Superconductivity in Co-doped SmFeAsO

Yanpeng Qi, Zhaoshun Gao, Lei Wang, Dongliang Wang, Xianping Zhang and Yanwei Ma

Key Laboratory of Applied Superconductivity, Institute of Electrical Engineering, Chinese Academy of Sciences, PO Box 2703, Beijing 100190, People’s Republic of China

E-mail: ywma@mail.iee.ac.cn

Received 4 August 2008, in final form 30 August 2008
Published 25 September 2008
Online at stacks.iop.org/SUST/21/115016

Abstract

Here we report the synthesis and characterizations of SmFe$_{1-x}$Co$_x$AsO ($x = 0.10, 0.15$) for the first time. The parent compound SmFeAsO itself is not superconducting but shows an antiferromagnetic order near 150 K, which must be suppressed by doping before superconductivity emerges. With Co doping in the FeAs planes, antiferromagnetic order is destroyed and superconductivity occurs at 15.2 K. Similar to LaFe$_{1-x}$Co$_x$AsO, the SmFe$_{1-x}$Co$_x$AsO system appears to tolerate considerable disorder in the FeAs planes. This result is important, suggesting a different mechanism for cuprate superconductors compared to the iron-based arsenide ones.

(Some figures in this article are in colour only in the electronic version)

The recent discovery of high-$T_c$ superconductivity in iron pnictides has generated highly intensive research activities in solid state physics [1–9]. After the first report on LaFeAsO$_{1-x}$F$_x$ with a critical temperature $T_c$ of 26 K [1], even higher transition temperatures up to 55 K in SmFeAsO$_{1-x}$F$_x$ followed quickly, which is the first non-copper-oxide superconductor with $T_c$ exceeding 50 K. The system has attracted much attention not only for its high transition temperature but also from the point of view that many related systems can be derived by substitution of the constituent elements. The parent compound ReFeAsO (Re = rare earth element) itself is not superconducting but shows an anomaly at around 150 K; electron doping by F suppresses this anomaly and recovers the superconductivity. Theoretical calculations indicated the itinerant character of Fe 3d electrons in the iron-based superconductors [10, 11]. In order to get a deeper insight into 3d electrons and find the origin of the superconductivity, it is necessary to perform a doping experiment on the Fe site, since doping was generally performed on sites in between the Fe–As layers present, either on the Re site or on the O site in the ReFeAsO compounds. Recently, Sefat et al. reported superconductivity in Co-doping LaFeAsO [12] and BaFe$_2$As$_2$ [13]. Leithe-Jasper et al. reported superconductivity with $T_c$ up to 20 K in SrFe$_{2-x}$Co$_x$As$_2$ [14]. Despite the new insights provided by these studies, the question of high-temperature superconductivity continues to elude description by physical models. We consider that the detailed investigation of Co doping in the FeAs planes would give more important clues for understanding the mechanisms on iron-based superconductors. Here we report that superconductivity was realized by doping the magnetic element cobalt into the superconducting-active FeAs layers in SmFeAsO. The antiferromagnetic spin-density-wave transition in the parent compound was suppressed and superconductivity with $T_c \sim 15$ K was induced. This result is important, indicating an essential difference between cuprate superconductors and the iron-based arsenide ones.

The synthesis of Co-doped SmFeAsO was carried out by a one-step solid state reaction. The details of the fabrication process are described elsewhere [9]. Stoichiometric amounts of the starting elements Sm, CoO$_3$, Fe, Fe$_2$O$_3$ and As were thoroughly ground by hand and encased in pure Nb tubes. After packing, this tube was subsequently rotary swaged and sealed in an Fe tube. The sealed samples were heated at 1180°C for 45 h. High purity argon gas was allowed to flow into the furnace during the heat-treatment process. The sintered samples were obtained by breaking the Nb tube. It is noted that the sample preparation process, except for annealing, was performed in a glove box under high purity argon.

Phase identification and crystal structure investigations were carried out using x-ray diffraction (XRD) using Cu Kα radiation. Resistivity measurements were performed by the conventional four-point-probe method. The AC magnetic
The susceptibility of the samples was measured by a Quantum Design physical property measurement system (PPMS).

