Plain superconducting films as magnetic field tunable two-dimensional rectifiers

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(Received 8 June 2005; accepted 15 December 2005; published online 10 February 2006)

Longitudinal and transversal permanent electric fields generated by an ac current through superconducting Pb and Nb thin strips have been studied as the function of the drive frequency ($10^3 < f < 10^8$ Hz), temperature, and magnetic field. At low frequencies ($f < 10^4$ Hz) and below the critical temperature, the superconducting strips behave as one-dimensional rectifiers, whereas for higher drive frequencies ($f > 10^5$ Hz) the rectification becomes two dimensional. The rectification strongly depends on the magnetic field, temperature and ac drive. The unusual dc electric field topology generated by the ac current in the superconducting strips can be explained by a local rectification due the oppositely directed asymmetric edge (Bean-Livingston type) barriers. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2171788]

Rectifiers (diodes), where the transformation of an ac into a dc voltage occurs, represent one of the most important components of modern electronics. Recent proposals of the new types of rectifiers such as molecular,[1] carbon nanotubes,[2] ballistic nanojunctions,[3] tunneling,[4] or superconding[5] ratchets explore the one-dimensional (1D) asymmetry of these systems. A renewed interest in the rectification in superconductors is due to its importance in understanding the ac drive induced net motion in cell biology[6] and the vortex motion in superconducting devices.[7] The control over the vortex motion in superconducting films is important, as it enables the removal of unwanted vortices.[8] Concerning the dimensionality, a uniform electric field rectification (the 1D rectification) could be expected in the previous rectification experiments involving two different surfaces contacting superconductor,[9–11] anisotropic pinning centers,[6] their arrangement,[12] combined action of a dc current and dc magnetic field,[13,14] dc and ac currents,[15] and some others.[16]

Here we study the dimensionality of the dc electric field generated by a sinusoidal current with the frequencies ranging from kilohertz (kHz) to megahertz (MHz) driven through a six-terminal plain superconducting film in the form of a strip with two current and four voltage contacts [upper sketch in Fig. 1(a)], subjected of an applied perpendicular dc magnetic field.

A sinusoidal current ranging from a few kHz to 147 MHz, was supplied by an RS300 generator through the capacitors, protecting the sample from an unwanted dc bias coming from the generator and maximizing the power matching. Superconducting Pb films with the thickness of 50- and 100-nm-thick Nb films were deposited on Si substrates. The Pb films were covered by a 20 nm Ge protection layer. For the details on the sample preparation and characterization we refer to Ref. 17. The dc voltage was measured from four pairs of contacts: U12/U34 for the longitudinal and U23/U41 for the transverse [upper sketch in Fig. 1(a)] by using a Keithley 2182 nanovoltmeter. The width of Pb (Nb) strips is 100(40) μm, whereas the distance between the potential contacts is 150(40) μm.

Figure 1(a) shows the typical longitudinal and transverse dc voltages as a function of the temperature, generated in the Pb film at the low drive frequency (9 kHz) for a fixed magnetic field. Moving clockwise around the four pairs of the potential contacts, independently of the applied magnetic field, one finds nearly opposite dc voltages for the longitudinal contacts at the opposite sides of the strips and relatively small transverse potential differences [see the sketch of the corresponding dc potential in the lower part of Fig. 1(a)]. The resulting nearly uniform longitudinal electric field can be explained in terms of the ac driven net 1D vortex flow in the direction transverse to the strip, with the direction indicated by the arrow. For all studied superconducting strips, for the typical applied currents, the asymmetry of *I-V* characteristics, as shown in Fig. 1(b) by summing left and right branches, does not exceed 3%. The inset in Fig. 1(b) confirms this quantifying the anisotropy by comparing critical currents (determined with 10 μV criterion) for the positive and negative branches of the *I-V* curves. The origin of *this rather small anisotropy* could be related to unavoidable bulk pinning anisotropy and/or defect induced[18–20] difference between surface barriers for the left and right sides of the superconducting strip. This, hardly noticeable from the *I-V* curves in Fig. 1(b), anisotropy is sufficient to account for the observed low frequency dc voltage and its 1D symmetry. The origin of the surface barrier is discussed later.

