Chemical pressure effect on $T_c$ in BiS$_2$-based Ce$_{1-x}$Nd$_x$O$_{0.5}$F$_{0.5}$BiS$_2$

Joe Kajitani, Atsushi Omachi, Takafumi Hiroi, Osuke Miura, Yoshikazu Mizuguchi

Tokyo Metropolitan University, 1-1, Minami-Osawa, Hachioji, Tokyo 192-0397, Japan

Abstract

We have investigated the crystal structure and superconducting properties of the BiS$_2$-based layered superconductor Ce$_{1-x}$Nd$_x$O$_{0.5}$F$_{0.5}$BiS$_2$. Bulk superconductivity was observed for $x \geq 0.4$, and the transition temperature was enhanced with increasing Nd concentration. The highest transition temperature was 4.8 K for $x = 1.0$. With increasing Nd concentration, the length of the $a$ axis decreased, while the length of the $c$ axis did not show a remarkable change. The chemical pressure along the $a$ axis upon Nd substitution seemed to be linked with the inducement of bulk superconductivity. We found that the chemical pressure effect did not completely correspond to the external pressure effect.

Keywords: BiS$_2$-based superconductor; chemical pressure effect
1. Introduction

Layered materials have been actively studied in the field of superconductivity because superconductors with unconventional paring mechanisms and/or high transition temperature ($T_c$) had been discovered in layered crystal structures. Recently, we have reported superconductivity in several layered materials possessing a BiS$_2$-type superconducting layer [1,2]. The crystal structure composed of an alternate stacking of the BiS$_2$ superconducting layers and blocking layers is quite similar to those of the Cu-oxide and Fe-based superconductors. So far, three types of BiS$_2$-based materials, Bi$_2$O$_3$S$_3$, REOBiS$_2$ family (RE = La, Ce, Pr, Nd, Yb) and SrFBiS$_2$, have found to become superconducting upon electron doping into the Bi-$6p$ orbitals within the BiS$_2$ layers [1-9]. Electrical resistivity measurements under high pressure revealed that the $T_c$ of BiS$_2$-based family was sensitive to application of pressure and can be significantly enhanced [10-12] as observed in the Fe-based family [13].

In the CeOBiS$_2$, bulk superconductivity has not appeared under ambient pressure, but appeared under high pressure with $T_c$ of 8 K. While in the NdOBiS$_2$, the bulk superconductivity has appeared under ambient pressure with $T_c$ of ~5 K. These facts indicate that the superconducting properties of BiS$_2$-based family depend on both the applied pressure and the structure of the blocking layer. In this article, we have investigated the crystal structure and superconducting properties of Ce$_{1-x}$Nd$_x$O$_{0.5}$F$_{0.5}$BiS$_2$ synthesized to clarify chemical pressure effect on $T_c$ of the REOBiS$_2$ family.

2. Experimental

The polycrystalline samples of Ce$_{1-x}$Nd$_x$O$_{0.5}$F$_{0.5}$BiS$_2$ ($x = 0.0 - 1.0$) were prepared by a solid-state reaction method. Bi grains, Ce$_2$S$_3$ powder, Nd$_2$S$_3$ powder, BiF$_3$ powder, Bi$_2$O$_3$ powder and Bi$_2$S$_3$ powder were used as the starting materials. The Bi$_2$S$_3$ powder was synthesized by a direct reaction of Bi grains and S grains at 500 °C in an evacuated quartz tube. Other chemicals were purchased from Kojundo-Kagaku laboratory. The mixture of the starting materials with compositions of Ce$_{1-x}$Nd$_x$O$_{0.5}$F$_{0.5}$BiS$_2$ ($x = 0.0 - 1.0$) was well-mixed, pelletized and sealed into an evacuated quartz tube. The Ce$_{1-x}$Nd$_x$O$_{0.5}$F$_{0.5}$BiS$_2$ pellets were heated at 700 °C for 10h. The obtained products were ground, sealed into an evacuated quartz tube and heated again with the same heating conditions to homogenize the samples. The obtained samples were characterized by X-ray diffraction using the $\theta$-2$\theta$ method. Changes in the lattice volume were discussed with the peak shifts. The temperature dependence of magnetization was measured by a superconducting quantum interface device (SQUID) magnetometer with an applied field of 5 Oe after both zero-field cooling (ZFC) and field cooling (FC).

