Microwave losses of MgB$_2$ thin films in dc magnetic field

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Abstract. The microwave surface impedance ($Z_s = R_s + iX_s$) of in situ MgB$_2$ thin films was measured as a function of temperature and parallel dc magnetic field at several frequencies between 5.7 GHz and 18.5 GHz using a dielectric resonator technique. The results are consistent with the expectations for a classical type-II superconductor and, consequently, quite different from those of the high-$T_c$ cuprates. The films cooled in zero-field revealed a clear indication of the lower critical field, $B_{c1}$. At higher fields (up to 2 T at 3 K) both $R_s$ and $X_s$ showed a linear increase with field in good agreement with the vortex state model introduced for type-II superconductors by Coffey, Clem and Brandt. The curves measured in sweeping fields (e.g. $-2$ T $< B < 2$ T at 3 K) revealed a narrow hysteresis loop in the range $|B| < (3 \div 4) B_{c1}$ and were perfectly symmetrical with respect to the ordinate axis.

1. Introduction
Magnesium diboride attracts much attention regarding the fundamental physics of its superconducting properties. Although MgB$_2$ exhibits a remarkably high critical temperature ($T_c$) of up to 40 K, it behaves like a classic BSC-superconductor and reveals little analogy with high-temperature superconducting (HTS) cuprates. The microwave properties of MgB$_2$ were also successfully explained within the theoretical framework for classical superconductors. Thus, the temperature dependence of the complex microwave surface impedance ($Z_s = R_s + iX_s$) of MgB$_2$ films in zero dc field showed a good quantitative agreement with the BCS-theory [1, 2]. The temperature dependence of the London penetration depth $\lambda_L(T)$ was strictly BSC-like, i.e., clearly different from the linear $\lambda_L(T)$ of the HTS cuprates.

Recently we examined the microwave properties of MgB$_2$ thin films in dc magnetic field [3] and found a good agreement with the vortex state model introduced for type-II superconductors by Coffey, Clem [4] and Brandt [5], including the frequency dependences of both the surface resistance and the surface reactance. In the present work we present more detailed data on the effect of sweeping dc magnetic field on the hf surface impedance of the MgB$_2$ films.

2. Experimental
Our superconducting MgB$_2$ thin films were prepared in situ in a ‘direct growth’ process using a combination of rf magnetron sputtering of a planar boron target and thermal evaporation of magnesium from a specially designed intense vapor source [6]. The films had preferred c-axis texture and exhibited $T_c$ of up to 36 K and critical current densities of over 10 MA/cm$^2$ at $T < 20$ K. The residual

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normal-state resistivity, $\rho(40\text{K})$, was about 20 $\mu\Omega\text{m}$. For the hf measurements 250-300 nm thick films on 14x14 mm$^2$ $r$-cut sapphire substrates were used. The hf properties of these films in zero dc field have been reported recently in detail [3]. At 18.8 GHz, $R_s(20\text{K}) \approx 0.9$ m$\Omega$ and $R_s(10\text{K}) \approx 0.1$ m$\Omega$ were obtained.

The hf measurements were performed using an Agilent N5230A vector network analyser operating up to 20 GHz and a copper shielded resonator in which a dielectric cylinder (6 mm in diam., 3 mm height) was fixed between two nominally identical MgB$_2$ films. In order to measure the hf losses at different frequencies two dielectric materials were used: sapphire with the (001) crystallographic axis parallel to the cylinder axis and rutile with the (001) axis parallel to the cylinder axis. The sapphire resonator was excited in its lowest TE$_{011}$ mode with the resonant frequency $f_0 \approx 18.5$ GHz. The rutile resonator provided several suitable modes, from which the TE$_{011}$, TE$_{012}$, and TE$_{022}$ with $f_0$ of 5.75 GHz, 9.29 GHz, and 11.67 GHz, respectively, were used. The measurements were performed in dc magnetic fields applied parallel to the film surface in an Oxford superconducting magnet system combined with a He-flow cryostat. The samples were cooled down to the measurement temperature in zero applied field. Then, the variation of the hf surface resistance, $\Delta R$, and the hf surface reactance, $\Delta X$, were measured as a function of the dc magnetic field, $B$, using the variation of the unloaded quality factor and the resonant frequency, respectively. In each particular measurement the highest obtained $B$ was limited by the accuracy of the hf measurements, which degraded in higher fields due to increased losses in the resonator and distorted resonant peaks.

