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Suppression of superconducting critical current density by small flux jumps in MgB_2 thin films

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By doing magnetization measurements during magnetic field sweeps on thin films of the new superconductor MgB_2, it is found that in a low-temperature and low-field region small flux jumps are taking place. This effect strongly suppresses the central magnetization peak leading to reduced nominal superconducting critical current density at low temperatures. A borderline for this effect to occur is determined on the field-temperature (H-T) phase diagram. It is suggested that the small size of the flux jumps in films is due to the higher density of small defects and the relatively easy thermal diffusion in thin films in comparison with bulk samples.

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I. INTRODUCTION

For applications of superconductors, a high transition temperature T_c and superconducting critical current density j_c are desirable. The discovery of the new superconductor MgB_2 (Ref. 1) with a remarkably high transition temperature of 39 K and high critical current density j_c provides a promising candidate for such applications.[2–6] One big issue concerns the stability of the critical current and what process dominates the flux motion in the new superconductor MgB_2. For bulk samples the flux dynamics and the vortex phase diagram have been intensively investigated.[7–9] Usually it is believed that the j_c is controlled by either continuous flux creep (in intermediate- and high-temperature region) or sudden, large, and discontinuous flux jumps (in low-temperature region).[10,11] The former can give rise to a continuously and parallel marching flux front and thus a continuous magnetization versus field $M(H)$ curve, whereas the latter will generate many big blasts at the flux front leading to big discontinuous steps on the $M(H)$ curves. Since there are generally more defects (so more pinning centers) in thin films, it is interesting to know whether the same flux dynamics is occurring in thin films as in bulk samples. In this paper, we present the experimental observation of many small flux jumps (SFJ) in low temperature and field region of MgB_2 thin films. It is further shown that the central magnetization peak of the magnetization-hysteresis-loop (MHL) is smeared out and the nominal j_c is suppressed by this effect in comparison to that due to the continuous flux creep.

II. EXPERIMENT

The thin films of MgB_2 were fabricated on (1102) Al_2O_3 substrates by using the pulsed laser deposition technique, which was described clearly in Ref. 12. They are typically 400 nm thick with predominant c-axis orientation (the c axis is perpendicular to the film surface). A rectangular sample of size 2.1 mm×4.9 mm was chosen for the magnetic measurements. The temperature dependence of the diamagnetic moment was carried out by a quantum design superconducting quantum interference device (SQUID, MPMS 5.5) and the MHL were measured with a vibrating sample magnetometer (VSM 8 T, Oxford 3001) at temperatures ranging from 2 K to T_c and an external field up to 8 T along the c axis. The $M(H)$ curve was measured with a field sweep rate of 0.01 T/s and integration time of 60 ms. The pressure of helium gas in the sample chamber for thermal exchange was kept at 0.04 bar during the measurement.

III. RESULTS

In the inset of Fig. 1, we show the temperature dependence of the zero-field-cooled (ZFC) magnetization measured by SQUID at $\mu_0 H = 0.001$ T. It is clear that the superconducting transition temperature T_c is about 38 K and the transition is rather sharp, indicating a good quality of the film.

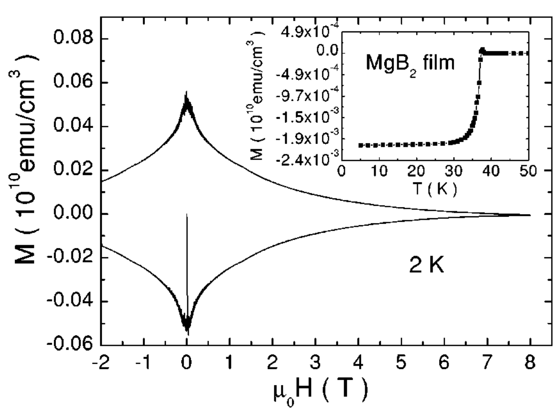

FIG. 1. Magnetization hysteresis loop measured by VSM at 2 K. The curve is nearly closed at 8 T and many small magnetic instabilities can be seen at low field. The inset shows the temperature dependence of the ZFC magnetization of the MgB_2 film measured by SQUID at $\mu_0 H = 0.001$ T.

