Strong increase in critical field and current in magnet-superconductor hybrids

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Superconducting properties of 60 nm thick lead bismuth ($Pb_{82}Bi_{18}$) films in a spatially varying magnetic field created by a hybrid structure of soft magnetic (25 μm wide iron) and nonmagnetic (250 μm wide brass) layers perpendicular to the superconducting film surface are reported. The applied homogeneous external magnetic field is redistributed in the superconducting film due to the high magnetic permeability of iron. This results in alternating parallel stripes of regions of low and high magnetic field. Thus the values of second critical field H_{C2} and critical current density are also much higher for current parallel to the magnetic stripes than in a control superconducting film without any magnetic field modulation. For the current perpendicular to the magnetic stripes, the superconductor behaves like an inhomogeneous resistor with regions of low and higher T_C in series. Thus, the critical current I_C for the perpendicular case is much less than either the control film or the case for current parallel to the magnetic sheets. These results demonstrate that it is possible to strongly increase I_C and H_{C2} by simple redirection of magnetic flux with a soft magnetic microstructure. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3076517]

I. INTRODUCTION

Several hybrid magnet-superconductor systems have been studied in the past dozen years both experimentally and theoretically (see reviews[1–3] and references therein). Practically all studies were focused on weak (millitesla) magnetic fields from arrays of pancakelike magnetic dots[1,3] or from a network of domain walls in the underlying magnetic film or crystal (see recent works[4–6] and Refs. 1 and 5). With probably a single exception[6] magnetic fields from domain wall networks are also in the millitesla range.[1,5] The typical scale of magnetic field inhomogeneity in all these works on magnet-superconductor hybrids is in the micrometer range. Typical for most magnet-superconductor hybrids studied, the second critical field H_{C2} is shifted in the 1–10 mT range with respect to a control superconducting system.[1–3,5] The critical current changes more strongly.[1–3,5] Arrays of magnetic dots provide a two-dimensional modulation of the magnetic field. Locally domain walls can be parallel with reasonable accuracy. However, on the scale of tens of microns they are randomly oriented. Thus, it is very interesting to study the phase diagram and critical current I_C in a one-dimensionally periodic magnetic field. A much stronger influence is expected on superconductivity for this case than from those produced by arrays of magnetic dots or irregular domain wall networks.

In this study an array of linear magnetically soft iron layers is used to redistribute the magnetic field, as shown in Fig. 1. Lyuksyutov and Naugle[7–9] previously predicted vortex pinning enhancement by magnetic defects in magnet-superconductor hybrids. They also predicted that soft magnetic rods embedded into a superconductor can increase H_{C2}.[9] In this paper, experiments for the extreme case when an inhomogeneous magnetic field pins vortices are discussed. A homogeneous magnetic field cannot pin vortices; however, an inhomogeneous external magnetic field creates barriers for vortex motion. The study of this phenomenon can be of great importance for understanding vortex matter in superconductors and for practical applications. In this work there is a very large period variation in the magnetic field. Nevertheless, with field variations on the scale of tens of microns, the effect of an inhomogeneous field on both H_{C2} and pinning is already strong. Previously an anisotropy was produced in a superconducting film placed atop an array of nickel stripes with inplane magnetization.[10] Strong anisotropy of I_C was found. However, the role of mechanical modulation of the film due to the underlying nickel stripes is not clear. Thus it is difficult to identify the main source of anisotropy in that experiment.

II. EXPERIMENT

Alternating sheets of 25 μm Fe and 250 μm brass shims were silver soldered to fabricate a laminate magnetic

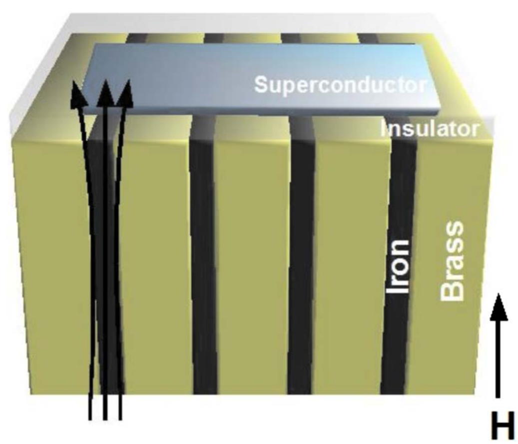

FIG. 1. (Color online) Schematic design of the magnet-superconductor hybrid system and sketch of the magnetic field distribution.

