Hole and Electron Contributions to the Transport Properties of Ba(Fe$_{1-x}$Ru$_x$)$_2$As$_2$

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We report a systematic study of structural and transport properties in single crystals of Ba(Fe$_{1-x}$Ru$_x$)$_2$As$_2$ for $x$ ranging from 0 to 0.5. The isovalent substitution of Fe by Ru leads to an increase of the $c$ parameter and a decrease of the $c$ parameter, resulting in a strong increase of the As-Fe-As angle and a decrease of the As height above the Fe planes. Upon Ru substitution, the magnetic order is progressively suppressed and superconductivity emerges for $x \geq 0.15$, with an optimal $T_c \simeq 20$K at $x = 0.35$ and coexistence of magnetism and superconductivity between these two Ru contents. Moreover, the Hall coefficient $R_H$ which is always negative and decreases with temperature in BaFe$_2$As$_2$, is found to increase here with decreasing $T$ and even change sign for $x \geq 0.20$. So for $x_{Ru} = 0.35$, photo-emission studies have shown that the number of holes and electrons are similar with $n_e = n_h \simeq 0.11$ carriers/Fe, that is twice larger than found in BaFe$_2$As$_2$ [1]. Using this estimate, we find that the transport properties of Ba(Fe$_{0.65}$Ru$_{0.35}$)$_2$As$_2$ can be accounted for by the conventional multiband description for a compensated semi-metal. In particular, our results show that the mobility of holes is strongly enhanced upon Ru addition and overcomes that of electrons at low temperature when $x_{Ru} \geq 0.15$.

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INTRODUCTION

In iron pnictides the appearance of high-$T_c$ superconductivity induced by carrier doping or pressure in close proximity to the antiferromagnetic (AF) phase, appears very similar to the behavior of cuprates and heavy-fermion superconductors and has been taken as the signature of unconventional superconductivity in these compounds. It seems now well established that magnetism and superconductivity (SC) are intimately correlated and directly connected to the peculiar features of the electronic structures of these compounds. More precisely the changes in the Fermi surface and the modifications of the nesting conditions between the hole and electron pockets have been proposed to be the driving force for the suppression of antiferromagnetism and the emergence of superconductivity with a sign reversing $s_\pm$ symmetry [2].

So far a lot of studies have been devoted to the 122 family as superconductivity can be induced not only by doping with holes [3] or electrons [4, 5] but also through chemical or physical pressure [6, 7]. Several investigations have been done in order to find out a relevant parameter allowing to explain the modifications of the electronic structure and the emergence of superconductivity in these different systems. On one hand, it has been argued that structural modifications could be more important than doping in achieving superconductivity, either through the height of As with respect to Fe planes [8] or the value of the As-Fe-As bonding tetrahedral angle [9]. On the other hand, in the case of electron doped compounds, the steric effect due to different atomic substitutions in the Fe planes, has been shown to be of minor importance compared to the effect of doping [10]. Let us note that the very low level of substitution sufficient to induce SC in this latter case is compatible with weak structural distortion effects. However, in the case of hole doping for which large substitution level (around 35%) is necessary to get the optimal $T_c$, it seems more difficult to distinguish between doping and structural modifications.

Studies of transport properties are a priori one of the simplest way to investigate the modifications of the electronic structure. However the situation in the 122 family is far from being clear. In the undoped BaFe$_2$As$_2$ parent, for which the electron and hole contents are identical ($n = n_e = n_h$), it is found quite surprisingly that the Hall coefficient $R_H$ is always negative, indicating that electrons dominate the transport properties both above and below the structural/magnetic transition at $T \simeq 140$K. The same observation has been found for Co doped samples all over the phase diagram [11, 12]. For all these compounds, it seems that the holes are highly scattered and thus not directly visible in the transport properties [13]. The case of isovalent substitution of As by P is even more intriguing as a negative Hall coefficient is also found for all P contents [14]. In fact, positive $R_H$ have been only reported for K and Cr doped BaFe$_2$As$_2$, as naturally expected for hole doped compounds [15, 16].

