Hall effect in superconducting $Fe(Se_{0.5}Te_{0.5})$ thin films

I. Tsukada,[1,3,*] M. Hanawa,[1,3] Seiki Komiya,[1,3] T. Akiike,[2,3] R. Tanaka,[2,3] Y. Imai,[2,3] and A. Maeda[2,3]
[1]*Central Research Institute of Electric Power Industry, 2-6-1 Nagasaka, Yokosuka, Kanagawa 240-0196, Japan*
[2]*Department of Basic Science, The University of Tokyo, 3-8-1 Komaba, Meguro-ku, Tokyo 153-8902, Japan*
[3]*JST, TRIP, Sanbancho, Chiyoda-ku, Tokyo 102-0075, Japan*
(Received 28 October 2009; revised manuscript received 5 January 2010; published 22 February 2010; corrected 8 March 2010)

The Hall effect is investigated for eight superconducting $Fe(Se_{0.5}Te_{0.5})$ thin films grown on MgO and $LaSrAlO_4$ substrates with different transition temperatures (T_c). The normal Hall coefficients (R_H) have positive values with magnitude of $1\sim1.5\times10^{-3}$ cm^3/C at room temperature for the all samples. With decreasing temperature, we find two characteristic types of behavior in $R_H(T)$ depending on T_c. For thin films with lower T_c (typically $T_c<5$ K), R_H start decreasing approximately below $T=250$ K toward a negative side, some of which shows sign reversal at $T=50\sim60$ K, but turns positive toward $T=0$ K. On the other hand, for the films with higher T_c (typically $T_c>9$ K), R_H leaves almost unchanged down to $T\approx100$ K, and then starts decreasing toward a negative side. Around the temperatures when R_H changes its sign from positive to negative, obvious nonlinearity is observed in the field-dependence of Hall resistance as to keep the low-field R_H positive while the high-field R_H negative. Thus, the electronic state just above T_c is characterized by n_e (electron density) $>n_h$ (hole density) with keeping $\mu_e<\mu_h$. These results suggest the dominance of electron density to the hole density is an essential factor for the occurrence of superconductivity in Fe-chalcogenide superconductors.

DOI: 10.1103/PhysRevB.81.054515 PACS number(s): 74.78.−w, 74.25.F−, 74.62.Dh, 74.70.Dd

The discovery of superconductivity in iron oxypnictides[1] opened routes for exploration of high-temperature (high-T_c) superconductors other than cuprates. Triggered by the discovery of $LaFeAs(O_{1-x}F_x)$,[1] a tremendous number of studies were very quickly undertaken on these materials. The presence of superconductivity in Fe-based binary compounds, FeSe,[2,3] is surprising, because the T_c of a FeSe system exceeds 36 K under high pressure despite its simple crystal structure,[4] which is comparable to MgB_2, another binary compound superconductor. Interestingly, FeSe had already been investigated in detail, but for its properties as a ferromagnetic semiconductors. According to the first investigation by Feng *et al.*,[5] and by several other related works,[6–8] the transport properties of FeSe have been summarized in the following four characteristic features. First, a majority of the charge carriers at room temperature are holes, and the resistivity decreases with increasing hole concentrations. Second, spontaneous magnetization is present at room temperatures. Third, band calculations suggest the coexistence of hole- and electron-type carriers at room temperature. Finally, sign reversal of the Hall coefficient R_H occurs below 100 K when the material is doped sufficiently with holes. However, the relationship between these normal-state electronic properties and the superconducting properties of these materials has not yet been clarified.

