Coexistence of ferromagnetic and superconducting domains in Co-doped $BaFe_2As_2$ superconductors probed using infrared Faraday measurements

A. Mukherjee[1], M.M. Arik[1], J. Seo[1], H. Xing[1], P. Taheri[1], H. Zeng[1], I.I. Mazin[2], H. Sato[3], H. Hiramatsu[3], H. Hosono[3] and J. Cerne[1]

[1]University at Buffalo, SUNY, Buffalo, NY 14260 USA
[2]Naval Research Laboratory, Washington DC 20375, USA
[3]Tokyo Institute of Technology, Yokohama, Japan

***Abstract*—We explore the electronic and magnetic properties of superconducting iron pnictide films by probing their infrared Hall conductivity as a function of probe energy (0.1- 1.3 eV), temperature (10-300 K) and magnetic field (B = 0-7 T). We find hysteretic behavior in the complex infrared Faraday angle, θ_F, at low B over the entire temperature range. At higher B, θ_F is linear in B and we observe a peak in the high B-field slope near 50 K, which may be related to the superconducting phase of the films.**

I. Introduction

Iron-based high temperatures superconductors (HTS) exhibit rich behavior due to the competition of many different phases. As opposed to cuprate HTS, the parent compounds of Fe-based superconductors are antiferromagnetic metals, for instance $BaFe_2As_2$ (Ba-122) is an anti-ferromagnetic metal with a Néel temperature T_N~130 K. Substituting about 8.5% of the Fe atoms with Co results in an optimally doped superconductor with a T_c around 26 K [1]. Longitudinal conductivity σ_{xx} measurements on Ba-122 superconductors [2,3] have found many rich features, including an infrared pseudogap phase, related to a spin density wave. In addition, iron-based superconductors exhibit unconventional DC Hall conductivity [4,5]. We expand the range of study by exploring the frequency-dependent Hall conductivity σ_{xy}, which is proportional to the infrared complex Faraday angle θ_F. θ_F in Ba-122 superconducting films and reference Fe films is measured as a function of energy, temperature and magnetic field B. θ_F in Ba-122 films is consistent with a soft ferromagnet (FM) having a step-like feature near B=0. This is surprising, since the level of Fe and/or Co impurities is very low in these samples, according to x-ray diffraction measurements. Furthermore, our experience with FM impurities/precipitates in GaMnAs suggests that these FM islands contribute weakly to the Faraday/Kerr signals, which probe the overall optical properties of the bulk material [6]. Whether the FM signal is intrinsic (for example, canting of Fe spins due to nearby Co dopants) or extrinsic (for example, segregated FM impurity domains), this material offers exciting new possibilities to study the interaction of FM, superconducting and possibly other phases (spin density wave, nematic, etc).

II. Results

We explore several Ba-122 and Fe films. An optimally doped 230 nm thick Ba-122 film was specially grown [1] using pulsed-laser deposition on BaF_2, which is transparent in the mid-infrared. In order to compare the Ba-122 signal to that from a standard FM material, 10 nm thick Fe films were sputtered onto BaF_2 substrates. The samples were placed inside a 7 T

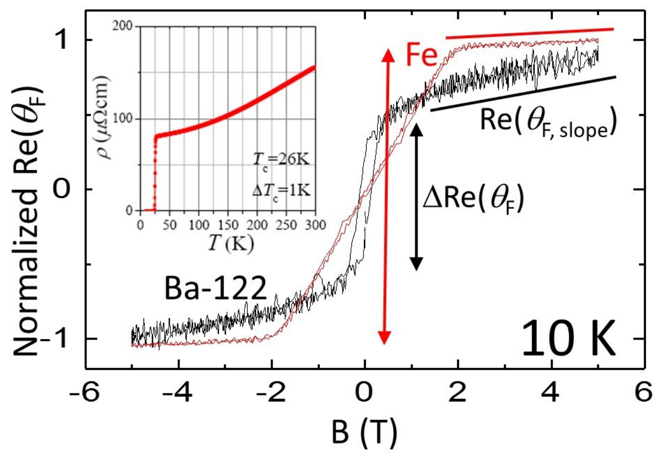

Fig. 1. Magnetic field dependence of the Re(θ_F) of Ba-122 and Fe film at a probe energy of 117 meV at 10 K. ΔRe(θ_F) and Re($\theta_{F, slope}$) are defined. Inset shows the measured resistivity of the film as a function of temperature T.

superconducting magneto-optical cryostat and were probed at a photon energy of 117 meV using a polarization-resolved system [6,7]. The normalized Re(θ_F) as a function of B for Fe and Ba-122 films at 10 K is shown in Fig. 1. Re(θ_F) corresponds to the rotation (Faraday rotation) of the transmitted radiation. The signal from the Fe film saturates and remains flat above 2 T, whereas the signal from the Ba-122 film shows a clear non-zero slope above 2 T. We analyze our data by separating the linear

