Magnetic field tuned reentrant superconductivity in out-of-equilibrium aluminum nanowires

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Perpendicular-to-the-plane magnetic field tuned reentrant superconductivity in out-of-equilibrium, quasi-one-dimensional (quasi-1D) planar nanowires is a novel, counterintuitive phenomenon. It was not until recently that a microscopic mechanism explaining the phenomenon as arising from the coexistence of superconductivity with phase-slip driven dissipation was developed. Here we present results on reentrance phenomena in quasi-1D aluminum nanowires with in-plane magnetic fields, transverse and longitudinal to the nanowire axis. The response to in-plane transverse magnetic fields in this geometry is qualitatively different from that previously reported for perpendicular-to-the-plane field experiments and for in-plane longitudinal field studies. The different feature in the data is an abrupt return to the superconducting state with increasing field at values of field corresponding to a single flux quantum for a short wire and a fractional flux quantum for a long wire. Since these findings are dramatically different from those involving perpendicular-to-the-plane magnetic fields, a different mechanism, as yet unidentified, may be at work.

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I. INTRODUCTION

Quasi-one-dimensional (quasi-1D) superconductors provide a unique platform for the study of the out-of-equilibrium properties of the superconducting state [1]. They are also of current interest because they serve as circuit elements in superconducting qubits [2,3]. A superconducting nanowire is in the quasi-1D limit if its transverse dimensions are less than the Ginzburg-Landau (GL) coherence length (ξ_{GL}). However, the nanowire will not be electronically 1D unless its Fermi wavelength is larger than its transverse dimensions. In the case of quasi-1D wires, dissipation at temperatures below the superconducting critical temperature T_C is due to phase-slip processes of the GL order parameter [4–6].

Nanowires coupled to either bulk superconductors, or wider and longer thin film leads, have exhibited a novel and counterintuitive effect referred to as the antiproximity effect, found in electrochemically produced wires [7], and magnetic (H) field induced superconductivity, found in electron beam lithography (EBL) fabricated nanowires [8]. In the latter case, the proposed explanation involves the extinction of an out-of-equilibrium state. Phase slips in the nanowire generate dissipative out-of-equilibrium quasiparticles which diffuse along the length (L) of the wire. Quasiparticles relax and rejoin the condensate upon traveling a distance L_{QP}. If L satisfies the condition $\xi_{GL} < L < L_{QP}$, out-of-equilibrium quasiparticles undergo multiple Andreev reflections at the nanowire/lead interfaces. This process occurs as long as the leads are superconducting and in equilibrium. The multiple Andreev reflections produce a normal current coexisting with the supercurrent (I_S) [9]. One observes this state in the $I - V$ characteristic as a finite voltage plateau where the voltage level ($V_{0,Al}$) is $V_{0,Al} = 0.49\Delta_{0,Al}$ for $H = 0$ Oe with $\Delta_{0,Al} = 1.76k_BT_C$ [9]. $\Delta_{0,Al}$ is half of the Bardeen-Cooper-Schrieffer superconducting energy gap in Al at $T = 0$ K. The application of a weak H field suppresses the order parameter in the leads. Once the leads are driven normal, quasiparticles no longer undergo Andreev reflections at the interfaces and the voltage plateau vanishes. Instead, quasiparticles exit the nanowire because there are states available at the Fermi level in the leads. Therefore, the nanowire reenters the superconducting state because these dissipative quasiparticles are no longer trapped in the nanowire for an extended period of time.

In the present work, we report the results of investigations of the out-of-equilibrium behavior of planar nanowires subjected to in-plane H fields. The in-plane case is different from that of the perpendicular-to-the-plane case because of the substantial in-plane enhancement of the critical field of the leads ($H_{C,Leads,||} \approx 450$ Oe) relative to the bulk critical field, $H_{C,B,Al} \approx 105$ Oe [1,10]. We found that for in-plane longitudinal H fields, nanowires respond in a manner similar to previous measurements with perpendicular-to-the-plane H fields. However for in-plane transverse H fields, nanowires exhibit unexpectedly abrupt reentrance to the superconducting state at H-field values corresponding to a single flux quantum for a short wire and fractional flux quantum for a longer wire. We define the flux quantum over an area determined by the product of the distance between the voltage probes and the nanowire thickness. This striking result cannot be explained by the picture proposed for perpendicular-to-the-plane H-field reentrance.

