

Switching current modulations induced by vortices rearrangement in mesoscopic superconducting loops

S. Adam,^{*} X. Hallet, and L. Piraux*Institute of Condensed Matter and Nanosciences, Université catholique de Louvain, Croix du Sud 1, B-1348 Louvain-la-Neuve, Belgium*

D. Lucot and D. Mailly

Laboratoire de Photonique et de Nanostructures (LPN-CNRS), Route de Nozay, F-91460 Marcoussis, France

(Received 4 May 2011; revised manuscript received 13 July 2011; published 12 September 2011)

Periodic modulations in the switching current of niobium mesoscopic thin loops have been observed as a function of a perpendicular magnetic field. These modulations reflect the formation of specific vortices configurations in the arms and in the contacts of the loops. The voltage measured just before the current-driven transition to the normal state takes either zero or nonzero values depending on whether the vortices are efficiently pinned or move under the action of the applied current. This switching voltage varies sharply in the vicinity of the regularly spaced matching fields at which the switching current is minimum. This reflects the rearrangement of the vortices pattern from an unstable configuration into a more stable one. In addition, multimodal switching current distributions obtained at a constant field highlight that the few vortices involved in the field-cooling process freeze into a limited number of configurations. Finally, the spacing between the matching fields allows us to extract the critical field for complete vortex expulsion of the samples. Electrical transport measurements appear to be an efficient tool to determine the superheating field of submicrometer-wide structures, which is not obvious when measured by scanning probe microscopy.

DOI: [10.1103/PhysRevB.84.104512](https://doi.org/10.1103/PhysRevB.84.104512)

PACS number(s): 74.25.Uv, 74.78.Na, 74.25.Sv, 74.25.F–

I. INTRODUCTION

Probing the entrance and the (re)arrangement of vortices in mesoscopic type-II superconducting structures is a long-standing issue, which is still the subject of intensive work.^{1–5} The reduction of the sample sizes down to the coherence length or the magnetic penetration depth is known to deeply modify the vortex structure, especially due to the competition between the vortex-vortex interaction and the vortex-boundary interaction. Reducing the sample size perpendicular to the applied magnetic field also widens the magnetic-field region over which a sample stays free of vortices.^{6,7} Indeed, to penetrate into the interior of a superconductor, vortices must overcome the well-known Bean-Livingston surface barrier.^{8,9} The latter results from the competition between an attractive force toward the surface due to an image antivortex located outside the superconductor, and a repulsive force that comes from the circulating surface currents. This energy barrier vanishes at the so-called critical field for complete vortex expulsion (or more commonly, the superheating field B_{SH}). This characteristic field is inversely proportional to the square of the sample size perpendicular to the applied field¹⁰ (i.e., $B_{SH} \propto \Phi_0/W^2$, where $\Phi_0 \equiv \frac{h}{2e} = 2.07 \times 10^{-15} \text{ T m}^2$ is the flux quantum and W is the width), so that a mesoscopic superconductor exhibits a complete metastable Meissner state up to a higher magnetic field than the bulk value B_{c1} .

Insofar as the applied magnetic field is higher than the superheating field, a typical field-cooling procedure results in the freezing of the vortices at a temperature that is very close to the critical temperature T_c .^{1,6} The exact location of the vortices depends mainly on the sample size and shape as well as on the number of vortices involved. It is well known that at low fields, the strong repulsive interaction with the circulating currents tends to align the vortices along the center of the strip. This leads to the formation of a one-dimensional chain.¹¹ As the

magnetic field is increased, vortices become closer together, leading to an increase of the vortex interaction energy. At some field, the anisotropic lattice becomes unstable and splits into two chains. Similar rearrangements occur at regularly spaced matching fields B_N that correspond to the transition from N to $N + 1$ vortices rows.¹² Interestingly, the rearrangement of an unstable vortices pattern into a more stable one goes hand in hand with a minimum of the critical current.^{13,14} One way to probe the relative stability of the frozen vortices configurations is thus to study their response to a direct transport current.

Recently, Michotte *et al.*¹⁵ have shown on rectangular niobium loops that studying the evolution of the switching current as a function of a perpendicular magnetic field is an efficient tool to probe the fluxoid quantization effect at temperatures far below T_c . In particular, they highlighted the impact of the current leads location, either symmetrically or asymmetrically positioned around the loop. This latter point was discussed theoretically by Berdiyrov *et al.*,¹⁶ who mentioned the ability to detect the entry of individual vortex by transport measurements. The field scale $B_{\Phi_0} = \frac{\Phi_0}{\pi r_M^2}$ is given by the area enclosed by the mean radius r_M of the loop (Φ_0 is the flux quantum). This periodicity for the fluxoid quantization is rather different from the one associated with the rearrangement of the vortices configurations, which is directly related to the superheating field.¹³ These two behaviors can be discriminated unambiguously because the characteristic fields B_{Φ_0} and B_{SH} depend differently on the sample sizes.

In this paper, the vortices arrangements that occur during the field cooling of thin mesoscopic niobium loops are probed by electrical transport measurements. Periodic modulations of the switching current as a function of a perpendicular magnetic field are observed with a field spacing much higher than the periodicity that governs the fluxoid quantization effect. The local switching current minima are related to unstable vortices

TABLE I. Critical temperature at half the normal state resistance for the loops ($T_{c,\text{loop}}$) and their contacts ($T_{c,\text{contact}}$), inner (r_i) and outer (r_o) radii, branch width ($r_o - r_i$), and width of the narrowest contact of the loops L1, L2, and L3. The critical width (i.e., the width of the cross section where the critical current density is first reached) is underlined.

