Magnetic field enhancement of superconductivity in ultra-narrow wires

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We study the effect of an applied magnetic field on sub-10nm wide MoGe and Nb superconducting wires. We find that magnetic fields can enhance the critical supercurrent at low temperatures, and does so more strongly for narrower wires. We conjecture that magnetic moments are present, but their pair-breaking effect, active at lower magnetic fields, is suppressed by higher fields. The corresponding microscopic theory, which we have developed, quantitatively explains all experimental observations, and suggests that magnetic moments have formed on the wire surfaces.

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Magnetic fields have long been known to suppress superconductivity through two main effects: first, by aligning the electron spins (i.e., the Zeeman effect) and second, by raising the kinetic energy of electrons via Meissner screening currents (i.e., the orbital effect) [1]. However, some exceptions to this general convention have been observed in nanoscale systems, where the field can penetrate, essentially unattenuated, throughout the sample. For instance, a small applied magnetic field has been observed to cause negative magneto-resistance (i.e., a decrease of resistance with increasing field) in narrow superconducting strips [2]. More strikingly, an applied magnetic field has been shown to strongly enhance superconductivity in nanowires: the so-called anti-proximity effect [3]. We know of no commonly accepted theoretical explanations for these effects in nanoscale systems.

Several (non-mutually exclusive) theoretical pictures have been proposed for how magnetism or magnetic fields may enhance superconductivity. First, the applied field may reduce the charge-imbalance relaxation time associated with phase-slip centers, thus resulting in negative magneto-resistance at high currents and near $T_c$ [4]. Second, the field may enhance dissipative fluctuations, thus localizing the phase of the superconductor and, thereby stabilizing superconductivity [5]; this is thought to be relevant to the anti-proximity effect [3]. Third, in disordered superconductors having grain boundaries, negative magneto-resistance may arise from interference between normal and $\pi$ junctions [6]. Finally, the pair-breaking effect of magnetic moments may be quenched by either an applied field [7] or an exchange field [8], the latter being relevant to magnetic superconductors.

In this Letter, we present results from experiments on ultra-narrow, sub 10nm wide MoGe and Nb homogeneous superconducting wires that are nominally free of magnetic impurity atoms. We have found that at low temperatures magnetic fields can enhance their critical currents by up to 30%, reaching a maximum at fields of $(2 - 4)T$. This behavior is present both in parallel and perpendicular field orientations, disappears at high temperatures, and has the largest relative magnitude for the thinnest wires. To explain this behavior we conjecture that magnetic moments (due, e.g., to the surface oxide [9]) are present in the nanowires. Correspondingly, we have developed a microscopic theory [10], which shows that if such local moments exist, a magnetic field can enhance the superconducting critical current, $I_c$, and, in line with recent work by Kharitonov and Feigel'man [7], raise $T_c$. The essential physics involves the polarization of the magnetic moments by the magnetic field [11], which quenches their exchange-coupling with the electrons in Cooper pairs. Our theory is consistent with all our experimental observations, and also suggests that in the present experiments the magnetic moments are located on the surfaces of the wires.

To fabricate sub-10 nm wide wires we have used a recently-developed molecular templating technique [12]. Our nanowires were made from the superconducting amorphous alloy Mo$_{0.79}$Ge$_{0.21}$ or Nb, deposited on to a free-standing carbon nanotube (or bundle of tubes) suspended over a trench in a multilayered Si/SiO$_2$/SiN substrate. Combined fraction of Fe, Co and Ni was less than $10^{-4}$ at.% in MoGe sputtering target and less than $10^{-2}$ at.% in Nb target. The cross-section of the nanowire is determined by the width of the templating nanotube and the nominal thickness of material deposited. We exposed the MoGe wires to the ambient atmosphere, which led to the oxidation of their surfaces. This process reduces the width of the conducting core by about 5nm [13]. Our Nb nanowires were covered with protective Si layer [14]. The parameters of the wires are given in Table I.

