Available online at www.sciencedirect.com
SCIENCE DIRECT
Physica C 437–438 (2006) 1–6
PHYSICA C
www.elsevier.com/locate/physc

Generation of DC electric fields due to vortex rectification in superconducting films

F.G. Aliev *

Dpto. de Física de la Materia Condensada, Instituto "Nicolás Cabrera" de Ciencia de Materiales, Universidad Autónoma de Madrid, 28049 Madrid, Spain

Available online 7 February 2006

Abstract

The introduction of the manuscript reviews different mechanisms of generation of permanent electric fields by AC driven vortex lattices in type-II superconductors due to artificial symmetry breaking. The second part shows that superconducting Pb and Nb films (strips or crosses) with or without symmetric periodic pinning centers, subject to a magnetic field perpendicular to the film plane, also exhibit magnetically tunable AC current rectification. At low drive frequencies, not far below the critical temperature, the superconducting films work as one-dimensional rectifiers (i.e. generate an uniform DC electric field along the direction of the AC current) due to unavoidable small vortex pinning asymmetry. At higher frequencies, above 10^5 Hz, rectification gradually becomes two-dimensional with a strongly non-uniform generated DC electric field. DC voltages, either longitudinal or transversal to the AC current are tunable with the applied magnetic field. The rectified voltage depends strongly on the temperature and the AC drive intensity. In superconductors with periodic pinning centers the rectified voltage varies periodically with the number of vortices per pinning center. Not far below T_c, the generated DC electric field is nearly opposite on the opposite film sides. The unusual two-dimensional character of rectification at high frequencies close to T_c could be qualitatively understood in terms of local rectification due the oppositely directed asymmetric edge barriers (Bean–Livingston type) or by slowly relaxing electric fields generated by local critical current excess. Anisotropic pinning effects represent a dominant contribution to the rectification further below T_c. Since in experiments on rectification in superconductors this electric field adds to the one due to, e.g., anisotropic vortex pinning, one has to take into account its presence when interpreting the rectification experiments.
© 2006 Elsevier B.V. All rights reserved.

Keywords: Vortex rectification; Pinning asymmetry; Surface barrier

1. Introduction

This manuscript reviews different mechanisms of appearance of permanent electric fields in type-II superconductors with AC current (i.e. rectification). This discussion is quite timely due to the renewed interest in rectification phenomena in superconductors which aroused recently [1–3]. We shall consider: (i) rectification phenomena in superconducting systems with intrinsic anisotropy and (ii) other less trivial situations where the non-uniform DC electric field could be created by a sinusoidal current in apparently symmetric superconducting films, subjected to a perpendicular magnetic field.

We shall not discuss experiments where the DC electric field originates by the simultaneous application of an external AC magnetic field and a DC current (rectification of the AC magnetic field resulting in the appearance of so-called vortex flow resistance) [4,5]. Neither are we considering the situation when rectification is a consequence of the displacement of the "working point" of the IV curve by biasing with the DC current [6]. Finally, our paper does not treat the case when the DC voltage is generated in granular films supposedly due to Josephson Junction (JJ) type contacts [7] (i.e. due to the inverse Josephson effect). In order

* Tel.: +34 91 4978596; fax: +34 91 4973961.
E-mail address: farkhad.aliev@uam.es

0921-4534/$ - see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.physc.2005.12.070

to account for rectification voltages of interest one has to assume that the superconducting films are close to the percolating limit and are constituted of more than 10^3 synchronous JJs, which is not the case [8]. After brief introduction to rectification effects due to "artificial" patterns we will discuss "natural" rectification experiments in plain and nanostructured superconducting films with AC drive frequencies between a few kHz and 10^8 Hz.

The possibility of rectification in superconductors with some apparent asymmetry was first considered in the sixties by Swartz and Hart [9] and later by Morrison and Rose [10]. Initial studies were made on superconducting wires with a triangular cross-section, which provided a difference between the surface critical currents for positive or negative current polarities of about a factor of three for the magnetic field applied perpendicular to the wire and along the surface plane. Such geometry creates a maximum rectification effect [9]. An alternative method [10] explores the intentional modification of one of the surfaces of a superconducting film either by creating microgrooves [10], or by contacting the surfaces of the superconducting film with a nonsuperconducting metal (rectifier based on bimetallic foil) [11]. In order to sense the asymmetry between the two superconducting surfaces, the magnetic field has to be parallel to the film plane.