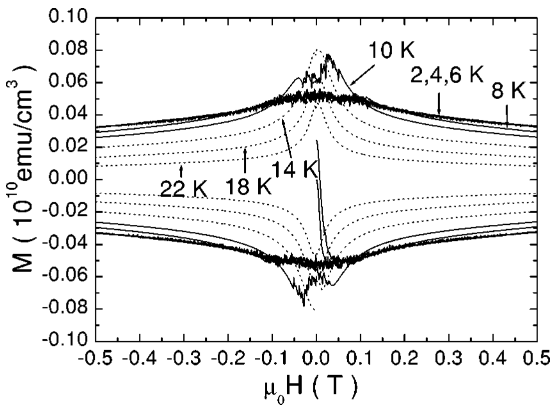

FIG. 2. MHL's measured for a MgB_2 thin film at temperatures of 2, 4, 6, 8, 10, 14, 18, and 22 K with the external field sweep rate 0.01 T/s. In low field region and at temperatures from 2 to 10 K (solid line), there are many small flux jumps leading to the suppression of the nominal superconducting critical current density j_c.

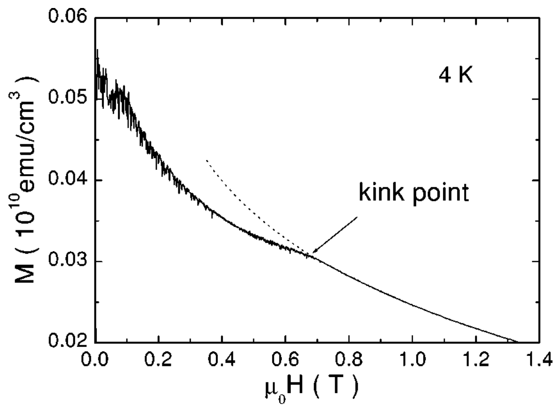

FIG. 3. An enlarged view for the MHL at 4 K and the field ranging from 0 to 1.4 T on the field descending branch. We can clearly see that the SFJ begin at 0.7 T and a kink point appears on the MHL curve. The dotted line represents the extrapolation from the high-field data.

The main frame of Fig. 1 shows a typical MHL measured at 2 K with the external field sweep rate of 0.01 T/s. One can see that the MHL is symmetric about the $M=0$ axis showing the dominance of the bulk superconducting current here. Another interesting finding is that the MHL is almost closed at about 8 T, being very similar to the observation on bulk MgB_2.[9] This relatively low irreversibility field H_{irr} determined from the closing point of MHL was first attributed by Wen *et al.*[4] to the existence of quantum vortex liquid in the rather clean system of MgB_2. The nominal j_c estimated using the Bean critical state model is about 1.2×10^7 A/cm^2 at 2 K and zero field, which is about one order of magnitude higher than that in high-pressure synthesized bulk samples. This further indicates a rather good quality of the film. Worthy of noting here is that multiple small and irregular instabilities appear in the magnetization in a low field region. These irregular instabilities have magnitudes typically in the order of 10^{-3} emu. They are much higher than the noise background (10^{-5} emu) of our VSM. The magnitude of these instabilities are much larger in low fields than in high fields [where the $M(H)$ curve becomes smooth] although the field sweep rate and the data acquisition speed are the same, indicating that the instabilities are not due to the noise background of the VSM. These instabilities have been rechecked with caution in a sense that after one week and two weeks, the same MHL's were obtained during the remeasuring process on MgB_2 thin films, confirming the reproducibility of the instabilities in MgB_2 thin films.

In order to know whether these irregular instabilities are related to the flux jumps appearing in bulk MgB_2 samples,[10,11] we have carried out detailed measurements at different temperatures. The results are shown in Fig. 2. One can clearly see the following interesting findings: (i) the instabilities in the magnetization appear in a region below a certain value of field and temperature, e.g., below 1.3 T at 2 K; (ii) when these instabilities appear the central magnetization peak is strongly flattened out (see, e.g., the data of 2, 4, 6, and 8 K) revealing a suppression of the nominal j_c; (iii) the magnetizations at 2, 4, 6, and 8 K nearly merge at low field, though at higher fields they are separated gradually showing the usual order of the j_c vs. H and T, i.e., a higher j_c at a lower field and temperature; (iv) when the temperature is increased, the small instabilities will evolve into some larger ones (at 10 K) and disappear completely at a higher temperature (at 14 K). The larger instabilities here look similar to those appearing in bulk samples, therefore it is tempting to regard these instabilities as small flux jumps.

