Magnetic Field Induced Superconductivity in Out-of-Equilibrium Nanowires

Yu Chen, S. Snyder, and A. M. Goldman

School of Physics and Astronomy, University of Minnesota, Minneapolis, MN 55455, USA

(Date textdate; Received textdate; Revised textdate; Accepted textdate; Published textdate)

Abstract

Four-terminal resistance measurements have been carried out on Zn nanowires formed using electron-beam lithography. When driven resistive by current, these wires re-enter 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 magnetic field enhanced critical currents. We suggest that our observations are associated with the damping of phase slip processes by the enhancement of dissipation by the quasiparticle conductance channel resulting from the application of a magnetic field.

Systems of reduced dimension are frequently governed by quantum behavior not found in bulk materials. The Tomonaga-Luttinger Liquid phenomenon in one dimension is a striking example [1]. Quasi-one dimensional superconductors, whose widths and thicknesses are larger than the Fermi wavelength but already smaller than the superconducting coherence length, are not exceptions. There has been on-going interest in problems such as the crossover between thermal and quantum phase slip processes [2], and the superconductor-insulator transition controlled by either total wire resistance or resistance per unit length in such systems [3]. In addition, attention has been focused on the enhancement of superconductivity by an applied magnetic field, which has been reported as a negative magnetoresistance in some cases [4, 5] or an enhancement of the critical current in others [6, 7]. Recently a phenomenon called the “antiproximity effect” has been reported [8]. In this work, superconducting nanowires were prepared using an electrochemical technique and connected in a two-terminal arrangement to electrodes with higher transition temperatures. The wires, because of their confined geometry, have a higher critical magnetic field than the electrodes. In contrast with the usual proximity effect, at certain temperatures the wires were found to re-enter the superconducting state when the electrodes are driven normal by a magnetic field. The present work was motivated by the goal of seeing whether this phenomenon would occur in wire configurations prepared using a top-down lithographic technique rather than a bottom-up electrochemical technique and whether the effect could be observed in a four-terminal planar configuration. In this Letter we report a different phenomenon, reentrant superconductivity resulting from the application of small magnetic fields to wires driven out of equilibrium and into a resistive state by externally supplied currents.

Standard four-terminal configurations of an 80nm wide Zn wire with 1µm wide Zn electrodes, 1.5µm apart, as shown in Fig.1(a), were prepared using electron-beam lithography. The 150 nm thick Zn films for the wires and electrodes were deposited in a single step at a rate of 6Å/sec onto SiO\(_2\) substrates held at 77 K. The system pressure was around \(1 \times 10^{-7}\) 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 resultant wires. The issue of the fragile nature of the liftoff process for these samples was circumvented by utilizing a bilayer of PMMA 495K A4/950K C2 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.

In the low current limit, the temperature dependence of the wire resistance was quite conventional. As shown in Fig.1(b), the resistance dropped to zero at \(T_c \sim 0.85\) K with a width of a few tens of mK. We estimated the zero-temperature coherence length, \(\xi(0) \sim (\xi_0l_c)^{1/2}\), to be around 2100 Å, where \(\xi_0\) is the BCS coherence length, and \(l_c\) is the mean free path. Here we used the same approach as that employed in the antiproximity effect work to obtain \(l_c\) from the product \(\rho_{zz}l_c = 2.2 \times 10^{-14}\Omega \cdot \text{cm}^2\) at 4.2 K [9].

FIG. 1: a) Scanning Electron Microscope (SEM) image of the sample, the white scale bar is 1µm long. b) Temperature dependence of the wire resistance, at \(H = 0\) Oe, with current ranging from 0.4µA to 6 µA, every 0.4 µA.
As the applied current increased, the onset temperature decreased and the transition broadened to several hundreds of mK in the high current limit. Accompanying the broadened transition was a shoulder-like structure, which separated the transition into two parts.

