Magnetic phase diagram and critical current of $BaFe_2As_2$ single crystals with hole- and electron-doping

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Magnetic phase diagram and critical current of $\mathrm{BaFe_2As_2}$ single crystals with hole- and electron-doping

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Abstract.
We report on comparative study of magnetic phase diagram and critical current of the hole- and electron-doped $\mathrm{BaFe_2As_2}$ single crystals with close values of superconducting critical temperature, T_c, (slightly underdoped $\mathrm{Ba_{0.64}K_{0.36}Fe_2As_2}$ with T_c=25K and optimally doped $\mathrm{BaFe_{1.9}Ni_{0.1}As_2}$ with T_c=20K) obtained from measurements of the temperature dependence of ac-susceptibility and isothermal irreversible magnetization loops, M(H), in magnetic fields parallel to the c-axis of the crystal. From ac-susceptibility measurements we get estimation of a slope of the upper critical field, H_{c2}, in dependence on temperature, $dH_{c2}/dT \approx -4.2T/K$ for $\mathrm{BaFe_{1.9}Ni_{0.1}As_2}$ single crystal and $H_{c2}/dT \approx -1.75T/K$ for $Ba_{0.64}K_{0.36}Fe_2As_2$ sample that in accordance with Werthamer, Helfand, and Hohenberg (WHH) model gives $H_{c2}(0) = 0.69T_c((dH_{c2})dT) \approx 56T$ for $\mathrm{BaFe_{1.9}Ni_{0.1}As_2}$ sample and lower value of $H_{c2}(0) \approx 31T$ for $\mathrm{Ba_{0.64}K_{0.36}Fe_2As_2}$ crystal. However, obtained from $M(H)$ measurements temperature dependence of the irreversibility field, $H_{irr}(T)$, for $\mathrm{BaFe_{1.9}Ni_{0.1}As_2}$ crystal located below the one for$\mathrm{Ba_{0.64}K_{0.36}Fe_2As_2}$ crystal. Furthermore, at T=4.2K and higher temperatures our results for critical current density, J_c, calculated from $M(H)$ curves clearly show slower reduction of J_c with increasing field in even underdoped $\mathrm{Ba_{0.64}K_{0.36}Fe_2As_2}$ sample compared to optimally doped $\mathrm{BaFe_{1.9}Ni_{0.1}As_2}$ crystal demonstrating higher capacity of K-doped 122 compounds for production of superconducting cables and wires with high critical current in strong magnetic fields.

1. Introduction

At present, about 5 years after discovery of superconductivity in iron based superconductors (FBS) [1] great potential of these compounds for practical applications becomes increasingly evident. To date a few different families of FBS superconductors are known. The highest values of superconducting critical temperature, $T_c \sim 55K$, and upper critical field, $H_{c2}(0)$ exceeding 100T were found in 1111 family (REO(F)FeAs, where RE - rare earth element) [2,3]. However, single phase 1111 compounds may be prepared using extreme growth conditions with high temperature $\sim 1300^o$C and high pressure $\sim$50 kbar that makes a serious problem to produce practical 1111 superconducting elements with high critical parameters. On the other hand the simplest from the point of view of its chemical composition and synthesis parameters FeSe compound has rather low $T_c \sim 11-12K$ [4]. For this reason, essential efforts of various research groups to produce superconducting wires using FBS were focused on 122 family materials ($BaFe_2As_2$) with hole- or electron-doping, in particular, $Ba_{1-x}K_xFe_2As_2$, $BaFe_{2-x}Co_xAs_2$ and $BaFe_{2-x}Ni_xAs_2$ compounds. Among these candidates for practical use $BaFe_{2-x}Ni_xAs_2$ single crystals with optimal doping ($x \approx 0.1$) have the lowest $T_c \sim 20K$ compared to optimally doped $Ba_{1-x}K_xFe_2As_2$ ($x \approx 0.4$) and $BaFe_{2-x}Co_xAs_2$ ($x \approx 0.15$) crystals with $T_c \sim 38K$ and $T_c \sim 25K$, respectively [5]. At the same time recently very high value of critical current density around $\sim 3 \times 10^6 A/cm^2$ in $BaFe_{2-x}Ni_xAs_2$ crystals at T=4.2K in low magnetic fields exceeding J_c data for other 122 superconductors was reported [6]. In order to estimate potential of $BaFe_{2-x}Ni_xAs_2$ compound for applications in more detail in this paper we report on comparative study of magnetic phase diagram and critical current of optimally doped $BaFe_{1.9}Ni_{0.1}As_2$ and slightly under-doped $Ba_{0.64}K_{0.36}Fe_2As_2$ crystals with close T_c values.

