Superconductivity induced by doping Pd in SrFe$_{2-x}$Pd$_x$As$_2$

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Superconductivity in the FeAs-based systems has received tremendous attention in last year with the hope that the superconducting transition temperature could be raised to a higher value. The superconducting transition temperature was promoted above 50 K by replacing lanthanum with other rare-earth elements in LaFeAsO$_{1-x}$F$_x$, or by substituting the alkaline elements with rare earth elements in (Ba,Sr,Ca)FeAsF. Meanwhile, the hole-doped superconductors were discovered both in the FeAs-1111 and the FeAs-122 family. The FeAs-122 phase, due to the much simpler structure, less elements in the compound and easy growth of large scale single crystals, provides us a great opportunity to investigate the intrinsic physical properties. Meanwhile, people found that a substitution of Fe ions with Co or Ni can also induce superconductivity with maximum $T_c$ or $H_c$ of about 8.7 K was achieved at the doping level of $x$ = 0.15. The general phase diagram of $T_c$ versus $x$ was obtained and found to be similar to the case of Ni and Co doping to the Fe sites. Our results suggest that superconductivity can be easily induced in the FeAs family by adding electrons into the system, regardless with the transition metals of 3d or higher d-orbital electrons.

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Superconductivity induced by doping Pd in SrFe$_{2-x}$Pd$_x$As$_2$. The systematic evolution of the lattice constants indicated that the Fe ions were successfully replaced by the Pd. By increasing the doping content of Pd, the antiferromagnetic state of the parent phase is suppressed and superconductivity is induced at a doping level of about $x$=0.05. Superconductivity with a maximum transition temperature $T_c$ of about 8.7 K was achieved at the doping level of $x$ = 0.15. The general phase diagram of $T_c$ versus $x$ was obtained and found to be similar to the case of Ni and Co doping to the Fe sites. Our results suggest that superconductivity can be easily induced in the FeAs family by adding electrons into the system, regardless with the transition metals of 3d or higher d-orbital electrons.

The x-ray diffraction measurement was performed at room temperature using an MXPI18A-HF-type diffractometer with Cu-K$_\alpha$ radiation from 10° to 80° with a step of 0.01°. The analysis of x-ray powder diffraction data was done by using the software of Powder-X and the lattice constants were derived by having a general fitting (see below). The DC magnetization measurements were done with a superconducting quantum interference device (Quantum Design, SQUID, MPMS7). The zero-field-cooled magnetization was measured by cooling the sample at zero field to 2 K, then magnetic field was applied and the data were collected during the warming up process. The field-cooled magnetization data was collected in the warming up process after the sample was cooled down to 2 K at a finite magnetic field. The resistivity measurements were done with a physical property measurement system PPMS-9T (Quantum Design) with the four-probe technique. The current direction was changed for measuring each point in order to remove the contacting thermal power.

In order to have a comprehensive understanding to the evolution induced by the doping process, we have measured the X-ray diffraction patterns for all samples. The lattice constants of $a$-axis and $c$-axis are thus obtained.

In Figure 1, we present the x-ray diffraction patterns of SrFe$_{2-x}$Pd$_x$As$_2$. It is clear that all main peaks of the samples can be indexed to a tetragonal structure. The peaks marked with asterisks arise from the impurity phase. By fitting the data to the structure calculated with the software Powder-X, we get the lattice constants.

In Figure 2, we show $a$- and $c$- lattice parameters for the SrFe$_{2-x}$Pd$_x$As$_2$ samples. One can see that, by substituting the Pd into the Fe site, the lattice constant $a$ shrinks a bit, while $c$ expands slightly. This tendency is similar to the case of doping the Fe with Ir or Ru in SrFe$_{2-x}$Ir$_x$As$_2$ and BaFe$_{2-x}$Ru$_x$As$_2$.

In Figure 3, we present the temperature dependence of resistivity for samples SrFe$_{2-x}$Pd$_x$As$_2$ with $x$ = 0, 0.05, 0.1, 0.15, 0.20 and 0.25 respectively. As we can see, the
parent phase exhibits a sharp drop of resistivity (resistivity anomaly) at about 215 K. By doping more Pd, the resistivity drop was converted to a uprising. This occurs also in the Co-doped samples. We found that the superconductivity appears in the sample with nominal composition of x = 0.1. In the sample of x = 0.15, the resistivity anomaly disappeared completely. This sample shows a superconducting transition at about 8.7 K which is determined by a standard method, i.e., using the crossing point of the normal state background and the extrapolation of the transition part with the most steep slope (as shown Fig.6). The transition width determined here with the criterion of 10-90 % $\rho_n$ is about 1.2 K. With higher doping level (x = 0.2) the transition temperature declines slightly. The superconductivity again disappeared when the doping content x is over 0.25.

