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THE TEMPERATURE ANOMALIES OF THE $YBa_2Cu_3O_{6.9}$ CHARGE CARRIERS DENSITY FROM 290 K TO T_C

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A possibility of HTSC’s electronic properties investigating by means of measuring the electrical resistance r_C of HTSC/normal metal interface is grounded. An existence of the correlations between anomalies of r_C and anomalies of density n_f of HTSC charge carriers is shown. The correlations between the anomalies of dependence $r_C(T)$ for interface $YBa_2Cu_3O_{6.9}$/In and anomalies of temperature dependences of $YBa_2Cu_3O_{6.9}$ lattice cell parameters *b* and *c* are demonstrated. The conclusion is made that the reason of anomalies r_C at $T>>T_C$ is pairing the hole charge carriers of $YBa_2Cu_3O_{6.9}$ to positive bosons. Sharp and deep r_C-anomaly before *n*-*s*-transition correlates to well-known sign-reversal effect of Hall coefficient. It is explained by bosons disintegration and posterior intensive conversion of hole carriers to electrons.

INTRODUCTION

It was established [1, 2] that electrical conductance of surface layer of high temperature (*T*) superconductor (HTSC), having metallic hole (h) electrical conductance (i. e. $HTSC^h$), is changed on semiconducting (SmC) one due to contacting $HTSC^h$ with electronic (e) metal (Me^e). The phenomena was stipulated [3] by presence into interface two regions having opposite sign charge carriers due to annihilation of native fermi-holes with «guest» free electrons of Me^e. The inverse region is appeared because $n_f^e>>n_f^h(x)$ [4], (n_f^e and n_f^h are densities of Me^e-electrons and $HTSC^h$-holes), it has electronic conductance and is ranged from x=0 to someone x_{AFD}, Fig. 1,a. Inverse region is limited in the depth of $HTSC^h$ by coordinate x_{AFD}, satisfying the condition $n_f^e(x_{\mathrm{AFD}})=n_f^h$, which means resultant carriers density is equal to nought: $n_f^{\Sigma}=[n_f^e(x_{\mathrm{AFD}})-n_f^h]=0$. The poor region, having hole-type conductance, is ranged from x_{AFD} to someone x_0 satisfying the condition $n_f^e(x_0)=0$, moreover, n_f^{Σ} is increased towards to x_0. The electrical conductance (σ) of inverse and poor regions is metallic except of x_{AFD}-neighbouring which determines interface SmC-conductance the whole in view of unimportant of n_f^{Σ} magnitude. The poor region is not monotonous:– its part on right of x_{AFD} is found into antiferromagnetic dielectric (AFD) state with $n_f^{\Sigma}(x)$ changing from $n_f^{\Sigma}(x_{\mathrm{AFD}})=0$ to $n_f^{\Sigma}=n_0=n_f^hV_0\sim(0.05…0.07)$, ($V_0$ – lattice cell volume (LCV), n_0 – magnitude corresponding to dielectric-metal phase transition [4, 5]). Finiteness of interface conductance indicates a possibility of charge carriers tunneling through AFD layer.

Attention to $HTSC^h/Me^e$-interface of SmC-type (metallic ones available too) is accounted by sensitivity of its electrical resistances (r_C) to electronic and structural anomalies of $HTSC^h$-massive. Thus, the dependence $r_C(T)$ demonstrates the anomalies at all characteristic temperatures of $HTSC^h$ where be available anomalies of the following characteristics: specific electrical resistance [5], Hall and thermoEMF coefficients [6, 7], specific heat and heat conductivity [8, 9], heat expansion [10], elastic properties [11–13] and so on.

These work’s one aim is an establishing the mutuality between temperature anomalies of r_C and n_f^h.. Their existences are proved by enumerated correlations. Analysis results were used to interpretation of anomalies of dependences $r_C(T)$ obtained experimentally into interval 290 K–T_C for interfaces $YBa_2Cu_3O_{6.9}$/In. We also discuss a features of charge transport of $YBa_2Cu_3O_{6.9}$ in frames of local pairs (LP) theory conception [14–21].

