Effect of antimony substitution in iron pnictide compounds

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Abstract

In the present study we have examined the effect of negative chemical pressure in iron pnictides. We have synthesized substitution series replacing arsenic by antimony in a number of 1111- and 122-iron arsenides and present their crystallographic and physical properties. The SDW transition temperature in LaFeAs$_{1-x}$Sb$_x$O decreases with increasing antimony content, while the superconducting transition temperature in LaFeAs$_{1-x}$Sb$_x$O$_{0.85}$F$_{0.15}$ initially increases with Sb substitution. 1111-compounds with samarium instead of lanthanum have a smaller unit cell volume. In these phases, no Sb solubility is observed. There is also no apparent solubility of antimony in the 122-iron arsenides.

Keywords: Fe-based superconductors, powder metallurgy, chemical pressure, electrical transport, X-ray diffraction, phase diagram

1. Introduction

The discovery of superconductivity in fluorine doped LaFeAsO (1111) compounds [1] was followed by quite a large amount of experimental and theoretical work, which was aimed at understanding the physical properties of iron pnictides. Beside the superconducting 1111 iron pnictides which crystallize in the tetragonal ZrCuSiAs-type structure, superconductivity was found in the 122 compounds which crystallize in the ThCr$_2$Si$_2$ structure type [2] and the 111 compounds with PbFCl-type structure [3]. In the present study we concentrate on the 1111-type compounds with formula REFeAsO (RE: rare earth) and 122-type compounds with formula AEF$_2$As$_2$ (AE: alkaline earth). Both structure types are characterized by layers of FeAs which are separated by layers of rare earth oxide or of alkaline earth atoms.

Upon cooling, the undoped compounds undergo a structural phase transition from tetragonal to orthorhombic. Beside this structural transition, there is also a magnetic phase transition to long range antiferromagnetic order. This transition is ascribed to the occurrence of a spin-density-wave (SDW) [4]. In the 122-compounds, the structural and magnetic phase transition takes place at the same temperature whereas in the 1111-compounds the transition temperature of the structural transition is somewhat higher than the magnetic transition temperature [5].

By appropriate doping, it is possible to suppress the SDW and as a consequence superconductivity (SC) may arise. There are several concepts for doping. In the 122-compounds, hole doping on the alkaline earth site by substitution with potassium or sodium results in the highest superconducting transition temperature $T_c = 38\,\text{K}$ for Ba$_{0.6}$K$_{0.4}$Fe$_2$As$_2$ [6]. In the 1111-compounds, hole doping can be achieved by substituting the rare earth by an alkaline earth. For example, the substitution with Sr induces superconductivity with a maximum $T_c$ of 25 K [7]. In both types of compounds, electron doping was achieved by replacing Fe with e.g. Co [8], Ni [9], Ru [10], Pd or Rh [11] which leads to superconductivity with a maximum $T_c = 25\,\text{K}$ for BaFe$_{2-x}$Co$_x$As$_2$ [12]. By substituting the iron with cobalt in the 1111-compounds, superconductivity was obtained with transition temperatures up to 17 K [13, 14]. These atomic substitutions of an alkaline element for AE, AE for RE or iron by some other transition element of neighbor groups not only changes the electron concentration but at the same time leads to a change in unit cell volume. The effect of such a volume change alone can be observed by the application of hydrostatic pressure.

In both compounds, BaFe$_2$As$_2$ and LaFeAsO, superconductivity can be induced under high pressure, where BaFe$_2$As$_2$ reaches a maximum $T_c$ of 29 K at a pressure of 4 GPa [15] while for LaFeAsO a maximum $T_c$ of 21 K is reached at 12 GPa [10].

Similar effects might be obtained by “chemical pressure”, i.e. a change in unit cell volume by isoelectronic substitution on one of the lattice sites. Positive chemical pressure results from the substitution of As through substitution with potassium or sodium results in the highest superconducting transition temperature $T_c = 38\,\text{K}$ for Ba$_{0.6}$K$_{0.4}$Fe$_2$As$_2$ [6]. In the 1111-compounds, the substitution was predicted to cause an enhanced Fermi surface nesting and the 1111-compound with antimony is described as a candidate for higher $T_c$ values [19].
the 122-compounds no enhanced nesting is predicted [20].
For both the 1111- and 122-compounds with antimony, ex-
pected lattice parameters have been calculated [19; 20; 21].

