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BOROCARBIDE THIN FILMS AND TUNNELING MEASUREMENTS

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1. Introduction

Thin films represent the basic element for most electronic devices, but can be also a very convenient sample form to realize fundamental physics experiments. In particular in the field of superconductivity thin films have been profitably used for microwave surface impedance measurements, that represent key experiments to discriminate between the possible superconducting gap symmetries, and for the realization of planar juncions, necessary for accurate tunneling or Andreev reflection experiments.

With this in mind our group has grown and extensively characterized both non-magnetic and magnetic superconducting borocarbide [1,2] thin films. Using magnetron sputtering technique, it was possible to produce for the first time in-situ, high quality, c-axis oriented thin films [3].

In the present paper we will briefly review our previous activity mainly related to non magnetic borocarbides (RE=Y, Lu) and present recent results concerning microwave surface impedance measurements and S/N planar junctions based on $LuNi_2B_2C$ thin films. The body of our data unambiguously confirm the BCS nature of superconductivity in borocarbides.

2. Film preparation and characterization

Re-Ni_2B_2C (Re=Y,Er,Lu) films were prepared by planar magnetron sputtering technique as described in ref. 3. Two-inch diameter Re-Ni_2B_2C targets were prepared by arc melting stoichiometric amounts of the raw materials under a dry argon atmosphere. MgO, Al_2O_3, $LaAlO_3$ and diamond substrates were placed "on axis" at 9 cm from the target surface and heated up to about 800°C using a molybdenum heater. The base system pressure P_{in} just before sputtering was in the low 10^{-6} Pa range. A key role

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in obtaining high quality films was played by the substrate temperature T_S and by the target quality.

Although superconducting films were obtained on all the substrates used, high quality films with Tc≅Tc(bulk) and high residual resistivity ratio (RRR=ρ(300K)/ρ(20K) ≥ 6) were reproducibly obtained only for YNi_2B_2C on MgO substrates. Due to the inferior target purity for Re=Er and Lu these films showed lower RRR (≤ 3) and similar results were obtained using different substrates. The film resistivity, determined by a four probe arrangement, was close to bulk values for YNi_2B_2C (50 $\mu\Omega$cm at 300 K) and larger for both $ErNi_2B_2C$ and $LuNi_2B_2C$ (170 and 100 $\mu\Omega$cm at 300 K respectively). The temperature dependence of the resistivity of our films is extensively discussed in [4] and exhibits a conventional linear dependence at room temperatures with a tendency towards a high temperature "saturation" for lower quality samples. The low temperature data could be described by a T^2 power law as in single crystals [5].

For all films the X-ray Θ-2Θ diffraction pattern revealed the predominant presence of (00n) reflections.

3. STM measurements

STM measurements on YNi_2B_2C films were performed at Argonne National Laboratory with a home built low temperature STM using a Pt/Ir tip. The system allows measurements of conductance vs. voltage (dI/dV vs. V) characteristics at selected points, recording simultaneously the surface topography. With this apparatus a square Abrikosov vortex lattice in $LuNi_2B_2C$ single crystals was observed for the first time [6].

No surface treatment was applied to the samples prior to mounting on the STM. The dI/dV vs. V characteristic presented in Figure 1 is the result of the averaging of 20 individual characteristics recorded at the same spot, after normalization by a slightly parabolic background. The data could be well fitted with a smeared version of the BCS density of states:

$$N(E) = \mathrm{Re}\left\{ \frac{|E - i\Gamma|}{\sqrt{(E - i\Gamma)^2 - \Delta^2}} \right\} \tag{1}$$

which includes the broadening parameter Γ [7]. The resulting fitting parameters are Δ=2.1 meV and Γ=0.4 meV. Combined with a value of Tc=15.1 K the corresponding BCS ratio 2 Δ/k_BTc is equal to 3.2±0.2. These values are compatible with previous reports in the literature [8], which confirms the substantial weak-coupling nature of YNi_2B_2C. More details of the measurements and fitting procedure are reported in ref. 4.

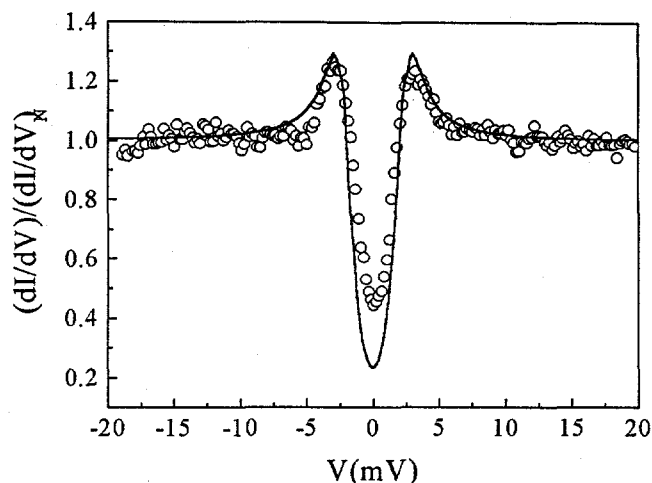*Figure 1*. Normalized experimental(dots) and calculated (line) conductance vs. voltage characteristic for a YNi$_2$B$_2$C film at T= 4.2 K.

4. Planar junctions

Planar tunnel junctions were produced in situ by a special set-up for the interchanging of tantalum shadow masks. In situ cross-type junction geometry (cross-section about 100μm x 100μm) could be produced using different oxide barriers. Some junctions were also made on high quality LuNi$_2$B$_2$C films deposited on MgO by pulsed laser ablation [9]. In this case the bottom layer and the barrier (Al$_2$O$_3$,MgO or CeO$_2$) were in-situ deposited, while the upper layer was a narrow stripe of lead evaporated in a following stage.