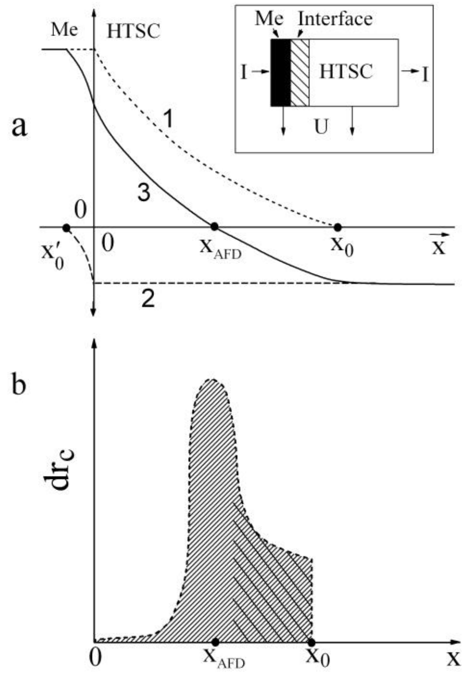

Fig. 1. Free charge carriers distribution into $HTSC^h/Me^e$ interface (a), graph of dependence $dr_C(x)$ (b): 1 – dependence $n_f^e(x)$; 2 – dependence $n_f^h(x)=const$; 3 – dependence $n_f^{\Sigma}(x)=[n_f^e(x)-n_f^h]$

THE METHOD SUBSTANTIATION

Let’s present r_C at $T_{300\,K}>>T_C$ in the shape of

$$r_C=\int_0^{x_0} dr_C(x)=r_C^{inv}+r_C^{poor}+r_C^{SmC},$$

r_C^{inv} and r_C^{poor} – electrical resistances of «metallic sections» of inverse and poor regions, r_C^{SmC} – electrical resistance of interface section having $n_f^{\Sigma}<<n_f^h$. Fig. 1,b displays the qualitative graph of resistance dr_C of paral-

lel to contacting plane thin layer versus x constructed from conditions $n_f^e(x=0)>>n_f^h(T)$ and $n_f^e(x_0)=0$. From first one is followed, in particular, that ordinates magnitudes of poor and inverse regions are satisfied the condition $dr_C(x<x_{\mathrm{AFD}})<<dr_C(x>x_{\mathrm{AFD}})$ and that $x_{\mathrm{AFD}}\sim x_0$. So, x_{AFD} is situated on a «tail» of curve $n_f^e(x)$ therefore the dimensions on Fig. 1 are not reflected validity. On the contrary, a descending section of curve $dr_C(x)$ into interval x_{AFD}-x_0 is reflected a real qualitative decreasing specific resistance ρ as x approaches to x_0, because n_f^{Σ} is increased in poor region towards x_0. It is necessary to elucidate: 1) how will be changed an area S of hatched figure under curve $dr_C(x)$ on Fig. 1,b, which proportional to r_C, owing to decreasing T?; 2) how will be influenced r_C owing to anomaly of dependence $n_f^h(T)$ in shape of virtual jump δn_f^h?

Let's suppose all electronic changes of HTSC$^{\mathrm{h}}$ are provoked because of decreasing T only and metallic conductance of HTSC$^{\mathrm{h}}$ at $T_{300\,\mathrm{K}}$ is provided with hole carriers of density $n_f^h(T_{300\,\mathrm{K}})\neq f(x)$ only. Let's suppose also Me$^{\mathrm{e}}$ is classic metal, i. e. the value x_0 doesn't depend from T, othergates, the curve $n_f^e(x)$ configuration doesn't change with changing T.