Experimentally, it was possible to substitute the As by
Sb in the LaFeOAs compounds. With increasing Sb con-
tent, there is a decrease of the SDW and structural phase
transition temperature, however, no superconductivity is
induced [22]. To complement the investigations on the flu-
orine free 1111-compounds we have synthesized both the
lanthanum and samarium compounds.

Wang et al. reported on Sb substitution in fluorine
doped 1111-samples and found a recovery of the SDW
transition in LaFeAs$_{1-x}$Sb$_x$O$_{0.9}$F$_{0.1}$ with $x > 0.1$ [23].
In order to expand the phase diagram of the fluorine
doped system, we prepare an antimony substitution se-
ries with a fluorine content of 0.15. So far, to the best of
our knowledge, there are no experimental results avail-
able about the possibility of Sb substitution in BaFe$_{2}$As$_{2}$.
In order to compare the 1111- and 122-compounds with
respect to the influence of Sb substitution on the SDW
transition as well as on the superconducting transition we
used non-superconducting BaFe$_{2}$As$_{2}$ and superconducting
BaFe$_{1.83}$Co$_{0.17}$As$_{2}$ as parent compounds for our Sb substi-
tution experiments with the 122-compounds.

2. Materials and Methods

Due to the air sensitivity of the Ba-containing precur-
sors, all preparation steps were carried out in a glove box
filled with dry Ar-gas. The synthesis of the polycrystalline
samples was carried out in sealed quartz glass tubes under
inert atmosphere, by solid state reaction of the precur-
sors BaAs, Fe$_2$As (Alfa Aesar 99.5 %), Co$_2$As and Fe$_2$Sb,
respectively. The precursor BaAs was synthesized by a
vapour transport method. It was important that Ba and
As were not in direct contact since their highly exothermic
reaction lead to a rapid increase of vapour pressure, even
at moderate temperature, which could break the quartz
tube.

To avoid such uncontrolled reactions, Ba chunks (Alfa
Aesar 99.2 %) were kept in a corundum crucible inside
a quartz glass container while As pellets (Alfa Aesar
99.99 %) in a 1:1 molar ratio were placed underneath or
around this crucible. The tube was evacuated, sealed un-
der Ar at a pressure of 0.05 bar and heated up slowly in
a box-type furnace to 973 K. This temperature was kept
for 5 d. After the heat treatment, the As had evaporated
and quantitatively reacted with the Ba. The reaction re-
results in dark grey lumps with mean composition BaAs.
The Co$_2$As and Fe$_2$As precursors were prepared by slowly
heating stoichiometric mixtures of the elements (Fe pow-
der Grüssing 99.9%, Co powder Alfa Aesar 99.8 %, Sb shot
Alfa Aesar 99.9999 %) and keeping them at 973 K for 48 h
in an evacuated quartz capsule. In order to synthesize the
substitution series, the precursors were ground, mixed to-
gether in the appropriate ratio, pressed into pellets and
heated at a rate of 100 K h$^{-1}$ up to 1123 K under Ar at-
mosphere. After the 48 h treatment, dark grey pellets were
obtained which are reasonably stable in air.

Polycrystalline samples of 1111 compounds were ob-
tained by solid state reaction of the stoichiometric mix-
ture of REAs (RE: La, Sm), RESb, Fe$_2$O$_3$, REF$_3$ and Fe
powders. The mixture was prepared in an Ar filled glove-
box, pressed into pellets, sealed in quartz tubes with an Ar
pressure of 0.05 bar and heated in a box-type furnace with
a rate of 50 K h$^{-1}$ to 1373 K. After 48 h the furnace was
switched off and cooled down to room temperature. After
the heat treatment dark grey pellets were obtained, which
are reasonably stable in air. The rare-earth arsenide and
antimonide precursors were prepared by heat treatment of
a stoichiometric mixture of the elements at 670 K for 12 h
in an evacuated quartz tube.

