Point-contact study of the LuNi$_2$B$_2$C borocarbide superconducting film

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Abstract

We present point-contact (PC) Andreev-reflection measurements of a superconducting epitaxial $c$-axis oriented nickel borocarbide film LuNi$_2$B$_2$C ($T_c = 15.9$ K). The averaged value of the superconducting gap is found to be $\Delta \simeq 2.6 \pm 0.2$ meV in the one-gap approach, whereas the two-gap approach results in $\Delta_1 \simeq 2.14 \pm 0.36$ meV and $\Delta_2 \simeq 3 \pm 0.27$ meV. The better fit of the Andreev-reflection spectra for the LuNi$_2$B$_2$C–Cu PC obtained by the two-gap approach provides evidence for multiband superconductivity in LuNi$_2$B$_2$C. For the first time, PC electron–phonon interaction (EPI) spectra have been measured for this compound. They demonstrate a pronounced phonon maximum at $8.5 \pm 0.4$ meV and a second shallow one at $15.8 \pm 0.6$ meV. The electron–phonon coupling constant $\lambda$ estimated from the PC EPI spectra turned out to be small (with $\lambda_{PC} \sim 0.1$), like in other superconducting rare-earth nickel borocarbides. Possible reasons for this are discussed.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Among the rare-earth nickel borocarbide superconducting ReNi$_2$B$_2$C family, the system with Re = Lu belongs to the nonmagnetic ones with the highest $T_c$ of about 16 K. Although numerous experiments have been undertaken to study the superconducting state in this compound, there is still space for more detailed investigation. This is most probably due to the complicated band structure in this compound which may certainly lead to the anisotropy of the superconducting gap and multiband superconductivity. Point-contact (PC) Andreev-reflection spectroscopy is a direct tool to clarify the superconducting gap characteristics, i.e. its value and anisotropy as well as the temperature and magnetic field dependences of the gap. Furthermore, PC spectroscopy itself provides straightforward information on the PC electron–phonon interaction (EPI) function $\alpha^2 F(\omega)$ [1], which can be a test for the phonon-mediated superconductivity.

Several PC studies have been performed on single crystals of LuNi$_2$B$_2$C [2, 3]. These experiments have shown an anisotropy of the superconducting order parameter (gap). In [2], the authors claimed that the data are in favor of a two-gap model. A similar conclusion was made also by a study of single crystals and films of the related compound YNi$_2$B$_2$C in [4–6]. In this study, we present PC spectroscopy data for epitaxial $c$-axis oriented LuNi$_2$B$_2$C films in order to compare these data with the results obtained for LuNi$_2$B$_2$C single crystals and to receive information about EPI in LuNi$_2$B$_2$C.
2.1. PC spectroscopy of the superconducting energy gap

Spectroscopic information about the superconducting energy gap is available in the case where the contact diameter $d$ is smaller than the inelastic electron mean-free path as well as the coherence length $\xi(0)$. LuNi$_2$B$_2$C is characterized at low temperatures by a coherence length of about $\xi \approx 6$ nm [8] and an elastic electron mean-free path of $l \approx 10$ nm evaluated from the $\rho l$ value mentioned below. Estimation of the contact size from its resistance $R_{PC}$ using the Wexler formula [1]

$$R_{PC} \simeq 16\rho l / 3\pi d^2 + \rho/2d,$$

(1)
gives $d \leq 10$ nm for the typical PC resistance $R_{PC} = 10 \Omega$ with $\rho \approx 2.7 \mu\Omega$ cm and $\rho l \simeq 3.6 \times 10^{12} \Omega$ cm$^2$ [9].

Thus, all the mentioned lengths are of the same order of magnitude, therefore it is not possible to say a priori whether the investigated PCs are in the ballistic (or diffusive), in other words, the spectroscopic regime. Independent of the PC resistance (of course the higher the resistance the higher the probability to be in the spectroscopic regime), each PC spectrum should be tested in order to display the spectroscopic features both in the normal (phonons) and superconducting (gap minima) state.

