Abstract

The 122 iron arsenide unconventional superconductors are part of a new class of iron-based superconductors. Co-doped BaFe₂Co₁₋ₓAs₂ (Ba-122) iron superconductors sample have been examine by scanning Hall probe microscopy (SHPM) technique to find out the magnetic properties of Ba-122. Has been completed the evolution of profiles of vortices which has well isolated and it is as function of temperature, then utilized suitable technique to extract the temperature depending on penetration depth λ(T). So, this allowed to deduce the temperature dependent on density of superfluid and it has been compared with α-model consequences for a (2-band) of superconductor. When the superfluid density for the BaFe₂Co₁₋ₓAs₂ (Over D x= 0.113) sample. As result, the two gap α-model has been fitted to the data with Δ₁=4.25kTc, Δ₂=1.92kTc, p=0.708, α₁=0.293 then α₂=1. However, When values of λ(T) for the BaFe₂Co₁₋ₓAs₂ (Over D x= 0.075) sample. Result of the superfluid density for BaFe₂ₓCo₁₋ₓAs₂ with parameters are (Δ₁=3.9k, Δ₂=1.6k), p=0.615 for Δ₁, and α₁=0.237, α₂=1. Suitable parameters produce refer into the symmetry of the order parameter at hole pockets with the electron, and then the relative supports of the bands to the density of superfluid in the iron-based crystals.

Keywords: GaAs/AlGaAs heterostructures, 2DEG Hall-probe sensor,scanning Hall probe microscopy technique.

Introduction

Early in 2006 superconductivity was found in LaFePO with a transition temperature Tc=5 K by Hosono’s group. Around the same time, various families of transition-metal oxide were discovered to be superconducting with similar low transition temperatures. However, in January 2008 the superconductivity community was surprised by another breakthrough of Hosono’s group when they reported that Tc=26 K in the closely related system LaFeAsO₁₋ₓFₓ [1]. The highest value achieved by replacing La by Sm in SmFeAsO₁₋ₓFₓ₀.₁ which was Tc=55K. The number of iron-based superconductors quickly increased after this as well as it is now divided into several families, for instance, the ternary ‘122’ compounds MF₂As₂ with the ThCrSi₂ crystal structure (M = Sr, Ba, Ca), so it is based on FeAs layers [2]. The compounds MF₂As₂ have the simplest crystal structure, also the structural and magnetic transitions occur simultaneously in this material (Tₐ=135K in BaFe₂As₂). Superconductivity has been discovered in different 122-compounds with hole or electron doping [3]. Furthermore, hydrostatic pressure can induce a superconducting state in the 122 - parent compounds for example CaFe₂As₂, SrFe₂As₂, and BaFe₂As₂. Both the magnetic penetration depth, (λ(T)), temperature dependence are sensitive probes of the superconducting gap and order parameter. The advantage of these measurements are directly probe the normalised superfluid density, (ρₛ = (λ(0)/λ(T))²). As result, to find out electrons numbers in (superconducting case). Scanning Hall probe microscopy (SHPM) technique was used in this work to find out temperature which is depending onλ(T), by imaging single vortices of BaFe₂ₓCo₁₋ₓAs₂ samples in very high quality single crystals with different doping levels. A measure gap fitting technique which was used to find out the density of superfluid model, yielding understandings at the Fermi surface by both the number with structure of superconducting gaps [4].

Lately, but, which has been shown very highly disordered vortices lattice in signal crystal sensor. So, reason behind that which is the introduction these defects by heavy ion irradiation be able to considerably improve jₑ, as well powerfully control the rates of sprawl vortex. Therefore, in order to understanding both vortex matter as well pinning potentials of these materials which that display significant to enable high current applications at the future [5, 6].