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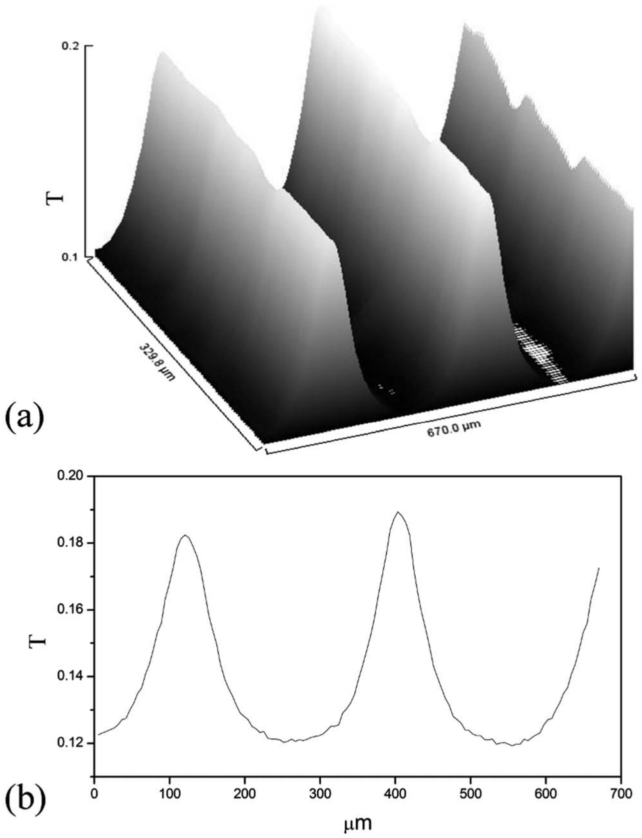

FIG. 2. (a) Normal component of magnetic field about 10 μm above Fe-brass laminate measured with SHPM. (b) SHPM line scan perpendicular to the magnetic field stripes in (a).

structure. The laminate Fe-brass structure was cut perpendicular to the sheets and polished to form substrates. A 5 μm thick photoresist, SU-8 2005, was spin coated at 3000 rpm onto the substrate and exposed to UV light to form an insulating barrier. Superconducting thin films of 60 nm thick were deposited on this barrier in parallel and perpendicular orientations to the stripes at 77 K by thermal evaporation using a shadow mask. A control sample was deposited on an equivalent nonmagnetic substrate.

A Nanomagnetics Instruments scanning Hall probe microscope (SHPM) was used to image the perpendicular component of the surface magnetic field distribution [shown in Fig. 2(a)]. The sample was scanned at room temperature on a motorized X-Y stage at a height of approximately 5 μm above the film. During the scan the sample was mounted on a permanent rare-earth magnet to keep it magnetized. This image illustrates the redistribution of the magnetic field by the magnetic sheets. The permanent magnet is used to apply a uniform field of about 0.15 T. Figure 2(b) shows a SHPM line scan taken perpendicular to the magnetic field stripes. Samples were later field cooled to 10 K in a 1 T applied field. The applied field was then removed, and resistance versus temperature $R(T)$ data were collected using a standard four-point method in a Quantum Design physical property measurement system at various fields up to 1.4 T. $H_{C2}(T)$ of the three samples at different applied field values was determined by extrapolating the steepest part of the $R(T)$ curve to the residual resistance value [$\approx R(8\ \text{K})$ with $H=0$]. Typical normalized resistance curves for the current parallel and perpendicular to the magnetic sheets and the control sample are shown in Fig. 3 for different values of the magnetic field ($\mu_0 H=0,0.1,0.3,0.5$ T). Figure 4 shows $\mu_0 H_{C2}(T)$ for current parallel and perpendicular to the magnetic stripes and for the control sample. The sample with current perpendicular to the magnetic stripes exhibits parts with quite different $T_C(H)$ that are effectively in series so that defining J_C is complicated and somewhat meaningless for that sample. This also gives an anomalous extra broadening of $R(T)$ in a magnetic field which makes $H_{C2}(T)$ less reliable for that case. Often the midpoint of the $R(T)$ curve or the extrapolation of the steepest part to $R=0$ is choosen to determine $H_{C2}(T)$ for inhomogeneous thin films. Athough the slopes of $H_{C2}(T)$ change with these choices, the relative behavior is not qualitatively different from that shown in Fig. 3.

