Microwave properties of superconducting $MgB_2$

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Measurements of the 10GHz microwave surface resistance of dense $MgB_2$ wire and pellet are reported. Significant improvements are observed in the wire with reduction of porosity. The data lie substantially above the theoretical estimates for a pure BCS s-wave superconductor. However the $R_s(20K)$ of the wire is an order of magnitude lower than that of polycrystal $YBa_2Cu_3O_{6.95}$ and matches with single crystal $YBa_2Cu_3O_{6.95}$. The results show promise for the use of $MgB_2$ in microwave applications.

The discovery [1] of superconductivity in $MgB_2$ with $T_c = 40K$ has raised a flurry of interest. An important scientific issue is whether $MgB_2$ is a conventional type II superconductor or falls in to a different category, such as the high temperature superconducting cuprates which are believed to have an exotic order parameter. A particularly interesting technological possibility is the use of this material as a replacement for $Nb$ in microwave applications such as superconducting cavities and accelerators. A 40K s-wave superconductor would be of enormous benefit for microwave applications since the microwave absorption would be lower than the normal state by $10^{-5} - 10^{-4}$ at $T \sim T_c/2 \sim 20K$, a temperature easily accessible with modern cryo coolers.

Microwave measurements provide accurate determination of applied and fundamental parameters of superconductivity including $Z_s(T)$, superconducting gap $\Delta(T)$, penetration depth $\lambda(T)$, pairing symmetry, vortex dynamics and pinning force constant $k(T)$. Careful study of superconductivity in $MgB_2$ is essential to determine the mechanism of microwave absorption and thereby synthesizing better quality materials with low microwave loss. In this report we present the first measurements of the microwave surface impedance $Z_s = R_s - iX_s$ of $MgB_2$.

Two types of samples were studied. The first (P-1) is a polycrystalline pellet ($\sim 1 - 2mm$ cubic dimensions) of moderate density which is synthesized by reacting stoichiometric amounts of B and Mg at 950$^\circ$C for approximately two hours. The other W-1 is a high density $MgB_2$ wire (outer diameter $140\mu m$) [2]. To synthesize $MgB_2$ wire (W-1) powder Mg and a boron fiber of $100 \mu m$ diameter, with central core of Tungsten Boride (15 $\mu m$), in a nominal ratio of $MgB_2$ are sealed in to a $Ta$ tube. The sealed $Ta$ tube is then placed in $950^\circ$C in a box furnace for 2 hours and quenched to room temperature. The density of the wire is at least 80% of the theoretical density. Both samples P-1 and W-1 have been extensively characterized by a variety of probes such as XRD, resistivity, SEM and various other probes [3]. Very low dc resistivity $\sim 0.4\mu \Omega - cm$ [4] at $T_c$ has been observed in the wire which is lower than polycrystal samples by approximately two orders of magnitude ($\sim 70\mu \Omega - cm$ [4]). The wire is more than 80% dense, shows the full $\chi = -1/4\pi$ shielding in the superconducting state and has a sharp transition of width 0.9K at $T_c = 39.4K$.

The high precision microwave measurements were carried out in a 10GHz $Nb$ superconducting cavity with a variable temperature sample pedestal [5]. This technique has been used extensively for characterizing the microwave properties of small specimens of high $T_c$ and borocarbide superconductors [6,7]. The sample is placed in the maximum of the microwave magnetic field of $TE_{011}$ mode and as it is warmed slowly the surface impedance, $Z_s = R_s - iX_s$ is measured.

The superconducting microwave surface resistance $R_s(T)$ of P-1 and W-1 are shown in Fig. 1. The polycrystalline sample is observed to have higher $R_s$ when compared to that of wire. Both samples show approximately similar temperature dependence of $R_s(T)$ but differ by a large scale factor. The microwave resistivity $\rho_{sn}(T)$ (Fig. 2) in the normal state is obtained from the surface resistance $R_{sn}(T)$ using $\rho_{sn}(T) = 2R_{sn}(T)/\mu_0\omega$. The data are in good agreement with independent dc resistivity measurements of the wire. The agreement between the dc and microwave resistivities confirms that the classical skin-depth regime applies in the normal state.

