2007

Josephson-vortex flow resistance in Bi2Sr2Ca2Cu3Oy single crystals and its possible application in the manipulation of spin and charge textures in diluted magnetic semiconductors

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

C T Lin
Max-Planck-Institut für Festkörperforschung, Germany

B Liang
Max-Planck-Institut für Festkörperforschung, Germany

S Yu
National Institute for Materials Science, Japan

S Ooi
National Institute for Materials Science, Japan

See next page for additional authors

Josephson-vortex flow resistance in Bi2Sr2Ca2Cu3Oy single crystals and its possible application in the manipulation of spin and charge textures in diluted magnetic semiconductors

Abstract

In this work, the flow of the Josephson vortices (JVs) has been studied for the highly anisotropic $Bi_2Sr_2Ca_2Cu_3O_y$ (Bi2223) single crystals. A giant flow of JVs or giant positive magnetoresistance (MR) of over 500%-2000% was obtained in fields of 0.1-5 T and remained almost constant over a wide temperature range from 110 down to 4 K, in contrast to superconducting vortices (SVs), which only produced MR in the vicinity of T_c. The flow of the JVs is expected to be much faster than that of SVs. It is proposed that the Josephson vortices could be used to manipulate the spin and charge in magnetic semiconductors in the same way as SVs [M. Berciu, T. G. Rappoport, and B. Jank, Nature (London) 435, 71 (2005)]. Hybrid systems consisting of layered superconductors with Josephson junctions and magnetic semiconductors will be discussed.

Keywords

Josephson, vortex, flow, resistance, Bi2Sr2Ca2Cu3Oy, single, crystals, its, possible, application, manipulation, spin, charge, textures, diluted, magnetic, semiconductors

Disciplines

Engineering | Physical Sciences and Mathematics

Publication Details

Wang, X, Lin, CT, Liang, B, Yu, S, Ooi, S, Hirata, K, Ding, S, Shi, D, Dou, SX, Lin, ZW & Zhu, JG (2007), Josephson-vortex flow resistance in Bi2Sr2Ca2Cu3Oy single crystals and its possible application in the manipulation of spin and charge textures in diluted magnetic semiconductors, Journal of Applied Physics, 101 (9, Part 2), pp. 09G116-1-09G116-3.

Authors

Xiaolin Wang, C T Lin, B Liang, S Yu, S Ooi, K Hirata, S Y Ding, Dongqi Shi, S X. Dou, Zhi W. Lin, and Jian G. Zhu

JOURNAL OF APPLIED PHYSICS **101**, 09G116 (2007)

Josephson-vortex flow resistance in $Bi_2Sr_2Ca_2Cu_3O_y$ single crystals and its possible application in the manipulation of spin and charge textures in diluted magnetic semiconductors

X. L. Wang[a)]
Spintronic and Electronic Materials Group, Institute for Superconducting and Electronic Materials, University of Wollongong, New South Wales, 2522 Australia

C. T. Lin and B. Liang
Max-Planck-Institut für Festkörperforschung, Heisenbergstrasse 1, D-70569 Stuttgart, Germany

S. Yu, S. Ooi, and K. Hirata
National Institute for Materials Science, 1–2–1 Sengen Tsukuba, Ibaraki 305–0047, Japan

S. Y. Ding, D. Q. Shi, and S. X. Dou
Institute for Superconducting and Electronic Materials, University of Wollongong, New South Wales, 2522 Australia

Z. W. Lin and J. G. Zhu
Faculty of Engineering, University of Technology, Sydney, New South Wales, 2007 Australia

(Presented on 10 January 2007; received 30 October 2006; accepted 23 January 2007; published online 7 May 2007)

In this work, the flow of the Josephson vortices (JVs) has been studied for the highly anisotropic $Bi_2Sr_2Ca_2Cu_3O_y$ (Bi2223) single crystals. A giant flow of JVs or giant positive magnetoresistance (MR) of over 500%–2000% was obtained in fields of 0.1–5 T and remained almost constant over a wide temperature range from 110 down to 4 K, in contrast to superconducting vortices (SVs), which only produced MR in the vicinity of T_c. The flow of the JVs is expected to be much faster than that of SVs. It is proposed that the Josephson vortices could be used to manipulate the spin and charge in magnetic semiconductors in the same way as SVs [M. Berciu, T. G. Rappoport, and B. Jankó, Nature (London) **435**, 71 (2005)]. Hybrid systems consisting of layered superconductors with Josephson junctions and magnetic semiconductors will be discussed. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2714304]