3. Results and discussion

Figure 1 (a) shows the crystal structure of REOBiS$_2$ (RE = Ce, Nd). The X-ray diffraction pattern for the Ce$_{1-x}$Nd$_x$O$_{0.5}$F$_{0.5}$BiS$_2$ samples is displayed in Fig. 1(b). Almost all of the obtained peaks were explained using the tetragonal $P4/mmm$ space group. The profiles exhibit quite similar tendency upon Nd substitution except for the slight differences in peak shifts corresponding to the lattice contraction. The estimated peak positions of the (200) and (004) peaks are plotted in Figure 2. The shift of the (200) peak to a higher angle corresponds to the shrinkage of the $a$ axis, while that of (004) peak corresponds to the shrinkage of the $c$ axis. Therefore, in this system, the $a$ axis decreases with increasing Nd concentration, while $c$ axis does not show a remarkable dependence on Nd concentration. Figure 3 (a) shows the temperature dependence of magnetic susceptibility for Ce$_{1-x}$Nd$_x$O$_{0.5}$F$_{0.5}$BiS$_2$. Figure 3(b) shows the Nd concentration dependence of the transition temperature ($T_c$) for Ce$_{1-x}$Nd$_x$O$_{0.5}$F$_{0.5}$BiS$_2$ estimated from the magnetization measurements. Superconductivity is observed for $x \geq 0.4$. The transition temperature ($T_c$) is defined as a temperature at which the magnetic susceptibility begins to decrease. The $T_c$ increases with increasing Nd concentration and reach 4.8 K for $x = 1.0$, NdO$_{0.5}$F$_{0.5}$BiS$_2$. 

2
The chemical pressure effect induces the lattice shrinkage along the $a$ axis. Bulk superconductivity is observed for $x \geq 0.4$ where the $a$ axis is significantly decreased. The contraction of the $a$ axis seems to be linked with the appearance of superconductivity in the Ce$_{1-x}$Nd$_x$O$_{0.5}$F$_{0.5}$BiS$_2$ system. However, the obtained $T_c$ is clearly lower than that observed in the external pressure studies on $T_c$ of CeO$_{1-x}$F$_x$BiS$_2$. The pressure dependence of $T_c$ in CeO$_{0.5}$F$_{0.5}$BiS$_2$ shows a transition-like behavior and exceeds 6 K under high pressure above 2.61 GPa [11]. In fact, the chemical pressure effect on $T_c$ in CeO$_{0.5}$F$_{0.5}$BiS$_2$ does not completely correspond to the external pressure effect. Therefore, further increase of $T_c$ at ambient pressure in the Ce$_{1-x}$Nd$_x$O$_{0.5}$F$_{0.5}$BiS$_2$ system should require optimization of some crystal structure parameters other than the simple contraction of the $a$ axis.

4. Conclusion

In this study, we have systematically synthesized the Ce$_{1-x}$Nd$_x$O$_{0.5}$F$_{0.5}$BiS$_2$ polycrystalline samples, and investigated the crystal structure and superconducting properties. On the basis of systematic investigation on the lattice contraction and the susceptibility, we found that chemical pressure effect induced lattice shrinkage along the $a$ axis. Bulk superconductivity was observed for $x \geq 0.4$, and the transition temperature was enhanced with increasing Nd concentration. In this system, the chemical pressure along the $a$ axis upon Nd substitution seemed to be linked with the inducement of bulk superconductivity. However, the chemical pressure effect on $T_c$ in CeO$_{0.5}$F$_{0.5}$BiS$_2$ does not completely correspond to the external pressure effect. To clarify the detailed correlation between superconductivity and crystal structure, studies using single crystals are required.

Acknowledgement

This work was partly supported by a Grant-in-Aid for Scientific Research for Young Scientists (A) and The Thermal and Electric Energy Technology Foundation.