Experimental

GaAs/AlGaAs heterostructure sample is cleaved into (6 X 6) mm square chips. The chips are cleaned by three solvent cleaning steps in a standard way, namely keeping for 5 minutes in trichloroethylene, acetone and isopropanol, respectively in an ultrasonic bath at 18 % power. The chips are dried by high pressure nitrogen gas and then clean chips are stuck on glass cover slips using Shipley Micro posit S1813 photore sist with the active side facing up. Later, they are baked at 90°C for 30 minutes. Shipley Micro posit photore sist is spun onto the chips at 3500 rpm for 30 seconds to get a thick resist layer and baked in an oven at 90°C for 10 minutes. So, the chips are soaked in chlorobenzene. To obtain the formation of an overhang profile when patterned. Again, the resist is baked for same time. To pattern Ohmic contacts, the resist is exposed for about 10 to 20 seconds using a Karl Suss (MJB3) mask aligner. These samples are then developed using Micro posit 351 developer.

The surface oxide of chips are removed by dipping them in a 1:1 HCl: H₂O solution for 20-30 seconds and the oxide is removed when these chips are
mounted in a thermal evaporator. The contact material such as 66nm of Ge, 134nm of Au, 10-20nm of Ti and 200nm of Au, are evaporated sequentially in the same operation under high vacuum (3x10^-6 mbar). As a result, the chips are annealed under forming gas (90% N₂ and 10% H₂) at 415°C for 10 seconds which it leads form good electrical contact to the 2DEG. The 2DEG regions between Ohmic contact leads are removed by wet chemical etching using same process as well as the resist was then stripped in acetone with an optical microscope. By the same way, all patterning and cleaning steps were performed for the Ohmic contacts except the resist spin speed was increased from (4000-5000) rpm for 30 seconds. The sample tip was formed from a 10 nm of Ti thick layer and then followed by 50 nm layer of Au, without any annealing. The design for making the STM tip places it at the highest point near the corner of the Hall probe of sensors to ensure that it comes into contact with the sample first. Deep etching to a depth of ~1µm was performed in the same way as for coarse lead etching except the etching solution was (1:8:80) H₂SO₄:H₂O₂:H₂O with an approximate etch rate of 540 nm/min, shown in figure 1. After etching, the chips were cleaved into four Hall probes. The resist was then removed by the same way with acetone and isopropanol. The Hall sensors were mounted on a chip carrier using Oxford Instruments low temperature epoxy. The Ohmic contact leads were then bonded to the chip carrier using 25 µm diameter gold wire in an ultrasonic wire bonder. The chip carrier was then screwed onto the SHPM Head. The sample puck was then mounted on the SHPM Head then the angle between the sample plane and the Hall probe adjusted around 1-2 degrees. Later, the system has cooled below Tc, a coarse 'stick-slip' approach mechanism was used for both the sample and Hall probe until a tunnel current was detected at the tip. The puck was then retracted one step, the corners of the sample checked and the sample scanned.

Results and discussion
Both figures (2 and 3) show typical magnetization loops for Ba(Fe₀.₉₃Co₀.₀₇)₂As₂ and Ba(Fe₀.₈₉Co₀.₁₁)₂As₂ single crystals at different temperatures below Tc. These results were taken of the sample (Hall sensor) about (300-500) nm from the (surface of the crystal) with using magnetic field about (H=±70) G. The best measure of the diamagnetic screening about at (Hₑ=±/25G) which graph is shown in figures (2 and 3) which are shows as a function of temperature. The diamagnetic signal above the critical temperature of both samples is probably due to weak diamagnetism in the normal state. Figure 2 appears the estimated value of the critical temperature Tc=23.3±0.05K of the Ba (Fe₀.₉₃Co₀.₀₇)₂As₂ single crystal, which has been inferred from the intercept of the linear extrapolation of ∆M with temperature. Comparable data yielding the critical temperature (Tc =9.62±0.05K) of Ba (Fe₀.₈₉Co₀.₁₁)₂As₂ single crystal shown in figure 3.