One of the features that make Fe-based superconductors exotic is its paring symmetry as was first proposed for $LaFeAs(O_{1-x}F_x)$ by Mazin *et al.*,[9] and Kuroki *et al.*,[10] which requires (π,π) nesting of the Fermi surface. However, for the FeSe system, it remains a point of argument whether (π,π) nesting[11,12] or another $(\pi,0)$ nesting[13] is responsible for the formation of Cooper pairs. This controversy gathers our attention and leads us to an important question whether the Fe-pnictides and Fe-chalcogenide is essentially the same sumperconductor, or not. To resolve this it is important to quantitatively investigate the electronic transport properties in the relation to the superconductivity. Recently, we succeeded in growing superconducting $Fe(Se_{0.5}Te_{0.5})$ thin films on MgO and $LaSrAlO_4$ (LSAO) substrates,[14] in which we found that a choice of substrates was crucial for the growth of Fe(Se,Te) films. The strong substrates dependence has been also discussed with respect to an epitaxial strain in previous works on FeSe and Fe(Se,Te) thin films.[15–21] In this paper, we report the results of detailed Hall-effect measurements on several $Fe(Se_{0.5}Te_{0.5})$ thin films with different T_c's, conducted in order to obtain deeper insight into the electronic states of this material, and to investigate potential routes toward a higher T_c. We confirm the coexistence of electrons and holes first, and, in addition, we find (1) that there is an intimate relation between the temperature dependence of R_H and T_c, and (2) that the electronic state just above T_c is characterized by n_e (electron density) $>n_h$ (hole density) with keeping $\mu_e<\mu_h$.

$Fe(Se_{0.5}Te_{0.5})$ films highly oriented along the c axis were grown by pulsed-laser deposition (PLD) as described elsewhere.[14] We prepared eight thin-film samples for the Hall-effect measurements. Detailed specifications of the films are summarized in Table I. Six films were prepared from a stoichiometric $FeSe_{0.5}Te_{0.5}$ sintered target, and two were prepared from a $FeSe_{0.5}Te_{0.75}$ target containing excess Te. We prepared two films simultaneously during each deposition, one on MgO(100) and the other on $LaSrAlO_4(001)$ in order to purely extract the substrate dependence. Samples A and D, B and E, C and F, and G and H were each grown in the same deposition process. All of the films were deposited in a six-terminal shape using a metal mask appropriate for both resistivity and Hall-effect measurements. The crystal structure was investigated by an ordinary θ-2θ x-ray diffraction. Thicknesses of the films were estimated by Dektak 6M stylus profiler. Resistivity and Hall-effect measurements were obtained using PPMS for temperatures down to $T=2$ K.

TABLE I. Specifications of the $Fe(Se_{1-x}Te_x)$ films.

Name	Substrate	Target	T_c (K)	Thickness (nm)	c-axis length (Å)	Se/Te ratio
Sample A	MgO(100)	$FeSe_{0.5}Te_{0.5}$	9.2	55	5.92	0.668/0.332
Sample B	MgO(100)	$FeSe_{0.5}Te_{0.5}$	8.8	164	5.90	
Sample C	MgO(100)	$FeSe_{0.5}Te_{0.5}$	4.6	135	5.86	
Sample D	$LaSrAlO_4$(001)	$FeSe_{0.5}Te_{0.5}$	<2	80	5.79	0.666/0.334
Sample E	$LaSrAlO_4$(001)	$FeSe_{0.5}Te_{0.5}$	2.0	250	5.88	
Sample F	$LaSrAlO_4$(001)	$FeSe_{0.5}Te_{0.5}$	<2	190	5.84	
Sample G	MgO(100)	$FeSe_{0.5}Te_{0.75}$	9.4	212	5.93	0.588/0.412
Sample H	$LaSrAlO_4$(001)	$FeSe_{0.5}Te_{0.75}$	3.4	348	5.90	0.552/0.448

All the films shown in this paper have a highly c-axis oriented structure in common, while their c-axis length is a little bit scattered. As was shown in our previous paper[14] and is summarized again in Table I, the c-axis length of the prepared films spreads out from 5.79 to 5.93 Å, which are shorter than that reported for polycrystalline samples.[22] Thus, we suspected that the chemical composition of the films was deviated largely from that of the target, and carried out an EDX measurement to the selected films. The obtained results of Se/Te ratio is shown in Table I for samples A, D, G, and H. The Se content is richer than that of Te in common, which is probably the main reason for the observed short c-axis lengths. This tendency is also consistent with the fact that we obtain the films with more Te content when using the $FeSe_{0.50}Te_{0.75}$ target (compare samples A and G, for example). Such a deviation of the chemical composition between targets and films is probably due to the difference of the vapor pressure of Se and Te, which become crucial in the thin-film growth process using high-vacuum conditions like our PLD method. However, it should be also emphasized that the Se/Te ratio is not different much between the films prepared at the same time (compare samples A and D, for example). This means that the observed differences between the films on MgO and those on $LaSrAlO_4$ substrates are not caused by the difference of the Se/Te ratio, but rather by the difference of substrate materials. A more comprehensive investigation of the crystalline structure using four-circle x-ray diffractomator and transmission electron microscopy (TEM) is necessary for revealing how the substrate gives influence to $Fe(Se_{0.5}Te_{0.5})$ on it.