The critical current I_C was determined by measuring I-V curves at various temperature and applied field values. The criterion for the I_C was chosen to be the current value at

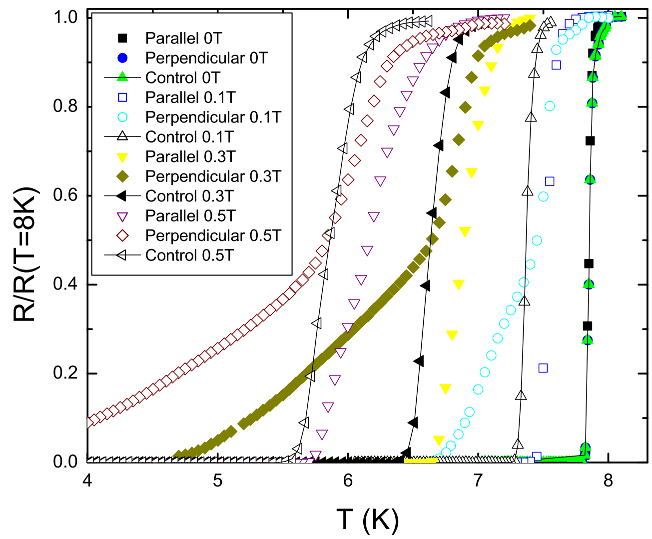

FIG. 3. (Color online) Normalized resistance curves $R(T)/R(8\ \text{K})$ for the current parallel and perpendicular to the magnetic stripes and for the control sample for $\mu_0 H=0$, 0.1, 0.3, and 0.5 T.

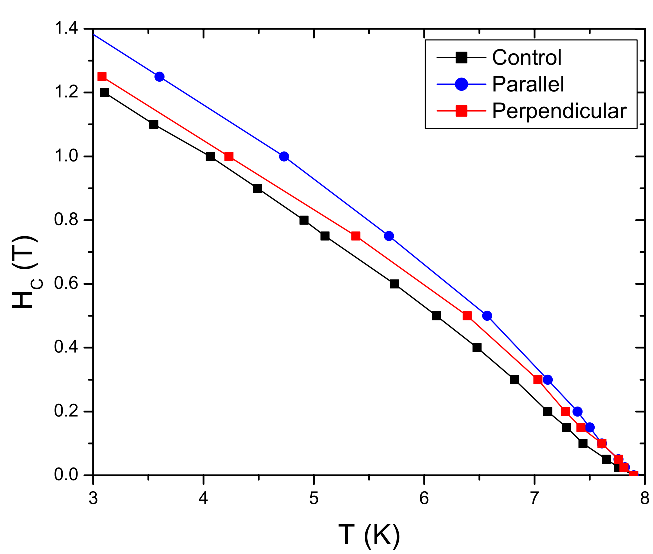

FIG. 4. (Color online) $\mu_0 H_{C2}(T)$ for the current parallel and perpendicular to the stripes and for the control film.