Figure 1. It shows optical images of the chip after: (a) deep etching, (b) cleaving.
Figure 2. Dia-magnetic signal estimated of Ba (Fe$_{0.93}$Co$_{0.07}$)$_2$As$_2$ single crystal. (The inset above displays a typical $M_l$–$H_z$ captured at $T$ = 22.78 K)

Figure 3. Dia-magnetic signal estimated of Ba (Fe$_{0.89}$Co$_{0.11}$)$_2$As$_2$ single crystal. (The hysteresis loop taken at $T$ = 8.8 K)

Several vortices images of sample (Ba (Fe$_{0.93}$Co$_{0.07}$)$_2$) through temperature 12K resolved by (SHPM) technique (shows in Fig 4) with using magnetic fields (-6 to +2) G as well as somewhat of earth’s field about -2G. The (Ba (Fe$_{0.93}$Co$_{0.07}$)$_2$) sample has $H_z$=+1G from above $T_c$. Has noted that in this process, all images were crucial to capture by (SHPM) with every new temperature. These images are captured with size of scan about 9.0X9.0µm.

Figure 4. It shows images of vortices in a Ba (Fe$_{0.93}$Co$_{0.07}$)$_2$As$_2$ single crystal images using scanning Hall probe microscopy technique
In figure 5 illustration comparable vortices images captured by SHPM technique starting at (6k from T>12K) on a (Ba (Fe₀.₈⁹Co₀.₁₁)₃As₂ ) single crystal in somewhat magnetic fields applied from(-5 to +5)G. Furthermore, earth’s field around +2 G. These images are captured with size of scan about (7.0 X3.0) μm.

It is well established that the temperature depending on density of the superfluid, (ρₛ(T)), of BaFe₂Co₃As₂ single crystal samples which has been probed at various x-concentrations across the superconducting, optimally doped (OptD) x≈ 0.075 over doped (OD) x = 0.113. In addition, the magnetic penetration depth, λ(T), dependent on temperature in BaFe₂Co₃As₂ (OptD x = 0.07), after field cooling at H=+1G at different temperatures up to Tc which it was extracted by fitting the magnetic profile of a well-isolated single vortex after field cooling at H=+1G at different temperatures up to Tc. A variation model due to Clem with a modification suggested by Kirtley et al [7,8] which it was used to fit the data assuming λ(0)=0.250 μm, and ξx = 2.5nm/√1−T/Tc, width (w), of Hall probe (an active part )about (800)nm with z = 2.295μm as a fit parameter. As previously mentioned, the temperature-dependent normalised superfluid density (ρₛ(T)/ρₛ(0) = λ(0)²/λ(T)²) [9]. As a result, it was calculated using the extracted values of penetration depth. Basically, these data were then fitted to (2 band) α-model with (2 full gaps) and then it supposed to (ρₛ(T) = p₀ρₛ(T) + (1−p)ρ₂(T)), where (ρ₁(T), (ρ₂(T))) densities of superfluid in the dissimilar 2-bands with(ρ₂) are capture into measure the relative contribution from every one. Densities of superfluid were calculated from equations (1), (2) as below: [10].

\[ \rho_1(T) = 1 - \frac{1}{2kT} \int_0^{\infty} \cosh^{-2}\left(\sqrt{\frac{x^2 + \Delta(T)}{2kT}}\right) dx, \]  

Where the gap found via

\[ \Delta_0(T) = \Delta_0(0) \tanh\left[\frac{2kT}{\Delta_0(0)} \sqrt{\alpha_1 \left(\frac{T}{T_c} - 1\right)}\right] \]  

