δ-doped LaAlO₃-SrTiO₃ interface: Electrical transport and characterization of the interface potential

A. Rastogi¹, S. Tiwari², J. J. Pulikkotil³, Z. Hossain¹, D. Kumar² and R. C. Budhani¹,³

¹ Condensed Matter - Low Dimensional Systems Laboratory, Department of Physics, Indian Institute of Technology Kanpur 208016, India
² School of Physical Sciences, Jawaharlal Nehru University - New Delhi 110067, India
³ CSIR - National Physical Laboratory, Dr. K. S. Krishnan Marg - New Delhi 110012, India

received 6 March 2014; accepted 20 May 2014
published online 9 June 2014

PACS 73.20.–r – Electron states at surfaces and interfaces
PACS 73.40.–c – Electronic transport in interface structures
PACS 73.50.Lw – Thermoelectric effects

Abstract – Here we investigate the LaAlO₃-SrTiO₃ heterostructure with δ-doping of the interface by LaMnO₃ at less than one monolayer. This doping strongly inhibits the formation of a mobile electron layer at the interface. This results in a giant increase of the resistance and the thermopower of the heterostructure. Several aspects of this phenomena are investigated. A model to calculate the carrier concentration is presented and the effect of doping with detailed temperature dependence is analyzed in terms of model parameters and weak-scattering theory. The large enhancement of the thermopower is attributed to the increased spin and orbital entropy originating from the LaMnO₃ monolayer.

Copyright © EPLA, 2014

Introduction. – The recent discovery of a highly mobile two-dimensional electron liquid (2-DEL) at the interface of two perovskite oxides has naturally evoked a huge amount of interest [1–3]. These heterostructures have been widely investigated both experimentally and theoretically, a) to understand the mechanism of formation of 2-DEL [4–7] b) to investigate its properties and examine new phenomena exhibited by it [8–11] and c) for exploitation of its unique properties for technological ends [12,13]. Here we contribute to this effort by investigating a δ-doped interface. We have prepared a series of heterostructures with δ-doping by fractions of a monolayer layer of LaMnO₃ at the interface of SrTiO₃ and LaAlO₃. Figure 1(a) shows the layer structure of our system.

We report the electrical transport, the resistance and the thermoelectric power (TEP) of these heterostructures. Our key finding is that the Mn-doping even in a single layer has a drastic effect on the properties of the interface. The resistance and thermopower increase considerably compared to the undoped interface. These effects are undoubtedly related to the mechanism of formation of the nearly 2-DEL at the interface. We find that our set of measurements offer an opportunity to develop a simple model which extends the standard polar-catastrophe ideas. While interface physics is rather complex due to several factors, like relaxation of ionic positions, resulting electrostatic forces, disorder and other interface reconstruction effects, our analysis of transport properties does pave way for a better understanding of some key issues of the interface physics.

Experimental details. – The pulsed laser deposition (with a KrF laser of wavelength 248 nm) technique has been employed for layer-by-layer growth of LaAlO₃ films on a TiO₂-terminated (001)-oriented SrTiO₃ single-crystal substrate. To tailor atomically sharp interfaces, growth parameters such as O₂ partial pressure and substrate temperature have been critically examined since these parameters determine the film stoichiometry and defects [14–16]. The substrate was kept 7 cm away from the target. The laser pulses were fired at 2 Hz and at a fluence ~1 J cm⁻² per pulse, which leads to a growth rate of ~ 0.15 Å/s. Further details of growth are described in our earlier publications [17,18]. A fraction δ (0 ≤ δ ≤ 0.6) of a monolayer of LaMnO₃ was first deposited on the TiO₂-terminated SrTiO₃ substrate at 10⁻⁴ mbar of O₂ pressure and 800 °C, followed by a 20 u.c. thick LaAlO₃ film. The sample was thereafter cooled under the same deposition pressure. These heterostructures were characterized by X-ray diffraction on PANalytical X'PERT
ious effects of the Mn-doping, we first note that no heterostructure with δ with the temperature of samples with doping fractions δ > 0.0 to 0.6 in the temperature range from 5 K to 200 K. No metallic behavior for 0.0 to 20 μ.

Referring to fig. 1(a), recall that LAO due to its alternating charged layers (LaO)⁺ and (AlO₂⁻) creates a large positive potential at the interface compared to the ground or surface potential. In the ideal picture layers can be treated as capacitors in series, the potential offset is proportional to the number k of such pairs. Therefore a certain minimum number of unit cells of LAO are needed to provide a threshold potential which closes the excitation gap for electrons in STO. The potential catastrophe with increasing k is clearly avoided by the solid by relaxation of ionic positions, buckling of layers etc., which screen the field. This makes the resulting potential far smaller and saturate rapidly with k.