As shown in Fig. 2(a), the higher resistance part of the transition moved to lower temperatures with increasing magnetic field. The lower resistance part exhibited a different behavior, moving to higher temperatures with increasing field. Also the temperature at which the wire resistance vanished increased. As a result, the transition became sharper with increasing field. However this eventually stopped and the transition onset temperature as well as the temperature at which the resistance vanished, both moved together towards lower values upon increasing the field. The direct consequence is that there is a magnetic field induced re-entrance into the superconducting state over the range of temperatures corresponding to the lower part of the zero field transition as illustrated in Fig. 2(b). Over this range of temperatures, the wire is made resistive by applying a high current. Magnetic field drives the wire superconducting until the field is strong enough to destroy the amplitude of the order parameter. In the higher temperature regime, a magnetic field only suppresses superconductivity.

Plotting the data as color maps, as shown in Fig.3, permits us to identify three states of the wire, the normal state (green), the superconducting state (blue) and the resistive state (colors between these two). The latter is the transition regime. Increasing the current not only moves the transition regime to lower temperatures but also greatly broadens it (Fig.3(a)). When the magnetic field is turned on, shown in Fig.3(b), it gradually narrows this regime by pulling down the boundary between the normal state and the resistive state while pulling up the boundary between the resistive state and the superconducting state. This gives rise to a magnetic field induced re-entrance into the superconducting state at the bottom part of the transition regime. The current dependence of the wire resistance is similar to its temperature dependence, shown in Fig.3(c). In zero field, the superconductor-normal metal transition with current is broad and exhibits a shoulder-like structure. A relatively small applied magnetic field moves the current at the threshold for resistance to higher values, and the current at which the normal resistance is attained to lower values. As a consequence, superconductivity reappears in weak magnetic fields, at currents slightly higher than the critical current at which zero resistance disappears in zero field. This enhancement disappears a higher fields, or at currents above the shoulder. This is different from the anti-proximity effect, in which the wire switches abruptly from the normal to the superconducting state when the magnetic field reaches the critical field of the bulk electrodes. The re-entrance into the superconducting state here is a smoother and broader transition from the resis-
tive state. In addition, the magnetic field needed is much weaker than the critical field of the bulk electrodes and its value is a function of temperature and current.

Before considering possible physical mechanisms for this “magnetic-field enhanced superconductivity,” we need to rule out several other phenomena, which might produce similar results. One possibility is that the wires are heated by the currents and the effect of the magnetic field is to enhance their thermal conductivity by increasing the quasiparticle density. The wire would then cool to a lower temperature relative to that of the thermometer. 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 happen to the latter. However, as shown in Fig. 4, at low currents, an applied magnetic field does not enhance superconductivity, but destroys it above some critical value. This also distinguishes the present observations from the negative magnetoresistance reported for Pb wires [4], which was attributed to fluctuations in the sign of the Josephson coupling [11]. In addition, the fact that magnetic field affects the higher and lower resistance parts of the transition differently provides support for the assertion that the effect is not thermal in origin.

A second possibility relates to the negative magnetoresistance of the Cernox® thermometer used in the PPMS 3He insert [11]. The response of the control system would be to interpret the resistance change as a temperature increase. In order to maintain the set point, the system would cool down, and the resistance of would be reduced because the temperature is decreased. We rule this effect out by carrying out an estimate of the magnetoresistance. For the resistance of the wire to drop from its zero magnetic field value to zero at T = 0.6 K, the temperature would have to fall below 0.46K. This would correspond to a magnetoresistance $\Delta R/R >100\%$, whereas the actual magnetoresistance is less than 10% up to 2T at 0.6K. This field is much higher than any in the experiment. Furthermore there is a correction for magnetoresistance in the PPMS software, which compensates for the magnetoresistance. As a consequence thermometer magnetoresistance is irrelevant.

