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Magnetic vortex flux pinning in silicon-oil-doped MgB_2

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ABSTRACT

The field dependence of the critical current density, j_c (B), of MgB_2 doped with 10 wt.% of a liquid precursor, silicon oil, was measured. The obtained j_c (B) was enhanced compared with the value of pure MgB_2. The temperature dependence of the crossover field, $B_{sb}(T)$, from the region of a single vortex to the region of small vortex bundle pinning shows that δl pinning, which is associated with mean-free-path fluctuations of the charge carriers, is dominant in this superconductor.

1. Introduction

Magnesium diboride, MgB_2, is a very attractive material because of its high superconducting transition temperature ($T_c \approx 39$ K) [1]. In this superconductor, j_c is as high as 10^{5-6} A/cm^2 at low temperature without a magnetic field. However, the critical current density drops rapidly with increasing magnetic field because pinning of the vortex flux is weak in this superconductor [2–9]. Various kinds of doping has been tried to increase the critical current density, j_c, in a magnetic field. The j_c of MgB_2 has been increased by more than one order of magnitude in high magnetic field by adding SiC [7]. Also, the pinning forces of the magnetic flux have been reported to be enhanced when grain size of the bulk MgB_2 becomes smaller [8]. One way to satisfy the above two conditions is by using an atomic size dopant that contains both Si and C. The liquid precursor, silicon oil, is one of the best candidates which can produce Si and C in atomic scale [5,9] in MgB_2 samples.

In this research, we used a liquid precursor, silicon oil, to produce silicon-oil-doped MgB_2 samples, and we investigated the critical current density and the pinning mechanism. The collective pinning theory was adopted to explain the experimental results. The dominant pinning in a high magnetic field was found to be caused by the mean-free-path (δl) fluctuation of the charge carriers in this MgB_2 samples.

A polycrystalline MgB_2 superconductor with 10 wt.% silicon oil added was prepared by using the solid-state powder processing technique. A low sintering temperature of 600 °C was chosen since a low temperature treatment will produce grains of small size. The superconducting critical temperature was 35.2 K. The M-H hysteresis loops of the MgB_2 were measured and the critical current densities were obtained from these M-H loops by using the Bean critical state model.

The critical current density as a function of applied magnetic field for various T is presented in Fig. 1. At applied field of 4 T and a temperature of 20 K, the value of j_c is over 10^4 A/cm^2, which is almost one order of magnitude higher than that of pure MgB_2, which implies that flux pinning is highly enhanced.

The collective pinning theory is well known to predict a single vortex pinning mechanism for fields below B_{sb} where the B_{sb} is proportional to the critical current density, while for fields higher than B_{sb}, the critical current density, j_c, decreases rather quickly with an exponential behavior.

To understand the pinning mechanism of the critical current densities, we re-plotted j_c (B) in a double log form of log $[j_c(B)/j_c(0)]$ as a function of B at $T = 25$ K (circles) and 29.5 K (rectangles) at the inset in Fig. 2. The two points of deviation from the linearity in the central linear region, B_{sb} and B_{th}, are shown by arrows. From the inset in Fig. 2, we can see that collective pinning describes intermediate fields of small vortex bundle pinning quite well. The deviation below B_{sb}, occurs in the region of single vortex-pinning. The j_c for field above B_{th} deviates from the behavior at the intermediate field due to large thermal fluctuations.

The last point we would like to address is the origin of the pinning mechanism for this Si-oil-doped MgB_2 bulk. This should be understood because the critical current density is quite enhanced compared to the value for a pristine MgB_2 bulk. In a broad sense, pinning can be categorized into two kinds. One is δT_c pinning in which fluctuations in the transition temperature pin the vortex. The other is δl pinning in which mean-free-path fluctuations of

