Doping effect on the carrier scattering in iron-pnictide superconductors studied by charge transport

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Abstract

In order to reveal the role of “carrier doping” in the iron-based superconductors, we investigated the transport properties of the oxygen-deficient iron-arsenides LnFeAsO_{1-y} ($\text{Ln} = \text{La, Ce, Pr and Nd}$) over a wide doping range. We found that the effect of “doping” in this system is mainly on the carrier scattering rather than carrier density, quite distinct from that in high- T_c cuprates. In the case of La system with lower T_c , the low temperature resistivity is dominated by T^2 term and fairly large magnetoresistance is observed. On the other hand, in the Nd system with higher T_c , carriers are subject to stronger scattering showing nearly T -linear resistivity and small magnetoresistance. Such strong scattering appears intimately correlated with high- T_c superconductivity in the iron-based system.

Keywords:

superconductors, superconductivity, transport properties

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1. Introduction

The high- T_c cuprate and iron-based superconductors have several similarities. Among them, one important feature is that the parent compounds show antiferromagnetic order and superconductivity appears by doping carriers. In the case of high- T_c cuprates, carrier doping mainly controls carrier density and T_c is controlled by the superfluid density. On the other hand, in the iron-based superconductors, superconductivity can be induced through various methods; (1) electron doping ($\text{LnFeAsO}_{1-x}\text{F}_x$ [1, 2], $\text{Ba}(\text{Fe}_{1-x}\text{Co}_x)_2\text{As}_2$ [3], *etc.*), (2) hole doping ($\text{Ba}_{1-x}\text{K}_x\text{Fe}_2\text{As}_2$ [4], *etc.*), (3) isovalent doping ($\text{BaFe}_2(\text{As}_{1-x}\text{P}_x)_2$ [5], $\text{Ba}(\text{Fe}_{1-x}\text{Ru}_x)_2\text{As}_2$ [6], *etc.*) and (4) applying pressure. As for latter two cases, carrier density is apparently unchanged. This indicates that carrier density is not so crucial for superconductivity in iron-based superconductors as in cuprates. Furthermore, it is empirically known that T_c of LnFeAsO system correlates strongly with the crystal structure and becomes maximum when FeAs_4 forms a nearly ideal tetrahedron [7]. However, it is still an unresolved puzzle why T_c is so different among different classes. In this work, we investigate the transport properties of the oxygen-deficient oxypnictides LnFeAsO_{1-y} ($\text{Ln} = \text{La, Ce, Pr and Nd}$) to explore how

the charge transport in the normal state is correlated with the superconducting T_c in this class of pnictides.

2. Experimental procedures

Polycrystalline samples of LnFeAsO_{1-y} were prepared by a high-pressure synthesis technique using a cubic-anvil-type apparatus (Riken CAP-07). [8] Well-sintered samples of high density, sufficient for transport measurements, were obtained by applying a pressure of 2 GPa during the synthesis. Because some of the starting materials are quite reactive to oxygen, we could not prevent their oxidation in the synthesis procedure. The actual amount of oxygen deficiency y was estimated with reference to the lattice constants [7] which were slightly smaller than those of the nominal composition. In order to make the distribution of the oxygen deficiency homogeneous, the samples were annealed in air at 450 °C. A standard four-terminal method was used for the resistivity measurements. The Hall resistivity and the transverse MR were measured in a cryostat equipped with a superconducting magnet (PPMS, Quantum Design Inc.) with the magnetic field normal to the widest plane.

3. Results and Discussion

Figures 1 (a) - (d) display the temperature dependence of resistivity $\rho(T)$ for LaFeAsO_{1-y} , CeFeAsO_{1-y} , PrFeAsO_{1-y} and

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Figure 1: Temperature dependence of the resistivity of LaFeAsO_{1-y} for y in the range $0 \leq y \leq 0.23$ (a), CeFeAsO_{1-y} for y in the range $0.06 \leq y \leq 0.11$ (b), PrFeAsO_{1-y} from Ref. 10 (c), and NdFeAsO_{1-y} for y in the range $0 \leq y \leq 0.17$ (d).