Figure 1 shows the temperature dependence of the resistivity for the eight samples. The resistivity at room temperatures are spread only within 450 and 700 $m\Omega$ cm, which is sufficiently low for metallic (and superconducting) behavior. However, we find that $\rho(T)$ may be classified into three groups from the measurements down to $T=2$ K. Figure 1(a) represents the most metallic group (samples A and G), which exhibits crossover from semiconducting ($d\rho/dT<0$) to metallic ($d\rho/dT>0$) behavior with decreasing temperature. T_c exceeds 9 K, which is the highest such value among all the films. The second group represents an "intermediate" group (samples B, C, D, and H) and is illustrated in Fig. 1(b). This group is also characterized by $d\rho/dT>0$ at intermediate temperatures, but the slope turns again to $d\rho/dT<0$ before the transition to superconductivity. The samples in this group also exhibit lower T_c than those in the first group. The third group (samples E and F) is the most insulating group [Fig.

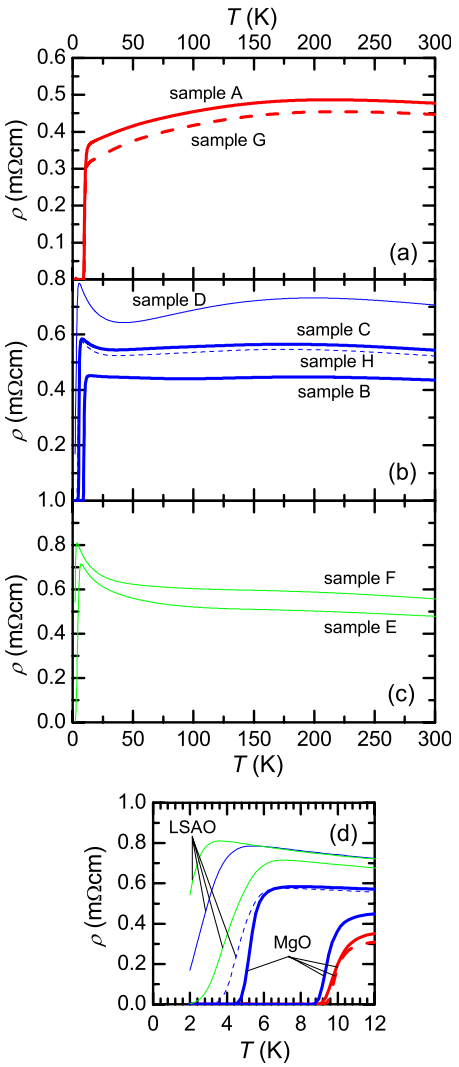

FIG. 1. (Color online) Temperature dependence of resistivity of (a) samples A and G (red line), (b) samples B, C, D, and H (blue line), and (c) samples E and F (green line). Thick and thin lines are for the films grown on MgO and $LaSrAlO_4$, respectively. (d) $\rho(T)$ around T_c regions.

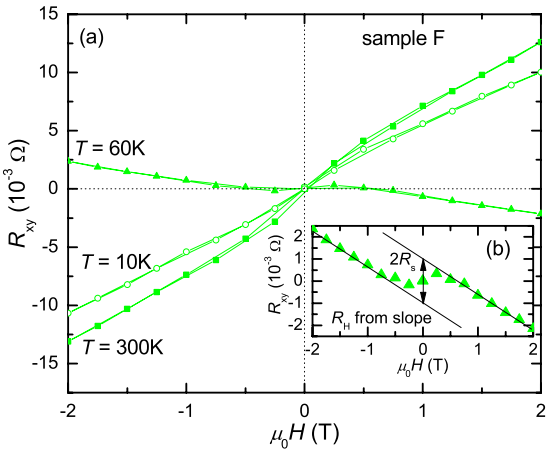

FIG. 2. (Color online) (a) Hall resistance (R_{xy}) of sample F measured by sweeping field as $\mu_0 H = 0 \rightarrow 2 \rightarrow -2 \rightarrow 0$ T taken at $T = 300$, 60, and 10 K. (b) The close-up figure of $T = 60$ K data.

