Magnetoresistance, critical current density, and magnetic flux pinning mechanism in nickel doped BaFe2As2 single crystals

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Magnetoresistance, critical current density, and magnetic flux pinning mechanism in nickel doped BaFe$_2$As$_2$ single crystals


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The critical current density, $J_c$, flux pinning behavior and magnetoresistance results of BaFe$_{2-x}$Ni$_x$As$_2$ single crystal have been investigated in fields up to 13 T over a temperature range of 2 to 20 K. The magnetoresistance below the superconducting transition temperature ($T_c$) shows Arrhenius thermally activated behavior: $\rho = \rho_0 \exp(-U_0/(k_B T))$, where $U_0$ is the thermally activated energy. BaFe$_{2-x}$Ni$_x$As$_2$ exhibits high thermally activated flux flow energy with a very weak field dependence. $J_c$ is as high as $2 \times 10^5$ A/cm$^2$ for zero magnetic field at 2 K. $J_c$ was found to decrease for $B < 1$ T, but showed a very weak field dependence and remained nearly constant with increasing magnetic field for $B > 1$ T at $T = 2, 5,$ and 10 K. Flux jumping was also observed in magnetization loops at very low temperature for large sample, which is related to the high $J_c$ in the single crystal. A peak effect was observed at 10 K. © 2011 American Institute of Physics. [doi:10.1063/1.3563057]

The discovery of the first iron based superconductor, fluorine doped LaFeAsO$_4$, aroused great interest due to the high upper critical field $H_{c2}$, high $J_c$, and very high intrinsic pinning potential compared with MgB$_2$ and other conventional superconductors and even cuprate superconductors. Doped BaFe$_2$As$_2$ has a maximum $T_c$ of 38 K. The parent compound shows an anomalous decrease in the resistivity at $T = 140$ K, which is related to structural change combined with spin density wave transition, and superconductivity occurs by hole doping with alkali metals such as Na, K, or Cs, or by electron doping achieved by replacing a small fraction of Fe with a large transition metal.3–12

A second peak effect has been observed in BaFe$_{2-x}$Co$_{x}$As$_2$, BaFe$_{2-x}$Ni$_x$As$_2$, and Ba$_{1,4}$K$_{0.6}$Fe$_2$As$_2$ single crystal.13,14 The second peak effect can be resulted by a crossover from the elastic collective creep to the plastic vortex creep or it is associated with the structural phase transition from a rhomb lattice at low field to a square lattice above a transition field.15 The absence of the second magnetization peak effect in CaFe$_{2-x}$Co$_x$As$_2$ indicated that the vortex dynamics in this compound is consistent with plastic creeping rather than the collective creep model.18

(Ba,K)Fe$_2$As$_2$ superconductor with nearly isotropic superconductivity, very high intrinsic pinning, $H_{c2}$ as high as 200 T, and high pinning potential, as high as $10^5$ K is a promising candidate for high magnetic field application. Flux jumping has also been observed in the Ba$_{1.4}$K$_{0.6}$Fe$_2$As$_2$ single crystal.20 However, flux jumping and pinning potential behavior have not been reported in the electron doped BaFe$_{2-x}$Ni$_x$As$_2$ so far. In this paper we present the pinning potential behavior in optimal electron doped BaFe$_{1.9}$Ni$_{0.1}$As$_2$ single crystal. The pinning potential is as high as 5300 K at low magnetic field for both $ab$ plane and $c$ direction. Estimated $H_{c2}$ from the slope of $dH_{c2}/dT$ is $H_{c2}^{ab} = 81.5$ T, which higher than the Bardeen–Cooper–Schrieffer (BCS) paramagnetic limit. Flux jumping is observed at low temperature and low magnetic field.

Single crystal with the nominal composition BaFe$_{1.9}$Ni$_{0.1}$As$_2$ was prepared by a self-flux method. Details of the single crystal growth will be reported elsewhere. The grown single crystal was cleaved and cut into a rectangular shape for measurement. The transport properties were measured over a wide range of temperature and magnetic fields up to 13 T with applied current of 5 mA using a physical properties measurement system (PPMS, Quantum Design). The temperature dependence of the magnetization and the $M$-$H$ loops were measured using magnetic properties measurement system (MPMS, Quantum Design). The critical current density was calculated using the Bean model.

The temperature dependence of the resistivity of BaFe$_{1.9}$Ni$_{0.1}$As$_2$ for applied field parallel to the $ab$ plane and $c$ direction is shown in Fig. 1. The resistivity decreases with decreasing temperature from 300 to 19.4 K, supporting metallic behavior of this compound for $H//c$. The resistance drops to zero at $T_c = 17.6$ K for $H//c$ in zero magnetic field. The $T_c$ value is lower than that reported in Ref. 21. The onset of superconductivity slowly shifts to lower temperature with increasing magnetic field, which is related to the nearly isotropic superconductivity in the 122 family.22 The superconducting transition width, $\Delta T_c = 0.8$ K, was calculated using the temperature difference between the 90% and 10% values in the drop-off of the resistivity at zero magnetic field, which indicates a sharp superconducting transition temperature and high quality single crystal.

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been estimated for BaFe$_{2-x}$Ni$_x$As$_2$ single crystal in different magnetic field up to 13 T.

FIG. 1. (Color online) Temperature dependence of resistivity of a BaFe$_{1.9}$Ni$_{0.1}$As$_2$ single crystal in different magnetic field.

FIG. 2. (Color online) Temperature dependence of the upper critical field and irreversibility field.