A somewhat more complicated vortex rectification was observed by Jiang and Lobb [12] in superconducting $Pb_{0.9}Bi_{0.1}$ alloy films grown on sapphire or glass substrates and placed in a magnetic field parallel to the film plane and perpendicular to the current. Interestingly, the critical current difference ($I_{c+}-I_{c-}$) changes sign as a function of temperature and magnetic field. These experiments were explained within the model based on the vortex movement in the presence of two Bean–Livingston surface barriers plus inhomogeneous bulk pinning supposed to be a linear function of the distance to the interface. The vortex pinning anisotropy in the direction perpendicular to the substrate-superconducting film interface could appear due to the growth conditions. Few vortices could be also confined between the edges of a mesoscopic superconductor [13]. In the latter case, the vortex rectification effect was observed in a strip with a closed end and was attributed to asymmetric vortex flow.

Since the late nineties a number of hybrid superconductor/magnetic and superconducting nanostructures have been modeled and investigated experimentally to work as rectifiers, vortex lenses, etc. Lee et al. [1] have suggested that special choice of an asymmetric (ratchet) potential the rectification effect could be used to remove unwanted vortices from superconducting devices such as quantum interferometers [1]. Although not noticed by the authors, the proposed ratchet potential, when being created in a finite strip perpendicular to the current flow, should induce DC electric fields of different signs at the opposite strip sides. In other words, at sufficiently high drive frequencies the proposed ratchet potential scheme creates only a nonuniform electric field in the superconducting film without net vortex flow. Similar effects, as we demonstrate below, exist in superconducting films in restricted geometry.

The early work on asymmetric shape pinning traps may be found in Ref. [14]. An extension of this model was made by Wambauch et al. [15], who supposed that the vortex pinning energy is infinite except in specially designed saw-tooth shape channels with a 2D profile. It was suggested to create "vortex diodes" or "vortex lenses" which concentrate or disperse the vortices in special parts of the sample by the appropriate choice of the form of these channels. The net vortex flow under the AC current drive and the corresponding DC electric field disappears at high drive frequencies, when vortices oscillate around some position.

Another way to create a net vortex flow with an AC current drive is by using a gradient of the vortex pinning potential [16]. The key ingredient of this model is the long-range interaction between vortices, rather than interacting directly in a particle manner, creating an effective saw-tooth potential felt by the mobile vortices. The predicted ratchet effect is a low frequency effect and dies out at sufficiently high frequencies when vortices have no time to explore the relatively smooth anisotropic potential. A qualitatively new aspect of the above work is the consideration for the first time of both pinned and interstitial vortices as a part of the rectification process. This idea adds complexity to the phenomena and allows observing some qualitatively new features in the vortex rectification [3]. These results are applicable also to other AC driven systems with repelling movable objects, such as JJ arrays, colloidal systems with optical traps or Wigner crystals. Rectification is observed both for fields below and above the first matching field H_1 and only above some threshold drive period P_c proportional to the relation between pinning lattice constant $\mathbf{a}$ and Lorentz force $\mathbf{F}_L$ (which is in its turn is proportional to the vortex velocity), i.e. $P_c \propto \mathbf{a}/\mathbf{F}_L \propto \mathbf{a}/\mathbf{V}$. By taking a typical pinning lattice period of 1 μm and a vortex velocity of about 10^2 m/s one obtains an estimation for the threshold drive frequency of around 100 MHz. Just below the threshold frequency, rectification is maximum because the periodic vortex displacement explores only one anisotropic pinning center. Contrary to Ref. [16] where only the motion of the interstitial vortices is rectified, in Ref. [3] only the motion of interstitial vortices is not rectified. The small interstitial effect, which appears for subthreshold drives, leads to the small inversion of rectification as a function of applied drive force [3].

Let us now discuss in brief recent reports on the experimental observation of vortex rectification in superconductors with asymmetric periodic pining arrays. Inspired by the prediction of similarity between biological (protein) motors and AC driven superconducting vortices interacting with different asymmetric potentials, driven by nonequilibrium fluctuations [17,18], Villegas et al. [19] studied DC electric field (vortex rectification) created by an AC current applied to a superconducting Nb film with an array of triangular Ni dots. At temperatures very close to the critical temperature ($T/T_c = 0.99$), the authors observed maximum

DC voltage as a function of AC drive amplitude. Rectification is absent when the current is applied along the Y-axis so that the Lorentz force acts along the symmetric X-axis. It would be more correct to make this comparison in scales normalized by the corresponding critical currents.