II. SAMPLE PREPARATION AND EXPERIMENTAL METHODS

We first solvent cleaned a bare Si wafer and then patterned leads, alignment marks, and wirebond pads employing photolithography. Following this, we formed Ti/Au contacts by electron beam evaporation and lifted off the mask. The Al nanowire and leads were patterned in a single step using EBL and a poly(methylmethacrylate) and polymethylglutarimide bilayer resist stack. After exposure and development, we transferred the devices to a dedicated Al evaporator. We affixed the devices to a Cu block and quench deposited Al while holding the Cu block at $T = 77$ K. The deposition rate was ~2–4 Å/sec and the chamber pressure was 1–3 × 10^{-7} Torr

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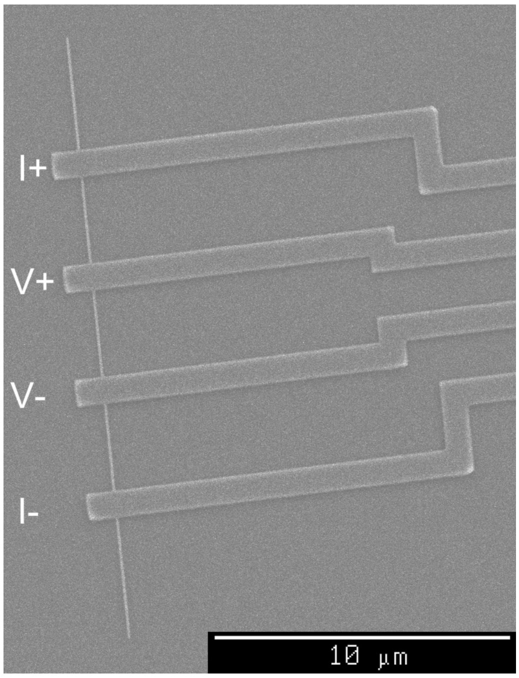

FIG. 1. An SEM micrograph of a device.

during evaporation. Following lift off, we attached the samples to a sample puck using GE Varnish and wirebonded the sample leads to the puck pads. The typical geometry of our devices is shown in the scanning electron microscope (SEM) micrograph of Fig. 1.

We measured the devices in a Quantum Design Physical Properties Measurement System equipped with a ^{3}He refrigerator insert. We employed a four-terminal dc measurement configuration using an external current source and voltmeter. Typically, our resistance measurement resolution was 0.01 Ω. We determined a nanowire's T_C from the half point of the resistive transition in $H = 0$ Oe, and its elastic mean free path l_e from the normal state resistance at $T = 2$ K and the Drude model.

We estimated the zero-temperature dirty limit GL coherence length from $\xi_{GL}(T=0) \approx 0.855(\xi_{BCS} l_e)^{1/2}$, where ξ_{BCS} is the Bardeen-Cooper-Schrieffer coherence length which for Al is $\xi_{BCS} = 1.6\ \mu$m [1,10]. Postmeasurement, we used atomic force microscopy and scanning electron microscopy to determine the dimensions of the nanowire and leads. Table I summarizes the properties of four representative devices. L is defined as the length of the nanowire between the two inner voltage leads. w and t are the width and thickness of the nanowire, respectively. The values of ξ_{GL} in Table I are those at the base temperature of the refrigerator, $T_{base} = 450$ mK.

TABLE I. Sample parameters and H direction.

Sample	L (μm)	w (nm)	t (nm)	T_C (K)	ξ_{GL} (nm)	H dir.
A	2	130	90	1.25	128	Lng.
B	3	130	90	1.23	134	Lng.
C	1.47	105	95	1.22	183	Trn.
D	2.43	105	95	1.23	210	Trn.

