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Andreev-reflection study of superconducting RNi_2B_2C compounds

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Abstract

A comparative study has been made of the current–voltage characteristics of RNi_2B_2C–Ag point contacts with R = Y, Er, and Ho, at various temperatures and magnetic fields. At low temperatures the double-minimum structure in the differential resistance dV/dI, characteristic for Andreev-reflection processes, can be well described by the Blonder–Tinkham–Klapwijk (BTK) model, yielding an energy gap $\Delta = 2.42 \pm 0.07$, 1.7 ± 0.2, and 1.04 ± 0.06 meV for, respectively, the Y-, Er-, and Ho-based compounds. For the Y- and Er-based compounds, the temperature dependence of the spectra is in quantitative agreement with the BTK prediction. However for the Ho-based compound, an anomalous temperature dependence with two superconducting transitions at 8.5 and 6.5 K has been observed. The ratio $2\Delta/k_BT_c$ amounts about 3.7 for all compounds (providing one takes $T_c^* \simeq 6.5$ K for the critical temperature of the Ho compound), corresponding to a moderate electron–phonon coupling strength.

A new class of superconductors, the rare-earth (R) borocarbides RNi_2B_2C, has been recently discovered [1, 2] showing an interesting interplay between superconductivity and magnetic ordering. The variation in the superconducting critical temperature T_c between the different compounds scales systematically with the magnetism of the rare-earth element [3]. For the magnetic elements (Tm, Er, Ho), antiferromagnetic ordering is observed below the superconducting transition temperature. This magnetic ordering leads to a suppression of superconductivity below T_c close to the antiferromagnetic ordering [3]. The Ho-based compound shows the most prominent re-entrant behavior to the normal state below T_c.

In the present investigation we have measured the current–voltage characteristics of normal-superconductor contacts with RNi_2B_2C compounds in order to study the Andreev-reflection process, i.e. the retroreflection of a hole-like quasi-particle by an incident electron-like quasi-particle leaving a Cooper pair in the superconductor for the electrical transport across the NS boundary [4]. Such an investigation gives direct access to the superconducting order parameter which is of interest in view of the anomalous superconducting behavior close to the antiferromagnetic ordering in these compounds.

The investigated polycrystalline samples have the superconducting transitions at 15.4 K for YNi_2B_2C, at 10.8 K for $ErNi_2B_2C$, and at 8.5 K for $HoNi_2B_2C$. The antiferromagnetic transition occurs for $ErNi_2B_2C$ at 6 K, and for $HoNi_2B_2C$ between 6 and 5.2 K [5–7]. A sharpened Ag needle was used as the normal counter electrode of the NS contact. The adjustment was made by a differential screw mechanism with a possibility of lateral movement along the sample surface to vary the contact position during one measuring cycle. Standard phase-sensitive techniques were used for the recording of the current (I)–voltage (V) characteristics of the contacts, and their first derivatives $dV/dI(V)$. Typical contact resistances were in the range from 1 to 10 Ω.

In Figs. 1 and 2 we have plotted the point-contact $dV/dI(V)$ spectra for YNi_2B_2C and $HoNi_2B_2C$, respectively, for different temperatures. For the $ErNi_2B_2C$ system, the point-contact data are very similar to the results obtained for YNi_2B_2C. Below the superconducting transition

