

Transport properties of the underdoped $Y_{0.5}Pr_{0.5}Ba_2Cu_3O_{7-\delta}$ films in high magnetic fields

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Abstract. – The effect of magnetic field and disorder on the transport properties of the underdoped $Y_{0.5}Pr_{0.5}Ba_2Cu_3O_{7-\delta}$ films has been investigated in a broad temperature range in magnetic fields up to 50 T. In ultrathin films with *strong disorder*, where the mean free path l corresponds to $k_F l < 4$, a convincing power law resistivity *vs.* temperature $\rho_{ab} \sim T^{-2\gamma}$ ($\gamma = 0.31-0.39$) is observed in a very broad temperature range $T \approx 2-40$ K. However, in superconducting thicker films with much *weaker disorder* ($k_F l > 14$ in normal state), the high magnetic field, by suppressing superconductivity, recovers the normal-state transport behavior with the $\rho_{ab} \sim \ln T$ -dependence at low temperature in ~ 50 T field. The two different transport behaviors indicate that the normal-state transport properties of the underdoped cuprates are very sensitive not only to the hole concentration but also to the degree of the disorder.

Introduction. – The magnetic-field or disorder-induced superconductor-insulator transition has been studied in several high- T_C superconducting cuprates, such as $La_{2-x}Sr_xCuO_4$ crystals and films [1–4], $Bi_2Sr_2CuO_y$ and La-doped single crystals [5, 6], and $Y_{0.47}Pr_{0.53}Ba_2Cu_3O_{7-\delta}$ single crystals [7]. Similar phenomena have also been observed in two-dimensional ultrathin films including some amorphous composite materials (InO_x [8] and $MoGe$ [9], for example) and amorphous metals [10]. The investigations in the underdoped high- T_C cuprates open new possibilities to study the competition between the attractive interaction of electrons forming pairs and the pair-breaking effects induced by magnetic field or disorder.

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However, the available experimental data on the normal-state transport behavior at low temperature in high- T_C superconductors are still quite controversial. Ando *et al.* [1] found that in magnetic fields up to 60 T, the in-plane resistivity ρ_{ab} of the underdoped $(\text{La, Sr})_2\text{CuO}_4$ sample crosses over to the $\rho_{ab}(T)$ behaviour with resistivity diverging approximately logarithmically with temperature $T \rightarrow 0$. Nevertheless, the low-temperature increase of $\rho_{ab}(T)$ was interpreted [11] as a manifestation of a power law, $\sigma \propto T^\alpha$, due to a crossover in a spin-charge separation regime at low temperature. Recently, the power law, $\sigma_{ab}/\sigma_c \propto a + b \cdot T^{-2/3}$, was used to describe the normal-state properties of $\text{Y}_{0.47}\text{Pr}_{0.53}\text{Ba}_2\text{Cu}_3\text{O}_{7-\delta}$ in magnetic field [7]. Therefore, it is not clear when and why a specific $\rho_{ab}(T)$ -dependence, $\ln T$ or power law, is observed and what are the mechanisms responsible for such behaviors.

In the underdoped cuprates, one possible reason for the insulating behavior at low temperature is that the chemical substitution introduces disorder into the “pure” samples. The enhanced disorder reduces the mean free path l of the charge carriers, and, then, causes their localization. In fact, many experiments have suggested that such a crossover from superconducting to insulating behavior occurs at the resistivity corresponding approximately to $k_F l \sim 4$ per CuO layer, where k_F is the Fermi wave vector [4, 12]. However, even the underdoped cuprates with a low level of disorder can be eventually transformed into material showing an insulating $\rho(T, H)$ behaviour in high magnetic field, as indicated by many former experiments. This means that the magnetic fields may unveil the normal-state behavior of the high- T_C cuprates at low temperatures $T < T_C$, *i.e.* the ground state of the high- T_C superconductor in fields.

On the other hand, there are rapidly growing experimental evidences [13–17] for the existence of the spin-charge stripes (dynamic or static), or phase separation, in the underdoped cuprates. In the $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ system, recent experiments [13–15] have shown that at low oxygen content $\delta = 0.4$, the low-frequency spin fluctuations in this material change from commensurate to incommensurate on cooling with the incommensurability first appearing at temperatures above T_C , which may be viewed as a signature of a stripe phase. A 1D quantum spin-ladder-like transport model is applicable [18–20], when metallic stripes appear in the underdoped cuprates at low temperatures $T < T^*$. Since the mobile carriers in this case are expelled from the surrounding Mott insulator phase into the 1D stripes, the transport properties of the cuprates at $T < T^*$ are very sensitive to the formation of the stripes —both static and dynamic. It is also quite evident that the stripe transport properties can be substantially modified due to the presence of a strong disorder.

