Intermodulation and Power Handling in MgB$_2$ Thin Films

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Abstract
The nonlinear surface impedance and intermodulation distortion (IMD) products of MgB$_2$ thin films have been measured as a function of power and temperature from 1.7 K to $T_C$. Both dielectric and metallic substrates have been employed. The measurements on dielectrics use a stripline-resonator technique at 2 GHz. The measurements on metallic substrates have been carried out using a dielectric-resonator method at 10 GHz. The films were grown using the deposition technique of reactive evaporation onto LaAlO$_3$, sapphire, and buffered copper, and stainless steel substrates. The low-power $R_S(T)$ is comparable to that of sputtered Nb films on sapphire, and lower than that of YBCO at the corresponding reduced temperatures. The rf-magnetic-field dependence at $T < 20$ K follows a moderate slope without breakdown for $H < 500$ Oe, the limit of the experiment. The measurements of IMD are compared with a theoretical analysis that assumes uncoupled $\pi$ and $\sigma$ channels and intrinsic nonlinearity to the lowest nonlinear order in the radiation field. While the temperature dependence of the measured IMD on dielectric substrates reflects the calculations qualitatively, it shows features that are not consistent with pure s-wave behavior.

1. Introduction
Magnesium diboride, MgB$_2$ is a medium-temperature superconductor with $T_C \approx 40$ K [1]. It is believed to be a conventional s-wave superconductor that is described by the BCS theory, but has the interesting property of having two energy gaps and four conduction bands relevant for the superconductivity. For deposition using reactive evaporation (see Sec. 2), MgB$_2$ is simpler to grow than the cuprate high-temperature superconductors since it has fewer elements, there is no need to control relative rates of different species, and no need for oxidation. The material also has a longer coherence length than the cuprates, which gives the expectation that grain boundaries are not weak links, and epitaxial growth is not necessary for excellent microwave properties with good power handling. Thus, as in niobium one can expect good microwave properties in polycrystalline films. Since it is an s-wave superconductor, it may have lower intermodulation distortion (IMD) than the d-wave cuprates, which have recently been shown to have IMD dominated by the intrinsic d-wave nonlinear Meissner effect [2]. The lower IMD is very important for electronic applications.
Magnesium diboride is also a strong type II superconductor and has higher critical field than niobium. It therefore holds promise for replacing niobium in accelerator-cavity applications where the ability to sustain large rf-magnetic-field strengths along with high \( Q \) values are the most important attributes. For this application the MgB\(_2\) thin films would be deposited on the inside of a accelerator cavity fabricated from a metal compatible with the MgB\(_2\). In this case the lack of needed epitaxy is of critical importance.

2. Films

The films were deposited by the reactive evaporation technique, which has been described earlier [3, 4]. Briefly, boron is deposited in vacuum onto a substrate that rapidly rotates through a region of high-pressure magnesium vapor where MgB\(_2\) is formed. This method allows fabrication of very clean, stable, large-area, double-sided MgB\(_2\) films on a multitude of substrate materials. The films have a \( T_C = 39 \) K and low resistivity. More detail is given in [5]. The films characterized in this work were deposited onto 2"-diameter substrates of r-plane sapphire, lanthanum aluminate (LAO), stainless steel, and TiO\(_2\)-buffered copper. The deposition temperature was 550 °C, and the film thickness is 500 nm. The films are polycrystalline, and on sapphire (001) texturing was observed [5].

3. Microwave properties on dielectrics

The films were characterized using a stripline-resonator technique that has been described previously [6]. As presented earlier, the stripline resonator is used for measurements of surface impedance as a function of rf current or equivalently magnetic field, and for measurements of IMD.

3.1. Low-power (linear) surface resistance vs temperature

The low-power surface resistance vs reduced temperature is given in Fig. 1, along with results for niobium on sapphire and YBCO on LAO, all measured by stripline resonator at Lincoln Laboratory.

![Fig. 1. RS vs reduced temperature for MgB2 on sapphire ■, compared with niobium on sapphire ▲, and YBCO on LAO ●, all measured by stripline resonator at Lincoln Laboratory.](image)

We have also found that the surface resistance is very stable over time and temperature cycling. The surface resistance of the film on sapphire did not change after nearly three years and approximately 10 cycles between room temperature and 4 K.
3.2. Surface resistance vs rf magnetic field

The power dependence of the surface resistance is given in Fig. 2. Plotted is $R_S$ vs $H_{rf}$ for two MgB$_2$ samples at 20 K, one on sapphire and one on LAO, compared with a niobium sample at 4.2 K. The MgB$_2$ samples demonstrate better power handling than the niobium sample at these temperatures. The niobium sample and the MgB$_2$ sample on LAO show very little variation at low power, while the MgB$_2$ sample on sapphire shows dependence that is approximately linear in the field. This dependence is often an indication of weak links in the film and will have consequences for the IMD as will be discussed later.

