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Current crowding effects in superconducting corner-shaped Al microstrips

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The superconducting critical current of corner-shaped Al superconducting microstrips has been investigated. We demonstrate that the sharp turns lead to asymmetric vortex dynamics, allowing for easier penetration from the inner concave angle than from the outer convex angle. This effect is evidenced by a rectification of the voltage signal otherwise absent in straight superconducting strips. At low magnetic fields, an enhancement of the critical current with increasing magnetic field is observed for a particular combination of field and current polarity, confirming a theoretically predicted competing interplay of superconducting screening currents and applied currents at the inner side of the turn. © *2013 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4790625]

The ability of superconductors to carry electricity without resistance holds in a restricted current density range $j < j_{max}$. Several physical mechanisms can be identified as responsible for determining j_{max} such as the presence of pinning centers, the edge or surface barriers for vortex penetration or eventually when the pair-breaking current, j_{pb}, is reached.

In principle, it is possible to attain the ultimate limit $j_{max} = j_{pb}$ by properly choosing the dimensions of the superconducting strip. Indeed, if the width w of the strip is such that $w < 4.4\xi$, where ξ is the coherence length, vortices cannot fit into the sample[1] and therefore j_{max} cannot be limited by a vortex depinning process. In 1980, Kupriyanov and Lukichev[2] were able to determine theoretically j_{pb} for all temperatures, by solving the Eilenberger equations, and only two years later their predictions were experimentally confirmed by Romijn *et al.*[3] using *straight* Al strips. These works focused on the case where $w \ll \Lambda$, with $\Lambda = 2\lambda^2/d$ the Pearl length,[4] λ the London penetration depth, and d the thickness of the superconductor.

Recently, a renewed interest for understanding the limiting factors of j_{max} in *non-straight* strips has arisen, partially motivated by the ubiquitous presence of sharp turns in more realistic architectures as those used in the superconducting meanders for single photon and single electron detectors.[5,6]

Early, theoretical calculations by Hagerdorn and Hall[7] showed that a sharp bend in a superconducting wire leads to current crowding effects at the inner corner of the bend, which in turn reduces the total critical current when compared to a straight wire. Not only sharp angles along the superconducting bridge, but any sudden change in the cross section of the wire, can lead to a reduction of the critical current. For instance, it has been pointed out in Ref. 8 that a sudden increase in the cross section of a transport bridge leads to severe modifications of the voltage-current characteristics rendering unreliable those measurements performed in cross-shaped geometries. More recently, Clem and Berggren[9] have theoretically demonstrated that sudden increases in the cross section of a transport bridge, as those caused by voltage leads, also produce current crowding effects and the consequent detriment of the critical current, similarly to right-angle bends. These predictions have been independently confirmed experimentally by Hortensius *et al.*[10] and by Henrich *et al.*[11] in submicron scale samples of NbTiN and NbN, respectively, and found to be also relevant in larger samples.[12]

The effect of a magnetic field applied perpendicularly to the plane containing the superconducting wire with a sharp turn has been discussed in Refs. 10 and 13. Strikingly, in Ref. 13, it is theoretically predicted that due to compensation effects between the field induced stream-lines and the externally applied current at the current crowding point, the critical current of thin and narrow superconducting bridges ($\xi \ll w \ll \Lambda$) should *increase* with field for small fields values and for a particular polarity of the applied field.

In this work, we provide experimental confirmation of the theoretical predictions of Ref. 13 and show that current crowding leads also to a clearly distinct superconducting response for positive and negative fields (or currents), making these asymmetric superconducting nanocircuits potentially voltage rectifiers.

