Unconventional pinning in iron based superconductors of 122 family

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Abstract

We report on comparative analysis of vortex pinning in Fe-based superconductors of the 122 family with different types of doping within the models proposed by Griessen et al [Phys. Rev. Lett. 72 (1994) ] and Dew-Hughes [Phil. Mag. 30 (1974) 293]. We found that FBS 122 superconductors with electron and hole-doping demonstrate strong pinning with position of peak maximum $h_p \sim 0.3-0.45$ in normalized pinning force curve vs. reduced field $h=H/H_{irr}$, whereas for samples with isovalent doping (i.e. substitution As for P) our analysis shows $h_p \sim 0.7$ indicating weak pinning. We argue that pinning in FBS with isovalent doping can be successfully described within Griessen et al $\delta T_c$ and $\delta l$ models, while pinning in FBS 122 superconductors with electron and hole-doping shows significantly different behavior from the $\delta T_c$ or $\delta l$ model predictions.

1. Introduction

The discovery of superconductivity in LaFeAsO$_{1-x}$F$_x$ at $T_c = 26K$ (Kamihara et al. (2008)) in 2008 induced great interest to new iron based superconductors (FBS). Since that time, more than 100 FBS compounds have been synthesized, so-called 11 (Shahbazi et al. (2013b)), 111 (Parker et al. (2009)), 122 (Pervakov et al. (b); Sun et al. (2009)) and 1111 (Wang et al. (2010)) families. Taking into account their superconducting properties the most promising families for practical usage are 122 (Bukowski et al. (2009); Huan Yang and Wen) and 1111 (van der Beek et al. (2010)). However, due to complicated synthesis and great cost of 1111, it is improbable that it would be widely used in applications. The main superconducting properties essential for practical applications are critical current density ($J_c$), critical temperature ($T_c$) and the upper critical field ($H_{c2}$). It is well known that the behavior and value of the $J_c$ depends on the type and strength of the flux pinning. For this reason we concentrated our study on vortex pinning...
Fig. 1: Temperature dependence of ac-susceptibility for for BaFe$_{1.91}$Ni$_{0.09}$As$_2$ in field up to 9 T applied along c-axis.

of the 122 family with an electron (n-type) (Pervakov et al. (b); Shen et al. (2010)), hole (p-type) (Sun et al. (2009); Pramanik et al.) and isovalent (Fang et al. (2011); van der Beek et al.) doping of parent compound.

The most effective tools to investigate the flux pinning mechanisms are models proposed by Griessen et al (Griessen et al.) and Dew-Hughes (DH) (Dew-Hughes (1974)). The fist one describes behavior of the temperature dependence of $J_c$ in terms of $\delta T_c$-pinning (spatial fluctuations of the critical temperature and extended pinning centers) and $\delta l$-pinning (random deviations of the mean free path charge carriers and point like pinning centers). The DH model evaluates the strength of pinning force depending on the position of the peak maximum ($h_p$) on the curve of normalized pinning force ($f=F_p/F_{p\max}$) versus reduced field ($h=H/H_{c2}$), where $F_p=J_cB$ is flux pinning force. According to the theory, the scaled pinning force can be fitted by expression $F_p/F_{p\max}=Ah_p(1-h)^q$, where $A$ is a numerical parameter, $p$, and $q$ are fitting parameters. The location of the maximum $f$ vs. $h$ indicates strong pinning centers when $h_p < 0.5$, while the position of the $h_p > 0.5$ stands for weak pinning. The $h_p$ position can be given by the expression $\approx p/(p + q)$.

In this work we carried out a comparison of the experimental data for different FBS compounds and discuss the properties of flux pinning of these superconducting materials. Additionally, we present some new data of $J_c(T)$, $f(h)$ and $H_{c2}$ of 122 single crystals with electron and hole-doping. Our analysis shows evidence of an unconventional pinning in 122 superconducting systems with strong pinning.