The samples were characterized at room temperature
by X-ray powder diffraction using a Seifert XRD 3000
diffractometer in Bragg-Brentano geometry with CuK$_\alpha$
radiation and secondary Ge(002) monochromator. Data
was collected from 10° - 100° in steps of 0.02°. To de-
terminate the lattice parameters and the atomic positions,
we used the LeBail method and Rietveld refinement, re-
spectively. Crystal quality was tested by SEM/EDX using
a Zeiss LEO 1530 (FE-SEM with Schottky-field-emission
cathode, in-lens detector, Back Scattered Electron Detect-
or) using an accelerating voltage of 10 kV. The EDX data
was collected by an INCA Energy System from Oxford
Instruments. The temperature dependence of dc resistiv-
ity was measured with a standard four probe technique.
Small rods with a length of 5 mm and thickness of 1 mm
were cut from the pellets and four copper wires were con-
ected with conductive silver. To confirm the occurrence
of superconductivity, we used a home made magnetic ac-
susceptometer and measured the screening signal at a fre-
quency of 2.7 kHz.

3. Results

**Ba122 samples**

The powder patterns of non-superconducting cobalt-
free samples with composition BaFe$_{2}$As$_{2}$-$x$Sb$_x$ could be
well indexed with the tetragonal ThCr$_2$Si$_2$-type structure
of space-group I4/mmm. The lattice parameters of the
Sb-free samples $a = 3.9623(2)$ Å and $c = 13.024(1)$ Å agree
with the results published by Rotter et al. [4] and, judged
from powder X-ray results, the samples are single-phase.
For the antimony free sample we obtain a residual from
Rietveld refinement of $R_p = 4.49$ %. The lattice param-
ers and unit cell volume versus nominal Sb concentra-
tion of the substitution series are plotted in Fig. [4]. A slight
increase of the lattice parameters with $x$ is suggested, how-
ever, this increase is smaller than the standard deviation
of the measured values and thus cannot be taken as evi-
dence for the solubility of antimony in this structure. In
order to confirm this, we released the occupation numbers
of arsenic and antimony in the refinement. For the $x = 0$ and $x = 0.4$ samples we found no occupation of antimony at the arsenic site. There is an increase of the residual to $R_p = 10.47\%$ at $x = 0.4$. In the qualitative phase analysis we found impurity phases up to an impurity level of 20\%. We were able to identify iron arsenide and iron antimonide as well as barium silicate which appears to be a reaction product of the alkaline earth with the quartz glass ampoule.

The temperature dependent measurement of resistivity down to 4.2 K for the antimony free sample reveals a transition at 136(5) K related to the SDW transition. This transition temperature is not affected by increasing the nominal antimony content. Blue: non-superconducting samples ($y = 0$) with SDW-transition; Red: superconducting compounds ($y = 0.17$). The tiny trend of increasing lattice parameters is within the standard deviation errors and therefore no proof for a successful Sb substitution in the 122-compounds.

![Figure 1: Lattice parameters versus Sb content in BaFe$_{2+y}$Co$_{0.1}$As$_2-x$Sb$_x$. Blue: non-superconducting samples ($y = 0$) with SDW-transition; Red: superconducting compounds ($y = 0.17$). The tiny trend of increasing lattice parameters is within the standard deviation errors and therefore no proof for a successful Sb substitution in the 122-compounds.](image1)

The non-superconducting samples show two transitions at 136(5) K related to the SDW transition. This transition temperature is not affected by increasing the nominal antimony content.

![Figure 2: Lattice parameters of LaFeAs$_{1-x}$Sb$_x$O$_{1.5}$F$_y$ versus the nominal antimony content. Blue: Non-superconducting ($y = 0$) compounds; Red: superconducting ($y = 0.15$) compounds. The parameters follow Vegard’s law (see eqns. 1–4). For the non-superconducting compounds the limit of solubility lies at $x = 0.5$ and for the superconducting compounds at $x = 0.25$.](image2)

For higher nominal antimony concentrations $x > 0.5$, no homogeneous samples were obtained. The lattice parameters of the ZrCuSiAs-type phase do not increase further, instead, impurity phases appear.

