Spin injection into MgB$_2$

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Abstract.

We report spin injection from nearly 100 % spin-polarized ferromagnet La$_{0.67}$Ca$_{0.33}$MnO$_3$ into hot isostatically pressed MgB$_2$. The injected spin-polarized current suppresses the supercurrent in MgB$_2$ in the proportion of about 100 units of critical current for each unit of the injected current. Such unusually high current gain could pave the way for using MgB$_2$ in spintronics applications. We overcome incompatibility of MgB$_2$ and La$_{0.67}$Ca$_{0.33}$MnO$_3$ by preparing a small-area ab-plane mechanical contact.

Spin injection is a powerful tool in exploring and modifying properties of materials on a quantum mechanical level. For a long time spin injection was considered and attempted as a way to control superconducting properties in thin films and bulk materials. A successful injection has been demonstrated in conventional superconductors (see review [1] and references therein), but this has not been translated [2] into high temperature superconductors (HTS). The reason lies in the mechanism of HTS that employs antiferromagnetic spin fluctuations, which, in turn, are strong scattering centers for spin-polarized electrons [3]. As a result, the injected electrons are depolarized on a sub-micron scale, and the current gain is typically a few percent only [3,4].

MgB$_2$ is one of the last non-explored conventional superconductors with a record high critical temperature of about 40 K. One could expect the gain to be largest when spin-polarized electrons are injected into thin films of thickness comparable to the spin diffusion depth, but MgB$_2$ thin films are incompatible with most spin-polarized materials. For instance, MgB$_2$/La$_{0.67}$Ca$_{0.33}$MnO$_3$ bilayers cannot be grown epitaxially. Also the diffusion of elements from La$_{0.67}$Ca$_{0.33}$MnO$_3$ (LCMO) suppresses the critical temperature of MgB$_2$. We measured several samples of this bilayer prepared in three different batches, but found only a modest suppression of critical current about 50 % above the injected current. In order to overcome the incompatibility of MgB$_2$ and LCMO, we have explored a possibility of direct mechanical contact of ex-situ prepared MgB$_2$ and LCMO. As the MgB$_2$ counterpart we chose hot isostatic pressed (HIP) samples. HIP samples are of nearly single crystal mass density and show very high critical current density, above $10^6$ A·cm$^{-2}$ at low temperatures and zero magnetic field [4]. LCMO is chosen in the form of a thin film prepared by pulsed laser deposition on SrTiO$_3$ substrates with c-axis perpendicular to the surface of the film. The MgB$_2$ surface was freshly polished before placing in contact with LCMO.

A schematic of the c-axis device is shown in Fig. 1. The current is passed from I$_1$ to I$_2$ and the voltage is measured between V$_1$ and V$_2$. Spin-polarized current is injected from one of I$_{inj1}$ and I$_{inj2}$ to one of I$_1$ and I$_2$. The area of the contact is about 1 mm$^2$. In the device, the LCMO film is pressed and fixed permanently in contact with MgB$_2$. Unfortunately, we
found that the \( c \)-axis injection is not efficient and the contacts do not show reproducibility in temperature dependence of resistance (\( R(T) \)). Following a few experiments, we decided to use the configuration shown in Fig. 2. This configuration provides low area (about \( 3 \cdot 10^{-4} \text{ mm}^2 \)) \( ab \)-plane contacts and gives reproducible \( R(T) \).

**Figure 1.** Schematics of the \( c \)-axis spin-injection device. \( I_1 \) and \( I_2 \) are current leads, \( V_1 \) and \( V_2 \) are potential leads and \( I_{\text{inj}1} \) and \( I_{\text{inj}2} \) are injection leads.

**Figure 2.** Schematics of \( ab \)-plane spin-injection device.

Fig. 3 shows the temperature dependence of resistance of an \( ab \)-plane LCMO/MgB\(_2\) contact. \( R(T) \) has been measured passing current between \( I_{\text{inj}1} \) and \( I_1 \), and measuring voltage between \( I_{\text{inj}2} \) and \( I_2 \). This method of measuring contact resistance is very convenient in that it does not involve resistance of electrodes. Three merged \( R(T) \) curves are shown in Fig. 3. One of the curves was recorded straight after the preparation of the contact and two others on the fifth and sixth days, respectively, after thermocycles between 300 and 4.2 K. There is virtually no difference between the curves on the scale of the plot. The arrows in Fig. 3 indicate two important anomalies in the resistance. One is the change in the slope of \( R(T) \) at about 260 K, which is the Curie temperature of LCMO. Another is an unexpected decrease in resistance at about 175 K. The insert in Fig. 3 shows \( R(T) \) in the vicinity of \( R(T) \) maximum. Three different sets of points are well distinguished in the inset and show a small increase in the resistance with time and thermocycling.

Having reproducible \( R(T) \), we extended the experiments to the measurements of current-voltage (IV) characteristics with the injection of current from the LCMO. Fig. 4 shows a set of six IV curves measured at temperature 37.5 K and different injection currents: 1) 0, 2) 0.2, 3) 0.4, 4) 0.6, 5) 0.8 and 6) 1.1 mA, from top to bottom as marked in the right hand side of the plot. IV curves have been measured passing current between \( I_1 \) and \( I_2 \), and measuring voltage between \( V_1 \) and \( V_2 \). Current was injected between \( I_{\text{inj}1} \) and \( I_2 \). One can see that a very small injection current of about 1 mA causes considerable change of IV curves on the scale of 100 mA. In Fig. 5, critical current (\( I_c \)) is plotted as a function of the injection current (\( I_{\text{inj}} \)) for two temperatures: 37.5 K (upper curve) and 38 K (lower curve). \( I_c \) has been derived on the voltage criterion of 1 \( \mu \)V at a distance between potential leads of about 3 mm. The thin straight line between the curves is a line with current gain (\( \Delta I_c /\Delta I_{\text{inj}} \)) equal to 100, where \( \Delta I_c \) and \( \Delta I_{\text{inj}} \) are changes in the critical and injection current, respectively. The current gain given by experimental points is very high, about 100, and it is increasing with the decrease of temperature. The increase of the gain at lower temperatures is a general property of non-equilibrium superconductivity and is frequently used to distinguish the effect of injection from the current summation or instrumental effects in injection devices [2]. The temperature behaviour does not allow, however, to distinguish between spin and heat suppression of superconductivity, because the heat suppression is also
a non-equilibrium phenomenon and its effectiveness increases at lower temperatures. The only reliable way to prove the spin-polarized nature of the injection is to change the polarization of the magnetic material at constant temperature and constant current and to examine how this change is affecting $I_c$.