FIG. 3. (Color online) Arrhenius plot of the electrical resistivity at different magnetic fields parallel to the $ab$ plane and $c$ direction.

$H_{c2}$ is characterized as the field at which the resistance becomes 90% of the normal state resistivity; while the irreversibility field, $H_{irr}$, is defined by 10% of the normal state resistivity. Figure 2 shows the temperature dependence of $H_{c2}$ and $H_{irr}$ as a function of temperature, based on the magnetoresistance measurement. The estimated slopes for $H_{c2}$ and $H_{irr}$ are $-6.69$ and $-4.22$ for $H||c$. Different slopes, $dH_{c2}/dT$, have been estimated for BaFe$_{2-x}$Ni$_x$As$_2$ iron based superconductor ranging from $5.42$ TK$^{-1}$ for $x = 0.09$ (Ref. 13) to the high value of $9.9$ TK$^{-1}$ for $x = 0.1$ (Ref. 23) single crystal. $H_{c2}$ was estimated by using the conventional one-band Werthamer–Helfand–Hohenberg (WHH) theory: $H_{c2}(0) = -0.69T_c$, $dH_{c2}/dT$, assuming that $H_{c2}$ is limited by the orbital pair breaking effect. The $H_{c2}$ values estimated to be 46.6 and 81.5 T along the $ab$ plane and $c$ direction, respectively. The estimated $H_{c2}$ values are the field at which the resistance becomes 90% of the normal state resistivity; while the irreversibility field, $H_{irr}$, is defined by 10% of the normal state resistivity.

Using the value of $H_{c2}^{ab}$, we calculated the Ginzburg–Landau coherence length, $\xi_{GL} = (\Phi_0/2\pi H_{c2}^{ab})^{1/2}$, where $\Phi_0 = 2.07 \times 10^{-7}$ Oe cm$^2$. The obtained coherence length $2.7$ and $2.01$ nm along $ab$ plane and $c$ direction at $T=0$ K, respectively. According to our data, the estimated anisotropy $\gamma = H_{c2}^{ab}/H_{c2}^{ab} = 1.7$, for the temperature range of $12 < T < 18$ K which indicates nearly isotropic superconductivity in this compound.

Thermally activated flux flow is responsible for the broadening of the resistivity transition and can be described by the following equation: $\rho(T, H) = \rho_n \exp \left(-U_o(T, H)/k_B T\right)$, where $\rho_n$ is the normal state resistivity, $U_o$ is the pinning potential and $k_B$ is the Boltzmann constant. In Fig. 3, we plot $\log \rho$ vs $1/T^2$ at different magnetic fields. The linearity of $\log \rho$ vs $1/T^2$ indicates the thermally activated energy behavior of the resistivity. The slope of the curves is the pinning potential, $U_o$.

The best fit to the experimental data yields a value of the pinning potential of 5300 K for $H||c$ and $H||ab$ at the low magnetic field of 0.1 T. The pinning potential value for BaFe$_{1.9}$Ni$_{0.1}$As$_2$ single crystal is 5 times greater than that of Bi-2212 crystal. This value is lower than the reported value of 9100 K for Ba$_{0.5}$K$_{0.5}$Fe$_2$As$_2$ single crystal for $H||ab$, probably due to the different dopants. The magnetic field dependence of the pinning potential is shown in Fig. 4. The activation energy drops very slowly with increasing applied magnetic field for $B < 1$ T, and then decreases slowly as $B$ $^0.56$ for $B > 1$ T for $H||c$. This means that the pinning potential is almost field independent for $B < 1$ T.

Figure 5 shows the $M$–$H$ loops measured at $2, 5, 10,$ and $15$ K in the field range of $-5 \leq H \leq 5$ T for
BaFe$_{1.9}$Ni$_{0.1}$As$_2$ single crystal for $H//c$. Flux jumping was observed at 2 K at low magnetic field, similar to what was observed in K doped 122 single crystal.\cite{10}

The temperature dependence of the superconducting diamagnetic moment of the sample is shown in the inset of Fig. 5. BaFe$_{1.9}$Ni$_{0.1}$As$_2$ single crystal exhibited its superconducting transition temperature at 17.6 K. This value is the same as the $T_c$ value from the resistivity measurement. Figure 6 shows the $J_c$ calculated by using the Bean model:\cite{13}$J_c = 20\Delta m/(a (1-a/3b))$ ($a < b$), where $\Delta m$ is the height of the magnetization loop, and $a$ and $b$ are the length and width of the sample, respectively. $J_c$ is as high as $5.4 \times 10^5$ and $1.14 \times 10^8$ A/cm$^2$ at 2 and 10 K in zero magnetic fields, respectively. The estimated $J_c$ at 10 K is in good agreement with the $J_c$ value of similar compounds.\cite{13} $J_c$ decreases with increasing magnetic field up to 1 T and after that, becomes nearly field independent, which is related to the very high pinning potential in this compound. The second magnetization peak can be seen at $T = 10$ K, possibly due to softening of the vortices. At this temperature, vortex can find pinning centers more easily, which results in a higher flow of supercurrent in certain magnetic fields. The applied magnetic field is not high enough to allow the second magnetization peak to be observed at 2 and 5 K. A similar peak effect has been reported for the 122-FeAs family.\cite{13}

In summary, the BaFe$_{1.9}$Ni$_{0.1}$As$_2$ single crystal exhibits high pinning potential, although it has a very small coherence length. It is possible that its nearly isotropic properties are responsible for the high pinning potential value of this compound. A peak effect was observed at $T = 10$ K. Flux jumping occurred at 2 K at very low magnetic field.

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