1(c)], as it never exhibits metallic ($d\rho/dT > 0$) behavior. As shown in Fig. 1(d), all the films become superconducting even though this state is not observed for $T \geq 2$ K for samples D and F.

For the evaluation of R_H, we first need to measure transverse resistance R_{xy} by sweeping the magnetic field, because the presence of the anomalous Hall effect (AHE) (Ref. 23) has already been reported for FeSe by Feng *et al.*[5] An example of the typical behavior is shown for sample F in Fig. 2(a). We sweep the magnetic field from $\mu_0 H = 0 \rightarrow 2 \rightarrow -2 \rightarrow 0$ T, and observed that R_{xy} showed a steplike behavior around the $H = 0$ T indicating a contribution from the AHE. Thus, it is likely that the present Fe($Se_{0.5}Te_{0.5}$) thin films has spontaneous magnetization, although we cannot measure the magnetization due to the insufficient sample volume. R_{xy} is expressed as the sum of a normal Hall term ($R_H B$) and an anomalous Hall term ($R_s \mu_0 M$). A steep increase in R_{xy} is only observed between -0.5 T $< \mu_0 H < 0.5$ T [Fig. 2(b)], so we reasonably determine R_H by linearly fitting of R_{xy} vs $\mu_0 H$ between -2 T $< \mu_0 H < -1$ T. Figure 2(a) also shows that $R_H > 0$ at $T = 300$ K, that $R_H < 0$ at $T = 60$ K, and that $R_H > 0$ at $T = 10$ K. It should be noted that the sign of R_s is not influenced by the sign reversals of R_H. Although we do not further discuss the detailed T dependence of R_s in this paper, R_s appears roughly proportional to $\rho(T)$ and/or $\rho^2(T)$, which is consistent with conventional scenarios of skew scattering effect and/or side jump effects.[24]

After removing the contribution associated with AHE, we plot R_H in the weak-field limit for all samples as shown in Fig. 3. R_H is almost independent of T around room temperature, and has a value between $1 \sim 1.5 \times 10^{-3}$ cm^3/C. This is consistent with the value reported by Feng and co-workers,[5,6] but it is half of the value reported by Wu *et al.*[15] The most metallic group of the samples maintains a nearly constant R_H down to 100 K. Below this temperature, R_H starts decreasing. We observe sign reversal only once for both samples A and G. It is surprising that these samples show almost identical $R_H(T)$ and also $\rho(T)$, even though they were prepared from different targets. This suggests the existence of a close correlation between ρ and R_H. The T dependence observed here

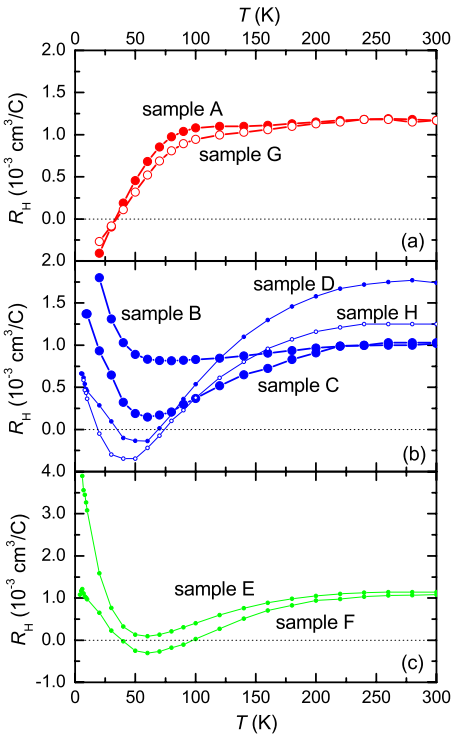

FIG. 3. (Color online) Temperature dependence of weak-field normal Hall coefficients of Fe($Se_{0.5}Te_{0.5}$) thin films of (a) samples A and G (red line), (b) samples B, C, D, and H (blue line), and (c) samples E and F (green line). Thick and thin lines are for the film grown on MgO and $LaSrAlO_4$, respectively.

is similar to that observed for Fe($Se_{0.5}Te_{0.5}$) thin films by Wu *et al.*,[15] in which the author claimed that the sign reversal is strong evidence of the multiband nature of the band structure. Figures 3(b) and 3(c) show the R_H value of the samples belonging to the second and the third groups, as a function of temperature. These R_H values typically become more positive at low temperatures. This suggests that the normal-state transport properties for $T \gtrapprox T_c$ are dominated by holetype conduction, which is a clear contrast to the behavior observed in samples A and G.

