Transport properties and anisotropy of Rb$_{0.8}$Fe$_2$Se$_2$ single crystals

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Single crystals of Rb$_{0.8}$Fe$_2$Se$_2$ are successfully synthesized with the superconducting transition temperatures $T_{c}^{\text{onset}} = 31$ K and $T_{c}^{\text{zero}} = 28$ K. A clear anomaly of resistivity was observed in the normal state at about 150 K, as found in a similar system K$_x$Fe$_2$Se$_2$. The upper critical field has been determined with the magnetic field along ab-plane and c-axis, yielding an anisotropy of about 3.5. The angle dependent resistivity measured below $T_c$ allow a perfect scaling feature based on the anisotropic Ginzburg-Landau theory, leading to a consistent value of the anisotropy which decreases from about 3.6 at around $T_c$ to 2.9 at 27 K. Comparing to the anisotropy determined for Ba$_{0.6}$K$_{0.4}$Fe$_2$As$_2$ and Ba(Fe$_{0.92}$Co$_{0.08}$)$_2$As$_2$ using the same method, we find that the present sample is more anisotropic and the Fermi surfaces with stronger two dimensional characters are expected.

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Iron pnictide superconductors have received tremendous attention in last two years since Kamihara et al. reported superconductivity at 26 K in LaFeAsO$_{1-y}$F$_y$.\cite{1} The family of the FeAs-based superconductors has been expanded rapidly. A typical example is the (Ba,Sr)$_2$Fe$_2$As$_2$ (denoted as FeAs-122) system: the antiferromagnetic order is suppressed and superconductivity is induced by either K doping in the Ba or Sr sites \cite{2,3} or Co and Ni doping in the Fe sites.\cite{4,5} On the other hand, superconductivity was also found in the FeAs-based parent phase LiFeAs (denoted as FeAs-111) \cite{6,7} and Sr$_2$VO$_3$FeAs (denoted as FeAs-21311).\cite{8} Compared to these iron pnictides, FeSe has a more simple structure of only FeSe layers and no toxic arsenic \cite{9}, which shows superconductivity at 8 K at ambient pressure and the transition temperature can be increased dramatically to 37 K under a high pressure.\cite{10} Moreover, recent report showed that superconducting and magnetic properties of Fe$_{1-x}$Se$_x$Te$_{1-x}$ not only depend on the concentration ratio of Se/Te, but also strongly depend on the interstitial Fe content.\cite{11} Additionally, angle resolved photoemission spectroscopy (ARPES) showed that the normal state of FeSe$_{0.42}$Te$_{0.58}$ is a strongly correlated metal, which is significantly different from the FeAs-111 and FeAs-122 systems.\cite{12} Therefore, the FeSe-layered materials deserve intensive studies for both fundamental physics and potential applications.

Very recently, superconductivity at around 30 K was reported in K$_x$Fe$_2$Se$_2$ (denoted as FeSe-122)\cite{13}, where the potassium ions could be intercalated into the Fe$_2$Se$_2$ layers. This discovery was quickly repeated by other groups with the nominal composition K$_{0.8}$Fe$_2$Se$_2$.\cite{14} Introducing potassium into the system makes the structure change from 11-type(P4/mmm) to 122-type(14/mmm). Up to now, the system FeSe-122 gives the highest $T_c$ among the FeSe-layered compounds under ambient pressure. Shortly after that, Krzton-Maziopa et. al. reported the crystal growth of an analog compound Cs$_{0.8}$(FeSe$_{0.98}$)$_2$.\cite{15} Furthermore, Fang et al.\cite{16} synthesized the systematically doping (TLK)Fe$_{2-x}$Se$_2$ and found that the superconductivity might be in proximity of a Mott insulator. If just counting on the electron numbers, one would assume that A$_x$Fe$_2$Se$_2$ (A = alkaline metals) might be a purely electron doped sample. Thus it is curious to know whether the Fermi surfaces are close to or far different from their relatives Ba(Sr)Fe$_2$As$_2$. The anisotropy is one of the important parameters that characterize the electronic properties. In this work, we report the successful synthesis of a new compound Rb$_{0.8}$Fe$_2$Se$_2$. The onset and zero-resistivity transition temperature were estimated to be 31 K and 28 K, respectively. We also present the temperature, magnetic field and angle dependence of resistivity. Our results point to a higher anisotropy in Rb$_{0.8}$Fe$_2$Se$_2$ compared to electron and hole doped Ba(Sr)Fe$_2$As$_2$.

Single crystals were grown from the melt of the mixture of Rb$_{0.8}$Fe$_2$Se$_2$ using the Bridgeman method. First, FeSe powders were prepared with high-purity powder of the FeSe-layered compounds under ambient pressure.
selenium (Alfa, 99.99%) and iron (Alfa, 99.9%) by a similar method described in ref. Then, FeSe and Rb (Alfa, 99.75%) were mixed in appropriate stoichiometry and were put into alumina crucibles and sealed in evacuated silica ampoule. The mixture was heated up to 1030 °C and kept over 3 hours. Afterwards the melt was cooled down to 730 °C with the cooling rate of 6 °C/h and finally the furnace was cooled to room temperature with the power shut off. Well formed black crystal rods were obtained which could be easily cleaved into plates with flat shiny surfaces. The good c-axis orientation of the crystals has been demonstrated by the X-ray diffraction (XRD) analysis which show only the sharp (00l) peaks. The dc magnetization measurements were done with a superconducting quantum interference device (Quantum Design, SQUID, MPMS7). The electrical transport data were collected on the Quantum Design instrument physical property measurement system (PPMS) with magnetic fields up to 9 T. The temperature stabilization was better than 0.1% and the resolution of the voltmeter was better than 10 nV.