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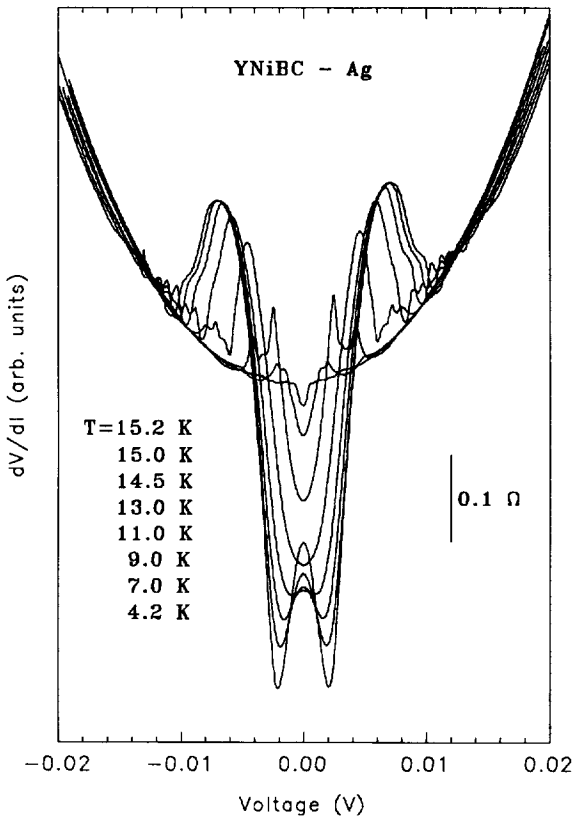

Fig. 1. dV/dI characteristics for a YNi_2B_2C–Ag point contact with zero-bias resistance $R_0 = 0.8\,\Omega$ at the indicated temperatures showing the Andreev-reflection structure below $T_c = 15.3\,K$.

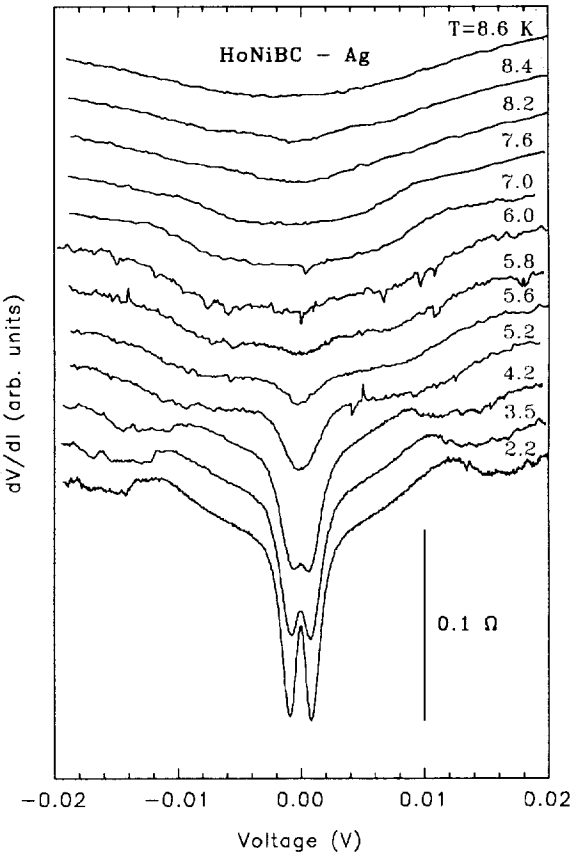

Fig. 2. dV/dI characteristics for a $HoNi_2B_2C$–Ag point contact with $R_0 = 1.2\,\Omega$ at the indicated temperatures showing the appearance of distinct structures around zero-bias at $T_c = 8.5\,K$ and at $T_c^* = 6\,K$.

temperature, a structure appears in the dV/dI curves around zero-bias voltage related to the Andreev-reflection process for the charge transport across a ballistic NS point-contact corresponding to the so-called excess current. At the lowest temperatures this structure develops in the double-minimum structure characteristic for the Andreev reflection process in junctions with non-ideal transmission of the charge carriers across the interface due to a barrier [4]. The voltage position of these minima are close to the corresponding value of the superconducting order parameter Δ. At higher applied voltages above the superconducting energy gap, maxima are observed in the dV/dI spectra. These "horn-like" structures correspond to the partial suppression of superconductivity in the contact area by the applied current resulting in a decrease of the excess current. The detailed structures of these maxima at above-gap voltages are not reproducible from one contact to the other. Ideal NS point-contacts with an unchanging NS boundary upon carrier injection would not show this artifact in the dV/dI spectra (see also Ref. [8] for the observation of such effects in Bi and Sb point contacts).