The isovalent substitution of Fe by Ru provides another alternative to study the modifications of the transport properties in the 122 family. It has been shown recently on polycrystalline samples [17, 18] that the introduction of Ru suppresses the SDW magnetic order and...
induces SC. Density functional calculations show that Ru substitution does not induce any charge imbalance between the bands and no additional bands related to Ru appear at the Fermi level [10]. However a negative Hall coefficient with a weak $T$ dependence has also been reported for polycrystalline BaFe$_{1.25}$Ru$_{0.75}$As$_2$ [12].

Here we report on structural, resistivity and Hall effect data obtained on single crystals of Ba(Fe$_{1-x}$Ru$_x$)$_2$As$_2$ for $x$ ranging from 0 to 0.5. As reported previously, we confirm the suppression of the magneto-structural transition and the emergence of SC for $x \gtrsim 0.15$ with an optimal $T_c \sim 20K$ at $x \sim 0.35$. We find that the lattice parameters $a$ ($c$) respectively increases (decreases) upon Ru addition, so that $a/c$ increases markedly. As for the transport properties, our Hall effect measurements evidence the contribution of both holes and electrons in the transport properties, as the Hall coefficient changes sign, from negative to positive with decreasing temperature. On the other hand, Angle Resolved Photo-Emission Spectroscopy (ARPES) measurements performed on similar single crystals with $x = 0.35$ [3] confirm that Ru-substituted BaFe$_2$As$_2$ behave as a compensated metal with essentially the same number of holes and electrons, i.e. $n = n_e = n_h \simeq 0.11$ carriers/Fe. Assuming a two band model to describe the transport properties, we show that it is possible here to disentangle the respective contributions of electrons and holes. Quite surprisingly the deduced electron and hole resistivity curves display similar $T$ dependences as those found respectively for Co-doped and K-doped BaFe$_2$As$_2$ at optimal doping. Their evolutions with Ru content show that the mobility of holes is more affected than that of electrons. The strong modification of the electronic structure of BaFe$_2$As$_2$ with Ru substitution revealed by ARPES [1] might be the key factor for governing these properties.

SAMPLES AND STRUCTURAL MEASUREMENTS.

Single crystals of Ba(Fe$_{1-x}$Ru$_x$)$_2$As$_2$ with Ru contents $x$ ranging from 0 to 0.50 were grown using a FeAs/Ru+As self-flux method. Small Ba chunks, FeAs powder and RuAs (or Ru+As) powders were mixed in the ratio Ba:(FeAs+RuAs)$=1:4$. Starting products were put in an alumina crucible and sealed in an evacuated quartz tube which was put into a tubular furnace. The samples were heated to 1180°C, held at this temperature for 4h, cooled slowly first to 1000°C (3-6°C/h) and then more rapidly to room temperature. Clean crystals of typical dimensions 0.5x0.5x0.05 mm$^3$ were mechanically extracted from the flux. It is worth pointing out here that it is very difficult to get homogeneous single crystals for $x_{Ru} \geq 0.2$, probably due to the very high melting temperatures of Ru and RuAs with respect to that of FeAs. Consequently, the Ru composition of each studied crystal has been determined with a Camebax SX50 electron microprobe in several spots of the surfaces.

The structural properties were characterized by single crystal X-ray diffraction on very thin platelets ($\sim 0.10 \times 0.05 \times 0.01 mm^3$). The data were collected at room temperature on a Nonius Kappa-CCD area detector diffractometer [20] using graphite-monochromated Mo Kα radiation ($\lambda = 0.71073 \AA$). The data (combinations of $\varphi$- and $\omega$-scans giving complete data sets up to $\theta = 27.4$ deg. at least and a minimum redundancy of 4 for 90% of the reflections) were processed with HKL2000 [21]. Absorption effects were corrected empirically with the program SCALEPACK [21]. The structures were refined in the tetragonal space group $I4/mmm$ by full-matrix least-squares on $F^2$ with SHELXL-97 [22]. All the atoms were refined with anisotropic displacement parameters, so that 10 parameters were refined on $\sim 100$ independent reflections. Fe and Ru were constrained to retain the same displacement parameters, which enabled to refine the Ru content $x$. The final $R_1$ indices are in the range 0.020 − 0.042 and the $wR_2$ values in the range 0.043 − 0.113 [23].

