Nucleation of superconductivity in an Al mesoscopic disk with magnetic dot

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We have studied the nucleation of superconductivity in a mesoscopic Al disk with a Co/Pd magnetic dot placed on the top by measuring the normal/superconducting phase boundary $T_c(B)$. The measurements have revealed a pronounced asymmetry in the phase boundary with respect to the direction of the applied magnetic field, indicating an enhancement of the critical field when an applied magnetic field is oriented parallel to the magnetization of the magnetic dot. The theoretical $T_c(B)$ curve is in a good agreement with the experimental data. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1604939]

Superconductivity at the submicrometer scale has been extensively studied over the past decade (e.g., Ref. 1, and references therein). Recently, hybrid mesoscopic ferromagnetic/superconducting systems have attracted a considerable attention, since it is believed that the interaction between ferromagnetism and superconductivity at the mesoscopic scale may lead to a number of physical effects.[2–6] In addition, these structures are considered a prominent candidate for technological applications as they offer a possibility of tuning the field range in which superconductivity nucleates.

A mesoscopic disk in a nonuniform magnetic field, resembling a magnetic dot with the perpendicular magnetization or a current loop, has recently been studied theoretically by using the Ginzburg–Landau equations.[2] We report results on an individual hybrid mesoscopic ferromagnetic/superconducting structure, consisting of an Al disk with a Co/Pd magnetic dot on the top. The magnetic dot has a perpendicular magnetization. The measurements have revealed a pronounced asymmetry in the superconducting $T_c(B)$ phase boundary with respect to the direction of a perpendicular applied magnetic field.

The sample was prepared on a SiO_2 substrate, by electron beam lithography on a PMMA950K and copolymer electron beam resists in three steps. In each step, a desired structure was patterned, the material(materials) evaporated and the final structure obtained in with a lift-off in warm acetone. The thickness of the Al disk is 450 Å, whereas the magnetic dot consists of a 25 Å Pd buffer layer and ten Co/Pd bilayers with the thicknesses 4 and 10 Å, respectively. The magnetic dot is separated from the disk by a layer of Al oxide, which forms nearly instantly on the surface when the structure is exposed to the air.

Figure 1 shows a scanning electron micrograph of the structure. A bright area in the image is the magnetic dot. The radii of the disk and magnetic dot are 1 and 0.5 μm, respectively. The disk has wedge-shaped contacts with the opening angle of 15° since these have proved to be the optimum for transport measurements of mesoscopic superconducting structures.[7–9] The magnetic dot is displaced, approximately by 130 nm, from the center of the disk, despite a painstaking alignment procedure. We believe that, in addition to the limitations of the electron beam writer at our disposal, a minor displacement of the alignment markers may have contributed to the shift of the magnetic dot.

The chosen composition of Co and Pd provides perpendicular magnetization of the magnetic dot, as confirmed by the magneto-optical Kerr measurements of the coevaporated reference film at room temperature, which revealed a full remanence and the coercive field of 350 mT. For a thorough analysis of the properties of patterned Co/Pd structures we refer to Ref. 6. Figure 2 shows the calculated stray field of the magnetic dot $\langle b(r)\rangle$, averaged over the thickness of the superconducting disk for the radius and height of the dot $r_d = 500$ nm and $h_d = 16.5$ nm, respectively. The brighter area in the schematic is the magnetic dot, darker area is the superconducting disk whereas the arrows indicate the field distribution.

Prior to the measurements, the magnetic dot was magnetized perpendicularly in a magnetic field of 450 mT. Superconducting phase boundary $T_c(B)$ was obtained from four-point transport measurements, using an ac current with the rms of 100 nA and frequency 27.7 Hz, in a cryogenic setup with the temperature stability of 0.2 mK. The phase boundary was measured resistively by sweeping magnetic field at a very slow rate at a constant temperature and making use of a lock-in amplifier in order to improve the signal-to-noise ratio.

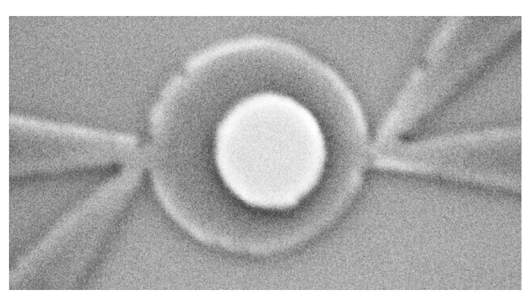

FIG. 1. A scanning electron micrograph of the structure.

