The formation and propagation of flux avalanches in tailored MgB$_2$ films

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Abstract. The applications of superconducting magnesium diboride are substantially limited by the presence of magnetic flux avalanches at low temperatures. Here, quickly moving magnetic vortices create large amounts of heat and magnetic noise. Such avalanches can be suppressed by evaporating metal layers to the surface of the superconductor, which acts both as a heat sink and as an electromagnetic drag by induced eddy currents. We show that it is necessary to distinguish between the mechanisms that are responsible for the formation and the propagation of avalanches. A high critical current favors avalanche formation but avalanche propagation is suppressed. The diverse consequences for creation and propagation explain the preference of avalanches for inhomogeneous superconductors.

After the discovery of the metallic superconductor MgB$_2$ in 2001 [1], it was soon realized that at temperatures below $T = 10$ K a chaotic behavior of flux penetration can occur that had already been found in conventional superconductors [2] and YBa$_2$Cu$_3$O$_{7-\delta}$ [3]. The magnetic flux penetrates into the superconductor by forming vortex avalanches on a wide range of lengthscales [4]. Since vortex velocities in avalanches are extremely high [5], this dissipative flux motion leads to a high level of disadvantageous magnetic noise. Magnesium diboride films are, in principle, attractive for application in making magnetic sensor devices. The reasons for this are the high superconducting transition temperature and the advantages of processing a metallic material. Additionally, the coherence length is large when compared to the size of grain.

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boundaries. A strict prerequisite is, however, to avoid the presence of magnetic avalanches at low temperatures.

The formation of avalanches is described by a thermomagnetic model [6], which will be briefly presented here. Magnetic avalanches occur due to the electric field generated by moving magnetic flux. This electric field leads to a dissipative motion of normal conducting electrons in the superconductor and, hence, to a local increase of temperature. This, in turn, reduces flux line pinning and enhances the mobility of the vortices. The so-created positive feedback loop leads to magnetic avalanches as a consequence of this thermomagnetic instability. Since a high Lorentz force is required as a driving force for vortex motion, this effect occurs only at low temperatures, where the local critical current density is high and so a large Lorentz force density occurs. Another reason why avalanches occur only at low temperatures is the strong dependence of heat transfer and thermal conductivity from temperature [7]. That means that at low temperatures local heating is strongly supported, which is also necessary for the thermomagnetic instability.

The formation of avalanches can be avoided by covering the superconductor with a metallic layer [8]. Usually, this was explained by the enhanced thermal conductivity of the cover layer. Now a recent work has shown that a metallic layer can suppress avalanches even without a close contact with the superconductor [9]. Colauto et al. [9] suggested that eddy currents induced in the metallic layer inhibit the propagation of avalanches. In this work, we show experimentally that both thermal conductivity and electromagnetic induction have to be taken into account for a description of avalanche behavior. In particular, it is necessary to distinguish between the mechanisms for the formation and the propagation of avalanches. This will be evident on considering a property like the critical current density $j_c$. The critical current density can, on the one hand, favor the formation of the thermomagnetic instability [10] and, on the other hand, suppress the propagation of an avalanche. As a consequence, flux motion and avalanches prefer inhomogeneous [11], granular [12] or perforated superconductors [13, 14], where a spatial variation of the critical current is present. Here, avalanches created in areas of high current densities can easily propagate in channels exhibiting reduced $j_c$.

For a detailed study of these issues, MgB$_2$ films were prepared on r-cut Al$_2$O$_3$ substrates by sequential deposition of magnesium and boron layers using conventional electron beam evaporation and a subsequent annealing process [15]–[17]. These films have a lateral size of 5 × 5 mm$^2$ and typical thicknesses of 300 nm. The superconducting transition occurs at 35 K and the current density is up to $1.5 \times 10^{11}$ A m$^{-2}$ at 10 K.

Figure 1 shows sketches of three different film geometries that were chosen for our investigations, namely a partly gold-covered film (A), a film with anisotropic current density (B) and a film with an inside area of enhanced current density (C).