Electrical transport measurements were performed on the wires in a $^3$He cryostat equipped with carefully filtered leads. The zero-bias resistance $R$ of the wires, measured in the linear-response regime, is shown as a function of temperature $T$ in Fig. 1. For each $R(T)$ curve, the higher-temperature transition corresponds to the superconducting transition in the film electrodes, which are connected in series with the wires. The resistance measured immediately below the film transition is taken as the normal-state resistance $R_N$ of the wire. Each curve also shows a lower-temperature transition, corresponding to the appearance of superconductivity in the wire itself. In effectively one-dimensional super-
TABLE I: Summary of nanowire parameters (all lengths are in nm). The symbols (⊥) and (∥) indicate orientations of the magnetic field. Wire sample parameters: \( t \)–nominal thickness; \( w \)–width measured via SEM; \( L \)–length; \( R_N \)–normal-state resistance; \( d_R \)–diameter, estimated from \( R_N \), \( L \) and the resistivity of MoGe (170 \( \mu \Omega \) cm) and Nb (30 \( \mu \Omega \) cm) \[14\]; \( I_c(0) \)–zero-field critical current at 0 K. Parameters produced by the fitting of \( R \) vs. \( T \) curves at \( B = 0 \) T using TAPS theory: \( T_c \)–critical temperature of the wire; \( \xi(0) \)–superconducting coherence length in the wire. Parameters used to fit our theory to \( I_c(B) \) data (Fig. 2): \( \tau_B \)–exchange-scattering time due to local magnetic moments; \( d_{lt} \)–effective diameter of wire, assuming circular cross-section; \( T_{co} \)–critical temperature of the wire without local moments; \( I_c(0)/I_{c,lt}(0) \)–rescaling factor.

| Sample | \( t \) | \( w \) | \( L \) | \( R_N \) (k\( \Omega \)) | \( d \) | \( L_c(0) \) (nA) | \( T_c \) (K) | \( \xi(0) \) | \( \tau_B \) (ps) | \( d_{lt} \) | \( T_{co} \) (K) | \( I_c(0)/I_{c,lt}(0) \) |
|--------|-----|-----|-----|-------------|-----|-------------|------|------|--------|--------|---------|------------------|
| MG1 (⊥) | 10  | 21  | 106 | 2.14        | 10.4 | 1930        | 3.8  | 18   | 3.6    | 8.9    | 5.0     | 1.01            |
| MG1 (∥) |     |     |     | 2.26        | 10.0 | 1760        | 3.7  | 19   | 3.5    | 8.9    | 5.0     | 0.92            |
| MG2 (⊥) | 8   | 17  | 128 | 3.24        | 9.2  | 1010        | 3.6  | 17   | 2.4    | 8.7    | 5.6     | 0.69            |
| MG3 (⊥) | 7   | 17.5| 156 | 3.86        | 9.4  | 880         | 2.9  | 17   | 3.4    | 8.5    | 4.4     | 0.75            |
| MG3 (∥) |     |     |     | 3.86        | 9.4  | 800         | 2.9  | 17   | 3.1    | 8.3    | 4.4     | 0.82            |
| MG4 (∥) | 8   | 12.5| 104 | 4.84        | 6.8  | 63          | 1.9  | 39   | 1.9    | 9.1    | 4.6     | 0.22            |
| Nb1 (⊥) | 7   | 18  | 120 | 0.70        | 8    | 7170        | 5.7  | 8.1  | 5.9    | 6.4    | 6.5     | 0.89            |
| Nb2 (⊥) | 4   | 11  | 110 | 4.25        | 3.1  | 109         | 1.5  | 28.5 | 4.9    | 3.1    | 2.5     | 0.72            |

For thicker samples (MG1-MG3), increasing the magnetic field \( B \) (not shown here) shifts the resistive transition of the wire to progressively lower temperatures, in agreement with previously observed behavior \[17\]. However, for the thinnest sample (MG4), the \( R(T) \) curve displays a more complex response to the magnetic field: whereas at the highest fields (\( B \approx 5 – 9 \) T) the aforementioned suppression of superconductivity is observed, there is a regime of lower fields (\( B \approx 0 – 3 \) T) for which the resistive transition of the wire shifts oppositely, i.e., to higher temperatures with increasing \( B \), as shown in the inset to Fig. 1. This constitutes negative magnetoresistance, which has also been observed in Pb wires \[2\], and indicates that in this lower-field regime the magnetic field enhances superconductivity.

