Magnetic-Field-Induced Superconducting State in Zn Nanowires Driven in the Normal State by an Electric Current

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(Received 17 January 2009; revised manuscript received 2 July 2009; published 18 September 2009)

Four-terminal resistance measurements have been carried out on Zn nanowires formed using electron-beam lithography. When driven resistive by current, these wires reenter the superconducting state upon application of small magnetic fields. The data are qualitatively different from those of previous experiments on superconducting nanowires, which revealed either negative magnetoresistance near T_c or high-magnetic-field-enhanced critical currents.

DOI: 10.1103/PhysRevLett.103.127002 PACS numbers: 74.78.Na, 74.40.+k, 74.78.Db, 74.81.Fa

The enhancement of superconductivity by magnetic fields is a counterintuitive phenomenon. The usual scenario is that fields suppress superconductivity by either orbital or spin effects [1]. However, in certain complex compounds, superconductivity can be enhanced either through the compensation of an applied magnetic field by the exchange field of rare-earth magnetic moments (the Jaccarino-Peter effect [2]) or by the suppression of spin fluctuations by an applied field [3]. These processes have been realized in a variety of physical systems [4]. Enhancement by magnetic fields has also been observed in far simpler nanowires, either as a low-field negative magnetoresistance [5,6] or as a relatively high-field enhancement of the critical current [7,8]. Recently, an even more counterintuitive phenomenon called the ''antiproximity effect'' was reported [9]. In contrast with the usual proximity effect, at certain temperatures wires were found to enter the superconducting state from the normal state when the electrodes were driven normal by a magnetic field. The work reported here was motivated by the goal of determining whether the antiproximity effect would manifest itself in wire configurations prepared using lithographic rather than electrochemical techniques and whether the effect could be observed in a four-terminal planar configuration. In pursuing this effort, we found a different but possibly related phenomenon, the reentrance of superconductivity upon the application of *small* magnetic fields to wires driven out of equilibrium and into a resistive state by high externally supplied currents.

Samples as shown in Fig. 1(a) were prepared by electron-beam lithography followed by a quenched deposition of Zn at 77 K. By finishing the writing as well as the deposition of the electrodes and wire in the same step, a totally transparent boundary was obtained between them. The Zn electrodes shown in Fig. 1(a) were 1 μm wide, 1.5 μm apart, and 10 μm long, which eventually join to macrosized Au contacts used for electrical wire bonding. The Zn electrodes were made long to remove any nonequilibrium effects generated at the Au normal metal/Zn superconductor boundaries. The deposition of Zn films for the wires and electrodes was done at rates $\backsim$5 Å/ sec onto SiO_2 substrates held at 77 K. The system pressure was $\backsim 1 \times 10^{-7}$ torr during deposition, and the starting material was of 99.9999% purity. The relatively small size of the Zn grains formed under these conditions ensured continuity of the wires. The fragile nature of the liftoff process for these samples was circumvented by utilizing a bilayer of polymethyl methacrylate as the resist. In order to minimize surface oxidation, the wires were immediately transferred after liftoff into a high vacuum and low temperature environment, a Quantum Design physical properties measurement system (PPMS) equipped with a ^{3}He insert. The linear resistances of the wires $R = \frac{V}{I}$ were measured using a conventional four-probe method. The two outer electrodes shown in Fig. 1(a) supplied current, and the two inner ones were used to measure voltage.

In Fig. 1(b), we show the resistance as a function of temperature $R(T)$ in the absence of an applied magnetic field. In the low current limit, $R(T)$ is conventional, falling to zero at $T_c \sim 0.85$ K with a width of a few tens of mK. As the applied current increased, the onset temperature decreased, and the transition broadened to over several hundreds of mK, developing a shoulderlike structure.