In Fig. 3 we show a part of the MHL measured at 4 K. One can clearly see that when the field is swept through 0.7 T from above, the continuous MHL curve becomes discontinuous: small and irregular instabilities appear in low-field region. Interestingly these two regions are separated by a clear kink point on the MHL. The same feature appears for other MHL's measured at 2, 6, and 8 K. This kink may be understood in the following way: the SFJ appearing in low-field region suppresses the magnetic moment (thus the nominal critical current density) of the sample; while in high-field region the $M(H)$ curve will behave in another way since no SFJ occurs there. However, we are not sure whether this kink point is corresponding to a phase transition of the vortex system.

IV. DISCUSSION

Figure 4 shows the field dependence of the nominal j_c determined using the Bean critical state model via $j_c = 20\Delta M/Va(1-a/3b)$, where ΔM is the width of the MHL; and V, a, and b are the volume, width, and length $(a<b)$ of the sample, respectively. Although for a system with flux jumps the Bean critical state model may be inapplicable; it can be used to estimate the nominal j_c value for a qualitative comparison. At 14 K and near zero field, the estimated j_c is as high as 1.7×10^7 A/cm^2, which is rather high. It is necessary to note that the j_c value at 14 K is a real magnetic critical current density instead of a nominal one since here no flux jumps occur. However, at lower temperatures, the nominal j_c is clearly suppressed by these SFJ in low field region. In the high-field and -temperature region

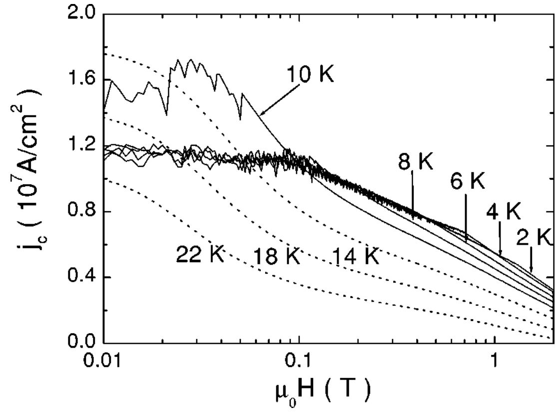

FIG. 4. The nominal critical current density $j_c(H)$ derived from the magnetization in Fig. 2 based on the Bean critical state model. The maximal value reaches about 1.7×10^7 A/cm^2 at 14 K.

the $M(H)$ curve becomes continuous showing the gradual setting in of the normal flux creep.

To get a more comprehensive understanding to the SFJ observed in a MgB_2 thin film, it is worthwhile to compare it with that in bulk MgB_2.[10,11] The MHL's of a high-pressure synthesized bulk sample are presented in Fig. 5. It is clear that after each flux jump, the optimal slope may not be fully recovered, while there is no suppression of the central magnetization peak (and thus the nominal j_c) near zero field at 2 and 4 K, in contrast to what was observed in MgB_2 films. In other words, although strong flux jumps occur at 2 and 4 K in bulk, the outlines of the MHL's at these temperatures are still wider than those at higher temperatures where no flux jumps are observed.