3.3. Intermodulation distortion

The IMD for MgB$_2$ films on sapphire and LAO at 20 K is shown in Fig. 3. Plotted is the normalized IMD power $P_{imd\ norm}$ vs circulating power $P_{circ}$ in the resonator. The $P_{imd\ norm}$ removes the effects of the different resonator $Q$ values and insertion losses. For a full explanation, see ref. [6]. Included in the plot is a line of slope three for reference. As seen, the film on LAO has lower IMD than the film on sapphire. This is expected based on differences in the measurements of the power-dependent surface impedance in Fig. 2.

The IMD of the MgB$_2$ films is higher than that of YBCO on LAO. Fig. 4 shows the $P_{imd\ norm}$ at 5-dBm circulating power vs reduced temperature for the MgB$_2$ films on sapphire and LAO on the same plot as the best YBCO film measured at Lincoln Laboratory. The YBCO data was reported in ref [6] and the film is described in [9]. This plot shows again that the film on LAO has lower IMD than the film on sapphire and that the IMD in MgB$_2$ in both cases is larger than that in YBCO. Note, however that the IMD values of MgB$_2$ at low temperatures are comparable to those of YBCO at 77 K, which is the operating temperature used for commercial YBCO microwave filter systems. The reason for the higher IMD is not understood at this time. As discussed, MgB$_2$ may show lower IMD because of the $s$-wave symmetry of the order parameter. It is not known if the IMD measured here is of intrinsic or extrinsic origin. As mentioned in relation to the surface resistance, the film on sapphire seems to exhibit weak-link behavior. This would point to an extrinsic cause for the IMD and indicate that substantial improvements might be possible. It should also be mentioned that Dahm and Scalapino [10] have calculated IMD that is close in value to that in YBCO.

Fig. 5 shows more detail of the IMD vs $T$ for films on sapphire from two different wafers. Also shown are the results of theoretical calculations discussed in the next section. While there is some scatter in the data, some general observations can be made: the films show a broad minimum in IMD at temperatures between 10 and 20 K; the structure at low temperatures is

![Fig. 3. IMD vs $P_{circ}$ at 20 K. ▢ MgB$_2$ on sapphire, ● MgB$_2$ on LAO.](image)

![Fig. 4. IMD vs $T$ at +5 dBm circulating power. ▢ MgB$_2$ on sapphire, ● MgB$_2$ on LAO, ▲ YBCO on LAO.](image)
reproducible and unexpected; and the expected decrease at low temperatures is absent. Indeed the IMD seems to increases at low temperatures in both films. The low-temperature increase is also observed in the films on LAO. The broad shallow minimum at 10-20 K is compatible with the theory, but the upturn at low temperatures is unexplained. The upturn may be the result of a small admixture of symmetry other than s-wave to the order parameter, which could result in an increase of the nonlinearity at low temperatures, as is the case in the cuprates. A second possible explanation is the nonlinearity of the residual surface resistance due to weak links. At low temperatures the $R_S$ of MgB$_2$ as well as other superconductors, tends to a constant value. That is

$$R_S(T) = R_S^{RCS}(T) + R_S^{Res}$$  \(1\)

where $R_S^{RCS}$ is the theoretical BCS surface resistance, which vanishes exponentially at low temperature, and $R_S^{Res}$ is the temperature-independent residual resistance. The residual resistance is dependent on the current in a manner similar to the BCS surface impedance. This power dependent residual resistance can also generate IMD. While the residual resistance argument explains the absence of a decrease, it does not explain the apparent increase at low temperatures.

4. Films on metallic substrates

For applications in accelerator cavities it is necessary to deposit on the inside surface of a microwave cavity of complicated shape. MgB$_2$ films are a good candidate for this application, as this material yields excellent microwave properties in polycrystalline form. The films reported in the preceding sections are polycrystalline, and the excellent properties reported are the grounds for exploring the properties on metal substrates. The films on metals cannot be tested in the stripline resonator since the substrate is part of the resonant cavity, and a normal metal would limit the $Q$ to very low values as well as shorting out the fields.

We have begun the investigation of the films on metal substrates by using a sapphire-puck Hakki-Coleman dielectric resonator that has been reported previously [11]. The resonator is shown in Fig. 6. The resonant frequency is approximately 10.7 GHz in the TE$_{011}$ mode, and by measuring the resonator $Q$, the surface resistance of the film can be measured independently of the substrate, because the fields and currents are confined to the sapphire puck and the films under test. The resonator requires two identical films for the surface resistance determination. The results for the first sample of MgB$_2$ on copper with a Ti buffer layer and on stainless steel are shown in the Fig. 5. IMD vs T. Points are measured from two different sapphire wafers. — calculated $\sigma$-band contribution, — calculated $\pi$-band contribution. — total IMD assuming equal contributions from the $\pi$ and $\sigma$ bands. The circulating power is 0 dBm.

