# Momentum-Dependent Scanning Tunneling Spectroscopy in $MgB_2$

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**Abstract**

We present study of the anisotropic superconductor $MgB_2$ using a combination of scanning tunneling microscopy and spectroscopy. The results reveal two distinct energy gaps at $\Delta_1$=2.3 meV and $\Delta_2$=7.1 meV. Different spectral weights of the partial superconducting density of states are a reflection of different tunneling directions in this multi-band system. Our experimental observations are consistent with the existence of two-band superconductivity in the presence of interband superconducting pair interaction and quasiparticle scattering. Temperature evolution of the tunneling spectra follows the BCS scenario with both gaps vanishing at the bulk $T_c$. The data confirm the importance of Fermi-surface sheet dependent superconductivity in $MgB_2$ proposed in the multigap model by Liu et al. [1]

*Key words:* $MgB_2$; STM; scanning tunneling spectroscopy; multi-gap superconductivity

## 1. Introduction

The discovery of superconductivity in $MgB_2$ [2] at 39K sparked great interest in the fundamental physics and practical applications of this material. Two-gap scenario has been predicted theoretically by Liu et al. [1]. First principle calculations show that the Fermi surface of $MgB_2$ consists of 2D cylindrical sheets arising from $\sigma$ antibonding states of B $p_{xy}$ orbitals, and 3D tubular networks arising from $\pi$ bonding and antibonding states of B $p_z$ orbitals. In this theoretical framework [1] two different energy gaps exist, the smaller one being an induced gap associated with the 3D bands and the larger one associated with the superconducting 2D bands. Furthermore both superconducting gaps should vanish at the bulk critical temperature $T_c$.

Scanning tunneling spectroscopy is a unique technique that allows direct measure of the DOS near the Fermi energy and since the contribution to the tunneling conductivity of electronic states with finite momentum in the tunneling direction is exponentially larger than the contribution of states with momentum perpendicular to tunneling direction, the STM can distinguish between the 2D bands with little or no c-axis component of Fermi velocity and 3D bands with considerable c-axis component. In the clean limit($l \gg 2\pi\xi$) the direction of the tunneling current selects which band and which superconducting gap is probed. In this paper we report direct evidence of orientation-dependent double-gap structure in the quasi-particle energy spectra as determined from tunneling spectroscopy.

## 2. Results

Compact samples of $MgB_2$ were synthesized from amorphous B powder (4N's purity) and high purity Mg. The B powder was pressed into pellets under 6 kbar pressure. These pellets were reacted with Mg vapor at 850 C for 2 hr in a BN container under 50 bar of Ar. The typical critical temperature of these gold-colored

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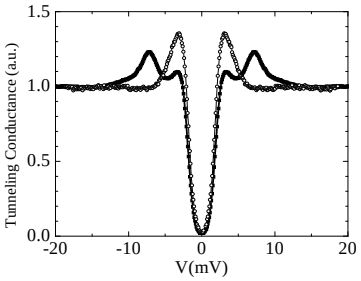


Fig. 1. Tunneling conductance spectra recorded on c-axis oriented (open) and a/b-axis oriented (closed) grains at 4.2K. The tunneling resistance is 0.1 GΩ. The spectra have been normalized to the conductance value at -20 mV.

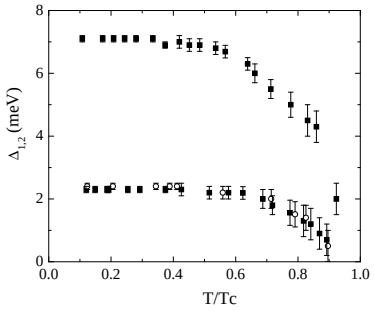


Fig. 2. Superconducting gap values as a function of the temperature in case of pellets (closed symbols) and c-axis oriented thin films (open symbols).

pellets is 39K. The 400 nm thick c-axis oriented $MgB_2$ films used in this study were grown via a pulsed laser deposition technique on an $Al_2O_3$ substrate resulting in an oriented film with the crystallographic c-axis perpendicular to the substrate surface [3].

The typical grain size in the pellets is of the order of 50 nm and the spectra are remarkably reproducible within the same grain both with respect to location and tunneling resistance. The spectra reveal a flat background and very low zero-bias conductance with very little broadening other than thermal smearing. In Fig.1 we present two typical spectra obtained on different grains. On one of the grains two peaks are present at $V_1 \sim 3$ mV and $V_2 \sim 7.5$ mV, symmetrically for both injection and emission of electrons and they stay within 10% of these values when changing between grains and/or samples. On the second grain only the smaller gap is pronounced. The main characteristics of the spectra, including the spectral weight of each peak, do not change with the tunneling resistance from 0.1 to 2 GΩ.

We find a striking similarity between the spectrum obtained on the second grain and the typical spectrum we recorded earlier on c-axis oriented films [4]. In the c-axis tunneling on $MgB_2$ epitaxial films the contribution from the 3D Fermi surface is expected to dominate the tunneling conductance. Thus we believe that the distinct spectra attributable to the two grains are a reflection of different crystallographic grain orientation with respect to the tunneling direction.

The distinct tunneling conductance spectra that we observe are consistent with the two-gap BCS model taking into account interband impurity scattering (see, e.g., [5]). According to this model the partial densities of states (PDOS) of two bands $N_{1(2)}(\omega)$

$$N_{1(2)}(\omega) = N_{1(2)}(0)\,\mathrm{Re}\left[\frac{u_{1(2)}}{\sqrt{u_{1(2)}^2 - 1}}\right],$$

are determined by two dimensionless functions $u_{1(2)}(\omega)$ that depend on the gap parameters of each band $\Delta_{1,2}$ and the inteband scattering rates $\Gamma_{12}$ and $\Gamma_{21}$, with $\Gamma_{12}/\Gamma_{21} = N_2(0)/N_1(0)$. We use a linear combination of the two PDOS to obtain the total DOS

$$N_{tot}(\omega) = \alpha N_1(\omega) + \beta N_2(\omega)$$

that we compare with the experimental tunneling conductance spectra.

The values of $\Delta_1$(T) and $\Delta_2$(T) are extracted from the theoretical curves and the results are reported in Fig.2. The high-energy gap follows a BCS behavior. The smaller gap remains constant up to 20K and follows the BCS predictions with a critical temperature far beyond the one expected for such a small gap ($T_c \approx$14K) with a ratio $2\Delta/kT_c \approx$1.4. Such behavior clearly demonstrates that the gap in the 3D band is mainly induced by the interband pairing interaction rather than produced by pairing interaction inside this band, in agreement with theoretical expectations [1,6].

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