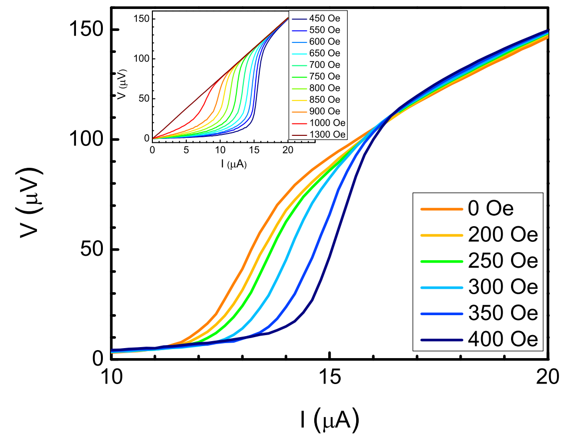

FIG. 2. $I - V$ characteristic of sample A at $T = 460$ mK. The current step size was 200 nA. The H field was applied in plane and longitudinally along the nanowire axis. Inset: High H-field regime.

"H dir." refers to the direction of the in-plane H field, either longitudinal (Lng.) or transverse (Trn.) to the nanowire axis.

III. RESULTS

We first discuss the experiments on samples A and B, which were subjected to in-plane longitudinal H fields. In Fig. 2, we show the H-field dependence of the $I - V$ characteristic for sample A.

For $H \leqslant 450$ Oe, we enhanced superconductivity in the nanowire by applying an H field after having driven it resistive with current. Currents which would drive the wire into a nonzero voltage state at $H = 0$ Oe are pushed towards zero voltage. The voltage level prior to the $I - V$'s intersecting at different H fields is $V_{0,Al} = 93\ \mu$V. As seen in the inset of Fig. 2, in the high-field regime for $H > 450$ Oe, we suppressed superconductivity with higher fields. We drove the nanowire normal for all currents at $H = 1300$ Oe.

For the same device, we observed reentrant behavior in $R(H,T)$. As seen in Fig. 3, which is a plot of $R(T)$ at the

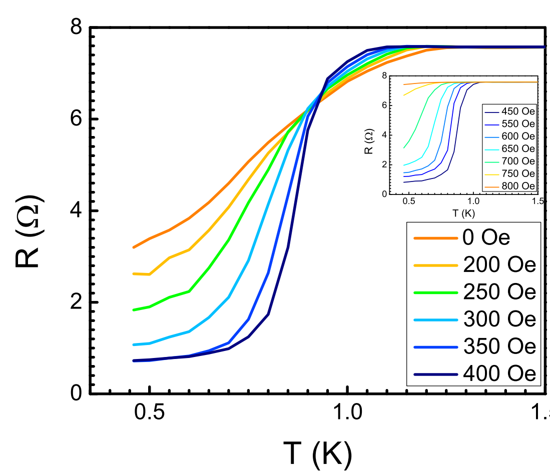

FIG. 3. $R(T)$ of sample A at different H fields with $I = 13\ \mu$A. The H field was applied in plane and longitudinally along the nanowire axis. Inset: High H-field regime.

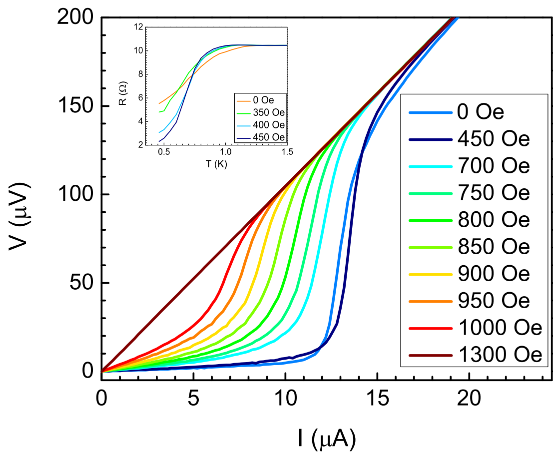

FIG. 4. $I-V$ characteristic of sample B at $T = 460$ mK. The current step size was $200\,nA$. The H field was applied in plane and longitudinally along the nanowire axis. Inset: $R(T)$ in the reentrant regime with $I = 13\ \mu$A.