Figure 1 shows XRD patterns for the prepared samples. It is seen that all main peaks can be well indexed based on the ZrCuSiAs tetragonal structure, indicating that the samples are single phase. The lattice parameters are $a = 3.9412$ Å and $c = 8.4802$ Å for the sample with $x = 0.10$, while they are $a = 3.9411$ Å and $c = 8.4638$ Å for the sample with $x = 0.15$. Clearly, Co doping leads to an obvious decrease in the $c$-axis lattice while the $a$ axis remains nearly unchanged. Similar behavior is observed in LaFe$_{1-x}$Co$_x$AsO [15]. Compared to the parent compound SmFeAsO, the apparent reduction of the lattice volume upon Co doping indicates a successful chemical substitution. A small amount of impurity phases, perhaps mostly FeAsO, was also observed in the XRD patterns. Such impurity phases might be reduced by optimizing the heating process and stoichiometry ratio of the starting materials.

Figure 2 shows the temperature dependence of resistivity for SmFe$_{1-x}$Co$_x$AsO samples. As reported by Chen et al., the undoped SmFeAsO sample exhibits a clear anomaly near 150 K [2], which is ascribed to the spin-density-wave instability and structural phase transitions from tetragonal to orthorhombic symmetry. For SmFe$_{0.9}$Co$_{0.1}$AsO, the room temperature resistivity $\rho_{300}$ K = 2.6 m$\Omega$ cm: this value is much smaller than for the parent sample. As seen from figure 2, the resistivity of the $x = 0.1$ sample decreases slowly with decreasing temperature. Then the resistivity increases below 120 K, which is similar to the undoped sample. Finally, we can observe a rapid transition at the onset temperature 15.2 K, indicating the good quality of our samples. Up to 15% doping, the overall resistivity decreases obviously, while the transition temperature remains almost unchanged with different doping levels, implying the essential nature of this superconductor. Compared to SmFeAsO$_{1-x}$F$_x$, the transition temperature is significantly lower, which is likely to be due to the stronger effect of the disorder induced by doping in the FeAs layers. It is noted that the Co content for superconductivity is even smaller than the F content required, demonstrating that Co doping is effective and strongly suppresses the antiferromagnetic order.

In order to further confirm the superconductivity of SmFe$_{1-x}$Co$_x$AsO, an AC susceptibility measurement was also performed. Figure 3 shows the temperature dependence of AC magnetization for the SmFe$_{0.9}$Co$_{0.1}$AsO sample. The sample shows a good diamagnetic signal. The onset critical temperature is 14.2 K, which corresponds well to the middle transition point of resistance. The sharp magnetic transitions of the AC curves suggest the good quality of our superconducting samples.

It is very interesting that superconductivity was realized by doping the magnetic element cobalt into the superconducting-active FeAs layers, which would give more important clues for understanding the mechanism of iron-based superconductivity. Firstly, it is surprising that superconductivity is induced by Co doping, which challenges our previous understanding of superconductivity theory. It is known that there are a lot of examples in which superconductivity occurred by chemical substitution, such as Ba-doped La$_2$CuO$_4$ [16], K-doped BaBiO$_3$ [17], F-doped ReFeAsO [1], K-doped BaFe$_2$As$_2$ [18], etc. It should be noted that all the above
dopants are non-magnetic, since superconductivity is not compatible with magnetism and magnetic atoms generally break superconducting Cooper pairs. However, cobalt is a typical magnetic element and the evidence of Co-doping-induced superconductivity is contrary to all previous assumptions about the competition between superconductivity and magnetic moments. Therefore, there should be some underlying mechanisms we cannot understand completely at present. Secondly, the Fe–As layer is usually thought to be responsible for superconductivity and the Re–O layer is a carrier reservoir layer to provide electron carriers in ReFeAsO compounds. Similar to the cuprate superconductors, superconductivity can also be induced by charge doping from a reservoir layer in ReFeAsO compounds. In addition, Fe and Cu are both 3d elements, so an analogy between the high-temperature superconductor in the cuprates and the iron arsenide layer compounds was suggested by large numbers of reports [12–15]. However, recently superconductivity was induced by Co doping in LaFeAsO [12] and SrFe2As2 [14] and here we report that superconductivity occurred in SmFeAsO compounds by substitution of Co for Fe. The relatively high \( T_c \) occurrence by doping in the FeAs conducting layers clearly demonstrates that the in-plane disorder is highly tolerated in SmFeAsO compounds. This result is different from cuprate superconductors, in which superconductivity is always damaged by doping in the CuO2 planes, thus further demonstrating that an analogy with high-temperature superconductivity in the cuprates is not appropriate. Therefore the model and mechanism of two classes of high-temperature superconductors should be different. To investigate the origin of this behavior, further experimental and theoretical studies are required.