**Figure 3.** Temperature dependence of resistance of an LCMO/MgB$_2$ $ab$-plane contact. Inset shows the sets of data near the maximum in $R(T)$. The data has been recorded in first, fifth and sixth days after the preparation, from bottom to top.

**Figure 4.** Current-voltage characteristics of MgB$_2$ at 37.5 K with and without injection of current from LCMO. The injecting current (curves marked 1 to 6, from top to bottom) is: 1) 0, 2) 0.2, 3) 0.4, 4) 0.6, 5) 0.8 and 6) 1.1 mA.

**Figure 5.** Critical current of MgB$_2$ as a function of the injection current for two temperatures: 37.5 K (upper curve) and 38.0 K (bottom curve). The thin straight line in-between shows a gradient of critical current with the current gain equal to 100.

**Figure 6.** Field dependence of voltage in MgB$_2$ at a temperature of 35.0 K and a constant transport and injected current through the sample. Thin line shows magnetization loop of LCMO.

The polarization of a magnetic material can be changed by a magnetic field. Fig. 6 shows a
hysteresis loop of LCMO with the corresponding scale of the magnetic moment on the right hand side of the plot. In the positive magnetic field of about 800 Oe all spins of LCMO conductive electrons are directed along the field. In the field equal to minus 800 Oe LCMO is also totally polarized, but with the spins in the opposite direction. In-between there are coexisting magnetic domains with differently polarized spins. On average, spins are depolarized in the coercive field, where the magnetic moment of the LCMO is equal to zero. For LCMO at low temperatures this field is about 200 Oe. The magnetization loop in Fig. 6 reflects the growth and disappearance of domains and is highly hysteretic. If the magnetic field is increased to saturation, decreased to zero and then increased once more, not changing the direction of the field, the sample remains in the same state of polarization with only a minor influence of the state of superconductor. In contrast, crossing the coercive field leads to depolarization of the magnetic material.

If the origin of the suppression in superconductivity in Figs. 4,5 is in the spin polarization, one could expect a higher critical current in the coercive field. Alternatively, when in the resistive state, one could expect a smaller voltage at a fixed current through the sample. To check this, we stabilized the temperature at 35 K, polarized LCMO at -800 Oe, then reduced the field to zero and started recording the field dependence of voltage (V(H)) measuring V between V₁ and V₂, injecting 290 µA from LCMO and passing a constant transport current of about 200 mA between I₁ and I₂. For the V(H) shown in Fig. 6 we changed the magnetic field from zero to 800 Oe, then from 800 to -800 Oe and back to zero. This resulted in a butterfly-like change of the voltage with minima at the coercive field. When in the totally polarized state, V(H) is linear. Depolarization causes a decrease in the voltage at the coercive field, which is the signature of the increase in the critical current. The V(H) behavior is hysteretic. For example, when after the described cycle, still being polarized by a negative field, H was reduced to -800 Oe, V(H) followed a linear dependence as is shown in Fig. 6 by the line with the double row of small arrows. The minimum did not appear because LCMO was not depolarized. V(H) in Fig. 6 gives very strong evidence that the origin of the suppression in superconductivity is in the spin-polarized nature of electrons injected from LCMO.

We need to emphasize that the amplitude of the change in V due to the change in polarization shown in Fig. 6 is much larger than is usually observed in high temperature superconductors [3], which indicates the unusual strength of the effect in MgB₂. Still we believe that not all the suppression of I_c is caused by spin-polarized electrons. The reported current gain of about 100 is probably the largest gain reported so far in any system involving spin polarized electrons. It is surprising to have such a large gain on injection into a polycrystal, although of very high quality. We must mention that MgB₂ with a very high density of critical current has a tendency to the development of thermomagnetic instabilities [2] caused by overheating of the sample. Because of that, we cannot exclude the possibility that suppression of I_c starts from the effect of the injection of spin-polarized electrons, but takes strength due to accumulation of heat. To clarify this, we could suggest short time pulse measurements and also injection into single crystals, possibly using anscanning tunnelling microscope with spin-polarized tip.

In conclusion, we report on spin injection into MgB₂ with a high current gain of about 100. Evidence is given that suppression of superconductivity is due to the spin-polarized nature of electrons. The effect could be used in a range of superconducting microelectronic devices including transistors, spin valves and spin based memory units.

References
[1] Johnson M 2001 Journ. of Supercond. 14 273
[2] Gim Y, Kliensasser A W and Barner J B 2001 J. Appl. Phys. 90 4063
[3] Mikheenko P, Chakalova R and Muirhead C M 2005 Phys. Rev. B 71 184517
[4] Mikheenko P, Chakalov R and Colclough M S 2004 Supercond. Sci. Technol. 17 S511
[5] Shields T C, Kawano K, Holdom D and Abell J S 2002 Supercond. Sci. Technol. 15 202