Surface impedance of $BaFe_{2-x}Ni_xAs_2$ in the radio frequency range

A. Abbassi[1], M. Saint-Paul[2], R. Dkiouak[1], M. R. Britel[3], Zhao-Sheng Wan[2,4], Huinqian Luo[4], Xiagye Lu[4], Cong Ren[4], and Hai-Hu Wen[4,5]

[1] Faculté des Sciences et Techniques de Tanger, BP 416 Tanger, Université Abdelmalek Essaâdi, Morocco.
[2] Institut Néel, CNRS, Université Joseph Fourier, BP 166, Bât E, F 38042 Grenoble Cedex 9, France.
[3] Laboratoire des Technologies Innovantes, ENSAT , Université Abdelmalek Essaâdi UAE, BP 1818 Tanger, Morocco.
[4] Institute of Physics and National Laboratory for Condensed Matter Physics, Chinese Academy of Sciences, P.O Box 603, Beijing 100190, People's Republic of China.
[5] National Laboratory for solid State Microstructures, Department of Physics, Nanjing University, 210093 Nanjing, People's Republic of China.
*corresponding author, E-mail:abdellatif1966@hotmail.com

Abstract

We report measurements of the temperature dependence of the surface impedance in superconducting $BaFe_{1.93}Ni_{0.07}As_2$ crystals using the radiofrequency reflection technique in the 5<T<30K temperature range. An LC resonant circuit with a phase sensitive detection was used at 92MHz. A measurement assembly with point contacts was used at 30MHz. The recent discovery of iron based arsenide superconductors $BaFe_{2-x}Ni_xAs_2$ has attracted much interest. For a Ni doping level of 7% the superconducting phase transition is found around 20K. The temperature dependence of the superconducting penetration depth was determined.

1. Introduction

The recent discovery of iron based arsenide superconductors $BaFe_{2-x}Ni_xAs_2$ has attracted much interest [1-3].

The measurements of the surface impedance $Z_S = R_S + iX_S$ probe the complex conductivity [4-7]. The real part of the surface impedance is proportional to the loss of the radio frequency power and caused by the normal carriers. The imaginary part is determined by the response of the superconducting carriers and characterized the non dissipating energy stored in the superconducting surface layer λ which is the magnetic penetration depth. When the sample is superconducting magnetic field is fully shielded from the sample's interior, the magnetic field is limited to the superconducting depth λ, which is approximately 1 μm. After the sample passes from the superconducting to the normal sate, the magnetic field penetrates into the sample a much larger distance equal to the normal skin depth δ. For our samples, this distance is of the order of 70 μm at 100 MHz.

The second probe for the superconducting carriers is the use of ultrasonic measurements. When a sound wave propagates through a metal the microscopic electric field due to the displacement of the ions can impart energy to electrons removing energy from the wave. In a superconductor well below the superconducting transition T_C attenuation of sound waves are markedly lower than in a normal metal.

2. EXPERIMENT

We report measurements of the surface impedance in the (ab) plane of superconducting $BaFe_{1.93}Ni_{0.07}As_2$ crystals.

2.1. Experimental set up

The crystals were grown using an Fe/Ni-As self flux method, details are given [3]. Typical crystals have dimensions of 7x5x0.2 mm^3. The crystallographic c-axis is perpendicular to the plane of plate-like crystals along the smallest dimension.

To determine change in the surface impedance, the sample is placed inside a coil which is part of resonant series LC (capacitor) circuit, resonant frequency of 92 MHz having a quality factor Q of 80. The sample is mounted on the end of sapphire plate with a small amount of silicon grease. RF magnetic field is applied parallel to the (ab) plane. In this geometry screening currents flow around the crystal in both a, b and c axes directions. The dimension along the c-axis is very small it results that the c-axis contribution is small in comparison to the contribution given by the (ab) plane. Measurements were done at 92 MHz by monitoring the reflected RF power at resonance. The reflected power is measured using a phase sensitive detector. A balanced mixer multiplies the reflected RF voltage v_r with the forward RF voltage v_i . After removing the ac components by a low pass filter, the dc component V_0 is proportional to the reflected RF voltage v_r. V_0 is expressed with the amplitudes and the phase shift between v_R and v_I.

$$V_0 = |v_I| * |v_R| * \cos(\theta) \qquad (1)$$

The sample was mounted in a non resonant circuit with spring contact connectors at the end of a coaxial line. Two spring contacts were pressed to the surface of the sample.