2. Experiment and discussion.

$Ba_{0.64}K_{0.36}Fe_2As_2$ and $BaFe_{1.9}Ni_{0.1}As_2$ single crystals were grown using the self-flux method as described elsewhere [6, 7]. For measurements we used crystals of the in-plane size of 2÷3 mm and thickness around 0.1÷0.2 mm. The mass of $Ba_{0.64}K_{0.36}Fe_2As_2$ and $BaFe_{1.9}Ni_{0.1}As_2$ crystals was 34 mg and 56 mg, respectively. Temperature dependence of ac-susceptibility was measured by the Quantum Design PPMS system. Irreversible magnetization loops we obtained using home-built low-frequency (3.6 Hz) vibrating sample magnetometer with a step motor [8].

High quality of crystals of both compositions was confirmed by X-ray diffraction analysis demonstrating absence of any foreign phases as well as by the results of ac-susceptibility measurements of zero-field superconducting transition showing transition width (10%-90%) of about 1K. As an example in Fig.1 one can see data for $Ba_{0.64}K_{0.36}Fe_2As_2$ sample at H=0.

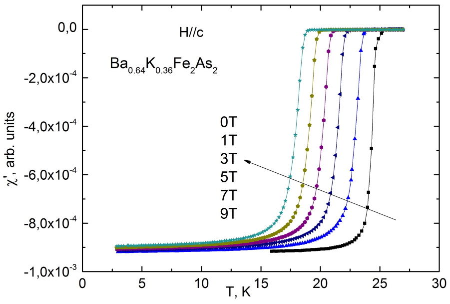

Figure 1. Temperature dependence of ac-susceptibility of $Ba_{0.64}K_{0.36}Fe_2As_2$ sample in the region of superconducting transition in magnetic field up to 9T.

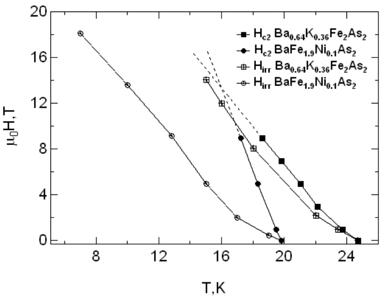

Figure 2. Temperature dependence of the upper critical field and irreversibility field for $Ba_{0.64}K_{0.36}Fe_2As_2$ and $BaFe_{1.9}Ni_{0.1}As_2$ single crystals.

In Fig. 1 we also show superconducting transitions obtained for $Ba_{0.64}K_{0.36}Fe_2As_2$ crystal by ac-susceptibility measurements in magnetic field up to 9T parallel to the c-axis. With increasing field transition curves moved to lower temperatures without any broadening of the transition. Very similar data were found for $BaFe_{1.9}Ni_{0.1}As_2$ crystal [6]. The difference between two sets of data for $Ba_{0.64}K_{0.36}Fe_2As_2$ and $BaFe_{1.9}Ni_{0.1}As_2$ single crystals is the following: due to lower zero-field T_c transition curves for $BaFe_{1.9}Ni_{0.1}As_2$ sample located at lower temperatures while the total temperature shift of the transition by 9T field is larger for $Ba_{0.64}K_{0.36}Fe_2As_2$