different H fields, we initially drove the nanowire resistive for $H = 0$ Oe using $I = 13\ \mu$A at all T. Upon increasing the magnetic field to $H = 400$ Oe, the initially broad $R(H = 0\ \text{Oe}, T)$ sharpened and the value of the resistance at the lowest temperatures was $< 1\ \Omega$. The small nonzero resistance was likely due to residual inelastic scattering of quasiparticles. Furthermore, as seen in the inset of Fig. 3, larger H fields completely suppressed superconductivity in the nanowire.

As we increased L, we reduced the reentrant behavior. Longer length nanowires can be in a regime where $L \geqslant L_{QP}$ and a significant fraction of quasiparticles relax prior to reaching the nanowire/lead interfaces. We believe this to be illustrated by sample B, as shown in Fig. 4.

In Fig. 4, the $I-V$ characteristic of sample B exhibited a reentrant regime between $H = 0$ and $H = 450$ Oe. The voltage plateau region occurred at $91\ \mu$V prior to the $H = 0$ and $H = 450$ Oe $I-V$'s intersecting. Furthermore, as seen in the inset of Fig. 4, the $R(T)$ of sample B did not exhibit as

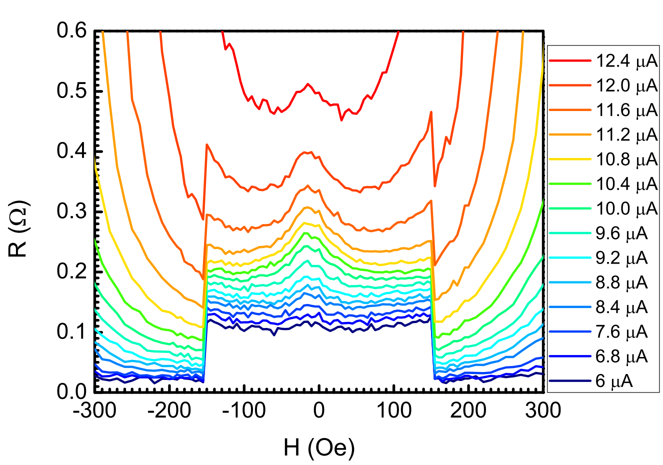

FIG. 5. $R(H, T = 450$ mK) of sample C. Each color trace corresponds to a different applied current. The H field was applied in plane and transverse to the nanowire axis.

