Temperature and field dependence of MgB$_2$ energy gaps from tunneling spectra

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We have synthesized MgB$_2$/Pb planar junctions to study the temperature and field dependence of the superconducting energy gap of MgB$_2$. The major peak occurs at $\Delta$ of about 2 meV, and this corresponds to a $2\Delta/k_B T_c$ value of 1.18. While this is significantly smaller than the BCS weak coupling value, there are features in the tunneling spectra indicating the possibility of another larger gap. By fitting the $dI/dV$ curves with a simple model, the larger gap is estimated to be about 4.5 times the smaller gap. The study of the effect of magnetic field on the junctions shows a stability only up to a field of 3.2T then junctions "collapsed" into Josephson tunneling for higher fields. Estimation of the major energy gap from Josephson tunneling is consistent with that from quasiparticle tunneling.

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I. INTRODUCTION

One interesting feature in the superconductivity of MgB$_2$ ($T_c = 40$ K) is the possibility of coexistence of two energy gaps. This immediately leads to many intriguing questions, like whether the two gaps follow $\Delta_{BCS}(T)$ and share the same critical temperature. There have been numerous tunneling spectroscopic studies to investigate this phenomenon at low temperatures. Most of these studies are performed with scanning tunneling microscope or point contact. To provide the needed stability for temperature and field dependence studies, we have synthesized planar tunnel junctions on bulk MgB$_2$ with Pb as the counter electrode.

II. RESULTS AND DISCUSSIONS

As indicated in figure 1, the major peak ($\Delta_1$) in most of our junctions occurs consistently around 2 meV. This is significantly smaller than the BCS value. The second gap ($\Delta_2$) appears as a small feature at around 9 meV. For conductance curves when Pb is normal, we can fit the data with a simple model by mixing two BCS density of states (with energy gaps $\Delta_1$ and $\Delta_2$) at a ratio of C. A depairing term $\Gamma$ is introduced to account for different deparing effects, and barrier strength $Z$ is also included to account for the zero bias offset by Andreev reflection. Thermal broadening is included at the particular temperature of the fitting. C, $\Gamma$, and $Z$ are determined by the curve at temperature = 7.78 K above Pb $T_c \approx 7.2$ K. They have the best fitted values of 0.064, 0.95 meV, and 1.33 meV respectively. These values are then fixed for all subsequent fittings at higher temperatures. $\Delta_1$ and $\Delta_2$ are the only adjustable parameters for higher temperature curves.

The temperature dependence of the two energy gaps is shown in the right insert of figure 1. It is clear that both energy gaps follow a BCS-like behavior and both gaps survive up to the bulk $T_c$ of MgB$_2$. From this we can conclude that the commonly observed small energy gap is not a result of surface degradation, but a true bulk property of MgB$_2$. $\Delta_1(0)$ and $\Delta_2(0)$ are 1.8 meV and 8.2 meV respectively, and the ratio $\Delta_2/\Delta_1$ is about 4.5 through out the temperature range. This ratio is close to both the theoretically predicted and experimentally
FIG. 2: Josephson tunneling at different temperatures. The listed temperatures are in the same order as the curves presented. Insert: $I_c R_N$ vs. $T$.

The left insert in figure 1 shows the field dependence of the major peak position at 4.2 K. At low fields, this corresponds to the sum of Pb gap ($\Delta_{\text{Pb}}$) and $\Delta_1$. It can be seen that there is a discontinuity in the peak position at the critical field of Pb ($H_c(0) \approx 0.08 T$), when Pb ceases to be superconducting. The peak position corresponds to $\Delta_1$ at all higher fields. At a field of about 3.2 T most of our junctions "collapse" into Josephson tunneling and the change is not reversible.

The behavior of one of these Josephson junctions is shown in figure 2. The Josephson tunneling is between MgB$_2$ and Pb. The normal resistance ($R_N$) varies only very slightly with temperature. $I_c R_N$ is estimated to be about 2.1 mV (insert, Fig. 2) for the curve at 4.2 K. If we assume $I_c R_N \approx \frac{\Delta_1 \Delta_{\text{Pb}}}{\epsilon \Delta_1 + \Delta_{\text{Pb}}}$ and $\Delta_{\text{Pb}}(at4.2K) \approx 1.08$ meV, we can estimate $\Delta_1$ to be 1.75 meV. This is consistent with our result from the quasiparticle tunneling discussed above.

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