The relative lattice parameters are plotted in Fig.1 versus the refined value of $x_{Ru}$, while numerical data are reported in table 1 for $x = 0$ (undoped BaFe$_2$As$_2$) and $x = 0.38$ (optimal doping). Upon substitution, the a pa-
TABLE I: Crystallographic data taken at room temperature for the parent and Ru-substituted (x= 0.38) Ba(Fe$_{1-x}$Ru$_x$)$_2$As$_2$. The space group of both compounds is I4/mmm and the atomic coordinates are: Ba(0,0,0), Fe/Ru(0.5,0,0.25) and As (0,0,z). $\alpha_1$ and $\alpha_2$ are the bonding tetrahedral angles as sketched in Fig.1.

| $x$  | a (Å)         | c (Å)       | V (Å$^3$)   | $z_{As}$     | $\alpha_1 \times 2$ (deg) | $\alpha_2 \times 4$ (deg) | As height (Å) | Fe-As interatomic distance (Å) | FeAs layer spacing (Å) |
|------|---------------|-------------|-------------|-------------|---------------------------|--------------------------|--------------|-------------------------------|------------------------|
| 0    | 3.9633(4)     | 13.022(2)   | 204.55(4)   | 0.35424(6)  | 111.18(3)                 | 108.624(15)           | 1.3575       | 2.402(2)                      | 3.796                  |
| 0.38 | 4.0342(5)     | 12.749(2)   | 207.49(5)   | 0.35328(8)  | 113.73(4)                 | 107.39(2)              | 1.3165       | 2.409(2)                      | 3.741                  |

rameter and the cell volume increase while the c parameter decreases in about the same proportion (by 2-3% for $x = 0.5$) in agreement with data on polycrystalline samples [17]. The main effect of Ru substitution is thus to strongly increase the ratio ($a/c$). This results in a strong increase of the As-Fe-As tetrahedral bonding angle $\alpha_1$ displayed in fig.1(b) which varies by 4% for $x = 0.5$. Moreover, while the $z$ parameter of As and the Fe-As interatomic distance are nearly unaffected by Ru substitution, the vertical distance of As from the Fe layers decreases, due to the strong c decrease. These tendencies can be explained quite naturally by the larger size of Ru$^{2+}$ compared to Fe$^{2+}$ which expands the distances within Fe-Ru planes. Also the larger delocalization of the Ru 4d orbitals with respect to Fe 3d reinforces the hybridization with As and then reduces the $c$ axis parameter [19]. Let us note that the variation of the lattice parameters upon Ru substitution displays the same trend as that observed in electron doped BaFe$_2$As$_2$ compounds, although the incidence on the structure appears much weaker in this latter case [10, 23]. However it is at odds to the tendency found for hole doping or pressure which both $a$ and the As-Fe-As $\alpha_1$ angle are found to decrease.

RESISTIVITY MEASUREMENTS AND PHASE DIAGRAM

Transport measurements were performed on crystals cleaved to thicknesses lower than 20 µm and cut to get square samples with $\sim 0.2 - 0.3$ mm width (See fig.2(c)). Contacts were done with silver epoxy in the Van der Pauw configuration [26].

Fig.2(a) shows the $\rho(T)$ curves as a function of Ru content. In BaFe$_2$As$_2$, the combined structural and magnetic (S-M) transition at $T_0$=137 K is signalled by a decrease of the resistivity [23]. For the lowest Ru content $x = 0.05$ studied here, we still observe a resistivity decrease at the S-M transition but with a much wider transition as seen in fig.2(b) which shows $d\rho/dT$ versus $T$. For the $x = 0.26$ sample, the arrow corresponds to the maximum of the Hall coefficient as explained in the text. (c) Picture of a typical sample mounted in the Van der Pauw configuration.