	$T_{c,\text{loop}}$ (K)	$T_{c,\text{contact}}$ (K)	r_i (nm)	r_o (nm)	Branch width (nm)	Contact width (nm)
L1	7.75	8.06	215	365	<u>150</u>	380
L2	7.75	8.02	420	580	<u>160</u>	<u>300</u>
L3	7.65	8	255	715	460	<u>400</u>

patterns, whose rearrangement causes a cancellation of the critical voltages (i.e., measured just before the current-driven transition to the fully normal state). In addition, multimodal distributions of the switching current reveal that the few vortices involved in the field-cooling process can freeze into different configurations, even at a single field. Finally, the critical field for complete vortex expulsion is determined from the spacing between the matching fields, in good agreement with recent studies based on scanning probe microscopy.^{6,7} Here, the main benefit of the electrical transport measurements is that they allow one to probe the superheating field in the narrower structures, with no limitation due to the spatial resolution of the experimental setup.

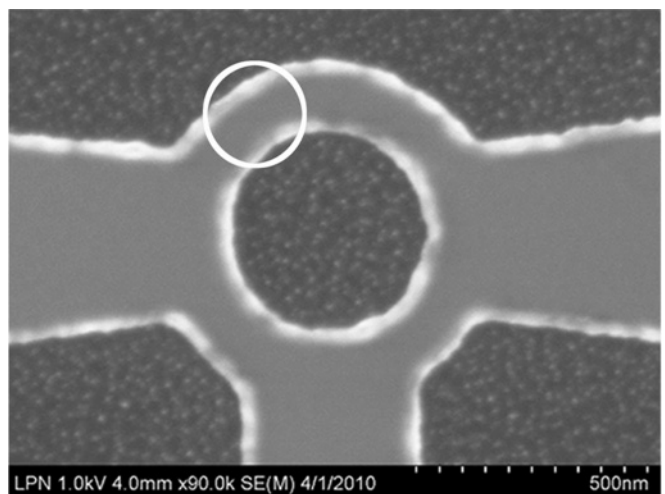
The paper is organized as follows. The experimental details (sample shape and measurement setup) are described in Sec. II. The results are presented in Sec. III and are discussed in Sec. IV. The conclusions are given in Sec. V.

II. EXPERIMENTAL DETAILS

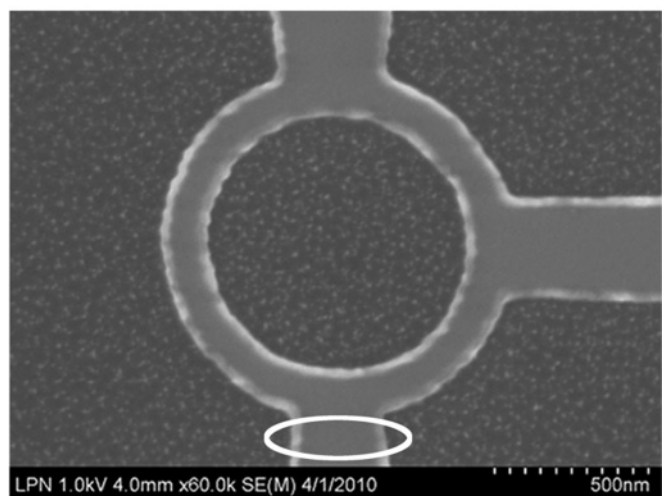
The superconducting loops were fabricated using the same 20-nm-thick niobium film. The film was obtained by reactive dc magnetron sputtering at room temperature from a pure (99.9%) Nb target at a total Ar pressure of 9.75 mTorr (1000 W dc power). The multicontact structures were obtained by SF_6 reactive ion etching using a 40-nm-thick Al_2O_3 mask patterned with standard e-beam lithography. The loops and the contacts are thus made from the same superconducting material. Typical configurations are shown in Fig. 1. All the experimental results reported in this paper were obtained by using the symmetrical contacts that split up in two (not shown), so that a pseudo-four-contacts arrangement is used to apply the bias and measure the resulting voltage. The electrical transport measurements were performed in a He flow pulse-tube cryocooler with a base temperature of 1.5 K. All the measurement lines were filtered using a combination of RC and LC filters operative up to 40 GHz. The normal-superconductor transition is measured at low direct current and spreads from ~ 8 K (for the widest parts, i.e., the contacts) down to around 7.6–7.4 K (depending on the loop branch width). The critical temperatures at half the normal state resistance are summarized in Table I for the loops and their contacts. The normal state resistivity determined just above the transition is around $10 \mu\Omega \text{ cm}$.

The Ginzburg-Landau coherence length at zero temperature has been determined from the relation $\xi(0) = [\Phi_0/2\pi B_{c2}(0)]^{1/2}$, where $B_{c2}(0) = 0.69T_c | \frac{dB_{c2}(T)}{dT} |_{T=T_c}$ is the

reduced upper critical field at zero temperature.¹⁷ The temperature dependence of B_{c2} has been monitored for each loop in a perpendicular magnetic field up to 3 T. The expected linear dependence at $T \approx T_c$ is verified for all the samples¹⁸ and one obtains that $\xi(0) \sim 9.5$ nm. Furthermore, the magnetic penetration depth at zero temperature is expressed in the dirty limit by the Bardeen-Cooper-Schrieffer expression $\lambda(0) = \sqrt{\frac{\hbar \rho_n}{\pi \mu_0 \Delta(0)}}$, where $\hbar$ is the reduced Planck constant, ρ_n is the normal-state resistivity, μ_0 is the vacuum permeability, and $\Delta(0)$ is the energy gap at zero temperature. Niobium is in the intermediate-coupling limit with the superconducting energy gap given by $2\Delta(0) \approx 3.6k_B T_c$ (k_B is the Boltzmann constant).^{19,20} For our samples, the energy gap at zero temperature is around 1.2 meV so that the magnetic penetration depth at zero temperature amounts to ~ 120 nm, in agreement with the results of Gubin *et al.*²¹ In addition, in accordance with the



(a) Loop L1



(b) Loop L2

FIG. 1. Scanning electron microscope images of 20-nm-thick niobium loops. The surrounded areas highlight the weak regions, i.e., the regions where the critical current density is first reached under a direct applied current.