We were able to obtain PC $dV/dI$ characteristics, which demonstrate clear Andreev-reflection (gap) structures—pronounced minima at $V \approx \pm \Delta$ at $T < T_c$ as is shown in figure 1. For the investigated PCs the temperature of the vanishing of the superconducting main minimum in $dV/dI$ was close to 16 K, that is, close to $T_c$ of the LuNi$_2$B$_2$C film, testifying that superconductivity in the PCs is not degraded. To retrieve the superconducting gap value $\Delta$ and other parameters from the Andreev-reflection spectra the generalized Blonder–Tinkham–Klapwijk (BTK) theory [10] is commonly used. The application of the one-gap BTK model to the $dV/dI$ curves from figure 1 (bottom panel) results in a moderate fit to the experimental curves. Furthermore, the parameter $\Gamma$, which implies a finite lifetime of carriers due to inelastic scattering of charge carriers, was found to be rather high (about half of the $\Delta$ value) for this PC. Such a high $\Gamma$ as compared to $\Delta$ can be connected with the anisotropy of the superconducting gap or a possible two-gap superconductivity. The two-gap(band) model is supported by a recent three-dimensional study of the Fermi surface of LuNi$_2$B$_2$C [15], where the contributions to the density-of-states (DoS) at the Fermi energy from the three bands equal 0.24%, 22.64% and 77.1%, respectively, was found. That is, two bands basically contribute to the DoS.

As we can see from figure 1 (bottom panel) the fitting within the two-gap model gives a much better agreement with the experimental $dV/dI$ data. Applying the two-gap fit the temperature dependences of the superconducting gaps $\Delta_1$, $\Delta_2$ (triangles), barrier parameter $Z$ (diamonds), contribution (weight factor) $K$ of $\Delta_1$ (squares), scaling parameter $S$ (open circles), positions of minima in $dV/dI$ (stars) for the PC from figure 1. The dotted lines represent the BCS-like gap behavior.
Table 1. Average, minimal and maximal values of the superconducting gap $\Delta$, the ‘smearing’ parameter $\Gamma$ and the ‘barrier’ parameter $Z$ retrieved from the one- and two-gap approaches.

|                | $\Delta$ (meV) | $\Gamma$ (meV) | $Z$       | $2\Delta/kT_c$ |
|----------------|----------------|----------------|-----------|----------------|
| Average        | 2.6 ± 0.2      | 0.54 ± 0.2     | 0.48 ± 0.06 | 3.8 ± 0.3 |
| Minimal        | 2.12           | 0.22           | 0.32      | 3.21         |
| Maximal        | 2.85           | 0.9            | 0.57      | 4.16         |

|                | $\Delta_1$ (meV) | $\Gamma_1$ (meV) | $\Delta_2$ (meV) | $\Gamma_2$ (meV) | $Z$ |
|----------------|------------------|------------------|------------------|------------------|-----|
| Average        | 2.14 ± 0.36      | 0.36             | 3 ± 0.27         | 0.25             | 0.47|
| Minimal        | 1.65             | 0                | 2.6              | 0                | 0.32|
| Maximal        | 2.6              | 0.74             | 3.45             | 0.73             | 0.54|

Figure 3. Second harmonic signal averaged for both polarities $V_2 \propto d^2V/dI^2$ (solid curve) measured in a magnetic field of 7 T for the PC from figure 1 taken at $T = 2.4$ K in comparison with the phonon DOS for LuNi$_2$B$_2$C [11] (solid circles). The open circles show $d^2V/dI^2$ with subtracted background in a form similar to log($V$) above 6 mV (see also figure 4). Dashed and dotted curves show raw data of $d^2V/dI^2$ for this contact for the two bias polarities.

The data for the two superconducting gaps presented in figure 2 well agree with results reported for LuNi$_2$B$_2$C single crystals for the $c$-direction [2]. The averaged gap value of $\Delta \approx 2.6 \pm 0.2$ meV for all contacts (about 30) calculated in the one-band approach turned out to be close to the averaged gap of $\Delta \approx 2.4-2.5$ meV reported for PCs on single crystals for the $c$-direction [2, 3]. Thus, the quality of the investigated films is comparable to that of the best single crystals. The mean gap values $\Delta_1 \approx 2.14 \pm 0.36$ meV and $\Delta_2 \approx 3 \pm 0.27$ meV established for about 15 PCs from the two-gap approach are also in line with data obtained for LuNi$_2$B$_2$C single crystals [2]. The characteristic values of the fitting parameters for the measured contacts are presented in table 1 for both the one- and the two-gap approaches.

