TUNNELING SPECTROSCOPY OF THE ENERGY GAP IN MgB_2 UNDER MAGNETIC FIELDS*

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Effects of magnetic field on the multiple-gap structure in the superconductor MgB_2 have been studied by break junctions. With increasing the field, the gap value decreases with filling up of the states inside of the gap. The gap-closing field B_c correlates with the gap size. The extrapolated B_c value for the larger gap is almost consistent with the upper critical field of this compound.

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1. Introduction

The existence of the multiple-gap structure in the quasiparticle density of states is one of the intriguing features of the novel binary superconductor MgB_2 [1,2]. This peculiar feature can be attributed to the 2-band superconductivity associated with the boron p_{xy} and p_z bands [3], the induced gap by a proximity effect [2], or the gap anisotropy arising from the hexagonal crystal structure [4]. Since this multiple-gap feature is seen up to $T_c = 39$ K, another way to suppress the multiple superconducting order parameters should be effective to investigate further its origin. Here we report on the tunneling measurements under magnetic fields to address this issue. The tunneling technique provides the most direct probe to measure the energy gap. The

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measurements were done using the break junction, in which the polycrystalline sample was cracked at 4.2 K by applying adjustable bending force. By this technique, *in situ* junction interface is obtained, from which the reliable tunneling spectra can be observed. The magnetic fields were applied perpendicular to the tunneling current. The measurements were done at 4.2 K.

2. Results and discussion

Figure 1 (a) shows representative tunneling conductance dI/dV, which reflects the superconductor-insulator-superconductor (SIS) junction spectrum arising from the break junction. The SIS conductance fitting using the weighted sum of the BCS density of states $N(\Delta_1, \Delta_2) = aN_1(\Delta_1) + bN_2(\Delta_2)$ gives $\Delta_1 = 2.3$ meV and $\Delta_2 = 6.6$ meV, respectively, where $N_i(\Delta_i)$ $(i = 1, 2)$ represents $|\,\mathrm{Re}[(E - i\Gamma_i)/[(E - i\Gamma_i)^2 - \Delta_i^2]^{1/2}]\,|$ with the phenomenological broadening parameter Γ_i ($\Gamma_1 = 0.1$ meV and $\Gamma_2 = 0.8$ meV). In the fitting, the ratio of coefficients $a/b > 4$ is required, where the density of states for the smaller gap is dominated. These fitted gap values are consistent with $\Delta_1 = 2.5$ meV and $\Delta_2 = 5.5$ meV obtained from the inner and outer *peak-to-peak* separations (V_p) in (a).

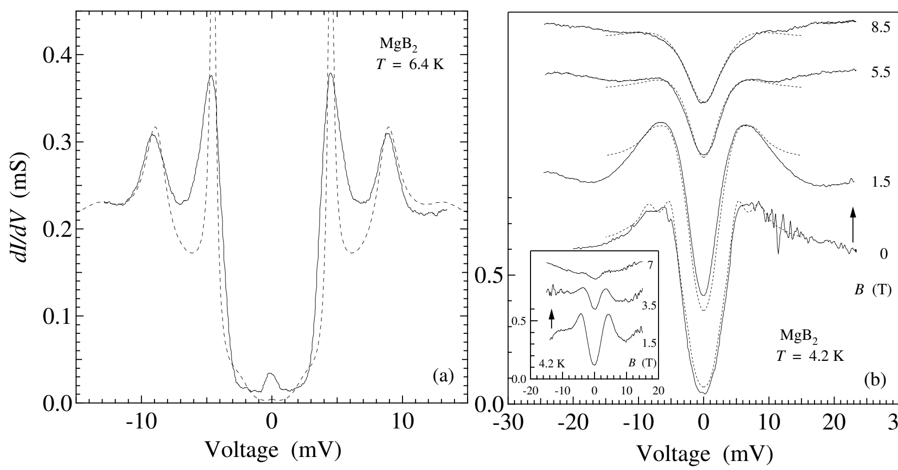

Fig. 1. (a) The tunneling conductance for an MgB_2 break junction. (b) The tunneling conductance for MgB_2 break junctions under various magnetic fields. The inset shows the data from the different junction. The broken curves in (a) and (b) represent the calculated $N(\Delta_1, \Delta_2)$ (see text).

It should be interesting to see the field evolution of such a distinct double-gap conductance feature. Unfortunately, when the external field is applied, the break junction with such a feature often becomes mechanically unstable.