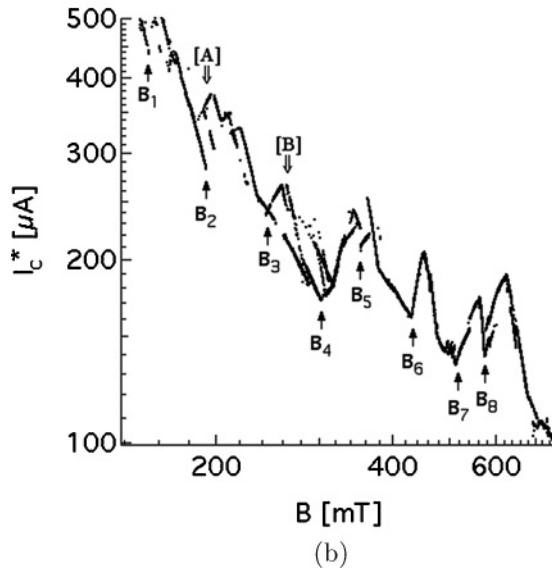
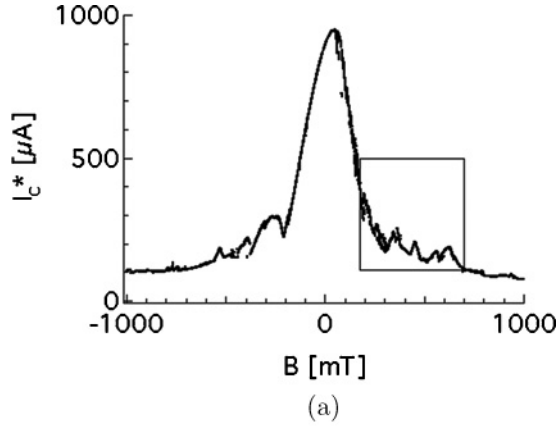


FIG. 2. (a) Evolution of the switching current of the loop L1 as a function of a perpendicular magnetic field. The bath temperature (3 K) lies far below the critical one. (b) Enlargement of the rectangular frame of (a). The field values B_N that correspond to local minima of the switching current are numbered for $N = 1, 2, \dots$. The symbols [A] and [B] refer to two particular magnetic fields studied in more details in Fig. 3.

Einstein relation, the electron mean free path can be expressed by $\ell = 3(e^2 v_F N_0 \rho_n)^{-1}$, where v_F is the Fermi velocity, e is the electron charge, and N_0 is the density of states at the Fermi level. For a one-gap dirty superconductor, the product $N_0 \rho_n$ can be extracted from the upper critical field at zero temperature following the Werthamer-Helfand-Hohenberg¹⁷ expression $B_{c2}(0) = 0.69 T_c \frac{4\pi k_B}{\pi} N_0 \rho_n$. Taking a typical value for the Fermi velocity ($v_F \sim 8 \times 10^5 \text{ m s}^{-1}$),^{21,22} the mean free path is estimated to be $\sim 3 \text{ nm}$. As a consequence, the dirty limit condition $\ell < \xi(0) < \lambda(0)$ is fulfilled for all the samples.

The following results were obtained on three loops, named L1, L2, and L3. They differ from their inner (r_i) and outer (r_o) radii, their branch width ($r_o - r_i$), as well as from the contacts width (see Table I). It is worth noting that the transport current density is maximum either in a branch of the loop or in the area close to the contact, depending on their relative size.

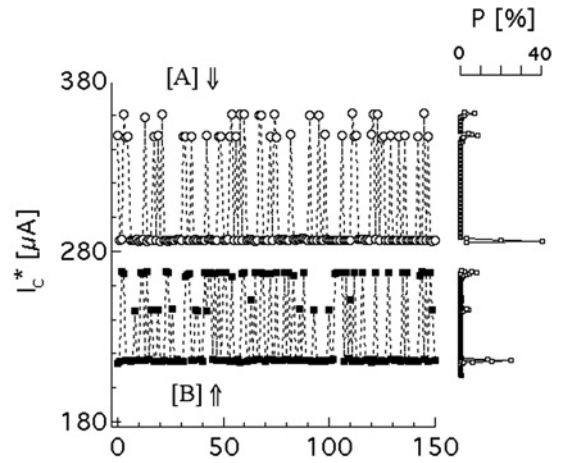


FIG. 3. Numerous switching current measurements for the loop L1 obtained at fixed magnetic fields ([A], 193 mT; [B], 265 mT). A total of 500 measurements have been performed, and only the first 150 are shown. Three well-defined values are observed at each field. The narrow distributions are depicted on the right side.

The loop L1 [Fig. 1(a)] has a contact width larger than twice the branch width so that the weak region (i.e., the region where the critical current density is first reached) is located in one of the two branches. In contrast, the loops L2 and L3 [illustrated for L2 in Fig. 1(b)] have a contact width smaller than twice the branch so that the critical area is close to the contact. The critical widths W to take into account are underlined in Table I and amount to 150 nm (for L1), 300 nm (for L2), and 400 nm (for L3).