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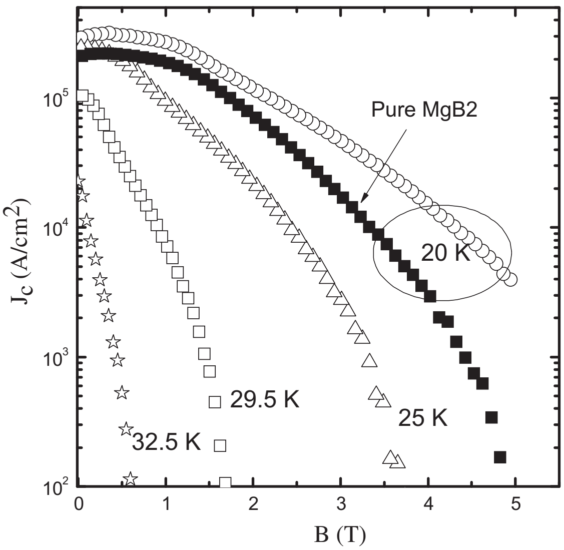

Fig. 1. Magnetic and temperature dependence of the critical current density j_c.

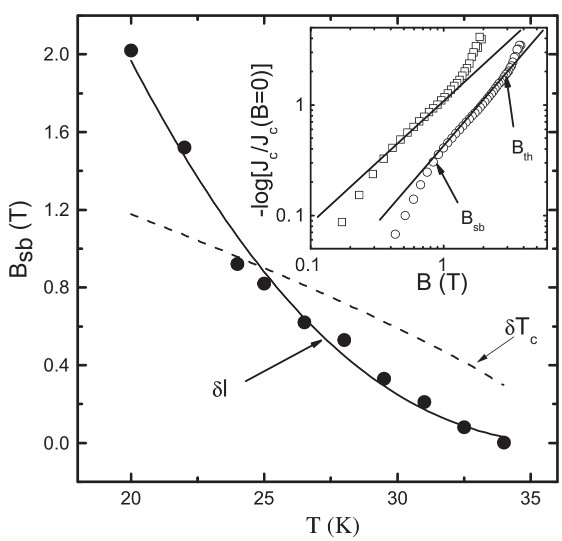

Fig. 2. Plot of B_{sb} as a function of temperature, which indicates the δl pinning. For comparison, δT_c pinning is shown. The inset shows a plot of $j_c(B)/j_c(0)$ as a function of B at T = 25 K (circles) and 29.5 K (rectangles). The crossover fields, B_{sb} and B_{th}, are shown by arrows.

the charge carriers pin the vortices. Griessen et al. [6] described B_{sb} as being proportional to $(1 - t^2/1 + t^2)^{\upsilon}$, where t is the reduced temperature. The exponent υ is 2/3 for δT_c pinning and 2 for δl pinning. In this Si-oil-doped MgB_2, υ = 2 which indicates a dominant δl pinning mechanism.

Fig. 3 shows the phase diagram for vortex pinning. At low magnetic fields and temperatures, single vortex pinning dominates, but it change to small bundle vortex pinning at the intermediate magnetic fields and temperatures and finally, vortex liquid at high magnetic fields and temperatures.

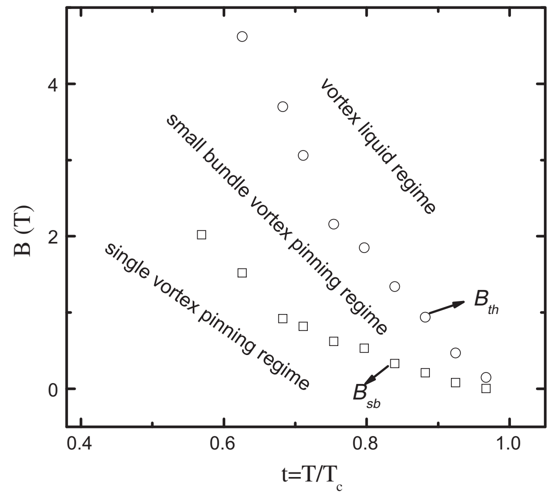

Fig. 3. Phase diagram for 10-wt.% silicon-oil-doped MgB_2. B_{sb} and B_{th} were obtained from the experimental $j_c(B)$ data.

2. Conclusion

In conclusion, we observed an enhanced critical current density, j_c, in silicon-oil-doped MgB_2 and obtained B_{sb}. Through a comparison with the collective pinning theory, we found the dominant δl pinning mechanism, which is quite different from the δT_c pinning in a pure MgB_2 superconductors.

Acknowledgments

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