Ferromagnet-superconductor interfaces: the length scales of interactions

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Abstract. Heterostructures and superlattices consisting of the half-metal ferromagnet La_{0.67}Ca_{0.33}MnO_3 (LCMO) and the superconductor YBa_2Cu_3O_7 (YBCO) stacked along the c-axis of the superconductor were fabricated by pulsed laser deposition techniques. Apart from their structural characterization by x-ray diffractometry and high resolution TEM, the magnetic as well as electronic interaction at the interfaces and between the layers is studied by a variety of techniques ranging from transport measurements to magnetic, neutron diffraction and XMCD analysis. It turns out that these interaction effects occurring at several different length scales. At a short length scale of ~ 3 nm, charge transfer and/or orbital reconstruction as revealed by resonant x-ray absorption and XMCD measurements are dominant, the length scale of ~ 10 nm is the regime of self-injection of spin-polarized quasiparticles and at a scale in the 100 nm range and above magnetic interactions are present affecting the flux-line lattice of the superconductor, the domain structure of the magnetic layer as well as the interlayer coupling. The different and controversially discussed ferromagnet/superconducting interactions in YBCO/LCMO hybrids are analyzed and combined to a universal picture.

1. Introduction
Artificial superlattices (SL) as well as their natural counterparts represent a major research topic in condensed matter physics and modern device technology. Whereas in natural superlattices – e.g. the higher numbers \( n \) of Ruddlesden-Popper series of the \( A_{n+1}B_nO_{3n+1} \) type with \( A \) representing a rare earth and \( B \) a transition metal ions, respectively – the intrinsic anisotropic behaviour is at the focus of interest, artificial superlattices offer the possibility to adjust material properties by tailoring the electronic structure of the interface and the interactions across individual layers. Artificially tailored semiconductor heterostructures and superlattices are demonstrated to generate high-mobility electron systems with tunable densities at their interface and have proven to form the basis for unexpected advances in science and device technology over the past decades. Similarly, the attempt to replicate such multilayer using transition metal oxides pave the way for an even more exciting research area due to the rich intrinsic phase behavior of correlated oxide compounds and the delicate interplay of spin-, charge- and orbital ordering arising from the occupancy of the 3d shell of transition metals. In contrast to elemental semiconductors and semiconductor III-V compounds, where the constituents show basically all one valency, independent of doping, the main characteristics of the transition metals in correlated oxide compounds is their chemical stability in different and even in mixed valence states. Combining such transition metal oxides in heterostructures or superlattices can give rise to expectations that at interfaces novel quantum states are appearing with properties and functionalities qualitatively beyond those attainable in semiconductors. In the past few years this field has attracted
increasing interest in the science community and is listed amongst the “runners-up” in the breakthrough of the year in Science magazine [1-5].

Correlated oxide compounds with the perovskite structure can be found in almost every possible physical ground state such as metallic, insulating, ferromagnetic (FM), antiferromagnetic and superconducting (SC), etc. Many of them show strong electron correlations in contrast to semiconductors whose electronic properties can be described to a great extent by the adiabatic single particle approximation. This complexity leads to a strong competition between lattice-, orbital-, charge- and spin ordering, all of them occurring at similar energy scales. Candidates for heteroepitaxial thin-film growth of complex oxides can be chosen from a long list of materials with nearly perfect lattice match and good chemical compatibility. Thus, structurally highly ordered interfaces can be grown with negligible cation interdiffusion. The growth properties of complex oxides are governed by the constraint of preserving charge neutrality and stoichiometry imposed by the dominant ionic character of the chemical bonding of the constituents. Consequently, the minimum growth unit is a complete unit cell giving rise to a cell-by-cell growth mechanism that allows the formation of atomically sharp interfaces. The chemical bonding in most of these materials is dominated by the ionic character confining potential charge-transfer processes to distances of one unit cell. As Ohtomo et al. [1] have demonstrated in a pioneering paper, valence or polarity mismatch can alter the physical properties at the interface and such self-doping causes conductivity at the interface of two insulating constituents. Changes in the bonding characteristics at the interface may modify the spin properties because of the strong interaction between the spin and orbital degrees of freedom. Furthermore, electronic reconstruction at the interface and broken lattice symmetry modifies the orbital occupancy at the interface thus affecting the exchange interactions [6]. Consequently, the physical properties of an interface dominated sample will be different from those of the individual layers and the simple picture of a linear combination of the properties of both constituents is far from the reality. The concept of investigating heterostructures and superlattices of correlated oxide compounds opens a possibility for interface engineering, and unexpected phenomena can emerge which can not be understood in conventional band pictures.