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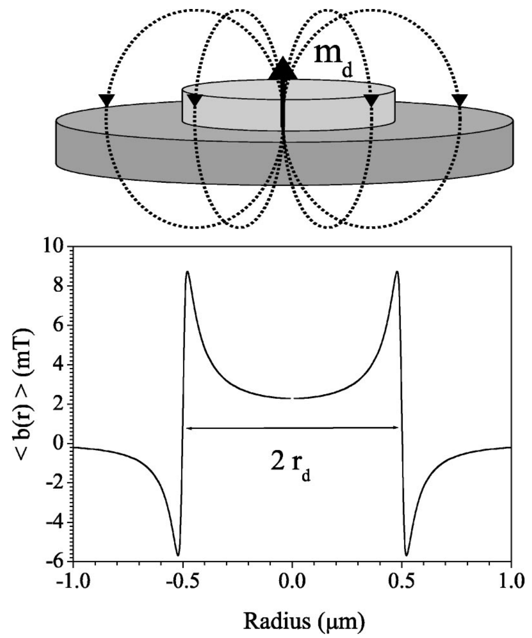

FIG. 2. The calculated stray field of Co/Pd magnetic dot with the radius of $r_d = 500$ nm and height $h_d = 16.5$ nm, averaged over the thickness of the Al disk.

Figure 3 presents the resistance of the structure versus temperature measured in a constant external field. The curve with crosses is the resistive transition in zero applied field, filled curves correspond to the case when the magnetization of the dot and external fields are parallel whereas open curves give the resistive transition for the antiparallel orientation. The values of the applied fields were ± 1, ± 2, and ± 3 mT, respectively. Plus signs indicate parallel and minus signs indicate antiparallel orientation. This convention will be used throughout the letter.

The horizontal line indicates the resistive criterion $R_n/2$ ($R_n = 4\ \Omega$ is the resistance in the normal state) that was used for the determination of the phase boundary. There is a clear asymmetry between the resistive transitions for the same value but different orientation of an applied magnetic field with higher critical temperatures for positive applied fields. Moreover, when the applied magnetic field is 1 mT, the critical temperature is slightly higher than the critical temperature in zero field, which is a clear evidence that for the particular parameters of the disk and magnetic dot, this external magnetic field provides an enhancement of superconductivity in the disk. The enhancement demonstrates that ferromagnetic/superconducting mesoscopic structures make it possible to tune the field range in which superconductivity nucleates.

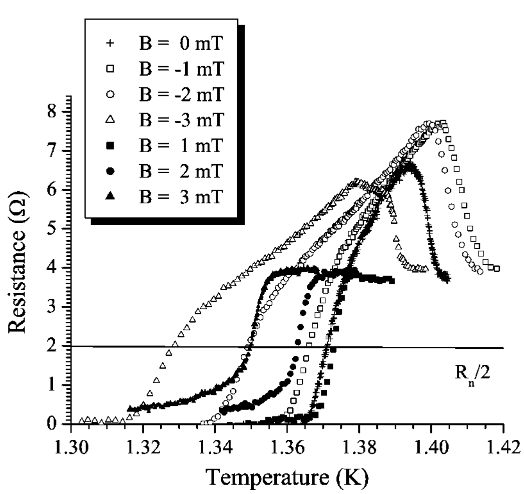

FIG. 3. Resistive transitions $R(T)$ for zero and ± 1, ± 2, and ± 3 mT applied fields. The curve with crosses is the resistive transition in zero field, filled curves are the resistive transitions when an applied field, and the magnetization of the magnetic dot are parallel (positive fields), whereas the open curves indicate resistive transition for antiparallel orientation (negative fields).

Since the magnetic dot generates a finite flux through the disk in zero field, its critical temperature is effectively decreased when compared to the mesoscopic contacts and superconductivity nucleates nonuniformly. As a result, the resistive transition in zero applied field is broad and has a temperature dependent slope. When increasing temperature first the disk becomes normal, and the slope of the transition, now mainly determined by the mesoscopic contacts, changes. When a uniform positive magnetic field is applied the effective magnetic induction in the disk locally increases in the region below the dot, whereas in the rest the disk decreases. For a negative uniform field the situation is just the opposite. Given the intensity of the stray and applied fields, it is clear that the negative applied fields further suppress superconductivity and decrease the critical temperature of the disk thus causing broader transitions. Accordingly, the slope of the transitions changes at a lower temperature as the negative applied field increases. The transitions for the positive applied fields are steep, and more importantly, steeper then the transition in zero field, due to the reduction of the local magnetic induction in the disk around the magnetic dot and, consequently, an increase in its critical temperature. The tails in the transitions are a result of the flux flow.