To summarize, we have successfully synthesized the iron-based Co-doped layered compound SmFe\(_{1-x}\)Co\(_x\)AsO by a one-step solid state reaction method. Co doping is effective and superconductivity is observed at 15.2 K. Similar to LaFe\(_{1-x}\)Co\(_x\)AsO, the SmFeAsO system appears to tolerate considerable disorder in the FeAs planes, suggesting the difference between cuprates and the iron-based arsenide ones. Our data demonstrates that an analogy between the high-temperature superconductor in the cuprates and in the iron arsenide layer compounds is not really appropriate. Co doping in the FeAs planes is interesting, which would give us important clues for understanding the mechanisms in iron-based superconductors.

Acknowledgments

The authors thank Professors Haihu Wen, Liye Xiao and Liangzhen Lin for their help and useful discussions. This work is partially supported by the Beijing Municipal Science and Technology Commission under grant no. Z07000300700703, the National ‘973’ Program (grant no. 2006CB601004) and the National ‘863’ Project (grant no. 2006AA03Z203).

References

[1] Kamihara Y, Watanabe T, Hirano M and Hosono H 2008 J. Am. Chem. Soc. 130 3296

[2] Chen X H, Wu T, Wu G, Liu R H, Chen H and Fang D F 2008 Nature 453 376

[3] Wen H H, Mu G, Fang L, Yang H and Zhu X 2008 Europhys. Lett. 82 17009

[4] Chen G F, Li Z, Wu D, Li G, Hu W Z, Dong J, Zheng P, Luo J L and Wang N L 2008 arXiv:0803.3790 [cond-mat]

[5] Ren Z A, Yang J, Lu W, Yi W, Che G C, Dong X L, Sun L L and Zhao Z X 2008 arXiv:0803.4283 [cond-mat]

[6] Ren Z A et al 2008 Europhys. Lett. 82 57002

[7] Ren Z A et al 2008 Chin. Phys. Lett. 25 2215

[8] Cheng P, Fang L, Yang H, Zhu X Y, Mu G, Luo H Q, Wang Z S and Wen H H 2008 Sci. China G 51 719

[9] Ma Y W, Gao Z S, Wang L, Qi Y P, Wang D L and Zhang X P 2008 arXiv:0806.2839 [cond-mat]

[10] Singh D J and Du M H 2008 Phys. Rev. Lett. 100 237003

[11] Haule K, Shim J H and Kotliar G 2008 Phys. Rev. Lett. 100 226402

[12] Sefat A S, Huq A, McGuire M A, Jin R Y, Sales B C, Mandrus D, Cranwrick L M D, Stephens P W and Stone K H 2008 arXiv:0807.0823 [cond-mat]

[13] Sefat A S, McGuire M A, Jin R Y, Sales B C and Mandrus D 2008 arXiv:0807.2237 [cond-mat]

[14] Leithe-Jasper A, Schnelle W, Geibel C and Rosner H 2008 arXiv:0807.2223 [cond-mat]

[15] Wang C, Zhu Z W, Jiang S, Chi S, Luo Y K, Ren Z, Tao Q, Wang Y T, Cao G H and Xu Z A 2008 arXiv:0807.1304 [cond-mat]

[16] Bednorz J G and Muller K A 1986 Z. Phys. B 64 189

[17] Cava R J, Batlogg B, Krajewski J J, Farrow R, Rupp L W, White A E, Short K, Peck W F and Kometani T 1988 Nature 332 814

[18] Rotter M, Tegel M and Johrendt D 2008 arXiv:0805.4630 [cond-mat]