A special topic in the field of transition metal oxide heterostructures is to combine materials with different ground states (functionalities) in the form of epitaxially grown thin films and to investigate their mutual interaction. Oxide ferromagnets and superconductors serve as prototypes for the combination of materials with different functionalities. Ferromagnetism and superconductivity are long range ordering principles with a mutual exclusion in homogeneous systems. However, if the layers are spatially separated as e.g. in thin film heterostructures or superlattices, both properties are appearing simultaneously in one stack and their interaction mechanisms can be studied. In the case of oxide ferromagnetic/superconducting junctions, there has been an increasing amount of papers published in the recent years aimed to understand effects of coupling between the FM and SC order parameters [7–12]. It has been predicted that the presence of a SC layer next to the ferromagnet causes a suppression of the magnetic order, while the FM induces a small magnetic moment in the SC layer [4]. There are several natural length scales determining the physical properties of such superlattices, namely, the superconducting coherence length, $\xi_s$, the superconducting magnetic penetration depth, $\lambda_s$, the diffusion length of spin-polarized quasiparticles in the superconductor, $l_{QP}$, and the long-range local extension of the magnetic stray fields arising either from the flux-line lattice of the superconductor or the domain structure of the ferromagnet. Furthermore, in analogy to interlayer coupling effects in ferromagnetic/metallic superlattices giving rise to the giant magnetoresistance (GMR) effect, novel interlayer coupling phenomena can be expected. In this paper, the recent experimental findings of interface controlled properties in LCMO/YBCO superlattices are compiled and an attempt is made to find an unified view of the underlying physics. Heuristically, as the valence electrons in both, cuprates and manganites, are subject to strong magnetic interactions, the magnetization at the interface is expected to have a decisive influence on the charge transport in these systems, so far, however, very little is known about the interfacial electronic structure and the magnetization profile.
2. Sample preparation and basic characterization

Employing SrTiO$_3$ (100) - oriented single crystal substrates, superlattices consisting of $m$ unit cells of YBa$_2$Cu$_3$O$_{7-x}$ and $n$ unit cells of LCMO repeated $N$ times have been deposited using a conventional home-made pulsed laser deposition system [13]. We applied a deposition temperature, $T_D$, of 730$^\circ$C, an oxygen background pressure of 0.4 mbar for the LCMO layer and 0.6 mbar during the YBCO deposition, respectively. The laser energy density on the target is 2 J/cm$^2$ and a pulse frequency of 2 Hz is used resulting in a deposition rate of 0.1 nm/pulse for the YBCO and 0.036 nm/pulse for the LCMO layers. To ensure complete and homogeneous oxygenation, the SL’s were in-situ annealed in 1atm oxygen for 1 hour at 530$^\circ$C. The deposition system (high vacuum chamber in conjunction with a KrF Excimer laser) is equipped with a FIR pyrometer to control the temperature of the radiatively heated substrate and the growing film. A special computer program has been developed to account for the different emission coefficients of the substrates and the films during the run to ensure a constant temperature at the growth front. A computer controlled target exchange system accommodating up to 5 different targets facilitates the fabrication of the desired superlattices, thus different modulation lengths, $\Lambda = t_{\text{YBCO}} + t_{\text{LCMO}}$, can easily be realized. Thickness control of the individual layers $t_{\text{YBCO}}$ and $t_{\text{LCMO}}$ is done by pulse counting after some calibration runs to ensure the stability of the growth rate. We prepared superlattices and heterostructures with layer thicknesses of $t_{\text{YBCO}}$ and $t_{\text{LCMO}}$ in the 5-50 nm range. Structural studies are carried out by x-ray diffraction (XRD) at room temperature, the resistance $R(T)$ is measured with evaporated chromium gold contacts using the standard four-probe technique. The temperature dependence of the magnetization $M(T)$ is recorded in a magnetic field parallel to the film plane using a Quantum Design MPMS superconducting quantum interface device (SQUID) magnetometer. X-ray diffractometry confirmed the phase purity of the c- axis oriented films.