In Figure 4, the temperature dependence of the DC magnetization for the sample SrFe$_{1.85}$Pd$_{0.15}$As$_2$ was shown. The measurement was carried out under a magnetic field of 20 Oe in zero-field-cooled and field-cooled processes. A clear diamagnetic signal appears below 8.2 K, which corresponds to the middle transition temperature of the resistivity data. A very strong Meissner shielding signal was observed in the low temperature regime, which is similar to the case in SrFe$_{2-x}$Ir$_x$As$_2$.

In Figure 5, a phase diagram of SrFe$_{2-x}$Pd$_x$As$_2$ within the range x from 0 to 0.25 was given. Both $T_{on}$ and $T_c$ was defined as temperature of the anomaly in resistivity and the superconductivity transition by resistivity and susceptibility, respectively. Like the other samples in FeAs-122 phase, with increasing Pd-doping, the temper-
signal was observed. A strong Meissner shielding effect was done under a magnetic field of 20 Oe in zero-field-cooled and field-cooled modes.

![Graph](image)

**FIG. 4:** (Color online) Temperature dependence of DC magnetization for the sample SrFe\textsubscript{1.85}Pd\textsubscript{0.15}As\textsubscript{2}. The measurement was done under a magnetic field of 20 Oe in zero-field-cooled and field-cooled modes. A strong Meissner shielding effect was observed.

![Graph](image)

**FIG. 5:** (Color online) Phase diagram of SrFe\textsubscript{1-x}Pd\textsubscript{x}As\textsubscript{2} within the range of x = 0 to 0.25. The temperature of resistivity anomaly represents the upturning point of resistivity which indicates a deviating point from a rough T-linear behavior in the high temperature region. The superconductivity starts to appear at x = 0.1, reaching a maximum T\textsubscript{c} of 8.7 K at x = 0.15. The dashed line provides a guide to the eyes for the possible AF order/structural transitions near the optimal doping level.

![Graph](image)

**FIG. 6:** (Color online) Temperature dependence of resistivity for the sample SrFe\textsubscript{1.85}Pd\textsubscript{0.15}As\textsubscript{2} at different magnetic fields. The inset gives the upper critical field determined using the criterion of 90%\(\rho_n\). A slope of -dH\textsubscript{c2}/dT = 4.2 T/K near T\textsubscript{c} is found here. The irreversibility line H\textsubscript{ir} taking with the criterion of 0.1% \(\rho_n\) is also presented in the inset.

In Figure 6 we present the temperature dependence of resistivity broadening induced by using different magnetic fields. Just as many other iron pnictide superconductors, the superconductivity is also very robust against the magnetic field in the present sample although the T\textsubscript{c} is only 8.7 K. We used the criterion of 90%\(\rho_n\) to determine the upper critical field and show the data in the inset of Figure 6. Surprisingly a high slope of -dH\textsubscript{c2}/dT = 4.2 T/K can be obtained here. By using the Werthamer-Helfand-Hohenberg (WHH) formula\textsuperscript{25}

\[
H_{c2}(0) = -0.69(dH_{c2}/dT)|_{T_c}\text{,}
\]

the value of zero temperature upper critical field can be estimated. Taking T\textsubscript{c} = 8.7 K, we get H\textsubscript{c2}(0) ≈ 25.1T roughly. Because of the low superconducting critical temperature, the present Pd-doped sample has a smaller upper critical field, compared with K-doped\textsuperscript{18} and Co-doped samples\textsuperscript{19}.

The superconductivity mechanism in the FeAs-based superconductors remains unclear yet. One widely perceived picture would be that the pairing is established via the inter-pocket scattering of electrons through exchanging the AF spin fluctuations.\textsuperscript{20,21,22} By doping electrons or holes into the parent phase, the condition for forming the AF order will be destroyed gradually. Instead the short range AF order will provide a wide spectrum of spin fluctuations. This picture can certainly give a qualitative explanation to the occurrence of superconductivity. However, it is still unclear why the superconducting transition temperature varies in doping different elements. For example, the maximum T\textsubscript{c} by doping Co, Ni, Ru or Ir can be as high as 24-26 K,\textsuperscript{11,13,14,15} while
that by doping Pd in the present case is only about 8.7 K. In addition, in most cases, the substitution to the Fe sites by other transition metal elements in the 1111 phase gives only a rather low superconducting transition temperature. This puzzling point certainly warrants further investigations. Our data here further illustrate that the superconductivity can be easily induced by doping the Fe sites with many other transition metals which are not restricted to the ones with 3d orbital electrons.

In summary, superconductivity has been found in Sr$_{Fe-1-x}$Pd$_x$As$_2$ with the maximum $T_c = 8.7$ K. The phase diagram obtained is quite similar to that by doping Co, Ni, Ru or Ir to the Fe sites. The superconductivity is rather robust against the magnetic field with a slope of $-dH_c^2/dT = 4.2$ T/K near $T_c$. Our results clearly indicate that the superconductivity can be easily induced in (Ba,Sr)Fe$_2$As$_2$ by replacing the Fe sites with many different transition metal elements which are not restricted to ones nearby the iron with 3d orbital electrons.

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