For increasing antimony content following Vegard’s law at antimony contents of 0 and 0.5 with:

\[
\begin{align*}
    a &= \left[0.087(11) \cdot x + 4.040(3)\right] \text{Å} \quad (1) \\
    c &= \left[0.196(10) \cdot x + 8.737(3)\right] \text{Å} \quad (2)
\end{align*}
\]

For higher nominal antimony concentrations $x > 0.5$, no homogeneous samples were obtained. The lattice parameters of the ZrCuSiAs-type phase do not increase further, instead, impurity phases appear.

The $R_p$ factor for the antimony free sample was determined to 4.66\%, indicative for a single phase sample. The lattice parameters were $a = 4.0348(1)$ Å and $c = 8.7362(4)$ Å. The lattice parameters increase with increasing antimony content following Vegard’s law between an antimony content of 0 and 0.5 with:

\[
\begin{align*}
    a &= \left[0.146(7) \cdot x + 4.023(1)\right] \text{Å} \quad (3) \\
    c &= \left[0.32(7) \cdot x + 8.72(1)\right] \text{Å} \quad (4)
\end{align*}
\]

For higher nominal antimony concentrations $x > 0.25$, no homogeneous samples were obtained.

The non-superconducting samples show two transitions in the resistivity signal similar to those described in [5].
The first transition refers to the structural phase transition from a tetragonal to an orthorhombic structure. For the $x = 0$ sample we found the transition temperature $T_S = 160$ K. The second transition refers to the Néel temperature $T_N = 135$ K. The temperature difference between the structural and magnetic transition is constant over the investigated antimony range, thus, for the sake of simplicity, we plot the mean of the transition temperatures $(T_S + T_N)/2$ in figure 3 labelled SDW and emphasized by blue color. With higher antimony concentration, the transition temperatures decrease. Within the homogeneous range we found a minimum mean transition temperature of 100 K for $x = 0.5$ but no superconductivity down to 4.2 K. For higher Sb concentration, the semiconducting behaviour of impurities dominates the resistivity signal and it became impossible to extract transition temperatures for the LaFeAsO phase.

With a fluorine content of $y = 0.15$, the samples are superconducting. For Sb-free samples we found a transition temperature of $T_c = 9$ K which agrees with the phase diagram suggested in Oka et al. [25]. With increasing antimony content, the transition temperature increases up to a maximum $T_c$ of 28 K in the resistivity signal and 25 K in the ac susceptibility signal. The black data points in figure 4 show the mean transition temperature of our resistivity and susceptibility measurements. The additional points plotted in green and blue are taken from Wang et al. [29].

**Sm1111 samples**

When lanthanum is replaced with samarium, the cell volume of the 1111 phase is smaller. We measured $a = 3.939(5)$ Å and $c = 8.49(1)$ Å in good agreement with [26]. However, with increasing nominal antimony content, merely the impurity level increases and the crystallographic and physical properties of the 1111 phase remain constant. Thus, we conclude that there is no solubility of antimony in SmFeAs$_{1-x}$Sb$_x$O.

**4. Discussion**

The invariance of the crystallographic and physical properties in the 122-compounds against nominal Sb concentration as well as direct structure refinements prove the absence of solubility of Sb in this structure. BaFe$_2$As$_2$ has the highest unit cell volume in the class of known 122 iron arsenides. It is thus unlikely that Sb can be substituted into 122 iron pnictide compounds with smaller unit cell volume. The unit cell size of BaFe$_2$As$_2$ appears to be at the stability limit of this class of compounds.

The measured lattice parameters of the non-superconducting La1111 parent compounds agree well with the values computed in [21] or [19]. However, the slope of the linear regression with Vegard’s law differs from the measured data. In [21] the slope of $a$ is 0.1271 Å and 0.6078 Å for $c$ and in [19] it is 0.107 Å for $a$ and 0.551 Å for $c$. Our smaller slope of 0.087 Å for $a$ and 0.196 Å for $c$ may be a result of increasing disorder which was neglected in the calculation of the lattice parameters in the theoretical studies. We find that La1111 compounds show a solubility up to an antimony concentration of $x = 0.5$ in the non-superconducting compounds confirming [22] and $x = 0.25$ in the superconducting fluorine doped compounds with $y = 0.15$. Carlsson et al. found slightly larger lattice parameter for the non-superconducting Sb-substituted compounds but the same trend in the the SDW transition temperature [22]. With increasing lattice parameters, that is negative chemical pressure, the interlayer distance between the FeAs layers increases due to the larger c axis and thus the magnetic interaction is weakened. As a consequence, the SDW transition temperature decreases from 150 K for $x = 0$ to 100 K for $x = 0.5$.