Now we have a close look at the part of MHL's where the flux jumps occur. In Figs. 6(a) and 6(b) the magnetization M and the derivative dM/dH are plotted against the field in the flux jump region for the bulk and the thin film, respectively. Two types of flux jumps can be clearly seen here for these two different samples. The jumps in the bulk sample are sparse and relatively large. After each jump, the magnetization changes significantly and then it gradually comes back

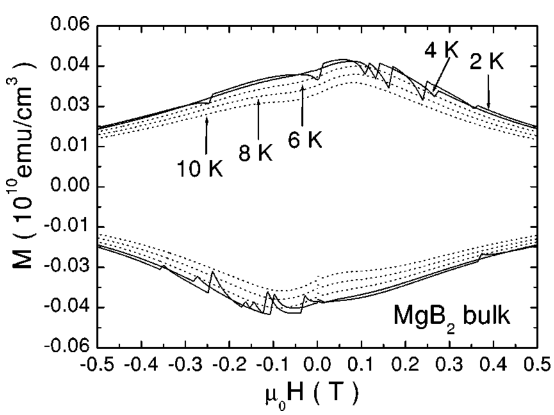

FIG. 5. The MHL's measured for a high-pressure synthesized MgB_2 bulk at temperatures of 2, 4, 6, 8, and 10 K with the field sweep rate 0.01 T/s. There is no suppression of the j_c at 2 and 4 K. The flux jumps are relatively big and sparse.

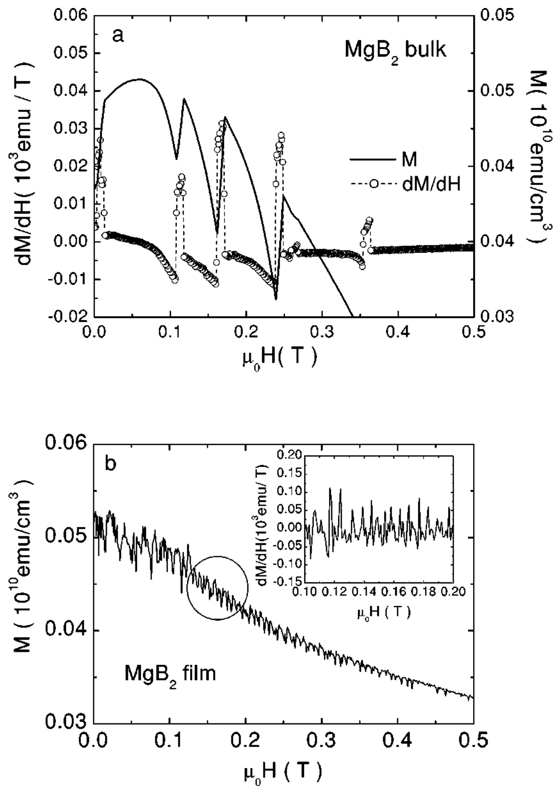

FIG. 6. Field dependence of the $M(H)$ and dM/dH for (a) the bulk and (b) the film at 2 K and the same field region from 0 to 0.5 T on the field descending branch of MHL. For the bulk there are only few large flux jumps. And the occurrence of the jumps is repeatable even in detail. (b) For the film many small irregular jumps can be observed. The details of these small jumps are completely irreproducible.

to the main branch of MHL. A nearly constant field interval for every jump (about 0.07 T) is observed. During multiple measurements, the jumps repeatably tend to occur at the same field with the same magnitude. All these can be qualitatively understood based on the Swartz-Bean adiabatic theory.[13] The flux jump can be triggered when the gradient of magnetic flux profile inside the sample exceeds some critical value. After a very short time [usually in the order of milliseconds (Ref. 15)] the magnetic profile drops to a new configuration with a lower gradient, then the flux only creeps slowly until the gradient of magnetic flux profile induced by varying the external field exceeds the critical value again. In each jump many vortices are involved in the thermomagnetic avalanche which normally expands to a large part of the sample volume. In thin films, however, the situation is completely different: many small local avalanches occur [as shown in Fig. 6(b)]. Although the H-T region for flux jumps to appear does not change in different round of measurement in MgB_2 thin films under identical conditions, the specific positions and the magnitude of the SFJ are, however, completely unrepeatable. All these cannot be explained by the adiabatic theory. The different avalanches observed in bulk samples and thin films may be induced by the different structural details and thermal diffusibility.[14] For example, in bulk samples, there are many large grain boundaries, which act as strong pinning centers. The gradient of the flux profile near these boundaries can be broken at a certain limit. Once a blast occurs in a bulk sample, the thermal energy induced by drastic flux motion cannot easily diffuse out and be carried away by the environment. Therefore this self-heating will lead to an increase in the region in which the vortex instability occurs, leading to a large jump on the magnetization in a bulk superconductor.[15] One can also understand from this picture that the number of flux jumps cannot be large in bulk samples. In thin films the situation can be very different. On one hand scanning-electron-microscope (SEM) data indicate a high density of small defects formed during the preparation process of the thin films leading to much stronger critical current densities. Therefore there are many places for the avalanche to occur. On the other hand, thermal diffusion is much easier in thin film samples due to their very small thickness and large surface area exposed to the environment. Therefore in thin films each avalanche is small in magnitude but the number of avalanches can be huge. This picture may give an explanation to many small vortex avalanches observed in the Nb film[16] and the YBCO film.[17] However, why some of these small avalanches will grow in a dendritic structure[16] is still an open question. But clearly the very fine disorder structure and the relatively better thermal diffusion in thin films are two key factors to be considered here.