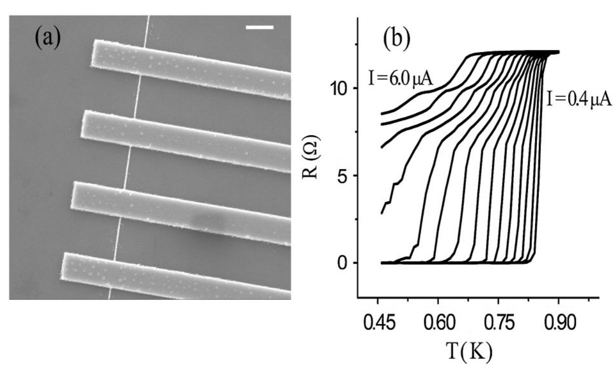

FIG. 1. (a) Scanning electron microscope image of the sample; the white scale bar is 1 μm long. (b) Temperature dependence of the wire resistance, at $H = 0$ Oe, with current ranging from 0.4 to 6 μA, every 0.4 μA.

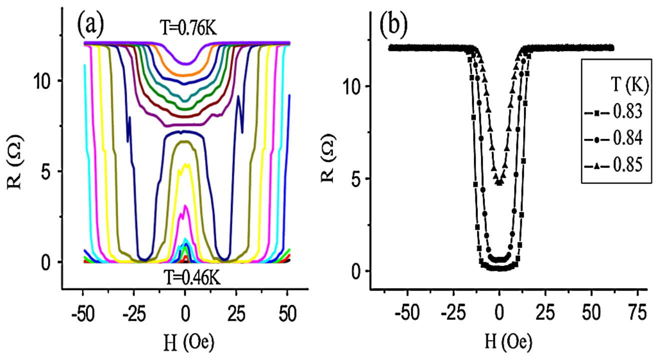

FIG. 2 (color online). (a) Magnetic-field dependence of wire resistance, at $I = 4.4\ \mu$A, with temperatures ranging from 0.46 to 0.76 K, every 0.02 K. (b) Magnetic-field dependence of wire resistance, at $I = 0.4\ \mu$A, with temperatures ranging from 0.83 to 0.85 K, every 0.01 K.

Although it is not clear how the transport mechanism changes when going from above to below the shoulder, the response of the wire resistance to the field is drastically different in these two regimes. As shown in Fig. 2(a), it changes from a conventional positive magnetoresistance to a large negative magnetoresistance when the temperature goes across the shoulder. The most striking observation is that this large negative magnetoresistance even induced the reentrance of superconductivity over a significant range of temperature. With decreasing current, the range of temperature over which this effect is observed shrinks, along with the tail of the resistive transition and the shoulderlike structure. The effect vanishes in the low current limit. In this limit, as shown in Fig. 2(b), only a conventional positive magnetoresistance is observed.

Phase diagrams can be visualized by plotting the data as color maps, as shown in Fig. 3. These permit the identification of three regimes, the normal state (green), the superconducting state (blue) and the transition regime (colors between these two). Increasing the current not only moves the transition regime to lower temperatures but also greatly broadens it [Fig. 3(a)]. An applied magnetic field as shown in Fig. 3(b) generates two effects: It suppresses superconductivity in the wire, in that it decreases the temperatures at which resistance returns to its normal state value (follow the boundary between the normal state and the transition regime). It also enhances superconductivity, in that it increases the threshold temperatures for the zero resistance (follow the boundary between the superconducting state and the transition regime). This enhancement gives rise to a magnetic-field-induced reentrance into the superconducting state at the bottom part of the transition regime, as shown in Fig. 2(a). An enhancement is also found when the transition is tuned by current, as shown in Fig. 3(c). Similarly, an applied magnetic field, up to a certain value, increases the current required for the onset of the resistance while reducing the current at which the normal resistance is attained. This gives rise to