Rectification as a function of the magnetic field (n = number of vortices per dot) shows qualitative changes above $n = 3$ [19], with the DC electric field becoming a non-monotonic function of the AC drive amplitude. This has been interpreted as if, in addition to the vortices pinned by the Ni triangles, another type of movable interstitial vortices appear above H_3. It is suggested that for $H > H_3$ the asymmetric potential rectifies pinned and unpinned vortices in opposite directions creating a kind of reversible rectifier [19]. A simple estimation made by multiplying the vortex velocity (10^2 m/s) times the drive period (10^{-4} s) shows that the typical distance explored by the vortices during a half period (1 cm) exceeds by a factor of 10 the sample transversal dimensions, indicating that vortices explore both edge barriers and ratchet potentials, which is not taken into account by the model. In addition, a recent report [20] shows that similar rectification effects exist if Cu triangle pinning centers substitute Ni dots. Absence of the magnetic stray fields in the latter case make difficult for Cu triangular dots to pin vortices similarly to the magnetic Ni dots. The enhancement of the maximum amplitude of the rectification when temperature is lowered [21] was attributed to the decrease of the thermal noise below T_c. According to simulations [22], both pinned and interstitial vortices should move chaotically at high velocities.

Van de Vondel et al. [23] reported on rectification effects in Al film with asymmetric periodic pinning centers. It has been demonstrated that the rectification is due to two critical depinning forces of the asymmetric potential. For the whole field range between 0 and 1.1 H_1 an asymmetry which was largest just below H_1 was observed. This was explained in terms of cancellation of vortex–vortex interaction near the first matching field. The strong hysteresis in the IV characteristics could not be reproduced in MD simulations and was attributed to vortex inertia due to vortex elongation. The authors did not discuss the characteristic times for relaxation of an elongated vortex, which should be longer than the experimental measurement period of a few msec. Wördenweber et al. [24] have demonstrated that vortex ratchets could be realised by asymmetric vortex pinning centers arrangement.

2. Experimental

A sinusoidal current ranging from a few kHz to 147 MHz, was supplied by the RS300 generator through the capacitors, protecting the sample from an unwanted DC bias coming from the generator and maximizing the power matching (see inset to Fig. 1). Superconducting Pb films with the thickness of 50 nm and 100 nm thick Nb films were deposited on Si substrates. The Pb films were

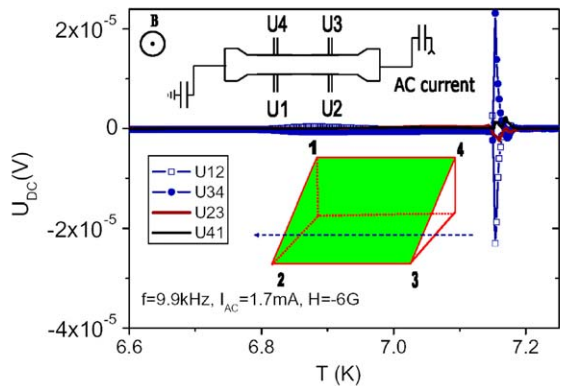

Fig. 1. LFR: Longitudinal and transversal rectification voltage for Pb strip. Upper inset schematically shows experimental configuration. Lower inset shows generated DC voltage profile and dominant net vortex flow.

covered by a 20 nm Ge protection layer. For the details on the sample preparation and characterization we refer to Ref. [25].

The discussed above rectification effects are supposed to have a one-dimensional character with an uniform DC electric field generated along the AC current. Therefore, the measurements were always made only from one of the sample sides. Moreover, the typical AC drive periods exceed in about a factor of 1000 the threshold period theoretically estimated. Finally, all MD simulations were made for infinite systems (i.e. without considering the possible influence of the edges). In the present work the DC voltage was measured from four pairs of contacts: two opposite longitudinal and two opposite transversal by using the Keithley 2182 nanovoltmeter. The width of Pb (Nb) strips is 100 (40) μm, whereas the distance between the potential contacts is 150 (40) μm.