For the lowest Ru content $x = 0.05$ studied here, we still observe a resistivity decrease at the S-M transition but with a much wider transition as seen in fig.2(b) which shows $d\rho/dT$ versus $T$. Then for larger Ru contents, the resistive signature of the S-M transition, determined by the deviations in $d\rho/dT$, changes shape towards a step-like increase of the resistivity as observed in electron doped compounds. In contrast, let us point out that the S-M transition is always signalled by a decrease of the resistivity in polycrystalline samples [17, 18], which might be related to inhomogeneities in the samples or directional averaging due to different in-plane and out of plane resistivity variations at the S-M transition. For $x = 0.15$, it is possible to distinguish between the structural and magnetic transitions, using the same criteria based on the variation of $d\rho/dT$ as proposed for Co-doped samples (arrows in fig.2(b)) [5, 27]. This would give 95 and 88K

FIG. 2: (color on line) (a) Temperature dependence of the in-plane resistivity $\rho(T)$ of Ba(Fe$_{1-x}$Ru$_x$)$_2$As$_2$ single crystals. The arrows point the strong anomalies in the $\rho(T)$ curves that signal the occurrence of the magneto-structural transition. They are determined more precisely in (b) which shows $d\rho/dT$ versus $T$. For the $x = 0.26$ sample, the arrow corresponds to the maximum of the Hall coefficient as explained in the text. (c) Picture of a typical sample mounted in the Van der Pauw configuration.
respectively for $T_S$ and $T_{SDW}$. For the other samples, this distinction is not possible and microscopic investigations are needed to determine the respective values of $T_S$ and $T_{SDW}$.

Superconductivity appears for $x \geq 0.15$ and a maximum $T_c$ of $19.5 \pm 0.5K$ is found for $x = 0.35$, in excellent agreement with the value found for polycrystalline samples of Ru substituted Ba(Sr)Fe$_2$As$_2$ [17, 18]. The $T - x$ phase diagram obtained for Ba(Fe$_{1-x}$Ru$_x$)$_2$As$_2$ is displayed in fig.3. One can notice that the superconducting region is rather small, particularly in the ”overdoped” region where $T_c$ is found to drop rapidly beyond $x = 0.35$. As in the doped compounds, coexistence between magnetism and superconductivity is clearly evidenced, with the optimal $T_c$ occurring when long range magnetic order is fully suppressed. This points here again to the importance of spin fluctuations for superconductivity in these systems. From these resistivity data, it is not possible to know whether the coexistence between magnetism and superconductivity occurs at the atomic scale like in Co-doped samples [29] or comes from phase segregation as observed in K-doped samples [30, 31] and further studies at the microscopic level are needed to assess this point.

We find here that superconductivity is induced upon Ru addition while the FeAs$_{1-x}$ tetrahedra become strongly distorted as both the $\alpha_1$ and $\alpha_2$ angles deviate from 109.5 deg, the ideal tetrahedral value. This observation conflicts with the claim that the regularisation of tetrahedra is the optimal condition for achieving superconductivity in pnictides [3, 34, 35]. Let us also note that Ru substitution in the 1111 PrFeAsO compound induces similar crystallographic modifications as those observed here in BaFe$_2$As$_2$ [36] with suppression of the magnetic order but no apparition of superconductivity.

On another hand, band structure calculations have pointed out the important impact of the vertical distance $d_{Fe-As}$ on the Fermi surface topology of iron pnictides [37]. Mizugushi et al. [8] have recently shown that a striking correlation between $T_c$ and the Fe-As distance is followed by a lot of different FeAs superconductors. This plot is symmetric with a peak around $d_{Fe-As}=1.38\AA$. We find that the point corresponding to Ba(Fe$_{0.62}$Ru$_{0.38}$)$_2$As$_2$ ($d_{Fe-As}=1.3165\AA$) and $T_c \approx 20K$ is on the left branch while the one for pressure or hole doping is located on the right one. Even though other factors are clearly at play for governing the apparition of superconductivity in the 122 family, the relationship between the values of $T_c$ and $d_{Fe-As}$ may provide a helpful hint to understand the modifications of the electronic properties.