Finally, polarization of the magnetic moments of surface oxides, which would quench pair-breaking spin fluctuations resulting in enhanced critical currents [6], is also not relevant, as the field applied, tens of Oe, is too weak to polarize impurity magnetic moments at 0.5K. In addition, one can rule out compensation of the self-field by the applied field, since the self-field, being the order of 0.1 Oe, is orders of magnitude smaller than the applied field.

![FIG. 4: Magnetic field dependence of the wire resistance in the vicinity of the transition temperature, at a low current with $I = 0.4\mu A$.](image)

We now suggest that the underlying physical mechanism for our observations is damping of phase fluctuations by magnetic-field enhanced dissipation. From numerous experiments on wires [12], it is generally believed that the resistive state at the bottom of the transition regime is characterized by a nonzero order parameter with the resistance coming from phase slip processes within the wire [13]. Frequently a resistively shunted Josephson junction picture is used to describe the wire. In this picture the dynamics of the phase are described by a tilted washboard potential and the applied current determines the tilt [14]. When the applied current is low, the probability for phase slip is low at low temperature and is significant only near $T_c$. As the current increases, approaching the depairing current, the washboard potential is tilted further and the energy barrier for phase slip is reduced [13]. The wire is driven resistive when the probability for a phase slip, and diffusion down the washboard potential becomes detectable even at temperatures well below the transition temperature. Dissipation provides damping for this process. This dissipation can originate from the quasiparticles, either locally within the wire [14, 16] or in the electrodes connected to it [17]. For mesoscopic Josephson tunneling junctions the phase can also be localized in one of the wells of the washboard potential when the shunt resistance falls below $h/4e^2$ resulting in superconductivity [18]. This is dissipation-induced localization of the phase. The application of a magnetic field, even though suppressing the superconductivity by smearing the density of states and increasing the quasiparticle population and the quasiparticle conductance channel, increases dissipation and therefore enhances the damping of phase slip processes. This would appear to occur in a manner sufficient to localize the phase, resulting in a return to the superconducting state. With further increase of the magnetic field, too large a transport current or too high a temperature, the barrier heights are no longer
large enough to localize the phase fluctuations and the resistive state is reentered.

Vodolazov [19] has argued, based on a generalized time-dependent Ginzburg-Landau equation [20], that magnetic fields can enhance superconductivity as a consequence of the magnetic field dependence of the charge imbalance relaxation length and the presence of normal metal/superconductor boundaries. In the present experiment, the fields at which reentrance occurs are not sufficient to drive the electrodes into normal state and temperatures are well below the transition temperature. As a consequence we believe the considerations of Vodolazov are not applicable.

Many of the samples we fabricated exhibited only very large negative magnetoresistances and did not reenter the superconducting state. Examination of these samples revealed that their transition temperatures and residual conductivities were lower than those of samples which re-entered, suggesting they were dirtier with shorter coherence lengths. SEM imaging showed that the Zn electrodes of reentrant samples were smooth, and therefore the associated wires should exhibit greater uniformity in their cross-section areas. If the dissipation comes from the leads, the argument can be made that a shorter coherence length results in weaker coupling between the wire and leads which eventually results in a damping of fluctuations not sufficient to localize the phase. It might also be argued that greater inhomogeneity in the wire structure can produce more weak points in the wire, which remain in normal state despite the damping of phase fluctuations.

In summary, we have demonstrated that applied current plays an important role in driving phase fluctuations or phase slip in quasi-one dimensional superconducting wires. When the current is close to the depairing value, the wire enters a regime in which zero resistance is lost over a wide range of temperatures well below the transition temperature. Unlike thermal phase slips near $T_c$, this current driven phase slip regime can be damped and the superconducting state reentered by enhancing the dissipation through increasing the magnetic field. An important, perhaps unanswered question is whether the resistive state results from thermal or quantum diffusion of the phase. If the latter is the case, then the observed behavior, the reentrance into the superconducting state with the application of a magnetic field, is an example of a dissipative phase transition or the suppression of macroscopic quantum tunneling of the phase by interaction with a dissipative environment [21].