3. Low frequency rectification effects in plain Pb, Nb films and Nb with symmetric periodic pinning centers

We turn to the discussion of our recent rectification experiments on plain superconducting Pb and Nb films (strips or crosses) with or without symmetric periodic pinning centers. When situated in a magnetic field perpendicular to the film's plane these, apparently symmetric, structures exhibit magnetically tunable AC current rectification. We discriminate between two qualitatively different regimes. The low frequencies (below 100 kHz) rectification (LFR) in superconducting films seems to be a result of unavoidable small (bulk plus interface) sample anisotropy. For AC drives approaching to and exceeding the MHz range, we observe a qualitative change in the symmetry together with an increase of the magnitude of longitudinal and transversal DC voltages. Both strip-like and cross-like superconducting films showed qualitatively similar results.

Fig. 1 shows longitudinal LFR measured from four pairs of contacts for Pb strip , while Fig. 2 shows typical longitudinal rectification voltage (U_{DC}) vs. AC drive

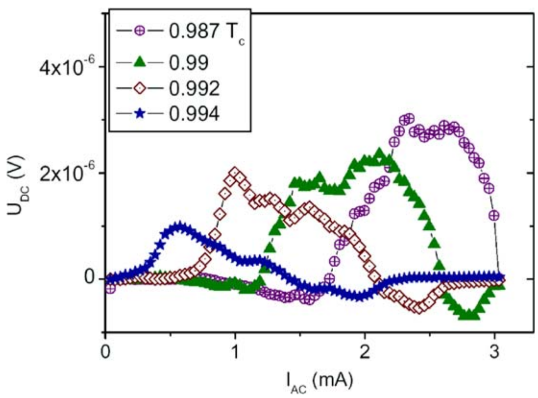

Fig. 2. Longitudinal LFR in Nb films with circular PPCs measured with an AC drive frequency of 43 kHz and magnetic field of 150 G.

amplitude (I_{AC}) in a Nb film with circular pinning periodic centers (PPCs). For temperatures relatively close to T_c ($T/T_c \sim 0.99$) one clearly observes a maximum in U_{DC} followed by a minimum. Decreasing temperature enhances the threshold values for the AC drive and increases the maximum rectification voltage. This dependence of $U_{DC}(I_{AC})$ is rather similar to the one reported by Villegas et al. for Nb films with PPCs of triangular Ni dots [19]. A similar longitudinal rectification has been observed for single Pb films patterned in strip-like geometry [27] (see also Fig. 1). The main source of the LFR in the plain superconducting films could be some intrinsic system's asymmetry (i.e. anisotropic bulk pinning and/or difference between left–right surface energy barriers). It seems that LFR in our Nb and Pb films is similar to the one reported before for superconductors with deliberately enhanced surface or bulk pinning anisotropy [9–12]. In addition, the recent study [27] shows that with low frequency AC drives the rectification voltage, as expected for the purely anisotropic case, has predominantly a longitudinal (along the AC drive direction) character creating an almost uniform DC voltage along the AC drive with dominant net vortex flow along the films anisotropy direction.

We have tried to evaluate the order of this anisotropy by estimating the asymmetry in the IV curves (Fig. 3(a)) and by comparing the critical currents from the opposite sides of the strip (Fig. 3(b)). Clearly, the superconducting films under study are nearly symmetric, showing only a small (less than 3%) difference between positive/negative branches in the critical current and between critical currents on the opposite sides. However, even this relatively small difference anisotropy (which is of the same order as the one found for Nb with triangular Ni dots [21]) is sufficient to explain the observed LFR DC voltages.

4. High frequency rectification effects in plain Pb and Nb films

Increase of the AC drive frequency above 100 kHz induces qualitative and quantitative changes in the rectification phenomena in plain Pb and Nb superconducting films. Fig. 4 compares longitudinal HFR and the LFR data obtained with I_{AC} close to 1.2 mA and magnetic field of 100 G for the Nb cross film.

