Magnetic-Field Enhancement of Superconductivity in Ultrananowires

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We study the effect of an applied magnetic field on sub-10-nm wide MoGe and Nb superconducting wires. We find that magnetic fields can enhance the critical supercurrent at low temperatures, and do 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.

Correspondingly, we have developed a microscopic theory [10], which shows that polarization of such local moments by a magnetic field can quench their exchange coupling with the electrons in Cooper pairs [11] and enhance the superconducting critical current \( I_c \). Our theory is consistent with all 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 the molecular templating technique [12,13]. Our nanowires were made from the superconducting amorphous alloy \( \text{MoGe}_x \) or Nb, deposited onto a freestanding fluorinated carbon nanotube suspended over a trench in a multilayered Si/SiO\(_2\)/SiN substrate. The combined fraction of Fe, Co, and Ni was less than 10\(^{-4}\) at. % in the MoGe sputtering target and less than 10\(^{-2}\) at. % in the Nb target. We exposed the MoGe wires to the ambient atmosphere, which led to the oxidation of their surfaces. This process reduced the width of the conducting core by about 5 nm [14]. A transmission electron microscopy study of MoGe wires fabricated under the same conditions indicated that the wires are homogeneous [14]. Our Nb nanowires were covered with a protective Si layer [15]. 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 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. To fit resistance data we have used a phenomenological formula, \( R = R_N \exp[-\Delta F/k_BT] \) [16], that accounts for thermally activated phase slips (TAPS) below critical temperature \( T_c \), where \( \Delta F \) is the free-energy barrier for phase slips [17]. The fitting parameters that determine \( \Delta F \) are \( T_c \) and the...
TABLE I. Summary of nanowire parameters (all lengths are in nm). The symbols (⊥) and (∥) indicate orientations of the magnetic field. Wire sample parameters: \( t \) is the nominal thickness of deposited MoGe or Nb; \( w \), width measured via scanning electron microscopy (actual width and thickness of the conducting core of wires are reduced, compared to \( t \) and \( w \), due to oxidation); \( L \), length; \( R_N \), normal-state resistance; \( d_R \), diameter, calculated from \( R_N \), \( L \) and the resistivity of MoGe (180 \( \mu \Omega \text{ cm} \)) and Nb (30 \( \mu \Omega \text{ cm} \)) [15], assuming circular cross section; \( I_c(0) \), zero-field critical current at 0.3 K. Parameters produced by the fitting of \( R \) vs \( T \) curves at \( B = 0 \) T using TAPS theory: \( T_c \) is the critical temperature of the wire; \( \xi(0) \), dirty-limit coherence length. Parameters used to fit our theory to \( I_c(B) \) data (Fig. 2): \( \tau_B \) is the exchange-scattering time due to local magnetic moments; \( d_{\text{eff}} \), effective diameter of the wire; \( T_{c0} \), critical temperature of the wire without local moments; \( I_c(0)/I_{dp}(0) \), rescaling factor.