crystal signaling lower value of a slope of the temperature dependence of the upper critical field, $H_{c2}(T)$, for $\mathrm{Ba_{0.64}K_{0.36}Fe_2As_2}$ crystal compared to $\mathrm{BaFe_{1.9}Ni_{0.1}As_2}$ sample. This result is much more clearly seen from Fig. 2 where we plot $H_{c2}(T)$ dependence for $\mathrm{Ba_{0.64}K_{0.36}Fe_2As_2}$ and $\mathrm{BaFe_{1.9}Ni_{0.1}As_2}$ samples. Superconducting transition point was obtained by extrapolation of a linear part of the transition to zero level. Estimation of the slope of the $H_{c2}(T)$ dependence gives $dH_{c2}/dT \approx -4.2T/K$ and $\approx -1.75T/K$ for $\mathrm{BaFe_{1.9}Ni_{0.1}As_2}$ and $\mathrm{Ba_{0.64}K_{0.36}Fe_2As_2}$ crystals, respectively. Using these data and Werthamer, Helfand, and Hohenberg (WHH) expression [9] we obtain $H_{c2}(0) = 0.69T_c((dH_{c2})/dT) \approx 56T$ for $\mathrm{BaFe_{1.9}Ni_{0.1}As_2}$ sample and lower value of $H_{c2}(0) \approx 31T$ for $\mathrm{Ba_{0.64}K_{0.36}Fe_2As_2}$ crystal suggesting crossing of $H_{c2}(T)$ lines for these samples as presented in Fig.2 by linear extrapolation of $H_{c2}(T)$ dependences shown by dotted lines.

Also in Fig. 2 we present temperature dependence of the irreversibility field, $H_{irr}(T)$, for both samples obtained at different temperatures from irreversible magnetization loops, $M(H)$, shown in Fig.3 and Fig.4. To get H_{irr} at fixed temperature for closed $M(H)$ loops we used value of field when $\Delta M(H) = M_{down}(H) - M_{up}(H)$, where M_{up} and M_{down} - magnetization measured with increasing and decreasing field, falls below instrument resolution limit. For opened $M(H)$ loops in order to estimate H_{irr} (somewhat arbitrarily) we employed an empirical extrapolation to zero of a part of $M(H)$ curves at fields lower than the value of the inflection point [6]. As one can see from Fig. 2 in striking contrast to expected crossing behavior of $H_{c2}(T)$ lines $H_{irr}(T)$ line for$\mathrm{BaFe_{1.9}Ni_{0.1}As_2}$ crystal located this one for $\mathrm{Ba_{0.64}K_{0.36}Fe_2As_2}$ crystal at all fields and temperatures used in our study reflecting higher field and temperature limits of the vortex solid region with non-zero critical current for $\mathrm{Ba_{0.64}K_{0.36}Fe_2As_2}$ crystal.

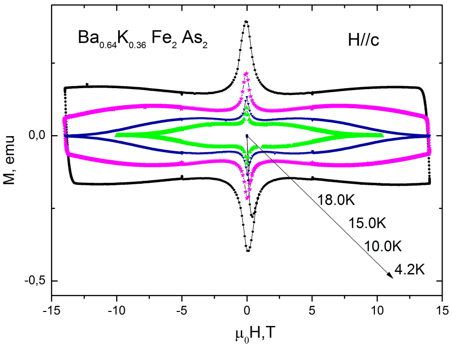

Figure 3. Isothermal magnetization loops in fields up to 14T for $\mathrm{Ba_{0.64}K_{0.36}Fe_2As_2}$ single crystal at various temperatures.