Some knowledge about of dependence $n_f^h(T)$ of real HTSC$^{\mathrm{h}}$ may extract from graphs of Hall and thermoEMF coefficients (R_H and S) temperature dependences [6, 22, 23], see, for example, Fig. 2,a. It may see until first characteristic temperature T^* that is the temperature of pseudogap (PG) appearance [4, 5], the density $n_f^h(T)$ is constant: $n_f^h(T^*)=n_f^h(T_{300\,\mathrm{K}})$, ($n_f^h\sim 1/eR_H$). Therefore, decreasing T into interval $T_{300\,K}$-T^* doesn't change a position of x_{AFD} so far as curve's $dr_C(x)$ transformation consists of increasing the curve maximum. I. e., the temperature dependence $r_C(T)=r_C^{inv}(T)+r_C^{poor}(T)+r_C^{SmC}(T)$ will be formed by component $r_C^{SmC}(T)$ mainly. A small decreasing r_C^{poor} owing to σ expenses will be not appreciable on background of $r_C^{SmC}(T)$ growth, a smaller change of r_C^{inv} doesn't mention.

According to existing ideas, charge scattering into interval $T_{300\,\mathrm{K}}$-T^* is checked by electron-phonon (E-P) and electron-electron (E-E) interactions, to that be up to the requirements the constancy of n_f^h into interval indicated [5]. To begin at T^* the density n_f^h will be decreased with decreasing T – that follows, for example, from increasing the coefficients R_H [22], Fig. 2,a, and S [23]. But simultaneous crop up so-called surplus electrical conductance that is increased with further decreasing T, Fig. 2,b [5]. These two facts are found an explanation by local pairs (LP) theory [14–21] by means of assumption about of hole fermions pairing in strong coupling bosons (in real space) having charge $2e$ [17]:

$$n_f(T)=n_f^{h,b}(T)=n_f^h(T)+2n^b(T),\ n_f^h>>n^b,\ T\leq T^*,$$

n^b – bosons density.

Because assumption indicated E-E scattering is decreased but at conservation of summary charge. That is the reason of surplus conductance appearance. The sign of local pair's charge is clarified itself by concrete course of temperature dependences $R_H(T)$ and $S(T)$ under T^*: both are increased. That means the sign indicated is plus.

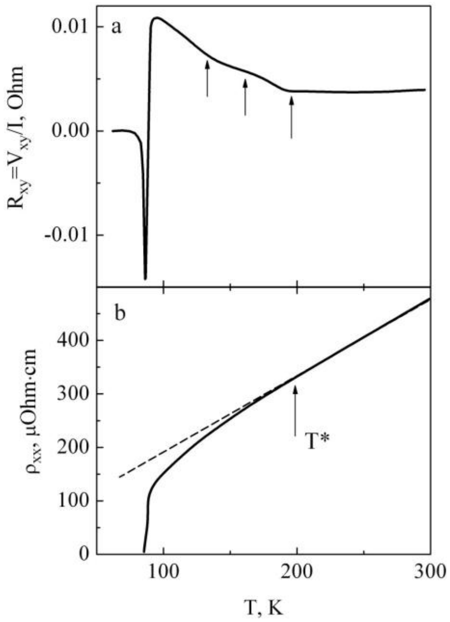

Fig. 2. Temperature dependence of Hall potential for films YBaCuO: smoothed curve according [22] (a); definition of pseudogap appearance temperature T using the feature of temperature dependence ρ(T) [5] (b)*

Decreasing $n_f(T)$ one can visualize virtually in shape of approaching the direct line 2 (see Fig. 1,a) to axis x. (Under T^* direct line 2 on Fig. 1,a is the line $n_f(T)$ which also doesn't dependent on x). In consequence of the coordinate x_{AFD} will be moved on right along axis x that will be extended inverse region and reduced poor one. In consequence of the $dr_C(x)$-curve's maximum will be increased at expensing the component $r_C^{\mathrm{AFD}}(T)$. A priori may approve that ordinates of graph $dr_C(x)$ into poor region will be decreased in consequence of increasing conductance σ of HTSC$^{\mathrm{h}}$-massive owing to decreasing T. Thus, the area S will be increased because of decreasing T lower T^* as before in consequence of increasing r_C^{AFD}. But now a quantitative ratio between r_C^{inv} and r_C^{poor} will be changed in consequence of displacement of x_{AFD} and transformation of hatched figure on Fig. 1,b.