Another important point to note is that, if the layers are charge-balanced they only produce this potential offset, i.e. the potential is constant outside the set of charged layers. To generate the electron layer at the interface one needs an electric field which physically comes from the ionic reconstruction described above. We model it here as an unbalanced positive charge on the LaO layer at the interface. Electrons drawn to the conduction band of STO occupy mostly the Ti dₓᵧ levels of the TiO₂ layer at the interface [20]. These electrons screen the positively charged LaO layer at the interface [20–22]. This leads us to account for the role of LAO layers by two parameters: a potential offset φ₀ and an excess charge density which we express as αε/Å² (α = lattice parameter of LaO layer). Due to potential offset, the excitation gap in STO is reduced to Δ = (1.6 – ε₀φ₀) eV. The charge density produces an electric field E₀ = αε/(2ε₀εₛ Å²), where εₛ is the dielectric constant of STO which is also temperature dependent. We now use the Thomas-Fermi theory to find a self-consistent equation for the potential on the STO side. Taking the z-axis to be perpendicular to the interface, the carrier density N(z) is given in terms of potential V(z) as N(z) = 2g(u(z) + Δ)/λₑ³. Here u(z) = βV(z), β = (kB T)⁻¹ and λₑ = h/(2m* kB T)¹/₂, where m* denotes the effective mass in the conduction band of STO. The function g(u) is essentially the Fermi-Dirac

PRO, revealing a tetragonal strained perovskite structure. Top electrodes of Ag/Cr were deposited in van der Pauw and standard four-probe geometry on films using shadow masking. The thermoelectric measurements were carried out in the Quantum Design PPMS.

**Results and discussion.** In order to describe various effects of the Mn-doping, we first note that no interfacial electronic conductivity was observed when LaMnO₃ films of several unit cells were deposited on TiO₂-terminated SrTiO₃ substrates [19]. The interfacial conduction could be observed only with less than one layer of LaMnO₃. This implies a unit cell of single Mn₃Al₁₋₄O₂ and LaO layers at the interface as shown in fig. 1(a). Whereas for the LAO-STO system a minimum of 4 to 5 unit cells of LAO is required on the TiO₂ side. Taking the number of LAO unit cells required to achieve the same is a lot larger and strongly depends on the Mn concentration in the layer. Figure 1(b) shows the change of sheet thickness for δ = 0.5. One sees that R_idle at room temperature increases sharply by three orders in magnitude as the LAO thickness decreases from 20 to 10 μ. The presence of even half a monolayer of LaMnO₃ changes the number of LAO layers required to achieve a good conducting 2-DEL, to 17–20 as compared to 4–5 for the STO-LAO interface.

We show next the variation in R_idle(T) as a function of the LaMnO₃ monolayer fraction (δ) for a fixed LaAlO₃ over-layer (20 μ.) in fig. 1(c). A rapid rise is seen in resistance when δ exceeds 0.2, confirming again that the LaMnO₃ monolayer inhibits the formation of 2-DEL at the interface in a strong way. Figure 1(d) shows the variation of the sheet resistance (R_idle) with temperature in the range from 2 K to 300 K for six films with monolayer Mn-doping in the range 0 ≤ δ ≤ 0.6 and an optimal LAO thickness of 20 μ. For δ = 0.6 the interface is non-metallic. The remaining curves show a minimum in temperature range from 40 K to 50 K. The resistance decreases from room temperature to the minimum rather sharply, by a factor of about 7 to 8. At lower temperatures there is a slow increase of resistance suggesting a weak-scattering regime.

In spite of many factors involved in the physics at the interface as mentioned above, we find it useful to develop a simple model in order to understand this set of results. The model primarily calculates the density of the electron liquid at the interface as a function of temperature. Referring to fig. 1(a), recall that LAO due to its alternating charged layers (LaO)⁺ and (AlO₂⁻) creates a large positive potential at the interface compared to the ground or surface potential. In the ideal picture layers can be treated as capacitors in series, the potential offset is proportional to the number k of such pairs. Therefore a certain minimum number of unit cells of LAO are needed to provide a threshold potential which closes the excitation gap for electrons in STO. The potential catastrophe with increasing k is clearly avoided by the solid by relaxation of ionic positions, buckling of layers etc., which screen the field. This makes the resulting potential far smaller and saturate rapidly with k.

