Transport Critical Current in Superconductor/Ferromagnet Trilayered films

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Abstract

We have measured the critical current density, J_c, in rf-sputtered Co/Nb/Co trilayers under magnetic fields parallel to the film surface. Unlike usual low-field dependence of J_c in conventional superconductors, J_c depends on the remanent state of ferromagnetic layer above superconducting temperature and shows an anomalous dip around zero field, associated with the hysteresis. This observation indicates that the critical current density is strongly reduced by in-plane magnetization of ferromagnetic layer in contact with superconducting one.

Key words: critical current; superconductor/ferromagnet heterostructure; flux pinning

Recent progress in fabrication of artificially manufactured materials enables to study the interplay between magnetism and superconductivity in magnetic-superconducting (F/S) heterostructures. In particular, the behavior of critical current density, J_c, under the influence of magnetic order [1,2] is one of currently developing subjects due to possibilities for new superconducting device. For instance, in the regular arrays of magnetic dots covered by a superconducting film under perpendicular field, vortex pinning by magnetic moments produces an enhancement of J_c as well as asymmetric field dependence of J_c depending on the relative alignment between magnetic moments and vortices [3]. On one hand, in F/S layered systems, zero-field behavior of J_c has been extensively investigated in terms of pair breaking effect due to ferromagnetic layer [2,4], however, the influence of magnetic order on the field dependence of J_c was less studied in detail.

In this paper, we report on investigations of field dependence of J_c under the parallel field orientation in Co/Nb/Co trilayerd films, where anomalous reduction in J_c due to the ferromagnetic layer is observed.

For transport critical current measurements, patterned stripes of rf-sputtered Co/Nb/Co trilayers were prepared on Si(111) substrate by standard photolithographic method combined with lift-off technique. The patterned stripes are 20 μm in width and the length between voltage path is 140 μm. The sublayer thickness is $d_{\rm Co} = 500$ Å for Co and $d_{\rm Nb} = 500-1500$ Å for Nb. Both Co and Nb sublayers are polycrystalline with no preferred orientation. The magnetization, taken above superconducting temperature T_c, showed that ferromagnetic Co layer has in-plane anisotorpy with coecivity field of 40 Oe.

The dc transport critical current measurements under magnetic fields parallel to the film surface were performed with conventional four-probe technique. The current was in the direction parallel to the film plane and perpendicular to the external field, yielding maximum Lorentz force on vortices toward the direction perpendicular to surface. The critical current was derived from I−V curve using voltage criterion of 0.5 μV. All the prepared samples exhibited similar behavior, therefore, we will show the representative data of the sample with $d_{\rm Nb} = 1000$ Å and $T_c = 6.2$ K.

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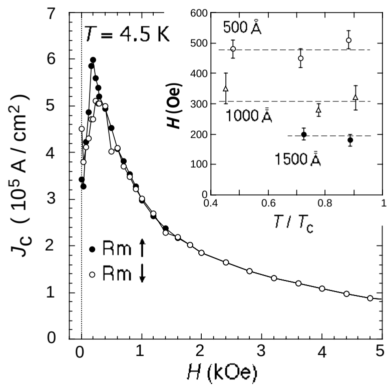

Fig. 1. Magnetic field dependence of J_c at T = 4.5 K of the sample with d_{Nb} = 1000 Å, obtained after ZFC with ferromagnetic layer with positively (solid circles) or negatively (open circles) magnetized remanent state. The inset shows the temperature variation of the low-field peak position for samples with different d_{Nb}.

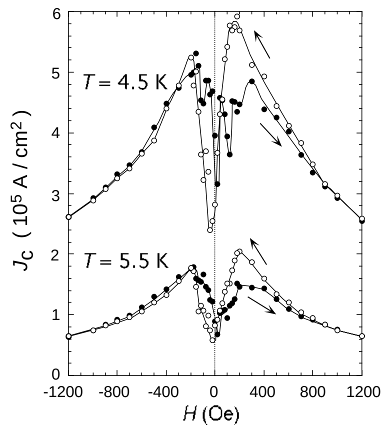

Fig. 2. Hysteresis curve of J_c at T = 4.5 K and 5.5 K of the sample with d_{Nb} = 1000 Å. The solid and open circles show the data, taken on increasing and decreasing fields, respectively.

Fig. 1 shows the field dependence of J_c at $T = 4.5$ K after zero- field cooling (ZFC) with different initial remanent state of ferromagnetic layer; the positively (negatively) magnetized remanent state was obtained by saturating the Co layer at $H = +5$ kOe (-5 kOe) above T_c. With slightly increasing field, for both remanent states, J_c sharply increases and shows a maximum at a low field of $H \sim 200$ Oe, followed by monotonic decrease with field. As is seen in the inset in Fig. 1, the position of the maximum is nearly temperature independent for all the samples investigated. This observation is in contrast with usual behavior of J_c after ZFC in conventional superconductors where J_c has a maximum at zero field and monotonically decreases with field. In addition, we found that J_c at low fields is dependent on the initial remanent state, indicating the pronounced influence of magnetic order on J_c.

Fig. 2 shows the hysteresis curves of J_c, taken at $T =$ 4.5 K and 5.5 K. These curves were obtained by increasing field from -2 kOe to +2 kOe and then decreasing to -2 kOe, after ZFC. We found that low-field maximum of J_c appears at both positive and negative fields, associated with a narrow dip around $\mid H \mid \sim 20$ Oe, and that J_c shows hysteresis in the maximum value and dip position. With decreasing temperature, the maximum grows and the dip becomes pronounced, while the location both of the maximum and dip is weakly temperature dependent.

In present measurements, even at low fields below H_{c1}, the I−V curve was associated with the resistive states due to vortex motion rather than instantaneouos increase of output voltage due to depairing mechanism. Therefore, the low-field variation of J_c can be explained within the context of vortex motion. When the Co layer which is in contact with the superconducting one is fully magnetized, the stray field antiparallel to the Co magnetization will penetrate into superconductor as anti-vortices. Recent analytical work [5] suggested that anti-vortices induced by ferromagnet result in the disppation even in the absence of external field when small current is flowing, and that J_c will have a maximum at non-zero field where the annihilation of anti-vortices by penetrating flux due to external field is complete. Since in our case the Co magnetization and the external field are always parallel in the field range except around zero field, the appearance of maximum of J_c at $H \sim \pm$ 200 Oe can be due to such annihilation effect. Further, this effect is also consistent with the observed hysteresis behavior in the dip position shown in Fig. 2, because the annihilation of anti-vortices is expected to be most ineffective at the field between zero field and coecivity field where the external field becomes antiparallel to the Co magnetization. Note that fine structure in J_c around the dip may reflect complicated domain structure of ferromagnetic layers.

In conclusion, we have investigate the influence of magnetic order on the field dependence of J_c in Co/Nb/Co trilayered films and have shown that J_c at low fields is strongly reduced by ferromagnetic layers with in-plane magnetization.

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