The samples investigated were all co-fabricated on the same chip and consist of electron-beam lithographically defined Al structures of thickness $d = 67 \pm 2$ nm, deposited by rf sputtering on top of a Si/SiO_2 substrate. We focus on two different geometries. Sample S90 consists of a 3.3 μm wide transport bridge with a 90° corner equidistant from two voltage probes separated 9.6 μm from the inner angle of the sharp bend. Similarly, S180 is a conventional straight transport bridge 3.7 μm wide and with voltage probes separated by 20.9 μm. These dimensions depart from the nominal values and were obtained via atomic force microscopy as

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shown in Figures 1(a) and 1(b). For all samples, we found a residual resistivity ratio, $\rho(2\,\mathrm{K})/\rho(300\,\mathrm{K})$, between 2.2 and 2.5.

The field dependence of the superconducting-to-normal metal transitions, $T_c(H)$, determined as $0.95R_N$, where R_N is the normal state resistance, and using an ac-current[14] of $1\,\mu$A, is basically the same for the two samples studied (see Figure 1(c)). This similarity of the phase boundaries allows us to make reliable and direct comparisons between the two samples without the necessity to work with reduced temperature or field units. The critical temperature at zero field is $T_{c0} = 1.320 \pm 0.008\,\mathrm{K}$ and the superconducting coherence length obtained from the Ginzburg-Landau approximation is $\xi(0) = 121 \pm 3\,\mathrm{nm}$. The BCS coherence length for Al of similar characteristics[3] (T_{c0} and d) as the one used here is $\xi_0 = 1320\,\mathrm{nm}$, indicating that our Al falls in the dirty limit $\ell \ll \xi_0$, with ℓ the electronic mean free path. Using the relation $\xi(0) = 0.855\sqrt{(\xi_0 \ell)}$, we deduce $\ell \sim 15\,\mathrm{nm}$. An independent estimation of $\ell \sim 17\,\mathrm{nm}$ can be obtained from the normal state resistivity $\rho = 2.0 \pm 0.1 \cdot 10^{-8}\ \Omega\ \mathrm{m}$, and taking[3] $\rho\ell = 4 \cdot 10^{-16}\ \Omega\ \mathrm{m}^2$. In the dirty limit, the magnetic penetration depth is given by $\lambda(0) = \lambda_L(0)\sqrt{\xi_0/\ell} \approx 145\,\mathrm{nm}$, where $\lambda_L(0) = 16\,\mathrm{nm}$ is the London penetration depth. For thin film geometry with a perpendicular external field, we need to use the Pearl length[4] $\Lambda = 2\lambda^2/d$. In the considered samples, $\Lambda > 2w$ for $T > 1.19\,\mathrm{K}$.

Let us now concentrate on the current-voltage characteristics, $V(I)$, of the considered systems. At zero external field, the $V(I)$ curves and, in particular the critical current, I_c, should be uniquely defined, irrespective of the direction of the applied current. This independence on the direction of the current persists at all fields for the S180 sample, but does not hold for the S90 sample. Indeed, on the one hand, the outer angle of the sharp corner has a larger surface nucleation critical field H_{c3} (a factor $\sim$1.16 higher for the S90) when compared to the critical field at the inner corner[15] thus making the outer corner a point of enhanced superconductivity.[6] On the other hand, stream-lines of the applied current tend to conglomerate at the inner corner,[7] depleting the order parameter at that place. Notice that both effects, larger surface nucleation field and lower applied current density at the outer corner, share the same origin in the impossibility of both, screening or applied currents, to reach the tip of the bend. It is worth mentioning that the analysis by Clem and Berggren[9] based on London equations, i.e., neglecting the depletion of the order parameter, also leads to asymmetric vortex penetration. This shows that the key ingredient for observing this effect is the current crowding at the inner corner of the bend and the consequent reduction of the Gibbs free-energy barrier against nucleation of a vortex.

The reduction of the surface barrier for vortex penetration[9,13] together with an applied current such that the Lorentz force pushes vortices from the inner towards the outer corner, corresponds to the onset of dissipation. However, if the current is reversed, vortices will not penetrate from the outer corner (where total current is nearly zero) but rather symmetrically from the straight legs of the bridge.[13] As a consequence of this different nucleation position and nucleation condition for the two opposite current directions, it is predicted that such a simple corner shape wire will give rise to asymmetric $V(I)$ characteristics and therefore to a vortex ratchet effect.

