), \(|J|/k_B = 155 \) K, \( r_0 = 0.145 \) Ω·cm, \( r_1 = 1.026 \times 10^{-4} \) Ω·cm·K$^{-3/2}$$. We used these parameters and a closed expression for \( \langle \cos \vartheta_{ij} \rangle \) at \( H \neq 0 \) to calculate the model curves \( \rho(T, H) \) at the increased values of the parameter \( S = 2\mu H/|J| \) (see Fig.4).

**FIG. 4.** Resistivity vs. temperature. The lines represent theoretical curves based on the model of intergrain tunneling for various \( S \) (normalized field). The open circles are the experimental results observed for La$_{0.5}$Pb$_{0.5}$MnO$_3$: 10 at. % Ag.
It appears, that in the considered version of the model a quantitative agreement with the experiment cannot be achieved with any choice of \( \mu \) because of lacking the property of highest magnetic-field response at the lowest fields observed in the experiment. Really, the largest drop of \( \rho(T, H) \) occurs experimentally at \( 0 < H \leq 0.2 \) T and at higher \( H \) the change is slower (see Fig.2). The calculated curves demonstrate much more gradual change in low-field region (see Fig.4). Nevertheless, the predictions of the model concerning the generic behavior of the resistivity minimum under the increase of \( H \) are in a well qualitative agreement with the experiment. Finally, if we equate the value of \( S \sim 1 \) at which the minimum disappears in the model to its value at \( H_{cr} \approx 1.5 \) T we retrieve \( \mu \sim 200 \mu_B \). Low values of \( P \) and \( \mu \) may express the fact that really a small part of a grain with reduced magnetic order contributes to the tunneling.

IV. CONCLUSIONS

A characteristic shallow minimum of the resistivity was found to occur in various polycrystalline doped manganites \( \text{La}_{1-x}\text{A}_x\text{MnO}_3 \) where \( \text{A} = \text{Ca}, \text{Sr}, \text{Ba} \) or \( \text{Pb} \). Usually this minimum occurs at low temperatures \( (T < 50 \) K), shifts towards lower \( T \) upon applying a magnetic field and disappears at some field \( H_{cr} \). Two models were considered to account for this minimum: (i) bulk scattering with quantum corrections to conductivity and (ii) tunneling between AFM coupled grains. The resistivity minimum in the first model, in disagreement with experiment, is almost insensitive to \( H \) in the range of interest. The second model provides a fairly well qualitative description of the effects observed. Even in a rough approximation it agrees with experiment.

Very recent experimental data also strongly support the suggested nature of the effect considered. For example, the minimum of \( \rho(T, 0) \) and its gradual vanishing under external \( H \) are observed in a ceramic sample of \( \text{La}_{0.8}\text{Sr}_{0.2}\text{MnO}_3 \) while no such an effect is detected on a single crystal of the same composition. The same effect is observed in an epitaxial bicrystal film of \( \text{La}_{0.67}\text{Ca}_{0.33}\text{MnO}_3 \) with an artificially created single grain boundary, but is absent in an epitaxial film of the same composition. It also should be noted that the spin-dependent tunneling of charge carriers in ceramic manganites discussed in this paper is similar to that observed earlier in granular ferromagnetic media - see, for example.

V. ACKNOWLEDGMENTS

This research was supported by the Israeli Science Foundation administered by the Israel Academy of Sciences and Humanities. The authors thank to Dr. A. Shames for the help in our experiments.

1 “Colossal Magnetoresistance Charge Ordering and Related Properties of Manganese Oxides”, ed. by C.N.R.Rao and B. Raveau, World Scientific Publishing Co., 1998.
2 A.P. Ramirez, J. Phys.: Cond. Matter., 9, 8171 (1997).
3 J.M.D. Coey, M. Viret and S. von Molnar, Adv. in Phys., 48, 167 (1999).
4 N. Zhang, F. Wang, W. Zhong and W. Ding, Solid State Comm., 107 (1998), p. 417; J. Phys.: Cond. Matter, 11, 2625 (1999).
5 N. Zhang, W. Ding, W. Zhong, D. Xing and Y. Du, Phys. Rev., B56, 8138 (1997).
6 A.E. Kar’kin, D.A. Shulyatev, A.A. Arsenov, V.A. Cherepanov and E.A. Filonova, JETP, 89, 358 (1999).
7 P. Raychaudhuri, K. Sheshadri, P. Taneja, S. Bandyopadhyay, P. Ayyub, A.K. Nigam, R. Pinto, S. Chaudhary and S.B. Roy, Phys. Rev., B59, 13919 (1999).
8 R. Mahendiran, S.K. Tiwary, A.K. Raychaudhuri, T.V. Ramakrishnan, R. Mahesh, N. Rangavittal and C.N.R. Rao, Ibid., B53, 3348 (1996).
9 T. Venkatesan, M. Rajeswari, Z.-W. Dong, S.B. Ogale and R. Ramesh, Phil. Trans. Roy. Soc. 356, 1661 (1998).
10 J. Fontcuberta, B. Martinez, V. Lausk, L. Baleells, X. Obradors, C.H. Coherca and R.F. Jardim, Ibid., 1577.
11 A. Barman, M. Ghosh, S. Biswas, S.K. De and S. Chatterjee, Solid State Comm., 106, 1998, 691; J. Phys.: Cond. Matter, 10, 9799 (1998).
12 A. Tiwari, K.P. Rajeev, Solid State Comm., 111, 33 (1999).
13 E. Rozenberg, G. Gorodetsky, N. Froumin, J. Pelleg, M. Polak, I. Felner and B.K. Chaudhuri, J. Phys. IV, 8, 359 (1998).
14 J.M.D. Coey, Phil. Trans. Roy. Soc. 356, 1519 (1998).
15 B.L. Altshuler and A.G. Aronov, Sov. Phys. JETP 50, 968 (1979)
16 P.A. Lee and T.V. Ramakrishnan, Rev. Mod. Phys. 57, 287 (1985)
17 J. Klein, C. Hoffer, S. Uhlenbruck, L. Alf, B. Buchner and R. Gross, Europh. Lett., 47, 371 (1999).
18 I.L. Aleiner, B.L. Altshuler and M.E. Gershenson, Waves in Random Media, 9, 201 (1999).
19 T. Okuda and T. Kimura, Phys. Rev. B60, 3370 (1999).
20 M. Julierre, Phys. Lett., 54A, 225 (1975).
21 J.C. Slonczewski, Phys. Rev., B39, 6995 (1989).
22 O. Ciftija, M. Luban, M. Auslender and J. Luscombe, Phys. Rev., B60, 10122 (1999).
23 N. Kobayashi, S. Onhuma, S. Murakami, T. Matsumoto, S. Mitani and H. Fujimori, J. of Magn. and Magn. Mater., 188, 30 (1998).
24 H. Fujimori, S. Mitani and K. Takanashi, Mat. Sci. Engin., A267, 184 (1999).