Fig.2 (a) shows the temperature dependence of resistivity for a single crystal of Rb$_{0.8}$Fe$_2$Se$_2$. A superconducting transition appears at the temperature of 31 K (onset) which is similar to that of K$_{0.8}$Fe$_2$Se$_2$\cite{15}. The bulk superconductivity of our sample is also confirmed by DC magnetization measurement which is shown in Fig.2 (b), diamagnetism is clearly observed in both zero-field-cooling and field-cooling measurement. The relatively broad magnetic transition suggest that the sample is still inhomogeneous with probably the Rb distributed non-uniformly. The normal state resistivity of our sample exhibits a possible semiconductor-to-metal like transition around 150 K. The similar behavior was also observed in K$_{0.8}$Fe$_2$Se$_2$\cite{15} although in a different temperature region (about 110 K in K$_{0.8}$Fe$_2$Se$_2$\cite{15}). This resistivity anomaly could also be caused by a structure or magnetic phase transition which is very typical in the AFe$_2$Se$_2$ superconductors. Further experiments need to be done to clarify the origin of this transition. It also should be noticed that the absolute value of normal state resistivity is quite large. The maximum value exceeds 700 m$\Omega$ cm, which is hundreds of times larger than that in other typical iron-based superconductors. This phenomena could be attributed to the semiconductor background in these iron selenide superconductors.

The temperature dependence of resistivity from 15 K to 40 K with different magnetic fields applied along ab-plane or c-axis are presented in Fig. 3 (a) and (b). We adopt a criterion of 90%$\rho_{0}(T)$ to determine the upper critical fields. The upper critical fields of Rb$_{0.8}$Fe$_2$Se$_2$ are determined in this way and shown in Figure 4. The upper critical fields H$_{c2}$ exhibit a rather linear temperature dependence for both orientations. Thus we can easily get the values of the slope for two different di-
The upper critical fields of Rb$_{0.8}$Fe$_2$Se$_2$ single crystal for H//c and H//ab respectively.

The anisotropy determined by anisotropic Ginzburg-Landau theory at different temperatures of Rb$_{0.8}$Fe$_2$Se$_2$, Ba$_{0.6}$K$_{0.4}$Fe$_2$As$_2$ and Ba(Fe$_{0.92}$Co$_{0.08}$)$_2$As$_2$ single crystals are shown in Fig. 6. It is found that, the anisotropy of Rb$_{0.8}$Fe$_2$Se$_2$ decreases slightly with decreasing temperature. This kind of temperature dependence of $\Gamma(T)$
is consistent with other FeAs-122 superconductors, such as Ba$_0.6$K$_0.4$Fe$_2$As$_2$, Ba(Fe$_{0.92}$Co$_{0.08}$)$_2$As$_2$, etc. This may be understood as the multiband effect, or the effect due to gradual setting in of the pair breaking. It should be noted that the good scaling behavior suggests a field-independent anisotropy in the temperature and field range we investigated. Compared to MgB$_2$ and cuprate superconductor, anisotropy of Rb$_{0.8}$Fe$_2$Se$_2$ is very small and lower than that of FeAs-1111 family, such as NdFeAsO$_{1-x}$F$_x$, while it is higher than that in hole and electron doped FeAs-122 superconductors and similar to that of KFe$_2$As$_2$ with the same structure. It is however very strange that KFe$_2$As$_2$ should reside in the two terminals of the phase diagram, the former is strongly hole doped, while the latter is heavily electron doped. The larger anisotropy in K$_x$Fe$_2$Se$_2$ may suggest a more two dimensional Fermi surface in this material. So far no angle resolved photo-emission spectroscopy (ARPES) on the $\text{A}_x\text{Fe}_2\text{Se}_2$ family has been reported. The difference between the anisotropy in Ba$_{0.6}$K$_0.4$Fe$_2$As$_2$ and Rb$_{0.8}$Fe$_2$Se$_2$ may hinge on that the latter has less warped Fermi surface. Our results here should be stimulating in fulfilling a quantitative calculation and further studying on the electronic structure of this new family, and ultimately providing an understanding to the underlying mechanism of superconductivity.

In conclusion, we successfully fabricate single crystals of Rb$_{0.8}$Fe$_2$Se$_2$ with the superconducting transition temperatures $T_{c\text{onset}} = 31$ K. A clear anomaly of the resistivity was observed in the normal state at about 150 K. We also determined the upper critical fields along ab-plane and c-axis. The anisotropy of the superconductor determined by the ratio of $H_{c2}^a$ and $H_{c2}^c$ is estimated to be 3.5. The angle dependent resistivity measured below $T_c$ allow a perfect scaling based on the anisotropic Ginzburg-Landau theory. The consistent value of the anisotropy is acquired which decreases from about 3.6 at 30 K around $T_c$ to 2.9 at 27 K. Comparing to the anisotropy determined for Ba$_{0.6}$K$_0.4$Fe$_2$As$_2$ and Ba(Fe$_{0.92}$Co$_{0.08}$)$_2$As$_2$ using the same method, we expect that the Fermi surfaces in the new system $\text{A}_x\text{Fe}_2\text{Se}_2$ is less warped.

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