# Multiple-gap structure of the binary superconductor $MgB_2$

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**Abstract**

Electron-tunneling measurements on the superconductor $MgB_2$ with $T_c = 39$K have been carried out using a break-junction technique. We have observed the double-gap structures with several combinations of the gap sizes. The largest $\Delta = 9$ meV gap can be observed as a single gap, which gives very strong-coupling ratio $2\Delta/k_BT_c = 5.3$-$5.7$.

*Key words:* Tunneling spectroscopy; Multiple-gap structure; Break junction; $MgB_2$;

## 1. Introduction

The recent discovery of superconductivity in $MgB_2$ with $T_c = 39$K has attracted a number of research groups [1]. Several spectroscopy measurements on sintered polycrystalline samples of $MgB_2$ have revealed various gap values [2,3]. In this paper, we present tunneling measurements on $MgB_2$ in order to study the multiple-gap feature. The measurements were done by *in situ* break-junction technique. In this method, the sample is cracked at 4.2K, which forms a superconductor-insulator-superconductor (SIS) junction with undamaged interface. For the SIS junction with the single-gap feature, the peak-to-peak bias separation in the tunneling conductance ($dI/dV$) corresponds to $4\Delta$/e, where $2\Delta$ represents the superconducting energy gap.

## 2. Results and discussion

Figure 1 shows the representative tunneling conductance $dI/dV$ at 4.2K. This type of spectrum often accompanies the hump structures at the outside of the main peaks as shown in Fig. 1 (a). The intensities of hump structures vary among the spectra, while the peak-to-peak bias separations are almost unchanged. In Fig. 1 (b), the conductance peaks for $V_S$ are stronger than those for $V_M$, while the peaks for $V_L$ are weaker than those for $V_M$. The features of $V_S$ and $V_M$ in Fig. 1 (b) are similar to those of the main peaks and hump structures in Fig. 1 (a), respectively. The mutual relationship among the three peaks structures is expressed by $V_M = (V_S + V_L)/2$. From this relationship, it is likely that there exist two energy gaps in each side of the SIS junction. Using the weighted sum of quasiparticle density of states $N(\Delta_1, \Delta_2) = (1-x)N_1(\Delta_1) + xN_2(\Delta_2)$, we evaluate the experimental spectra, where $N_j(\Delta_j)$ ($j$ = 1,2) corresponds to the broadened BCS density of states $|Re\{(E-i\Gamma_j)/[(E-i\Gamma_j)^2-\Delta_j^2]^{1/2}\}|$, $\Gamma_j$ ($j$ = 1,2) is a broadening parameter, and $x$ is a coefficient. The thin curves in Fig. 1 show the calculation results. It is evident from these fittings that the experimental conductance can be expressed by $N(\Delta_1, \Delta_2)$ with $x = 0.1$. The peak positions correspond to $V_S = 4\Delta_1/e$, $V_M = 2(\Delta_1+\Delta_2)/e$ and $V_L = 4\Delta_2/e$. Note that the peaks of the larger gaps ($V_L$) are easily reduced by the slight increase in $\Gamma_j$(see figure). The calculated value of smaller energy gap $\Delta_1$ is about 2 meV, while the larger one is $\Delta_2 \sim 6.5$ meV. Then the gap values lead to the ratio $2\Delta_1/k_BT_c$=1.2 and $2\Delta_2/k_BT_c$=3.8, respectively.

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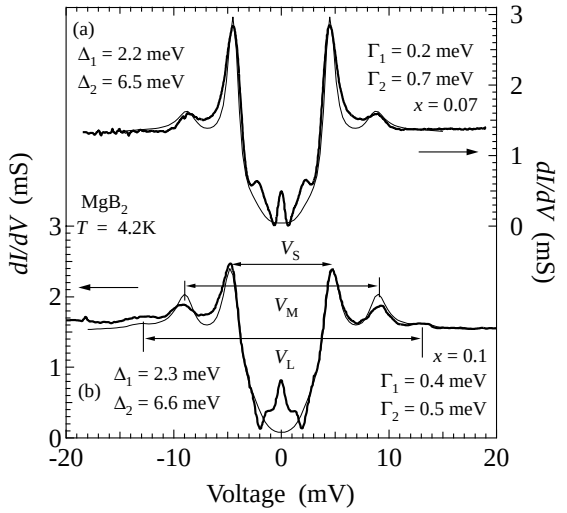


Fig. 1. Tunneling conductance from $MgB_2$ break junctions showing the two-gap feature at 4.2K. The thick curves represent the experimental results, while the thin curves represent the calculation using $N(\Delta_1, \Delta_2)$.

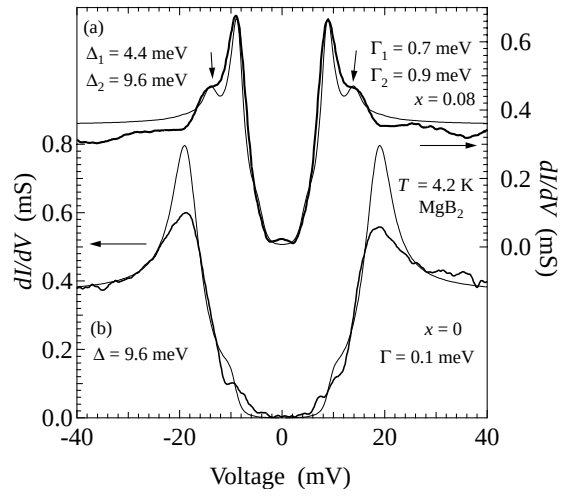


Fig. 2. Tunneling conductance for $MgB_2$ break junctions (thick curves). The thin curves are the calculated results by $N(\Delta_1, \Delta_2)$. The spectrum(a) is fitted by the two-gap feature($x$ = 0.08), while (b) is by the simple BCS model($x = 0$),respectively.

The thick curve in Fig. 2 (a) shows the representative spectrum with the gap size twice larger than $V_S$ of Fig. 1. This type of spectrum also accompanies the outer hump structures, but the strength of them is weakened as shown by the arrows in Fig. 2 (a). The thin curve is the calculated result by $N(\Delta_1, \Delta_2)$. The fitted energy gap values are $\Delta_1 = 4.4$ meV and $\Delta_2 = 9.6$ meV, which gives the ratio $2\Delta_1/k_BT_c = 2.6$ and $2\Delta_2/k_BT_c$=5.7, respectively. It should be interesting to note that the single gap of $\Delta = 9.6$ meV is also observed as shown in Fig. 2 (b). This spectrum is approximately expressed by the SIS conductance of a single BCS density of states except for the gap peak region. To our knowledge, this gap ratio $5 \sim 6$ shows the largest value except for copper-oxide superconductors [4]. The origin of the multiple-gap structure can be primarily due to multiple-band or anisotropic-gap structure [5,6]. However, there is another possibility arising from the proximity effect [7]. Within this interpretation, the two-gap structure reflecting both the superconducting and induced phases can appear in the spectrum. In the two-gap structure we have observed, the combination of two gap values strongly depends on the spectra. Therefore, the origin of the multiple-gap structure still remains to be experimentally clarified.

## 3. Conclusion

The tunneling measurements reveal various energy gaps with the ratio $2\Delta/k_BT_c$ = 1.2-5.7. We have observed the multiple gap structures showing the different gap-energy scales. The observed largest ratio implies that this compound is very strong-coupling superconductor. The further study using single crystals is needed.

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