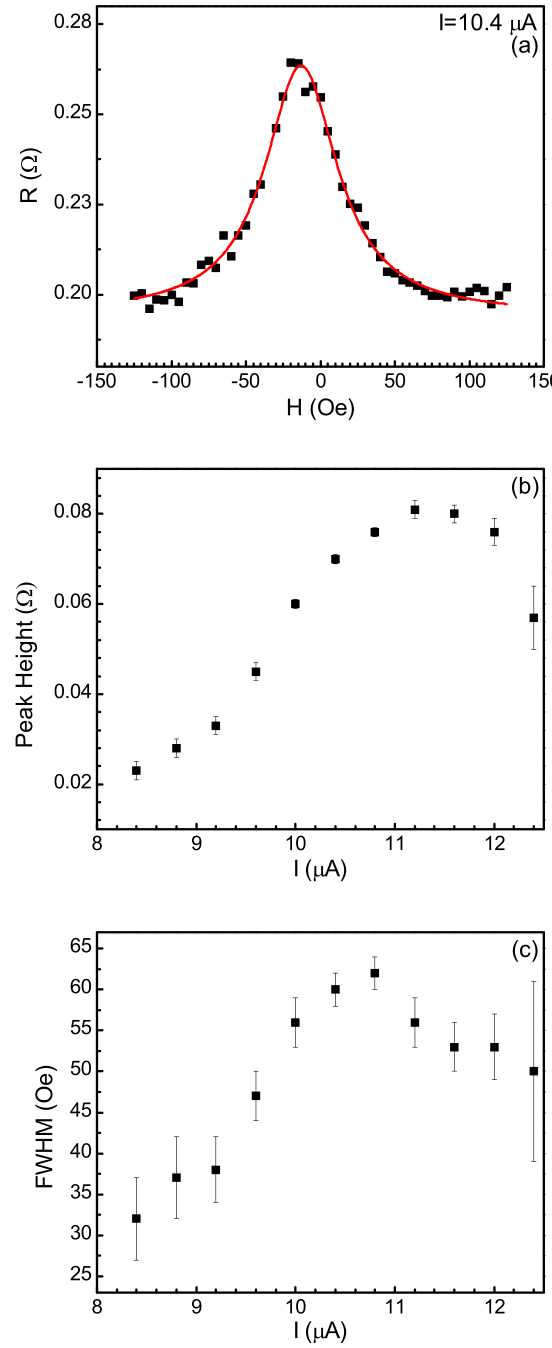

FIG. 6. (a) Lorentzian fit of $R(H)$ for $I = 10.4\ \mu$A, (b) peak height, and (c) FWHM from the $R(H)$ fitting of sample C.

pronounced an enhancement of superconductivity as compared to sample A. We believe this to be a consequence of $L \geqslant L_{QP}$.

We now turn our attention to H fields oriented in plane and transverse to the nanowire axis as measured for samples C and D. In this case, we found different behavior in both nanowires' response to H fields. This is most easily seen in the plot of $R(H, T = 450$ mK).

As seen in Fig. 5, sample C's $R(H, T = 450$ mK) exhibited a flat plateau at low current values. Upon increasing the current, a peak in $R(H)$ near $H = 0$ Oe emerged out of the plateau. Empirically, the $R(H)$ peak could be fit well by a Lorentzian function, as seen in Fig. 6(a). The $R(H)$ peak height and the

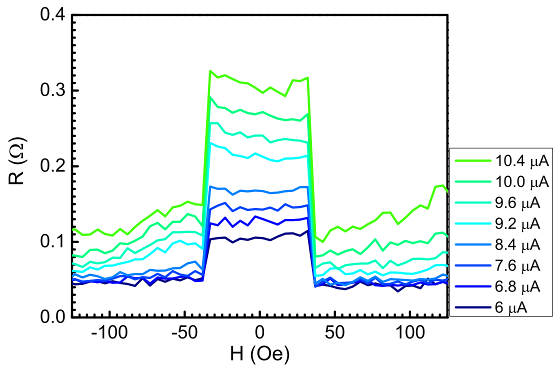

FIG. 7. $R(H,T = 450\text{ mK})$ of sample D. Each color trace corresponds to a different applied current. The H field was applied in plane and transverse to the nanowire axis.

full width at half maximum (FWHM) extracted from the fitting initially grew in height and width as a function of current, as seen in Figs. 6(b) and 6(c). Then they both exhibited a maximum as a function of current. The maximum voltage level of the peak occurred at $V_{peak\ max} \sim 0.33k_BT_C = 3.5\ \mu$V when $I = 11.2\ \mu$A. This is an order of magnitude less than $V_{0,Al} = 91\ \mu$V for sample C. Above $I = 12.4\ \mu$A, we drove the nanowire normal and the peak disappeared.

The striking result for this nanowire was that it also exhibited an abrupt reentrance into the superconducting state. This sharp reentrance occurred when the H field applied to the wire corresponded to a single flux quantum. In other words, $R(H = \pm 155\text{ Oe}, T = 450\text{ mK}) = 0\ \Omega$ occurred when $\frac{\Phi}{\Phi_0} = \frac{H\times tL}{\Phi_0} = 1.05$ and is thus within 5% of a single flux quantum ($\Phi_0 = \frac{hc}{2e}$). This is different from the result of measurements in an in-plane longitudinal H field where the reentrant behavior was gradual over an extended H-field regime.

