Correlation of microwave surface impedance of MgB$_2$ thin film with material parameters and a temperature niche for microwave applications

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Abstract

Two issues related to the microwave surface impedance $Z_s$ of MgB$_2$ thin film are discussed in this Letter, both being significant for potential microwave applications. At first, a correlation between $Z_s$ and $\alpha = \xi_0/A$ was found, where $\xi_0$ is the coherence length, and $A$ is the mean free path. The surface resistance $R_s$ decreases with $\alpha$ at moderate and large values of $\alpha$ and saturates when $\alpha$ approaches one. The values of the penetration depth at zero temperature $\lambda(0)$ for different films could be well fitted by $\lambda_L(1+\alpha)^{1/2}$, yielding a London penetration
depth $\lambda_L$ of 33.6 nm. The second issue is to find a temperature niche for possible microwave applications. Between 10K and 15K, our best MgB$_2$ films possess the lowest $R_s$ values compared with other superconductors such as NbN, Nb$_3$Sn and the high-temperature superconductor YBa$_2$Cu$_3$O$_{7-\delta}$.

The superconductor MgB$_2$ has generated a great deal of interest because of its simple structure, its relatively high critical temperature ($T_c$) and a pronounced two-gap nature [1]-[4]. One of the potential applications of MgB$_2$ are high-frequency devices. To some extend, the relevance of MgB$_2$ can be elucidated by a systematic study of the microwave surface impedance [5]. In our previous work a sapphire resonator technique has been successfully employed to measure $Z_s = R_s + j \omega \mu_0 \lambda$ of MgB$_2$ thin films at a frequency $f = \omega / 2 \pi = 18$ GHz [6][7]. Here $R_s$ is the microwave surface resistance, $\omega$ is the angular frequency, $\mu_0$ is the free-space permeability, and $\lambda$ is the penetration depth. In our present work we use the same method to investigate eight different MgB$_2$ thin films of different quality prepared by chemical vapor deposition (CVD) with post-deposition annealing [8], pulsed laser deposition (PLD) with in-situ annealing [9], and in situ hybrid physical-chemical vapor deposition (HPCVD) [10] methods. The three films deposited on MgO substrates by the CVD method are randomly oriented with a thickness of about 600 nm. The three films deposited on Al$_2$O$_3$ by PLD are c-axis oriented with a thickness of about 400 nm. The remaining two films are epitaxial films deposited by HPCVD on Al$_2$O$_3$ and SiC, respectively, with thickness values of about 100 nm (on Al$_2$O$_3$) and 300 nm (on SiC), respectively. $T_c$ measurements show that all samples exhibit sharp transitions of the dc resistivity with a width of less than 0.3 K. For the sample on SiC, the highest $T_c$ of 41.3 K was observed.

From the measured temperature dependence of $Z_s$, the quantities $R_s(T)$, $\lambda(0)$, $\Delta(0)$ and $\rho_0$ were extracted according to a procedure described in Ref. [7] Here, $\Delta(0)$ is the value of $\pi$-band energy gap at zero temperature. $\rho_0$ represents the dc resistivity right above $T_c$ as being determined from the $R_s$ according to skin effect theory. Since the residual surface resistance $R_{res}$ ($R_{res} = R_s(T \rightarrow 0)$) of the MgB$_2$ thin film is less than the
resolution of $R_s$ for our setup (about 50$\mu$Ω [6]), the measured $R_s(T)$ represents just the change of $R_s$ with temperature.

Fig. 1 shows the $\Delta_d(0)$ dependence on $\rho_0$. It should be noticed that $\Delta_d(0)$ roughly increases monotonically with $\rho_0$. Qualitatively, this observation is likely to reflect the two-gap nature of $MgB_2$: The increase of $\rho_0$ is accompanied by an increase of interband impurity scattering between the two bands, which results in a tendency to equalize the size of the two gaps. Thus, the small gap will increase with $\rho_0$. In the inset of Fig. 1 we show $\Delta_d(0)/T_{c0}$ as a function of $T_c/T_{c0}$. Here, $T_{c0}$ is the $T_c$ of the film on SiC, which is close to the clean limit. The solid line shows the change of the small gap with $T_c$ based on interband impurity scattering theory [11] assuming $\Delta_d(0)/\Delta(0) = 0.28$ ($\Delta(0)$ is the value of the energy gap of the $\sigma$-band at zero temperature). Details of this analysis will be discussed in a later contribution.