In order to resolve the controversy on the normal-state transport behavior of the underdoped high- T_C superconductors, we have prepared a series of epitaxially grown $\text{Y}_{0.5}\text{Pr}_{0.5}\text{Ba}_2\text{Cu}_3\text{O}_{7-\delta}$ (YPBCO) films with different level of disorder induced by reducing the thickness. The transport properties of these films have been investigated in high magnetic fields up to 50 T. We have found that, depending on the degree of disorder, two different low-temperature transport behaviors are observed. A *strong disorder*, corresponding at room temperature to $k_F l < 4$, which is close to the Yoffe-Regel criterion ($k_F l = 1$) for the metal-insulator transition, reduces relevant electron-electron correlations responsible for the formation of the 1D stripes, and the variable range hopping (VRH) regime seems to be dominated by the 1D Luttinger-liquid tunneling behavior. A *weak disorder*, giving $k_F l \sim 14$ at room temperature, leads to a qualitatively different $\rho_{ab}(T)$ -dependence with the $\rho_{ab}(T)$ obeying the $\ln T$ law accompanied by a power law crossover, distinctly seen in the weak-disorder samples in ~ 50 T field. At low temperatures with the $\ln T$ behavior, the ρ_{ab} has a temperature-dependent correction, which may be consistent with the predictions of the 2D weak localization model.

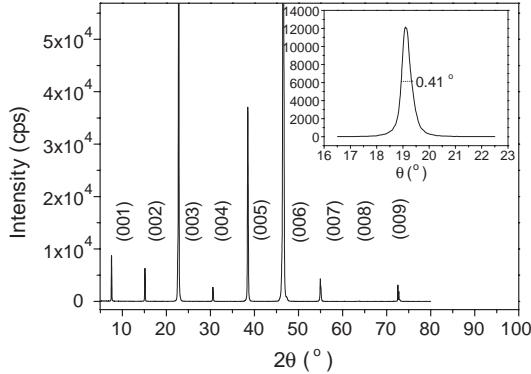


Fig. 1 – The XRD and rocking curve (inset) of the c -axis YPBCO film (sample I). The FWHMs of the (001), (002) and (005) peaks are 0.19, 0.18 and 0.21, respectively.

Sample preparation and characterization. – The YPBCO films were grown on the single crystal (100) SrTiO₃ substrates by magnetron sputtering. We have studied thin films which were made under the same conditions except for the deposition time. Two of the superconducting YPBCO films (100 nm thick, identically grown) are designated as sample I with zero resistance temperature at zero field, T_{C0} , of 18 K. The other two YPBCO films (sample II, III, non-superconducting) are ultrathin ones, with thickness of 12.5 nm, 10.0 nm, respectively. The films were all grown under the optimum conditions with post-growth annealing in high-purity oxygen. A study on the thickness dependence of the resistivity was performed with the similar results as that reported before [21]. For transport measurements, we etched the sample I into a $40\ \mu\text{m} \times 200\ \mu\text{m}$ bridge, and sample II, III into $100\ \mu\text{m} \times 500\ \mu\text{m}$ bridges (to avoid the possible deterioration effects in the ultrathin films).

The high magnetic-field (up to 50 T) measurements of sample I were performed in a $\varnothing 5$ mm cavity of the pulsed field coil with the field perpendicular to the sample surface. Before applying the field pulse, the sample was thermally cycled to room temperature and zero-field-cooled down to the nominal measurement temperatures. The temperatures changed less than ± 0.5 K during the total pulse duration of about 20 ms. The low-field magnetic properties were studied by using a SQUID magnetometer (Quantum Design MPMS-5).

The XRD and rocking curves (fig. 1) of sample I indicate that the films are c -axis oriented and excellently crystallized—the peaks are sharp and only (00L) peaks can be observed in the logarithm plot of the data, and the FWHM (full width of half-medium) of the (001), (002), (005) peaks is 0.19° , 0.18° , 0.21° , respectively. The FWHM of (005) peak, given by the rocking curve, is 0.41° . The average grain size of the sample I is $\sim 0.4\ \mu\text{m}$, and that of the samples II and III is $\sim 0.1\ \mu\text{m}$, measured by an atomic-force microscope.