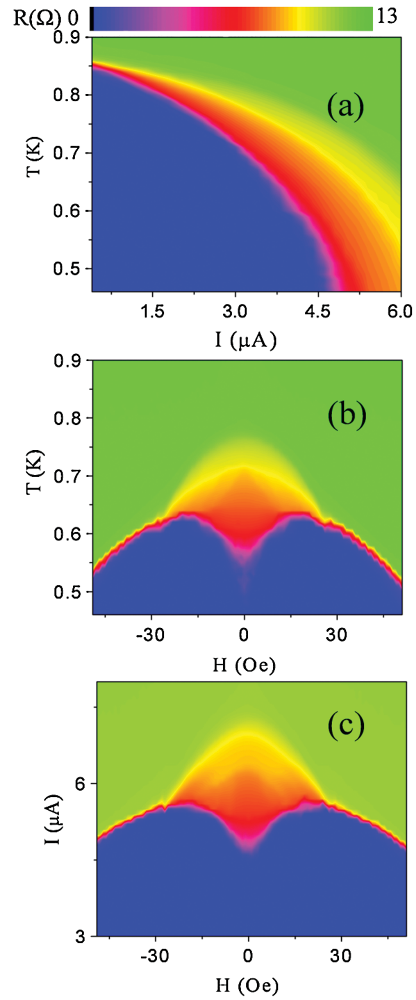

FIG. 3 (color). Color contour plot of the wire resistance as a function of (a) temperature and applied current, at $H = 0$ Oe, (b) temperature and applied magnetic field, at $I = 4.4\ \mu$A, and (c) applied current and magnetic field, at $T = 0.46$ K. (The color scale bar represents the resistance of the wire, where blue corresponds to zero resistance and green to the normal state resistance.)

magnetic-field-enhanced superconductivity over a range of currents. With increasing temperature the range of current leading to an enhancement decreases, and eventually the effect vanishes. This is different from the antiproximity effect, in which the wire abruptly reenters the superconducting state when the magnetic field reaches the critical field of the bulk electrodes [9]. Here the reentrance is a smooth and broad transition from the resistive state. The magnetic field needed is also much weaker than the critical field of the bulk Zn electrodes, and its value is a function of temperature and current.

This magnetic-field enhancement of superconductivity is a robust effect which has been observed in almost all of the samples studied, including some Al wires (not shown) that are currently under investigation. In Fig. 4, the magnetoresistances at 460 mK are demonstrated for four rep-

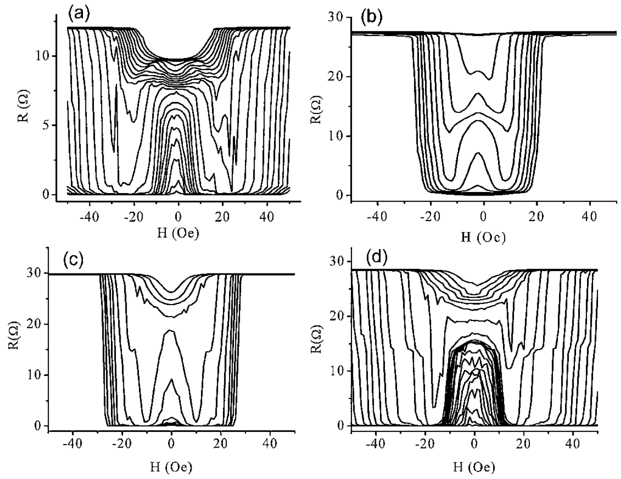

FIG. 4. Magnetoresistances with varying currents at 460 mK for the samples listed in Table I. Note that the current step is 0.1 μA for all of the samples. The lowest currents (bottom) for each sample are (a) 4.5, (b) 3.0, (c) 3.5, and (d) 3.5 μA.

resentative Zn samples, and their key parameters are listed in Table I, including the one we have discussed above (sample a). The widths (w) and thicknesses (t) of the wires were obtained by averaging several measurements. The transition temperatures T_c were taken as the temperatures at which the resistances fell to half the normal value at an applied current of 0.1 μA. The zero-temperature coherence length was computed from $\xi(0) = 0.8(\xi_0 l_e)^{1/2}$, where ξ_0 is the BCS coherence length and l_e is the electron mean free path. We estimated l_e from the product $\rho_{Zn} l_e = 2.2 \times 10^{-11}\ \Omega\,cm^2$ at 4.2 K, which was the approach employed in the antiproximity effect work [10]. So far, it is not clear how the evolution of the effect systematically depends upon the thicknesses and widths of the wires. However, transition temperature seems to play a role in sample-to-sample variations in the ranges of temperatures and currents over which resistances remain below 0.01 Ω, which was the measurement noise floor taken to be zero resistance. Actually, preliminary data show that samples which have a transition temperature around 0.75 K do not exhibit any enhancement over the whole accessible temperature range.