2. Results and discussion

BaFe$_{1.91}$Ni$_{0.09}$As$_2$ and Ba$_{0.64}$K$_{0.36}$Fe$_2$As$_2$ single crystals were grown by self-flux method as described before (Pervakov et al. (b)). The susceptibility measurements were done using Quantum Design PPMS. As an example Fig. 1 presents the data of magnetic susceptibility measurements vs. temperature of BaFe$_{1.91}$Ni$_{0.09}$As$_2$ single crystal in field up to 9 T ($H \parallel c$). The high quality of single crystals is illustrated by quite sharp superconducting transition of our samples. One can see transition width of about 1.5 K. Similar data were obtained for Ba$_{0.64}$K$_{0.36}$Fe$_2$As$_2$ single crystal. The value of the transition width and its sharpness evidents high quality of our samples.

The critical transition was determined by the deviation of the susceptibility vs. $T$ curve from linear signal and obtained value was about 18.9 K for Fe$_{1.91}$Ni$_{0.09}$As$_2$ and 25.5 K for Ba$_{0.64}$K$_{0.36}$Fe$_2$As$_2$. The slope of the upper critical field vs. temperature gave us value of $dH_{c2}/dT = -2.04$ T/K for Fe$_{1.91}$Ni$_{0.09}$As$_2$ and $dH_{c2}/dT = -1.75$ T/K for Ba$_{0.64}$K$_{0.36}$Fe$_2$As$_2$. Applying Werthamer, Helfand and Hohenberg (WHH) expression (Werthamer et al.) for dirty limit ($H_{c2}(0) = -0.693T_c(dH/dT)_{T_c}$) we estimate the value of upper critical field ($H_{c2}(0)) \approx 26$ T and 31 T for BaFe$_{1.91}$Ni$_{0.09}$As$_2$ and Ba$_{0.64}$K$_{0.36}$Fe$_2$As$_2$ single crystal respectively. The magnetization measurements were made using hand made vibrating sample magnetometer in magnetic field applied along the $c$-axis up to 14 T (Nizhankovskii and Lugansky). In Fig. 2 we present the bulk magnetization hysteresis loops (M(H)) of single crystal with electron doping (BaFe$_{1.91}$Ni$_{0.09}$As$_2$) at different temperatures. The field sweeping rate was about 100 Oe/s. As depicted in Fig. 2, all M(H) curves are quite symmetric indicating the bulk pinning and absence of magnetic impurities.
It is interesting to note, just like in cuprate superconductors (Koblischka et al.), a quite noticeable peak (fishtail) effect (PE) was observed for both BaFe$_{1.91}$Ni$_{0.09}$As$_2$ and Ba$_{0.64}$K$_{0.36}$Fe$_2$As$_2$ samples, which correlates with the data from other studies (Pervakov et al. (b); Sun et al. (2009)). The observable PE shifts to a zone of higher fields with reduction the temperature of the sample. The nature of the PE is still the subject of discussion, as it could be caused by several mechanisms (Salem-Sugui et al. (2010)). As it was mentioned above the FBS superconductors have significant difference between upper critical field (H$_{c2}$) and the irreversibility field (H$_{irr}$) see e.g. (Pervakov et al. (a)). For this reason H$_{irr}$ are usually used to determine reduced field. The H$_{irr}$ value can be obtained from the fusion point in hysteresis magnetization loops.