III. RESULTS

The overall evolution of the switching current I_c^* under a perpendicular magnetic field is given in Fig. 2(a) for the loop L1. At each magnetic-field step, the sample is brought to the normal state by the applied direct current so that the critical electronic temperature is exceeded under the influence of the Joule heating. The sample is then field-cooled when the current source is switched off, although this is not a temperature-driven field cooling as the bath temperature is maintained constant during the whole measurement. The magnetic-field increment is $100 \mu\text{T}$ and measurements have been performed in both the positive and negative orientations. Figure 2(a) is representative of the low-temperature behavior for all the samples²³ (here $T = 3 \text{ K}$, i.e., well below the critical temperature of the loop). Figure 2(b) depicts in more detail the wide variety of switching current modulations that appear in the rectangular frame of Fig. 2(a). A relevant feature is that the local minima are regularly spaced, with a period that amounts to around 65 mT (the magnetic-field values B_N associated with the local switching current minima are numbered for $N = 1, 2, \dots$). Here, the period of interest is much larger than that observed in the low-field part of the curve, where a sawtooth-shaped evolution of the switching current arises with a periodicity of 7.8 mT. This latter value is in excellent agreement with the periodicity of the fluxoid quantization [i.e., $B_{\Phi_0} = \frac{\Phi_0}{\pi(290 \text{ nm})^2} \approx 7.83 \text{ mT}$], which is calculated with the mean radius of the loop

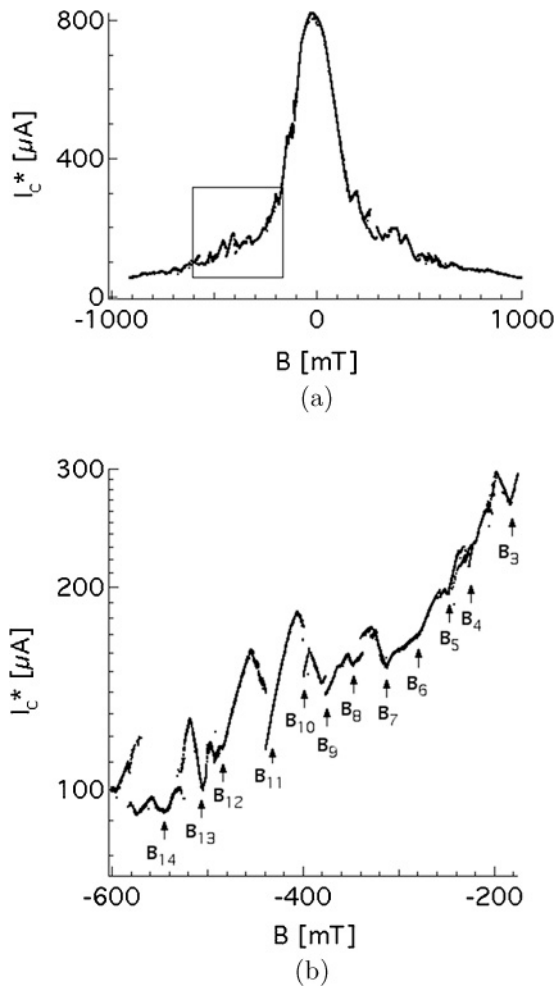


FIG. 4. (a) Evolution of the switching current of the loop L2 as a function of a perpendicular magnetic field. The bath temperature (4 K) lies far below the critical one. (b) Enlargement of the rectangular frame of (a). The field values B_N that correspond to local minima of the switching current are numbered for $N = 3, 4, \dots$.

L1. The modulations observed in the low-field region are very similar to the one recently observed on nonoxidized niobium nanosquids.²⁴

It is also noteworthy to measure very different values of the switching current at a given magnetic field (see, for example, the fields denoted [A] and [B] in Fig. 2(b), where I_c^* spreads from 280 to 360 μA and from 220 to 270 μA , respectively). The measurements have been reproduced 500 times at these particular fields (see Fig. 3, in which only the first 150 are shown). The three critical current levels pointed out at each field nicely match the overall curve. The spreading is very narrow, and the lowest values appear to be more frequently probed. Multimodal distributions at fixed magnetic field reveal that the sample is randomly stabilized in different states during the current-driven field cooling that follows each critical current detection (i.e., a larger switching current is related to a better stabilized starting state).

The behavior depicted in Fig. 2 for the loop L1 has been similarly observed on the loops L2 and L3. This is highlighted for the sample L2 in Fig. 4 with the overall evolution of the switching current [Fig. 4(a)] and an enlargement of the

rectangular frame in the negative field orientation [Fig. 4(b)]. The bath temperature is 4 K. Once again, the regularly spaced I_c^* minima can be numbered. This is done for $N = 3, 4, \dots$ as the two first minima are located in the central peak, which is not enlarged in Fig. 4(b). The field period amounts to ~ 33 mT, around half the value determined for the loop L1. Compared to the loops L1 and L2, the loop L3 is characterized by broader distributions of the switching current (see Fig. 5). The local minima (numbered from $N = 1$ to 5) remain, however, clearly defined with a smaller field period of ~ 18 mT.

Contrary to the loop L1, for which the fluxoid quantization manifests itself in the low-field part of the curves, no similar feature has been observed for the loops L2 and L3. This is consistent with the position of the critical width, which is located either in a branch of the loop (for L1) or near the contacts (for L2 and L3). Indeed, the circulating currents that ensure the quantization of the fluxoid flow in the branches of the loops. They subtract from the applied transport current in one branch and add in the other one where the switching current is first reached. The situation alternates periodically from one branch to the other with a total field period given by B_{Φ_0} . The sawtooth evolution of the switching current (with respect to the applied field) thus directly indicates the presence of the circulating currents in the branches of the loops (see, e.g., the work of Michotte *et al.*¹⁵ on the evolution of the switching current of a niobium superconducting loop far below the critical temperature). For the loops L2 and L3, the presence of the circulating currents is not probed in the magnetic-field evolution of the switching current because they do not impact the net current that flows through the contacts. If the fluxoid quantization effect would be probed, the theoretical field period would be noticeably less than the ones involved in Figs. 4 and 5. Indeed, B_{Φ_0} would amount to 2.6 mT for L2 and to 2.9 mT for L3, while the observed field spacing between the switching current minima is 33 and 18 mT for the loops L2 and L3, respectively.