| Sample  | \( t \) (nm) | \( w \) (nm) | \( L \) (nm) | \( R_N \) (\( k\Omega \)) | \( d_R \) (nm) | \( I_c(0) \) (nA) | \( T_c \) (K) | \( \xi(0) \) (K) | \( \tau_B \) (ps) | \( d_{\text{eff}} \) (nm) | \( T_{c0} \) (K) | \( I_c(0)/I_{dp}(0) \)
<table>
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<tbody>
<tr>
<td>MG1a (⊥)</td>
<td>10</td>
<td>21</td>
<td>106</td>
<td>2.14</td>
<td>10.6</td>
<td>1930</td>
<td>3.8</td>
<td>18</td>
<td>3.6</td>
<td>8.9</td>
<td>5.0</td>
<td>1.01</td>
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<tr>
<td>MG1b (∥)</td>
<td>8</td>
<td>17</td>
<td>128</td>
<td>3.24</td>
<td>9.5</td>
<td>1010</td>
<td>3.6</td>
<td>17</td>
<td>2.4</td>
<td>8.7</td>
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<tr>
<td>MG2 (⊥)</td>
<td>7</td>
<td>17.5</td>
<td>156</td>
<td>3.86</td>
<td>9.6</td>
<td>880</td>
<td>2.9</td>
<td>17</td>
<td>3.4</td>
<td>8.5</td>
<td>4.4</td>
<td>0.75</td>
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<tr>
<td>MG3a (⊥)</td>
<td>7</td>
<td>12.5</td>
<td>104</td>
<td>4.84</td>
<td>9.6</td>
<td>800</td>
<td>2.9</td>
<td>17</td>
<td>3.1</td>
<td>8.3</td>
<td>4.4</td>
<td>0.82</td>
</tr>
<tr>
<td>MG3b (∥)</td>
<td>8</td>
<td>12.5</td>
<td>104</td>
<td>4.84</td>
<td>9.6</td>
<td>800</td>
<td>2.9</td>
<td>17</td>
<td>3.1</td>
<td>8.3</td>
<td>4.4</td>
<td>0.82</td>
</tr>
<tr>
<td>Nb1 (⊥)</td>
<td>7</td>
<td>18</td>
<td>120</td>
<td>0.70</td>
<td>8</td>
<td>7170</td>
<td>5.7</td>
<td>8.1</td>
<td>5.9</td>
<td>6.4</td>
<td>6.5</td>
<td>0.89</td>
</tr>
<tr>
<td>Nb2 (⊥)</td>
<td>4</td>
<td>11</td>
<td>110</td>
<td>4.25</td>
<td>3.1</td>
<td>109</td>
<td>1.5</td>
<td>28.5</td>
<td>4.9</td>
<td>3.1</td>
<td>2.5</td>
<td>0.72</td>
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zero-temperature coherence length \( \xi(0) \) (see Table 1). The anomalously large \( \xi(0) \) (and small \( I_c \); see below) detected in the sample MG4 is not yet understood, but might reflect the proximity of this sample to the quantum critical point of the superconductor-insulator transition that for MoGe wires of length about 100 nm occurs at \( R_N = 6.5 \) k\( \Omega \) [12]. The \( R(T) \) dependence of our samples does not show any evidence of quantum phase slips [18].

For samples MG1-MG3, increasing the magnetic field \( B \) shifts the resistive transition of the wires to progressively lower temperatures, in agreement with previously observed behavior [19]. However, for the MoGe sample with the lowest \( T_c \) (i.e., MG4), the \( R(T) \) curve displays a more complex response to the magnetic field: whereas at the highest fields (\( B = 5-9 \) T) the aforementioned suppression of superconductivity is observed, there is a regime of lower fields (\( B = 0-3 \) 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 previously been observed in Pb wires [2].

We observed a much stronger enhancement of superconductivity in the low-temperature critical current of our nanowires. In Fig. 2(a) we show the normalized critical currents for several MoGe wires, 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. 2(c)]. For all MoGe samples, \( I_c \) displays remarkable behavior, initially growing with increasing magnetic field before reaching a maximum at \( B \approx 2-4 \) T. The relative magnitude of the enhancement of \( I_c \) grows with the reduction of the cross-sectional area of the wire. Nanowires made of Nb display the same tendency [see Fig. 2(b)].

To assess whether the effect is nonlocal in origin (e.g., is associated with patterns of supercurrent) we measured two wires (MG1 and MG3) both in parallel and perpendicular magnetic fields. Between measurements, each sample was removed from the cryostat and rotated on the chip. After this procedure, each wire changed slightly, due to additional oxidation. We use labels MG1a and MG3a for the wires before the rotation and MG1b and MG3b for the corresponding wires after the rotation. The critical current for sample MG3a and Mg3b, normalized by its value at zero field, is shown in Fig. 2(c). We found, at the qualitative level, that the curves \( I_c(B) \) are very similar for both field orientations. This suggests that the enhancement of \( I_c \) is local in origin.