With higher antimony concentration, no single phase samples were obtained. We conclude that there is a solubility limit for antimony near $x = 0.5$. In contrast to the phosphorus substituted compounds [15], we found no superconductivity in the antimony substituted compounds, in agreement with [22]. The SDW cannot be suppressed.
and superconductivity cannot emerge because of the enhanced Hund’s rule coupling discussed in [19]. The Fe d states are localized since the orbital overlap is reduced due to the larger iron-piucigen distance.

The results on the fluorine doped samples reveal an increase of the superconducting transition temperature with increasing Sb concentration. A problem is the exact determination of fluorine content. We have compared the transition temperature of our x = 0 compound with the phase diagram from [23] and find agreement with the 0.15 transition temperature of our x = 0 compound with the suggested phase diagram (blue triangle in Fig. 4). With our compounds and measurement techniques, we found a maximum Tc of 27 K in the LaFeAs1−xSb2O0.85F0.15 system. In contrast to the work of Wang et al. (green squares in Fig. 4), we found no recurrence of the SDW transition with higher antimony content. For concentrations higher than x = 0.25 we obtain no single phase compounds.

The smaller unit cell volume of the samarium compounds leads to a blockade of solubility of antimony. We found no variation of crystallographic and physical properties with nominal antimony content. Obviously, there is no solubility of antimony in the Sm1111-system.

5. Conclusion

We have investigated the solubility of Sb in some iron arsenides of the 122 and 1111 type. In the case of fluorine-free LaFeAs1−xSb2O compounds, the substitution was possible up to a solubility limit x = 0.5. The SDW transition temperature decreases with increasing Sb concentration. The solubility limit of Sb in the superconducting fluorine-doped compounds LaFeAs1−xSb2O0.85F0.15 is x = 0.25. We found a maximum Tc of 27 K at x = 0.15. No antimony substitution of arsenic was possible in the Sm1111 and the Ba122 compounds. With the application of “negative chemical pressure”, these compounds become unstable against the formation of foreign phases.

Acknowledgements

We thank M. Heider from the "Bayreuther Institut für Makromolekularchemie" for the SEM/EDX measurements. N. Kurz, L. Wehmeier and S. Wolf for their help with sample preparation and last but not least C. Kerling for the technical support in our lab.

References

[1] Y. Kamihara, T. Watanabe, M. Hirano, H. Hosono, Iron-based layered superconductor LaO1−xFexAs (x = 0.05–0.12) with Tc = 26 K, Journal of the American Chemical Society 130 (11) (2008) 3296–3297. doi:10.1021/ja800073m

[2] M. Rotter, M. Tegel, D. Johrendt, Superconductivity at 38 K in the iron arsenide Ba1−xFexAs2, Physical Review Letters 101 (10) (2008) 107006. doi:10.1103/PhysRevLett.101.107006

[3] J. H. Tapp, Z. Tang, B. Lv, K. Saasmal, B. Lorenz, P. C. W. Chu, A. M. Guloy, LiFeAs: An intrinsic FeAs-based superconductor with Tc=18 K, Physical Review B 76 (6) (2008) 060505. doi:10.1103/PhysRevB.76.060505

[4] M. Rotter, M. Tegel, D. Johrendt, I. Schellenberg, W. Hermes, R. Pöttgen, Spin-density-wave anomaly at 140 K in the ternary iron arsenide BaFe2As2, Physical Review B 78 (2) (2008) 020503. doi:10.1103/PhysRevB.78.020503