The transitions for zero and the negative applied fields exhibit a considerable overshoot in the resistance with respect to the resistance in the normal state, nearly 100% for applied fields of -1 and -2 mT. This effect comes about due to the charge imbalance effects at a superconductor/normal metal junction that are caused by a geometrically imposed difference in the critical temperatures of the structure itself and the contacts or a local suppression of superconductivity in the narrowest part of the contacts by a transport current. For the details we refer to Ref. 7. When there is a considerable difference in the critical temperature of the disk and mesoscopic contacts, that is, for zero and negative applied fields, overshoots appear in the resistive transition.

The order parameter is strongly suppressed at the superconductor-normal metal boundary due to the proximity effect.[10] In spite of the oxide layer on the disk, Co/Pd dot suppresses superconductivity inside the disk below the magnetic dot. Therefore, the disk with the magnetic dot may be approximated by a superconducting loop of a finite width. Note that we have also studied experimentally the nucleation of superconductivity in an Al disk with the radius of 800 nm and the same magnetic dot, but were unable to drive the system to the superconducting state. We believe that this is a result of the suppression of the Cooper pair density by the contact with the metal. We have used a simple model assuming that the order parameter is constant within the effective loop, and that the inner radius of the loop equals the radius of

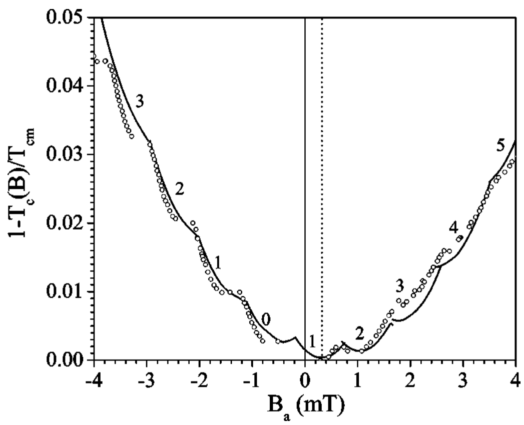

FIG. 4. Superconducting phase boundary $1-T_c(B)/T_{\mathrm{cm}}$ vs the applied field B_a. The open symbols show the experimental phase transition, whereas the solid line presents the theoretical results.

the dot. In the vicinity of the phase boundary, the local field in the loop is equal to the sum of an applied field and the stray field, whereas the modulus of the order parameter is cylindrically symmetric, with the winding number (vorticity) $L=0$ representing the Meissner state, $L=1$ single-vortex state and $L>1$ giant-vortex state.[1]

Figure 4 shows the superconducting phase boundary, displayed as the normalized critical temperature $1-T_c(B)/T_{\mathrm{cm}}$ versus the applied field. $T_{\mathrm{cm}}=1.376$ K is the maximum critical temperature. Open symbols and solid lines correspond to the experimental and theoretical results, respectively. The theoretical data were obtained for the coherence length $\xi(T=0)=76$ nm and the outer loop radius which is 25% bigger than the real radius of the disk. This discrepancy can be accounted for by the influence of the mesoscopic contacts, as well as by the displacement of the magnetic dot from the center of the disk. Even though a simplistic theoretical model has been used, the agreement between the experimental data and theoretical curve is good. The quasiperiodicity of the phase boundary is a result of transitions from the normal state to the phases with different vorticities L. Numbers in Fig. 4 show the values of L. Note that the magnetization of the dot is high enough to create one vortex in the sample even in the absence of an external field. The superconducting phase boundary strongly depends upon the direction of an applied magnetic field, with higher critical fields for the parallel orientation (positive applied fields) in the whole range of investigation.

In conclusion, we have fabricated a mesoscopic superconducting disk made up of Al with a Co/Pd magnetic dot on the top. The superconducting properties of the system have been investigated by measuring the superconducting/normal state phase boundary $T_c(B)$. It has been demonstrated that the critical field is higher when an applied magnetic field and the magnetization of the magnetic dot are parallel. The experimental data are in a good agreement with the theoretical $T_c(B)$ curve.

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