The dependence of $Z_s$ on the material parameters $\lambda_L$, $v_F$, $\Delta_d(0)$ and $\ell$ or the two dimensionless quantities $\alpha = \xi_0/\ell$ and $\gamma(\ell=\infty) = \lambda_L/\xi_0$ can be described within BCS-theory[12]. Here, $\lambda_L$ is the London penetration depth, $v_F$ is the Fermi velocity, and $\ell$ is the mean free path. Because our study is restricted to MgB$_2$ samples only, $\gamma$ is a constant, and only the $Z_s$ dependence on $\alpha$ is presented. Here we only consider the $\pi$-band coherence length. There is another coherence length corresponding to the $\sigma$ band. However, we have found in our previous work the conductivity is dominated by the $\pi$ band [7]. According to BCS theory $\xi_0 = \hbar v_F/\pi \Delta_d(0)$ [13], where $\hbar$ is Planck’s constant, $v_F = 5.35 \times 10^5$ m/s is the Fermi velocity of the electrons in the $\pi$ band [14]. The mean free path can be calculated from $\rho_0$ by $l = v_F/\rho_0 \omega_p^2 \varepsilon_0$, where $\hbar \omega_p = 5.9$ eV is the plasma energy [3] and $\varepsilon_0$ is free-space permittivity. From this analysis we found that the coherence length $\xi_0$ scatters between 43 and 53 nm, which agrees with the value of 49.6 nm determined by vortex imaging of single crystals [15]. Fig. 2 shows the $R_s$ dependence on $\alpha$ at $T = 15$ K (solid) and 20 K (open). A monotonic increase can be found for large $\alpha$ values, which tends to saturate as $\alpha$ decreases. The 100 nm-thick epitaxial film on a sapphire substrate prepared by HPCVD deviates strongly from the general trend of the
other samples. TEM analysis has demonstrated that there is a 30 - 40 nm thick non-superconducting layer between the Al₂O₃ substrate and MgB₂ thin film [10], which is expected to have a large influence on the properties of very thin films.

Fig.3 shows the measured $\lambda(0)$ as a function of $\alpha$. According to the BCS model, $\lambda(0)$ can be described by $\lambda(1+\alpha)^{1/2}$ [13]. The solid line represents the fit yielding $\lambda_\ell$ of 33.6 nm. The inset shows the $\lambda(0)$ dependence on $(1+\alpha)^{1/2}$, indicating a high level of confidence for the BCS model. The value of $\lambda_\ell$ determined by this analysis was found to be in excellent agreement with the plasma frequency used for band structure calculations [3]. This value also agrees roughly with the one obtained from microscopic calculations (=39.5 nm) in the clean limit[16].

In contrast to the observed $\lambda(0)$ dependence on $\alpha$, the observed $R_s$ dependence on $\alpha$ is still not fully understood. In particular, the effect of the anomalous coherence peak [7] requires further studies.

For conventional s-wave superconductors such as Nb ($T_c = 9.2K$), NbN ($T_c = 16K$) and Nb₃Sn ($T_c = 18K$) very low $R_s$ values can be achieved at working temperatures much lower than $T_c$, because $R_s$ is proportional to $\exp(-\Delta(0)/kT)$ for $T < T_c/2$. Above $T_c/2$, $R_s$ increases even more rapidly. On the other hand, the high-temperature superconductor YBCO has a finite $R_s$ value below a certain temperature and does not exhibit any exponential temperature dependence due to its d-wave nature [5]. Fig. 4 shows the temperature dependence of $R_s$ below 20 K for the samples with the lowest $R_s$ of each type of orientation. For comparison, the $R_s$ values of high-quality epitaxial YBCO films deposited on LaAlO₃ and r-cut sapphire, NbN and Nb₃Sn films are also depicted [17][18][19]. One can easily see that MgB₂ has the lowest $R_s$ between 10 K and 15 K. From cryogenic cooling point of view, 10 to 15 K can make a big difference to 4 K, in particular with regard to cost and power efficiency of closed-cycle refrigerators.

Apart from very low $R_s$, the epitaxial film made by HPCVD on SiC has the highest $T_c$, the longest $\xi_0$ and the lowest $\lambda(0)$. These parameters are of great importance for electronic application. The high $T_c$ allows for high working temperatures, the large value of $\xi_0$ should make MgB₂ favorable with regard to the possible realization of tunnel junctions. On the other hand, the low values of $\lambda(0)$ indicate that a small layer thickness
is sufficient for multilayer circuits and that kinetic inductance effects are rather small. Structural analysis has demonstrated that this particular film is composed of well-connected grains and has a smooth surface. Hence, this technique offers great promise for MgB$_2$ integrated circuits in the future with some potential to replace niobium.

In summary, our study clearly demonstrates a correlation between $Z_s$ and $\alpha$ in MgB$_2$ films, if material parameters describing the $\pi$-band are used. A temperature niche for microwave applications was found to exist between about 10 K and 15 K, where MgB$_2$ becomes competitive with other superconducting materials.

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**Figure Captions:**

Fig.1: The dependence of the \( \pi \)-band energy gap on resistivity of MgB\(_2\) thin films determined from \( Z_s \) measurements. The inset shows the \( \pi \)-band energy gap \( \Delta_\pi(0)/T_{c0} \) as a function of \( T_c/T_{c0} \). The solid line shows the dependence expected from interband impurity scattering in a two-gap superconductor.

Fig.2: The measured dependence of \( R_s \) on \( \alpha = \xi_0/\ell \) at 15 K (solid) and 20 K (open).

Fig.3: Experimental dependence of \( \lambda(0) \) on \( \alpha \) and a BCS fit yielding a London penetration depth \( \lambda_L \) of 33.6 nm. The inset clearly shows the linear relation between \( \lambda(0) \) and \( (1+\alpha)^{1/2} \).

Fig.4: Comparison of surface resistance of MgB\(_2\) with YBCO, NbN and Nb\(_3\)Sn films. The \( R_s \) curves of MgB\(_2\) thin films represent the best \( R_s \) values for films of different crystalline orientations.
Fig. 1

Fig. 2
Fig. 3

Fig. 4