Fig. 3 shows the curves of the $J_c$ at different temperatures for BaFe$_{1.91}$Ni$_{0.09}$As$_2$ and Ba$_{0.64}$K$_{0.36}$Fe$_2$As$_2$ single crystals. The calculations of the critical current density were carried out using the well known expression ($J_c = 20\Delta M/(a(1-a/3b))$, where a<b and a,b-width and length of the sample, $\Delta M$ width of the magnetization loop) obtained within Bean’s Critical State Model (Bean). The dimensions of Ba$_{0.64}$K$_{0.36}$Fe$_2$As$_2$ crystal were about 2.5 x 0.82 x 0.43 mm$^3$ and 2 x 1.3 x 0.28 mm$^3$ for BaFe$_{1.91}$Ni$_{0.09}$As$_2$ single crystal. In both cases with decrease of the temperature, $J_c$ significantly increases. The obtained values of the $J_c$ in BaFe$_{1.91}$Ni$_{0.09}$As$_2$ single crystal reached 3.9x10$^5$A/cm$^2$ and up to 2.3x10$^5$A/cm$^2$ in Ba$_{0.64}$K$_{0.36}$Fe$_2$As$_2$ single crystal in zero field at liquid helium temperature. As one can notice, despite the higher critical temperature in Ba$_{0.64}$K$_{0.36}$Fe$_2$As$_2$, the current carrying capacity of BaFe$_{1.91}$Ni$_{0.09}$As$_2$ single...
crystal was significantly higher. This fact can be explained by the higher pinning force according to DH model in a single crystal doped with nickel as it shown in Fig. 4.

DH analysis implies that the plotting of \( f_p \) versus \( h \) at different temperatures in case of one dominating pinning mechanism gives us a single scaled curve. In Fig. 4 we plot normalized pinning force \( f \) as a function of reduced field \( h = H/H_{irr} \) for \( \text{BaFe}_{1-x}\text{Co}_x\text{As}_2 \) and \( \text{BaFe}_{1.01}\text{Ni}_{0.09}\text{As}_2 \). The obtained indexes were \( p = 1.16, q = 2.76 \) for electron doped sample and \( p = 1.6, q = 1.8 \) for hole-doped sample. We also obtain \( h_p \) values of about \( \approx 0.3 \) and \( \approx 0.45 \) for the \( \text{BaFe}_{1.01}\text{Ni}_{0.09}\text{As}_2 \) and \( \text{BaFe}_{1.03}\text{Fe}_2\text{As}_2 \) single crystals respectively, giving us according to DH prediction an evidence of the strong intrinsic pinning force and one dominant pinning mechanism. These values are similar to presented data in other studies (Pervakov et al. (b); Sun et al. (2009); Shahbazi et al. (2013a)).

For type-II superconductors Griessen et al. (Griessen et al.) suggested that the behavior of the \( J_c \) curve could also give us information about the pinning nature. It describes pinning according to two dominating pinning mechanisms: \( \delta l \) and \( \delta T_c \) pinning. The \( \delta l \) defects should be small spot-like size, in the case of \( \delta T_c \) pinning extended defects are larger than the correlation length. The model predictions are the following: (i) \( J_c(t) / J_c(0) = (1-t^2)^{\frac{n}{6}}(1+t)^{\frac{q}{6}} \) for \( \delta T_c \) pinning, (ii) \( J_c(t) / J_c(0) = (1-t^2)^{\frac{n}{2}}(1+t^2)^{-\frac{q}{2}} \) for \( \delta l \) pinning. In this work the values of the critical current density were taken for the applied field of about 0.1 T. The obtained data were fitted by the expression \( J_c = J_{c}(0K)(1-(T/T_c)^n)^m \) (Talanov et al.), where \( J_c(0K) \) (critical current at zero temperature), \( n \) and \( m \) are adjustable parameters obtained by the method of least squares by minimizing the function. Evaluated \( J_c(0K) \) was used for the normalization of \( J_c \) at different temperatures.