Cross-sectional high resolution TEM analysis (Fig.1) reveals the SL formation and shows atomically flat interfaces. The epitaxial relation is clearly "cube-on-cube". Measurements of resistivity and magnetization show the features of both long range order properties, ferromagnetism and superconductivity. Fig. 2 represents the $R(T)$ and $M(T)$ plots of a [YBCO40nm/ LCMO20nm]$_5$ superlattice, showing a Curie temperature, $T_{\text{Curie}}$, of 150K and a transition temperature to superconductivity, $T_c$, of 70K. Both transition temperatures are substantially decreased with respect to the bulk values of 275K and 92 K, respectively [8]. The normal state transport properties are expected to be a superposition of the linear dependence $R \sim T$ of the YBCO and the features of the metal-insulator transition of the LCMO. The metal-insulator transition appears as a change in the slope of the $R(T)$ around $T_{\text{Curie}}$. The main features in Fig. 2 are the reduction of the ordering temperatures to FM and SC, respectively, and a substantially higher resistivity as compared to the corresponding single layers. Optical measurements using spectroscopic ellipsometry are used as a contactless method to probe the free carrier response as a function of frequency and temperature. The investigation of superlattices of different periodicity confirmed a systematic decrease of the real part of the optical conductivity with decreasing individual layer thickness and rule out significant contributions by additional scattering at internal surfaces as the reason for the enhancement of resistivity [14]. For a systematic study of these effects we prepared $[t_{\text{YBCO}}/t_{\text{LCMO}}]_N$ - type SL’s of different periodicities, keeping either $t_{\text{YBCO}}$ constant and change $t_{\text{LCMO}}$ or vice versa. The main results are summarized as follows: (i) Coexistence of ferromagnetism and superconductivity, (ii) composition dependent reduction of $T_c$ and $T_{\text{Curie}}$, and (iii) reduction of conductivity.

The synopsis of these measurements, probing the whole volume of the film, indicates that the properties of the superlattices are drastically affected by interactions localized at interfaces. Similar results have been reported by the Santamaria group [7, 10] and Przyslupski [9] for superlattices sputtered at substantially higher substrate temperatures of 900$^\circ$C. Substituting the ferromagnetic part by a paramagnetic metal such as LaNiO$_3$ or by PrBa$_2$Cu$_3$O$_7$ as an insulator isostructural to YBCO, the $T_c$ reduction is less pronounced and a few degrees only, clearly demonstrating that the magnetic interaction between the layers has to be accounted for the peculiarities of the findings. To shed some light on the potential magnetic interactions at the interface we used neutron reflectometry with unpolarized neutrons under specular condition [15]. We observed the occurrence of a structurally
forbidden Bragg peak in the FM state that highlights a significant difference between the nuclear and magnetic depth profiles in the superlattices. The neutron data were compatible with two physically very different scenarios: 1) a 2nm thick magnetically disordered (“dead”) layer in LCMO and completely nonmagnetic cuprate layers; and 2) a 1 nm thick layer with a suppressed (but nonzero) ferromagnetic moment in LCMO antiferromagnetically coupled to an approximately 2nm thick spin-polarized layer in YBCO. Subsequent careful measurements of the hysteresis loops of these superlattices revealed a pronounced exchange bias effect which is a fingerprint of an antiferromagnetic coupling at interfaces.