In order to demonstrate the existence of vortex motion rectification, we submitted the samples to an ac current excitation of zero mean, I_{ac}, while measuring simultaneously the dc drop of voltage V_{dc}. The results of these measurements $V_{dc}(I_{ac})$ are presented in Figure 2 for both samples. The chosen temperature $T = 1.22\,\mathrm{K}$ is such that $4.4\xi = 1.9\mu\mathrm{m} < w = 3\mu\mathrm{m} < \Lambda = 8.3\mu\mathrm{m}$ ensuring the existence of vortices within the superconductor. There are several points that deserve to be highlighted here, (i) rectification effects are almost completely absent in the S180 sample, (ii) there is a very strong ratchet signal for the S90 sample, (iii) the ratchet signal changes polarity at zero field. Ideally, we expect no ratchet effect at all from the S180 sample, however, the fact that both voltage contacts are on the same side of the strip already imposes a weak asymmetry in the system which can lead to asymmetric vortex penetration.[16,17] In any case, the rectification signal obtained in the S180 sample is negligible in comparison to that observed in the sample with the sharp turn. The fact that the rectification signal is positive at positive fields for the S90 sample, and according to the sign convention depicted in Fig. 1(a), we conclude that the easy direction of vortex flow is from the inner corner towards the outer corner, in agreement with the theoretical findings.[13] In Fig. 3, we show how the ratchet signal progressively disappears as the temperature approaches 1.280 K. For temperatures above this value, vortices cannot fit anymore in the bridge and consequently the difference between the two corners vanishes. Similar ratchet effects due to surface barrier

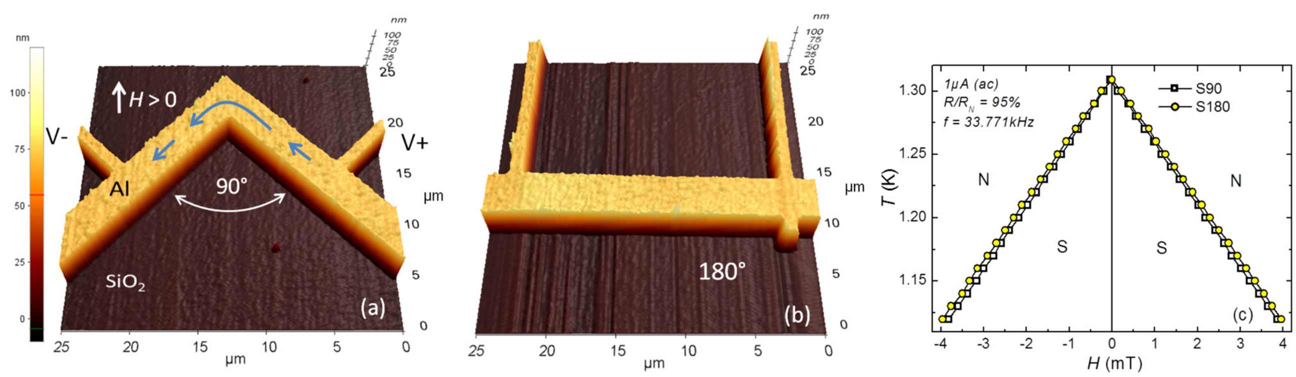

FIG. 1. Atomic force microscopy images of the two superconducting Al bridges studied: (a) S90 and (b) S180. Panel (c) shows the superconducting(S)-normal(N) H–T phase diagrams for both samples.