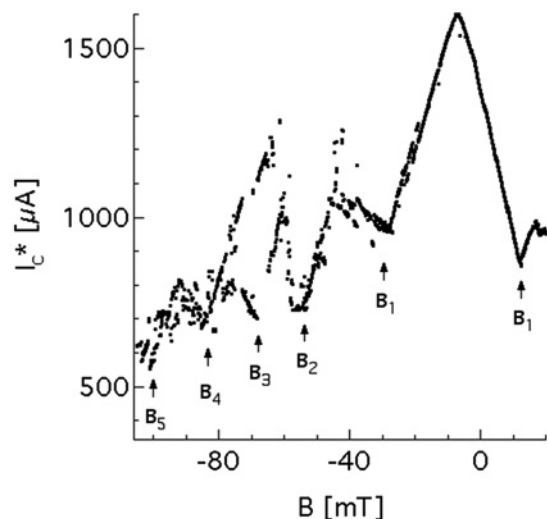


FIG. 5. Evolution of the switching current of the loop L3 as a function of a perpendicular magnetic field. The bath temperature is 3 K. The field values B_N that correspond to local minima of the switching current are numbered for $N = 1$ up to $N = 5$.

The evolution of the switching voltage V_c^* with respect to the magnetic field is also instructive. This is illustrated (together with the switching current I_c^*) in Figs. 6(a) and 6(b) for the loop L1 and L2, respectively. The switching voltage, which is measured just before the transition to the fully normal state, takes either zero or nonzero values depending on the magnetic-field range. The nonzero values are most often probed when the switching current is decreasing, and V_c^* generally drops at the local I_c^* minima. The ability to relate both I_c^* and V_c^* is the principal advantage of using a switching criterion rather than a criterion based on the appearance of resistance (or voltage). Furthermore, it has to be mentioned that the evolutions of I_c^* and V_c^* are reproduced nicely, either in an increasing or in a decreasing magnetic field. As was previously emphasized, the electrons are briefly heated above T_c each time I_c^* is reached, so that the sample undergoes a kind of thermal reset after each switching current detection. Therefore, the results are expected to be independent of the magnetic-field sweeping direction.

IV. DISCUSSION

The response of a type-II superconductor under a direct transport current depends mainly on the stability of the vortices pattern that freezes during the field-cooling procedure. In the mixed state, the vortices are forced to move when the Lorentz

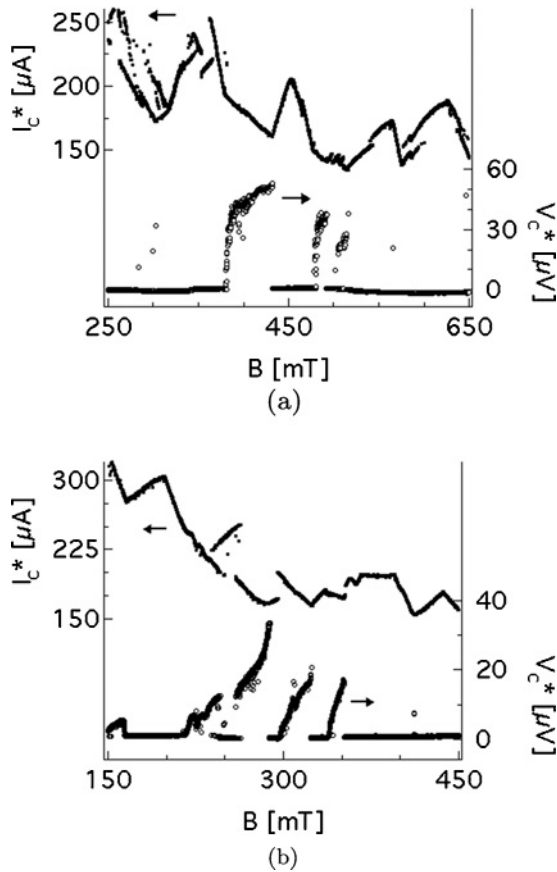


FIG. 6. Magnetic-field dependence of the switching current I_c^* (on the left) and of the switching voltage V_c^* (on the right) for the loop L1 [$T = 3$ K, part (a)] and for the loop L2 [$T = 4$ K, part (b)]. V_c^* drops at the magnetic fields at which I_c^* is minimum.

driving force, which is proportional to the applied transport current density, exceeds a certain pinning threshold.²⁵ If the threshold is small (i.e., the vortices configuration is not very stable), the vortices move at relatively low applied currents. The dissipation induced by their motion destroys the perfect superconducting state: a nonzero voltage appears at the extremities of the sample. A further increase of the applied current is required in order to entail the transition to the normal state. On the other hand, a large transport current must be applied when the pinning threshold is enhanced (i.e., for a more stable vortices configuration). In this case, the dissipation that results from the motion of a single vortex may be sufficient to induce the transition to the normal state, with a zero voltage measured just before the transition.