In Fig. 2a, we show the normalized critical currents of MoGe wires of various diameters, measured in a parallel magnetic field at \( T = 0.3 \) K. Experimentally, \( I_c \) is taken to be the current at which the wire switches to the resistive state (see the inset in Fig. 2a). For all measured MoGe samples, \( I_c \) displays remarkable behavior, initially growing with increasing magnetic field before reaching a maximum at \( B \approx 2 \) to 4 T. The relative magnitude of the enhancement of \( I_c \) grows with the reduction of the wire diameter; the largest enhancement (which occurs for the thinnest wire, MG4) is about 30% . Nanowires made of Nb display the same tendency (see Fig. 2b). Whereas the thicker wire Nb1 shows the expected monotonic decrease of \( I_c \), the critical current anomaly is present in the much thinner wire Nb2.

To assess whether the effect is non-local in origin (e.g., is associated with the pattern of supercurrent in the wire) we applied both parallel and perpendicular magnetic fields to samples MG3 and MG1 (always keeping the magnetic field parallel to the electrode films). Between measurements in distinct field-orientations the samples were removed from the cryostat, rotated on the chip and rewired. After this procedure, the zero-field critical current was found to decrease by about 10%, probably due to some shrinking of the cross-sectional area of the wire via additional oxidation (see Table I). The critical current for sample MG3, normalized by its value at zero

![Fig. 1: Temperature dependence of the resistance of MoGe nanowires. For each sample, the solid line indicates a fit to the TAPS theory \[15\]. Inset: \( R \) vs. \( T \) dependence of wire MG4 at \( B = 0 \) and 3 T.](image-url)
field, is shown in Fig. 2. We found that the initial rise is essentially the same for both field orientations. This strongly suggests that the enhancement of \( I_c \) is local in origin.

To understand the anomalous enhancement of superconductivity by magnetic fields in our nanowires, we have developed a theoretical model (see Ref. [10]) that yields the dependence of \( I_c \) on \( B \) and \( T \). We included the following ingredients: (i) local magnetic moments, which cause exchange scattering of electrons (with zero-field exchange scattering time given by \( \tau_B = E_F/2\pi\langle J^2 \rangle x_m \), where \( x_m \) is the fractional concentration of local moments, \( J \) is the exchange coupling, and \( E_F \) is the Fermi energy), and thus lead to the breaking of Cooper pairs; (ii) the vector potential (associated with the applied magnetic field), which scrambles the relative phases of the partners in a Cooper pair as they move diffusively in the presence of impurity scattering (viz., the orbital effect), which also suppresses superconductivity; (iii) the applied magnetic field, which polarizes the local magnetic moments, and thus decreases the rate of exchange-scattering, hence diminishing the contribution of process (i) to de-pairing and thus enhancing superconductivity; and (iv) the Zeeman effect, associated with the applied field, which splits the energy of the up and down spins of the Cooper pair and thus tends to suppress superconductivity. (Note that strong spin-orbit scattering tends to weaken de-pairing due to the Zeeman effect.) These ingredients, which were also employed by Kharitonov and Feigel’man in their work on critical temperatures, embody the competing tendencies produced by the magnetic field: de-pairing via the orbital and Zeeman effects, but also the mollification of the de-pairing caused by local magnetic moments.

To obtain the critical current we first derived the semi-classical Eilenberger-Usadel equations [13] for the anomalous Green function, taking into account terms that describe spin-orbit scattering (with scattering time \( \tau_{SO} \)), local magnetic moments, and the magnetic field [11]. Then we seek the current-carrying solution that maximizes the current, and identify it as the critical de-pairing current. To fit the experimentally-measured switching current we introduce the ratio of switching current to de-pairing current \( I_s(B)/I_{cs}(B) \) as a fitting parameter, and assume that this ratio does not depend on \( B \).