This work was supported by the U.S. Department of Energy under grant DE-FG02-02ER46004.

[1] For a review, see: L. I. Glazman and M. P. A. Fisher, in Mesoscopic Electron Transport, edited by L. L. Sohn, L. P. Kouwenhoven, G. Sch{"o}n (Kluwer, Dordrecht, 1997).
[2] For review, see: K. Y. Arutyunov, D. S. Golubev and A. D. Zaikin, Phys. Rep. 464, 1 (2008).
[3] A. Bezryadin, J. Phys.: Condens. Matter 20, 043202 (2008); A. T. Bollinger, R. C. Dinmore III, A. Rogachev, and A. Bezryadin, Phys. Rev. Lett. 101, 227003 (2008).
[4] P. Xiong, A. V. Herzog, and R. C. Dynes, Phys. Rev. Lett. 78, 927 (1997).
[5] P. Santhanam, C. P. Umbach and C. C. Chi, Phys. Rev. B 40, 11392 (1989).
[6] A. Rogachev, T. C. Wei, D. Pekker, A.T. Bollinger, P.M. Goldbart and A. Bezryadin, Phys. Rev. Lett. 97, 137001 (2006).
[7] D. Y. Vodolazov, D. S. Golubovic, F.M. Peeters and V. V. Moshchalkov, Phys. Rev. B 76, 134505 (2007).
[8] 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).
[9] U. Schulz et al., J. Low Temp. Phys. 71, 151 (1988); B. N. Aleksandrov, Sov. Phys. JETP 16, 286 (1963).
[10] A. Kivelson and B. Z. Spivak, Phys. Rev. B 45, 10 490 (1992).
[11] R. Rosenbaum, B. Brand, S. Hannah, T. Murphy, E. Palm and B. J. Pullum, Physica B 294, 489 (2001).
[12] R. S. Newbower, M. R. Beasley and M. Tinkham, Phys. Rev. B 5, 864 (1972); N. Giordano, Phys. Rev. Lett. 61, 2137 (1988); F. Altomare, A. M. Chang, M. R. Melloch, Y. Yong and C. W. Tu, Phys. Rev. Lett. 97, 017001 (2006); M. Zgirski, K. P. Riikonen, V. Tuboltsiev, K. Arutyunov, Nano Lett. 5, 1029 (2005).
[13] W. A. Little, Phys. Rev. 156, 396 (1967); J. S. Langer, V. Ambegaokar, Phys. Rev. 164, 498 (1967); D. E. Mccumber, B. I. Halperin, Phys. Rev. B 1, 1054(1970).
[14] G. Refael, E. Demler, Y. Oreg, D. S. Fisher, Phys. Rev. B 75, 014522 (2007).
[15] M. Tinkham, Introduction to Superconductivity: 2nd ed. (McGraw Hill, New York, 1996).
[16] A.D. Zaikin, D.S. Golubev, A. van Otterlo, G.T. Zimanyi, Uspekhi Fiz. Nauk 168, 244(1998).
[17] H. P. B"uchler, V. B. Geshkenbein, and G. Blatter, Phys. Rev. Lett. 92, 067007 (2004); H. C. Fu, A. Seidel, J. Clarke, and D.-H. Lee, Phys. Rev. Lett. 96, 157005 (2006).
[18] Yamaguchi Takahide, Ryuta Yagi, Akinobu Kanda, Youiti Ootuka, and Shun-ichi Kobayashi Phys. Rev. Lett. 85, 1974 (2000).
[19] D. Y. Vodolazov, Phys. Rev. B 75, 184517 (2007).
[20] L. Kramer and R. J. Watts-Tobin, Phys. Rev. Lett. 40, 1041 (1978).
[21] A. O Caldeira and A. J. Leggett, Annals of Physics 149, 374 (1983).