The experimental results presented in Sec. III reflect the above-described stability of the vortices arrangements that form in the arms and in the contacts of the thin mesoscopic niobium loops. The modulations of the switching current highlight that more or less stabilized initial states are formed during the field cooling that precedes each measurement. This point is corroborated by the correspondence between I_c^* and V_c^* (see Fig. 6). Indeed, nonzero values of V_c^* are observed when the switching current decreases. In these field intervals, less stable vortices configurations develop and the vortices are easily displaced by the direct current. On the contrary, zero switching voltages mean that more stable configurations arise. As was already mentioned, the critical current is the lowest when the unstable vortices system rearranges. In this sense, the sharp variations of V_c^* that occur in the vicinity of the I_c^* minima are of particular interest because they reinforce the occurrence of a transition from an unstable vortices configuration ($V_c^* \neq 0$) into a more stable one ($V_c^* = 0$) at the particular magnetic fields B_N . The dependence of these latter fields with respect to the number N of rows is summarized for the three samples in Fig. 7 (the data are shown for both the positive and the negative orientations of

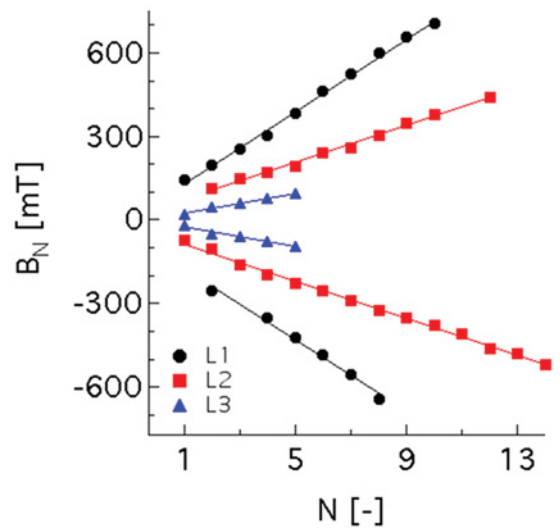


FIG. 7. (Color online) Evolution of the magnetic fields B_N that correspond to local minima of the switching current [loops L1 (black $\bullet$), L2 (red $\blacksquare$), and L3 (blue $\blacktriangle$)] as a function of the number N of rows of vortices. The B_N values are summarized for both the positive and negative orientations of the applied field.

the applied field). The different slopes result from the varying spacing between the fields B_N , which amounts to 65, 33, and 18 mT for loops L1, L2, and L3, respectively. The evolution of B_N with the number of vortices lines has been discussed in detail by Ziese *et al.*¹³ In the limit $\xi/\gamma W \ll 1$ (with γ an anisotropy factor that is close to 1 here and W the sample size perpendicular to the applied field), the fields B_N depend linearly on N according to Eq. (1),

$$B_N = B_{SH}(0.19 + 0.71N), \quad (1)$$

where B_{SH} is the superheating field, i.e., the maximum field for complete vortex expulsion without an applied transport current. One sees that the formation of the first vortices line is made easier under the action of a transport current ($B_1 < B_{SH}$). The superheating field B_{SH} can be extracted from the slopes of the curves in Fig. 7. For both orientations of the applied field, B_{SH} amounts to 91, 47, and 25 mT for loops L1, L2, and L3, respectively. It is of the greatest importance to stress again that the measurements are based on the application of a transport current, so that the probed area is the one where the switching current is first reached. In Sec. II, we have noticed that the critical region is located either in a branch of the loop (sample L1) or in a region close to the contact (samples L2 and L3). For this reason, the widths to take into account are 150 nm (for L1), 300 nm (for L2), and 400 nm (for L3). As expected, B_{SH} increases with a reduction of the sample width.

In the past few years, many theoretical^{10,26,27} and experimental^{4,6,7} works were dedicated to the impact of size and temperature on the superheating field B_{SH} (i.e., the critical field for complete vortex expulsion). Two theoretical models are based on the Gibbs free-energy profile of an isolated vortex located in a strip, while a third one deals with the formation of a vortex-antivortex pair. The first (metastable) solution argues that a vortex can penetrate into a strip insofar as the magnetic-field induction is large enough to induce a minimum of the Gibbs free energy at the center of the strip. This occurs for fields $B > B_0$, with B_0 given by Eq. (2),

$$B_0 = \frac{\pi \Phi_0}{4W^2}, \quad (2)$$

where W is the sample width. A further increase of the induction is required in order to induce an absolutely stable solution. This arises at a magnetic field B_s given by Eq. (3),

$$B_s = \frac{2}{\pi} \frac{\Phi_0}{W^2} \ln \left(\frac{\alpha W}{\xi} \right), \quad (3)$$

at which the Gibbs free energy at the center of the strip presents an absolute minimum (α is a constant that takes the value $2/\pi$ or $1/4$ depending on the assumption on the vortex core size). Recently, Kuit *et al.*⁷ proposed an intermediate model that takes into account the vortex-antivortex pair production energy. They show that the relevant critical induction is determined when the vortex generation rate is exactly balanced by the rate of escape, which occurs at a magnetic field B_K given by the following expression:

$$B_K = 1.65 \frac{\Phi_0}{W^2}. \quad (4)$$

A common feature of these models is that the superheating field is roughly proportional to Φ_0/W^2 . The B_{SH} values