Fig. 1. Transmission electron microscope and electron diffraction images of the [8nm/4nm]x20 superlattice.

Fig. 2. Resistance (upper panel) and magnetic moment (lower panel) of a [40 nm YBCO /20 nm LCMO]5 superlattice as a function of temperature. The ZFC measurement shows the diamagnetic signal.

3. Interactions at the nanoscale
A combination of neutron reflectometry and X-ray magnetic circular dichroism (XMCD) yields a detailed microscopic element specific picture of the magnetization profile both, parallel and perpendicular to the superlattice plane, and offers intriguing insights into the interplay between ferromagnetism and superconductivity at the interface [4]. XMCD is the difference between absorption spectra for left- and right-circular polarized x-rays. The measurement involves changing the magnetization direction at each energy point of the absorption curve to determine the absorption with photon helicity and magnetization parallel (I+) and antiparallel (I). The sum (I+I) provides structural information while the XMCD (I-I) is magnetic in origin and yields the chemical element-specific net magnetization. By its monolayer sensitivity and a penetration depth of typically several 10 nanometers, XMCD is well suited for investigations of nanoscale magnetism at “buried” interfaces. We used circularly polarized soft x-rays at the L-absorption edges of Mn and Cu, respectively. During
the experiments, total electron yield (TEY), x-ray magnetic reflectivity (XRMS), and fluorescence yield (FY) data were recorded simultaneously. The surface-sensitive TEY mode was used to acquire information about magnetism at the top-most interface, whereas the XRMS and FY modes allowed us to probe deeper layers. All the XMCD spectra were measured in remanence. A sketch of the experimental arrangement is shown in Fig.3. Figure 4 shows representative Cu and Mn XMCD spectra taken at the resonant L $^{2,3}$ edges ($2p \rightarrow 3d$ transition) at 30 K. Magnetic dichroism is clearly present at both Mn and Cu edges. Since the manganite layers undergo a ferromagnetic transition at around 180 K, the large dichroism at the Mn edge is expected. The presence of a net ferromagnetic magnetization on Cu is, however, surprising. We ruled out experimental artifacts by confirming the sign reversal of the XMCD signal with alternating photon helicity. In addition, the effect was also verified by reversing the applied magnetic field and keeping the photon helicity unchanged. The data thus provide clear evidence for the presence of an uncompensated induced magnetic moment in the YBCO layer in proximity to the LCMO interface. As seen in Fig. 4, the Cu dichroism is small compared to that of Mn ($>27\%$) and does not exceed 1.4 $\%$, indicating that only a small fraction of the volume shows the magnetic polarization on Cu. The mutual orientation of the Mn and Cu magnetic moments can be deduced from the relative sign of the L$_3$ peaks for the same helicity of light. Figure 4 demonstrates that the Mn and Cu L$_3$ peaks have opposite signs, which indicates an antiparallel orientation of the corresponding magnetic moments. To investigate the origin of the ferromagnetic polarization of Cu, we performed XMCD measurements over a wide range of temperatures at both, Mn and Cu edges. Comparing the temperature dependence of the XMCD normalized to the 4.2 K value with corresponding data for the magnetic moment we found that the re-scaled dichroic signal of Cu closely follows that of Mn and the bulk magnetization. The similar temperature dependence of both signals
indicates that the magnetic moment on Cu is induced by strong interactions between Cu spins and the ferromagnetic moment of Mn across the interface. Applying the combination of x-ray spectroscopy and neutron reflectometry methods has revealed a detailed, microscopic picture of the magnetization profile of a complex oxide superlattice. While much more work is required to understand the microscopic mechanisms underlying this behavior, the data presented here demonstrate the potential of the experimental methodology we have established to elucidate the interplay between competing electronic order parameters in heterostructures of materials with strongly correlated electrons.

