Magnetic vortex flux pinning in silicon-oil-doped MgB2

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\textbf{1. Introduction}

Magnesium diboride, MgB\textsubscript{2}, is a very attractive material because of its high superconducting transition temperature ($T_c \approx 39$ K)\cite{1}. In this superconductor, $j_c$ is as high as $10^{3-4}$ A/cm\textsuperscript{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\cite{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\textsubscript{2} has been increased by more than one order of magnitude in high magnetic field by adding SiC\cite{7}. Also, the pinning forces of the magnetic flux have been reported to be enhanced when grain size of the bulk MgB\textsubscript{2} becomes smaller\cite{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\cite{5,9} in MgB\textsubscript{2} samples.

In this research, we used a liquid precursor, silicon oil, to produce silicon-oil-doped MgB\textsubscript{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 ($\delta l$) fluctuation of the charge carriers in this MgB\textsubscript{2} samples. A polycrystalline MgB\textsubscript{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.

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The temperature dependence of the critical current density, $j_c$, of MgB\textsubscript{2} doped with 10 wt.% of a liquid precursor, silicon oil, was measured. The obtained $j_c$ was enhanced compared with the value of pure MgB\textsubscript{2}. The temperature dependence of the crossover field, $B_{c2}(T)$, from the region of a single vortex to the region of small vortex bundle pinning shows that $\delta l$ pinning, which is associated with mean-free-path fluctuations of the charge carriers, is dominant in this superconductor.

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\textsuperscript{2}, which is almost one order of magnitude higher than that of pure MgB\textsubscript{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 $B_{b1}$ where the $B_{b1}$ is proportional to the critical current density, while for fields higher than $B_{b1}$, 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 $j_c$ 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, $B_{b1}$ and $B_{b2}$, 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 $B_{b1}$ occurs in the region of single vortex-pinning. The $j_c$ for field above $B_{b1}$ 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\textsubscript{2} bulk. This should be understood because the critical current density is quite enhanced compared to the value for a pristine MgB\textsubscript{2} bulk. In a broad sense, pinning can be categorized into two kinds. One is $\delta T$ pinning in which fluctuations in the transition temperature pin the vortex. The other is $\delta l$ pinning in which mean-free-path fluctuations of
the charge carriers pin the vortices. Griessen et al. [6] described \( B_{s_b} \) as being proportional to \( (1/t^2 + t^2)^{2/3} \), where \( t \) is the reduced temperature. The exponent \( t \) is 2/3 for \( \delta T_c \) pinning and 2 for \( \delta l \) pinning. In this Si-oil-doped MgB\(_2\), \( t \approx 2 \) which indicates a dominant \( \delta l \) 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.

### 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 \( \delta l \) pinning mechanism, which is quite different from the \( \delta T_c \) pinning in a pure MgB\(_2\) superconductors.

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### References