Let's assume an origin of virtual anomaly of $n_f(T)$ in shape of small jump $\delta n_f(T)$ at fixed temperature $T_{an}=const<T^*$. Then, r_C-variation will be noted as $\delta r_C=\delta r_C^{inv}+\delta r_C^{poor}+\delta r_C^{AFD}$. The condition $T_{an}=const$ makes item $\delta r_C^{\mathrm{AFD}}$ be equal to nought in spite of all δn_f don't depend on value of curve $dr_C(x)$ maximum while SmC-layer will be moved the whole along x very slightly.

If $\delta n_f(T_{an})>0$ the direct line $n_f(T_{an})=const$ will be occupied the position $n_f(T_{an})+\delta n_f(T_{an})$ by jump *in direction from* axis x. In consequence of the coordinate x_{AFD} will be shifted by jump on left along axis x to point x'_{AFD}, that will be changed the square S of figure under curve $dr_C(x)$, Fig. 3. As a result – an evident increasing the area S, other gates, $\delta r_C>0$.

If $\delta n_f(T_{an})<0$ the direct line $n_f(T_{an})=const$ will be occupied the position $n_f(T_{an})$–$\delta n_f(T_{an})$ by jump *towards* axis x. That will be shifted x_{AFD} towards of greater x and will be decreased the area of hatched figure on Fig. 3: $\delta r_C<0$.

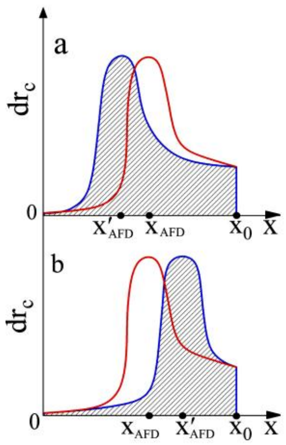

Fig. 3. Influence of area S owing to $n_f^h(T)$ anomaly. Free hatched – initial point of departure

Side by side with obtained from examination conducting the condition sign(δn_f)=sign(δr_C) there is an other evident conclusion: that is the assertion about of proportionality of absolute values δr_C and δn_f:

$$|\delta r_C| \propto |\delta n_f|.$$

Both conditions are correct in presence of n_f anomaly until n_f is decreased. Because n_f was chose the only variable of examination the first criterion decides a problem of definition of sign(δn_f) issue of sign(δr_C) – the last may define experimentally. The second assertion gives the possibility to estimate qualitative effect in δn_f issue of δr_C value.

SAMPLES AND EXPERIMENT

To investigating the interfaces $YBa_2Cu_3O_{6.9}$/In were used ceramic $YBa_2Cu_3O_{6.9}$, ($T_C \approx 90$ K), in capacity of substratum, made by hard-phase synthesis. These substratum had a form of a cylindrical pallets of diameter d~10 mm, thickness h~2…3 mm. Four indium “specks” of d~3 mm^2 were formed at T~300 K on clean $YBa_2Cu_3O_{6.9}$ surface by mechanical deposition of thin In layer (h~0.3 mm), Fig. 4. To indium «specks» are pressed copper current-and potential leads by means of indium too. Using potentiometric method and I_{AD} ~ (1…10) mA were measured such potentials: $U_{BC}(T)=R_{bulk}(T)\cdot I_{AD}$ (by means of four-terminal configuration); $U_{AB}(T)=R^{\Sigma}(T)\cdot I_{AD}=[r_C(T)+R'_{bulk}(T)]\cdot I_{AD}$ (by means of three-terminal configuration). The typical values measured were: $R_{bulk}(300\text{ K}) \sim 0.01\ \Omega$, $R^{\Sigma}(300\text{ K}) \sim 0{,}1\ \Omega$. Because R_{bulk} is decreased but r_C is increased owing to decreasing T the condition $R^{\Sigma}(T) >> R'_{bulk}(T)$ became intensify towards to T_C where was corrected the condition $r_C \approx 50R'_{bulk}$ allowing to approximate r_C by value R^{Σ} with acceptable accuracy in temperature region investigated.