Fig. 3 shows the scanning electron micrographs (SEM) of both P-1 and W-1 samples. The difference between $R_s$ of P-1 and W-1 can be attributed to different densities and grain sizes of these two samples. As can be seen from the figure the average grain size in W-1 is as large as 10 $\mu m$ while P-1 has smaller grains of size $\sim 0.5 - 5\mu m$. These differences in grain size and porosity lead to larger absorption in P-1 in two ways. Firstly, they result in coupled Josephson junctions with large effective junction penetration depth, and secondly smaller grain size in P-1 increases the effective surface area of and thereby $R_s$. In fact, correction to surface area of P-1 by a factor of 10 does reduce $R_s$ reasonably close to that of W-1. Fig.3(c) further clarifies the morphology of the $MgB_2$ sheath. Note that the Tungsten Boride core is not seen by the microwaves and is shielded by $MgB_2$.
because of the small penetration depth \( \lambda \sim 140 \text{nm} \), except for a small contribution at the wire ends which may be responsible for some of the residual loss.

The comparisons to measurements at the same frequency for Nb, Cu and single crystal and polycrystal of \( YBa_2Cu_3O_6.95 \) are shown in Fig. 1. The wire sample starts off with a very low normal state \( R_s \) slightly below Cu, and well below the normal state values for Nb. Very important to note is the comparison to \( YBa_2Cu_3O_6.95 \) where \( R_s(T < T_c) \) of MgB2 wire is far below that of polycrystal \( YBa_2Cu_3O_6.95 \) and comparable to single crystal (Fig. 1) and films of \( YBa_2Cu_3O_6.95 \) at 20K. At present the improvements in the superconducting state in \( MgB_2 \) are much smaller than in the other superconductors. Nb is well established to be an s-wave superconductor and the microwave data are in excellent agreement with BCS calculations of the microwave absorption for an s-wave superconductor with a gap that is consistent with other measurements. On the other hand the origin of the microwave absorption in \( YBa_2Cu_3O_{6+\delta} \) is still debated, even though a consensus has emerged that the order parameter is d-wave. In \( YBa_2Cu_3O_{6+\delta} \) the microwave absorption is much larger than expected even for a d-wave superconductor if one uses the quasiparticle scattering time extrapolated from the normal state.

Several reports have already claimed that \( MgB_2 \) is a conventional phonon-mediated superconductor with an s-wave order parameter \([1]\). In conventional s-wave superconductors the thermodynamic and transport coefficients decay exponentially and there is no quasiparticle excitation at low energies. Tunneling measurements report the ratio \( 2\Delta(0)/k_BT_c \sim 3 \) \([9]\) in \( MgB_2 \). A conventional BCS temperature dependence has been observed for the gap.

In order to investigate the mechanism of microwave absorption in \( MgB_2 \) the microwave data are compared with calculations for a BCS s-wave superconductor. We use the relation between the impedance \( R \) and the Mattis-Bardeen complex conductivity \( \tilde{\sigma} \) and its deviation from BCS calculation for an s-wave superconductor is more akin to the microwave \( R_s \) of \( RNi_2B_2C \) class superconductors which also clearly do not follow BCS s-wave. In both \( MgB_2 \) and \( RNi_2B_2C \) the microwave \( R_s(T) \) differs from the BCS calculation with a broad temperature dependence near \( T_c \) and high absolute values of \( R_s \).

The large microwave absorption observed in these materials was previously attributed to pair breaking, which in the magnetic members of the family could be possibly attributed to pair breaking due to magnetic ions \([4]\), although a possible additional mechanism due to strong electronic correlations may be required in the non-magnetic family \( YNi_2B_2C \). The absence of magnetic impurities in \( MgB_2 \) suggests a non-magnetic mechanism. The intriguing similarity between \( MgB_2 \) and \( RNi_2B_2C \) clearly deserves further attention.

In conclusion substantial improvements in \( R_s \) of \( MgB_2 \) have been achieved with improvement in sample density. A significant advantage of \( MgB_2 \) is the low normal state resistance due to the intermetallic nature of the compound. The \( R_s(20K) \) of W-1 is substantially lower than that of polycrystal of \( YBa_2Cu_3O_{6.95} \) and close to that of single crystal \( YBa_2Cu_3O_6.95 \). For a 10GHz \( TE_{011} \) cavity constructed of \( MgB_2 \) with a geometric factor \( \Gamma \sim 780 \), and using \( R_s(20K) = 800\mu\Omega \), the resulting \( Q(20K) = \Gamma/R_s > 10^6 \). This observation is very promising, and further improvements in sample quality would greatly enhance the prospects for microwave applications at temperatures accessible using cost effective cryo coolers.