Therefore, as shown in Fig. 1(b), we investigate using the broadened-gap feature, which is often stable against the field. The absence of Josephson current in zero field can be connected with such a broadened feature. The zero-field fitting using $N(\Delta_1, \Delta_2)$ is satisfactory as shown by the bottom broken curve, which gives the values of $\Delta_1 = 2.5$ meV ($\Gamma_1 = 0.8$ meV) and $\Delta_2 = 5.9$ meV ($\Gamma_2 = 1.1$ meV) with $a/b = 7.3$. These gap values agree with $\Delta_1 = 3$ meV and $\Delta_2 = 5.8$ meV obtained from the inner and outer $V_p = 12$ mV ($= 4\Delta_1/e$) and 17.6 mV ($= 2(\Delta_1 + \Delta_2)/e$), respectively.

By appplying the field, the gap structure is further broadened with filling up of the states inside of the gap. Since MgB_2 is a type-II superconductor with the Ginzburg–Landau parameter $\kappa \sim 26$ [5], the gap feature in the field seen by the break junction can be regarded as the specially averaged order parameter in the vortex states [6]. Since the energy of 0.6 meV corresponding to the field of 10 T is much smaller than the gap energy, the Zeeman splitting cannot cause the broadening. To evaluate the energy gap under magnetic fields, the conductance fitting is carried out using $N(\Delta_1, \Delta_2)$. The results are shown by the broken curves, where the fitting is shown to be almost satisfactory. These fittings reveal the decrease in Δ_i and the increase in Γ_i with increasing the field. The decrease in Δ_i is due to the field suppression of the averaged order parameter, while the increase in Γ_i can be connected with the field increase in the pair-breaking magnitude, although the origin of the residual Γ_i values in zero field is left unknown. The inner gap in the double-gap feature under the field is not apparent in the raw data despite of the satisfactory fits using $N(\Delta_1, \Delta_2)$. Therefore, the field variations of the smaller single gap Δ_1 from the different break junction are shown in the inset of Fig. 1 to demonstrate its existence more explicitly. The observation of single gap suggests that the double-gap feature is not essential, or there might be a momentum selection in the tunneling current.

In Fig. 2, the field dependence of the gap parameter $\Delta_i(B)$ is plotted. The circles represent the fitted Δ_i at each field from the double-gap conductance in Fig. 1(b), while the triangles represent the smaller gap parameter $\Delta_1 = eV_p/4$ of the Fig. 1(b) inset. For the smaller gap parameter Δ_1, both the fitted gap and the $eV_p/4$ agree each other, justifying the correctness of the fittings. To evaluate the behavior of the gap in the field, the theoretical prediction $\Delta_i(B) = \Delta_i[1 - B/B_c^i]^{1/2}$ for a type-II BCS superconductor is also plotted, where B_c^i represents the gap-closing field (the B_c^2 corresponds to the upper critical field) [6]. The experimental data for $\Delta_1 = 2.5$ meV almost agree with the calculated curve with $B_c^1 \simeq 10$ T. Assuming the same relationship, the B_c^2 for $\Delta_2 = 5.9$ meV can be extrapolated to be $\sim$13.5 T. Therefore, the magnetic field distinguishes the behaviors of the gaps. This is in contrast to the temperature dependence of Δ_i, where the different gap sizes possess the same $T_c = 39$ K.

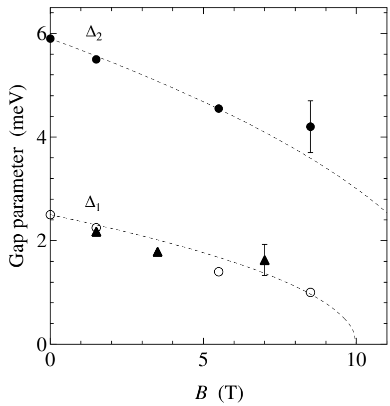

Fig. 2. The field dependence of the energy gap in MgB_2. The broken curves represent $\Delta_i(B) = \Delta_i[1 - B/B_c^i]^{1/2}$ $(i = 1, 2)$.

3. Conclusion

The break-junction tunneling measurements of MgB_2 under magnetic fields reveal that the extrapolated gap-closing fields are $B_c^1 \simeq 10$ T and $B_c^2 \sim 13.5$ T for $\Delta_1 = 2.5$ meV and $\Delta_2 \simeq 6$ meV, respectively. The B_c^2 value is roughly the same as the upper critical field obtained by the transport and magnetization measurements [5, 7].

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