Interaction between Josephson and pancake vortices investigated by the induced microwave dissipation by ac magnetic field technique

D. Shaltiel,[1,*] H.-A. Krug von Nidda,[2] B. Ya. Shapiro,[3] B. Rosenstein,[4] A. Loidl,[2] B. Bogoslavsky,[1] I. Shapiro,[3] and T. Tamegai[5]
[1]*Hebrew University of Jerusalem, Israel*
[2]*Experimental Physics V, Center for Electronic Correlations and Magnetism, University of Augsburg, 86135 Augsburg, Germany*
[3]*Department of Physics, Bar-Ilan University, Ramat-Gan, 52100, Israel*
[4]*National Chiao Tung University, Department of Electrophysics, Hsinchu, Taiwan, People's Republic of China*
[5]*Department of Applied Physics, The University of Tokyo, Hongo, Bunkyo-ku, Tokyo 113–8656 Japan*
(Received 12 March 2008; revised manuscript received 30 April 2008; published 23 June 2008)

In the "induced microwave dissipation by ac magnetic field" (IMDACMF) technique, only the motion of Josephson vortices (JV) but not of pancake vortices (PV) induces microwave dissipation. This unique property is used to investigate the interaction between JV and PV in the high anisotropy superconductor Bi2212 as a function of magnetic field and tilting angle away from the *a-b* plane. In general, pinning of JV by PV inhibits the motion of the JV and, thus, reduces the microwave dissipation. Almost no pinning of JV is obtained at low dc magnetic fields even at high-tilting angles. Strong pinning of JV due to their interaction with PV is observed at higher magnetic fields and at tilting angles between 50° and 90°. The technique enables to observe transitions from the JV state to the crossing lattice state, without and with interaction between JV and PV, and to the one-dimensional vortex chains. The results obtained by the present technique are compared to results of surface imaging techniques, which investigate the interaction between PV and JV probing the PV.

DOI: 10.1103/PhysRevB.77.214522 PACS number(s): 74.25.Nf, 74.50.+r, 74.72.Hs

I. INTRODUCTION

A magnetic field applied parallel to the *a-b* plane in high-anisotropy cuprate superconductors such as $Bi2Sr2CaCu2O_{8+\delta}$ (Bi2212) forms elongated Josephson vortices (JV) centered between the cuprate planes. A magnetic field applied parallel to the *c* axis forms a pancake-vortex (PV) structure that resides within the conducting planes. In tilted magnetic fields both JV and PV are present, forming a rich vortex phase diagram due to the interaction between the two types of vortices (cf. Fig. 1). The investigation of this interaction in Bi2212 has been reported in an extensive number of publications where various techniques have been employed such as Hall probe,[1] Bitter decoration,[2] magneto-optical imaging.[3] and Lorenz microscopy.[4] They show that introducing PV by tilting the magnetic field forms different structures of chain vortices dependent on the tilting angle. These structures are attributed to the strong attractive interaction between the Josephson-vortex and the pancake-vortex sublattices.[5]

In the present work a dynamical experimental approach is applied to investigate the interaction between JV and PV. It is carried out by measuring the effect of a low-frequency ac magnetic field on the motion of Josephson vortices at different tilting angles of the magnetic field. The vortex motion is detected by means of the "induced microwave dissipation by ac magnetic field" (IMDACMF) technique.[6] Recent publication has shown that applying an ac field collinear with a dc field parallel to the *a-b* plane in a Bi2212 crystal induces a sharp increase in the microwave dissipation due to the shaking of Josephson vortices.[7] Microwave dissipation was not observed when the ac and dc fields were oriented parallel to the *c* axis. It indicates (see discussion below) that the motion of PV caused by the ac field induces only very small, if any, microwave dissipation. Assuming that the dissipation results only from the interaction of the ac field with JV, the microwave dissipation is expected to decrease with the cosine of the tilting angle away from the *a-b* plane. Thus, at a given tilting angle the comparison of the measured microwave dissipation with that calculated from the measured dissipation parallel to *a-b* plane, provides information on the strength of the interaction between both kinds of vortices due to pinning of JV by PV. The results illustrated below will show that the contribution of PV to the microwave dissipation is small at low dc fields and increases strongly with increasing dc field.