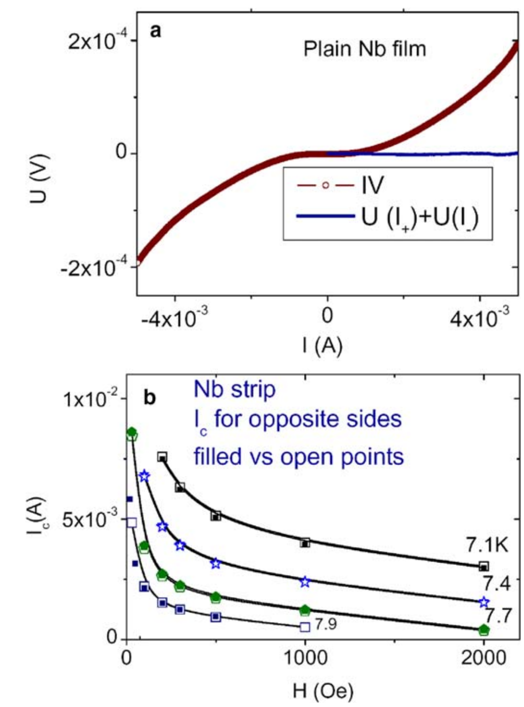

Fig. 3. (a) Typical IV curves measured in Nb film and analyses of the IV for a possible asymmetry and (b) Comparison of critical currents measured from opposite sides of the Nb strip.

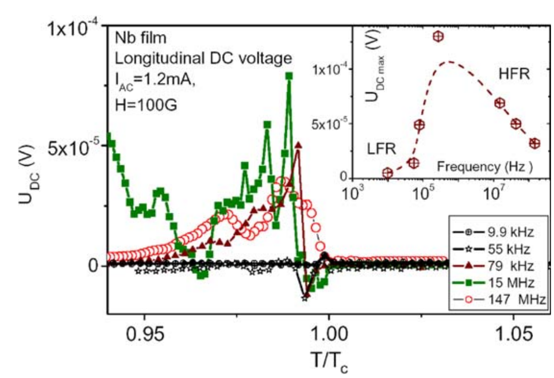

Fig. 4. Longitudinal LFR and HFR data obtained for the Nb cross film with I_{AC} of 1.2 mA and field of 100 G. Inset shows maximum rectification voltage as function of frequency for $I_{AC} = 1.2$ mA.

First, one notes that the HFR exceeds the LFR voltage in nearly one order of magnitude. Second, the HFR has a rather complicated temperature dependence including multiple sign inversions [26]. Third (not shown), the HFR voltage appears both in longitudinal and transversal directions. The generated transversal DC voltage is comparable to the longitudinal one [26]. Both for the LFR and HFR we observed inversion of the DC voltage with change of the direction of the applied magnetic field. A typical IV curve measured in the HFR regime (not shown) has DC offset depending on magnetic field polarity.

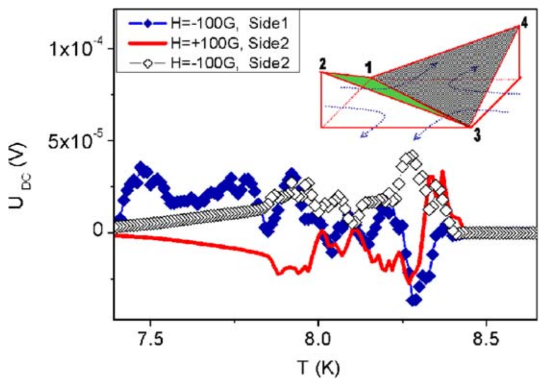

Fig. 5. Longitudinal HFR measured in Nb strip for opposite magnetic fields and opposite sides. AC drive is 43 MHz and 1.2 mA. Inset shows generated DC voltage profile and dominant net vortex flow.

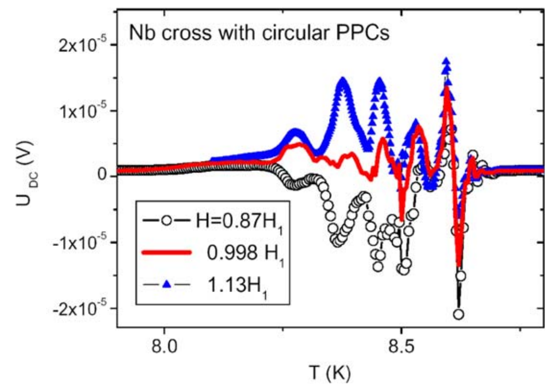

Fig. 6. HFR in Nb film with symmetric PPCs measured when crossing first matching field of 103 G. AC drive is 43 MHz and AC current is 1 mA.

The appearance of the transversal DC voltage is accompanied by qualitative changes in the two longitudinal DC voltages measured from the opposite strip/cross sides close to the T_c. Fig. 5 shows that these HFR voltages are different, and close to the T_c have opposite signs. This means that the topology of the DC voltage profile generated in the superconducting films may be very much different for low and high drive frequencies (see inset to Fig. 5).