Finally we suggest a criterion to identify the specific region for these SFJ on the H-T vortex phase diagram. The boundary point for SFJ is defined as the clear kink point shown in Fig. 3. Above this field no flux jumps could be observed above the noise background of the instrument. This is very helpful to illustrate the field and temperature region in which the application of the MgB_2 film can be hampered by the thermal instability. In Fig. 7 a borderline $H_{SFJ}(T)$ for the SFJ is plotted together with the irreversibility line $H_{irr}(T)$ determined from the closing point of the MHL with a criterion of $\Delta M = 10^{-4}$ emu. The SFJ appears only in the low temperature and low field region. Beyond this region the $M(H)$ curves continuously show normal flux creep with very low creep rate.[18] Therefore it is safe to conclude that the application in the large part of the vortex solid will not be influenced by the SFJ. However, it is important to point out that the SFJ observed in these films will prevent the use of the SQUID device made from these thin films at low temperatures.

We have been aware of a recent result by Johansen *et al.*,[19] who found the SFJ and some dendritic avalanches in MgB_2 thin films by doing the magneto-optical measurement. One can see from their data that many tiny avalanches occur first at the edge of the film and some of them will gradually grow into a dendritic structure. Each tiny jump on our MHL may correspond to a local avalanche or the growth on one branch of the dendritic structure. These tiny jumps cannot be observed from the MHL measured by SQUID as presented by Johansen *et al.* since the SQUID has a very low speed for data acquisition. They can be seen clearly from our data measured by VSM with a fast data reading capacity.

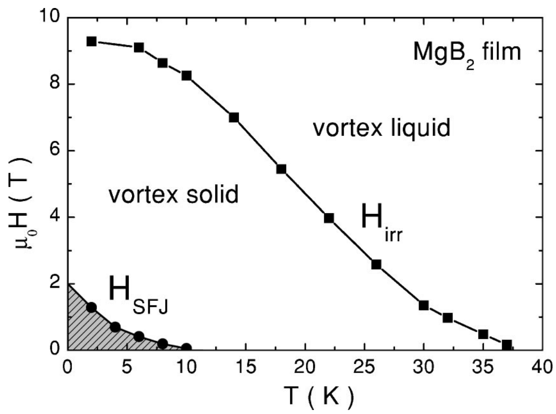

FIG. 7. The borderline $H_{SFJ}(T)$ (filled circles) separating the usual flux creep and the SFJ region. The SFJ region is marked by the shaded area. The irreversibility line $H_{irr}(T)$ is represented by the filled squares. The lines are a guide to the eye. The flux dynamics in the major part of the vortex solid state is dominated by the elastic flux creep with very slow creep rate.

V. CONCLUDING REMARKS

In conclusion, we have reported the observation of the suppression of the central magnetization peak and thus the nominal critical current density in the new superconductor MgB_2 film at low temperatures due to many small flux jumps. A comparison with a MgB_2 bulk sample is made. It is suggested that the small vortex avalanches in the thin film are closely related to the high density of small defects and the relatively easy thermal diffusion. A borderline for this effect to occur is determined on the H-T phase diagram. This gives helpful information for the application of MgB_2 films.

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