In the following the experimental set up and procedure will be explained. Then the experimental results will be presented. The discussion will focus on the effect of PV on the ac induced motion of JV.

II. EXPERIMENT

The experimental setup[8] consists of a Bruker ELEXSYS 500 X-band EPR spectrometer. The microwave source feeds a 9.3 GHz rectangular H102 cavity. A Bi2212 sample ($1\times1\times0.1$ mm^3) is positioned at its center, where only the magnetic microwave field is present. The sample, whose temperature could be varied down to helium temperature using a helium continuous-flow cryostat (Oxford instruments), is exposed to collinear dc (H_{DC}) and ac (h_{AC} with frequency 100 kHz) magnetic fields. Rotating the crystal along an axis perpendicular to the magnetic field and parallel to the *a-b* plane varies the orientation of the magnetic field from parallel to perpendicular to the *a-b* plane. The microwave magnetic field is applied parallel to the *a-b* plane along the axis of rotation. Thus, rotating the sample does not vary the intensity of the microwave magnetic field. The ac magnetic field induces a signal proportional to the microwave losses in

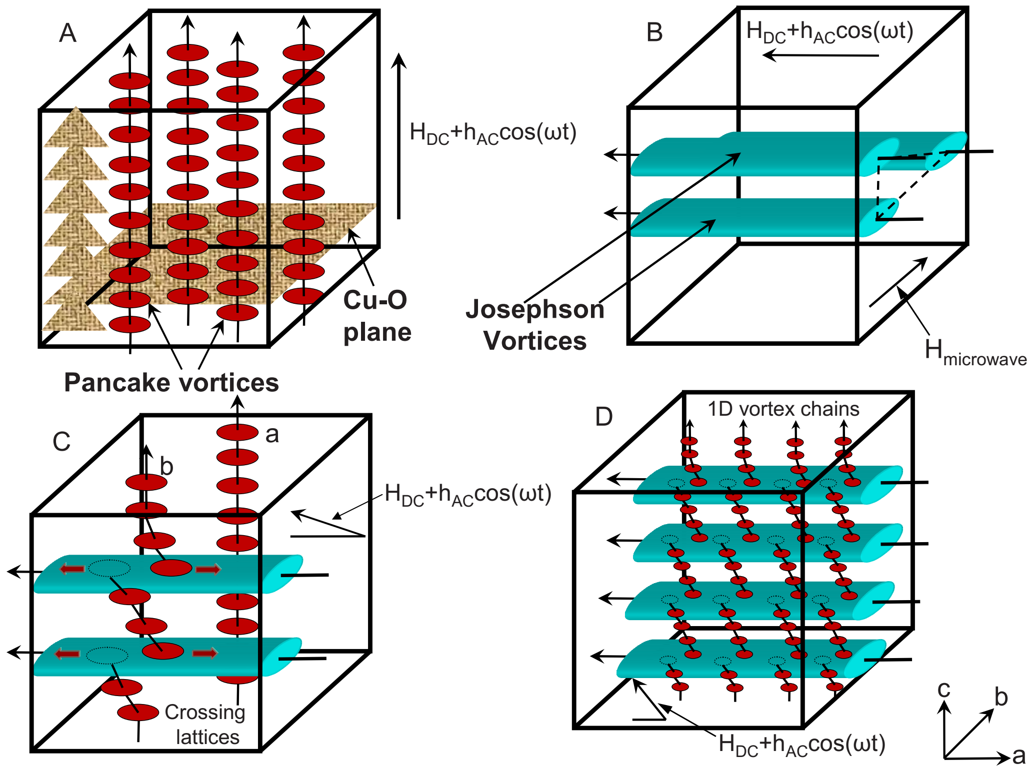

FIG. 1. (Color online) Vortex structure in high-anisotropy superconductors (inspired from the vortex structure of Fig. 1 of Ref. 1). A: magnetic field parallel to the *c* axis, only PV are excited that reside in the conduction layers, forming two dimensional hexagonal structures. B: magnetic field parallel to the conduction planes, only JV are exited forming a triangular vortex structure. C and D: magnetic field tilted away of the principal axis excites both PV and JV. Their mutual interaction forms a rich variety of vortex structures that depends on the density of the two types of vortices.