The temperature-dependent results suggest a finite correlation between the localization behavior of $\rho(T)$ and the upturn in R_H. The samples with T_c less than 5 K exhibit a gradual decrease of R_H with decreasing temperature starting from $T = 250$ K. R_H decreases continuously until a temperature of 60 K is reached, it attains its minimum regardless of its sign being positive or negative, and finally turns increasing again to the positive side toward T_c. The upturn in R_H toward $T = 0$ K is observed in samples C, D, E, F, and H while neither samples A nor G show such increase, which may allow us to relate the presence of this upturn to relatively low T_c. However, it should be noted that such an upturn toward T_c is also observed in sample B that shows $T_c = 8.8$ K as high as that of samples A and G, and we cannot say that $R_H(T)$ behavior at $T \gtrapprox T_c$ and its sign just above T_c is not directly related to T_c. Instead, we can find more robust correlation between R_H and T_c. Let us see $R_H(T)$ of sample B again. Despite a strong upturn of R_H in sample B below

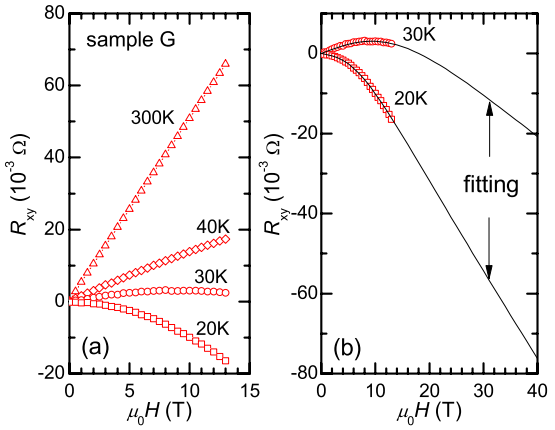

FIG. 4. (Color online) (a) High-field R_{xy} of sample G at $T=300$, 40, 30, and 20 K. The nonlinearity to H becomes enhanced at $T=30$ and 20 K as a signature of coexistence of p- and n-type carriers. (b) Fitting with Eq. (1) to the $T=30$ and 20 K data.

60 K, R_H looks almost independent of temperature between 100 K$<T<$250 K similar to that observed in samples A and G. Thus, we should conclude that a strong correlation exists between T_c and the T dependence of R_H below 250 K.

In order to further explore the normal-state transport properties of FeSe system, we need to explicitly treat the motion of electron- and holetype carriers. Fortunately, there are several band calculations in the literature for the FeSe system, and based on these, it has been accepted that, at least, four bands which originate from different Fe 3d orbital cross the Fermi level.[11,12] Two of these contribute holetype conduction, and the other two contribute electrontype conduction. To minimize complexity, we do not consider all four of these bands, at once. Instead, we apply a simplified two-carrier model including one electron band (with electron density n_e and mobility μ_e) and one holetype band (with hole density n_h and mobility μ_h), and from this try to extract phenomenological but essential behavior of $R_H(T)$. Since we do not know a mathematical expression of R_H suitable for two-dimensional cylindrical Fermi surfaces, we borrow a classical expression for the Hall coefficient of three-dimensional isotropic semiconductors in the presence of both electron- and holetype carriers:[25]

$$R_H = \frac{1}{e}\frac{(n_h - n_e b^2) + b^2\mu_h^2 B^2(n_h - n_e)}{(bn_e + n_h)^2 + b^2\mu_h^2 B^2(n_h - n_e)^2}, \quad (1)$$

where $b=\mu_e/\mu_h$, and B is a magnetic flux density. This equation predicts immediately a nonlinear dependence of R_{xy} ($=R_H B$) on applied field, which can be observed at field of several Tesla depending on the coefficients in the equation.