For $f \geqslant 100$ kHz, the transverse dc potential difference becomes comparable to the longitudinal one [Fig. 2(a)]. In all our experiments, independently of the drive frequency, the sum of the dc potential differences along all four pairs of the contacts (U1-U4) is very small [Fig. 2(a)]. This proves that the total number of the vortices inside the rectifier is

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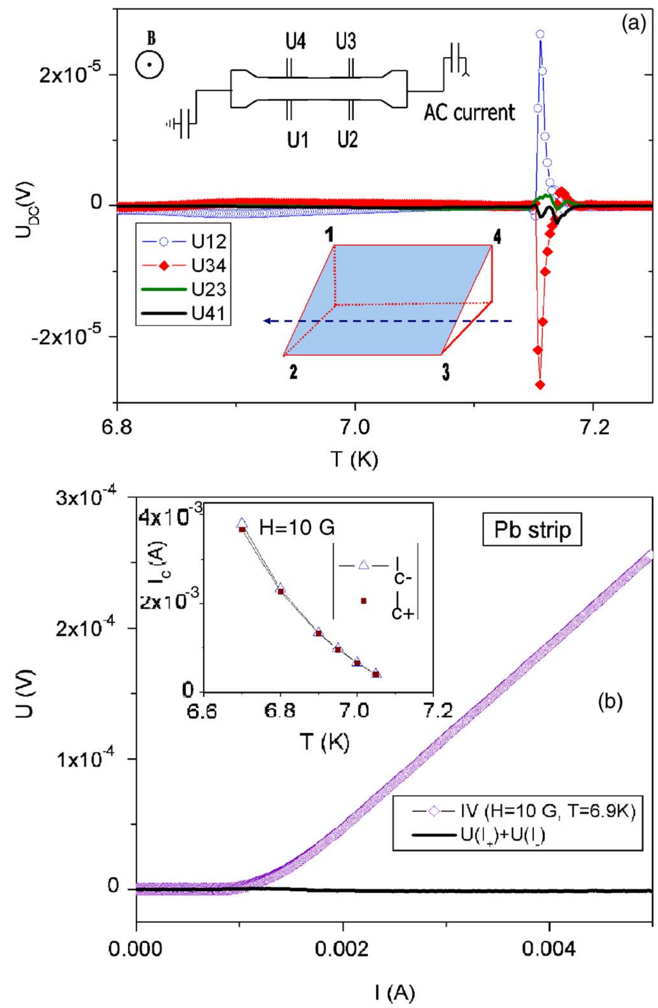

FIG. 1. (a) Two opposite longitudinal and two transversal rectification voltages as function of temperature measured for Pb strip with $H=2$ G, $f=9$ kHz, and $I_{ac}=1.7$ mA. The upper inset shows experimental configuration. The lower inset sketches rectification voltage profile generated at low ac drive frequencies. Arrow indicates dominant net vortex flow. (b) Analysis of the asymmetry of typical *I-V* characteristic by summing voltage for the left and right current branches. Inset compares critical currents for the positive and negative branches of the *I-V* curves close to T_c.

determined by the external magnetic field and remains nearly constant.

For the frequencies above a few MHz we have found an *essential similarity in the DC voltages measured at the opposite sides of the strips* when, as for the low frequency data, *the measurements were done by moving clockwise* [Fig. 2(b)]. One can also see that *the longitudinal and transverse generated potentials,* as shown in Fig. 2(c) for the Nb strip, *have nearly opposite values of the dc voltage*. The lower inset in Fig. 2(c) sketches the topology of the generated between the contacts dc electric potential with the drive frequency in the MHz range and at a fixed temperature close to T_c. Both the 1D and 2D rectifications are highly reproducible when cycling the temperature above T_c and can be tuned by varying the magnetic field (see inset in Fig. 3). In the whole frequency range studied, both the longitudinal and transverse dc voltages are nearly antisymmetric in values with respect to the polarity of the magnetic field (Fig. 3). We have also found that the generated dc voltage depends nonlinearly on the amplitude of the ac drive.