Before considering possible physical mechanisms for this "magnetic-field-enhanced superconductivity," we need to rule out possible artifacts, which might produce a similar effect. The first possibility is that the wires are heated by the current and the effect of the magnetic field is to enhance their thermal conductivity by increasing the quasiparticle density. Then the electron temperature of the wire would cool to a lower value. This cooling would then appear as an enhancement of superconductivity. If this were the case, one could in principle translate values of current into electron temperatures by relating the resistive states with high currents at low temperatures to the resistive states just above the critical temperature at low currents. As the former resistive states can be destroyed by a weak magnetic field, one would expect the same thing to happen to the latter. However, as shown in Fig. 2(b), at low currents, an applied magnetic field does not enhance superconductivity but destroys it above some critical value. In addition, the fact that the magnetic field affects the transition regime differently above and below the shoulder provides support for the assertion that the effect is not thermal in origin. A second possible artifact relates to the negative magnetoresistance of the Cernox® thermometer used in the PPMS ^{3}He insert [11]. This resistance change could be interpreted by the control system as a temperature increase, in which case the PPMS would cool down in order to meet the set point. This magnetoresistance is compensated by the PPMS software. Finally, the effect cannot be the result of the compensation of the self-field by the applied field, as the latter is 2 orders of magnitude larger than the former.

TABLE I. Widths, thicknesses, transition temperatures, and coherence lengths of wires in Fig. 4. See the text for a description of the manner in which they were determined.

Wire	w (nm)	t (nm)	T_c (K)	ξ (0 K) (nm)
a	85	150	0.85	171
b	80	90	0.81	155
c	70	65	0.81	192
d	60	80	0.84	190

There have been several theoretical models proposed to explain the reported magnetic-field-enhanced superconductivity in nanowires. In the following, we briefly discuss their application to our results.

One model associates the enhancement of superconductivity with the quenching by an applied magnetic field of pair-breaking spin fluctuations associated with impurity magnetic moments [7]. However, at the temperatures and magnetic fields of the present work, the Zeeman energy of electrons is much smaller than the thermal energy, and thus this effect would not occur.

A second model involves the reduction of the charge imbalance length by an applied magnetic field [12]. This can bring about a decrease of the boundary resistance due to charge conversion processes at the normal metal-superconductor boundaries of phase slip centers [13]. There is also a related approach based on a generalized time-dependent Ginzburg-Landau equation applicable near the transition temperature, which predicts an enhancement of critical currents by magnetic field [14]. In the present work, the temperatures are well below the mean field transition temperature. Whether or not this mechanism can be extended to low temperatures is an open question.

The critical currents of systems of coupled superconducting grains with a random distribution of the signs of the Josephson coupling are predicted to increase with the magnetic field [15]. It was realized by averaging out the first term of the expansion of the ensemble-averaged critical current, with the second order term having a negative sign. Xiong, Herzog, and Dynes have suggested this model as an explanation of the negative magnetoresistance observed in quench-condensed Pb nanowires [5]. The achievement of a random distribution would require a large ensemble of coupled grains. One could expect that a film might serve as a better realization of a random distribution of grains than a wire of restricted cross section and finite length. However, we found that only wires showed enhanced superconductivity with an applied magnetic field. A coevaporated film responded to the field in a normal manner, independent of current.

Finally, the enhancement of superconductivity by an applied field could come from the dampening of phase fluctuations by the enhancement of the dissipative quasiparticle channel in the wire by the application of a magnetic field. The interplay between phase fluctuations and dissipation was studied initially in resistively shunted Josephson junctions [16] and, later, in nanowires [17]. In the case of nanowires, at sufficiently low temperatures, an applied magnetic field has two effects: It can increase the probability of quantum phase fluctuations, and at the same time it can enhance dissipation by increasing the quasiparticle density. The latter can suppress fluctuations. For a certain range of low fields, the wire resistance will decrease as the enhanced dampening dominates. Eventually, the magnetic field may become large enough to suppress and ultimately destroy the order parameter so that the resistance will no longer be zero. It was pointed out later that the connected electrodes can also play a role in stabilizing phase fluctuations in finite-length wires [18,19]. Although it is not clear that the wire resistance induced by current is due to either quantum or thermal fluctuations, an enhanced quasiparticle conductance channel should suppress fluctuations of either type. This promising explanation is not supported by detailed calculations that include the current through the wire as a parameter. All of the theories discuss enhancement in the limit of zero current. In the present work, enhancement effects are not observed at low currents. The sample geometry we have employed, which involves a simple and highly regular structure, could provide significant constraints on a future theory.