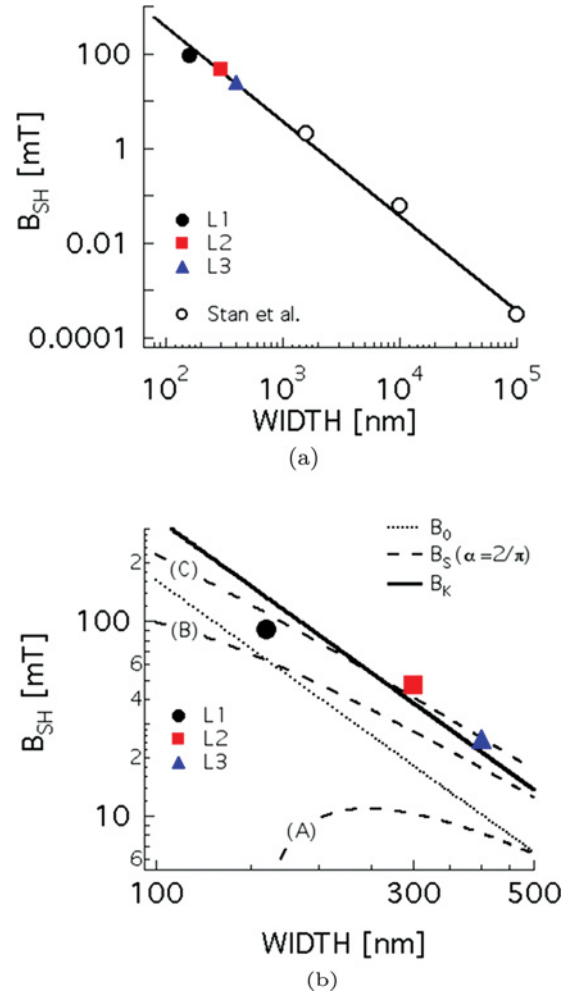


FIG. 8. (Color online) (a) Evolution of the superheating field as a function of the sample width. The full symbols are the values extracted from the electrical transport measurements for the loops L1, L2, and L3, respectively. The values reported by Stan *et al.*⁶ for wider niobium samples ($\circ$) are plotted for comparison. The curve corresponds to the relation $1.8\Phi_0/W^2$. (b) Comparison between the experimental data and some theoretical critical induction models, namely the metastable solution B_0 (dotted curve), the stable solution B_s (dashed curves), and the B_K solution (solid curve). The stable solution is depicted for three values of the coherence length that correspond to different vortices pinning temperatures [T_f amounts to $0.99T_c$ (curve A), $0.9T_c$ (curve B), and $0.4T_c$ (curve C)].

extracted here from electrical transport measurements are fully consistent with this predicted dependence on the sample width. This is illustrated in Fig. 8(a). The superheating field of loops L1, L2, and L3 are indicated with the full symbols, while the critical inductions experimentally determined by Stan *et al.*⁶ with a scanning Hall-probe microscope are indicated with the empty symbols. These values correspond to the maximum field at which the vortices are completely expelled by thin niobium strips whose width is in the μm range. One notices that the B_{SH} values extracted here follow nicely the general trend given (i) by the wider niobium strips and (ii) by the theoretical models. Indeed, the solid curve in Fig. 8(a) corresponds to the relation $k\Phi_0/W^2$ with the proportionality constant $k = 1.8$.

Figure 8(a) compares the experimental data with the three theoretical models. The proportionality term does not depend on the sample width for the B_0 (metastable) and the B_K models, so that they are both depicted by straight lines in this log-log plot (see the dotted curve for B_0 and the solid curve for B_K). Besides, the stable solution B_s depends on the coherence length at the temperature T_f at which the vortices become pinned during the field cooling. Many authors have indicated that the temperature T_f is very close to the critical one in a temperature-driven field cooling ($T_f \approx 0.99T_c$).^{6,28} However, whether this statement remains valid here is not so clear. Indeed, our mesoscopic superconductors are field-cooled by switching off the applied current at a fixed bath temperature so that the (unknown) temperature at which the vortices become pinned may be reduced or may even be close to the bath one. For this reason, the stable solution B_s (with $\alpha = 2/\pi$) is depicted for different T_f/T_c ratios, namely 0.99, 0.9, and 0.4 (see the dashed curves, labeled A, B, and C). This of course corresponds to different values of the coherence length $\xi(T_f)$ that are determined using the temperature dependence of the coherence length in the dirty limit,²⁹ i.e., $\xi(T) = \frac{\xi(0)}{(1-T/T_c)^{0.5}}$ with $\xi(0) = 0.855 (\xi_0 \ell)^{0.5}$. One obtains that $\xi(T_f) \approx 95, 30$, and 12 nm, respectively. Apart from the curve that corresponds to a pinning temperature very close to T_c , the stable solution B_s satisfactorily follows the experimental data. This is also the case for the B_K model, so that it appears to be very difficult to discriminate between these two models. Moreover, the metastable solution B_0 seems to underestimate slightly the results in the whole studied width range. A definitive conclusion concerning the theoretical model that is better suited to describe our experimental data would require us to know with precision the size of the vortices cores [$\sim \xi(T_f)$] at the temperature at which the vortices positions are frozen. This information is, however, not accessible in our measurements. In any case, the overall agreement between the theory and the experimental data highlights the fact that studying the matching fields at which the vortices lattice rearranges itself is an interesting tool to determine the superheating field of thin mesoscopic superconducting structures with a width of a few hundreds of nanometers (and probably less).

V. CONCLUSION

This paper highlights the fact that electrical transport measurements are efficient tools to probe the vortices arrangement

in superconducting mesoscopic niobium structures. The evolution of both the switching current and voltage (i.e., measured just before the current-driven transition to the fully normal state) was studied as a function of a perpendicular magnetic field. The modulations in the switching current confirm that the vortices rearrange themselves at regularly spaced matching fields. Here we highlight that this rearrangement from an unstable vortices pattern into a more stable one also causes a drop of the switching voltage. The latter takes either zero values (for stable vortices configurations) or nonzero values (for less stable vortices configurations) depending on the stability of the vortices patterns under a direct transport current. The observed multimodal distributions of the switching current obtained at a constant field show that the few vortices involved in the measurements can freeze into different configurations during the current-driven field cooling that precedes each measurement.