NdFeAsO_{1-y}, respectively. The evolution of $\rho(T)$ with y looks qualitatively similar for all compounds. The most remarkable difference is that the normal-state resistivity in the superconducting regime is dominated by a T^2 term in LaFeAsO_{1-y}, whereas by a T -linear term in NdFeAsO_{1-y}. In addition, $\rho(T)$ of CeFeAsO_{1-y} and PrFeAsO_{1-y} seem to show intermediate behavior of those two.

To reveal the correlation between charge transport and T_c , we investigated the exponent n of $\rho(T) \sim T^n$ for each sample. We fitted the data in the form of $\rho(T) = \rho_0 + A T^n$ in the temperature range between T just above T_c and $T = 150$ K, where ρ_0 is the residual component of resistivity. The exponent n plotted against T_c is shown in Fig. 2. NdFeAsO_{1-y} with higher T_c clearly belongs to a class distinct from LaFeAsO_{1-y}. On the same figure are also plotted the n -values for CeFeAsO_{1-y} and single crystals of PrFeAsO_{1-y} with T_c between 30 and 47 K. We can see a crossover from T^2 to T -linear dependence of resistivity associated with an increase of T_c . Then, one may conclude that the carrier scattering which gives rise to T -linear resistivity in the normal state is a possible ingredient for achieving T_c exceeding 50 K in iron-based superconductors.

Figure 3 shows magnetic field dependence of the transverse magnetoresistance (MR) for LaFeAsO_{1-y}, PrFeAsO_{1-y} and NdFeAsO_{1-y} for $y = 0.23, 0.22$ and 0.17 , respectively. Note that carrier density is expected to be almost same for each compound. The magnitude of MR, which provides a measure of carrier mobility assuming a two-carrier model, is fairly large in

Figure 2: Relationship between T_c and the exponent n of $\rho(T) \sim T^n$ for LnFeAsO_{1-y} ($Ln = \text{La, Ce, Pr and Nd}$).

LaFeAsO_{1-y} ($\sim 8\%$ at $H = 6$ T and $T = 50$ K). In contrast, MR is much smaller in NdFeAsO_{1-y} ($\sim 1\%$ at $H = 6$ T and $T = 70$ K). As for PrFeAsO_{1-y}, MR takes an intermediate value between LaFeAsO_{1-y} and NdFeAsO_{1-y} ($\sim 2\%$ at $H = 6$ T and $T = 50$ K). Thus, carrier scattering (mobility) seems to be getting stronger (higher) by replacing Ln from La to Nd.

In the band structure of nondoped LaFeAsO [11], the top of a hole band (called a γ band) centered at Γ is located just above the Fermi level. It moves down with electron doping and finally is located below the Fermi surface. In the case of NdFeAsO_{1-y} the top of the γ band is higher than that for LaFeAsO_{1-y} being always above the Fermi level regardless of electron doping level. It is argued that a Fermi surface derived from the γ band facilitates nesting between disconnected portions of electron Fermi surfaces, which would enhance “interband” scattering of electrons between the two nested Fermi surfaces and, in certain circumstances (*e.g.*, when coupled with spin fluctuations), would be a source of pairing interaction [12, 13]. In addition, the location of the γ band is found to be sensitive to local crystal structure, specifically, the As height from the Fe plane or the bond angle α of the FeAs₄ octahedron [11]. Then, the γ -Fermi surface seems to bridge between the known T_c - α correlation and the present T_c - n correlation we observed.

4. Conclusion

The present results strongly suggest that the strong carrier scattering which gives rise to T -linear resistivity is intimately correlated with high- T_c in the Fe-based superconductors. “Doping” is not a parameter controlling carrier density but also carrier scattering. However, in the case of cuprates, the carrier scattering rate is not necessarily related with T_c . T_c is controlled by the superfluid density, and the transport scattering rate is not strongly dependent on doping and material in the underdoped and optimally doped regimes. In view of the charge transport

Figure 3: Magnetic field dependence of the transverse magnetoresistance of LaFeAsO_{1-y} , PrFeAsO_{1-y} and NdFeAsO_{1-y} for $y = 0.23, 0.22$ and 0.17 , respectively.

demonstrated in the present work, the Fe-based superconductors apparently belong to a class different from the cuprates, and seem to have an aspect in common with other classes of superconductors in that the carrier scattering has some relevance to T_c .

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