Our low frequency experiments show the presence of the small 1D rectification with a uniform dc electric field along

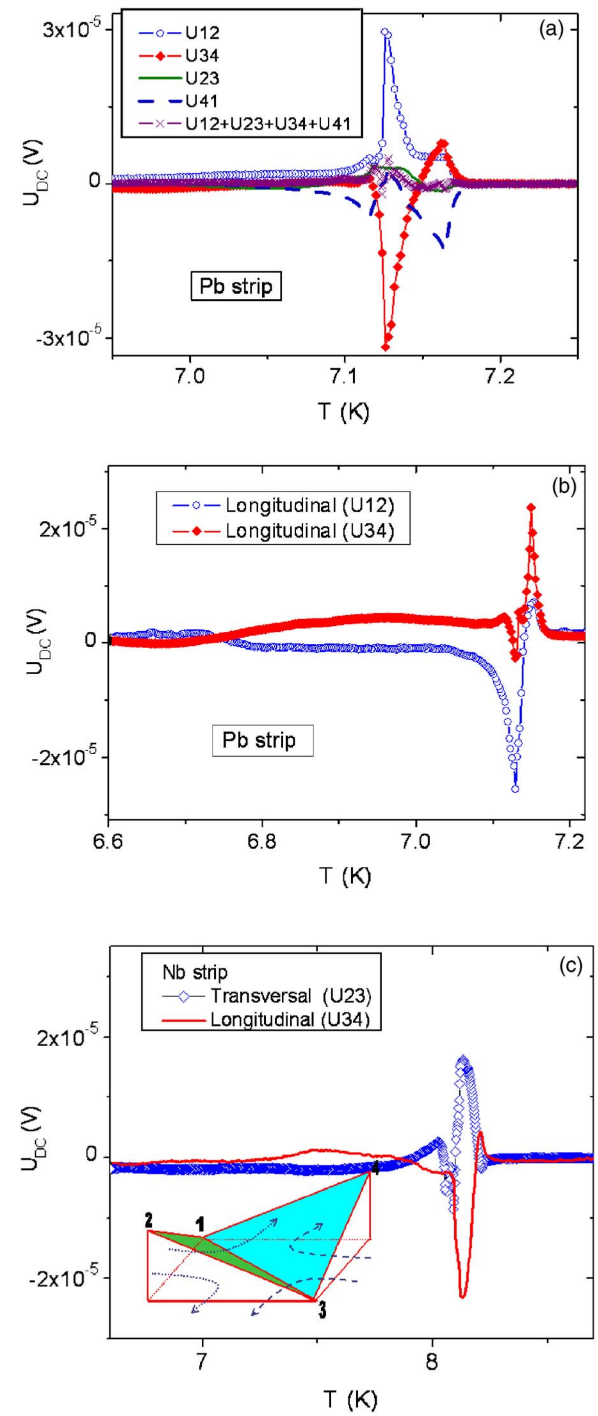

FIG. 2. (a) Same dc potentials as in Fig. 1(a) but measured for $f=99$ kHz, $H=8$ G, and $I_{ac}=1.7$ mA. The crosses show a sum of four different rectification voltages. (b) Rectification voltage measured in Pb strip from the opposite sides with $f=43$ MHz, $H=10$ G, and $I_{ac}=1$ mA. (c) Comparison of the transverse and longitudinal rectification for Nb strip measured with $f=43$ MHz, $I_{ac}=1.1$ mA, and $H=500$ G. The lower inset sketches rectification voltage profile generated in superconducting strip at high ac drive frequencies. Arrows indicate dominant vortex flow for each two half cycles (dotted vs dashed) of the ac drive.

the ac current, as suggested for superconducting films with some vortex pinning anisotropy.[9,10] The high frequency rectification, with the transverse electric field of the opposite signs for the opposite contacts, cannot be explained by similar arguments only. The resistive state model,[13,14] the Hall contribution or the presence of a transverse ac current component at high drive frequencies could not provide a plau-