the sample. The reflected microwave power is rectified by a diode and is fed into a lock-in detector. The lock-in detector gives the first harmonic signal intensity and phase at the ac frequency. Previous experiments have shown that changing the variables such as the dc and ac magnetic fields and temperatures affects not only the signal intensity but also its phase.[8] Therefore the signal intensity was determined from maximum intensity obtained by varying the phase of the lock-in detector between 0° and 360°. All measurements were carried out using zero field cooling from above T_c down to the measured temperature to ensure that vortices are not present before starting the measurement.

III. RESULTS

Figure 2 shows the signal intensity at 40 K as function of dc magnetic field for different orientations from less than 2° off the *a*-*b* plane up to parallel to the *c* axis (90°). For the magnetic field aligned close to the *a*-*b* plane, two peaks are observed at H_{DC}=2 mT and 24 mT, respectively. The position of the low-field peak is almost constant for all angles. The inset shows that its intensity decreases with increasing angle close to cos θ, where θ is the angle between the *a*-*b* plane and the magnetic field. The position of the high-field peak shifts to lower fields, its intensity decreases strongly and disappears above $\theta \approx 60°$. These features are presented in a clearer way in Fig. 3(a), which depicts the intensity as a function of θ at different dc magnetic fields from H_{DC} =2 mT to 45 mT. It shows that the higher the dc field, the larger the decrease in the microwave dissipation for the same tilting angle. Another instructive presentation of these results is obtained by normalizing the signal intensities at θ=0° to

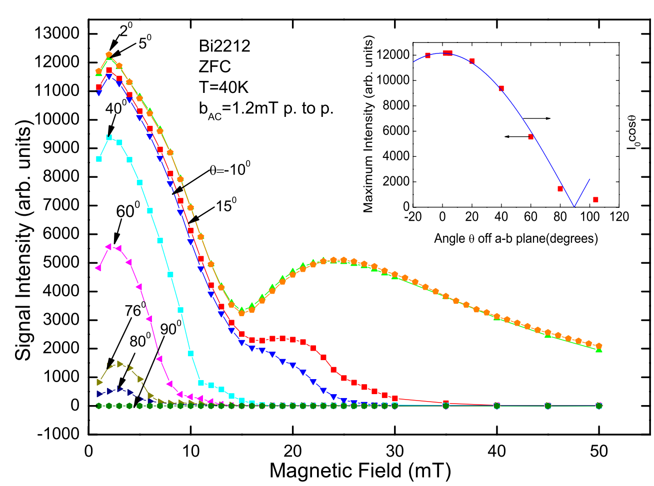

FIG. 2. (Color online) Signal intensity measured in a Bi2212 single crystal at T=40 K as a function of dc magnetic field for different angles θ of the magnetic fields, from H_{DC} close to the *a*-*b* plane (θ=0°) to H_{DC} parallel to the *c* axis (θ=90°). Inset: The squares represent the low-field-peak intensity at different angles. The solid curve is a I_0 cos θ fit, where I_0 is the intensity at θ=0°.