The fitting of R_{xy} is most successfully performed for sample G. To see how the sign change occurs in R_H, we plot R_{xy} by sweeping the field up to $\mu_0 H=13$ T [Fig. 4(a)]. Equation (1) predicts that $R_H=e^{-1}\cdot(n_h\mu_h^2-n_e\mu_e^2)/(n_e\mu_e+n_h\mu_h)^2$ in the limit of $B=0$, while $R_H=e^{-1}\times 1/(n_h-n_e)$ in the limit of $B=\infty$. At $T=300$ K, R_H looks almost linear in H, indicating the holetype transport is dominant. Furthermore, it is likely that holetype transport is dominant even at $T=40$ K. At $T=30$ K and 20 K, on the other hand, obvious nonlinear behavior is observed. We successfully fit both data with Eq. (1), as shown by the solid lines in Fig. 4(b), and obtain $n_e-n_h=3.38\times10^{22}$ cm^{-3} at $T=30$ K and $n_e-n_h=1.44\times10^{22}$ cm^{-3} at $T=20$ K. Although the values themselves are strongly dependent on the particular model that we used, in any case the density of electrontype carriers rapidly increases with T decreasing from higher temperature, and this density exceeds that of holetype carriers before superconducting transition. The data at $T=30$ K is most notable, because the slope at high field is negative while that at low field is positive, which means $p\mu_h^2-n\mu_e^2>0$ and $n_h-n_e<0$. This gives the relation that $\mu_h>\mu_e$, which is consistent with a result previously indicated in the literature.[6]

Let us first compare the present results to the reported Hall effect measured for single crystals. The normal-state Hall coefficients have been already reported for $Ba(Fe_{2-x}Co_xAs_2)$ and $Ba(Fe_2As_{2-x}P_x)$ single crystals.[26–28] They commonly exhibit negative R_H at room temperatures for $x=0$, which is explained as that the electron mobility dominates the hole mobility. The present results for $Fe(Se_{0.5}Te_{0.5})$ show a clear contrast to $Ba(Fe_2As_2)$; R_H shows a positive value exceeding 1×10^{-3} cm^3/C for the eight samples. By taking the fact that such positive R_H has been observed for Te-free FeSe thin films[5] and for Se-free FeTe thin films[29] into account, it is likely that $Fe(Se_{1-x}Te_x)$ has a positive R_H at any x ($0\leq x\leq 1$), which is probably one of the essential differences to distinguish FeSe-based superconductors from FeAs-based one. We may consider two possible origins of the difference. One is that the number of outer electrons is different between pnictogen and chalogen, and the other is more specific reasons, such as band structures. Actually our result indicates that the hole mobility is larger than the electron mobility, while the opposite relation is deduced for $Ba(Fe_{2-x}Co_xAs_2)$,[26,27] which can be attributed to the details and local features of the electronic band structure.

Next, we discuss how to understand the observed variation of T_c and the Hall coefficients in the context of reported theories. One of the anomalous features of Fe-based superconductors is their pairing symmetry.[10] A likely symmetry is $s_\pm$ wave, which requires a finite nesting condition between electron- and hole-type bands centered at the M and Γ points in a reciprocal space, respectively. Singh *et al.* discussed how this nesting condition is influenced by carrier doping.[30] They pointed out that spin density wave (SDW) instability becomes dominant over superconductivity when the nesting is too good, and with electron doping (shrinkage of the holetype Fermi surface), the nesting condition becomes worse and superconductivity results. Our findings would be consistent with this scenario if the films with higher T_c had smaller hole-type Fermi surfaces than the lower-T_c films, and they do appear this way. The gradual decrease of R_H below $T=250$ K and the associated increase of R_H at $T\gtrapprox T_c$ for films with lower T_c indicate the dominance of hole-type carriers throughout the whole temperature range. The dependence of

R_H on T may be due to the different T dependences of μ_h and μ_e. On the other hand, the higher-T_c films exhibit a drastic change from hole- to electron-type transport, which strongly indicates that the Fermi level of the higher-T_c films is located above that of the lower-T_c films around $T \gtrapprox T_c$. Thus, one possible reason why sample G has a higher T_c is the shrinkage of the hole-type Fermi surface. Experimentally, we confirm that the magnitude of the resistivity in the normal-state scales well with the c-axis length of the films.[14] Therefore, we infer that the short c-axis length and associated lattice deformations sensitively change the position of the Fermi level in $Fe(Se_{0.5}Te_{0.5})$ thin films, and that we are able to detect this shift using Hall-effect measurements. To confirm this inference, we need to carry out more comprehensive measurements of the Hall effect in FeSe systems as a function of doping and crystal structure.