Another important point to note is that, if the layers are charge-balanced they only produce this potential offset, i.e. the potential is constant outside the set of charged layers. To generate the electron layer at the interface one needs an electric field which physically comes from the ionic reconstruction described above. We model it here as an unbalanced positive charge on the LaO layer at the interface. Electrons drawn to the conduction band of STO occupy mostly the Ti dₓᵧ levels of the TiO₂ layer at the interface [20]. These electrons screen the positively charged LaO layer at the interface [20–22].

This leads us to account for the role of LAO layers by two parameters: a potential offset φ₀ and an excess charge density which we express as αε/Å² (α = lattice parameter of LaO layer). Due to potential offset, the excitation gap in STO is reduced to Δ = (1.6 – ε₀φ₀) eV. The charge density produces an electric field E₀ = αε/(2ε₀εₛ Å²), where εₛ is the dielectric constant of STO which is also temperature dependent. We now use the Thomas-Fermi theory to find a self-consistent equation for the potential on the STO side. Taking the z-axis to be perpendicular to the interface, the carrier density N(z) is given in terms of potential V(z) as N(z) = 2g(u(z) + Δ)/λₑ³. Here u(z) = βV(z), β = (kB T)⁻¹ and λₑ = h/(2m* kB T)¹/₂, where m* denotes the effective mass in the conduction band of STO. The function g(u) is essentially the Fermi-Dirac
Fig. 2: (Color online) We show theoretical fits of resistance measurements in the temperature range from 5 K to 50 K for four films with δ = 0.0, 0.1, 0.2 and 0.4. The fits use eq. (3) in which the carrier density \( N_2 \) used in the Drude term is obtained from eqs. (1) to (3). The inset shows the variation of \( N_2 \) with temperature for \( \delta = 0.0 \) and \( \alpha = 0.15 \).

\[ g(u) = \frac{2}{\sqrt{\pi}} \int_0^{\infty} x^{1/2} e^{-x} \, dx. \]  

This enables us to obtain the equation for the potential as

\[ \frac{d^2u}{dz^2} = \frac{1}{2\lambda^2} \left[ \frac{g(u + \beta \Delta)}{g(\beta \Delta)} - 1 \right], \]  

where \( \lambda^{-2} = \frac{(4\beta e^2g(\beta \Delta))}{(\epsilon_0 \epsilon_s \lambda_s^2)} \) gives the screening length. The equation is solved for the boundary condition given by the field \( E_0 \) and the profile of the carrier density is found. The sheet density \( N_2(T) \) is obtained by integrating \( N(z) \) over a depth of order \( \lambda \). The variation of \( N_2 \) with temperature for a typical set of parameters used here is shown in the inset of fig. 2. Parameters \( \Delta \) and \( \alpha \) mimic phenomena resulting from ionic relaxations, doping, temperature etc. Here they are obtained from experimental data as discussed below.

We first discuss the effect of doping in qualitative terms. As shown in fig. 1(a), when the LaMnO$_3$ layer is inserted, the Mn ions occupy the negatively charged layer next to LaO but away from the interface. We surmise that due to mixed-valent character of the Mn ion between states Mn$^{3+}$ and Mn$^{4+}$ a charge transfer occurs from the negatively charged Mn$_2$Al$_1$O$_2$ layer toward the LaO layer neutralizing its charge considerably. Further a reduced charge on the Mn layer would also lead to a relaxation of charge on other LAO layers, thereby affecting both \( \phi_0 \) and \( \alpha \). Small changes in these parameters can drastically affect the field on the TiO$_2$ layers at the interface and consequently a larger number of LaO layers are needed to generate the interfacial 2-DEL. Clearly, an ion with mixed-valent character greatly facilitates the charge transfer, which was restricted with Al ions.

Our surmise is supported to an extent by the work of Garcia-Barrio canal et al. [23], who studied superlattices of LaMnO$_3$ and SrTiO$_3$. They provide evidence of the mixed-valent character of Mn with the ratio of Mn$^{4+}$/Mn$^{3+}$ dependent on thicknesses of LMO and STO. We have carried out GGA+U calculations of this heterostructure (unpublished) and find that the partial density of states of Mn is different from what Mn$^{3+}$ and Mn$^{4+}$ have in a cubic environment.