We note that with the sample kept at low temperatures, the measured HFR voltage is highly reproducible. A rather small difference between zero field cooled (ZFC) and field cooled (FC) HFR data exists only close to the temperature where the DC voltage drops to zero, reflecting very strong vortex lattice pinning.

5. High frequency rectification effects for Pb and Nb films with symmetric pinning centers

The AC current rectification in superconductors with symmetric periodic pinning centers (PPCs) reveals at least two main differences in comparison with plain films. First of all, the much stronger vortex pinning induced by the PPCs increases the critical current J_c and lowers (in about an order of magnitude) the HFR DC voltage for the same AC drive current densities [26]. Secondly, and most interestingly, at lower temperatures, when the PPC potential becomes relatively strong, the DC voltage reverses sign not only with the magnetic field direction (as in plain films) but also when the intensity of the magnetic field crosses the matching fields.

Fig. 6 shows that in a Nb film with circular symmetric PPCs of Ni, the HFR voltage is a nearly antisymmetric function of the magnetic field, except close to T_c, when crossing first matching fields H_1, corresponding to one flux quantum per Ni dot.

6. Discussion

The physical mechanisms providing the net DC vortex flow out of sinusoidal AC current seems to be rather different for the low and high frequency drives. While, the LFR voltages in the Nb and Pb superconducting films are induced by some (small) asymmetry in the pinning potential felt by the vortices moving in the direction along the Lorentz force, (i.e. perpendicular to the AC drive), the HFR voltage profile close to T_c has a qualitatively different character. Two alternative scenarios could qualitatively explain the main features of the high frequency rectification close to the critical temperature by taking into account the restricted geometry of the films and the fact that the DC voltage is measured from pairs of contacts situated on one of the sides of the film.

The first scenario [26] considers the influence of eddy currents created by a transversal magnetic field in the superconductor phase. The resulting total current density (external plus Meissner currents) exceeds each half AC drive period the critical current density near one of the two opposite film sides. If the inverse frequency is smaller than the vortex relaxation time, each side of the superconductor works as a rectifier with opposite HFR voltage signs, as indeed observed experimentally.

An alternative model [27], applied to the case of a long strip, considers two surface energy barriers formed near each strip side. Even in the absence of defects or geometric asymmetry, such barriers (Bean–Livingston barrier [28]) should have oppositely directed asymmetric energy profiles as a function of the distance of vortex to each edge of the superconducting strip (see sketch drawn in Fig. 7). Note that at low drive frequencies the half period strongly

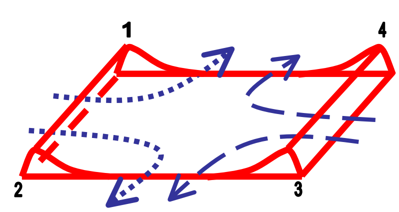

Fig. 7. Sketch showing two oppositely directed Bean–Livingston barriers at the opposite film sides. Dashed (dotted) line schematically indicates the net vortex flow appearing during positive (negative) half cycles of the AC current for the maximum barrier asymmetry.

exceeds the time needed to create, move and annihilate the vortices moving between the strip sides, which means that the influence of the two surface barriers is nearly compensated.

In the HFR regime, however, the distance to which vortices are driven is reduced and may become comparable to the typical extension of the surface energy barrier in the direction of its maximum anisotropy, i.e. perpendicular to the films edge. If, similarly to the first model, the vortex relaxation time is long enough in comparison with the inverse frequency, each of the two asymmetric surface barriers should work as 180° shifted rectifiers. The observed opposite sign of the HFR voltages in the opposite (longitudinal) sample sides is then naturally explained by the oppositely directed asymmetry of the corresponding surface barriers. We note finally that both models predict also transversal rectification voltages to appear and to have different signs when measured in the HFR regime from opposite transversal contacts, which was indeed observed experimentally close to T_c [26,27].

Summarizing, in the high frequency regime close to the T_c the HFR and the generated DC electric fields have local character, i.e. there is almost no net vortex flow crossing the structure between two opposite sides, as happens in the LFR case. Further below T_c both local and global (due to some pinning asymmetry) rectifications contribute to the DC voltage effects observed with high frequency drives.