HALL EFFECT AND ANALYSIS OF TRANSPORT PROPERTIES

The temperature dependences of the Hall coefficient $R_H$ are displayed in Fig.4 for different Ru concentrations. In the paramagnetic state of the samples, we have checked that the Hall resistivity is always linear in field up to 14T, which allows to define $R_H$ unambiguously [28]. This linearity is illustrated in the inset of Fig.4 for the $x = 0.35$ sample. The strong reduction in the Hall coefficient at the S-M transition is well correlated to the anomalies seen in $\frac{d\rho}{dT}$ and represented by arrows in the figure. It can be associated, as in the undoped parent, to the reduction of carrier density due to the reconstruction and/or partial gaping of the Fermi surfaces. The fact that $R_H$ remains negative indicates that electrons still dominate the transport properties in the magnetic phase of Ru-substituted samples.

Fig.5(a) shows an enlarged view of the evolution of the Hall coefficient in the paramagnetic phase. For comparison, we have also plotted in Fig.5(b) similar data obtained for Ba(Fe$_{1-x}$Co$_x$)$_2$As$_2$ at various dopings [11]. In this latter case, $R_H$ is always found negative, indicating that the contribution of electrons dominate the transport properties. However an opposite trend appears as soon as Ru is added to BaFe$_2$As$_2$. For $x = 0.15$, $R_H$ nearly reaches zero before dropping at the S-M transition and for higher Ru contents, a change of sign of $R_H$ occurs at low temperature. In particular for the $x \sim 0.25$ sample, we observe that $R_H$ increases and becomes positive upon cooling and then appears to slightly decrease again for $T \lesssim 50K$. This can be related to the flattening of the $\rho(T)$ curves observed in the same temperature range and this is for us the sign that the S-M transition takes place at $T \simeq 50K$ in this sample.
resistivity \( \rho \) of the vicinity of \( T = 0 \) for (a) Ba(Fe\(_{1-x}\)Ru\(_x\))\(_2\)As\(_2\) and (b) Ba(Fe\(_{1-x}\)Co\(_x\))\(_2\)As\(_2\), from ref. [11].

In multiband systems, it is well known that a temperature variation of the Hall coefficient can be assigned to different variations of hole and electron mobilities with temperature. The observation of a sign change of \( R_H \) in Ba(Fe\(_{1-x}\)Ru\(_x\))\(_2\)As\(_2\) indicates that holes and electrons contribute similarly to the transport in a large temperature range. More precisely ARPES data on crystals with 35\% Ru [11] have shown that the number of holes and electrons are similar, i.e. \( n = n_e = n_h \simeq 0.11 \) carriers/Fe.

It is worth pointing out that this value is significantly larger than that determined by ARPES in the paramagnetic phase of BaFe\(_2\)As\(_2\): \( n = 0.06(2) \) carriers/Fe [32], which indicates that even though Ru is isovalent of Fe, it induces important modifications of the electronic structure. This equality of \( n_e \) and \( n_h \) is consistent with the observation that the Hall resistivity \( \rho_{xy} \) is always linear with magnetic field. Indeed in a two band model, the Hall resistivity \( \rho_{xy} \) can be written out as:

\[
\rho_{xy} = \frac{1}{e} \frac{n_h \mu_h^2 - e \mu_e^2 + (\mu_h \mu_e)^2 (n_h - n_e) H^2}{(n_h \mu_h + n_e \mu_e)^2 + (\mu_h \mu_e)^2 (n_h - n_e)^2 H^2} H \quad (1)
\]

where \( \mu_h = |e| \tau_h / m_h \) (\( \mu_e = |e| \tau_e / m_e \)) are the mobilities of holes (electrons) and \( \tau_h \) (\( \tau_e \)) and \( m_h \) (\( m_e \)) their relaxation rates and effective masses. For \( n_e = n_h = n \), the \( H^2 \) term in the numerator and denominator of Eq.(1) vanishes resulting in linear variation of \( \rho_{xy} \) with \( H \), whatever \( H \) and \( T \).