![Fig. 6 Dielectric resonator. This operated in the TE$_{011}$ mode and the resonance frequency is 10.7 GHz](image)
Fig. 7. Films on both substrates show a superconducting transition near 35 K which is an indication of good quality, but the surface resistance is higher than that observed on the dielectric substrates. Further investigations are underway to improve the films to investigate the influence of the substrate on the properties of the dielectric resonator.

5. Theory of IMD

We have calculated the IMD in MgB$_2$ using the same method that has been successfully employed to calculate the IMD in YBCO [12]. Although applied to a d-wave superconductor in the case of YBCO, the method is general and can be applied to an s-wave superconductor as well. The IMD results from the nonlinear Meissner effect, which predicts that the penetration depth is dependent on the current [13, 14]. The calculation focuses on the constitutive relation (CR) that relates the current density and vector potential. In this treatment, the classic London theory corresponds to the linear term in the CR, while the lowest-order (third-order) nonlinear term yields the nonlinear Meissner effect. The static CR relating the Cooper-pair current density and the vector potential in momentum space has the form

$$ j_\pi (q) = \frac{c}{4\pi} K(q) \tilde{A}(q) = \frac{c}{4\pi} \left( \frac{1}{\lambda_0^2} + K_{NL} \left( \left| \tilde{A}(q) \right|^2 \right) \right) \tilde{A}(q) $$

(2)

where $j_\pi (q)$ and $\tilde{A}(q)$ denote the Cooper-pair current density and electromagnetic potential associated with the one dimensional momentum $q$, respectively. The chosen gauge is $\nabla \cdot A = 0$; $\lambda_0$ denotes the London penetration depth, and $K_{NL} \left( \left| \tilde{A}(q) \right|^2 \right)$ is the CR nonlinear kernel [15]. The calculation proceeds by expanding $K_{NL}$ in powers of $A$, and yields the nonlinear penetration depth $\lambda_{NL}$, where

$$ \lambda(T, j) = \lambda_0(T) + \lambda_{NL}(T, j) $$

(3)

The calculation must take into account the band structure of MgB$_2$ in that there are 4 conduction bands, pairs of which are nearly degenerate. The pairs of conduction bands lead to the well-established two-gap superconductivity in MgB$_2$. More detail is given in [16].

The results of the calculation of the IMD vs temperature are shown in Fig. 5 along with measured IMD data from the samples on sapphire at a circulating power of 0 dBm. The calculation is carried out in the clean limit without impurity or defect scattering. The calculation also assumes that there is no interband scattering among the various conduction bands. The IMD is plotted as relative units because the calculation at this time does not yield the IMD in absolute power. We have plotted separately the contributions for the $\pi$ and $\sigma$ bands. Also plotted is the total IMD assuming that the $\pi$ and $\sigma$ bands contribute equally to the total. The agreement between theory and experiments is not perfect, but the calculation reproduces some of the features of the data. At temperatures between 10 and 35 K the IMD both measured and calculated is quite independent of temperature. Near 10 K a shallow local maximum is evident. At lower temperatures, the IMD turns up and in the calculation drops off exponentially, which is a consequence of the $\pi$–band gap, the smaller of the two s-wave gaps, dominating the nonlinear performance. The initial drop of nonlinearity just below $T_c$ results from the $\sigma$-band gap, the larger of the two gaps, and while an s-wave exponential fall off is expected at about $T_c/2$, the fall off is frustrated by the presence of the $\pi$–band gap and leads to the broad plateau/shallow
local maximum near 10 K. The upturn at low temperatures is inconsistent with s-wave symmetry. This lack of agreement with the theory and incompatibility with s-wave symmetry is under investigation. We speculate that different gap symmetry may be present or the upturn could result from residual surface impedance power dependencies that are not anticipated.

6. Conclusions
Measurements of the microwave properties of MgB$_2$ thin films indicate that it is a potentially important material for microwave applications. Even these early films, which have been grown without extensive exploration of the parameter space for film deposition and little effort to optimize the microwave properties, show excellent low-power surface resistance and outstanding power-handling capability. The measurements of the IMD show significant departures from the theory. The IMD is higher than that measured in state-of-the-art YBCO films for reasons that are not yet understood. The IMD vs temperature reported here shows no s-wave-characteristic decrease at low temperatures. The IMD vs temperature shows structure that is not predicted by the present theory. It is possible that interference between conduction bands may explain the structure. While the theoretical method has been successful in describing the IMD in YBCO thin films [12], other effects such as interband interference will be investigated as enhancements of the theory in order to obtain a better agreement with the measurements, which will continue, at lower temperatures.

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