Samples A and B have already been part of earlier studies [10, 18]; however, the particular preparation technique of samples B and C will be briefly presented here. In the case of the anisotropic sample B, a vicinal cut sapphire substrate is used, which leads to a slight anisotropy of the pinning properties of the final superconducting MgB$_2$ film (see the top of figure 2). Even when the created anisotropy of the critical currents is only of the order of 10%, a drastic change in avalanche formation is observed at a temperature of $T = 10$ K [10]. In addition, we prepared a sample C with sophisticated properties. The sample exhibits an inner area of enhanced current density, which is realized by an incomplete first magnesium layer on the sapphire substrate (see the bottom of figure 2). As a consequence, a non-optimal superconducting phase is formed at the rim of the film, whereas the thermodynamic properties should remain almost constant in
Figure 1. Sketches of the MgB$_2$ films prepared for this work. Sample A is partly gold covered, sample B exhibits anisotropic pinning leading to areas of different $j_c$ and sample C has an inner part with enhanced $j_c$. In samples B and C, $j_{c1}$ is larger than $j_{c2}$.

Figure 2. Precursors of samples B and C. For sample B, a vicinal cut substrate was used to create anisotropic pinning. The first Mg-layer of the precursor of sample C was masked to realize an inner area of enhanced current density.

all areas of the sample. The unique feature of this sample is that avalanches are generated in regions of low $j_c$ and, furthermore, propagate into regions of high $j_c$.

Magneto-optical Faraday microscopy has been used for mapping the magnetic flux density distribution in the superconducting state of all samples. With our setup a spatial resolution of 1 µm and a magnetic resolution of a few microtesla are achieved. The typical dendritic avalanche structures appear as bright paths in magneto-optical images, indicating a constant flux density inside the avalanche traces [19]. These structures are observed in all three samples. Additionally, a numerical inversion scheme of the Biot–Savarts law provides a map of the current density distribution in the sample [20].

Figure 3 displays a magneto-optical image of sample A at a temperature of $T = 10$ K. After zero-field cooling an external field of $B_{ext} = 3.2$ mT has been applied, leading to a dendritic flux...
Figure 3. Overlay of a magneto-optical image and a photograph of sample A. False color representation was used for clarity. The magneto-optical part was obtained at $B_{\text{ext}} = 3.2 \text{ mT}$ and $T = 8 \text{ K}$.

Figure 4. Detail of the bottom part of figure 3 in a slightly increased field of $B_{\text{ext}} = 4.8 \text{ mT}$. The image shows the current density distribution at $T = 8 \text{ K}$ after ZFC. Bright areas correspond to a high local current density of $j_c = 8 \times 10^{10} \text{ A m}^{-2}$.

penetration in the semicircular non-covered areas of the sample. Parts of the film that are covered by 1 $\mu\text{m}$ of gold hardly show any avalanche formation at all.