The mean free path l can be estimated from the in-plane resistivity ρ_{ab} in a free-electron model for a layered 2D material, $k_{\text{F}}l = hc_0/\rho_{ab}e^2$, where k_{F} is the Fermi wave vector, and $c_0 \sim 5.85\ \text{\AA}$ is the interlayer distance of YPBCO. The normal-state resistivity of the sample I is very small, and $k_{\text{F}}l \approx 14$. The samples II and III have rather large resistivity and their $k_{\text{F}}l$ is less than 4 at low temperature.

We have studied the Hall effects of the sample I at 20 K just above the superconducting transition temperature [22], and the Hall number, $n_{\text{H}} = \frac{B_z}{R_{xy}d \cdot e} \cdot V_{\text{cell}}$, is near 0.3 at low magnetic field (fig. 2). This value is reasonable for the underdoped cuprates, and a comparable n_{H} value was reported by Matsuda [23]. Furthermore, the Hall number decreases linearly with

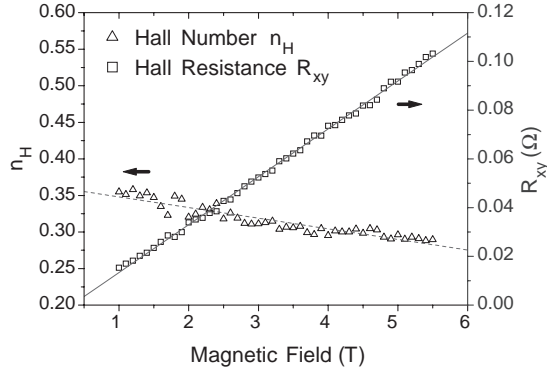


Fig. 2 – Hall resistance R_{xy} and Hall number n_H of the YPBCO films (sample I) measured at different magnetic field. Lines in the figure are linear fit of the data. See the text for detail.

the increase of the magnetic field from 1 T to 5.5 T, and the fitting gives $n_H = a - b \cdot H$, where $a = 0.36252$, $b = 0.01453T^{-1}$. The ratio of the two coefficients $a/b \approx 25$ T indicates the existence of a critical magnetic field which may drive the Hall number to zero. Due to the close relationship between the Hall number and the charge carrier density, we expect that the magnetic field $H \geq 25$ T may induce charge localization (or stripe pinning) in the underdoped YPBCO films. At this stage, however, the possibility of the superconducting fluctuations suppressed by magnetic field cannot be excluded. The R_{xy} increase in magnetic field might reflect then just the continuous recovery of the normal state in magnetic field.

Temperature dependences of resistivity. – The $\rho_{ab}-T$ curves of the sample I in different pulsed magnetic fields are shown in fig. 3. Superconductivity of the YPBCO film is completely suppressed in high fields and the film shows an insulating $\rho(T, H)$ behavior at $H \sim 50$ T with

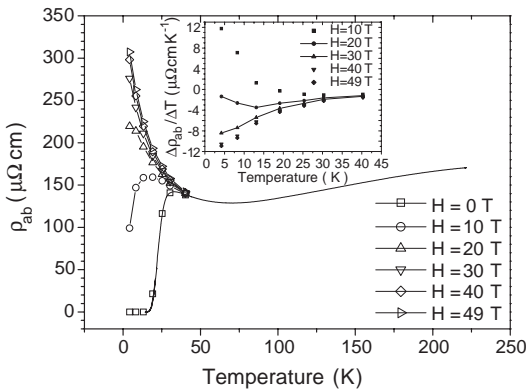


Fig. 3

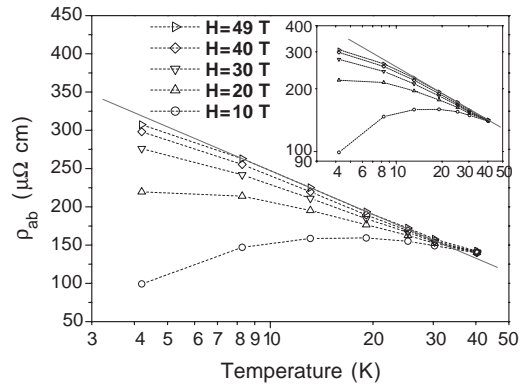


Fig. 4

Fig. 3 – $\rho_{ab}-T$ curves for the sample I under different pulsed magnetic fields. $\Delta\rho_{ab}/\Delta T$ derived from the data is shown in the inset, which indicates a critical magnetic field between 20 T and 30 T.