4. Interactions at the mesoscopic scale

Experiments probing ‘bulk’ properties of YBCO/LCMO superlattices such as the temperature dependence of magnetization, resistivity as well as the optical response as a function of the thickness of the individual layers in the SL indicate, that there is a length scale of interaction beyond that given by lattice and electronic reconstruction at the interface. The role of magnetism in determining the properties of the superlattices has been investigated using YBCO / LCMO superlattices with different compositions and modulation lengths. The length scale of effects due to lattice is confined to one or two unit cells. Reconstruction results from the difference of forces on the ions at interfaces from those in the bulk with consequences for the electronic structure, orbital occupancy and charge transfer. Especially, far infrared spectroscopic ellipsometry showed a drastic reduction of the optical conductivity in the whole frequency range in superlattices with individual layer thicknesses below 10-20 nm. In Fig.5 and Fig.6 the values for $T_c$ and $T_{Curie}$ are given for superlattices with constant $t_{YBCO} = 20$ nm and variation of $t_{LCMO}$ (Fig.5), and constant $t_{LCMO} = 20$nm and variation in $t_{YBCO}$ (Fig.6). Both results show, that there is a substantial mutual influence of the neighbouring layer in the superlattices causing a drastic reduction of the ordering temperatures.

**Fig. 5.** Evolution of $T_c$ as a function of the YBCO thickness in YBCO/LCMO superlattices with $t_{YBCO} = 20$ nm.

**Fig. 6.** Evolution of the Curie temperature for YBCO based superlattices with $t_{YBCO} = 20$ nm.

The reduction of $T_c$ is due to a mechanism additional to the short range surface reconstruction effects described earlier and can not be described quantitatively by them. The volume fraction of the sample where the short range effects are dominant amounts to less than 5% of the total volume and consequently can not be accounted for the reduction of $T_c$. The additional mechanism at work here is seen in the self-injection of spin-polarized quasiparticles (SPQ’s) into the superconductor and their pair breaking effect on Cooper pairs similarly to that of magnetic impurities. This phenomenon has been very early investigated by Gray [16] and the reduction of the superconducting gap can be written as

$$
T_c \sim \frac{1}{v_F} \ln \left( \frac{\mu}{\Delta_0} \right)
$$

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\[ \Delta n_{qp}(0) = 1 - 2n_{qp}/4N(0) \Delta(0) \]

where \( \Delta n_{qp} \) is the energy required to suppress the order parameter of the superconductor due to the presence of spin polarized quasiparticles with the density \( n_{qp} \). \( N(0) \) and \( \Delta(0) \) give the density of state and the order parameter at \( T = 0 \) K, respectively. The density of SPQ’s \( n_{qp} \) is generated by self-injection along the c-axis across the highly transparent interface and is governed by the high exchange splitting energy \( \Delta E_{ex}\sim3 \) eV of the magnetic layer. Treating the quasiparticle self-injection as a temperature dependent function and defining the spin-polarized quasiparticle diffusion length as

\[ l_{QP} = (l_0v_F\tau_s)^{1/2} \]

- \( l_0(T = 0 \text{ K}) \sim20 \) nm is the mean free path in YBCO and \( \tau_s \) the temperature dependent spin diffusion relaxation time - a relation is derived where the spin diffusion length is related to \( T_c \) with \( n_{qp}(T) \) being the only free parameter [17]. In Fig. 7 the fit of the experimental results with the model is depicted for LCMO/YBCO bilayers with various YBCO layer thicknesses and \( t_{LCMO} = 50 \) nm deposited on SrTiO\(_3\) and LaSrGaO\(_4\) substrates.