Next we discuss the temperature dependence of resistance as shown in fig. 1(d). We find that with our model we can address quantitatively the low-temperature regime below the resistance minimum. Here the behavior hints at a weak-scattering regime. Accordingly we use the following expression for conductance along with the variation of electron density with temperature and doping as described by the calculation described above:

\[ \sigma(T) = \frac{N_2(T)e^2}{m^*} - \frac{e^2}{4\pi^2\hbar} \left( 2\ln \left( \frac{\tau_0^{-1} + \tau_i^{-1} + \tau_{so}^{-1}}{\tau_i^{-1} + \tau_{so}^{-1}} \right) - \ln \left( \frac{\tau_0^{-1} + \tau_i^{-1}}{\tau_i^{-1}} \right) \right). \]  

The first term is the Drude term and the second one is the weak-scattering correction describing quantum interference effects [24–26]. Three relaxation times occur in this expression. The first is the elastic scattering time \( \tau_0 \) which is temperature independent. The second one is the inelastic scattering time \( \tau_i \) whose temperature dependence is taken to be of the form \( \tau_i(T) = \tau_i^0 / T^p \), where \( p \) depends on the inelastic scattering mechanism. The inelastic scattering typically gives rise to a logarithmic increase of resistance with decreasing temperature. Finally, \( \tau_{so} \) is the relaxation time due to spin-orbit scattering. This is important here due to the interface electric field, which being perpendicular to the interface acts as a magnetic field on electrons moving parallel to the interface [27]. The spin-orbit scattering works oppositely to the inelastic scattering and it slows down the increase of resistance at lower temperatures, where \( \tau_{so} > \tau_{sc} \).

We now describe how several parameters required to fit the data to the above formula have been obtained. The model parameters \( \Delta \) and \( \alpha \) are fixed from the estimates of the carrier density and thickness of 2-DEL (taken to be \( \lambda \) here). From estimates based on our Hall measurements (not reported here) and similar estimates available in the literature [2], the carrier density ranges between 6 and \( 8 \times 10^{13} \) cm$^{-2}$ for the undoped layer around 50 K. The estimates for the thickness of the electron layer are in the range 60–70 Å at room temperature. We have chosen \( \Delta \) and \( \alpha \) so that, between 5 K and 50 K, \( N_2 \) lies between 4 and \( 8 \times 10^{13} \) cm$^{-2}$ and \( \lambda \) ranges between 50 Å and 10 Å. These values are shown in table 1 for various dopings. For a typical value of parameters the inset of fig. 2 shows the variation of \( N_2 \) with temperature.

The value of \( \tau_0 \) cannot be determined unambiguously from our data, but using a survey of estimates in the literature we take \( \tau_0 = 2.25 \times 10^{-14} \) s which then gives consistent magnitudes for the other parameters. To determine the index \( p \) of \( \tau_i \), we plot measured \( \Delta \sigma(T) = \sigma(T) - \sigma_{Drude} \) with \( \ln T \). It shows an approximate linear behavior whose
Table 1: Values of model parameters used to fit resistance curves in the temperature range from 6 K to 46 K for δ = 0.0, 0.1, 0.2, 0.4 and 0.5 shown in fig. 1(d). The elastic scattering time for all curves is \( \tau_0 = 2.3 \times 10^{-14} \) s.

| δ   | 0.0 | 0.1 | 0.2 | 0.4 | 0.5 |
|-----|-----|-----|-----|-----|-----|
| α   | 0.15| 0.11| 0.086| 0.045| 0.025|
| Δ (eV) | 0.001| 0.001| 0.001| 0.001| 0.002|
| \( \tau_{so} \times 10^{-13} \) s | 1.6 | 1.9 | 2.5 | 3.0 | 3.9 |

slope 2.8 is taken to be \( p \). \( T_0 \) in the expression for \( \tau_i \) is adjusted in the fitting procedure and is found to be 95 K. The estimate for \( \tau_{so} \) is taken to be \( \tau_i(T_d) \) where \( T_d \) is the temperature where the increase of resistance with decreasing temperature begins to flatten, with fine-tuning to obtain the best fits. For the temperature range of interest we take \( \epsilon_i = 300 \). Our fits for four resistance curves corresponding to \( \delta = 0.0, 0.1, 0.2 \) and 0.4 are shown in fig. 2. The fits are reasonably good in the temperatures range 6–46 K with the parameters shown in table 1. A good fit is also obtained for \( \delta = 0.5 \), but is not shown.