3. Results

The dependences $\Delta R_s(B)$ and $\Delta X_s(B)$ obtained at different frequencies and temperatures exhibited the same shapes, which are consistent with the behaviour of a classic type-II superconductor in dc magnetic field. As a characteristic example we present in figures 1, 2 and 3 the data obtained at 5.75 GHz, 9.29 GHz, and 11.67 GHz, respectively, were used. The measurements were performed in dc magnetic fields applied parallel to the film surface in an Oxford superconducting magnet system combined with a He-flow cryostat. The samples were cooled down to the measurement temperature in zero applied field. Then, the variation of the hf surface resistance, $\Delta R$, and the hf surface reactance, $\Delta X$, were measured as a function of the dc magnetic field, $B$, using the variation of the unloaded quality factor and the resonant frequency, respectively. In each particular measurement the highest obtained $B$ was limited by the accuracy of the hf measurements, which degraded in higher fields due to increased losses in the resonator and distorted resonant peaks.

The first branch (filled circles) shows the field-up measurement for the samples cooled in zero applied field. An initial increase of $B$ towards the first critical field, $B_{c1} \approx 0.1$ T, did not produce any considerable changes of either $\Delta R_s$ or $\Delta X_s$. Reaching $B_{c1}$ resulted in a sharp increase of $\Delta R_s(B)$ and $\Delta X_s(B)$. At the same time $r$ peaks to ~100, which is a very high value for superconducting films usually attributed to the effect of weak links, or grain boundaries [7]. In the higher field range, $B > B_{c1}$, both $\Delta R_s(B)$ and $\Delta X_s(B)$ became linear with field indicating a homogeneous flux penetration into the films. A moderate value of $r = 17$ independent from the field supports the conclusion that the microwave losses are mostly due to the motion of Abrikosov vortices. Under these conditions the losses are proportional to the flux density in the film, i.e. $\Delta R \propto B$, $\Delta X \propto B$ and $r(B) = \text{const}$, as predicted by the Coffey, Clem [4] and Brandt [5] model.

The following reduction of the field magnitude (field-down measurement marked by open circles) reproduced the same linear $\Delta R_s(B)$ and $\Delta X_s(B)$ dependences, which indicates a homogeneous reduction of the flux density in the MgB$_2$ films with little flux remained pinned there. In the lower field range, $B < (0.5 \pm 0.6)$ T, the ‘field-down’ values of $\Delta R_s$ and $\Delta X_s$ became higher than the ‘field-up’ ones, see figure 2, and formed a hysteresis loop. This means, that the ‘field-down’ branches of the curves reveal higher flux density in the films, than the ‘field-up’ branches, because some vortices remained trapped at their pin centres.