In conclusion, we measure the temperature dependence of the normal Hall coefficients, which is positive in contrast to $Ba(Fe_2As_2)$, for several $Fe(Se_{0.5}Te_{0.5})$ thin films and find a strong correlation between $R_H(T)$ and T_c. $R_H(T)$ of the most metallic samples remains almost constant down to $T=100$ K, and then start decreasing toward negative side, which is driven by the change in the population of electron- and hole-type carriers, and the charge transport at temperatures just above T_c is dominated by electron-type carriers. On the other hand, in more insulating samples, the dominant carriers remain hole-type, and the R_H exhibits a different temperature dependence. We proposed the analysis of nonlinear Hall resistivity, which can be the entrance to decompose the role of carrier concentrations and mobilities on the electronic structure and superconductivity in the iron-chalcogenide superconductors.

We thank T. Kawaguchi, H. Ikuta, A. Ichinose, J. Shimoyama, and K. Kishio for fruitful discussions and for sharing the unpublished data. We also thank H. Kontani and K. Ohgushi for valuable discussions.

*ichiro@criepi.denken.or.jp

[1] Y. Kamihara, T. Watanabe, M. Hirano, and H. Hosono, J. Am. Chem. Soc. **130**, 3296 (2008).
[2] F. C. Hsu, J. Y. Luo, K. W. Yeh, T. K. Chen, T. W. Huang, P. M. Wu, Y. C. Lee, Y. L. Huang, Y. Y. Chu, D. C. Yan, and M. K. Wu, Proc. Natl. Acad. Sci. U.S.A. **105**, 14262 (2008).
[3] Y. Mizuguchi, F. Tomioka, S. Tsuda, T. Yamaguchi, and Y. Takano, Appl. Phys. Lett. **94**, 012503 (2009).
[4] S. Medvedev, T. M. McQueen, I. A. Troyan, T. Palasyuk, M. I. Eremets, R. J. Cava, S. Naghavi, F. Casper, V. Ksenofontov, G. Wortmann, and C. Felser, Nature Mater. **8**, 630 (2009).
[5] Q. J. Feng, D. Z. Shen, Y. J. Zhang, B. S. Li, B. H. Li, Y. M. Lu, X. W. Fan, and H. W. Liang, Appl. Phys. Lett. **88**, 012505 (2006).
[6] X. J. Wu, D. Z. Shen, Z. Z. Zhang, J. Y. Zhang, K. W. Liu, B. H. Li, Y. M. Lu, B. Yao, B. S. Li, C. X. Shan, X. W. Fan, H. J. Liu, and C. L. Yang, Appl. Phys. Lett. **90**, 112105 (2007).
[7] K. W. Liu, J. Y. Zhang, D. Z. Shen, C. X. Shan, B. H. Li, Y. M. Lu, and X. W. Fan, Appl. Phys. Lett. **90**, 262503 (2007).
[8] X. J. Wu, Z. Z. Zhang, J. Y. Zhang, B. H. Li, Z. G. Ju, Y. M. Lu, B. S. Li, and D. Z. Shen, J. Appl. Phys. **103**, 113501 (2008).
[9] I. I. Mazin, D. J. Singh, M. D. Johannes, and M. H. Du, Phys. Rev. Lett. **101**, 057003 (2008).
[10] K. Kuroki, S. Onari, R. Arita, H. Usui, Y. Tanaka, H. Kontani, and H. Aoki, Phys. Rev. Lett. **101**, 087004 (2008).
[11] A. Subedi, L. Zhang, D. J. Singh, and M. H. Du, Phys. Rev. B **78**, 134514 (2008).
[12] Y. Xia, D. Qian, L. Wray, D. Hsieh, G. F. Chen, J. L. Luo, N. L. Wang, and M. Z. Hasan, Phys. Rev. Lett. **103**, 037002 (2009).