References

[1] Mizuguchi Y, Fujihisa H, Gotoh Y, Suzuki K, Usui H, Kuroki K, Demura S, Takano Y, Izawa H, Miura O. BiS$_2$-based layered superconductor Bi$_2$O$_3$S$_2$. Phys. Rev. B 2012;86:220510(1-5).
[2] Mizuguchi Y, Demura S, Deguchi K, Takano Y, Fujihisa H, Gotoh Y, Izawa H, Miura O. Superconductivity in novel BiS$_2$-based layered superconductor LaO$_{1.25}$F$_{0.75}$BiS$_2$. J. Phys. Soc. Jpn. 2012;81:114725(1-5).
[3] Demura S, Mizuguchi Y, Deguchi K, Okazaki H, Hara H, Watanabe T, Denholme SJ, Fujioka M, Ozaki T, Fujihisa H, Gotoh Y, Miura O, Yamaguchi T, Takeya H, Takano Y. New Member of BiS$_2$-Based Superconductor NdO$_{1.85}$F$_{0.15}$BiS$_2$. J. Phys. Soc. Jpn. 2013;82:033708(1-3).
[4] Xing J, Li S, Ding X, Yang H, Wen HH. Superconductivity appears in the vicinity of semiconducting-like behavior in CeO$_{1-x}$F$_x$BiS$_2$. Phys. Rev. B 2012;86:214518(1-5).
[5] Jha R, Kumar A, Singh SK, Awana VPS. Synthesis and Superconductivity of New BiS$_2$ Based Superconductor PrO$_{0.5}$F$_{0.5}$BiS$_2$. J. Sup. Novel Mag. 2013;26:499-502.
[6] Yazici D, Huang K, White BD, Chang AH, Friedman AJ, Maple MB. Superconductivity of F-substituted LnOBiS$_2$ (Ln = La, Ce, Pr, Nd, Yb) compounds. Philosophical Magazine 2012;93:673-680.
[7] Lei H, Wang K, Abeykoon M, Bozni ES, Petrovic C. New Layered Fluorosulfide SrFBiS$_2$. Inorg. Chem. 2013;52:10685-10689.
[8] Lin X, Ni X, Chen B, Xu X, Yang X, Dai J, Li Y, Yang X, Luo Y, Tao Q, Cao G, Xu Z. Superconductivity induced by La doping in Sr$_{1-x}$La$_x$F$_2$BiS$_2$. Phys. Rev. B. 2013;87:020504(1-4).
[9] Yazici D, Huang K, White BD, Jeon I, Burnett VW, Friedman AJ, Lum IK, Nallaiyan M, Spagna S, Maple MB. Superconductivity induced by electron doping in La1-xMxBiS2 (M = Ti, Zr, Hf, Th). Phys. Rev. B 2013;87:174512(1-8).

[10] Kotegawa H, Tomita Y, Tou H, Izawa H, Mizuguchi Y, Miura O, Demura S, Deguchi K, Takano Y. Pressure Study of BiS2-Based Superconductors Bi4O3S3 and La(O,F)BiS2. J. Phys. Soc. Jpn. 2012;81:103702(1-4).

[11] Wolowiec CT, Yazici D, White B. D, Huang K, Maple MB. Pressure-induced enhancement of superconductivity and suppression of semiconducting behavior in LnO0.5F0.5BiS2 (Ln=La,Ce) compounds. Phys. Rev. B. 2013;88:064503(1-8).

[12] Tomita T, Ebata M, Soeda H, Takahashi H, Fujihisa H, Gotoh Y, Mizuguchi Y, Izawa H, Miura O, Demura S, Deguchi K, Takano Y. Pressure-induced Enhancement of Superconductivity in BiS2-layered LaO1.3F3BiS2. arXiv:1309.4250.
Figure 1. (a) Crystal structure of REOBiS$_2$ (RE = Ce, Nd). (b) X-ray diffraction pattern for $\text{Ce}_{1-x}\text{Nd}_x\text{O}_{0.5}\text{F}_{0.5}\text{BiS}_2$. The numbers indicate Miller indices.

Figure 2. Nd concentration dependence of the peak positions of the (a) (200) and (b) (004) peaks.
Figure 3. (a) Temperature dependence of magnetic susceptibility for Ce$_{1-x}$Nd$_x$O$_{0.5}$F$_{0.5}$BiS$_2$. (b) Nd concentration dependence of the transition temperature ($T_c$) for Ce$_{1-x}$Nd$_x$O$_{0.5}$F$_{0.5}$BiS$_2$. 