Acknowledgments

I would like to acknowledge fruitful collaboration with J. Sierra, V.V. Pryadun, A.P. Levanyuk, R. Villar (UA Madrid), J.L. Vicent and E. Gonzalez (UC Madrid), D. Golubovic and V.V. Moshchalkov (KU Leuven) and discussions with F. Peeters and V. Vinokur. This work was supported by the Grants GR/MAT/0252/2004 from CM, by MAT2003-02600 (Spanish MEC) and by ESF-VORTEX.

References

[1] C.S. Lee, B. Janko, I. Derenyi, A.-L. Varabais, Nature 400 (1999) 337.
[2] S. Savelév, F. Nori, Nature Materias 1 (202) 179.
[3] B.Y. Zhu, F. Marchesoni, V.V. Moshchalkov, Franco Nori, Phys. Rev. B 68 (2003) 014514.
[4] V.V. Andrianov, V.B. Zenkevic, V.V. Kurgozov, V.V. Sychev, F.F. Ternokski, Sov. Phys. JETP 31 (1969) 815.
[5] R.P. Huebener, V.A. Rove, Solid-State Commun. 7 (1969) 1763.
[6] A.N. Ulianov, J. Appl. Phys. 85 (1999) 3726.
[7] A.M. Saxena, J.E. Crow, M. Strongin, Solid-State Commun. 14 (1974) 799.
[8] A. Gerber, G. Deutscher, Phys. Rev. Lett. 64 (1990) 1585.
[9] P.S. Swartz, H.R. Hart Jr., Phys. Rev. 137 (1965) A818.
[10] D.D. Morrison, R.M. Rose, Phys. Rev. Lett. 25 (1970) 356.
[11] P.S. Swartz, H.R. Hart Jr., Phys. Rev. 156 (1967) 412.
[12] X. Jiang, C.J. Lobb, J. Low Temp. Phys. 100 (1995) 515.
[13] D.Y. Vodolazov, F. Peeters, I.V. Grigorieva, A.K. Geim, Phys. Rev. B 72 (2005) 024537.
[14] E.H. Brandt, J. Low Temp. Phys. 53 (1983) 41.
[15] J.F. Wambaugh, C. Reichhardt, C.J. Olson, F. Marchesoni, Franco Nori, Phys. Rev. Lett. 83 (1999) 5106.
[16] C.J. Olson, C. Reichhardt, B. Jankó, Franco Nori, Phys. Rev. Lett. 87 (2001) 177002-1.
[17] B.Y. Zhu, F. Marchesoni, F. Nori, Physica E 18 (2003) 318.
[18] B.Y. Zhu, F. Marchesoni, V.V. Moshchalkov, F. Nori, Physica E 18 (2003) 322.
[19] J. Villegas, Sergey Savel'ev, Franco Nori, E.M. Gonzalez, J.V. Anguita, R. Garcia, J.L. Vicent, Science 301 (2003) 1188.
[20] J.L. Vicent, Talk given at APS March meeting in LA, 2005.
[21] J.E. Villegas, E.M. Gonzalez, M.P. Gonzalez, J.V. Anguita, J.L. Vicent, Phys. Rev. B 71 (2005) 024519.
[22] C. Reichhardt, C.J. Olson, Franco Nori, Phys. Rev. Lett. 78 (1997) 2648.
[23] J. Van de Vondel, C.C. de Souza Silva, B.Y. Zhu, M. Morelle, V.V. Moshchalkov, Phys. Rev. Lett. 94 (2005) 057003.
[24] R. Wördenweber, P. Dumashevski, V.R. Misko, Phys. Rev. B69 (2004) 184504.
[25] A.V. Silhanek, L. van Look, S. Raedts, R. Jonkheere, V.V. Moshchalkov, Phys. Rev. B 68 (2003) 214504-1;
J.I. Martın, M. Velez, A. Hoffmann, I.K. Schuller, J.L. Vicent, Phys. Rev. Lett. 83 (1999) 1022.
[26] F.G. Aliev, A. Levanuyk, R. Villar, E.M. Gonzalez, V.V. Moshchalkov, Available from: cond-mat/045656.
[27] V.V. Pryadun, J. Sierra, F.G. Aliev, D.S. Golubovoc, V.V. Moshchalkov, Appl. Phys. Lett., in press.
[28] C.P. Bean, J.D. Livingston, Phys. Rev. Lett. 12 (1964) 14.