Here α_i refer to characteristic parameter which that meaning as following: (for instance, α_i=1, 4/3, 2 and 0.38 which firstly for isotropic s-wave pairing, secondly for two-dimensional d-wave, thirdly for s+g-wave and finally for nonmonotonic d-wave respectively) [11]. The best scan by SHPM technique is slightly superior than usually be expected as well as presumably the tilt angle of sensor is a bit better around 1° (one degree) in this process. Nevertheless, in order to extraction values of (λ(T)), at dissimilar temperatures of (Δλ(T) = λ(T) − λ(0)) see figure 6. Where it shows the extracted values of λ(T) for the BaFe₂Co₃As₂ (OptD x = 0.075) sample and figure. The calculated superfluid density for BaFe₂Co₃As₂ with parameters (Δ₁=3.9k, Δ₂=1.6k), p=0.615 for Δ₁, and α₁=0.237, α₂=1, [9,11].
Figure 6. It shows (a) extracted from fits on the BaFe$_2$Co$_x$As$_2$ (Opt. D x= 0.075) sample by $\Delta \lambda(T) = \lambda(T) - \lambda(0)$, which at (b) the red points appear the experimental the density of superfluid depending on the temperature (T).

At figure 7 (a,b) displays comparable data for the temperature dependence on the superfluid density for the BaFe$_2$Co$_x$As$_2$ (Over D x= 0.113) sample, which it was calculated by fitting $\Delta \lambda(T) = \lambda(T) - \lambda(0)$ on a well-isolated vortex at H=-1.50e where $\lambda(0)=0.2752 \mu$m, as well as z=1.547[9]. The two gap $\alpha$-model has been fitted to the data with $\Delta_1=4.25kT_c$, $\Delta_2=1.92kT_c$, $p=0.708$, $\alpha_1=0.293$ then $\alpha_2=1$ [11,12].

Figure 7. It shows (a) the BaFe$_2$Co$_x$As$_2$ (OverD x= 0.113) sample (b) red points show the experimental the density of superfluid depending on the temperature.

Both figures 6 and 7 show that the model of (2- gap) is a much best suitable to $\rho_0(T)$ than model of (1- gap) and has an $\approx8\%$ lower root-mean-square (RMS) error, while the error bars are completely large. In addition, the fitted values of $a_1=0.236$ for BaFe$_2$Co$_x$As$_2$ (Opt. x= 0.075) then $a_1=0.293$ for BaFe$_2$Co$_x$As$_2$ (OverD x= 0.113) would tend to implicate non-monotonic d-wave symmetry for the superconductivity gap symmetry with 45$^\circ$ nodes characteristic of the d-wave order parameter [11]. But, these results disagree other results in electron-doped pnictides where it gives proof for $\pm$ wave pairing [12]. Nevertheless, several recent reports literatures propose that the pairing symmetry in the BaFe$_2$As$_2$ compound undergoes a transition from s to d symmetry with potassium doping up to the fully doped KFe$_2$As$_2$ compound which has been identified as a d-wave superconductor[13,14].

Conclusions

1- In order to find the temperature dependent on $\lambda(T)$ in Co-doped BaFe$_2$As$_2$ single crystals has been used SHPM technique.
2- Our results have been modelled by assuming a picture of two fully gapped bands incorporating a free symmetry dependent parameter (a).
3- Analysis of vortex profiles has been made assuming that the small gap at the hole-like pockets is isotropic s-wave. Fit parameters suggest electron pockets have a strongly anisotropic OP in optimally doped Ba122 sample.

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The title translates as "The effect of Co doped BaFe2As2 on the superconducting properties.

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Co doping BaFe2As2 is considered a challenging task due to the complexity of the superconducting state and the nature of the FeAs layer. The addition of Co dopant is expected to affect the electronic structure of the system, thereby influencing the superconducting properties.

The authors investigated the superconducting properties of Co-doped BaFe2As2 thin films, using various techniques such as magnetization measurements and angle-resolved photoemission spectroscopy (ARPES).

The results showed that the superconducting transition temperature (Tc) increased with Co doping, indicating the enhancement of the superconducting properties. The critical current density (Jc) also increased, suggesting a possible enhancement in the superconducting connectivity.

Theoretical calculations were performed to understand the electronic structure and the superconducting transition temperature. The analysis showed that the doping of Co atoms in the FeAs layer had a significant impact on the electronic band structure, leading to an enhancement in the superconducting properties.

The study highlights the potential of Co-doped BaFe2As2 as a promising superconductor, offering opportunities for further research and development in the field of high-temperature superconductors.