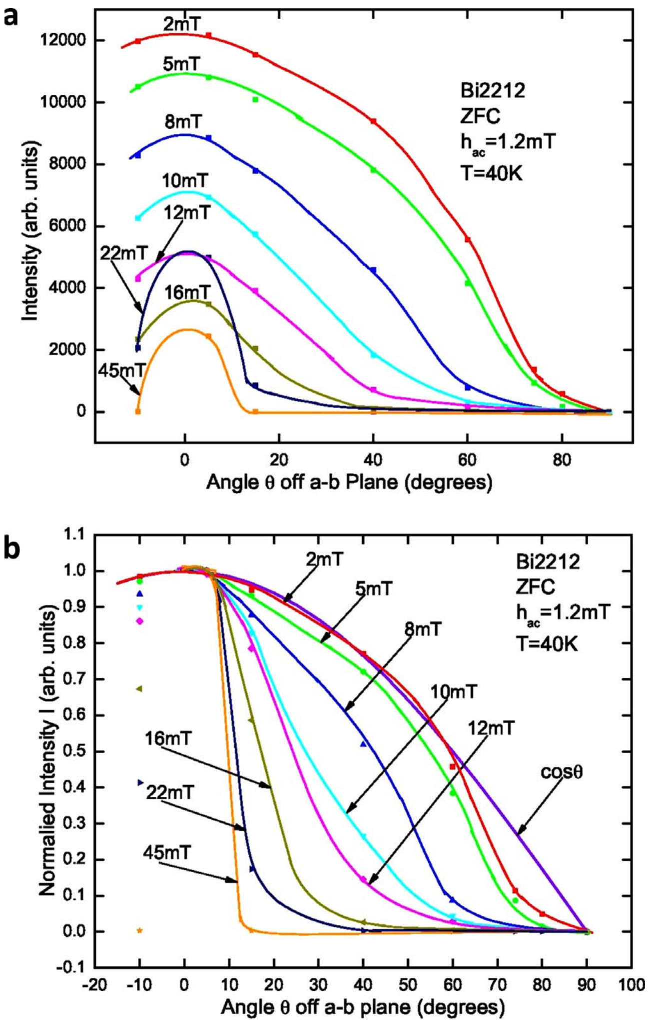

FIG. 3. (Color online) (a) Signal intensity as a function of the tilting angle θ for dc magnetic fields 2 to 45 mT, derived from Fig. 2. It shows that the larger the dc fields, the smaller the angle where the signal intensity goes to zero. (b) Signal intensity derived from (a) as a function of the tilting angle θ for dc magnetic fields 2 to 45 mT, normalized to the same intensity $I=1$ at $\theta=0°$. The curve $I(\theta=0)\cdot\cos\theta$ shows that the signal intensity for $H_{DC}=2$ mT starts to deviate from $\cos\theta$ only above 55°. At higher dc field the deviation starts already close to $\theta=5°$ and increases with dc field.

unity for all dc fields [Fig. 3(b)]. It clearly demonstrates that the relative decrease in the signal intensity toward zero value deviates the stronger from $\cos\theta$, the larger the tilting angle and the higher the magnetic field.

To analyze the above results it is necessary to recall the mechanism that induces the microwave signals by the ac magnetic field, h_{AC}, collinear to the dc magnetic field, for the magnetic field applied parallel to the *a*-*b* plane where only JV are present. Recent theoretical investigations indicate that the microwave dissipation for magnetic fields parallel to the *a*-*b* plane results from the interaction of the microwave magnetic field with Josephson vortices, which are depinned due to shaking by the ac field.[7]