[5] H.-H. Klauss, H. Luetkens, K. Klingeler, C. Hess, F. J. Litterst, M. Kraken, M. K. Morshunov, I. Eremia, S.-L. Drechsler, R. Khasanov, A. Amato, J. Hamann-Borrero, N. Leps, A. Kon-drat, G. Behr, J. Werner, B. Büchner, Commensurate Spin Density Wave in LaFeAsO: A Local Probe Study, Physical Review Letters 101 (7) (2008) 077005. doi:10.1103/PhysRevLett.101.077005

[6] S. Aswartham, M. Abdel-Hafiez, D. Bombor, M. Kumar, A. U. B. Wolter, C. Hess, D. V. Evtushinsky, V. B. Zabolotny, A. A. Kordyuk, T. K. Kim, S. V. Borisenko, G. Behr, B. Büchner, S. Wurmehl, Hole doping in BaFe2As2: The case of Ba1−xNa2xFe2As2 single crystals, Physical Review B 85 (22) (2012) 224520. doi:10.1103/PhysRevB.85.224520

[7] H.-H. Wen, G. Mu, L. Fang, H. Yang, X. Zhu, Superconductivity in 5 K hole-doped La1−xSrxFeAsO, EPL (Europhysics Letters) 82 (1) (2008) 17009. doi:10.1209/0295-5075/82/17009

[8] A. S. Sefat, R. Jin, M. A. McGuire, B. C. Sales, D. J. Singh, D. Mandrus, Superconductivity at 22 K in Co-doped BaFe2As2 crystals, Physical Rev. Lett. 111 (11) (2013) 117004. doi:10.1103/PhysRevLett.111.117004

[9] A. S. Sefat, M. A. McGuire, R. Jin, B. C. Sales, D. Mandrus, F. Ronning, E. D. Bauer, Y. Mochizuki, Structure and anisotropic properties of BaFe2−xNi2As2 (x = 0.1 and 0.2) single crystals, Physical Review B 79 (9) (2009) 094508. doi:10.1103/PhysRevB.79.094508

[10] S. Sharma, A. Bharathí, S. Chandra, V. R. Reddy, S. Paulraj, A. T. Satya, V. S. Sastry, A. Gupta, C. S. Sundar, Superconductivity in Ru-substituted polycrystalline BaFe2−xRu2As2, Physical Review B 81 (17) (2010) 174512. doi:10.1103/PhysRevB.81.174512

[11] N. Ni, A. Thaler, A. Kracher, J. Q. Yan, S. L. Budd’ko, P. C. Canfield, Phase diagrams of Ba(Fe1−xMnx)2As2 single crystals (M = Rh and Pd), Physical Review B 80 (2) (2009) 024511. doi:10.1103/PhysRevB.80.024511

[12] X. F. Wang, T. Wu, G. Wu, W. H. Liu, H. Chen, Y. L. Xie, X. H. Chen. The peculiar physical properties and phase diagram of BaFe2−xCo2As2 single crystals, New Journal of Physics 11 (4) (2009) 045003. doi:10.1088/1367-2630/11/4/045003

[13] A. S. Sefat, A. Hung, M. A. McGuire, R. Jin, H. C. Sales, D. Mandrus, L. M. D. Cranwick, P. W. Stephens, K. H. Stone, Superconductivity in LaFe1−xCoAsO, Physical Review B 78 (10) (2008) 104505. doi:10.1103/PhysRevB.78.104505

[14] C. Wang, Y. K. Li, Z. W. Zhu, S. Jiang, Y. K. Luo, S. Chi, L. J. Li, Z. Ren, M. He, H. Chen, Y. T. Wang, Q. Tao, G. H. Cao, Z. A. Xu, Effects of cobalt doping and phase diagrams of LFe1−xCoAsO (L = La and Sm), Physical Review B 79 (5) (2009) 054521. doi:10.1103/PhysRevB.79.054521

[15] P. L. Alireza, Y. T. C. Ko, J. Gillett, C. M. Petrone, J. M. Cole, G. G. Lonzarich, S. E. Sebastian, Superconductivity up to 29 K in SrFe2As2 and BaFe2As2 at high pressures, Journal of Physics: Condensed Matter 21 (1) (2009) 012208.

