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Surface impedance of $BaFe_{2-x}Ni_xAs_2$ crystals

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ABSTRACT

Measurements of the real σ_1 and imaginary σ_2 part of the conductivity were performed in optimally doped $BaFe_{1.9}Ni_{0.1}As_2$ and overdoped $BaFe_{1.88}Ni_{0.12}As_2$ crystals in the frequency range 20 MHz–1.5 GHz using a single coil technique. The temperature dependence of the London penetration depth follows a T^2 law. The conductivity σ_1 increases with decreasing temperature below T_c in agreement with the results obtained for the optimally Co doped $BaFe_{2-x}Co_xAs_2$ crystals. The increase of σ_1 in the superconducting state is attributed to a rapidly decrease of the quasiparticle scattering rate.

1. Introduction

A number of experimental works have been published recently concerning the surface impedance of iron based superconductors [1–6]. Low frequency, radiofrequency, microwave and optical reflectivity performed on crystals and thin films give information about the pairing of the superconducting in these materials. In particular the power law dependence of the London penetration depth in the *ab* plane $\lambda(T)-\lambda(0)\sim T^n$, with $n\sim 2$–2.8 [6] at $T<0.5T_c$. Such a behavior is attributed to pair breaking scattering in the so-called $s^{\pm}$ superconductivity [6]. Contradicting results on surface resistance have been reported. A coherence peak was observed in thin films with THz and optical measurements [3,4] but no coherence peak was observed in crystals with microwave experiments [1,2]. Here we report radiofrequency surface measurements on optimally doped $BaFe_{1.9}Ni_{0.1}As_2$ and overdoped $BaFe_{1.88}Ni_{0.12}As_2$ crystals in the frequency range 20 MHz–1.5 GHz with a single coil technique. Careful analysis of the impedance measurements permits us to extract the real part of the conductivity.

2. Experiment

The crystal were grown using Fe/Ni-As self flux method, details are given in [7]. The samples are platelikes with the plates being perpendicular to the crystallographic *c*-axis, they exhibit a multicrystal structure with approximately 100 μm size single crystals which are randomly oriented in the *ab* plane. Samples were cleaved from a larger crystal. We selected samples with typical dimensions $1000\times 1000\times 100\ \mu m^3$, the smallest dimension is along the *c* axis. The platelet samples are placed inside a copper coil (11 mm length, 2.6 mm diameter, 18 turns, inductance 0.2 μHenry). The coil is situated at the end of a coaxial line inside a terminal adapter. Radio frequency magnetic field is applied parallel to the *ab* plane. Incident radiofrequency power was fixed to −20 dBm. Non resonant measurements of the real (R) and imaginary (L) of the impedance of the coil were performed with an automated impedance analyzer Agilent 4395 in the frequency range 1–100 MHz. Measurements of the self LC resonant frequency and series resistance, $L=0.2\ \mu H$, $C=50$ fH, quality factor ~80, were performed at 1.5 GHz with a Hewlett Packard 8720B network analyzer. Resistance and inductance were measured separately in the absence of a sample and were subtracted from measurements with the sample present [8].

The formulation of the impedance of the coil surrounding the sample was obtained using the equivalent circuit based on a transformer analogy developed in [9]. In this model the primary of the transformer is the measuring coil L_0. The secondary is defined by an inductance L_2 which is related to the eddy currents induced in the sample, L_2 is a geometrical factor and does not depend on the sample properties. The mutual inductance M between the sample and the coil is defined by the mutual inductance between the primary and secondary, $M=k^2L_0L_2$, where k is the geometrical coupling factor between the primary and secondary. The inductance of the coil is given by

$$Z=R_0+\frac{k^2L_0L_2\omega^2R}{|R+j(X+L_2\omega)|^2}+j\left[L_0-\frac{k^2L_0L_2\omega\{X+L_2\omega\}}{|R+j(X+L_2\omega)|^2}\right]\omega \quad (1)$$

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where R and X are the real and imaginary parts respectively of the surface impedance of the sample, R_0 and L_0 are the resistance and inductance of the empty coil and ω is the angular frequency.

In the experiments the same coil $L_0=0.2$ μH was used. Parameters $k^2\sim0.1$ and $L_2\sim0.6$ nH were evaluated from the measurements in the normal state of the samples at a temperature T above superconducting transition T_c where the following equality is

$$X_N = R_N = \sqrt{\mu_0 \rho_{dc} \omega / 2} \tag{2}$$

where μ_0 is the magnetic permeability of vacuum and $\rho_{dc}=10^{-6}$ Ωm the dc sample resistivity measured in [7]. In the superconducting state R and X are deduced from Eq. (1).

The accuracy of our technique was tested by measurements on superconductor MgB2 powder. Data averaging techniques were used.

3. Results and discussion

The temperature dependence of R and X normalized to the value R_N measured at 25 K are shown for the optimal doped $BaFe_{1.9}Ni_{0.1}As_2$ and overdoped $BaFe_{1.88}Ni_{0.12}As_2$ crystals in Figs. 1 and 2. Below T_c the frequency dependence of X/R_N observed is $\omega^{0.5}$ which is expected in the superconducting state. Reactance X is proportional to the London penetration depth and frequency [10], $X=\mu_0\omega\lambda$, in the superconducting state and $R_N\sim\omega^{0.5}$ in the normal state.

