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Transport properties of multilayered MgB$_2$/Mg$_2$Si superconducting thin film

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Electronic transport measurements have been carried out on superconducting MgB$_2$/Mg$_2$Si multilayer film, using a standard four-probe method in perpendicular and parallel applied fields. The film, which was prepared by pulsed-laser deposition, has a layered structure with each MgB$_2$ layer being 40–50 nm thick and the Mg$_2$Si interlayers about 5 nm thick. The flux flow activation energy is deduced from the resistivity-temperature curves using an Arrhenius fit. The results show a clearly enhanced anisotropy of the vortex activation energy in the multilayered film. The irreversibility field and the vortex activation energy are significantly increased in parallel fields. © 2006 American Institute of Physics.

Inherent or artificially introduced layered structure is an interesting topic for superconductors. There have been a number of experimental reports on multilayered low temperature superconductors$^{1-4}$ and high temperature superconductors (HTS$^s$).$^{5-8}$ A layered superconductor usually shows different behaviors from that of the bulk, such as the crossover from three dimensional to two dimensional upper critical field ($H_{c2}$) behavior,$^{9,10}$ the scaling effect in the angular dependence of critical current density ($J_{c}$),$^{11}$ and enhanced anisotropy in the vortex pinning energy. $^{12}$ These phenomena can be a good tool in revealing the pinning mechanism and superconducting parameters for the superconductors.

Lawrence and Doniach have proposed a weak Josephson coupling model for superconductor/insulator superlattices.$^{13}$ The model was then extensively studied by Klemm et al.$^{14}$ and extended into superconductor/normal conductor superlattices by Takahashi and Tachiki.$^{15}$ The model explains successfully the temperature dependence of the upper critical field of the superconducting superlattices and intrinsically layered HTS$^s$.

The moderate temperature superconductor MgB$_2$ has a layered structure and two separate superconducting gaps.$^{14,15}$ The Ginzburg-Landau (GL) coherence length $\xi(0)$ is about 10 nm within the $a$-$b$ plane and 5 nm along the $c$ axis for MgB$_2$. $^{16}$ Because the coupling between the B layers in MgB$_2$ ($\epsilon=0.352$ nm) is strong, the superconductor does not display the intrinsic two dimensional pancake vortices that have been observed in HTS$^s$. $^{17}$

Mg$_2$Si is a very stable semiconductor and can be easily formed from Mg+Si at a temperature as low as 200° C. By sequentially switching the MgB$_2$ and Si targets during an off-axis pulsed laser deposition (PLD) process, we have successfully obtained a MgB$_2$/Mg$_2$Si multilayer structure in the thin film with an undamaged $T_c$. In this paper we report transport measurements on the MgB$_2$/Mg$_2$Si multilayer film using a standard four-probe method.

In the PLD process, a stoichiometric MgB$_2$ target (84% density), a Si target, and a magnesium target were set on a carousel in the chamber. The laser beam was generated by an excimer laser system (Lambda-Physik) operating on KrF gas ($\lambda=248$ nm, 25 ns). The chamber was first evacuated to a base vacuum of about $8\times10^{-8}$ Torr and then filled with high purity argon to 120 mTorr as the background gas. Before the deposition, the heater was kept at 250 °C. Sapphire c-cut substrates with dimensions of about $6\times2$ mm$^2$ were used. With an off-axis geometry, the substrate is parallel to the normal axis of the target surface and aligned to the center of the laser spot. The substrate is mounted onto the edge of the heater with silver paste. We switched the MgB$_2$ and Si targets ten times during the deposition. At the end of the deposition, the Mg target was switched to the deposition position to form a protective Mg cap layer. Then the Ar pressure was increased to 760 Torr before the in situ annealing. The films were heated to 650 °C in 12 min and kept at that temperature for 1 min. For comparison, monolayer MgB$_2$ films were prepared under the same conditions and are referred to as Mg$_2$B film in the following text. The resulting films have a thickness of 400–500 nm, as detected by atomic force microscopy (AFM) and transmission electron microscopy (TEM). The TEM works were done on a JEM-200 (JEOL) working at 200 kV. The cross-sectional TEM specimen was prepared with a focused ion beam using a Ga source.