IV. DISCUSSION

Microwave dissipation detected in our experiment is caused by nonpinned fluxons motion. On the other hand the flux dynamics is strongly affected by the pinning forces, which is strongly different for PV and JV. In fact the Abrikosov-like PV can be easily pinned by the point defects, in contrast to the coreless JV. The direction of the external dc magnetic field is essentially important because it determines the structures of both the PV and the JV lattices and hence the pinning force. Increasing the pinning constant decreases the signal intensity, and for large pinning constant the signal is negligibly small. Hence increasing the tilting angle at a constant magnetic field or increasing the magnetic field at a constant tilting angle results to larger density of PV and larger pinning constant that decreases the signal intensity. In fact, the applied magnetic field in the *c* direction creates only a strong pinned PV lattice whose contribution into the microwave dissipation is almost zero. On the other hand the magnetic field directed parallel to the layers creates the JV structures affected by negligibly small pinning force. Their dynamics is responsible for a large microwave dissipation in our experiment. Tilted applied magnetic field creates both PV and the JV. The interaction between these subsystems is crucially important. In fact more mobile JV can be pinned by the PV. This pinning constant (Labush constant K in our previous paper[7]) depends mainly on the angle between the tilted magnetic field and *a*-*b* plane. In fact the microwave dissipation induced by the ac field results only by the motion of the JV but not by the motion of the PV. This unique property enables to analyze dynamics of JV in the presence of PV. It is manifested in the present work (Fig. 2) by investigating the signal intensity as a function of magnetic field and tilted angle. As the density of JV or PV is proportional to the magnetic field H_{DC} applied parallel to the *a*-*b* plane or to the *c* axis, respectively; the vortex density for H_{DC} at a tilted angle θ away from the *a*-*b* plane would change as $H_{DC}\cos\theta$ and $H_{DC}\sin\theta$ for the JV and PV, respectively.[9] Assuming that the observed microwave dissipation is only proportional to the density of the JV, the signal intensity would vary as $H_{DC}\cos\theta$. Indeed, Fig. 3(b) shows that the signal intensity observed at $H_{DC}=2$ mT (i.e., at a relatively low H_{DC} field) follows a $\cos\theta$ behavior from small angles up to $\theta\approx 60°$, but deviates to lower values for higher angles. This deviation, which becomes more pronounced at higher magnetic fields, indicates that in addition to the decrease in the ac-induced microwave dissipation of the JV due to the decrease in the JV density by tilting the magnetic field, an additional mechanism decreases the dissipation.

Numerous investigations on the effect of magnetic-field tilting on the interaction between JV and PV in highly anisotropic superconductors have been published.[10,11] Most of them use methods of magnetic imaging, generated parallel to the crystallographic *a*-*b* surface. They show that magnetic tilting forms different vortex states as illustrated in Fig. 1.[1] The concept of vortex states was discussed by Bulaevskii[12] and later by Koshelev,[13] who has introduced the idea of the crossing-lattices state. The imaging results clearly indicate the presence of strong interaction between the PV and the JV, and that this interaction increases with the tilting angle

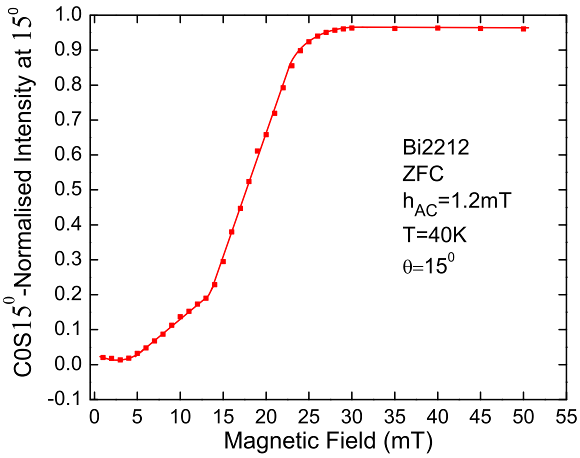

FIG. 4. (Color online) Differences between ΔI (the observed normalized intensity at the tilting angle of 15°) and cos 15° (the expected normalized microwave dissipation at 15°) as a function of magnetic field. The different slopes are attributed to phase transitions.

toward the c axis, which increases the PV density. We therefore conclude that the additional factor that reduces the microwave power dissipation arises from pinning of the JV by the PV, and that the pinning increases with the increase in the PV density. Thus, the present microwave-dissipation results can be readily interpreted by comparing them to the results obtained from the imaging measurements.[2]

As pointed out above the microwave dissipation arises from the interaction of the microwave field with the moving JV depinned by the ac field. At a magnetic field parallel to the a-b plane, only JV are present; their density as function of tilting angle is maximum and therefore the signal intensity is also maximum. At small tilting angles, $\theta < 5°$, the change in the concentration of the PV that increases as sin θ is small and the results show that the PV and the JV form a crossing-lattice state, where stacks of PV and JV do not intersect and behave almost independently. The signal intensity should, therefore, decrease as cos θ due to the decrease in the JV density. This is observed in Figs. 3(a) and 3(b), which show a very small decrease in the signal intensity for $\theta < 5°$ even at the highest magnetic fields up to 45 mT.