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\[ \Delta(0)/k_BT_c \] is variable in the calculations for \( \sigma_1 \) and \( \sigma_2 \) mentioned above. Rather good fits are achieved with \( \Delta(0)/k_BT_c = 0.18 \). Such a low gap is clearly different from the tunneling data \([10]\). The variable gap ratio in modified BCS calculation is a convenient method of parametrization of the data, although it is possible that there may be two energy scales in the material, with the larger being observed in the tunneling experiments, while the smaller value dominates the microwave absorption.

Interestingly the data for \( MgB_2 \) are similar to those in single crystals of \( RNi_2B_2C \) (\( R = Y, Er, Ho, Dy, Tm \)) family of superconductors \([4]\). The temperature dependence of microwave \( R_s \) of \( MgB_2 \) and its deviation from the BCS calculation for an s-wave superconductor is more akin to the microwave \( R_s \) of \( RNi_2B_2C \) class superconductors which also clearly do not follow BCS s-wave. In both \( MgB_2 \) and \( RNi_2B_2C \) the microwave \( R_s(T) \) differs from the BCS calculation with a broad temperature dependence near \( T_c \) and high absolute values of \( R_s \).

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1. J.Nagamatsu, N. Nakagawa, T. Muranaka, Y. Zenitani, and J. Akimitsu, Nature 410, 63 (2001).
2. P. C. Canfield, D. K. Finnemore, S. L. Bud’ko, J. E. Os- tenson, G. Lapertot, C. E. Cunningham, and C. Petrovic, Phys. Rev. Lett., 86, 2423 (2001).
[3] H. Srikanth and Balam A Willemsen and T. Jacobs and S. Sridhar and A. Erb and E. Walker and R. Flukiger, Phys.Rev. B., 55, R 14733 (1997).

[4] T. Jacobs, Balam A. Willemsen, S. Sridhar, R. Nagaranjan, Z. Hosain, L. C. Gupta, C. Majumdar, P. Canfield and B. K. Cho, Phys. Rev. B 52, R 7022 (1995).

[5] N. Belk, D. E. Oates, D. A. Feld, G. Dresselhaus, M. S. Dresselhaus, Phys. Rev. B 53, 3459 (1996).

[6] A. T. Findikoglu, S. R. Foltyn, P. N. Arendt, J. R. Groves, Q. X. Jia, E. J. Peterson, X. D. Wu, and D. W. Reagor, Appl. Phys. Lett. 69, 1626, 1996.

[7] S. Sridhar and Z. Zhai, Physica C : Proc. Of M2S-HTSC VI, 341-348, 2057 (2000).

[8] Z. Zhai, C. Kusko, N. Hakim and S. Sridhar, Rev. Sci. Inst. 71, 3151 (2000).

[9] D. K. Finnemore, J. E. Ostenson, S. L. Bud’ko, G. Lapertot and P. C. Canfield, Phys. Rev. Lett., 86, 2420 (2001).

[10] G. Karapetrov, M. Iavarone, W. K. Kwok, G. W. Crabtree, and D. G. Hinks, cond-mat/0102312.

[11] S. L. Bud’ko, G. Lapertot, C. Petrovic, C. E. Cunningham, N. A. N. Anderson and P. C. Canfield, Phys. Rev. Lett., 86, 1877 (2001).

FIG. 1. Microwave surface resistance of polycrystal pellet (P-1) and dense wire (W-1) of MgB2. For comparison, $R_s$ data are shown for (a) single crystal $YBa_2Cu_3O_{7-δ}$, (b) superconducting Nb, (c) polycrystal $YBa_2Cu_3O_{6.95}$, and (d) Cu. (e) Solid line represents $R_s$ for a BCS s-wave superconductor with gap ratio $\Delta(0)/kT_c = 1.76$. (f) Light gray line represents a modified BCS calculation.

FIG. 2. Microwave resistivity $\rho_{\omega n}(T)$ of pellet P-1 and wire W-1 of MgB2.

FIG. 3. SEM micrographs of pellet P-1 (a) and wire W-1 (b & c). P-1 is highly porous and results in weakly connected small grains. Large well aligned grains of average size 10 $\mu$m can be seen in W-1. (c) Wire W-1 cut through the midsection. Note that the Tungsten Boride core is shielded from the microwave fields by the MgB2 sheath.
\( \rho_{\mu n} \) (\( \mu\Omega \cdot \text{cm} \)) vs. \( T(K) \)