The following comments are in order. From table 1, we see that with doping \( \alpha \) decreases in accordance with our reasoning that Mn doping reduces charge and correspondingly the electric field on the TiO\(_2\) layer at the interface. It is corroborated further by the increase in \( \tau_{so} \). Thus the layer charge density (\( \alpha \)) accounts for an increase of resistance with doping. The gap parameter \( \Delta \) does not vary with doping till \( \delta = 0.4 \), beyond which it may rise rapidly. The rise of the resistance above the minimum is partially due to an increase in the scattering rate with temperature but it cannot be accounted for just by this factor. The model is inadequate in this regime.

In the above we have ignored the electron-electron interaction which also gives rise to \( \log(T) \) terms. These are incorporated through multiplication by a factor \((1 - F)\) to the weak-scattering correction term \([28]\). From the data, we cannot disentangle this factor as here it also depends on temperature through density. This interaction also leads to a \( \log(T) \) correction to thermopower \([29]\), but we find it too small to account for the data presented below. This is consistent with the remarks of Caviglìa \textit{et al.} \([27]\).

Figure 3 shows the temperature dependence of the thermopower \( S(T) \) for the LAO-STO heterostructure and two \( \delta \)-doped samples, with fractions \( \delta = 0.2 \) and \( \delta = 0.5 \) of the LaMnO\(_3\) monolayer between 5 K and 150 K. The inset shows the differences at lower temperatures in a zoomed plot.

reported larger values for \( T > 77 \) K. The LAO films in these studies are much thinner (4–6 u.c.) and have larger sheet resistance \( R_{||} \).

The other two curves in fig. 3 show the effect of the insertion of the LaMnO\(_3\) monolayer on the thermopower. At \( \delta = 0.2 \) one sees a modest increase but at \( \delta = 0.5 \) there is a substantial increase in the magnitude of \( S \) at temperatures higher than 60 K. At 150 K, the magnitude of \( S \) for \( \delta = 0.5 \) is 96 \( \mu \)V/K, which is more than twice than that of the LaAlO\(_3\)/SrTiO\(_3\) system (\( \sim 40 \) \( \mu \)V/K). The variation at low temperatures show features which require a detailed understanding of transport and scattering at the interface. However, the behaviour in the higher temperature range presents a simple feature which can be accounted for in our picture.

In the temperature range from 80 K to 150 K, one finds that curves for the \( \delta \)-doped system are almost parallel to the undoped system. This corresponds to a temperature-independent contribution which is suggestive of a Heikes-like contribution, which we attribute to the mixed-valent Mn ions in the Al\(_{1-x}\)Mn\(_x\)O\(_2\) layer following some earlier work. Beni and Chaikin \([32]\) extended the Heikes formula to strongly correlated systems at high temperatures \((k_B T \gg W; W \) is the bandwidth). They showed that under such conditions a large contribution to thermopower comes from the spin and orbital degrees of freedom, which is basically due to entropy associated with these degrees of freedom \([32]-34\). In LaMnO\(_3\) the Mn ions are in the 3\( d^4 \) state. As argued above, this monolayer loses some electrons in order to screen the positive field of the LaO layer. This assumption leads to the model in which Mn ions in the Al\(_{1-x}\)Mn\(_x\)O\(_2\) layer exist in states of 3\( d^3 \) and 3\( d^4 \). Given that the degeneracy of these states are \( g_4 = 10 \) and \( g_3 = 4 \), respectively, one obtains the following formula:

\[
S_{(\text{Mn})} = \frac{k_B}{e} \ln \left( \frac{g_4 \rho_h}{g_3 (1 - \rho_h)} \right),
\]

where \( \rho_h \) is the number of holes from the 3\( d^4 \) state. The correct magnitude for the observed thermopower is
obtained with $\rho_h = 0.44$ at $\delta = 0.5$ and $\rho_h = 0.31$ at $\delta = 0.2$. The charge transfer per cell implied by this is $(1 - \rho_h)\delta$ which has the same trend with doping as $\alpha$.

To summarize, we report the transport properties of the LaAlO$_3$-SrTiO$_3$ heterostructures subjected to interface $\delta$-doping by the insertion of a fractional monolayer of LaMnO$_3$. This inhibits the formation of 2-DEL at the interface reflected by an increase in the resistance and by the larger critical thickness of the LaAlO$_3$ over-layers needed to induce 2-DEL at the interface.

We have developed a simple model by extending the polarization catastrophe ideas. The above results are explained by arguing that the Al$_{1-x}$Mn$_x$O$_2$ layer due to the mixed-valent nature of Mn$^{3+}$ ion transfers charge to the LaO layer at the interface, thereby reducing the interface field. Further by using a weak-scattering mechanism we have provided theoretical fits to the resistance data at low temperatures and extracted the doping dependence of model parameters which substantiates the above reasoning. The $\delta$-doping of the interface also leads to an increase of its thermopower in the higher temperature range, above 60 K in the present case. This increase is constant in temperature and can be attributed to the contribution from the AlMnO$_2$ layer. This work opens interesting possibilities for further work in this direction.