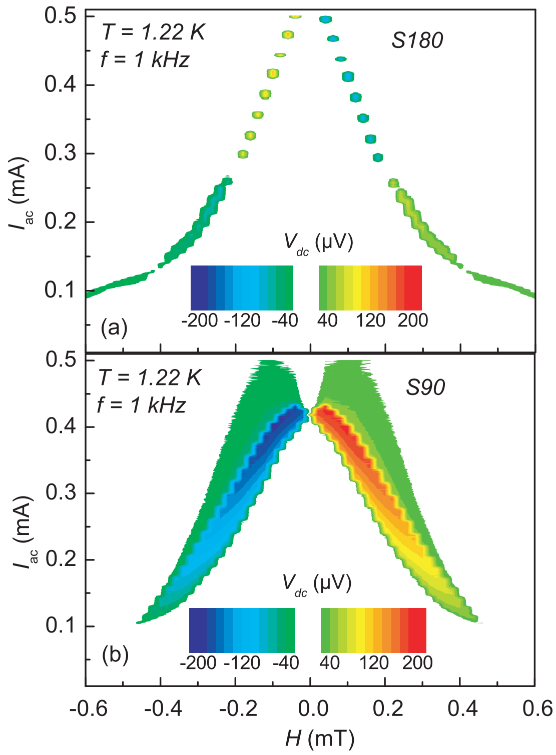

FIG. 2. Contour plot of the dc voltage $V(dc)$ as a function of magnetic field and ac current amplitude at $T = 1.220$ K, and frequency of 1 kHz for sample S180 (a) and sample S90 (b).

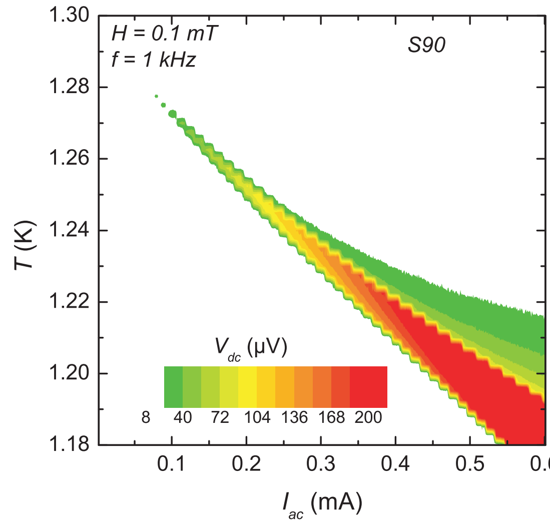

FIG. 3. Contour plot of the dc voltage $V(dc)$ as a function of temperature and ac current amplitude at $H = 0.1$ mT, and frequency of 1 kHz for the sample S90.

asymmetry have been recently reported[18] in high-Tc superconducting asymmetric nanobridges, with one side straight and the other having a constriction with an angle of 90°.

Notice that the ratchet effect here described results from the crowding of the applied current at the inner corner, and it would exist even if no screening currents were present. Let us now consider the additional effect of the screening currents. As it has been pointed out in Ref. 13 based on both, London and Ginzburg-Landau theories, for a given direction of the applied current (as indicated in Fig. 1(a)), a positive magnetic field will reinforce the total current (i.e., applied plus screening) at the inner corner and therefore the critical current will decrease as the field intensity increases. On the contrary, a negative applied magnetic field will induce a screening current which partially compensates the applied current at the inner corner and a field dependent increase of the critical current is expected.[13] We have experimentally confirmed this prediction by measuring the critical current using a voltage criterion of 1 μV as a function of field and current orientation. The results are presented in Figure 4(a) for three different temperatures and for the case where $\xi < w < \Lambda$. For positive current and field (as defined in Fig. 1(a)), we observe a monotonous decrease of I_c. In contrast to that, for positive current and negative field, a clear enhancement of I_c with field is observed for $H < H_{max}$, whereas for $H > H_{max}$ a monotonous decrease of I_c is recovered as a consequence of antivortices induced by the magnetic field[13] that starts to penetrate the sample. Reversing the applied current should lead to the opposite behavior, as indeed observed in