Additional findings are discovered when looking at the non-covered areas: the avalanches, which always evolve at the rim of the sample, propagate through these non-covered parts of the superconductor and are efficiently stopped on reaching the gold cover layer. This means that not only is the formation of avalanches suppressed by the presence of the noble metal but also that an already propagating avalanche is stopped. This suggests that it might be necessary to distinguish between avalanche formation and propagation in terms of different mechanisms. In the particular situation of a gold-covered MgB$_2$ film, this has the following implications. Firstly, the large thermal conductivity of gold removes the necessary heat for the formation of the dynamic avalanche process. Secondly, the large electrical conductivity of gold leads to large eddy currents slowing down vortex motion according to Lenz’s rule. Note that a gold cover layer does not influence the critical current density in the superconductor if no avalanches are present [18]. Figure 4 shows a detail of sample A in a slightly increased magnetic field of $B_{\text{ext}} = 4.8 \text{ mT}$. The avalanches now penetrate further into the gold-covered part of the film. The current density map in figure 4 shows that in the case of avalanche formation, the local current density is influenced by the gold layer. We find a distinct increase in the maximum
local values of $j_c$ from $6 \times 10^{10}$ to $8 \times 10^{10}$ A m$^{-2}$. This has two consequences: firstly, there is a correlation between the local current density and avalanche propagation; secondly, the critical state that is formed in the vicinity of avalanches is not equivalent to the classical critical state described by Bean’s model. This second issue will not be followed in this work. Since gold exhibits both a large thermal and a large electrical conductance, this experiment is not able to distinguish clearly between the two mechanisms, namely formation and propagation. A possible solution is offered by a sample exhibiting a variation of only one significant parameter. Our experiments show that the current density is an ideal parameter to observe differences in the formation and propagation of avalanches. The first sample with this property is sample B. Here, the current density along the vertical axis is about 10% larger than along the horizontal axis. Figure 5 shows a magneto-optical image of sample B at $T = 10$ K and $B_{\text{ext}} = 8$ mT after zero-field cooling (ZFC). Interestingly, avalanches are only formed in the horizontal direction, where pinning is stronger. This may seem unreasonable, but since avalanche formation is triggered by $j_c$, this finding agrees perfectly with theoretical models [10].

In sample C, a different approach to a spatially varying current density distribution is realized. Sample C exhibits a region with substantially increased current density where the areas of higher $j_c$ are not directly in contact with the edge of the film. This means that the rim of the sample, where avalanches are created, exhibits a lower current density than the inner area. A propagating avalanche subsequently penetrates the inner area of elevated current density.

Figure 6 characterizes the properties of sample C. Figure 6(a) shows an optical image of the sample surface. A clear variation is seen between the inner (1) and outer (2) parts. This is remarkable because only the first layer close to the substrate is incomplete. All other precursor layers cover the whole substrate. This leads to an almost spatially constant thermal conductivity.

The bottom left image (figure 6(c)) is a representation of the critical current density in this film obtained by quantitative magneto-optical microscopy. This result is obtained at $T = 12$ K in an external field of $B = 36$ mT. Bright colors refer to high current densities. Figure 6(c) shows that our preparation route successfully generated a sample with an elevated current density area that was located at the center of the film. We find the value for $j_{c2}$ to be $3 \times 10^{10}$ A m$^{-2}$ at the rim of the sample and the value for $j_{c1}$ to be $6 \times 10^{10}$ A m$^{-2}$ in the inner part, respectively.
Figure 6. (a) Photograph of sample C; (b) flux density distribution in the avalanche state at $T = 8$ K and $B_{\text{ext}} = 7.6$ mT after ZFC; bright areas correspond to high flux density; (c) current density distribution of sample C at $T = 12$ K and $B_{\text{ext}} = 36$ mT after ZFC; The green line indicates the borderline of the area of increased $j_c$; (d) current density distribution of (b); bright areas correspond to high current density.

Correspondence is obvious between figures 6(a) and (c). However, no clear separation between high-current and low-current areas is found in the left part of the film, as can be seen from the left part of figure 6(c). Figures 6(b) and (d) now depict the avalanche formation in this sample at $T = 8$ K in an external field of $B = 7.6$ mT. Figure 6(b) gives the magnetic flux density distribution and figure 6(d) gives the corresponding supercurrent distribution calculated by the numerical inversion scheme. In addition, a solid line is introduced, indicating the borderline between high-current and low-current areas.

Figures 6(b) and (d) show that the penetration of avalanches stops on reaching the borderline of the area with elevated critical current. Even if the borderline is very irregular as in our case, avalanches always stop on reaching the border. An exception is the left part of the film; this might be correlated with the non-sharp separation of the two areas in this region. Considering, finally, the corresponding currents (figure 6(d)), it can be seen that the critical state that is formed around the avalanches will be characterized by higher critical currents on reaching the inner area. This elevation of the critical current density is responsible for stopping the propagation of the avalanches. Here, the pinning force density increases, which stops flux line motion. This result is quite remarkable, because in figure 5 it is found that an increase of $j_c$ favors avalanches. These findings argue for the identification of two processes: firstly, the formation of avalanches, which is triggered by increased local current densities and leads to a threshold temperature below which the critical currents are large enough to let the critical state collapse; secondly, the propagation of avalanches, which can be suppressed by areas of higher...
critical current density or metallic covering layers that inhibit propagation by electromagnetic braking.