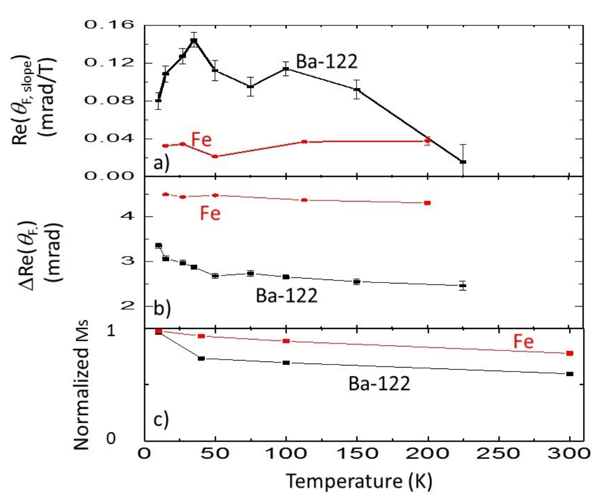

Fig. 2. Temperature dependence at 117 meV of a) Re($\theta_{F,}$ slope) b) ΔRe(θ_F), and c) the normalized saturation magnetization M_s for Fe and Ba-122 films.

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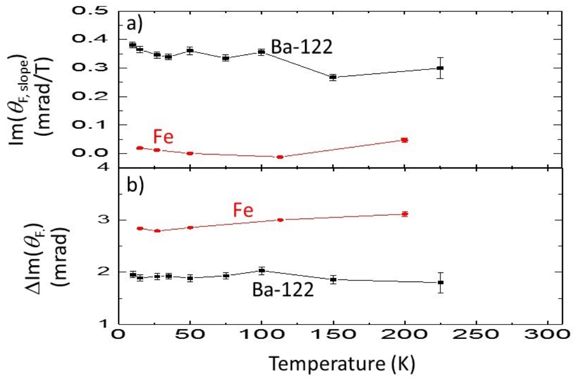

Fig. 3. Temperature dependence at 117 meV of a) Im($\theta_{F,}$ slope) and b) ΔIm(θ_F) for Fe and Ba-122 films.

field dependent signal ($\theta_{F,slope}$) above 2 T from the step ($\Delta\theta_F$) near B=0. Since the FM signal saturates, we assume that the step near B=0 is due to FM ordering, whereas the paramagnetic signal above 2 T is coming from the Ba-122 itself. The inset of Fig. 1 shows the resistivity of the Ba-122 film as a function of temperature. Figure 2 shows the temperature dependence of Re$\theta_{F,slope}$, ΔReθ_F, and the saturation magnetization M_s for Ba-122 and Fe films. The Fe reference films show little temperature dependence for any of these signals, which is consistent with its high Curie temperature of over 1000 K. ΔReθ_F for Ba-122 is also relatively flat, as one would expect from FM Fe or Co domains. ΔReθ_F (Fig. 2b) for both Fe and Ba-122 appear to follow M_s (Fig. 2c) closely. On the other hand Re($\theta_{F,slope}$) for the Ba-122 films shows non-monotonic temperature dependence with a peak near 50 K. Figure 3 shows the temperature dependence of Im($\theta_{F,,slope}$) and ΔIm(θ_F) for Ba-122 and Fe films. Im(θ_F) corresponds to the ellipticity (Faraday ellipticity, circular dichroism) of the transmitted radiation. Although Im($\theta_{F,slope}$) is significantly larger for the Ba-122 film than for Fe, these signals are flat with temperature. If one assumes that the films are isotropic in-plane, Re(θ_F) is sensitive to the difference in index of refraction for left and right circularly polarized light, whereas Im(θ_F) is sensitive to the difference in absorption for left and right circularly polarized light. This suggests that the temperature-dependent signal in Re($\theta_{F,slope}$) may be due to a transition that is not resonant with the probing radiation. We have also explored the energy dependence of the signals from Ba-122 and Fe up to 1300 meV. We see strong, hysteretic Faraday signals at all energies. Re$\theta_{F,slope}$, ΔReθ_F, and ΔImθ_F for Ba-122 and Fe behave similarly below 400 meV, with Re$\theta_{F,slope}$ and ΔImθ_F changing sign around 400 meV. On the other hand, Re$\theta_{F,slope}$ for Ba-122 and Fe diverge from each other at low energy, with the signal from Ba-122 growing and that from Fe decreasing as the probe energy approaches zero.

III. Discussion

Ba-122 provides an interesting system to study the interactions of superconducting and ferromagnetic domains. Our infrared Faraday measurements in Ba-122 have revealed behavior that is neither purely due to superconductivity nor FM ordering. The temperature dependence of Re(θ_F, slope) may provide new constraints on modelling Ba-122. Since the spin susceptibility of Ba(Fe,Co)$_2$As$_2$ increases with T, the induced magnetization should also increase with temperature above T_N. In the limit that M is small, Re(θ_F) is proportional to M, and should also grow with T. The fact that we observe the opposite behavior indicates that the local moments are large even in the formally paramagnetic phase and nematic fluctuations could play a large role. A theory of the Faraday effect taking into account nematic contributions does not exist and still needs to be worked out. Since we are applying magnetic fields above H_{c1}, interactions between vortices and magnetic impurities also could affect the high B-field Faraday response. The current work provides new insights into this system, but has uncovered more questions than answers.

ACKNOWLEDGMENTS

Work done at the University at Buffalo was supported by NSF Division of Materials Research Grants No. 1410599 (J.C.) and No. 1229208 (H.Z.), and by the US Department of Energy, Office of Basic Energy Sciences, Division of Materials Sciences and Engineering under Award No. DE-SC0004890 (H.Z.).

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