2.2. PC spectroscopy of quasiparticle excitations

As was mentioned in the introduction, the PC spectroscopy makes it possible to study the electron–phonon interaction (EPI). The second derivative of the $I(V)$ curve of the ballistic contact at low temperatures is directly proportional to the PC EPI function $a^2F(\omega)$ [1]. The latter can be expressed using measurable signals as

$$a^2F(\omega) = \frac{3}{2\sqrt{2}} \frac{h\nu_F}{e d} \frac{V_2}{V_1},$$

where $e$ is the electron charge, $d$ is the PC diameter, $\nu_F$ is the Fermi velocity, $V_1$ and $V_2$ are the rms amplitudes of the first and second harmonics of the modulating signal respectively, which are proportional to the first $dV/dI$ and the second $d^2V/dI^2$ derivatives of the $I(V)$ curve of the investigated PC, respectively.

In figure 3, the $d^2V/dI^2$ curves of the PC from figure 1 are shown. We applied the magnetic field to suppress the superconductivity in the PC, because the magnitude of the superconducting features in the PC spectra near zero bias is much larger than that of the maxima caused by the EPI. As we can see from figure 3, the magnetic field of 7 T was not high enough to suppress the superconductivity completely ($B_{c2} \approx 9$ T at 2 K [7]) and the huge feature at a bias of about 2 mV is due to the residual superconductivity. Besides the feature due to the superconducting gap, a clear-cut maximum slightly above 8 mV and a more smeared one at around 15 mV are well distinguished (see figure 3). The mentioned peaks correspond to the low energy phonon maxima in the phonon DOS of LuNi$_2$B$_2$C [11] (see figure 3, symbols). However, the high energy part of the obtained PC spectra contains no visible features. In figure 4, we present a set of $d^2V/dI^2$ curves for different PCs measured up to bias voltages of about 80 mV. By analyzing all of the obtained PC spectra (about 30) with visible phonon features, we have found that the $d^2V/dI^2$ curves of the LuNi$_2$B$_2$C PCs display phonon maxima at 8.5 ± 0.4 mV and 15.5 ± 1.0 mV (averaged for 8 PC) similarly to the PC from figure 3. In contrast they do not contain contributions from the other phonon peaks at 23, 33, and 50 mV observed in the phonon DOS of LuNi$_2$B$_2$C (shown in figure 4 by the circle symbols). Only the PC with $R = 3.7$ $\Omega$ in figure 4...
Figure 4. Upper panel: reduced second harmonic signal $V_2/V_1^2 \propto d^2V/dI^2 (dV/dI)^{-2} = R^{-1} dR/dV$, where $R = dV/dI$, measured in a magnetic field of 9 T for different PCs with $R = 3.7$, 5.6, 4.7 and 2.9 Ω (from top to bottom) taken at $T = 2.2$–4.2 K. The long-dashed line shows tentative background behavior for the upper curve in the form $a \log(b V) + c$. Bottom panel: PC spectrum (solid circles) with subtracted background for the contact with $R = 3.7$ Ω along with the phonon DOS for LuNi$_2$B$_2$C [11] (open circles).

shows a weak hump at 23 mV. The reason for the absence of contribution at high energy phonon maxima could be a deviation from the ballistic (spectroscopic) regime at higher voltages due to increase of the EPI and a shortening of the inelastic mean-free path of electrons. It is worth mentioning that in [12, 13] phonon softening of two branches was observed below $T_c$. In our case, we did not observe these modes around 4–5 meV, probably because we have measured PC EPI spectra by suppressing the superconducting state, while in the other case a huge gap maximum makes it impossible to see any other features below 5–6 meV (see, e.g., figure 3, where the superconducting state is not fully suppressed). Another interesting question arises, as to whether it is possible to separate the contribution of each (two) band to the PC EPI spectrum? The problem here is similar to the analogous one raised in the tunneling spectroscopy in [14], where the authors concluded that it is not possible to obtain several band split EPI functions from a single function of the tunnel current.