The transport measurements were carried out using a four-probe method with a dc current density of 10 A/cm$^2$. In both the $H//ab$-plane (parallel field) and $H//ab$-plane (perpendicular field) cases, the testing current was perpendicular to the applied field.

Figure 1 is a cross-sectional scanning electron micros-
copy (SEM) image of the Si-added MgB$_2$ film. It shows a multilayer structure within the film. A TEM bright field (BF) image is shown in the inset of Fig. 1, illustrating that the MgB$_2$ layers are 40–50 nm thick and the interlayers are about 5 nm thick. Each MgB$_2$ layer consists of very fine grains. Individual grains are less than 20 nm in size. The 5 nm thick interlayers between the ten MgB$_2$ layers are Mg$_2$Si, judging from the electron diffraction and x-ray energy dispersive spectroscopy (EDS) results. The existence of Mg$_2$Si is in accordance with previous reports on Si addition in the Mg-B system.$^{19,20}$ The zero resistivity $T_c$ of the multilayer film is 31 K, slightly suppressed by ~1.5 K compared with the MgB$_2$ film. The transition widths from 10% $\rho(40 \text{ K})$ to 90% $\rho(40 \text{ K})$ for both films are the same, about 0.5 K in zero field. The narrow transition width of the multilayered film indicates that the MgB$_2$ phase remains homogeneous after the addition of Mg$_2$Si interlayers.

Figure 2 shows the field dependence of the resistivity-temperature curves of the multilayer film in parallel and perpendicular applied field circumstances. The $T_c$'s are not shifted to lower temperatures as much in the parallel field condition, as with the perpendicular field condition. The $T_c$ transition width is also narrower in parallel applied fields, indicating better pinning in the fields.

The irreversibility fields of the multilayer film and the MgB$_2$ film were derived from the transport curves using the 10% $\rho(T)$ values and are shown in Fig. 3. The irreversibility field $H_{irr}^{ab}$ for the multilayer film is almost identical to the $H_{irr}^{ab}$ and $H_{irr}^{c}$ of the MgB$_2$ film, showing the same level of flux pinning in the three circumstances. However, the $H_{irr}^{ab}$ of the multilayer film has clearly increased, indicating a significant enhancement of pinning in parallel fields.

Although the activation energy of the thermally assisted flux flow (TAFF) for MgB$_2$ is significantly higher than that of HTS, TAFF is still detectable through the resistivity-temperature curves for different applied fields.$^{21,22}$ The activation energy $U_0$ of our MgB$_2$ and multilayer films is estimated from the Arrhenius law,$^{22,24}$$\rho = \rho_0 \exp(-U_0/k_B T)$, where $\rho_0$ is a field-independent preexponential factor and $k_B$ is Boltzmann's constant. The Arrhenius plots of resistance

![FIG. 1. Cross-sectional SEM image of the multilayer film. The inset is a TEM BF image of the multilayer film.](image1)

![FIG. 2. Resistivity vs temperature curves of multilayer film in parallel and perpendicular fields. (a) In perpendicular fields and (b) in parallel fields.](image2)

![FIG. 3. The irreversibility fields of the multilayer film and the MgB$_2$ film.](image3)
The coupling of vortices across the Mg$_2$Si layer is relatively decreased in perpendicular fields compared with the MgB$_2$ film, which may imply an easier TAF due to the vortex decoupling across the nonsuperconducting interlayer.

The thickness of the nonsuperconducting Mg$_2$Si interlayer is explained within GL theory for layered superconductors. The depression of anisotropy in film is 0.6–0.7 eV in the low field regime for both perpendicular and parallel fields. The depression of anisotropy in film is 0.6–0.7 eV in the low field regime for both perpendicular and parallel fields. The depression of anisotropy in film is 0.6–0.7 eV in the low field regime for both perpendicular and parallel fields.

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The introduced anisotropy of MgB$_2$ /Mg$_2$Si thin films. Much better pinning is observed in parallel fields, judging from the $p(T,H)$ curves. The activation energy of the MgB$_2$ is also observed in our MgB$_2$ films.

To conclude, strong differences in transport properties are introduced by artificially introduced multilayer structure in MgB$_2$/Mg$_2$Si thin films. Much better pinning is observed in parallel fields, judging from the $p(T,H)$ curves. The activation energy of the MgB$_2$ is also observed in our MgB$_2$ films.

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