Fig. 4 – The logarithm plot of the $\rho_{ab}-T$ curves of the sample I (replot of fig. 3). The double-log plot is also shown in the inset. From the uppermost curve to the downmost one, the magnetic fields are 49 T, 40 T, 30 T, 20 T and 10 T, respectively. The lines in the figure are guides to the eyes.

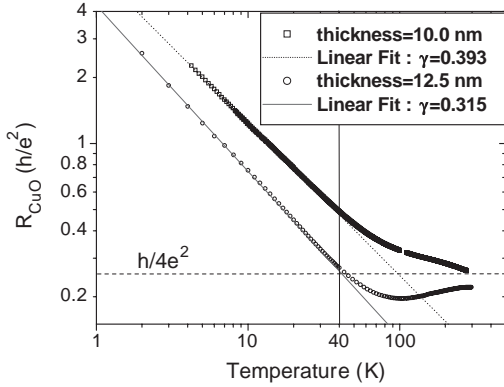


Fig. 5

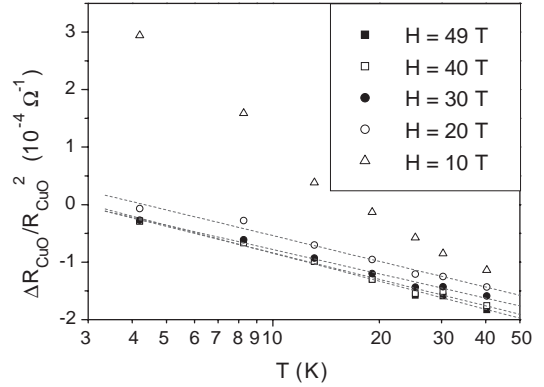


Fig. 6

Fig. 5 – The resistivity of sample III (square symbols), II (circle symbols) exhibits power law $\rho_{ab}(T) \sim T^{-2\gamma}$ behavior in a rather broad temperature range up to 40 K. See the text for details.

Fig. 6 – The logarithm plot of the temperature dependence of resistance correction, $\Delta R_{\text{CuO}}/R_{\text{CuO}}^2$. The values of the slope of the linear fit (dashed lines) are $-1.6 \times 10^{-4} \Omega^{-1} \text{K}^{-1}$ (at 49 T), $-1.5 \times 10^{-4} \Omega^{-1} \text{K}^{-1}$ (40 T), $-1.4 \times 10^{-4} \Omega^{-1} \text{K}^{-1}$ (30 T) and $-1.48 \times 10^{-4} \Omega^{-1} \text{K}^{-1}$ (20 T), respectively. We use the value at 49 T to calculate the exponent p in the text.

resistivity increasing rapidly with the decrease of temperature. The low magnetic fields cause a broadening of the transition and the decrease of T_C . As the magnetic field increases, a pronounced $\rho_{ab}(T)$ upturn appears in the $\rho_{ab}-T$ curves below T_{C0} , and the superconducting transition shifts to lower temperatures with the increasing fields. It should be noted here that there may be a critical magnetic field between 20 T and 30 T as indicated by the inset of fig. 3. This value is consistent with our estimation according to the fitting of the Hall data.

We plot the $\ln \rho_{ab}-T$ curves of the sample I in fig. 4. At the magnetic field of 49 T, the resistivity exhibits a logarithmic divergence in the temperature region from ~ 5 K to ~ 30 K, typical for the 2D localization-like effect discussed later. A fit of power law $\rho_{ab} \propto T^{-2\gamma}$ is also good, but there is a deviation from linearity at temperatures below 14 K (inset of fig. 4). This may be consistent with the explanation based on the Luttinger-liquid theory [24].