Knowing \( n \), it is then straightforward to deduce the respective contributions of electrons of holes to the transport for the \( x = 0.35 \) sample from the resistivity and Hall coefficient data, using:

\[
\frac{1}{\rho} = \sigma = \sigma_e + \sigma_h \quad (2)
\]

and

\[
R_H = \frac{1}{n e \mu_e + \mu_h} = \frac{1}{n e \sigma_e + \sigma_h} \quad (3)
\]

The resulting resistivity curves obtained for electrons and holes are displayed in Fig.6(a). It is striking to see that the shapes of the curves resemble those obtained respectively for electron and hole doped BaFe\(_2\)As\(_2\) at optimal doping. These similarities give strong support to the validity of the decomposition using the two band model. One can also notice that \( \rho_h(T) \) displays a nearly \( T^2 \) dependence as in Ba\(_{0.65}\)K\(_{0.35}\)Fe\(_2\)As\(_2\) [12] while \( \rho_e(T) \) exhibits a nearly linear \( T \)-dependence up to 150K as in Ba(Fe\(_{0.93}\)Co\(_{0.07}\))\(_2\)As\(_2\) [11]. These temperature variations appear then tightly connected to the type of carriers - hole or electrons - and indicate an intrinsic disparity between their respective properties.

It has been suggested that the linear \( T \) dependence of resistivity found in Ba(Fe\(_{1-x}\)Co\(_x\))\(_2\)As\(_2\) or BaFe\(_2\)As\(_{1-x}\)P\(_x\) near optimal doping might be a general property of unconventional superconductors near a SDW instability [33].
FIG. 6: (color on line) (a) Respective resistivities of electrons and holes for Ba(Fe$_{0.65}$Ru$_{0.35}$)$_2$As$_2$ obtained from the data of resistivity and Hall coefficient using Equations (2) and (3) with $n_e = n_h = 0.11$, as given by ARPES measurements on similar samples [1]. The raw data for resistivity and Hall coefficient are recalled in the inset. (b) The resistivity curves for Ba(Fe$_{0.93}$Co$_{0.07}$)$_2$As$_2$ [11] and Ba$_{0.65}$K$_{0.35}$Fe$_2$As$_2$ [15] are given for comparison.

or a signature of non Fermi liquid behavior [14]. The observation of a linear behavior for the electrons and not for the holes in the same sample clearly addresses the question of the real physical origin of this linearity. In Ba(Fe$_{1-x}$Co$_x$)$_2$As$_2$, the analysis of combined data of resistivity and Hall effect for $n_e > n_h$ led us to suggest that this linearity comes from an artefact due to a small variation of $n_e$ with temperature and that the scattering rates obey the $T^2$ behavior expected for Fermi liquids [11].

CONTRIBUTION OF ELECTRONS AND HOLES TO THE ELECTRONIC TRANSPORT

The most striking result of this study is that electrons and holes contribute similarly to the transport in Ba(Fe$_{1-x}$Ru$_x$)$_2$As$_2$. This is in contrast to the observations of negative Hall coefficient in the undoped parent [11, 12] or upon isovalent exchange of As by P [14]. An important question is thus to understand why the holes are more scattered than the electrons in these latter cases.

In BaFe$_2$As$_2$, ARPES data have shown that the number of carriers is $n_e = n_h = 0.06(2)$ carriers/Fe, about twice smaller than the estimate given by LDA calculations [32, 38]. We have then performed the same decomposition for BaFe$_2$As$_2$ in the paramagnetic phase, i.e. for $T > 140$K, as done above, using either $n = n_e = n_h = 0.06$ carriers/Fe or $n = 0.15$ carriers/Fe (Fig.7). It is clear that the results are much more sensitive to the actual value of $n$ for the holes than for the electrons: the electron resistivity always displays a metallic behavior with similar values while the hole one tends towards a semiconducting behavior when approaching the magneto-structural transition. The disparity between the two types of carriers appears more or less pronounced depending on the value taken for the carrier number.

