Evidence for vortex pinning induced by fluctuations in the transition temperature of MgB2 superconductors

M. J. Qin
University of Wollongong, qin@uow.edu.au

Xiaolin Wang
University of Wollongong, xiaolin@uow.edu.au

Hua-Kun Liu
University of Wollongong, hua@uow.edu.au

S. X. Dou
University of Wollongong, shi@uow.edu.au

Publication Details
This article was originally published as: Qin, MJ, Wang, XL, Liu, HK & Dou, SX, Evidence for vortex pinning induced by fluctuations in the transition temperature of MgB2 superconductors, Physical Review B, 2002, 65, 132508. Copyright 2002 American Physical Society. The original journal can be found here.
Evidence for vortex pinning induced by fluctuations in the transition temperature of MgB$_2$ superconductors

M. J. Qin, X. L. Wang, H. K. Liu, and S. X. Dou
Institute for Superconducting and Electronic Materials, University of Wollongong, Wollongong, New South Wales 2522, Australia

(Received 5 October 2001; published 19 March 2002)

The field-dependent critical current density $j_c(B)$ of a MgB$_2$ bulk sample has been obtained using magnetic measurements. The $j_c(B)$ curves at different temperatures demonstrate a crossover from single vortex pinning to small-bundle vortex pinning, when the field is larger than the crossover field $B_{cl}$. The temperature dependence of $B_{cl}(T)$ is in agreement with a model of randomly distributed weak pinning centers via the spatial fluctuations of the transition temperature (δ$T_c$ pinning), while pinning due to the mean-free-path fluctuations (δ$l$ pinning) is not observed.

DOI: 10.1103/PhysRevB.65.132508 PACS number(s): 74.70.Ad, 74.25.Dw, 74.25.Ha, 74.60.−w

The recent discovery of superconductivity in MgB$_2$ (Ref. 1) has led to intensive experimental and theoretical activities,2–15 with the purpose of understanding the basic mechanism of superconductivity and the vortex-pinning mechanism governing the critical current density $j_c$ in this new superconductor. Although $j_c$ has been improved greatly since its discovery, the underlying pinning mechanism is still under investigation.

In type-II superconductors, the most important elementary interactions between vortices and pinning centers are the magnetic interaction and the core interaction.16–22 The magnetic interaction arises from the interaction of surfaces between superconducting and nonsuperconducting material parallel to the applied field, which is usually very small in type-II superconductors with a high Ginzburg-Landau (GL) parameter $\kappa$. The core interaction arises from the coupling of the locally distorted superconducting properties with the periodic variation of the superconducting order parameter, which is usually more effective in technical type-II superconductors due to the high $\kappa$ value. Two mechanisms of core pinning are predominant in type-II superconductors, i.e., δ$T_c$ and δ$l$ pinning. Whereas δ$T_c$ pinning is caused by the spatial variation of the GL coefficient $\alpha$, which is associated with disorder in the transition temperature $T_c$, variations in the charge-carrier mean free path $l$ near lattice defects are the main cause of δ$l$ pinning.

It has been reported by Griessen et al.16 that the δ$l$ pinning is dominant in both YBa$_2$Cu$_3$O$_7$ and YBa$_2$Cu$_4$O$_8$ thin films. A high $\kappa$ value of 26 has been reported10 for MgB$_2$, indicating that the magnetic interaction is negligible, and the core interaction is more important. However, it has not been experimentally determined whether the δ$l$ pinning or the δ$T_c$ pinning is the dominant mechanism in MgB$_2$. The purpose of this paper is to report measurements of $j_c$ of this new material to achieve an understanding of the vortex-pinning mechanism and to demonstrate that in MgB$_2$ governed by bulk pinning, δ$T_c$ is the only important pinning mechanism.