The resistivity of the ultrathin nonsuperconducting samples II and III with a strong thickness-reduction-induced disorder, however, is clearly in a much better agreement with a power law at low temperatures, while a variety of other functional forms (including the $\ln T$ law) cannot fit the diverging resistivity. The power law (fig. 5) extends over a wider temperature range than the one for the fits to variable range hopping (VRH) mechanisms ($\ln \rho_{ab} \propto T^{-\nu}$, with $\nu = \frac{1}{3}$, and $\frac{1}{4}$). The VRH fit of the data deviates from the linearity at the temperature above 14 K, which suggests that a power law should be a preferred choice. The fit with $\nu = \frac{1}{2}$ (not shown), that relates to hopping with Coulomb interactions (Shklovskii-Efros law [25]), also suggests this point, with the deviation at a much lower temperature ~ 7 K. This power law behavior exists in the ultrathin YPBCO films with different thickness, and the fitting gives $\rho_{ab} \propto T^{-2\gamma}$, where $\gamma \approx 0.32$ and 0.39 for the 12.5 nm and 10 nm thick films, respectively. Note that the temperature dependence of the two samples is different at temperatures above 100 K: sample II has a resistivity which is proportional to temperature, and the resistivity of sample III becomes larger while the temperature decreases.

Such a power law $\rho_{ab}-T$ -dependence of the ultrathin YPBCO films is consistent with the result of a traditional strong localization model where a scaling size is smaller than localization

length [26]. However, as we noticed, $k_{\text{F}}l$ is larger than 1, which means that the mean free path extends over several unit cells, and the grain size of the ultrathin films is also rather large. Furthermore, as we noticed above, not only our experiments but also many other experiments give the similar results that the insulating behavior occurs at about $k_{\text{F}}l \sim 4$ instead of 1. So, we suggest that the precise criterion of this model may not hold in our case.

In the ultrathin YPBCO films, disorder caused by the Pr substitution of Y and a very small thickness leads to an inhomogeneous hole distribution. 1D-like highly conductive routes between the “localized superconductors” [27] shortcut the VRH routes and form a network which can be described by the multichannel and finite-temperature generalization of the Landauer formulation [28]. Therefore, the transport behavior of the ultrathin films exhibits the power law crossover in a proper temperature range. At lower temperatures, however, the VRH behavior seems to emerge below 14 K.

As for the superconducting YPBCO films (sample I), we should note that the high pulsed magnetic field, suppressing the superconductivity, not only reveals the ground state but also might enhance charge localization in the films, as suggested by our Hall measurements. However, such a localization is not like the one proposed by Malinowski [3], because our $\rho_{ab}(T)$ data at low temperatures is not a VRH behavior, but a logarithmic dependence accompanied by a power law crossover. This may be attributed to a rather low disorder that exists in our superconducting YPBCO films. It is important to note here that at temperatures $T \geq 35$ K (fig. 3) the magnetoresistance is very weak, all the way up to 50 T. This implies that in the normal state itself the field-induced changes in resistivity are negligibly small. Therefore, dramatic changes in resistivity at low temperatures $T < 35$ K (fig. 3) should be mostly associated with the suppression of superconductivity by magnetic field. This could be also reflected in the increase of the Hall resistance $R_{xy}(H)$ (fig. 2) in magnetic field.

A further consideration about weak localization should be added here. High magnetic field depairs the electrons and a normal state is recovered. Such a normal state at low temperature should have been a metal-like one if it were established in a optimum doped superconductor with homogeneous hole distribution. However, in the underdoped YPBCO, the substitution of Pr introduces a weak disorder in the layered cuprates. On the other hand, due to the low level of the disorder, the conduction electrons (holes) can be scattered by the impurities without losing their phase coherence. Therefore, a correction to the conductance can be introduced in the 2D disordered conductor at low but finite temperature [29],

$$\frac{\Delta R_{\square}}{R_{\square}^2} = -\frac{e^2}{2\pi^2\hbar} \log(\tau_i/\tau_0), \quad (1)$$

where τ_i (which is temperature dependent and considerably longer than τ_0), τ_0 are the inelastic lifetime and elastic lifetime, respectively. Such a logarithmic behavior can be seen as an evidence of the weak localization in the low-temperature normal-state of the YPBCO films, as shown in fig. 6. Supposed that $\tau_i \propto T^{-p}$ can be hold in our case, the linear fit of the data gives the value of the exponent $p \approx 11$ –13. The value p is much larger than that normally achieved in the metal thin films (2 for electron-electron and 3 for electron-phonon scattering). We think that this might indicate the presence of several (about 4–6) equivalent weak-localization-like resistors always needed to close the current path in the presence of an array of fragmented stripes. In this case, the large p value could just reflect the cascade-like character of the current path closure.