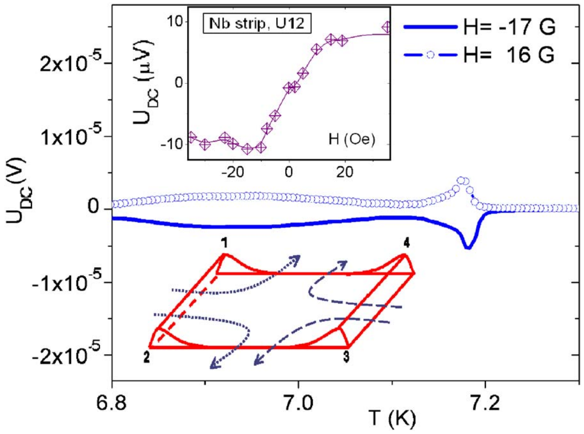

FIG. 3. Longitudinal dc voltage measured with $f=147$ MHz, $I_{ac}=0.46$ mA for two nearly opposite magnetic fields. The upper inset shows dependence rectification voltage U12 vs magnetic field for Nb strip when measured with $I_{ac}=1.3$ mA, and $f=43$ MHz and $T/T_c=0.99$. The lower inset schematically shows strip with two oppositely directed asymmetric BL barriers.

sible explanation, since all these mechanisms involve the generation of only a uniform (1D) permanent electric field.

The following qualitative model accounts for our main observations. Let us consider the influence of two Bean-Livingston (BL) type asymmetric barriers for vortex entry/exit.[21]. Edge geometry[22] and defects[18–20] influence the BL barrier, but do not suppress it completely.

Let us now consider periodically driven vortex system in superconducting strip *with two oppositely directed asymmetric BL barriers* (sketch in Fig. 3). At low drive frequencies ($f \leqslant 10$ kHz), when the vortex travel distance $L=v^*(1/f) \sim 500$ μm is much larger than the transverse dimensions of the strip (d), during each half-period the vortex motion "feels" negligible bulk pinning anisotropy, as well as some small (unavoidable) difference in the symmetrically reflected shape of the two (left and right) BL barrier profiles. Such periodic vortex motion with large amplitude provides the 1D rectification, as indeed observed experimentally [Fig. 1(a)]. At higher frequencies $f \approx 100$ kHz, the vortex travel distance is reduced and becomes comparable to the width of the strip, that is $L \approx d$. Here, we have used the vortex velocity of $v = 50$ m/s, which was estimated from the measured dc voltages, $H=10$ G and $d=100$ μm (Pb) or 40 μm (Nb). If the typical BL barrier width were taken to be about $b \sim 1$–5 μm, then at the drive frequencies of the order of $v/b \sim 10$–50 MHz the two opposite transversal vortex flow patterns would be generated during each of the half-cycles of the ac drive inside the superconducting strip due to edge ratchets [see dashed and dotted arrows in Figs. 2(c) and 3]. This would result in an excess vortex density closer to the center of the superconducting strip, thus creating two opposite longitudinal vortex flows, in accordance with the observed 2D rectification voltage profile. The nonuniform dc electric field, which is a nonequilibrium phenomenon, persists in superconducting films because the duration of the first stage of the relaxation of vortices may be relatively slow.[23,24] The earlier arguments imply that the dc voltage between the same lateral contacts should change the sign if the direction of the permanent field is changed. This case is shown in Fig. 3. Another natural conclusion is that the dc electric fields at the opposite sides of the strip are of the same value and have opposite signs. Near T_c the signs are, indeed, opposite but their absolute values are not equal [Fig. 2(b)]. Therefore, at high ac drive frequencies rectification has local character determined by combined effect of the small anisotropic vortex pinning and the vortex rectification by the two nonideal BL barriers.

Finally we discuss multiple sign inversion of the rectified voltage. It has been shown[25] that relaxation times due to vortex entry/exit through BL barrier are not only very different, but also show qualitatively different temperature dependences. Presence of the defects in the real superconducting film produces spatial variation of the BL barrier along the strip[18–20] naturally explaining multiple sign inversions for the longitudinal dc voltage as well as the linked to it transversal one.

This work has been supported in parts by the grants GR/MAT/0252/2004 from CM, by MAT2003-02600 (Spanish MEC).