The Andreev-reflection spectra taken at the lowest temperatures can be very well described by the BTK model [4]. More details of such an analysis will be given in a forthcoming publication [9]. From the fitting to the BTK-theory one obtains the values for the superconducting order parameter Δ. In Fig. 3 we have plotted the energy gap for the investigated compounds as a function of the critical temperature. The experimental data lay on a straight line corresponding to $2\Delta/k_BT_c = 3.7$, which corresponds to a moderate electron–phonon coupling. Taking the critical temperature $T_c = 8.5\,K$ for the Ho-based compound would yield an unreasonable small value $2\Delta/k_BT_c = 2.8$. In the following, we will motivate our choice for $T_c^* \simeq 6.5\,K$ of the Ho-based compound in Fig. 3.

The temperature dependence of the point-contact spectra for YNi_2B_2C (see Fig. 1) and $ErNi_2B_2C$ can be well described by the BTK theory of an NS contact with a BCS superconductor. Below T_c a minimum develops in the dV/dI curve around zero-bias voltage, getting more profound at lower temperatures before the double-minimum structure becomes visible at still lower temperatures. However, looking at the data for the contact with $HoNi_2B_2C$ shown in

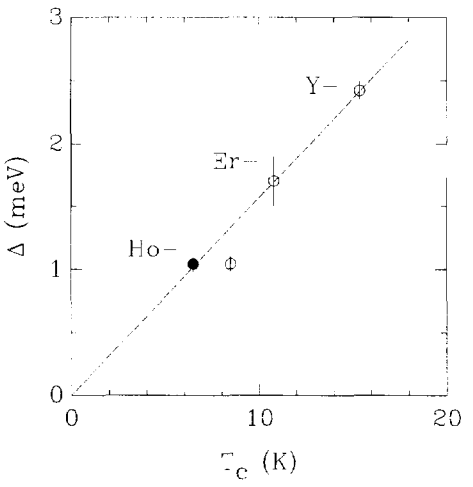

Fig. 3. Energy gap Δ as a function of T_c for the investigated RNi_2B_2C–Ag compounds. Taking $T_c^* \simeq 6.5$ K (data point with closed symbol) instead of $T_c \simeq 8.5$ K for the Ho-based compound yields a much better agreement with the ratio $2\Delta/T_c = 3.7$ given by the dashed line.

Fig. 2, an anomalous behavior is observed. For this compound also a minimum develops around zero-bias below $T_c \simeq 8.5$ K, but the minimum gets only broader upon lowering the temperature without a strong increase in the amplitude as expected for a BCS superconductor. Only around $T_c^* = 6.5$ K, a temperature much lower than T_c, the usual temperature dependence of the minimum sets in around zero-bias. This effect with T_c^* ranging from 6.0 to 6.8 K has been reproduced in many other contacts with the Ho-based compound, but not for the two other compounds. T_c ranged from 8.4 to 8.9 K between the different contacts. The structure around zero-bias just below T_c cannot be explained within the standard BTK theory. The structure has some resemblance with the above-mentioned horn-like structures observed at above-gap voltages, although with a much larger broadening. Like for these horn-like structures, the exact shape of this structure depends in its details on the investigated contact.