Conclusions. – In summary, we have identified two distinctly different normal-state behaviors at low temperature in underdoped high- T_{C} cuprates with the same composition. In the presence of a strong disorder ($k_{\text{F}}l < 4$) the self-organization of holes into stripes is

completely suppressed and disorder-dominated localization $\rho_{ab}(T) \sim T^{-2\gamma}$ takes place. On the contrary, our data on samples with a weak disorder ($k_{Fl} > 14$) have revealed interesting effects of the interplay between the disorder and the stripes, formed due to the electron-electron correlations, specific for high- T_C 's. In the presence of such a weak disorder, the 1D stripes still keep their identity, although they are now fragmented and pinned. High magnetic field induces the interstripe cascade hopping, thus recovering the 2D localization regime with $\rho_{ab} \sim \ln T$ and enhanced parameter p at lower temperatures, after a power law crossover.

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REFERENCES

- [1] ANDO Y. *et al.*, *Phys. Rev. Lett.*, **75** (1995) 4662.
- [2] KARPIŃSKA K. *et al.*, *Phys. Rev. Lett.*, **77** (1996) 3033.
- [3] MALINOWSKI A. *et al.*, *Phys. Rev. Lett.*, **79** (1997) 495.
- [4] BOEBINGER G. S. *et al.*, *Phys. Rev. Lett.*, **77** (1996) 5417.
- [5] ANDO Y. *et al.*, *Phys. Rev. Lett.*, **77** (1996) 2065.
- [6] ONO S. *et al.*, *Phys. Rev. Lett.*, **85** (2000) 638.
- [7] LEVIN G. A. *et al.*, *Phys. Rev. Lett.*, **80** (1998) 841.
- [8] HEBARD A. F., *Phys. Rev. Lett.*, **65** (1990) 927.
- [9] YAZDANI A., *Phys. Rev. Lett.*, **74** (1995) 3037.
- [10] MARKOVIĆ N., CHRISTIANSEN C. and GOLDMAN A. M., *Phys. Rev. Lett.*, **81** (1998) 5217.
- [11] ANDERSON P. W. *et al.*, *Phys. Rev. Lett.*, **77** (1996) 4241.
- [12] KABASAWA U. *et al.*, *Phys. Rev. B*, **55** (1997) R716.
- [13] DAI P., MOOK H. A. and DOĞAN F., *Phys. Rev. Lett.*, **80** (1998) 1738.
- [14] MOOK H. A. *et al.*, *Nature*, **395** (1998) 580.
- [15] MOOK H. A. and DOĞAN F., *Nature*, **40** (1999) 145.
- [16] ANDO Y., LAVROV A. N. and SEGAWA K., *Phys. Rev. Lett.*, **83** (1999) 2813.
- [17] LAVROV A. N. *et al.*, *Phys. Rev. Lett.*, **83** (1999) 1419.
- [18] MOSHCHALOV V. V., *Solid State Commun.*, **86** (1993) 715.
- [19] MOSHCHALOV V. V., cond-mat/9802281; MOSHCHALOV V. V. *et al.*, *Europhys. Lett.*, **46** (1999) 75.
- [20] MOSHCHALOV V. V. and VANACKEN J. A., *Physica C*, **341-348** (2000) 887.
- [21] KABASAWA U. *et al.*, *J. Appl. Phys.*, **81** (1997) 2302.
- [22] HAO Z. *et al.*, *Physica C*, **341-348** (2000) 1891.
- [23] MATSUDA A., *Phys. Rev. B*, **38** (1988) 2910.
- [24] ANDERSON P. W., *The Theory of Superconductivity in the High- T_C Cuprates* (Princeton University Press) 1997; CLARKE D. G. *et al.*, *Phys. Rev. Lett.*, **74** (1995) 4499.
- [25] EFROS A. L. and SHKLOVSKII B. I., *J. Phys. C*, **8** (1975) L49.
- [26] AL'TSHULER B. L. and ARONOV A. G., *JETP Lett.*, **37** (1983) 410.
- [27] MICHAEL MA and PATRICK A. LEE, *Phys. Rev. B*, **32** (1985) 5658.
- [28] YOSEPH IMRY, *Introduction to Mesoscopic Physics* (Oxford University Press, Inc.) 1997, pp. 31-33.
- [29] For a more complete discussion, see BERGMANN G., *Phys. Rep.*, **107** (1984) 1 and references therein.