***

AR acknowledges the financial support from the Council of Scientific and Industrial Research (CSIR), India and Indian Institute of Technology (IIT) Kanpur and also thank V. P. S. Awana for allowing him to use PPMS for thermopower measurements. RCB acknowledges the J. C. Bose National Fellowship of the Department of Science and Technology (DST), Government of India. DK acknowledges Raja Ramanna fellowship from the Department of Atomic Energy, Government of India.

REFERENCES

[1] Ohtomo A. and Hwang H. Y., Nature (London), 427 (2004) 423.
[2] Thiel S., Hammerl G., Schmehl A., Schneider C. W. and Mannhart J., Science, 313 (2006) 1942.
[3] Nakagawa N., Hwang H. Y. and Muller D. A., Nat. Mater., 5 (2006) 204.
[4] Herranz G. et al., Phys. Rev. Lett., 98 (2007) 216803.
[5] Willmott P. R. et al., Phys. Rev. Lett., 99 (2007) 155602.

[6] Lee J. and Demkov A. A., Phys. Rev. B, 78 (2008) 195104.
[7] Reinele-Schmitt M. L. et al., Nat. Commun., 3 (2012) 932.
[8] Reyren N. et al., Science, 317 (2007) 1196.
[9] Basletic M. et al., Nat. Mater., 7 (2008) 621.
[10] Biscaras J. et al., Nat. Commun., 1 (2010) 89.
[11] Janicka K., Velev J. P. and Tsymbal E. Y., Phys. Rev. Lett., 102 (2009) 106803.
[12] Hwang H. Y. et al., Nat. Mater., 11 (2012) 103.
[13] Mannhart J. and Schom D. G., Nat. Mater., 10 (2011) 168.
[14] Junquera J. and Ghozé P., Nature, 422 (2003) 506.
[15] Takizawa M. et al., Phys. Rev. Lett., 97 (2006) 057601.
[16] Yamada H., Ogawa Y., Ishi H., Sato H., Kawasaki M., Akoh H. and Tokura Y., Science, 305 (2004) 646.
[17] Rastogi A., Kushwaha A. K., Shiyani T., Gangawar A. and Budhani R. C., Adv. Mater., 22 (2010) 4448.
[18] Rastogi A., Pulikkotil J. J., Auluck S., Hossain Z. and Budhani R. C., Phys. Rev. B, 86 (2012) 075127.
[19] Kim H. S. and Christen H. M., J. Phys.: Condens. Matter, 22 (2010) 146007.
[20] Delugas P., Filippetti A., Fiorentini V., Bilc D. I., Fontaine D. and Ghozé P., Phys. Rev. Lett., 106 (2011) 166807.
[21] Popović Z. S., Satpathy S. and Martin R. M., Phys. Rev. Lett., 101 (2008) 256801.
[22] Pentcheva R. and Pickett W. E., Phys. Rev. B, 74 (2006) 035112.
[23] García-Barrio Can J. et al., Adv. Mater., 22 (2010) 627.
[24] Hikami S., Larkin A. I. and Nagaoka Y., Prog. Theor. Phys., 63 (1980) 707.
[25] Bergmann G., Phys. Rep., 107 (1984) 2.
[26] Purose A., Appl. Phys. Lett., 88 (2006) 252113.
[27] Cavigna A. D. et al., Phys. Rev. Lett., 104 (2010) 126803.
[28] Altshuler B. L. and Aranov A. G., in Electron-Electron Interactions in Disordered Systems, edited by Efros A. L. and Pollak M. (North-Holland, Amsterdam) 1985, p. 2.
[29] Ting C. S., Houghton A. and Senna J. R., Phys. Rev. B, 25 (1982) 1439.
[30] Palacchi I. et al., Phys. Rev. B, 81 (2010) 085414.
[31] Filippetti A. et al., Phys. Rev. B, 86 (2012) 195301.
[32] Chaikin P. M. and Beni G., Phys. Rev. B, 13 (1976) 647.
[33] Marsh D. B. and Parris P. E., Phys. Rev. B, 54 (1996) 7720.
[34] Koshiba W. and Maekawa S., Phys. Rev. Lett., 87 (2001) 236603.