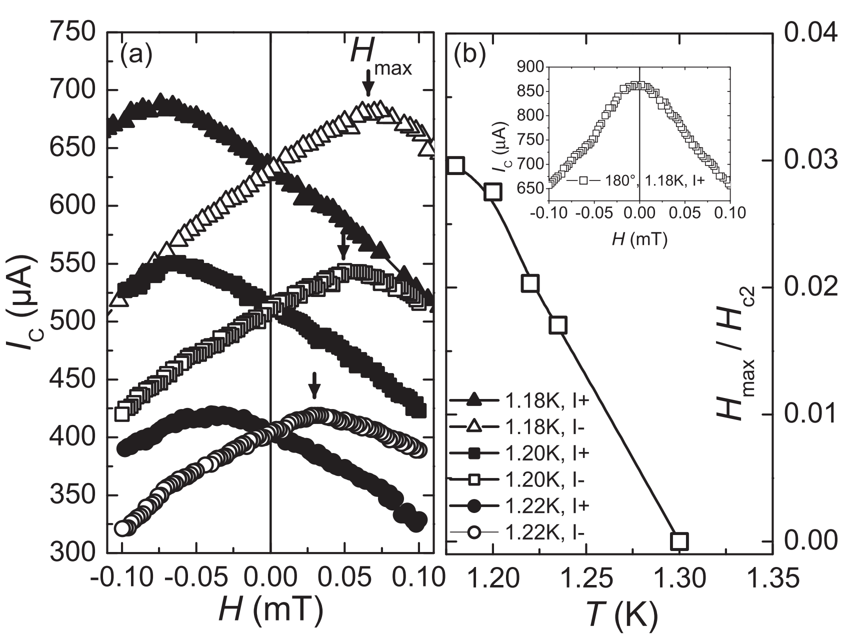

FIG. 4. The critical current I_c of sample S90 as a function of applied magnetic field for both polarities of the applied current (a). Panel (b) shows the maximum field H_{max} (normalized to the critical magnetic field H_{c2}) as a function of temperature. The inset in (b) shows for comparison the critical current of sample S180 versus magnetic field at positive applied currents.

Fig. 4(a). This double test for all polarities of current and field also permits us to accurately determine the value of zero external field at the point where both curves cross each other. This has been convincingly confirmed by independent measurement of the remanent field in the S180 sample. For the sake of comparison, in the inset of Fig. 4(b), we show the critical current for the S180 sample as a function of field. Notice that for this sample, the peak of maximum critical current is located at $H = 0$, in contrast to the behavior observed in sample S90. It is important to point out that according to the theoretical prediction of Ref. 13, the curves in Fig. 4(a) should correspond to sharp inverted V-shapes if a London model is used. However, using Ginzburg-Landau formalism the calculations yield a rounded top, which becomes sharper the smaller the ratio ξw.

The compensation field H_{max} is expected to depend on temperature since it is determined by the screening currents. In Fig. 4(b), we plot the temperature dependence of $H_{max}/H_{c2}(T)$ where it can be noticed that this compensation field H_{max} is a small fraction of the upper critical field $H_{c2}(T)$ in agreement with the theoretical calculations.[13]

To summarize, the superconducting properties of corner-shaped Al microstrips have been investigated. We show that sharp 90° turns lead to asymmetric vortex penetration, being easier for vortices to penetrate from the inner side than from the outer side of the corner. We provide experimental confirmation of the predicted[13] competing interplay of superconducting screening currents and applied currents at the inner side of the corner. We prove that current crowding leads to a distinctly different superconducting response for positive and negative fields (or currents). These effects are evidenced also by a field dependent critical current enhancement and also by a strong rectification of the voltage signal, thus making these asymmetric superconducting nanocircuits to act as voltage rectifiers. Complementary measurements done in samples with 30° and 60° corners (not shown) reproduce the results presented here, i.e., ratchet signal and field-induced increase of critical current.

A substantial part of the technological implications of our observations, directly concerning the architecture used in superconducting single photon detectors, has been already pointed out in the discussions of Ref. 13. However, there are at least two more important consequences that we should mention. First, the rectification effect resulting from the reduction of the energy barrier for vortex entrance implies that the commonly used transport bridge geometry with two voltage probes on one side will give rise to (unwanted) rectification signals. This effect has been largely ignored in most of the reports concerning vortex ratchet, and deserves a more in-depth experimental study. Second, the current crowding effects likely play a key role in understanding the puzzling morphology of flux avalanches in nanostructured superconducting films as reported in Refs. 19–21.