It has been suggested that spin fluctuations due to interband electron-hole scattering might play a crucial role to explain the asymmetric behaviors of holes and electrons in undoped and electron doped BaFe$_2$As$_2$ [12]. On the contrary, our Hall coefficient data displayed in Fig.5(a) for different Ru contents seem to indicate that the proximity of magnetism does not play here an important role on the respective mobilities of the carriers. This is more visible in Fig.8 where the decompositions in $\rho_e$ and $\rho_h$ are reported for different Ru contents, assuming a linear variation of $n$ with $x_{Ru}$. Even though this analysis is tentative, it gives some trends on the evolution of the transport properties of
BaFe$_2$As$_2$ upon Ru addition. In particular, one can notice that the decrease of the hole and electron resistivities cannot be entirely explained by the increase of $n$. This therefore points to a concomitant increase of their respective mobilities. As shown by ARPES measurements on the $x = 0.35$ sample, Ru substitution strongly modifies the electronic structure with respect to that of undoped BaFe$_2$As$_2$: not only the number of carriers has doubled but also the Fermi velocities have increased by a factor 2 or 3 \cite{1}. In fact the electronic structure of Ba(Fe$_{0.65}$Ru$_{0.35}$)$_2$As$_2$ can be reasonably accounted for by LDA calculations with negligible electron correlation effects. This tendency is not observed for electron or hole doped compounds with similar $T_c$ \cite{32,39,40}. However, the resemblance displayed in fig.6 between the resistivity curves deduced for electrons and holes suggests that the occurrence of optimal $T_c$ in all these compounds is linked with well defined features of the electron and hole bands. Further work, specifically studying the strength and the evolution of antiferromagnetic spin fluctuations with Ru contents, will hopefully allow to clarify the incidence of spin fluctuations, electronic correlations and filling of the electronic bands on the transport properties of these compounds.

Nevertheless the way how these band structure modifications can also affect the strength of spin fluctuations or the carrier mobilities is not clear at present. Moreover, the resemblance displayed in fig.6 between the resistivity curves found for electrons and holes and those measured in electron and hole doped compounds appears very puzzling, as it suggests that the transport properties of electrons and holes are defined by their own and are not tightly dependent on the system of interest.

**CONCLUSION**

The results presented here and in ref.\cite{1} clearly show that Ru is isovalent of Fe. We have confirmed that Ru substitution suppresses the magnetic state and induces superconductivity, which coexist in a given concentration range. Therefore it appears qualitatively very similar to the other types of substitutions.

From the structural point of view, we have shown that superconductivity can be induced although the FeAs$_4$ tetrahedra are strongly distorted upon Ru addition. These structural modifications are in total contrast to those induced under pressure or by hole doping. This thus demonstrates that the regularisation of tetrahedra cannot be the key structural factor for the occurrence of superconductivity as proposed recently \cite{3}. However, we find that the relationship between the optimal $T_c$ and the anion height above the Fe planes obeys the same plot as found for a lot of different iron based compounds \cite{8}. Even though this cannot be considered as the only parameter to drive superconductivity, this indicates that subtle details of crystal structure might tune specific properties of the Fermi surface necessary to optimize it.

We have demonstrated that a two band model approach is a prerequisite to get insight into the respective contribution of electrons and holes to the transport properties of these multi-band materials. Using combined studies of transport and ARPES measurements on the same samples, we have been able to disentangle the respective contributions of electrons and holes to transport properties. We have evidenced that their mobilities become comparable upon Ru addition, even in the close proximity to magnetism. In addition, we find that the mobility of holes overcomes that of electrons at low $T$ in superconducting samples. The observation that the $\rho(T)$ curves deduced for electrons and holes are very similar to those measured in electron or hole doped compounds suggests that the occurrence of optimal $T_c$ in all these compounds is linked with well defined features of the electron and hole bands.

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