[1] R. Rinaldi, A. Biasko, G. Maruccio, V. Arima, P. Visconti, R. Cingolani, P. Facci, F. De Rienzo, R. Di Felice, E. Molinari, M. Ph. Verbeet, and G. W. Canters, Appl. Phys. Lett. **82**, 471 (2003).
[2] G. Cuniberti, J. Yi, and M. Porto, Appl. Phys. Lett. **81**, 850 (2002).
[3] B. Hackens, L. Gence, C. Gustin, X. Wallart, S. Bollaert, A. Cappy, and V. Bayot, Appl. Phys. Lett. **85**, 4508 (2004).
[4] H. Linke, E. Humphrey, A. Löfgren, A. O. Sushkov, R. Newbury, R. P. Taylor, and P. Omling, Science **286**, 2314 (1999).
[5] S. Saveliev and F. Nori, Nat. Mater. **1**, 179 (2002); K. H. Lee, Appl. Phys. Lett. **83**, 117 (2003).
[6] J. Velligas, S. Savel'ev, F. Nori, E. M. Gonzalez, J. V. Anguita, R. Garcia, and J. L. Vicent, Science **203**, 1188 (2003); J. Van de Vondel, C. C. de Souza Silva, B. Y. Zhu, M. Morelle, and V. V. Moshchalkov, Phys. Rev. Lett. **94**, 057003 (2005).
[7] I. Zapata, R. Bartussek, F. Sols, and P. Hänggi, Phys. Rev. Lett. **77**, 2292 (1996).
[8] C.-S. Lee, B. Janko, I. Derenyi, and A.-L. Barabasi, Nature (London) **400**, 337 (1999).
[9] P. S. Swartz and H. R. Hart, Jr., Phys. Rev. B **137**, A818 (1965)
[10] D. D. Morrison and R. M. Rose, Phys. Rev. Lett. **25**, 356 (1970)
[11] R. P. Huebener, *Magnetic Flux Structures in Superconductors* (Springer, Berlin, 1979).
[12] R. Wördenweber and P. Dymashevski, Physica C **404**, 421 (2004).
[13] V. V. Andrianov, V. B. Zenkevic, V. V. Kurgozov, V. V. Sychev, and F. F. Ternokski, Sov. Phys. JETP **31**, 815 (1969).
[14] R. P. Huebener and V. A. Rove, Solid State Commun. **7**, 1763 (1969).
[15] A. N. Ulianov, J. Appl. Phys. **85**, 3726 (1999).
[16] H. Sadate-Akhavi, J. T. Chen, A. M. Kadin, J. E. Keem, and S. R. Ovshinsky, Solid State Commun., **50**, 975 (1984).
[17] A. V. Silhanek, L. van Look, S. Raedts, R. Jonkheere, and V. V. Moshchalkov, Phys. Rev. B **68**, 214504-1 (2003); J. I. Martin, M. Velez, A. Hoffmann, I. K. Schuller, and J. L. Vicent, Phys. Rev. Lett. **83**, 1022 (1999).
[18] A. Buzdin and M. Daumens, Physica C **332**, 108 (2000).
[19] D. Yu Vodolazov, Phys. Rev. B **62**, 8691 (2000).
[20] A. E. Koshelev and V. M. Vinukur, Phys. Rev. B **64** 134518 (2001); Th. Schuster, M. V. Indenbom, H. Kuhn, E. H. Brandt, and M. Konczykowski, Phys. Rev. Lett. **73**, 1424 (1994).
[21] C. P. Bean and J. D. Livingston, Phys. Rev. Lett. **12**, 14 (1964).
[22] E. Zeldov, I. Larkin, V. B. Geshkenbein, M. Konczykowski, D. Majer, B. Khaykovich, V. M. Vinokur, and H. Shtrikman, Phys. Rev. Lett. **73**, 1428 (1994).
[23] A. Gurevich, H. Küpfer, B. Runtsch, R. Meire-Hirmer, D. Lee, and K. Salama, Phys. Rev. B **44**, 12090 (1991).
[24] Y. Paltiel, E. Zeldov, Y. N. Myasoedov, H. Shtrickman, S. Bhattacharya, M. J. Higgins, Z. L. Xiao, E. Y. Andrei, P. L. Gammel, and D. J. Bishop, Nature (London) **403**, 398 (2000).
[25] L. Burlachkov, Phys. Rev. B **47**, 8056 (2003).