Assuming that local physics is at the core of the problem and is associated with localized spins, we have developed a theoretical model (see Ref. [10]) that yields the dependence of \( I_c \) on \( B \) and \( T \). We have included the following ingredients: (i) local magnetic moments, which cause ex-

FIG. 1. Temperature dependence of the resistance of MoGe nanowires. For each sample, the solid line indicates a fit to the TAPS theory [16]. Inset: \( R \) vs \( T \) dependence of wire MG4 at \( B = 0 \) and 3 T.
change scattering of electrons and thus lead to the breaking of Cooper pairs (the zero-field exchange-scattering time is given by $\tau_B = E_F / 2\pi\langle \tilde{J} \rangle x_m$, where $x_m$ is the fractional concentration of local moments, $\tilde{J}$ is the exchange coupling, and $E_F$ is the Fermi energy); (ii) the vector potential $i = EF / h$, for other fits, $g = 2$ and $\langle \tilde{J} \rangle / E_F = 0$. (b) Normalized critical current of Nb nanowires in a perpendicular magnetic field. (c) Normalized critical current of nanowires MG3a and MG3b at $T = 0.3$ K, measured in parallel and perpendicular magnetic fields. Inset: A typical hysteretic voltage vs current curve.

To obtain the critical current we first derive the semi-theoretical model provides excellent fits to the data (Fig. 2). 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 nonmonotonic 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 exhibit 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 times $\tau_{SO} = 5.0 \times 10^{-14}$ s for MoGe and $2.3 \times 10^{-13}$ s for Nb [19], and the diffusion constant for MoGe $D = 1$ cm$^2$/s [22]. Our theoretical model provides excellent fits to the data (Fig. 2).

An important consequence of the theory is that the behavior of $I_c$ at small fields is dominated by scattering from magnetic impurities, and thus should not depend on the relative orientation of the field and the wire. At larger fields the orbital effect becomes important, and is larger for the perpendicular field orientation. Figure 2(c) shows that our experimental data for samples MG3a and MG3b exhibit these properties. Further evidence in favor of our theoretical picture comes from the fact that the fits to

![Diagram](image-url)
moments. From other superconducting materials, unless a suitable behavior both in MoGe and Nb nanowires suggests that the anomaly is expected to diminish. This is indeed what we observe experimentally [Fig. 3(a)], at our lowest temperature (0.3 K) the anomaly is clearly observed; but at temperatures higher than roughly 1.8 K the anomaly is completely washed out. This loss of the anomaly at higher temperatures is consistent with the absence of any observed negative magnetoresistance for samples MG1-MG3.

Finally, in Fig. 3(b) we display $\tau_B$ as a function of the wire diameter $d$. Assuming that the magnitude of the exchange integral $|J| = 0.2$ eV (Ref. [23] p. 264), we find the magnetic-impurity fraction $x_m$ to be of order of 0.2 at. %. The content of magnetic atoms in fluorinated carbon nanotubes (1.4 wt. %) corresponds to an effective $x_m$ of about 0.003 at. % and is too small to account for the anomaly in $I_c(B)$. If the moments were distributed homogeneously throughout the MoGe then $x_m$, and therefore $\tau_B$, would not depend on the wire diameter. Instead, our 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 [14] samples do not reveal any change in $T_c$, compared to the bulk [22]. The observation of anomalous behavior both in MoGe and Nb nanowires suggests that such behavior is likely to occur for nanodevices made from other superconducting materials, unless a suitable treatment is applied to avoid the formation of local moments.

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FIG. 3. (a) Critical current vs magnetic field for various temperatures. Solid lines are fits to the microscopic theory. Only the $T = 0.3$ K curve was fitted. The same microscopic parameters were used to generate curves at higher temperatures. The rescaling ratio $I_c(0)/I_{tbp}(0)$ was adjusted at each temperature. (b) Exchange-scattering time vs wire diameter for MoGe nanowires. The straight line is the linear fit.

perpendicular- and parallel-field data return very close values for the $\tau_B$, which is proportional to the impurity concentration (Table I).

At high temperatures thermal fluctuations in the moment-orientations make the quenching by the applied field less effective and, hence, higher fields are required to quench the local moments. Thus, the anomaly is expected to diminish. This is indeed what we observe experimentally [Fig. 3(a)]: at our lowest temperature (0.3 K) the anomaly is clearly observed; but at temperatures higher than roughly 1.8 K the anomaly is completely washed out. This loss of the anomaly at higher temperatures is consistent with the absence of any observed negative magnetoresistance for samples MG1-MG3.

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