Planar junctions produced to date do not show reproducible tunneling behavior. Occasionally however, with most barriers, junctions exhibiting a clean and stable S/N interface behavior were obtained probably through pin-holes like defects in the barrier [10]. A typical I-V curve is reported in the inset of Fig.2. The I-V curves and their numerical derivatives were well described by the standard BTK theory [11]. From the conductance minima the value of the superconducting gap Δ=2.0mV at T=4.2 K for LuNi$_2$B$_2$C was obtained, that leads to 2Δ$_0$/kTc = 3.0 ± 0.2 in agreement with the STM results on single crystals [6].

Figure 2 shows the temperature dependence of Δ for two different junctions which agrees very well with the BCS prediction in the full temperature range. This is in contrast with a recent theoretical prediction based on the presence of significant pair-breaking effects in LuNi$_2$B$_2$C [12].
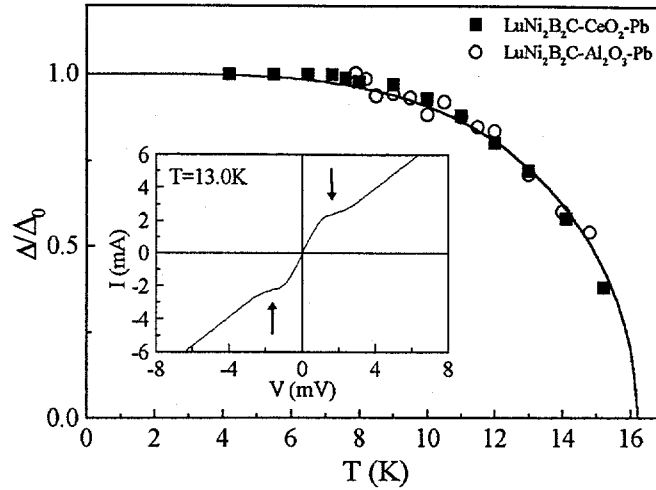
Figure 2. LuNi₂B₂C measured gap for two different junctions as a function of the temperature together with the theoretical BCS curve (solid line). Inset: typical I-V curve recorded at T=13.0K. The arrows show the gap value.

5. Surface impedance measurements

LuNi$_2$B$_2$C films grown on Al$_2$O$_3$, due to the optimal dielectric properties of this substrate, were used to perform microwave surface impedance measurements using a standard network analyzer. A dielectric resonator with a fundamental resonant frequency f= 19GHz, was realized in a Cu box making use of two superconducting 10×10 mm^2 samples to shield the end faces of a sapphire cylinder (height h=3.5 mm, diameter D=7 mm). For low loss dielectrics the resonator quality factor is limited by conductor losses within the shield.

The quality factor Q for the resonant system can be expressed as follows:

$$1/Q = R_s / A_{sup} + R_m / A_m \qquad (2)$$

where A$_{sup}$=250Ω and A$_m$=2900Ω are geometrical factors for the conducting surfaces of the resonant system, consisting of the superconducting material and the lateral copper shield, and R$_s$ and R$_m$ are the surface resistance values for the superconductors and the metal.

Frequency shifts Δf are associated with the penetration depth changes Δλ through the relation:

$$2\Delta f / f = \mu_0 \omega \left(\Delta\lambda_{sup} / A_{sup} + \Delta\lambda_m / A_m \right) \qquad (3)$$

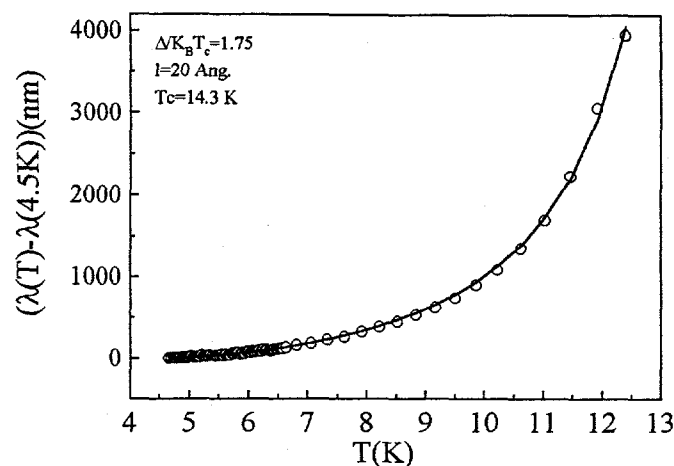(λ being proportional to the surface reactance X$_s$)

Figure 3 . Temperature dependence of the penetration depth for a LuNi₂B₂C films grown on sapphire. The continuous curve represent the BCS fit, in the figure are also reported the fit parameters corresponding to the theoretical curve.

Typical temperature dependence of the penetration depth, obtained by simultaneously measuring Δf as a function of the temperature is reported in Figure 3. The exponential dependence on temperature, characteristic of an activated behavior over a constant energy gap, is clearly exhibited for both curves. The theoretical fitting with standard BCS equations [13] gives a value of $2\Delta/K_B T_c = 3.5\pm0.4$ consistent with tunneling estimates. Two parameters needed for the BCS fit, the mean free path value at low temperature l (20 Å) and the critical temperature Tc (14.3 K), were evaluated from resistivity measurements and inductive measurements respectively.

6.Conclusions

The results obtained by our group in thin film fabrication and STM tunneling on superconducting borocarbides YNi_2B_2C have been be briefly reviewed. Results concerning the microwave surface impedance and the S/N planar junctions on $LuNi_2B_2C$ thin films have been also presented and analyzed. These new data unambiguously confirm the full BCS nature of the superconducting gap in borocarbides and the absence of significant pair-breaking effects in $LuNi_2B_2C$.

Aknowledgments

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