Sample D was longer than sample C. As seen in Fig. 7, there was a shift in the values of the H fields at which both the $R(H)$ peak and the abrupt reentrance were found. The $R(H)$ peak did not emerge out of the plateau. Instead, we observed peak signatures on the left-hand side of $R(H)$ and on the negative side of the $R(H)$ plateau for $I \geqslant 9.2\ \mu$A. The reentrance occurred at $H = \pm 38$ Oe, corresponding to $\frac{\Phi}{\Phi_0} = 0.42$ or within 5% of $\frac{\Phi}{\Phi_0} = \frac{2}{5}$.

IV. DISCUSSION

In both the in-plane longitudinal and transverse H field, we completely suppressed superconductivity in the nanowire at larger H fields as compared to the bulk H_C. In samples A and B at $T = 460$ mK, the in-plane longitudinal critical field of the nanowire ($H_{C,NW,Lng.}$) is $H_{C,NW,Lng.} = 1300$ Oe. On the other hand, the in-plane transverse critical field of the nanowire ($H_{C,NW,Trn.}$) is $H_{C,NW,Trn.} = 800$ Oe in samples C and D at $T = 450$ mK. The difference between the two configurations is $H_{C,NW,Lng.} \sim \frac{\Phi_0}{wt}$, while $H_{C,NW,Trn.} \sim \frac{\Phi_0}{\xi_{GL}t}$ [1].

We now discuss several possible mechanisms for the observed $R(H)$ peak and abrupt reentrance of samples C and D. We first consider the $R(H)$ peak. It is well known that in electronic systems of reduced dimensionality, weak localization of electrons leads to a small, typically less than 1%, negative change in $R(H)$ [11]. The percentage change in $R(H,T = 450\text{ mK})$ with $I = 8.4\ \mu$A is roughly 13% from peak to plateau. As we increase the current, the percentage change increases. Thus, even when the peak is measurable, the change in $R(H)$ at constant current does not agree with the quasiparticle weak localization picture, which would predict a much smaller effect.

Previously, a similar $R(H)$ peak was reported in out-of-equilibrium superconducting Al nanowires [12]. The authors developed a model for the observed $R(H)$ peak near T_C by accounting for the H-field dependence of L_{QP}. In their case, they qualitatively compared their observed $R(H)$ peak with a non-Lorentzian peak function and suppressed the peak by increasing the current. In our case, we observed a Lorentzian form for $R(H)$ in Fig. 6(a) and a more complicated current dependence as seen in Figs. 6(b) and 6(c).

In general, the normal-metal–superconducting boundary resistance due to charge conversion of a quasiparticle current to I_S depends on the quasiparticle lifetime τ_{QP}. τ_{QP} depends upon the pair-breaking time (τ_{pb}) and the inelastic electron-phonon relaxation time (τ_E) at the Fermi surface [13]. In out-of-equilibrium superconductors, the H-field dependence of τ_{pb} is given by

$$\tau_{pb}(H) = \frac{\hbar}{1.76k_BT_C}\frac{H^2_{C,NW,Trn.}(T=0)}{H^2}, \quad (1)$$

where $H_{C,NW,Trn.}(T=0)$ is the zero-temperature in-plane transverse critical field of the nanowire [13]. The presence of an H field will reduce L_{QP}. Computing $\tau_{QP}(I,H)$ depends on the details of the microscopic model and experiment [12–14]. There is no universal form for τ_{QP}.