Applications to spintronics are based on the use of electron spin or both electron spin and charge to store, manipulate, and carry information. The major challenge for spintronics is how to effectively control and manipulate both spin and charge. Electron spin can be manipulated by magnetic field, polarized light, and electric current. It has been proposed very recently by Berciu *et al.*[1] that the spin and charge in diluted magnetic semiconductors (DMSs) can be simply manipulated using superconducting (Abricosov) vortices (SVs). A hybrid superconductor and diluted magnetic semiconductor bilayer structure has been proposed.[1] The inhomogeneous magnetic field of SVs creates a large enough field variation on small length scales and induces localization of charge carriers and spin textures in the DMS.[2] The charge and spin textures remain attached to a moving vortex. Thus, the vortex acts as spin and charge tweezers. Control of the vortex's locations and dynamics is translated into controlled manipulation of the spin and charge textures in the DMS.[1] In layered superconductors, such as $Bi_2Sr_2Ca_{n-1}Cu_n$ [Bi-22$(n-1)n$, $n=2,3$] (BiSCCO), alternately stacked superconducting CuO_2 layers and BiO_2 insulating layers naturally form atomic-scale Josephson junctions along the c axis in their crystal structures.[3] When magnetic fields are applied in parallel with the CuO_2 layers, a Josephson-vortex (JV) core will be located at the insulating layer. An applied current along the c axis exerts a Lorentz force on the JVs perpendicular to the c-axis direction. Above a critical current, the JVs start to move, producing a finite voltage. This is the so-called Josephson-vortex flow.[4] We note that the velocity of the JV flow can reach 10^{-3} times that of the speed of light.[5] This would be highly desirable for high speed processing of information if the JVs can be integrated into the spintronic devices. The flow of JVs can be easily controlled by the magnitude of the applied magnetic field and electric current.[6] In this study, we investigate the JV flow resistance in highly anisotropic $Bi_2Sr_2Ca_2Cu_3O_y$ (Bi2223) single crystals under various magnetic fields. We also propose the possibility of using the JV to manipulate the spin and charge textures in diluted magnetic semiconductors in the same way as the SV.

The Bi-2223 crystals used in this study were grown using the traveling solvent floating zone method.[7] A platelet of single crystal was carefully cut into a narrow strip. After forming a four-contact configuration using silver paste, the center of the strip was milled by a focused ion beam (FIB). A schematic illustration of the junction is shown in Fig. 1. The dimensions of the measured sample were $w=8.6$ μm,

a)Author to whom correspondence should be addressed; electronic mail: xiaolin@uow.edu.au

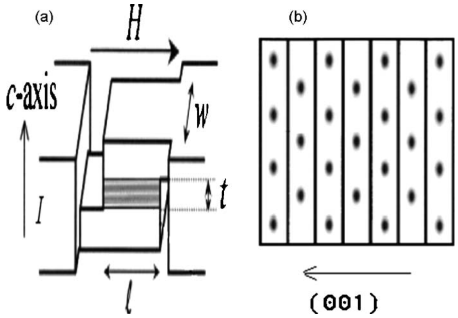

FIG. 1. A schematic illustration of the sample configuration (a). The magnetic field and the current are applied along the l and the c-axis direction, respectively. (b) A schematic drawing of the Josephson vortices viewed along the field direction.

$l=13.6\ \mu$m, and $t=1.2\ \mu$m. The resistance after the fabrication of the junction was $\sim 1000\ \Omega$ at 300 K. Therefore, the measured resistance is almost equal to the c-axis resistance of the junction. The superconducting transition temperature T_c is ~ 100 K. The c-axis resistance and the Josephson-vortex flow resistance were measured using a customized system (MPMS-5S with EDC option, Quantum Design), which was equipped with a vector magnet. A horizontal magnetic field was used to compensate for the misalignment between the *ab* plane and the vertical magnetic field, because it is difficult to align the field parallel to the *ab* plane with only a vertical magnetic field.

Figure 2 shows the temperature dependence of the c-axis resistance for the Bi-2223 sample. Two superconducting transitions are observed at about 100 and 80 K, respectively, while the susceptibility shows a sharp transition at about 103 K, indicating that an intergrowth of Bi-2212 phase coexists in the Bi-2223 sample. The flow of JVs can be observed as a vortex-flow voltage, which is clearly seen in Fig. 2. For zero field, the sample reached zero resistance at around 80 K. However, the sample lost its zero resistance in all the applied magnetic fields over a wide range of temperature from T_c (100 K) down to 5 K. This was caused by a giant flow of JVs on the application of magnetic field. A giant positive magnetoresistance $(\mathrm{MR}=[R(H)-R(0.5\ \mathrm{T})]/R(H=0.5\ \mathrm{T})\times 100\%)$ of over 500%–2000% was obtained (see Fig. 3) in fields of up to 5 T, and this remained almost constant over a wide temperature range

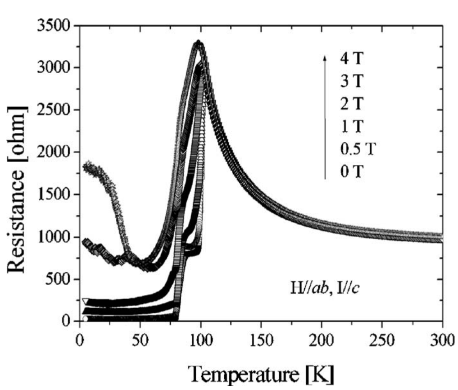

FIG. 2. The temperature dependence of resistance of a Bi2223 single crystal in various magnetic fields.