By carrying out this procedure for the case of spin-1/2 magnetic impurities we have obtained numerical solutions for a wide range of material parameters, temperatures and magnetic fields, and have thus found three distinct regimes: a naturally expected one, in which both \( I_c \) and \( T_c \) simply decrease with \( B \); and two anomalous variants. The first gives non-monotonic behavior for both \( I_c \) and \( T_c \), both first rising and then falling with \( B \). The second is even more striking: although \( T_c \) simply decreases with \( B \), at low temperatures \( I_c \) first rises and then falls. Most of our wires have behavior in this last regime. To make a quantitative comparison between our experiments and our theory, we have performed fits to our data, allowing variations in the wire diameter and the exchange scattering time. For the remaining parameters we have used following values: the \( g \)-factor \( g = 2 \), the spin-orbit scattering time \( \tau_{SO} = 5.0 \times 10^{-14} \text{s} \) for MoGe and \( 2.3 \times 10^{-12} \text{s} \) for Nb [17], and the diffusion constant...
for MoGe $D = 1 \text{ cm}^2/\text{s}$. An important consequence of our theory is that the initial behavior of the $I_c(B)$ curves should not depend on the relative orientation of the field and the wire. This is because the behavior of $I_c$ at small $B$ is dominated by scattering from magnetic impurities, which is a local property and thus insensitive to field orientation. At larger fields the orbital effect becomes important, and is larger for the perpendicular field orientation. Hence, we expect that the $I_c(B)$ curves should separate from one another, and that the maximum in the parallel field orientation should occur at a larger field than in the perpendicular orientation. Figure 2 shows that our experimental data exhibit all these properties. Further evidence in favor of our theoretical picture comes from the fact that the fits to perpendicular- and parallel-field data return essentially identical values for the magnetic-impurity scattering time, which is proportional to the impurity concentration, (Table I).

At higher temperatures thermal fluctuations in the moment-orientations make the quenching by the applied field less effective and, hence, higher fields (at which the orbital effect already becomes dominant) are required to quench the local moments. Thus, the anomaly is expected to diminish. This is indeed what we observe experimentally (Fig. 3a): at our lowest temperature ($0.3 \text{ K}$) the anomaly is clearly observed; but at temperatures higher than roughly $1.8 \text{ K}$ the anomaly is completely washed out. This loss of the anomaly at higher temperatures is consistent with the absence of any observed negative magneto-resistance for samples MG1-MG3, as their resistances become too small to measure at the temperatures for which the anomaly should appear.

Finally, in Fig. 3b we display $\tau_B$ as a function of the wire diameter $d$. Assuming that the magnitude of the exchange integral $\tilde{J} \approx 0.2 \text{ eV}$, we find the magnetic-impurity fraction $x_m$ to be of order of $0.2 \text{ at. %}$. If the moments were distributed homogeneously throughout the MoGe then $x_m$, and therefore $\tau_B$, would not depend on the wire diameter. Instead, data suggest that $\tau_B$ depends linearly on $d$, consistent with the magnetic moments being distributed over the surface of the wires. This is also supported by the fact that our thick film Nb and MoGe samples prepared under the same condition do not reveal any change in $T_c$ compare to the published data. Observation of anomalous behavior both in MoGe and Nb nanowires suggests that such behavior is likely to occur for nano-devices made from other superconducting materials, unless suitable treatment is applied to avoid the formation of local moments.

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[18] G. Eilenberger, Z. Phys. 214, 195 (1968). K.D. Usadel, Phys. Rev. Lett. 25, 507 (1970).
[19] J.M. Graybeal, Ph. D. Thesis, Stanford University, 1985; J.M. Graybeal and M.R. Beasley, Phys. Rev. B 29, 4167 (1984).