The signal intensity as a function of tilting angle at a magnetic field of 2 mT follows a cos θ dependence up to a tilting angle of 60° [Fig. 3(b)]. Above 60° the signal intensity decreases faster than cos θ, indicating pinning introduced by PV. The pinning results from intersection between PV stacks with JV stacks in the crossing-lattice state that leads to interaction between JV and PV, as shown in Fig. 1(c).

At a magnetic field of 8 mT, zero signal intensity is observed above a tilted angle of 80°. Further increase in the magnetic field lowers the tilting angle above which the intensity goes to zero. Zero intensity indicates the formation of a sublimated one-dimensional vortex state that leads to strong pinning of JV [Fig. 1(d)].

The formation of different vortex states is deduced also from Fig. 4, which shows the deviation of the JV signal intensity, ΔI, from the expected cos θ behavior at a constant tilting angle of 15° as a function of magnetic field. At constant angles increasing the magnetic field increases the density of both JV and PV, keeping their density ratio nearly constant. At $0 < H_{DC} < 5$ mT, ΔI is almost zero. It implies that the PV do not induce additional pinning of the JV. The system is in the crossing lattice state, where the stacks of JV and PV do not interact [Fig. 1(c)]. At 5 mT$< H_{DC} <$30 mT, the increase in ΔI with increasing field indicates that PV interact with JV. The system is still in the crossing-lattice state, and the interaction results as the PV stacks intersect with the JV stacks [Fig. 1(c)]. Two linear slopes are observed between 5 and 30 mT, where the change in slopes occurs at 15 mT. It suggests the presence of two phases. The higher-field slope is larger, indicating a stronger interaction between the PV stacks and the JV stacks at the high-field phase. This is expected as the densities of both the JV and the PV at this phase are larger than those of the low-field phase. Above 30 mT, ΔI is maximum and constant as the signal intensity in this region is almost zero due to the strong pinning of JV in the sublimated one-dimensional vortex state [Fig. 1(d)].

The decoration techniques and the IMDACMF technique investigate interaction between PV and JV. The decoration techniques are visual techniques that detect the distribution of PV stacks at the surface or close to it. The formation of a crossing-lattice state and of a sublimated one-dimensional vortex state are deduced from the different distribution of the PV stacks close to the surface.[14,15] From the variation in the formation of the PV stacks as a function of the tilting angle, it is possible to obtain information regarding the strength of the interaction between PV and JV. The IMDACMF technique observes the microwave-power dissipation due to the interaction between depinned JV (induced by ac magnetic field) and the microwave magnetic field. The present work shows that the decrease in the microwave dissipation as a function of the tilting angle results from stronger pinning of JV stacks by PV stacks. Thus, both methods are complementary in the study of the interaction between the two kinds of vortices.

