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Microwave properties of superconducting MgB2

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Abstract
Measurements of 10 GHz microwavesurface resistance, Rs, of dense MgB2wire 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 Bardeen–Cooper–Schrieffer s-wave superconductor. However, the Rs (20 K) of the wire is an order of magnitude lower than that of polycrystalYBa2Cu3O6.95 and matches with single-crystal YBa2Cu3O6.95. The results show promise for the use of MgB2 in microwave applications.

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Physics and Astronomy, Microwaves, Copper, Microwave spectroscopy, Polycrystals, Superconducting wires

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Microwave properties of superconducting MgB_2

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Measurements of 10 GHz microwave surface resistance, R_s, 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 Bardeen–Cooper–Schrieffer s-wave superconductor. However, the R_s (20 K) 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.
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The discovery[1] of superconductivity in MgB_2 with $T_c = 40\,\mathrm{K}$ 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 40 K 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 $T \sim T_c/2 = 20\,\mathrm{K}$, a temperature easily accessible with modern cryocoolers.

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 (~2 mm cubical dimensions) of moderate density which is synthesized by reacting stoichiometric amounts of B and Mg at 950 °C for approximately 2 h. The other W-1 is a high density MgB_2 wire (outer diameter 140 μm).[2] To synthesize MgB_2 wire (W-1) lump Mg and a boron fiber of 100 μm diameter, with a central core of tungsten boride (15 μm), in a nominal ratio of Mg_2B are sealed in a Ta tube. The sealed Ta tube is then placed in 950 °C in a box furnace for 2 h 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 x-ray diffraction, resistivity, scanning electron micrograph (SEM) and various other probes.[2] Very low dc resistivity $\sim 0.4\,\mu\Omega$ cm at T_c has been observed in the wire[2] which is lower than polycrystal samples by approximately two orders of magnitude ($\sim 70\,\mu\Omega$ cm).[1] The wire is more than 80% dense, shows the full $\chi = -1/4\pi$ shielding in the superconducting state and has a sharp transition (width 0.9 K) at $T_c = 39.4\,\mathrm{K}$.

The high precision microwave measurements were carried out in a 10 GHz Nb superconducting cavity with a variable temperature sample pedestal.[3] This technique has been used extensively for characterizing the microwave properties of small specimens of high T_c and borocarbide superconductors.[4,5] 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 is shown in Fig. 1. The polycrystalline sample is observed to have higher R_s when compared to

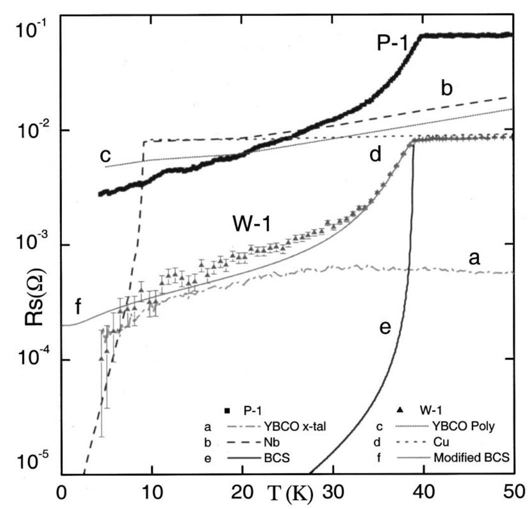

FIG. 1. Microwave surface resistance of polycrystal pellet (P-1) and dense wire (W-1) of MgB_2. For comparison, R_s data are shown for (a) single crystal $YBa_2Cu_3O_{6.95}$, (b) superconducting Nb, (c) polycrystal $YBa_2Cu_3O_{6.95}$, and (d) Cu. (e) Solid line represents R_s for a BCS s-wave superconductor with gap ratio $\Delta(0)/kT_c = 1.76$. (f) Light gray line represents a modified BCS calculation.

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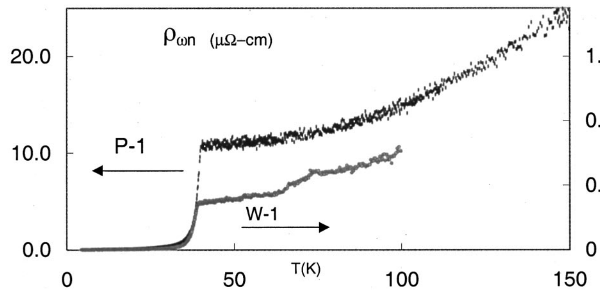

FIG. 2. Microwave resistivity $\rho_{\omega n}(T)$ of pellet P-1 and wire W-1 of MgB_2.

that of wire. Both samples show approximately similar temperature dependence of $R_s(T)$ but differ by a large scale factor. The microwave resistivity $\rho_{\omega n}(T)$ (Fig. 2) in the normal state is obtained from the surface resistance $R_{sn}(T)$ using $\rho_{\omega n}(T)=2R_{sn}^2(T)/\mu_0\omega$. 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.