The sample circuit block was fixed at the end of a semi-rigid coaxial cable in a liquid helium cryostat. Temperature was controlled with a calibrated germanium resistance thermometer.

Ultrasonic waves were generated and detected at 15 and 45 MHz with LiNbO3 transducers bounded to the crystal.

2.2. RESULTS

The temperature dependences of the voltage V_0 of the LC circuit with $BaFe_{1.93}Ni_{0.07}As_2$ crystal and $BaFe_{1.85}Ni_{0.15}As_2$ crystal, are reported in Fig 1. Measurements without sample are also shown.

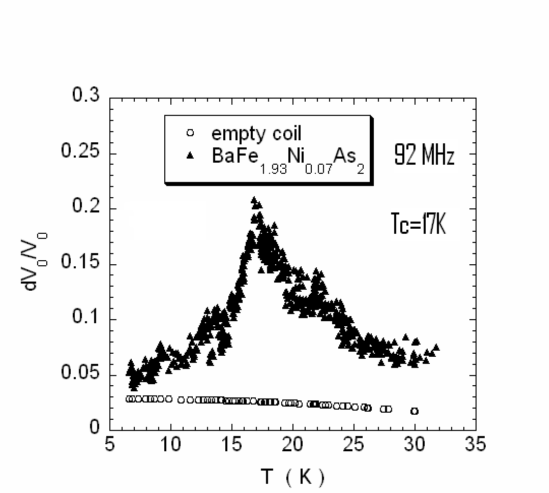

Figure 1: Temperature dependence of the relative change dV_0/V_0, LC circuit measured at 92 MHz with $BaFe_{1.93}Ni_{0.07}As_2$ crystal dimensions 7x5x0.2 mm^3, superconducting phase transition T_C = 17 K and the empty coil.

It is found that V_0 drops precipitously as the temperature is lowered through T_C in the $BaFe_{1.93}Ni_{0.07}As_2$ crystal Fig1.

A very sharp behaviour is observed at T_C =13K for the $BaFe_{1.85}Ni_{0.15}As_2$ crystal Fig 2. The effects observed with this second crystal are one order of magnitude smaller.

In reflection measurements reflected RF voltage v_R depends on the transmission line impedance Z and the characteristic line impedance Z_0, Z_0=50Ω .

$$\frac{v_R}{v_I} = \frac{Z - Z_0}{Z + Z_0} \quad \text{with} \quad \frac{Z}{Z_0} = \left[\frac{Z_L + jZ_0 \tan(\beta l)}{Z_0 + jZ_L \tan(\beta l)}\right] \qquad (2)$$

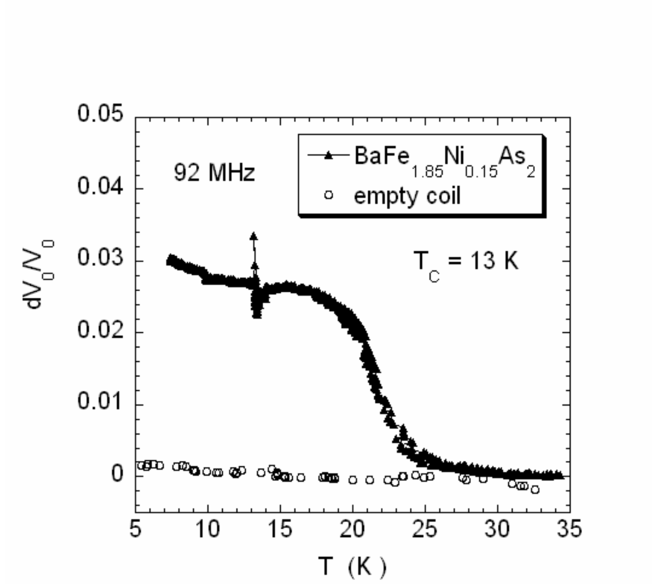

Figure 2: Temperature dependence of the relative change dV_0/V_0 , LC circuit measured with $BaFe_{1.85}Ni_{0.15}As_2$ crystal dimensions 7x5x0.2 mm^3, superconducting phase transition T_C = 13 K and the empty coil

Z_L is the impedance of the resonant LC circuit or the non resonant circuit, β is the electric wave vector and l is the coaxial line length. In our case an angle βl of 3.3π was estimated.