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[1]K. K. Likharev, Rev. Mod. Phys. **51**, 101 (1979).
[2]M. Yu. Kupriyanov and V. F. Lukichev, Sov. J. Low Temp. Phys. **6**, 210 (1980).
[3]J. Romijn, T. M. Klapwijk, M. J. Renne, and J. E. Mooij, Phys. Rev. B **26**, 3648 (1982).
[4]J. Pearl, Appl. Phys. Lett. **5**, 65 (1964).
[5]See L. N. Bulaevskii, M. J. Graf, and V. G. Kogan, Phys. Rev. B **85**, 014505 (2012), and references therein.
[6]Notice that the nucleation of superconductivity itself is also influenced strongly by the presence of the corners. See, for example, GL treatment of this problem in a wedge in F. Brosens, V. M. Fomin, J. T. Devreese, and V. V. Moshchalkov, Solid State Commun. **144**, 494 (2007) and in S. N. Klimin, V. M. Fomin, J. T. Devreese, and V. V. Moshchalkov, Solid State Commun. **111**, 589–593 (1999).
[7]F. B. Hagedorn and P. M. Hall, J. Appl. Phys. **34**, 128 (1963).
[8]A. V. Silhanek, J. Van de Vondel, V. V. Moshchalkov, A. Leo, V. Metlushko, B. Ilic, V. R. Misko, and F. M. Peeters, Appl. Phys. Lett. **92**, 176101 (2008).
[9]J. R. Clem and K. K. Berggren, Phys. Rev. B **84**, 174510 (2011).
[10]H. L. Hortensius, E. F. C. Driessen, T. M. Klapwijk, K. K. Berggren, and J. R. Clem, Appl. Phys. Lett. **100**, 182602 (2012).
[11]D. Henrich, P. Reichensperger, M. Hofherr, J. M. Meckbach, K. Il'in, M. Siegel, A. Semenov, A. Zotova, and D. Yu. Vodolazov, Phys. Rev. B **86**, 144504 (2012).
[12]J. I. Vestgarden and T. H. Johansen, Supercond. Sci. Technol. **25**, 104001 (2012).
[13]J. R. Clem, Y. Mawatari, G. R. Berdiyorov, and F. M. Peeters, Phys. Rev. B **85**, 144511 (2012).
[14]The transport measurements have been done with the sample immersed in superfluid ^{4}He for minimizing heating effects. Special care has been taken to avoid the high frequency noise signal (above ~1 MHz) using a pi-filter.
[15]V. A. Schweigert and F. M. Peeters, Phys. Rev. B **60**, 3084 (1999).
[16]D. Y. Vodolazov and F. M. Peeters, Phys. Rev. B **72**, 172508 (2005).
[17]D. Cerbu, V. N. Gladilin, J. Cuppens, J. Fritzsche, A. V. Silhanek, J. Tempere, J. T. Devreese, V. V. Moshchalkov, and J. Van de Vondel, "Vortex ratchet induced by controlled difference between the surface barriers" (unpublished).
[18]K. Kajino, K. Fujita, B. An, M. Inoue, and A. Fujimaki, Jpn. J. Appl. Phys., Part 1 **51**, 053101 (2012).
[19]N. Nakai, M. Machida, Physica C **470**, 1148 (2010).
[20]T. Tamegai, Y. Tsuchiya, Y. Nakajima, T. Yamamoto, Y. Nakamura, J. S. Tsai, M. Hidaka, H. Terai, and Z. Wang, Physica C **470**, 734 (2010).
[21]M. Motta, F. Colauto, W. A. Ortiz, J. I. Vestgarden, T. H. Johansen, J. Cuppens, V. V. Moshchalkov, and A. V. Silhanek, e-print arXiv:1109.2532.