Furthermore, the spacing between the matching fields allows one to extract the critical field for complete vortex expulsion of the samples, i.e., the so-called superheating field. The values are compared with several critical induction models, which describe the dependence of the superheating field with the sample width. The values extracted here from electrical transport measurements are fully consistent with the predicted evolution $B_{SH} \propto \Phi_0/W^2$. Both the stable solution and the model based on the vortex-antivortex pair production energy appear well-suited to explain the results. However, a definitive discrimination is difficult due to the unknown temperature at which the vortices become pinned in the field-cooled measurement. In addition, our data are in nice agreement with recent values obtained by scanning probe microscopy on wider niobium strips. Here, the main advantage is that the superheating field is determined for much narrower samples, with no limitation due to the experimental setup resolution.

ACKNOWLEDGMENTS

The authors would like to thank L. Couraud and C. Ulysse for the niobium thin-film deposition. S.A. is supported by the National Fund for Scientific Research (FNRS Research Fellow), Belgium. X.H. is supported by the National Fund for Training in Research in Industry and Agriculture (FRIA), Belgium. This work was partly supported by the Interuniversity Attraction Poles Program (P6/42)–Belgian State–Belgian Science Policy.

*sebastien.adam@uclouvain.be

¹R. B. G. Kramer, G. W. Ataklti, V. V. Moshchalkov, and A. V. Silhanek, *Phys. Rev. B* **81**, 144508 (2010).

²J. Van de Vondel, A. V. Silhanek, V. Metlushko, P. Vavassori, B. Ilic, and V. V. Moshchalkov, *Phys. Rev. B* **79**, 054527 (2009).

³I. Kokanović, A. Helzel, D. Babić, C. Sürgers, and C. Strunk, *Phys. Rev. B* **77**, 172504 (2008).

⁴B. J. Baelus, A. Kanda, F. M. Peeters, Y. Ootuka, and K. Kadowaki, *Phys. Rev. B* **71**, 140502 (2005).

⁵G. Karapetrov, J. Fedor, M. Iavarone, D. Rosenmann, and W. K. Kwok, *Phys. Rev. Lett.* **95**, 167002 (2005).

⁶G. Stan, S. B. Field, and J. M. Martinis, *Phys. Rev. Lett.* **92**, 097003 (2004).

⁷K. H. Kuit, J. R. Kirtley, W. van der Veur, C. G. Molenaar, F. J. G. Roesthuis, A. G. P. Troeman, J. R. Clem, H. Hilgenkamp, H. Rogalla, and J. Flokstra, *Phys. Rev. B* **77**, 134504 (2008).

⁸C. P. Bean and J. D. Livingston, *Phys. Rev. Lett.* **12**, 14 (1964).

⁹P. Müller, A. V. Ustinov, and V. V. Schmidt, *The Physics of Superconductors* (Springer, Berlin, 1997).

- ¹⁰P. Sánchez-Lotero and J. J. Palacios, *Phys. Rev. B* **75**, 214505 (2007).
- ¹¹J. Guimpel, L. Civale, F. de la Cruz, J. M. Murduck, and I. K. Schuller, *Phys. Rev. B* **38**, 2342 (1988).
- ¹²S. H. Brongersma, E. Verweij, N. J. Koeman, D. G. de Groot, R. Griessen, and B. I. Ivlev, *Phys. Rev. Lett.* **71**, 2319 (1993).
- ¹³M. Ziese, P. Esquinazi, P. Wagner, H. Adrian, S. H. Brongersma, and R. Griessen, *Phys. Rev. B* **53**, 8658 (1996).
- ¹⁴G. Carneiro, *Phys. Rev. B* **57**, 6077 (1998).
- ¹⁵S. Michotte, D. Lucot, and D. Mailly, *Phys. Rev. B* **81**, 100503 (2010).
- ¹⁶G. R. Berdiyrov, M. V. Milosević, and F. M. Peeters, *Phys. Rev. B* **81**, 144511 (2010).
- ¹⁷N. R. Werthamer, E. Helfand, and P. C. Hohenberg, *Phys. Rev.* **147**, 295 (1966).
- ¹⁸S. Bose, P. Raychaudhuri, R. Banerjee, and P. Ayyub, *Phys. Rev. B* **74**, 224502 (2006).
- ¹⁹S. Bose, R. Banerjee, A. Genc, P. Raychaudhuri, H. L. Fraser, and P. Ayyub, *J. Phys. Condens. Matter* **18**, 4553 (2006).
- ²⁰S. Bose, P. Raychaudhuri, R. Banerjee, P. Vasa, and P. Ayyub, *Phys. Rev. Lett.* **95**, 147003 (2005).
- ²¹A. I. Gubin, K. S. Il'in, S. A. Vitusevich, M. Siegel, and N. Klein, *Phys. Rev. B* **72**, 064503 (2005).
- ²²N. W. Ashcroft and D. N. Mermin, *Solid State Physics*, 1st ed. (Thomson Learning, Toronto, 1976).
- ²³The curve asymmetry with respect to positive and negative field orientations is believed to reflect the asymmetry of the sample configuration. Indeed the third contact is thought to locally modify the transport current density, although it is not used in the measurement.
- ²⁴M. Faucher, P. O. Jubert, O. Fruchart, W. Wernsdorfer, and V. Bouchiat, *Supercond. Sci. Technol.* **22**, 064010 (2009).
- ²⁵C. Peroz and C. Villard, *Phys. Rev. B* **72**, 014515 (2005).
- ²⁶E. Bronson, M. P. Gelfand, and S. B. Field, *Phys. Rev. B* **73**, 144501 (2006).
- ²⁷G. Catelani and J. P. Sethna, *Phys. Rev. B* **78**, 224509 (2008).
- ²⁸D. Kouzoudis, M. Breitwisch, and D. K. Finnemore, *Phys. Rev. B* **60**, 10508 (1999).
- ²⁹M. Tinkham, *Introduction to Superconductivity* (McGraw-Hill, New York, 1996).