V. SUMMARY AND OUTLOOK

In conclusion the present work shows that the IMDACMF technique successfully probes the interaction between JV and PV in highly anisotropic superconductors in tilted fields as a function of the variables involved. The interaction between both types of vortices in tilted fields is also obtained by the decoration techniques, where it is observed via the variation of the vortex-chain images on the superconductor surface again due to changes of the variables involved. Using both methods can yield a better understanding on the mechanism of the interaction and the formation of different phases. The present technique uses an EPR spectrometer that is simple to handle at temperatures from T_c down to 4 K at magnetic fields up to 1.5 T and at different angles. The frequency used was 9.3 GHz. The signal intensities were strong and could be observed directly on a digital oscilloscope without the use of a lock-in detector. It implies that dissipation signals can be obtained also with different spectrometers even of lower sensitivity, whose frequencies can range from a few megahertz[16] to hundreds of gigahertz;[17] thus, it can provide information on the interaction of the moving JV with the electromagnetic field at a very large frequency range. The ac frequency used in the present work was 100 kHz at magnetic field amplitude of 1.2 mT peak to peak. Earlier publications have shown that microwave dissipation is obtained at ac frequencies from 100 to 100 KHz, and that the signal intensity, its phase, and its shape strongly depend on the ac intensity. Investigation of the tilting effect at different frequencies below and above this frequency range and at a large range of ac intensities can give more information on the pinning strength induced by the PV on the JV.

ACKNOWLEDGMENTS

This work was supported in part by The Israel Science Foundation, Heinrich Hertz Minerva Center for High Temperature Superconductivity, by the German Bundesministerium für Bildung und Forschung (BMBF) under the Contract No. VDI/EKM 13N6917, and by the Deutsche Forschungsgemeinschaft (DFG) within Sonderforschungsbereich SFB 484 (Augsburg). B.R. is supported by DOE and NSC of R. O. C. Grant No. M93-2112-M009-023. T.T. is supported by Grant-in Aid for Scientific Research from the Ministry of Education, Culture, Sports, Science, and Technology, Japan.

*Author to whom correspondence should be addressed. shaltiel@vms.huji.ac.il

[1] A. Grigorenko, S. Bending, T. Tamegai, S. Ooi, and M. Henini, Nature (London) **414**, 728 (2001).

[2] M. Tokunaga, T. Tamegai, Yenina Fasano, and F. de la Cruz, Phys. Rev. B **67**, 134501 (2003).

[3] V. K. Vlasko-Vlasov, A. Koshelev, U. Welp, G. W. Crabtree, and K. Kadowaki, Phys. Rev. B **66**, 014523 (2002).

[4] A. Tonomura, H. Kasai, O. Kamimura *et al.*, Phys. Rev. Lett. **88**, 237001 (2002).

[5] A. E. Koshelev, Phys. Rev. B **68**, 094520 (2003).

[6] D. Shaltiel and T. Tamegai, Physica C **406**, 87 (2004).

[7] D. Shaltiel, H. A. Krug von Nidda, A. Loidl, B. Rosenstein, B. Y. Shapiro, I. Shapiro, T. Tamegai, and B. Bogoslavsky, Phys. Rev. B **77**, 014508 (2008).

[8] D. Shaltiel, J. Low Temp. Phys. **130**, 383 (2003).

[9] C. A. Bolle, P. L. Gammel, D. G. Grier, C. A. Murray, D. J. Bishop, D. B. Mitzi, and A. Kapitulnik, Phys. Rev. Lett. **66**, 112 (1991).

[10] T. Tamegai, M. Matsui and M. Tokunaga, Physica C **412-414**, 391 (2004)

[11] M. Tokunaga, M. Kishi, N. Kameda, K. Itaka, and T. Tamegai, Phys. Rev. B **66**, 220501(R) (2002).

[12] L. N. Bulaevskii, M. Ledvij, and V. G. Kogan, Phys. Rev. B **46**, 11807 (1992).

[13] A. E. Koshelev, Phys. Rev. Lett. **83**, 187 (1999).

[14] M. Tokunaga, M. Kobayashi, Y. Tokunaga, and T. Tamegai, Phys. Rev. B **66**, 060507(R) 2002.

[15] M. Yasugaki, K. Itaka, M. Tokunaga, N. Kameda, and T. Tamegai, Phys. Rev. B, **65**, 212502 (2002).

[16] D. Shaltiel, D. Ioshpe, A. Grayevsky, V. Zevin, and J. L. Smith, Phys. Rev. B **36**, 4090 (1987).

[17] B. Beeman, H. J. Fink, and D. Shaltiel, Phys. Rev. **147**, 454 (1966).