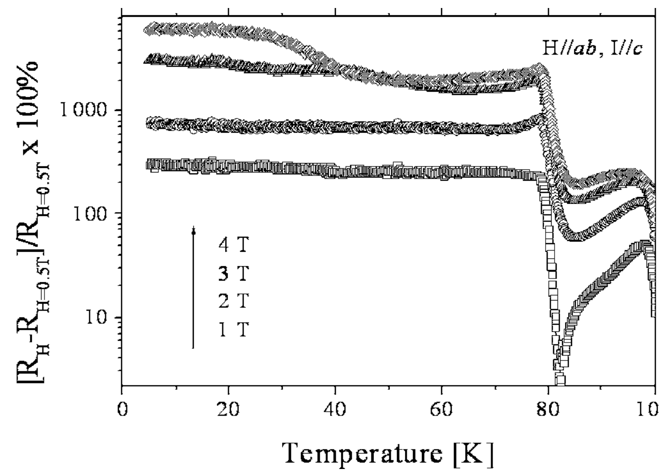

FIG. 3. The temperature dependence of the values of magnetoresistance below 100 K.

from 110 down to 5 K for the low fields. This is in contrast to the flow of SVs, which only produces positive MR in the vicinity of T_c.

The JV flow voltage (V) is equal to $tv_{\mathrm{ff}}B$, where t, v_{ff}, and B express the length of the stacking intrinsic Josephson junction (IJJ) (Fig. 1), the average velocity of the JVs, and the magnetic flux density, respectively. As the pinning in the BiO_2 layer is intrinsically much weaker than that of CuO_2 layers, it is believed that the velocity of JV flow is faster and easier than that of a SV under the same magnetic fields and currents. This is true at least for low temperatures or low fields as the SVs move so slowly, being called flux creep. For example, let $t=10$ nm, $B=10$ G, $V=1\ \mu$V, and $v_{\mathrm{eff}}=10^7$ cm/s from low temperatures up to T_c, in contrast to SVs whose velocity is too low to measure leading to the so-called zero resistance. The mechanism of the giant positive magnetoresistance in the BiSCCO superconductor due to the flux flow of JVs is completely different from what has been seen in the well-known colossal magnetoresistance manganites, whose MR is negative and is controlled by the reduction of electron scattering due to spin polarization under the application of magnetic field. The giant positive MR observed in the Bi-2223 crystal should also be useful as magnetic field sensors,[8] and the JVs could be used to manipulate the spin and charge textures in diluted magnetic semiconductors in a similar way to superconducting vortices, as discussed below.

A schematic configuration of BSCCO single crystal and DMS is shown in Fig. 4. A layer of DMS is arranged on top of the *ac* or *bc* plane of a layered superconductor such as Bi2212 or Bi2223 single crystal with the magnetic field parallel to the *ab* plane of the crystal. Therefore, the magnetic flux lines will penetrate into the crystal and would stay in the BiO_2 insulator layers, forming an assembly of Josephson vortices. In contrast to the superconducting vortex, the JVs do not have a normal core. Also, due to the large anisotropy in the penetration depth along the *ab* and *c* directions, a JV in the BSCCO system is much elongated along the *ab* plane and is narrow along the *c* direction.[4] This would cause a large inhomogeneity in the magnetic field created by the JVs. It is expected that the magnetic field variations would occur

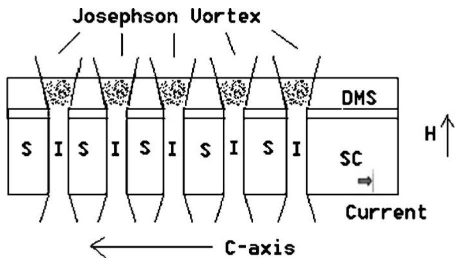

FIG. 4. Sketch of the hybrid consisting of highly anisotropic Bi–Sr–Ca–Cu–O single crystals and a diluted magnetic semiconductor. S and I denote superconducting and insulator layers. The Josephson-vortex core is located in the BiO_2 insulator layers. The spin and charge textures are trapped in the dark area in the DMS. When an electric current is applied perpendicular to the magnetic field, the JVs together with the trapped spin-charge texture will move along the insulator layer one dimensionally.

on small length scales, which is highly possible, at least along the *c* direction, as the penetration depth is as short as a few nanometers, and such a magnetic field will induce the localization of charge carriers in the DMS.[2] The inhomogeneous field imprinted onto the DMS layer would satisfy the conditions required for the spin and charge textures in the DMS.[1] Therefore, both spin and charge textures can be trapped in the high field regions inside the DMS in the same way as what has been predicted for the manipulation of spin and charge textures using superconducting vortices.[1] However, a numerical calculation is very necessary to obtain detailed information about the distributions of magnetic fields and spin and charge textures in a particular oxide DMS.

