Proceedings of the CSMAG'07 Conference, Košice, July 9–12, 2007

Point-Contact Spectroscopy of Superconducting $MgCNi_3$ Single Crystals

Z. Pribulová[a], P. Szabó[a], J. Kačmarčík[a], P. Samuely[a],
D.-J. Jang[b], H.G. Lee[b], H.S. Lee[b] and S.-I. Lee[b]

[a]Centre of Low Temperature Physics (CLTP) IEP SAS & FS UPJŠ
Watsonova 47, 040 01 Košice, Slovakia
[b]NCRICS and Department of Physics, Pohang University of Science and Technology, Pohang 790-784, Republic of Korea

The first point-contact spectroscopy measurements on $MgCNi_3$ single crystals of very good quality are presented. The measurements have been performed in the temperature range from 1.5 K up to 10 K and at magnetic fields up to 6 T. The superconducting energy gap Δ of the system is found to be scattered between 1 and 1.2 meV which gives the $2\Delta/kT_c$ ratio between BCS weak-coupling value of ~ 3.5 and a strong coupling of about 4.2. The excess current evaluated in magnetic field indicates the presence of a single energy gap.

PACS numbers: 74.50+r

1. Introduction

Even though $MgCNi_3$ is near a ferromagnetic instability [1] it clearly shows superconductivity [2]. However there is a lot of discrepancy in results of different experimental techniques. The specific heat [3] and tunnelling spectroscopic studies [4] have shown the s-wave BCS-type superconductivity while the penetration depth measurements exhibit a non-s-wave behaviour [5]. Recently the two-band model has been proposed to explain consistently different properties of this material. To resolve this controversial situation single crystals of good quality are highly desirable. Here we present a detailed study of the high quality $MgCNi_3$ single crystals by point-contact spectroscopy performed at different temperatures and magnetic fields.

2. Experimental details

Recently the long-standing problems of $MgCNi_3$ single-crystals preparation have been finally overcome. The samples were fabricated in a high-pressure closed system. Details of the synthesis can be found elsewhere [6]. Using an X-ray micro analyzer it was proved that carbon deficiencies in stoichiometry are negligible. However, in contrast to polycrystalline $MgCNi_3$, which has usually local carbon deficiency, in these single crystals the Ni site was partly deficient. This leads to the lower critical temperature $T_c \sim 6.7$ K [6] compared to the highest $T_c \sim 7.3$ K of polycrystalline samples.

The point-contact spectroscopy measurements were performed on several samples of the same batch. A standard lock-in technique at 10 kHz was used to measure the differential resistance as a function of applied voltage on the point contacts. The micro constrictions were prepared in situ by soft pressing of mechanically formed platinum tip to the surface of the sample. The special approaching system enabled both the lateral and vertical movements of the tip by differential screw mechanism.

The experimental conductance curves of our point-contacts were normalized to the conductance background at higher voltages above the energy gap. This allows us to fit the point-contact conductance to the standard point-contact model [7] and get the information about the energy gap Δ, parameter of the barrier z, and spectral broadening Γ.

3. Results and discussion

Tens of point-contact spectra and a few sets of their temperature dependences have been recorded on $MgCNi_3$ samples from the same batch. The point-contacts revealed an intermediate barrier strength between metallic and tunneling case (z ranges from 0.2 to 1). The majority of the measurements at the lowest temperatures revealed value of the energy gap scattered between 1 and 1.2 meV. Counting with $T_c \sim 6.7$ K we obtain the coupling ratio of $2\Delta/kT_c \sim 3.5$–4.2. Figure 1a shows the spectra of one point-contact measured at different temperatures. The circles are the best fit to the point-contact model for every temperature. The inset represents a temperature dependence of the energy gap (circles) obtained from the fitting procedure and comparison to the BCS-like behaviour (line). Let us note that the ratio $2\Delta/kT_c = 3.46$ for this contact is slightly lower than the BCS weak-coupling limit (3.52) but there is also a slight deviation from the BCS-type of temperature dependence of the energy gap.

In some measurements we have found the energy gap value at even smaller energies around 0.7 meV. Figure 1b displays such a point-contact spectrum measured at different temperatures up to the local critical temperature of given contact. The ratio $2\Delta/kT_c \sim 2.5$ of this contact is much lower than the BCS value of 3.52. Moreover, a strong deviation from the BCS behaviour of the temperature dependence $\Delta(T)$ above 3 K is obvious — see the inset of Fig. 1b. Such a low value of energy gap was observed also by Shan et al. by point-contact spectroscopy on polycrystals [4]. In the case of single crystals we suppose that this deviation may be due to degradation of the surface.