Figure 3 shows the 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 μm while P-1 has smaller grains of size $\sim$0.5–5 μm. These differences in grain size and porosity

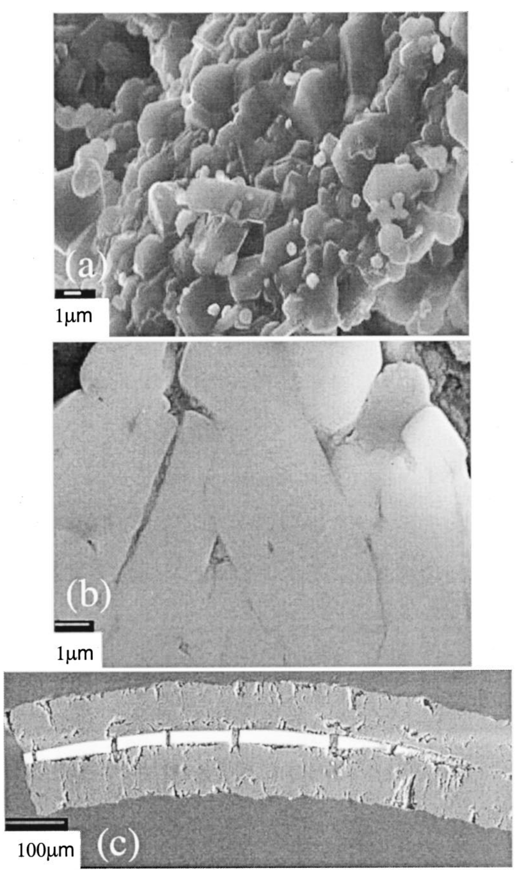

FIG. 3. SEM micrographs of pellet P-1 (a) and wire W-1 [(b) and (c)]. P-1 is highly porous and results in weakly connected small grains. Large well aligned grains of average size 10 μm can be seen in W-1. (c) Wire W-1 cut through the midsection. Note that the tungsten boride core is shielded from the microwave fields by the MgB_2 sheath.

lead to larger absorption in P-1 in two ways. First, they result in coupled Josephson junctions with large effective junction penetration depth, and second 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. Figure 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 $\lambda\sim140$ nm,[6] 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 $YBa_2Cu_3O_{6.95}$[4] 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 MgB_2 wire is far below that of polycrystal $YBa_2Cu_3O_{6.95}$ and comparable to single crystal (Fig. 1) and films[7,8] of $YBa_2Cu_3O_{6.95}$ at 20 K. 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 Bardeen–Cooper–Schrieffer (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 $YBa_2Cu_3O_{6+x}$ is still debated, even though a consensus has emerged that the order parameter is d wave. In $YBa_2Cu_3O_{6+x}$ 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.[9]

Several reports have already claimed that MgB_2 is a conventional phonon-mediated superconductor with an s-wave order parameter.[10] In conventional s-wave superconductors the thermodynamic and transport coefficients decay exponentially and there is no quasiparticle excitations at low energies. Tunneling measurements[11] report the ratio $2\Delta(0)/k_BT_c\sim3$ 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 $Z_s=(-\mu_0 i\omega/\tilde{\sigma}_s)^{1/2}$ and the Mattis–Bardeen complex conductivity $\tilde{\sigma}_s=\sigma_1-i\sigma_2$. The normalized conductivity can be calculated using $\sigma_1/\sigma_n=2/\hbar\omega\int_\Delta^\infty g(E)[f(E)-f(E+\hbar\omega)]dE$ and $\sigma_2/\sigma_n=2/\hbar\omega\int_{\Delta-\omega}^{\Delta}h(E)[1-2f(E+\hbar\omega)]dE$, where $g(E)$ and $h(E)$ are appropriate factors incorporating the density of states and BCS coherence factors, and f is the Fermi function. The gap temperature dependence was taken to be the well-known gap function for BCS. We have used experimental parameters $\omega=2\pi10^{10}(\mathrm{s})^{-1}$ and $T_c=39.4$ K. Using a weak coupling gap ratio $\Delta(0)/kT_c=1.76$, the calculated $R_s(T)$ is compared with the measured data (Fig. 1). It is clear that the measured data are well above the calculated values.

It is possible to arrive at a quantitative fit to the data by varying the gap parameter $\Delta(0)/k_BT_c$. Including a residual temperature independent contribution $R_{\rm res}=150\,\mu\Omega$, the experimental data are fit with $R_s(T)=R_{\rm res}+R_{\rm BCS-mod}(T)$, where $R_{\rm BCS-mod}(T)$ represents a modified BCS calculation in which the gap ratio $\Delta(0)/kT_c$ is variable in the calculations for σ_1 and σ_2 mentioned earlier. Rather good fits are achieved with $\Delta(0)/k_BT_c=0.18$. Such a low gap is clearly different from the tunneling data.[11] 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.[5] 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 the BCS s wave.[5] 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,[5] although a possible additional mechanism due to strong electronic correlations may be required in the nonmagnetic member YNi_2B_2C. The absence of magnetic impurities in MgB_2 suggests a nonmagnetic 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 (20 K) 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 10 GHz TE_{011} cavity constructed of MgB_2 with a geometric factor $\Gamma\sim780$, and using $R_s\,(20\,{\rm K})=800\,\mu\Omega$, the resulting $Q(20\,{\rm K})=\Gamma/R_s>10^6$. 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 cryocoolers.

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