The evidence of deviation from this theoretical predictions for FBS samples was found in several works before (Pramanik et al.; Prozorov et al. (2009); Klein et al. (2014); Prozorov et al. (2008)). As one can clearly see from Fig. 5 the data from different works (Pervakov et al. (b); Shen et al. (2010); Pramanik et al.; Yang et al. (2008); Tamegai et al. (2010); Prozorov et al. (2009)) show significant deviation from predictions Griessen et al. model (Griessen et al.). According to the estimates of Yang et al. (Yang et al. (2008)) the difference between estimated current at 2 K \( (T/T_c = 0.055) \) and 5 K \( (T/T_c = 0.139) \) in \( \text{BaFe}_{1.03}\text{Fe}_2\text{As}_2 \) single crystal should be about 5%, but we observed the difference more than 50%. The similar situation was mentioned in other papers showing no saturation of \( J_c \) at low temperatures. In recent work (Klein et al. (2014)) authors conclude that \( J_c \) behavior in Fe(Se,Te) single crystal is strongly different from both \( \delta l \) and \( \delta T_c \) pinning models. Since this compound has strong pinning (Shahbazi et al. (2013b)), this fact also confirms inaccuracy of Griessen et al. (Griessen et al.) model for FBS with strong pinning. On the other hand, in FBS compounds with weak pinning force: \( \text{KFe}_2\text{Se}_2 \) (Lei and Petrovic (2011)), \( \text{Ca(Fe}_{1-x}\text{Co}_x\text{)}_2\text{As}_2 \) (Pramanik et al. (2010)), \( \text{BaFe}_2(\text{As}_{1-y}\text{P}_y)_2 \) (van der Beek et al.) and cuprate (Griessen et al.) superconductors compounds theo-
Fig. 5: Normalized temperature dependence of the $J_c$ for $\text{Ba}_{1-x}\text{K}_x\text{Fe}_2\text{As}_2$ (Pervakov et al. (a); Yang et al. (2008)), $\text{BaFe}_{1.91}\text{Ni}_{0.09}\text{As}_2$ (Pervakov et al. (b)), $\text{BaFe}_{1.01}\text{Co}_{0.12}\text{As}_2$ (Shen et al. (2010); Tamegai et al. (2010)), $\text{Ca(Fe}_{1-x}\text{Co}_x\text{As}_2$ (Pramanik et al. (2010)), $\text{BaFe}_2\text{As}_{1-x}\text{P}_x\text{As}_2$ (van der Beek et al.), $\text{Ba}_{1-x}\text{Na}_x\text{Fe}_2\text{As}_2$ (Pramanik et al.) and $\text{K}_x\text{Fe}_2\text{Se}_2$ (Lei and Petrovic (2011)) samples at $B=0.1\ T$. The solid line corresponds to $\delta T$ and $\delta l$ pinning formula respectively.

Theoretical prediction works rather well (see Fig.5). The following two assumptions may explain this fact. The first one is related with the difference between the number, shape or/and the strength of pinning centers that may be one of the reasons resulting in additional vortex-vortex interactions of pinning cores. The second one may be related with dramatic changes in nature of pinning at low temperatures ($<5\ K$) in $122$ superconducting family with strong pinning centers contrasting to the suggestion of the Griessens et. al. (Griessen et al.) model. Considering the above, we believe that unconventional $J_c$ behavior in FBS is directly related with strong intrinsic pinning. Further investigations are needed to confirm this assumptions.

3. Conclusion

In conclusion, we have investigated isothermal irreversible magnetization loops of underdoped $\text{Ba(Fe}_{1-x}\text{Ni}_x\text{As}_2$ ($x = 0.09$) and $\text{Ba}_{1-x}\text{K}_x\text{Fe}_2\text{As}_2$ ($x = 0.36$) single crystals in magnetic fields up to $14\ T$ applied perpendicular to the $ab$-plane. The critical current density $J_c$ obtained from the $M(H)$ dependences are comparable with other hole and electron doped $122$ compounds. The analysis of field dependence of $J_c$ gave us indication of strong vortex pinning for both samples. In addition, we observed strong deviation from Griessens et al (Griessen et al.) model for $J_c$ of our samples as well for the data for electron- and hole doped $122$ samples obtained by other groups. At the same time our analysis shows no evidence of unconventional behavior in $J_c$ vs. $T$ curves in Fe-based compounds with weak pinning centers.

Acknowledgements

This study was supported by the Russian Foundation for Basic Research (grant 13-02-01180) of the Russian Federation.

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