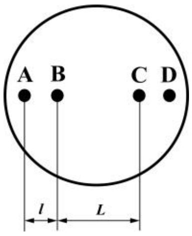

Fig. 4. Disposition of current and potential leads ($L \approx 3l \approx 5$ mm)

The dependences $R_{bulk}(T)$ and $R^{\Sigma}(T)$ were measured between 290 and 77 K in stepped cooling regime. The temperature was measured by differential thermocouple Cu-Const with accuracy ~ 0.1 K, the temperature stability of $YBa_2Cu_3O_{6.9}$ substratum was supported with accuracy ~ 0.1 K. One thermal junction of thermocouple was soldered to $YBa_2Cu_3O_{6.9}$ by In, the second one was situated in melting ice.

RESULTS AND DISCUSSION

Fig. 5 displays: *a* – graphs of dependences $R_{bulk}(T)/R_{bulk}(290\text{ K})$ and $R^{\Sigma}(T)/R^{\Sigma}(290\text{ K})$; *b* – graphs of dependences of $YBa_2Cu_3O_{7-x}$ lattice cell parameters (LCP) $b(T)$ and $c(T)$ in agreement with [24]. The anomalies of dependence $R^{\Sigma}(T)/R^{\Sigma}(290\text{ K})$ are showed by numbering arrows. In Table are showed the values $T_{ан}$ and the signs of δn_f in neighbouring of $T \le T_{ан}$ defined on conditions 1) decreasing T and 2) sign(δn_f) = sign(δr_C).

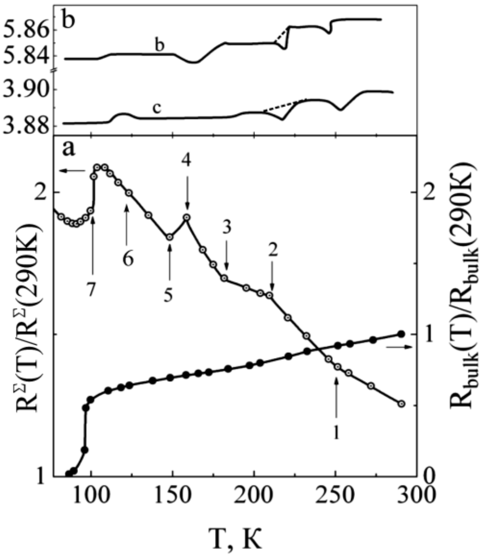

Fig. 5. Dependences $R_{bulk}(T)/R_{bulk}(290\text{ K})$ (1) and $R^{\Sigma}(T)/R^{\Sigma}(290\text{ K})$ (2) (a); Dependences b(T) and c(T) [24] (b)

From Fig. 5 follows all anomalies of dependence $R^{\Sigma}(T)$, which approximates the dependence $r_C(T)$, correlate with anomalies of temperature dependences of LCP of $YBa_2Cu_3O_{6.9}$, othergates, with the temperature anomalies of V_0. Some conclusions follow from here. First: it is confirmed experimentally the thesis about of mutuality between the temperature anomalies of electrical resistance r_C of a certain artificial formation (i.e. interface) and the temperature anomalies of a certain macroelectronic characteristic which is – that is obviously – the density n_f. Second: the correlation between the anomalies of dependences $r_C(T)$ and $n_f(T)$ shows the mutuality of electronic anomalies of $YBa_2Cu_3O_{6.9}$-massive and structural transformations. At last: the sign(δn_f) alternation, Table shows not monotonous of $n_f(T)$ into interval 290 K–T_C.