We interpret this anomalous temperature dependence of Andreev-reflection spectra of $HoNi_2B_2C$ in a change of the superconducting state around $T_c^* = 6.5$ K from a state of yet unknown nature to a standard BCS superconducting state at lower temperatures. From our evaluation of the order parameter (see Fig. 3) we conclude that the BCS-state at low temperatures has most probably the critical temperature T_c^*. The transition in this superconducting state at 6.5 K is very likely related to the antiferromagnetic transition in this range of temperatures. From neutron scattering studies it has been concluded that the antiferromagnetic transition occurs in two steps: around 6 K a spiral magnetic ordering

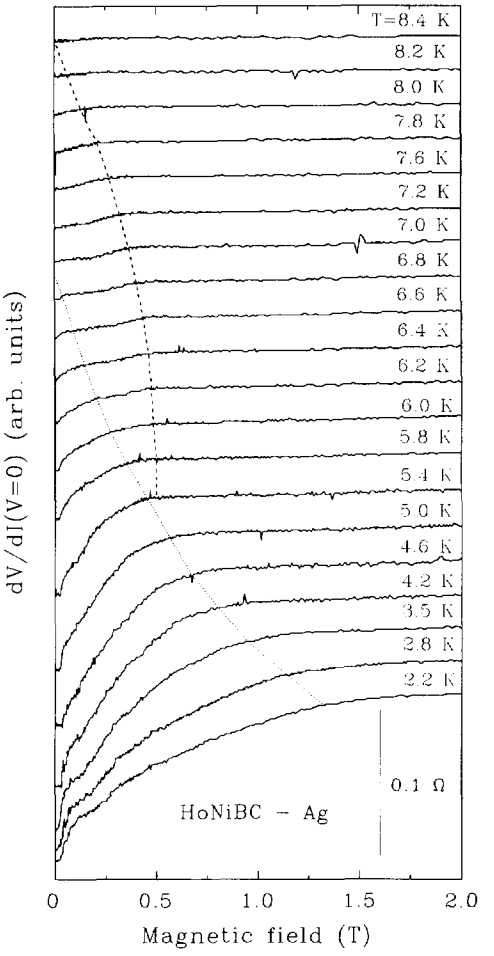

Fig. 4. Resistance $dV/dI(0)$ at zero-bias voltage as a function of magnetic field for the indicated temperatures. The dashed lines follow the anomalies corresponding to the transitions at $T_c = 8.3$ K and $T_c^* = 6.8$ K in zero field.

sets in which transforms into a commensurate antiferromagnetic ordering near 5 K [6, 5]. Just above this antiferromagnetic ordering a re-entrant behavior into the normal state is observed over a limited temperature range [3]. In recent work on single crystals this re-entrance into the normal state has only been observed in the presence of a magnetic field [10].

No decrease of the excess current is observed around the antiferromagnetic transition where the re-entrant behavior into the normal state occurs [9]. Assuming that the excess current is a measure for the superconducting order parameter, one can conclude from this that the modulus of the superconducting order parameter is not suppressed in the temperature region of normal-state re-entrance. In the resistance at zero-bias voltage, a change in the superconducting state

can be observed reflecting the overall change in the voltage dependence of the spectra $dV/dI(V)$. In Fig. 4 we give an example of the magnetic field dependence of the resistance $dV/dI(V = 0)$ at zero-bias voltage. In these curves, taken for different temperatures, one can observe the two transitions in the temperature interval between 5.4 and 6.8 K indicated as a guide for the eye by the dashed curves. Such a measurement allows us to reconstruct the phase diagram of the critical fields $H_c(T_c)$ and $H_c^*(T_c^*)$ for both transitions [9].

In conclusion, the Andreev-reflection process has been investigated in the point-contacts with three RNi_2B_2C compounds with R=Y, Er, and Ho. For the Y- and Er-based compound the standard behavior of the Andreev-reflection spectra for a BCS superconductor has been observed. However, the Ho-based compound shows an anomalous behavior in the point-contact spectra between the superconducting critical temperature $T_c \simeq 8.5$ K and $T_c^* \simeq 6.5$ K. In this temperature interval a superconducting state of yet unknown nature is revealed probably related to the interference between superconductivity and antiferromagnetic ordering. Below T_c^* a genuine BCS-type superconducting state develops upon lowering the temperature. One obtains $2\Delta/k_B T_c = 3.7$ for all three compounds (taking T_c^* for the superconducting temperature of the Ho-based compound).

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