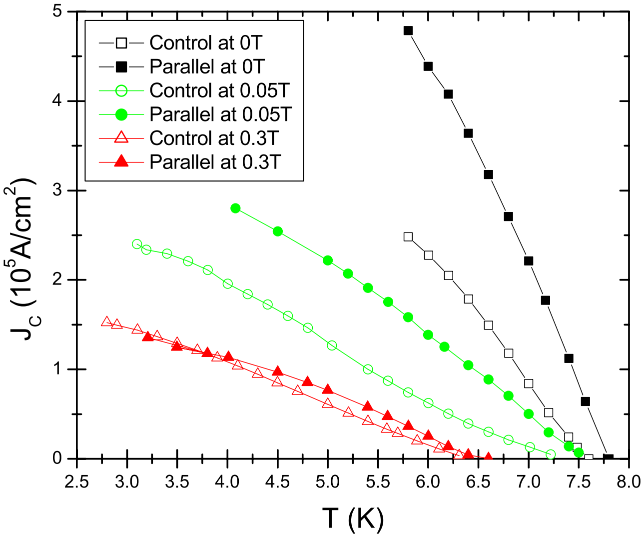

FIG. 5. (Color online) Average critical current density J_C for current parallel to the stripes and for the control sample for ($\mu_0 H=0,0.05,0.3$ T).

which the voltage drop across the sample reached 2 μV. The highest I_C value measured corresponds to only about 20 $\mu\Omega$, while for the lowest value it corresponds to about a milliohms, as opposed to the 10 Ω residual resistance value when the sample was in the normal state.

III. RESULTS AND DISCUSSION

The magnetic field distribution normal to the superconducting film has been measured by scanning Hall probe microscopy, as described in Sec. II [Figs. 2(a) and 2(b)]. The amplitude of magnetic field variation measured is smaller than that actually present on the surface of the film due to the decay of the field strength with distance from the surface (see, e.g., Ref. 11). These scans are taken at room temperature about 10 μm above Fe-brass laminate or, equivalently, 5 μm above $Pb_{82}Bi_{18}$ film.

The high amplitude periodic field variation in the surface of the superconducting film means that different values of the H_{C2} and critical current I_C for current directions parallel and perpendicular to the magnetic stripes and the control film are expected. Indeed, the resulting magnetic field at the superconducting film above the brass stripe is lower than the applied magnetic field H, and the resulting field at the film above the iron stripe is higher than H. The second effect, which needs to be taken into account, is that the effective field is distributed inhomogeneously across the stripes. Since H_{C2} increases as T decreases, a larger portion of the film over the brass becomes superconducting, while a smaller portion of the film over the iron is driven normal by the field as the temperature is decreased. These two effects can explain the differences between the measured H_{C2} for current parallel to the magnetic stripes compared to that of the control film, as shown in Fig. 4. In Fig. 5 the average critical current density J_C (determined as I_C divided by the film cross section) for current parallel to the stripes and the control film. For $H<0.3$ T, J_C is higher above 4 K for the film with current parallel to the magnetic stripes then for the control film. The enhancement in the self-field is orders of magnitude due to a greatly enhanced pinning by the magnetic stripes. Note that in an applied field, the local J_C is very inhomogeneous for the current parallel to the stripes since J_C is enhanced above the brass region and it is reduced above the Fe region by the inhomogeneous field.

Figure 2(b) shows the distribution of the normal component of the field at a distance $d=5$ μm from the superconducting film. The simple analysis presented in Ref. 11 shows that in a very large system the amplitude of the magnetic field variation drops exponentially with the distance from the film with a characteristic decay approximately equal to the period of the structure, i.e., 275 μm. This period is much larger than d. Thus Fig. 2(b) gives an estimate of the magnetic field variation in the superconducting film that is of the order of a few tenths of a tesla. Bulaevskii *et al.*[12] estimated vortex pinning due to the spatial variation in magnetic field due to domains of different polarity in the ferromagnet. Substitution of the magnetization of the ferromagnet with the magnetic field at the superconducting film generated by the magnetized Fe stripes leads to a simple formula for the critical current density $J_C \approx \mu_0^{-1} dB/dx$. dB/dx is estimated to be about 0.1 T over the length of 100 μm from the data in Fig. 2(b). As a result the critical current density is estimated to be about 10^5 A/cm^2, in order of magnitude agreement with the data in Fig. 5. This estimate is valid until vortex-vortex interaction is less than the vortex interaction with inhomogeneous magnetic field.

IV. CONCLUSION

It is demonstrated that an inhomogeneous magnetic field can effectively pin vortices in an otherwise homogeneous superconducting film. The enhancement in $H_{C2}(T)$ for this hybrid magnet-superconductor structure can be reasonably well described in terms of magnetic field redistribution due to the iron laminate.

ACKNOWLEDGMENTS

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