Anomalies of dependence $n_f(T)$ for $YBa_2Cu_3O_{6.9}$

No an.	1	2	3	4	5	6	7
$T_{ан}$, K	~250	~210	~180	~160	~150	~125	~103
Sign(δn_f)	+	–	+	–	+	–	–

The curve $R^{\Sigma}(T)/R^{\Sigma}(290\ \text{K})$ has four anomalies – No 2, 4, 6, 7 – for which are implemented the condition $\delta n_f<0$ (at decreasing T). The No 2 – anomaly's temperature (~ 210 K) agrees well with temperature T^* defined for similar YBaCuO combinations in different ways, for example, by convenient anomalies of dependences $R_H(T)$, $S(T)$, and $\rho(T)$ [6, 22, 23]. The courses of dependences $b(T)$ and $c(T)$ in neighbouring of anomaly No 2 produce an independent striking demonstration that T~210 K is the temperature T^* for our $YBa_2Cu_3O_{6,9}$. Namely: both parameters are decreased (see drawing lines on Fig. 5,b), i. e. $\delta V_0<0$. It is evident both inequalities – $\delta n_f<0$ and $\delta V_0<0$ – will be executable in common only if part of hole carriers will be united in some assemblies *in real space*. So, that result confirms the decreasing a number of charge carriers in elementary lattice cell, that doesn't contradict to LP theory. We also will be supposed such assemblies are bosons. The sign of bosons charge (+) are showed, as stated above, by temperature courses of coefficients R_H and S under T^*, Fig. 2,a.

The anomaly No 4 ($T_{ан}$~150 K) correlates with convenient anomaly of $R_H(T)$, Fig. 2,a, (and with anomaly of $S(T)$ at T ~ 150 K [23]). The courses of curves $b(T)$ and $c(T)$ in the neighbouring of anomaly No 4 doesn't give these case the obvious reasons to affirm about of unite of hole carriers to bosons like the previous: V_0 is increased, but n_f is decreased. In order to satisfy these conditions it is enough of lattice cell's holes number conservation. However, more intensive increasing R_H and S indicates, nevertheless, decreasing the number of hole curriers, in one's turn dependence $\rho(T)$ indicates also more intensive decreasing the resistance Fig. 2,b. From these facts is followed the decreasing n_f became more intensive. That correlates with effect on value of r_C ($|\delta r_C| \propto |\delta n_f|$). As regards of anomaly No 4 nature it can't suppose the Cooper's pairing because Cooper's pair has negative sign but increasing R_H and S under $T_{ан}$~150 K says about of positive charge of a new forms.

Course of curve $R^{\Sigma}(T)$ under ~ 125 K (anomaly No 6, δn_f <0) indicates also decreasing n_f. But now the convenient anomalies of dependences $R_H(T)$ and $S(T)$ witness about of appearance of other sign carriers, i. e. electrons. It may see hole-electron conversion also decreases n_f^h into interface that means according [3] the decreasing r_C. It should be remind about of observation in $YBa_2Cu_3O_{6.9}$ at T ~ 120 K of coherent negative charged Cooper's pairs [25]. From that follows Cooper's pairing is began after positive bosons disintegration.

Most approached to T_C anomaly of n_f, having $\delta n_f<0$, is happened in shape of deep jump at $R=R^n_{bulk}\approx const$, at ~ 103 K, i. e. much higher of T_C. In frames of [3] the large value of $|\delta r_C|$ means significant decreasing n_f. We assume the effect due to intensification of hole carriers conversion to electrons. In a case like that the reason of SmC interface conductivity appearance i. e. predominance of hole carriers over electrons in poor region is vanished. That became apparent experimental as a sharp and deep jumping the r_C. Therefore, well-knoun sign reversal effect of Hall coefficient before *n-s* transition (for example, Fig. 2,a) may consider as a possible confirmation our assumption. If it is right then inside the interval T_C – ~125 K are co-existed the positive bosons (local pairs) and electrons.