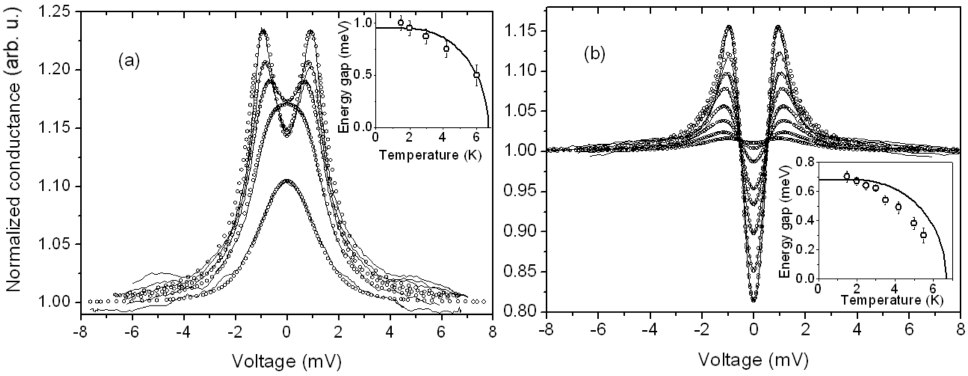

Fig. 1. Pt-MgCNi$_3$ point-contact spectra (solid lines) measured at (a) 1.5 K, 2 K, 3 K, 4.2 K, 6 K (b) 1.5 K, 2 K, 2.5 K, 3 K, 3.5 K, 4.2 K, 5 K, 5.5 K and fitting curves (circles). Inset: temperature dependence of energy gap with (a) $\Delta(0) \sim 1$ meV and (b) $\Delta(0) \sim 0.7$ meV, the line shows BCS-like curve.

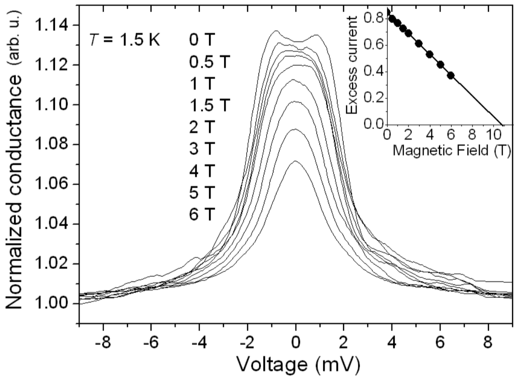

Fig. 2. Pt–MgCNi$_3$ point-contact measured in indicated magnetic fields. Inset: Excess current of the contact as a function of magnetic field. Line is guide to the eyes.

A similar, though less pronounced, deviation of $\Delta(T)$ from the BCS behaviour in the previous case, Fig. 1a, suggests that the proximity effect of bulk phase may be partially present also here and the real intrinsic energy gap is larger than 1 meV.

Figure 2 shows the normalized conductance spectrum of another point-contact measured at 1.5 K at various magnetic fields. The excess current calculated from the area between the normalized conductance spectrum and unity decreases with increasing magnetic field. It is connected to increasing number of vortices which cores represent a normal state area in the contact. Since the normal-state area of the junction increases linearly with increasing field up to upper critical field H_{c2}, the excess current will also shrink linearly. For MgB_2, a two-band superconductor, the excess current decreases with two different subsequent slopes in accordance with different filling rate of the two gaps. As could be seen in the inset of Fig. 2, the excess current decreases linearly in the whole magnetic field range in the case of MgNCi3 indicating the presence of only a single gap. Extrapolating the linear behaviour to higher magnetic fields we can estimate H_{c2} as the magnetic field, where the excess current disappears. The obtained value of H_{c2} (1.5 K) $\sim$ 10.5 T is in agreement with the one proposed from the transport measurements on the same batch of the samples [8].

4. Conclusions

In summary, we have performed the point-contact spectroscopy measurements on $MgCNi_3$ single crystals. The values of the gaps are scattered between 1 and 1.2 meV and $2\Delta/kT_c$ between 3.5 and 4.2. The detailed studies of the local temperature T_c are needed to resolve the real intrinsic Δ. The studies in magnetic fields indicate the presence of a single gap in the quasiparticle spectrum.

Acknowledgments

The work was supported by the Slovak Research and Development Agency under the contract No. APVV-51-016604 and LPP-0101-06. The CLTP is operated as the Centre of Excellence of the Slovak Academy of Sciences and P.J. Šafárik University. Liquid nitrogen for the experiments has been sponsored by U.S.Steel Košice, s.r.o.

References

[1] H. Rosner, R. Weht, M.D. Johannes, W.E. Pickett, E. Tosatti, *Phys. Rev. Lett.* **88**, 027001 (2002).

[2] T. He, G. Fuchs, K.-H. Müller, A. Handstein, K. Nenkov, V.N. Narozhnyi, S.-L. Drechsler, S. Shulga, L. Schultz, *Nature* **411**, 54 (2001).

[3] A. Wälte, Q. Huang, A.P. Ramirez, Y. Wang, K.A. Regan, N. Rogado, M.A. Hayward, M.K. Haas, J.S. Slusky, K. Inumara, H.W. Zandbergen, N.P. Ong, R.J. Cava, *Phys. Rev. B* **70**, 174503 (2004).

[4] L. Shan, H.J. Tao, H. Gao, Z.Z. Li, Z.A. Ren, G.C. Che, H.H. Wen, *Phys. Rev. B* **68**, 144510 (2003).

[5] R. Prozorov, A. Snezhko, T. He, R.J. Cava, *Phys. Rev. B* **68**, 180502 (2003).

[6] H.S. Lee, D.-J. Jang, H.-G. Lee, S.-I. Lee, S.-M. Choi, C.-J. Kim, *Adv. Mater.* **19**, 1807 (2007).

[7] A. Plecenník, M. Grajcar, Š. Beňačka, *Phys. Rev. B* **49**, 10016 (1996).

[8] H.S. Lee, D.-J. Jang, H.-G. Lee, W. Kang, S.S. Saxena, S.-I. Lee, to be published.