For the non resonant circuit we have plotted in Fig3 the reflected voltage normalized to its value just above Tc which is equivalent to the impedance normalized at its value in the normal state. This approximation is justified by the fact that small changes of Z_L induce a linear variation of the reflected voltage in equation (2). We plotted in Fig3 the normalized voltage V_0 to its value at Tc for the resonant circuit. The effect of the empty coil has been subtracted. The normalized reflected voltage is proportional to the superconducting penetration depth [6]:

$$\frac{v_R}{v_R^N} \approx \frac{\lambda}{\delta_N} \qquad (3)$$

δ_N being the skin depth in the normal sate.
The experimental data obtained with the non resonant circuit at 30 MHz and resonant circuit at 92 MHz with the $BaFe_{1.93}Ni_{0.07}As_2$ crystal follow the temperature dependence given by the two fluid model [4]

$$\lambda \approx \lambda(0)\left[1 - \left(\frac{T}{T_C}\right)^4\right]^{-1/2} \qquad (4)$$

The most striking feature of the data is the drastic change of the electric impedance concomitant with the sharp decrease of the ultrasonic attenuation at 15 and 45 MHz around Tc. This confirms that $BaFe_{1.93}Ni_{0.07}As_2$ crystal follows an unconventional superconducting behaviour. According to the BCS theory, ultrasonic attenuation drops after the carriers condensate below Tc, the exponential temperature decrease below Tc is related to the superconducting energy gap [9].

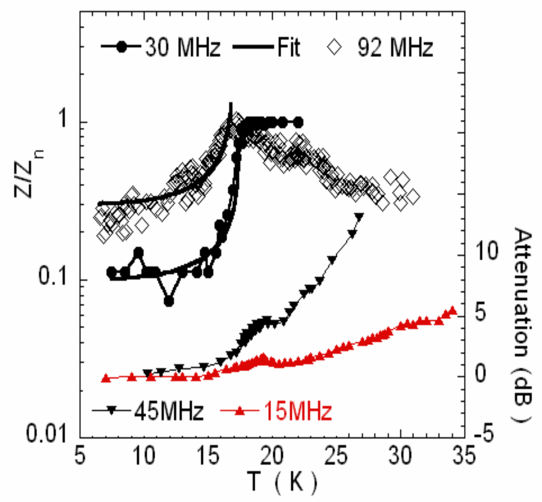

Fig 3 $BaFe_{1.93}Ni_{0.07}As_2$ crystal .Temperature dependence of the normalized impedance Z/Zn, non resonant circuit at 30 MHz, resonant circuit at 92MHz. The solid lines (Fit) are calculated with equation (4) with Tc= 17.5K, and Tc=18K.Temperature dependence of the ultrasonic attenuation at 15 and 45 MHz.

A penetration depth at 0K $\lambda(0) \sim 7\mu m$ is estimated with equation (3). This value is larger than the value expected for this material [5]. Surface roughness should lead to an exaggerate λ value via an underestimate of the effective sample area. The standard equivalent circuit model, ideal transformer, for the coupled system of coil and sample leads to the complex impedance:

$$Z_L = R_1 + R_2 \frac{M^2\omega^2}{R_2^2 + L_2^2\omega^2} + j\left[L_1 - L_2 \frac{M^2\omega^2}{R_2^2 + L_2^2\omega^2}\right]\omega \qquad (5)$$

Where R_1 and L_1 are the resistance and the inductance of the empty coil. M is the mutual inductance between coil and sample, k is the effective filling factor.

$M^2 = kL_1L_2$

R_2 and L_2 are the resistance and inductance related to the sample. This model works well for the normal conductors but for superconductors it is difficult to extract the intrinsic surface resistance and reactance of the sample.

Behavior of V_0 around the superconducting transition of the $BaFe_{1.85}Ni_{0.15}As_2$ crystal can be related to the sharp drop in inductance at Tc and a peak in RF losses just above Tc. Such a peak in RF losses can be attributed to weakly connected loops consisting of weak-link Josephson junctions created at the contacts between the microcrystals [7].

3. Conclusions

We have reported measurements of the temperature dependence of the penetration depth in the iron based superconductors $BaFe_{1.93}Ni_{0.07}As_2$ in the radio frequency range. Smaller RF effects were observed for the high Ni concentration x=0.15. The mechanism of superconductivity in the iron based superconductors is not well understood. It has been proposed that superconductivity depends on spin and orbitals fluctuations [8]. This can explain the unconventional behavior of the ultrasonic attenuation observed in the $BaFe_{2-x}Ni_xAs_2$ samples [4].

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