Fig. 7 shows clearly that there is a pronounced reduction of \( T_c \) starting at an YBCO layer thickness of \( \sim30 \) nm which correspond to a spin diffusion length of \( \sim10 \) nm. This result is in a good agreement with the estimation of Holden et al. [14] from the ellipsometry investigations. Holden’s results provide evidence that the free carrier response is strongly suppressed in these superlattices as compared to the one in the pure YBCO and LCMO films, and he estimates that a critical thickness for the YBCO is in the range of 20 nm.

5. Interactions at the microscopic scale

In addition to the short range interaction effects and those on a mesoscopic scale in cuprate/manganite superlattices discussed so far there are further mechanisms giving rise to modifications of the physical properties of superlattices and heterostructures as compared to single layer films. One rather surprising effect was observed first by muon spin rotation (\( \mu \)SR) experiments in YBCO/SrRuO\(_3\) superlattices [18]. The superlattices used had the composition \( [40 \text{ nm YBCO } / 20 \text{ nm SRO}]_5 \) and showed a \( T_c \) of 65K and \( T_{Curie} \) 115K, both reduced substantially compared to the bulk values. In this experiment we used the itinerant band ferromagnet SrTiO\(_3\) [SRO] rather than the Zener double exchange ferromagnet
LCMO because LCMO shows an inhomogeneous magnetization distribution presumably caused by mesoscopic phase separation effects within the LCMO layers and gives rise to an inhomogeneous depolarization of spin-polarized muons penetrating them. The $\mu$SR technique makes use of spin-polarized muon beams with a tunable energy between a few eV and a few tens of keV. The muons are used as microscopic magnetic probes by detecting their position of decay via the emitted positrons. Tuning the $\mu^+$ energy, the implantation depth can be varied between a fraction of an nm and several hundreds of nm, thus adding depth resolution to the $\mu$SR method [19]. The relevant quantity, the depolarization rate, $\lambda_2$, corresponding to the $1/T^2$ relaxation process, is plotted in Fig. 8 as a function of $T$. Solid (open) symbols represent the data with the muons stopped in the YBCO (SRO) layer. As expected $\lambda_2$ starts to increase below $T_{\text{Curie}}$ with small values ($\lambda_2 < 1\mu s^{-1}$) even in the magnetic layer. There are two surprising results, first, the relaxation rates are not very different in both layers and second, a sudden and drastic increase of $\lambda_2$ just below $T_c$ in both layers. This indicates a drastic increase of the internal magnetic fields. The observed relaxation rate in the superconducting film of $\lambda_2 \sim 17\mu s^{-1}$ at 10 K can not simply be explained by the formation of a spontaneous vortex state. A model is suggested, claiming an enhancement of the FM exchange coupling via the YBCO layers when they become superconducting. The increase in the magnetic exchange coupling below $T_c$ might have its origin in the change of the $c$-axis electronic properties of the YBCO in the superconducting state. The electronic response perpendicular to the CuO$_2$ planes has a high resistivity in the normal state and becomes coherently conducting in the superconducting state due to the onset of Josephson currents.

An additional evidence for drastic changes of the coupling across the layers comes from off-specular neutron scattering experiments in the presence of weak in plane magnetic fields below values required to saturate the magnetic hysteresis loop [4]. In Fig. 9 the intensities of the off-specular neutron reflectivity is given for temperatures above and below $T_c$ as a function of the wave-vectors $Q_x$ and $Q_z$ perpendicular and parallel to the film plane. The sharp peak above $T_c$ indicates the presence of large domains whereas below $T_c$ they split into small regularly aligned stripe-type domains below $T_c$. This effect is seen in conjunction with the coherent Josephson coupling in the superconducting state of YBCO making the superlattice essentially transparent to in-plane magnetic fields.