The changes in the London penetration depth $\Delta\lambda=\lambda(T)-\lambda(0)$ deduced from X/R_N are shown in Fig. 3. $\Delta\lambda$ follows a $\sim T^2$ temperature dependence at $T<T_c/2$ for optimally doped crystal.

At very low temperatures $T\ll T_c$, $\Delta\lambda$ following a power law $(T/T_c)^n$ with $n\sim2$–2.8 attributed to the effect of strong pair breaking scattering has been reported [6].

After averaging the data, a drop of three orders of magnitude in R/R_N is obtained below the superconducting transition T_c. R/R_N is proportional to $\omega^{1.5}$, it results that the expected variation $R\sim\omega^2$ is verified in the superconducting state [10]. Nevertheless the resistance values at $T\ll T_c$ in Figs. 1and 2 are larger by more than one order of magnitude than those reported in [1,2]. Similar residual surface resistance values are roughly extrapolated for the two different doped crystals in Figs.1 and 3.

Residual loss is a long standing problem in microwave studies of superconductors [11]. Residual losses are generally subtracted to obtain the intrinsic resistance. Our resistance measurements are well resolved in the vicinity of the superconducting transition. But at $T\ll T_c$ our experimental resolution is not sufficient to extract the

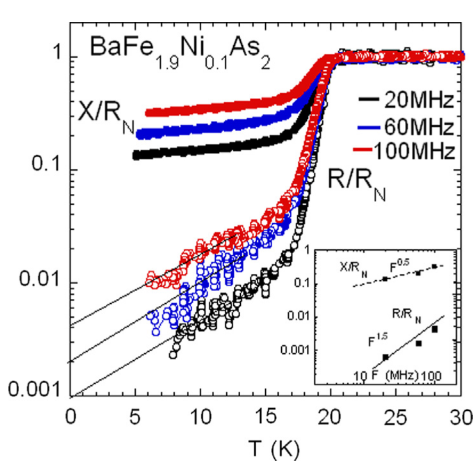

Fig. 1. (Color online) Temperature dependence of X/R_N (filled symbols) and R/R_N (open symbols) of surface impedance normalized to the value R_N obtained at 25 K for the optimally doped $BaFe_{1.9}Ni_{0.1}As_2$ crystals. Inset: Frequency dependences of X/R_N and R/R_N at 10 K.

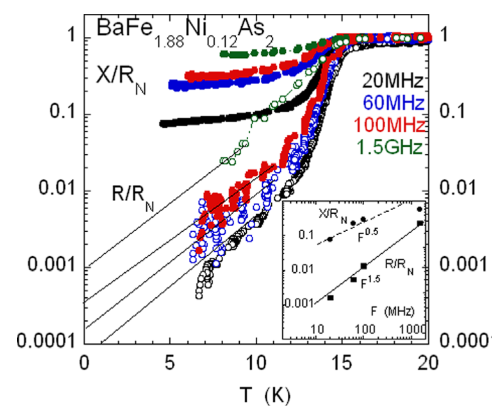

Fig. 2. (Color online) Temperature dependence of X/R_N (filled symbols) and R/R$_N$ (open symbols) of surface impedance normalized to the value R_N obtained at 25 K for the overdoped $BaFe_{1.88}Ni_{0.12}As_2$ crystals. Inset: Frequency dependences of X/R_N and R/R_N at 10 K.

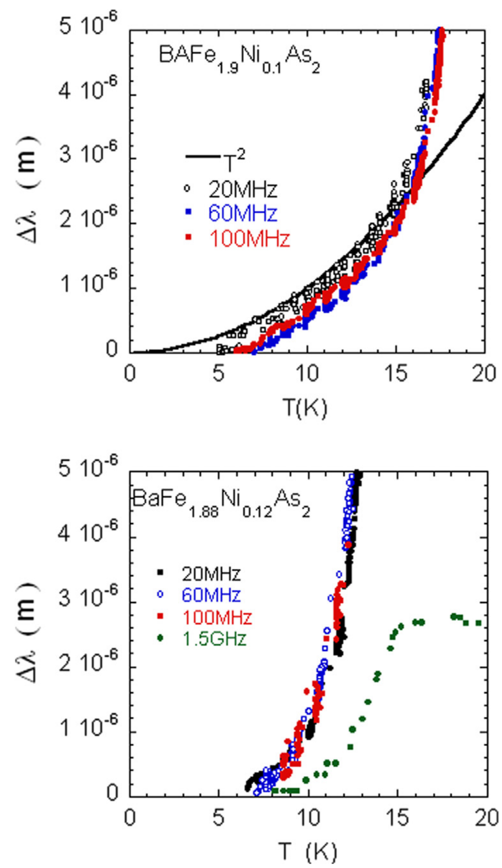

Fig. 3. (Color online) Temperature dependence of the London penetration depth variation $\Delta\lambda=\lambda-\lambda(0)$ at different frequencies.

intrinsic resistance. The real σ_1 and imaginary σ_2 parts of the conductivity are related to the surface impedance Z by the following relation [10]:

$$Z = R + jX = \sqrt{\frac{j\mu_0\omega}{\sigma_1 - j\sigma_2}} \tag{3}$$

The real and imaginary parts of the conductivity normalized to the value $\sigma_1(25\text{ K})=\sigma_N$ at 25 K in the normal state are obtained from the measurements of X/R_N and R/R_N using the following equations