At large out-of-equilibrium values of current, the $(H - H_0)^2$ dependence in $R(H)$ is due to the H-field dependence of $1/\tau_{pb}$. H_0 is a phenomenological offset field. The peak height and FWHM of $R(H)$ could be related to τ_E. In a short wire ($L < L_{QP}$), such as sample C, quasiparticles do not relax within its length. In a longer wire, $L > L_{QP}$, such as sample D, quasiparticles do relax. Using an expression for $L_{QP}(T)$ valid near the critical current I_C for $H = 0$ Oe suggests that $L_{QP} \approx 1.7\ \mu$m at $T = 450$ mK for both samples [15]. In addition, I_C may be enhanced in an H field leading to a negative $R(H)$ [16]. However, the main caveat is that both approaches compute $L_{QP}(T)$ and $I_C(H,T)$ using time-dependent Ginzburg-Landau theory, which is strictly valid only near T_C. Thus it is fair to state that we have no definitive explanation for the $R(H)$ peak.

We now turn to the matter of the abrupt in-plane transverse H-field reentrance phenomenon. At this writing, we have no detailed model to explain the data, only suggestions as to what might be involved. The apparent quantized reentrance behavior could be a signature of the phase-sensitive nature of quasiparticles in Andreev bound states (ABS) [17,18]. The lead/nanowire/lead system could effectively be a long superconductor–normal-metal–superconductor (S-N-S) Josephson junction when the nanowire is out of equilibrium and resistive and the leads are superconducting. Then I_S is carried between the two superconducting leads and through the nanowire by quasiparticles undergoing Andreev reflections at the nanowire/lead interfaces. The ABS energies, relative to

E_F, for a S-N-S junction are

$$E^{(n)}_{A\pm} = \frac{\hbar v_F}{2L}[2\pi(n+1/2) \pm \gamma], \quad (2)$$

where v_F is the Fermi velocity, L is the length of the junction, n is an integer, and γ is the gauge invariant phase difference across the junction [18]. We can change the value of $E^{(n)}_{A\pm}$ by applying an H field in the plane of the junction via $\gamma = \gamma_0 + 2\pi\frac{\Phi}{\Phi_0}$ [1]. Pursuing the analogy between the lead/nanowire/lead system and a S-N-S junction, the flux dependence of γ could change the value of $E^{(n)}_{A\pm}$. An energy level shift like this may be the source of the relationship between the H field at reentrance and the flux quantum.

Alternatively, the abrupt reentrance in sample A could be due to a single vortex entering the nanowire and producing currents which go in the opposite direction to screening currents. This process would be similar to the Little-Parks effect in superconducting loops where $T_C(H)$ is periodically enhanced when integer values of $\frac{\Phi}{\Phi_0}$ thread through the loop [19]. The Little-Parks effect also manifests itself as minima in $R(H)$ when $\frac{\Phi}{\Phi_0}$ is an integer for $T \lesssim T_C(H=0)$. However, in the nanowire, only a single vortex penetrates the nanowire and enhances T_C. When T_C increases, the energy barrier for thermally activated phase slips increases and thus the resistance drops [1].

Furthermore, low H-field reentrance has been seen in mesoscopic superconducting Al loops [20,21]. For H fields such that $\frac{\Phi}{\Phi_0} < 2$, additional minima and maxima in $R(H)$ appeared and were termed anomalous Little-Parks oscillations or M-like anomalies [20,21]. The authors found that the width of the M-shaped anomaly corresponded to an H-field value where $\frac{\Phi}{\Phi_0} = 1$ threaded through the area of the lines defining the loop [21]. Whether the reentrance mechanism in samples C and D is related to this is not known at the time.

V. CONCLUSION

In conclusion, we have observed magnetic field reentrant superconductivity in Al nanowires in an in-plane H-field orientation both longitudinal and transverse to the nanowire axis. Nanowires in an in-plane longitudinally oriented H field exhibit behavior like that previously seen in Zn nanowires [8,9]. The most striking feature of the behavior of nanowires in an in-plane transverse field is the abrupt reentrance. It may be a consequence of the phase-sensitive nature of Andreev bound states found in the system of the nanowire and superconducting leads or an interplay between vortex and screening currents in the nanowire. This study provides a further challenge to the theory of H-field tuned reentrant superconductivity in nanowires.

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