Switching the field sign to the opposite one (filled squares for the field-up and open squares for the field-down measurements, respectively) reproduced the same scenario: relatively small variation of $\Delta R_s$ and $\Delta X_s$ in the low field range and linear $\Delta R_s(B)$ and $\Delta X_s(B)$ at fields well above $B_{c1}$. In the remanent state ($B = 0$) the ‘field-up’ and the ‘field-down’ values of $\Delta R_s(0)$ were practically the same, as well as the ‘field-up’ and the ‘field-down’ $\Delta X_s(0)$ values. Thus, in the remanent state the number of vortices trapped at their pin centres was the same, independent from the history of the field changes.
Figure 1. Dependences of $\Delta R_S$ (a), $\Delta X_S$ (b) and their ratio $r$ (c) on the parallel dc magnetic field at 5.75 GHz and 3 K (zero-field cooled). Solid circles mark the first field-up measurement followed by the field-down one (open circles). Then, the field sign was changed: solid squares for field-up and open squares for field-down. Finally, the field sign was changed back: solid triangles for field-up and open ones for field-down measurements, respectively.
Figure 2. Detailed view in the lower field range of the data shown in figure 1: \( \Delta R_S \) (a), \( \Delta X_S \) (b) and their ratio (c). The meaning of the symbols is the same as in figure 1.
Figure 3. The data of figure 1 plotted on a logarithmic scale versus the absolute value of $B$, i.e. independent of the field sign: $\Delta R_S$ (a), $\Delta X_S$ (b). The meaning of the symbols is the same as in figure 1.

Switching the field sign back to the positive one (filled triangles for the field-up and open triangles for the field-down measurements, respectively) reproduced the same $\Delta R_S(B)$ and $\Delta X_S(B)$ curves. Actually, the sweeps of magnetic field (with exception for the very first one, started from the zero-field cooled state) produced the plots symmetrical with respect to the ordinate axis. This can be seen in figure 3, where the data are plotted versus the absolute value of $B$, i.e., the sign is omitted.

4. Discussion and conclusion

The behaviour of the microwave losses of the MgB$_2$ films in dc magnetic field was found to be consistent with the expectations for a classic type-II superconductor. The films cooled in zero-field revealed a clear indication of the lower critical field, $B_{c1}$. At higher fields (up to at least 2 T at 3 K) both $R_s$ and
$X$, increased linearly with field in good agreement with the vortex state model introduced for type-II superconductors by Coffey, Clem and Brandt. The curves measured in sweeping fields revealed a narrow hysteresis loop in the range $B < (3/4) B_{c1}$ and were symmetrical with respect to the vertical axis.

Remarkably, the MgB$_2$ films exhibited only a weak hysteresis of $\Delta R_s(B)$ and $\Delta X_s(B)$, see figure 2, compared to the huge hysteresis effects observed for Y-Ba-Cu-O films [8, 9]. The Y-Ba-Cu-O films usually do not exhibit any indication of $B_{c1}$, the field-up and field-down curves do not coincide in any field range and decreasing $B$ often leads to increasing $\Delta R_s(B)$ and $\Delta X_s(B)$, while the losses in the remanent state are on the same level as in the highest reached field. This implies a relatively weak pinning of the vortices in MgB$_2$ films compared with the Y-Ba-Cu-O films. It is natural to assume, that both $\Delta R_s$ and $\Delta X_s$ of superconducting films immersed in magnetic field are proportional to the density of the vortices inside the film [3-5,8,9]. Then, the linear $\Delta R_s(B)$ and $\Delta X_s(B)$ dependences of the MgB$_2$ suggest, that the vortex density in the films is proportional to the applied field, with relatively few vortices pinned there. Consequently, switching the sign of $B$ and introducing the anti-vortices (with the opposite direction of the screening current around the vortex core, and of the magnetic field inside the core) can not reduce the flux density in the MgB$_2$ film considerably, since there are not many vortices, with which the anti-vortices can interact and annihilate.

The regular linear dependences $\Delta R_s(B)$ and $\Delta X_s(B)$, see figures 1 and 2, do not show any indication of an avalanche-like flux penetration into the MgB$_2$ films. This effect has been often observed by magneto-optical measurements in magnetic fields applied perpendicularly to the film surface at temperatures below $\sim 15$ K in various MgB$_2$ films [10], including ours [11]. In the case of the microwave measurements such an avalanche-like increase of the flux density in the films would lead to a drastic step-like increase of the hf losses, which was not observed. Most probably, the flux avalanches did not appear because the magnetic field was applied parallel to the film surface, which does not lead to a strong field enhancement at the film edges, as in the case of perpendicularly applied fields.

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