After subtraction of the background from the measured PC spectra we established the EPI function according to (2) (using maximal $v_F = 3.6 \times 10^7$ cm s$^{-1}$ calculated for LuNi$_2$B$_2$C [9]) and estimated the EPI parameter $\lambda = 2 \int \alpha^2 F(\omega)\omega^{-1} d\omega$. The latter even for the spectra with the maximal intensity was found to be not larger than 0.1. This value is an order of magnitude smaller than the $\lambda$ values between 0.5 and 1 from dHvA data for the c-direction of LuNi$_2$B$_2$C [16, 17] or $\lambda \approx 0.5$–0.8 estimated from STM measurements on LuNi$_2$B$_2$C [18]. Such small values of $\lambda$ could be due to some simplifications of the PC spectroscopy theory where only the free electron model and a single band Fermi surface are used. Some issues of $\lambda$ evaluation from PC spectra were discussed in [20]. Most of all, the coupling constants estimated from PC spectra should be considered as lower bounds for the coupling constant $\lambda$ relevant for superconductivity. Here we also would like to mention that the discussed $\lambda$ parameter is some kind of transport EPI constant and in general its value is different from the Eliashberg EPI constant (see table 3.1 in [1]), but the difference by one order of magnitude is of course confusing. The calculation of the PC EPI function may shed light on this issue. It will allow us to separate the bands’ contributions, to estimate the integral intensity of the spectrum and to determine the relative contribution of each phonon branch to the PC EPI spectrum. It would certainly be a very helpful, but also a sophisticated task and it is beyond the scope of this experimental paper.

Another reason for a reduced intensity of the measured PC spectra might be the elastic scattering, which can be larger in the PC core than in the bulk sample due to less perfect surface properties and stresses at the PC formation. As follows from the PC spectroscopy theory, the magnitude of nonlinearity in PC spectra is proportional to $l/d$ [19] in the diffusive regime $l \ll d$. Figure 5 shows the intensity of the main peak in the PC spectra, which indeed shows strong scattering in the range of about one order. Since we do not see any trend in the intensity of the main peak versus PC resistance which related to the PC size (diameter), we expect that the spectra with the higher intensity are in (or close to) the ballistic regime. Thus, deviation from the ballistic regime of the current flow in the investigated contacts cannot be the reason for the small $\lambda$ values, which were calculated for the PCs with the maximal intensity.

Similar low $\lambda$ values to those we found for LuNi$_2$B$_2$C were obtained also from the PC spectra of YNi$_2$B$_2$C,
HoNi$_2$B$_2$C [5, 20, 21] and recently for TmNi$_2$B$_2$C (not yet published). There is also general similarity of PC spectra for the mentioned compounds which are characterized by a prevailing first phonon maximum (excluding crystal-electric-field peaks in HoNi$_2$B$_2$C and TmNi$_2$B$_2$C). As mentioned above, by determining one-gap model which is very close to the values reported for found to be about 2 meV(2 $\lambda_0$) in spectroscopy. The mean value of the superconducting gap is a notable large $\lambda_0$ value and the 'magnetic' peak contribution to $\lambda$. In this context, we can underestimate the superconducting EPI. In this context, $\lambda$ is again close to 0.1, if we eliminate the mentioned extra high $\lambda$ value and the 'magnetic' peak contribution to $\lambda$. 

3. Conclusion

We investigated the superconducting energy gap and EPI in LuNi$_2$B$_2$C using an epitaxial c-axis oriented film by PC spectroscopy. The mean value of the superconducting gap is found to be about 2.6± 0.2 meV ($\Delta_1/k_BTc = 3.8±0.3$) in the one-gap model which is very close to the values reported for PC measurements on single crystals [2, 3]. However, the fitting of $dV/dI$ curves favors the two-gap approach which provides strong support for the multiband superconducting state in this compound. For the two-gap approach the averaged gap values are found to be $\Delta_1 \simeq 2.14±0.36$ meV and $\Delta_2 \simeq 3±0.27$ meV.

For the first time for LuNi$_2$B$_2$C, we succeeded in measuring EPI PC spectra with the distinct phonon peaks at 8.5±0.4 meV and 15.8±0.6 meV. Therefore, we can conclude that these low energy phonons play a preferential role in the pairing mechanism. The EPI spectra are in general similar to those measured for other nickel borocarbides [5, 20–22] showing predominance of the first phonon peak in EPI for all these compounds.

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