CONCLUSION

A possibility have been placed for consideration for investigating the charge carries density n_f of *p*-type HTSC by means of measuring the electrical resistance r_C of interface between such HTSC and *n*-type metal. It was found analytical that all anomalies of dependence $r_C(T)$ are caused by someone sign of variation δn_f of dependence $n_f(T)$ anomalies: sign(δn_f)=sign(δr_C), in addition $|\delta r_C| \propto |\delta n_f|$. The anomalies of dependence $r_C(T)$ for interface $YBa_2Cu_3O_{6.9}$/In was found between 290 K and T_C where is estimated a strong sign(δr_C) alternation. From that it is followed nonmonotonous of $n_f(T)$. The anomalies of dependence $r_C(T)$ much higher T_C, which have $\delta r_C<0$ at decreasing T, are explained by pairing a small share of hole charge fermions to positive bosons in shape of local pairs. The attention is turned on deep and sharp jumping r_C to small value, which correlates to well-known sign reversal effect of Hall coefficient before *n-s*-transition. The reason of such r_C-jump may be intensive conversion of hole carriers to electrons.

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ТЕМПЕРАТУРНЫЕ АНОМАЛИИ ПЛОТНОСТИ НОСИТЕЛЕЙ ЗАРЯДА $YBa_2Cu_3O_{6,9}$ ОТ 290 К ДО T_C

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Обоснована возможность исследования электронных свойств высокотемпературного сверхпроводника (ВТСП) при помощи измерения электрического сопротивления r_C его интерфейса с нормальным металлом. Показано существование корреляций между аномалиями r_C и аномалиями плотности n_f носителей заряда ВТСП. Для интерфейса $YBa_2Cu_3O_{6.9}$/In установлены корреляции между аномалиями зависимости $r_C(T)$ и аномалиями температурных зависимостей параметров b и c элементарной ячейки $YBa_2Cu_3O_{6,9}$. Сделан вывод о том, что причиной аномалий r_C при $T \gg T_C$ является спаривание дырочных носителей заряда $YBa_2Cu_3O_{6,9}$ в положительно заряженные бозоны. Резкая и глубокая аномалия r_C перед *n-s*-переходом коррелирует с хорошо известным эффектом изменения знака коэффициента Холла. Она объяснена распадом бозонов и последующей интенсивной конверсией дырочных носителей в электроны.

ТЕМПЕРАТУРНІ АНОМАЛІЇ ЩІЛЬНОСТІ НОСІЇВ ЗАРЯДУ $YBa_2Cu_3O_{6,9}$ ВІД 290 К ДО T_C

В.О. Фролов

Обґрунтовано можливість дослідження електронних властивостей високотемпературного надпровідника (ВТНП) за допомогою вимірювання електроопору r_C його інтерфейсу з нормальним металом. Показано існування кореляцій між аномаліями r_C і аномаліями щільності n_f носіїв заряду ВТНП. Відносно інтерфейсу $YBa_2Cu_3O_{6,9}$/In встановлено кореляції між аномаліями залежності $r_C(T)$ і аномаліями температурних залежностей параметрів b і c елементарної комірки $YBa_2Cu_3O_{6,9}$. Зроблено висновок про те, що причиною аномалій r_C при $T \gg T_C$ є спарювання діркових носіїв заряду $YBa_2Cu_3O_{6,9}$ в позитивно заряджені бозони. Різка і глибока аномалія r_C перед *n-s*-переходом корелює з добре відомим ефектом зміни знаку коефіцієнта Холла. Вона пояснена розпадом бозонів і послідовною інтенсивною конверсією діркових носіїв в електрони.