The flow of SVs is affected by the flux pinning centers, which are usually introduced during sample fabrication. The flux pinning also becomes very strong (high critical current density J_c) when the temperature is reduced. For a high J_c SV, a high velocity of SV is only reached near its T_c or in a very strong magnetic field. Both factors would limit the flow of SVs and, in turn, affect the speed of the manipulation of the spin and charge textures in DMS. In addition, one-dimensional grooves need to be artificially fabricated for the realization of a one-dimensional spin-charge texture shuttle.[1] In contrast, due to the fact that the electric current flowing along the *c* direction in a layered SC is Josephson current, its J_c is very low and extremely sensitive to an applied field. The application of a small field parallel to the *ab* plane or a small current along the *c* direction will lead to a high velocity of JVs, as estimated above.

More importantly, the flow of the JVs is confined in the same BiO_2 insulator layer, and its movement is actually quasi-one-dimensional. This means that the spin and charge textures in the DMS attached to the moving JVs also move in one dimension. The flow of JVs also remains at a high speed over a long length scale, as the pinning from the BiO_2 layer is intrinsically very weak. The flow of the JVs is independent of temperature below T_c up to a particular field as has been illustrated by the temperature independent MR below T_c (Fig. 3). The speed of the flow of the spin and charge textures in the DMS is as fast as that of the JVs, as long as the Doppler shift in the bound state energy is smaller than the binding energy.[1] These are the obvious advantages of using JVs to manipulate spin and charge textures in DMS.

Other applications such as a spin-charge texture pump and texture cell automata, which have been proposed based on the idea of using SVs to manipulate spin and charge textures in DMS, could also be applied to the JVs. The major difference is that the sizes of the JVs in the two-dimensional (2D) layer structured high temperature superconductors (HTS) are much greater in one direction than that of SVs in conventional three-dimensional (3D) superconductors. $YBa_2Cu_3O_7$ (YBCO) and artificial superconducting-insulating superlattices, such as YBCO–PrBCO, are also candidates of JV creators. However, the use of anisotropic SVs in highly conventional 2D low T_c superconductors could be one of the options for reducing the size of the JVs.

As most of the HTS superconductors are oxide materials, this enables us to hybridize HTS with oxide DMSs, as both can be made in an oxygen atmosphere. Centimeter size large single crystals of BSCCO and YBCO are readily available in addition to artificial superconducting-insulating superlattices which can be fabricated by commercially available equipment. There are many oxide DMSs such as transition metal doped ZnO, In_2O_3, Cu_2O, and SnO_2. They could be deposited onto the plane where the JVs emerge with or without oxide buffer layers.

In summary, the flow of JVs has been studied for the highly anisotropic $Bi_2Sr_2Ca_2Cu_3O_y$ (Bi2223) single crystals. A giant flow of JVs or giant positive MR of over 500%–2000% was obtained in fields of 0.1–5 T and remained almost constant over a wide temperature range from 110 down to 4 K. The flow of the JVs is expected to be much faster than that of SVs. It is proposed that the Josephson vortices could be used to manipulate the spin and charge in magnetic semiconductors in the same way as SVs.

This work is supported by the funding from the Australian Research Council under Discovery Grant No. DP0558753. We would like to thank Professor H. Lee, Dr. T. Silver, and Dr. J. Horvat for carefully checking the manuscript and giving us valuable suggestions.

[1]M. Berciu, T. G. Rappoport, and B. Jankó, Nature (London) **435**, 71 (2005).
[2]M. Berciu and B. Jankó, Phys. Rev. Lett. **90**, 246804 (2003).
[3]R. Kleiner, F. Steinmeyer, G. Kunkel, and P. Müller, Phys. Rev. Lett. **68**, 2394 (1992).
[4]J. R. Clem and M. W. Coffey, Phys. Rev. B **42**, 6209 (1990).
[5]M. Tachiki, T. Koyama, and S. Takahashi, Phys. Rev. B **50**, 7065 (1994).
[6]S. Ooi, T. Mochiku, and K. Hirata, Phys. Rev. Lett. **89**, 247002 (2002).
[7]B. Liang, C. T. Lin, P. Shang, and G. Yang, Physica C **383**, 75 (2002).
[8]K. Hirata, S. Ooi, S. Yu, E. H. Sadki, and T. Mochiku, Supercond. Sci. Technol. **17**, S432 (2004).