[13] M. J. Han and S. Y. Savrasov, Phys. Rev. Lett. **103**, 067001 (2009).
[14] Y. Imai, R. Tanaka, T. Akiike, M. Hanawa, I. Tsukada, and A. Maeda, Jpn. J. Appl. Phys. (to be published).
[15] M. K. Wu, F. C. Hsu, K. W. Yeh, T. W. Huang, J. Y. Luo, M. J. Wang, H. H. Chang, T. K. Chen, S. M. Rao, B. H. Mok, C. L. Chen, Y. L. Huang, C. T. Ke, P. M. Wu, A. M. Chang, C. T. Wu, and Y. P. Perng, Physica C **469**, 340 (2009).
[16] T. G. Kumary, D. K. Baisnab, J. Janaki, A. Mani, R. M. Sarguna, P. K. Ajikumar, A. K. Tyagi, and A. Bharathi, Superconduct. Sci. Technol. **22**, 095018 (2009).
[17] M. Wang, J. Luo, T. Huang, H. Chang, T. Chen, F. Hsu, C. Wu, P. Wu, A. Chang, and M. Wu, arXiv:0904.1858 (unpublished).
[18] Y. F. Nie, E. Brahimi, J. I. Budnick, W. A. Hines, M. Jain, and B. O. Well, Appl. Phys. Lett. **94**, 242505 (2009).
[19] Y. Han, W. Y. Li, L. X. Cao, S. Zhang, B. Zu, and B. R. Zhao, J. Phys.: Condens. Matter **21**, 235702 (2009).
[20] E. Bellingeri, R. Buzio, A. Gerbi, D. Marre', S. Congiu, M. Cimberle, M. Tropeano, A. Siri, A. Palenzona, and C. Ferdeghini, Superconduct. Sci. Technol. **22**, 105007 (2009).
[21] W. Si, Z.-H. Lin, Q. Jie, W.-G. Yin, J. Zhou, G. Gu, P. D. Johnson, and Q. Li, Appl. Phys. Lett. **95**, 052504 (2009).
[22] M. H. Fang, H. M. Pham, B. Qian, T. J. Liu, E. K. Vehstedt, Y. Liu, L. Spinu, and Z. Q. Mao, Phys. Rev. B **78**, 224503 (2008).
[23] Anomalous Hall effect is classified in two groups from its mechanism; one has an internal mechanism originated from multiband effect and spin-orbit coupling discussed by Karplus and Luttinger, while the other has an external mechanism such as an skew scattering or side jump mechanisms investigated by Smit and Berger. In this paper, we refer to the latter one as AHE following to the previous research by Feng *et al.*, which report the presence of spontaneous magnetization in FeSe thin films.
[24] See, for example, *The Hall Effect and Its Applications*, edited by C. L. Chien and C. R. Westgate (Plenum Press, New York, 1980).
[25] See, for example, *Semiconductors*, edited by R. A. Smith (Cambridge Univerisity Press, Cambridge, England, 1978).
[26] F. Rullier-Albenque, D. Colson, A. Forget, and H. Alloul, Phys. Rev. Lett. **103**, 057001 (2009).
[27] L. Fang, H. Luo, P. Cheng, Z. Wang, Y. Jia, G. Mu, B. Shen, I. I. Mazin, L. Shan, C. Ren, and H. H. Wen, Phys. Rev. B **80**,

140508(R) (2009).
[28] S. Kasahara, T. Shibauchi, K. Hashimoto, K. Ikada, S. Tonegawa, R. Okazaki, H. Ikeda, H. Takeya, K. Hirata, T. Terashima, and Y. Matsuda, arXiv:0905.4427v3 (unpublished).
[29] Y. Han, W. Y. Li, L. X. Cao, X. Y. Wang, B. Xu, B. R. Zhao, Y. Q. Guo, and J. L. Yang, Phys. Rev. Lett. **104**, 017003 (2010).
[30] D. J. Singh, M. H. Du, L. Zhang, A. Subedi, and J. An, Physica C **469**, 886 (2009).