This has clear consequences for the preparation of avalanche-free superconducting MgB$_2$ films. If a high local current density supports the creation of avalanches and a low local current density is optimal for avalanche propagation, the worst case occurs in a film with inhomogeneous current density distribution. Here, areas of high $j_c$ values create avalanches, which can then propagate through low-$j_c$ channels. This explains what is found in superconductors with artificial perforation or films with granular microstructure [11]–[14].

In conclusion, we investigated the formation and propagation processes of avalanches in thin MgB$_2$ films. It has been shown that a high current density favors the formation of avalanches, whereas their propagation is inhibited by an increased current density. These findings show clearly that avalanche formation and propagation obey different mechanisms and have to be thoroughly distinguished. To reach a state of minimal avalanche contamination it is necessary to prepare homogeneous MgB$_2$ films.

References

[1] Nagamatsu J, Nakagawa N, Muranaka T, Zenitani Y and Akimitsu J 2001 Nature 410 63
[2] Harrison R B, Wright L S and Wertheimer M R 1973 Phys. Rev. B 7 1864
[3] Leiderer P, Boneberg J, Brüll P, Bujok V and Herminghaus S 1993 Phys. Rev. Lett. 71 2646
[4] Altshuler E and Johansen T H 2004 Rev. Mod. Phys. 76 471
[5] Bolz U, Biehler B, Schmidt D, Runge B U and Leiderer P 2003 Europhys. Lett. 64 517
[6] Denisov D V, Rakhmanov A L, Shantsev D V, Galperin Y M and Johansen T H 2006 Phys. Rev. B 73 014512
[7] Denisov D V et al 2006 Phys. Rev. Lett. 97 077002
[8] Baziljevich M, Bobyl A V, Shantsev D V, Altshuler E, Johansen T H and Lee S I 2002 Physica C 369 93
[9] Colauto F, Choi E, Lee J Y, Lee S I, Patino E J, Blamire M G, Johansen T H and Ortiz W A 2010 Appl. Phys. Lett. 96 092512
[10] Albrecht J, Matveev A T, Strempfer J, Habermeier H-U, Shantsev D V, Galperin Y M and Johansen T H 2007 Phys. Rev. Lett. 98 11
[11] Welling M S, Aegerter C M, Westerwaal R J, Enache S, Wijngaarden R J and Griessen R 2004 Physica C 406 100
[12] Treiber S and Albrecht J unpublished
[13] Wordenweber R, Dymashevski P and Misko V R 2004 Phys. Rev. B 69 184504
[14] Kemmler M 2008 PhD Thesis, Tübingen University
[15] Matveev A T, Albrecht J, Konuma M, Stuhlhofer B, Starke U and Habermeier H-U 2005 Supercond. Sci. Technol. 18 1313
[16] Matveev A T, Albrecht J, Konuma M, Cristiani G, Krockenberger Y, Starke U, Schütz G and Habermeier H-U 2006 Supercond. Sci. Technol. 19 299
[17] Shinde S R, Ogale S B, Greene R L, Venkatesan T, Caneld P C, Bud’ko S L, Lapertot G and Petrovic C 2001 Appl. Phys. Lett. 79 227
[18] Albrecht J, Matveev A T, Djupmyr M, Schütz G, Stuhlhofer B and Habermeier H-U 2005 Appl. Phys. Lett. 87 182501
[19] Barkov F L, Shantsev D V, Johansen T H, Goa P E, Kang W N, Kim H J, Choi E M and Lee S I 2003 Phys. Rev. B 67 064513
[20] Jooss Ch, Albrecht J, Kuhn H, Leonhardt S and Kronmüller H 2002 Rep. Prog. Phys. 65 651

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