It should be noted that the standard models of thermal and quantum phase slips in superconducting nanowires fail to fit the temperature dependence of the observed wire resistances, implying that other physics is involved [20]. The parameters of lithographically produced wire configurations including lengths, widths, and thicknesses of wires can be systematically changed. Experiments changing these parameters, as well as the direction of the magnetic field, are being carried out and should be helpful in determining the origin of the observed effects.

The authors thank Alex Kamenev and Steve Kivelson for useful discussions. This work was supported by the U.S. Department of Energy under Grant No. DE-FG02-02ER46004. Part of this work was carried out at the University of Minnesota Characterization Facility and the Nanofabrication Center, which receives partial support from the NSF through the NNIN program.

[1] M. Tinkham, *Introduction to Superconductivity* (McGraw-Hill, New York, 1996), 2nd ed.
[2] V. Jaccarino and M. Peter, Phys. Rev. Lett. **9**, 290 (1962).
[3] S. Maekawa and M. Tachiki, Phys. Rev. B **18**, 4688 (1978).
[4] For examples, see H. W. Meul *et al.*, Phys. Rev. Lett. **53**, 497 (1984); S. Uji *et al.*, Nature (London) **410**, 908 (2001); L. Balicas *et al.*, Phys. Rev. Lett. **87**, 067002 (2001).
[5] P. Xiong, A. V. Herzog, and R. C. Dynes, Phys. Rev. Lett. **78**, 927 (1997).
[6] P. Santhanam, C. P. Umbach, and C. C. Chi, Phys. Rev. B **40**, 11 392 (1989).
[7] A. Rogachev, T. C. Wei, D. Pekker, A. T. Bollinger, P. M. Golbart, and A. Bezryadin, Phys. Rev. Lett. **97**, 137001 (2006).
[8] D. Y. Vodolazov, D. S. Golubovic, F. M. Peeters, and V. V. Moshchalkov, Phys. Rev. B **76**, 134505 (2007).
[9] M. L. Tian, N. Kumar, S. Y. Xu, J. G. Wang, J. S. Kurtz, and M. H. W. Chan, Phys. Rev. Lett. **95**, 076802 (2005).
[10] U. Schulz *et al.*, J. Low Temp. Phys. **71**, 151 (1988); B. N. Aleksandrov, Sov. Phys. JETP **16**, 286 (1963).
[11] R. Rosenbaum, B. Brand, S. Hannah, T. Murphy, E. Palm, and B. J. Pullum, Physica (Amsterdam) **294B**, 489 (2001).
[12] J. Clarke, in *Nonequilibrium Superconductivity, Phonons, and Kapitza Boundaries*, edited by K. E. Gray (Plenum, New York, 1981).
[13] K. Yu. Arutyunov, Physica (Amsterdam) **468C**, 272 (2008).
[14] D. Y. Vodolazov, Phys. Rev. B **75**, 184517 (2007).
[15] S. A. Kivelson and B. Z. Spivak, Phys. Rev. B **45**, 10 490 (1992).
[16] S. Chakravarty, Phys. Rev. Lett. **49**, 681 (1982); A. Schmid, Phys. Rev. Lett. **51**, 1506 (1983).
[17] A. D. Zaikin, D. S. Golubev, A. van Otterlo, and G. T. Zimanyi, Usp. Fiz. Nauk **168**, 244 (1998).
[18] H. P. Büchler, V. B. Geshkenbein, and G. Blatter, Phys. Rev. Lett. **92**, 067007 (2004).
[19] H. C. Fu, A. Seidel, J. Clarke, and D.-H. Lee, Phys. Rev. Lett. **96**, 157005 (2006).
[20] W. A. Little, Phys. Rev. **156**, 396 (1967); J. S. Langer and V. Ambegaokar, Phys. Rev. **164**, 498 (1967); D. E. McCumber and B. I. Halperin, Phys. Rev. B **1**, 1054 (1970); N. Giordano, Phys. Rev. Lett. **61**, 2137 (1988); A. D. Zaikin, D. S. Golubev, A. van Otterlo, and G. T. Zimanyi, Phys. Rev. Lett. **78**, 1552 (1997).