All measurements have been performed using quantum design PPMS on a MgB$_2$ bulk sample with $T_c = 38.6$ K and dimensions of $2.18 \times 2.76 \times 1.88 \text{ mm}^3$, which was prepared by conventional solid-state reaction.23,24

Figure 1 shows the hysteresis loops of the MgB$_2$ sample every 2 K in the 14–36 K range. The results at lower temperatures, which have large flux jumping,25 are not shown here. The symmetric hysteresis loops with respect to the magnetic field indicate the dominance of bulk pinning up to temperatures near $T_c$, rather than surface barrier. As a comparison, we show in the inset of Fig. 1 the hysteresis loop of a pressed MgB$_2$ sample at 5 K. This sample is fabricated by pressing the MgB$_2$ powder into a pellet without sintering. The loop is highly asymmetric, showing a large reversible magnetization resulting from the surface current. The surface barrier has also been observed by Takano et al.13 in their powder sample and bulk sample sintered at low temperature.

From these $M(H)$ loops, we calculate $j_c = \Delta M/a(1 - a/(3b))$, with $a$, $b$ the width and length of the sample perpendicular to the applied field, respectively. The resultant $j_c(B)$ curves at various temperatures are shown in a double-logarithmic plot in Fig. 2 as different symbols. As can be seen from the plateau at low field, $j_c$ initially has a weak dependence on the field. When the field is increased beyond a crossover field, it begins to decrease quickly. The crossover field decreases with increasing temperature. Further increasing the field results in a faster drop in $j_c$ near the irreversible.
observed and has been explained by means of giant flux different pinning models yield different physical assumptions on summation of the elementary pinning force. The simplest model is the direct summation of \( j_{c}(B) \) characteristics. \( j_{c}(B) \) has been observed by other groups. Based on different pinning mechanisms in \( \text{MgB}_2 \). We, therefore, use Eq. (4) to fit the experimental data very well, while deviations from the fitting curves can be observed at both low and high fields. A clearer plot is shown in Fig. 4, where the \( j_{c}(B) \) curve at 24 K is shown in a double-logarithmic plot of \(-\log[j_{c}/j_{c}(B=0)]\) vs the applied field, which clearly shows a straight line at intermediate fields. The deviation at low fields is denoted as \( B_{sb} \), indicating the

\[
F_p = j_{c} B = n_{p} f_{p},
\]

where \( n_{p} \) is the density of pinning centers. When the influence of the flux-line lattice is taken into account, one has \( F_p = j_{c} B = n_{p} f_{p}(u_{0}/f_{p})d\log u_{0} \), where \( u_{0} \) is the maximum distortion of the flux-line lattice, caused by a point pinning force \( f_{p} \), \( d \) is the range of the pinning force, typically of the order of \( \xi \), and \( a_{0} \) the flux-line lattice constant. These two strong pinning models yield \( j_{c} \propto B^{-1} \) and \( j_{c} \propto B^{-0.5} \), respectively. Due to the large densities of the pins \( n_{p} \) and small \( f_{p} \), these two models are not representative for most real pinning systems. For randomly distributed weak pinning centers, the \( F_p \) can be estimated using the basic concept of collective pinning, which has been proved to be very successful in most real pinning systems.

\[
F_p = \sqrt{W/V_c} = \sqrt{W/(R_c L_c^2)}
\]

with the correlation volume \( V_c = R_c^2 L_c \), the correlation lengths \( R_c \) perpendicular to the field direction and \( L_c \) along the vortex line, and the pinning parameter \( W = n_{p} f_{p}^2 \). \( R_c \) and \( L_c \) depend on the applied field, the dimension of the flux-line lattice [three dimensional (3D) or 2D], and the elasticity or plasticity of the flux-line lattice. For the 3D elastic flux-line lattice, it has been derived by Blatter et al. that \( j_{c} \) is field independent when the applied field is lower than the crossover field \( B_{sb} \) (single vortex pinning)

\[
B_{sb} = \beta_{sb} j_{sv}/j_{0} B_{c2}
\]

where \( \beta_{sb} \approx 5 \) is a constant. \( j_{sv} = 4 B R_{c}/3 \sqrt{\mu_{0} \chi} \) the depairing current, \( B_{c2} = \Phi_0/2 \pi \chi \) the thermodynamic critical field, \( \xi \) the upper critical field, and \( j_{sv} \) the critical current density in the single vortex-pinning regime. When \( B > B_{sb} \) (small-bundle pinning), \( j_{c}(B) \) follows an exponential law.

\[
j_{c}(B) = j_{c}(0) \exp \left[ -\left( \frac{B}{B_{0}} \right)^{3/2} \right].
\]

When \( B > B_{sb} \), this large bundle-pinning regime is governed by a power law \( j_{c}(B) \propto B^{-3} \). The 2D elastic flux-line lattice shows single pancake pinning at low magnetic fields with field independent \( j_{c} \), then a 2D collective-pinning region at higher fields with \( j_{c} \propto 1/B \). For fields higher than a crossover field \( B_{c2}^{3D} \), three-dimensional pinning is predicted.