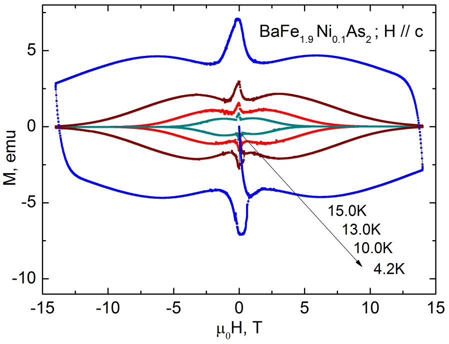

Figure 4. Isothermal magnetization loops in fields up to 14T for $\mathrm{BaFe_{1.9}Ni_{0.1}As_2}$ single crystal at various temperatures.

This result finds a support from Fig. 5 where we present field dependence of the critical current density for $\mathrm{Ba_{0.64}K_{0.36}Fe_2As_2}$ and $\mathrm{BaFe_{1.9}Ni_{0.1}As_2}$ single crystals at different temperatures. J_c value was calculated from irreversible magnetization loops shown in Fig.3 and Fig.4 using the well-known expression $J_c = 20\Delta M/a(1 - a/3b)$ obtained within Bean critical state model [10,11] where a and b ($b > a$) are the in-plane crystal sizes with field applied parallel to the c-axis. Presented in Fig. 5 data show substantially higher J_c values in about one order of magnitude for sample $\mathrm{BaFe_{1.9}Ni_{0.1}As_2}$ compared to $\mathrm{Ba_{0.64}K_{0.36}Fe_2As_2}$ crystal at fields below 1T. With further increase of field difference between J_c values for these two crystals rapidly decreases. At T=15K and $H > 4T$ as well as at T=10K and $H > 12T$ J_c value for $\mathrm{Ba_{0.64}K_{0.36}Fe_2As_2}$ crystal exceeds critical current density for $\mathrm{BaFe_{1.9}Ni_{0.1}As_2}$ sample. At T=4.2K higher J_c for $\mathrm{Ba_{0.64}K_{0.36}Fe_2As_2}$ crystal may be expected at fields above 15-16T. Thus, these results clearly demonstrate greater critical current potential of even under-doped $\mathrm{Ba_{0.64}K_{0.36}Fe_2As_2}$ compound

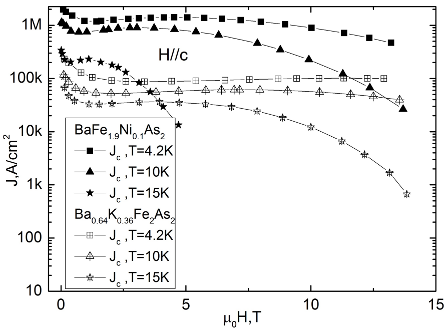

Figure 5. Calculated from M(H) curves field dependence of critical current density for $Ba_{0.64}K_{0.36}Fe_2As_2$ and $BaFe_{1.9}Ni_{0.1}As_2$ single crystals.

compared to optimally doped $BaFe_{1.9}Ni_{0.1}As_2$ sample in high magnetic fields.

3. Conclusions

We have studied magnetic phase diagram and critical currents in $BaFe_{1.9}Ni_{0.1}As_2$ and $Ba_{0.64}K_{0.36}Fe_2As_2$ crystals with approximately the same T_c values. Our results show that vortex solid phase boundary for $Ba_{0.64}K_{0.36}Fe_2As_2$ crystal located at higher temperature and magnetic field compared to $BaFe_{1.9}Ni_{0.1}As_2$ sample. Critical current density of $BaFe_{1.9}Ni_{0.1}As_2$ crystal exceeds J_c for $Ba_{0.64}K_{0.36}Fe_2As_2$ at fields below $\sim 1T$. With increasing field difference between J_c values for $BaFe_{1.9}Ni_{0.1}As_2$ and $Ba_{0.64}K_{0.36}Fe_2As_2$ crystals rapidly decreases, thus, demonstrating higher critical currents in $Ba_{0.64}K_{0.36}Fe_2As_2$ samples in strong magnetic fields above ~10-15T.

4. Acknowledgements

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