Fig. 8. Temperature dependence of the zero-field $\mu$SR relaxation rate $\lambda_2$ with the muons stopped in the YBCO and SRO layers, respectively. Inset: SQUID magnetization data at $H = 2$ kOe [18].
6. Conclusions

The investigation of the physical properties of YBCO/LCMO heterostructures and superlattices revealed components of a microscopic understanding of their transport and magnetic behavior based on charge redistribution and orbital occupancy at interfaces. This is regarded as a special example of the more general case of interfaces on correlated complex oxides. This understanding – however incomplete at the present stage – can be used in conjunction with advanced thin film preparation techniques to manipulate the electronic structure of oxide interfaces and prepare 2-dimensional electronic structures with controlled interactions. Potentially, novel systems can be stabilized opening new opportunities for superconductivity even at higher temperatures [20].

References

[1] Ohtomo A and Hwang H Y 2004 Nature 247 427
[2] Reyren N, Thiel S, Caviglia A D, Kourkoutis L F, Hammerl G, Richter C, Schneider C W, Kopp T, Ruetschi A S, Jaccard D, Gabay M, Muller D A, Triscone J M, Mannhart J 2007 Science 317 1196.
[3] Thiel S, Hammerl G, Schmehl A, Schneider C W, Mannhart J 2006 Science 1942
[4] Chakhalian J, Freeland J W, Srajer G, Strempfer J, Khaliullin G, Cezar J C, Charlton T, Dagliesh R, Bernhard C, Cristiani G, Habermeier H-U and Keimer B 2006 Nature Physics 2 244
[5] 2007 Science 317 1844
[6] Chakhalian J, Freeland J W, Habermeier H-U, Cristiani G, Khaliullin G, van Veenendaal M and Keimer B 2007 Science 318 1114
[7] Sefrioui Z, Arias D, Peña V, Villegas J E, Varela M, Prieto P, León C, Martínez J L and Santamaria J 2001 J. Appl. Phys. 89 8026
[8] Habermeier H-U, Cristiani G, Kremer R K, Lebedev O and van Tendeloo G 2001 Physica C 364 298
[9] Przyslupski P, Komissarov I, Dłuzewski P, Pelka J, Dynowska J E and Sawicki M 2003 Physica C 387, 40

Fig. 9. Off-specular neutron reflectivity of a YBCO/LCMO [10x10nm] superlattice as a function of the wave vectors Qx and Qz above (left) and below (right) the superconducting transition temperature (taken from [4]).
[10] Sefrioui Z, Varela M, Peña V, Arias D, León C, Santamaria J, Villegas J E, Martínez J L, Saldarriaga W and Prieto P 2002 Appl. Phys. Lett. 81 4568
[11] Habermeier H-U and Cristiani G 2004 Transactions of J-MRS 29 1422
[12] Habermeier H-U and Cristiani G 2002 J. of Supercond. 15 425
[13] Habermeier H-U 1991 Eur. J. Solid State Inorg. Chem 28 201
[14] Holden T, Habermeier H-U, Cristiani G, Golnik A, Boris A, Pimenov A, Humlček J, Lebedev O, van Tendeloo G, Keimer B and Bernhard C 2004 Phys. Rev. B 69 064505
[15] Stahn J, Chakhalian J, Niedermayer Ch, Hoppler J, Gutberlet T, Voigt J, Treubel F, Habermeier H-U, Cristiani G, Keimer B and Bernhard C 2005 Phys. Rev. B 71 140509(R)
[16] Gray K E “Nonequilibrium Superconductivity, Phonons and Kapitza Boundaries”, edited by K. E. Gray (Plenum, New York, 1981).
[17] Soltan S, Albrecht J and Habermeier H-U 2004 Phys. Rev. B 70 144517
[18] Bernhard C, Niedermayer Ch, Habermeier H-U, Suter A, Prokscha T, Luetkens H and Morenzoni E 2002 Annual Report PSI Villigen 84
[19] Morenzoni E, Prokscha Th, Hofer A, Matthiasa B, Meyberg M, Wutzke Th, Glückler H, Birke M, Litterst J, Niedermayer Ch and Schatz G 1997 J. Appl Phys. 81 3341
[20] Chaloupka J and Khaliullin G 2008 Phys. Rev. Lett. 100 016404