From the \( j_{c}(B) \) curves shown in Fig. 2, it is expected that the 3D elastic pinning model may explain the dominant pinning mechanism in \( \text{MgB}_2 \). We, therefore, use Eq. (4) to fit the \( j_{c}(B) \) curves, with fitting parameters \( j_{c}(0) \) and \( B_{0} \). The fitting results are shown as solid lines in Fig. 2. At intermediate fields, Eq. (4) fits the experimental data very well, while deviations from the fitting curves can be observed at both low and high fields.
crossover from the single vortex-pinning regime to the small-bundle-pinning regime. The point of deviation at high fields was first considered as the crossover field from small-bundle pinning to large-bundle pinning. However, when we fit the \(j_c(B)\) data at high fields to the power law \(j_c(B) \propto B^{-n}\), \(n\) is found to be as large as 20 rather than the theoretically predicted value of 3, making it unlikely that the system changes to the large-bundle-pinning regime. As the high-field deviation is very close to the irreversibility line, which results from giant flux creep, it is likely that the deviation at high field may result from large thermal fluctuations, which lead to the rapid decrease in \(j_c\). The inset of Fig. 4 shows that when the surface pinning is important, the exponential drop in \(j_c\) [see Eq. (4)] no longer applies, but a power law \(j_c(B) \propto B^{-1.2}\) is obvious.

The crossover field \(B_{ib}\) as a function of temperature is shown in Fig. 5 as open circles. We now compare the experimental data with theoretical predictions to get some insight into the pinning mechanism in MgB\(_2\). Using mental data with theoretical predictions to get some insight into the pinning mechanism in MgB\(_2\). Using mental data with theoretical predictions to get some insight into the pinning mechanism in MgB\(_2\), we have

\[
B_{ib} = B_{ib}(0) \left(1 - \frac{t^2}{1 + t^2}\right)^{2/3}
\]

for \(\delta T_c\) pinning, and

\[
B_{ib} = B_{ib}(0) \left(1 - \frac{t^2}{1 + t^2}\right)^2
\]

for \(\delta l\) pinning. The lines corresponding to Eqs. (5) and (6) are indicated as \(\delta T_c\) pinning and \(\delta l\) pinning, respectively. In sharp contrast, the \(\delta l\) pinning line shown in Fig. 5 is in total disagreement with the experimental data.

Having derived the crossover fields \(B_{ib}\) and \(B_{th}\), we reconstruct the \(B-T\) phase diagram shown in Fig. 3. The final \(B-T\) phase diagram is shown in Fig. 6. The vortex solid region is divided into three smaller regions. Single vortex pinning governs the region below \(B_{ib}\), between \(B_{ib}\) and \(B_{th}\), small-bundle pinning becomes dominant, while between \(B_{th}\) and \(B_{irr}\), thermal fluctuations are more important. Large-flux-bundle pinning is not observed in MgB\(_2\), but may be concealed by the thermal fluctuation effects.
In summary, we have found strong evidence for $\delta T_c$ pinning, i.e., pinning via the spatial fluctuations in the transition temperature, in MgB$_2$, while $\delta l$ pinning, i.e., pinning via the spatial fluctuations of the charge-carrier mean free path, is not observed. The $B$-$T$ phase diagram of the MgB$_2$ sample has been derived, showing that at low fields below $B_{\theta \phi}$ the system is dominated by single vortex pinning and changes to smaller bundle pinning when $B > B_{\theta \phi}$. When $B > B_{\theta \phi}$, this region in the vortex solid area is dominated by thermal fluctuations.

The authors would like to thank the Australian Research Council for financial support.