[16] H. Okada, K. Igawa, H. Takahashi, Y. Kamihara, M. Hirano, H. Hosono, K. Matsubayashi, Y. Uwatoko, Superconductivity under High Pressure in LaFeAsO, Journal of the Physical Society of Japan 77 (11) (2008) 113712. doi:10.1143/JPSJ.77.113712

[17] S. Kasahara, T. Shibatsuki, K. Hashimoto, K. Ikada, S. Tonegawa, R. Okazaki, H. Shishido, H. Ikeda, H. Tateyama, K. Hirata, T. Terashima, Y. Matsuda, Evolution from non-Fermi to Fermi-liquid transport via isovalent doping in BaFe2−xFexAs2 superconductors, Physical Review B 81 (18) (2010) 184519. doi:10.1103/PhysRevB.81.184519
[18] C. Wang, S. Jiang, Q. Tao, Z. Ren, Y. Li, L. Li, C. Feng, J. Dai, G. Cao, Z.-A. Xu, Superconductivity in \( \text{LaFeAs}_{1-x}\text{P}_x\text{O} \): Effect of chemical pressures and bond covalency, EPL (Europhysics Letters) 86 (4) (2009) 47002. doi:10.1209/0295-5075/86/47002

[19] C.-Y. Moon, S. Y. Park, H. J. Choi, Enhanced spin-density wave in \( \text{LaFeSbO} \) from first principles, Physical Review B 78 (21) (2008) 212507. doi:10.1103/PhysRevB.78.212507

[20] C.-Y. Moon, S. Y. Park, H. J. Choi, Dominant role of local-moment interactions in the magnetic ordering of iron pnictide superconductors: A comparative study of arsenides and antimonides from first principles, Physical Review B 80 (5) (2009) 054522. doi:10.1103/PhysRevB.80.054522

[21] S. Lebégue, Z. P. Yin, W. E. Pickett, The delicate electronic and magnetic structure of the \( \text{LaFePnO} \) system (\( \text{Pn} = \) pnicoen), New Journal of Physics 11 (2) (2009) 025004. doi:10.1088/1367-2630/11/2/025004

[22] S. J. E. Carlsson, F. Levy-Bertrand, C. Marcenat, A. Sulpice, J. Marcus, S. Pairis, T. Klein, M. Noz-Regueiro, G. Garbarino, T. Hansen, V. Nassif, P. Toulemonde, Effect of the isoelectronic substitution of Sb for As on the magnetic and structural properties of \( \text{LaFeAs}_{1-x}\text{Sb}_x\text{O} \), Physical Review B 84 (10) (2011) 104523. doi:10.1103/PhysRevB.84.104523

[23] C. Wang, Z. Ma, S. Jiang, Y. Li, Z.-A. Xu, G. Cao, Structural and superconducting properties in \( \text{LaFeAs}_{1-x}\text{Sb}_x\text{O}_1-y\text{F}_y \), Science China Physics, Mechanics and Astronomy 53 (7) (2010) 1225–1229. arXiv: 1004.2940. doi:10.1007/s11433-010-0197-8

[24] Y. Nakajima, T. Taen, T. Tamegai, Possible Superconductivity above 25 K in Single-Crystalline Co-Doped \( \text{BaFe}_2\text{As}_2 \), Journal of the Physical Society of Japan 78 (2) (2009) 023702. doi:10.1143/JPSJ.78.023702

[25] T. Oka, Z. Li, S. Kawasaki, G. F. Chen, N. L. Wang, G.-Q. Zheng, Antiferromagnetic Spin Fluctuations above the Dome-Shaped and Full-Gap Superconducting States of \( \text{LaFeAsO}_{1-x}\text{F}_x \) Revealed by \( ^{75}\text{As} \)-Nuclear Quadrupole Resonance, Physical Review Letters 108 (4) (2012) 047001. doi:10.1103/PhysRevLett.108.047001

[26] X. H. Chen, T. Wu, G. Wu, R. H. Liu, H. Chen, D. F. Fang, Superconductivity at 43K in \( \text{SmFeAsO}_{1-y}\text{F}_y \), Nature 453 (7196) (2008) 761–762. doi:10.1038/nature07045