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Magnetic field and temperature dependence of the critical vortex velocity in type-II superconducting films

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Abstract

We study the vortex dynamics in the instability regime induced by high dissipative states well above the critical current in Nb superconducting strips. The magnetic field and temperature behavior of the critical vortex velocity corresponding to the observed dynamic instability is ascribed to intrinsic non-equilibrium phenomena. The Larkin–Ovchinnikov (LO) theory of electronic instability in high velocity vortex motion has been applied to interpret the temperature dependence of the critical vortex velocity. The magnetic field dependence of the vortex critical velocity shows new features in the low-field regime not predicted by LO.

1. Introduction

In recent years static and dynamic states of Abrikosov vortex lattices have been widely studied in type-II superconductors and new phenomena due to different vortex matter phases have been observed in the transport properties of both low and high temperature superconductors (LTS and HTS) [1]. In particular, dynamic phenomena of the vortex lattice driven by an external current have been extensively investigated by current–voltage (I–V) characteristics measurements in the limit of low bias current, but interesting physical mechanisms in the high dissipation regime have also been reported [2, 3]. An electronic instability in the case of large Lorentz forces experienced by vortices has been observed in many LTS and HTS [4–7] and it has been described in the framework of Larkin and Ovchinnikov (LO) theory [2] and its extension due to Bezuglyj and Shklovskij (BS theory) [8]. The influence on the vortex instability of the 'quasiparticle heating' due to the finite rate of removing the dissipated power in the sample has been considered in BS theory. In this case, a characteristic magnetic field B_T has been introduced: for $B \ll B_T$ the pure LO mechanism prevails, while at $B \gg B_T$ the vortex instability is dominated by the heating effects and hence by a quasiparticle distribution at higher temperature. Nevertheless, there are also other possible instability mechanisms that can be considered, such as, for example, the simple thermal runway, the hot-spot effect, the vortex system crystallization and the phase-slip centers or lines. In the first case, high bias currents induce a power dissipation in the film that is high enough to destroy the superconducting state, leading to an abrupt increase of sample temperature above T_c. The second effect is related to a localized normal domain formation, i.e. hot spot, which appears in a place of maximum current concentration and is sustained by Joule heating. In the I–V curve it manifests itself by a counterclockwise hysteresis. In the vortex system crystallization the I–V curve is expected to show a jump-like transition, occurring at a current very close to the critical current, between a pinned static state and a coherently moving lattice at large velocities. Finally, if phase-slip centers or lines appear, then a voltage-step structure in the I–V curve is produced, where such segments of constant dynamic resistance show a magnetic-field-independent slope.

On the other hand, in the I–V curve, the LO instability appears as a sudden voltage jump above a threshold current I^* much higher than the critical current I_c. According to the LO theory, this jump is described in terms of an instability of the moving vortex system which occurs at a critical vortex velocity v^*. Following LO arguments, in the limit of high flux flow velocities v and for T close to the critical temperature T_c, an additional dissipative mechanism, due to the quasiparticle runaway from the normal vortex core, has to be taken into account. In particular, the energy increase of the quasiparticles in the core, due to the high electric field induced by the vortex motion, results in a progressive reduction of the vortex diameter as the vortex velocity is increased up to the critical value v^*. This shrinking of the vortex core and the corresponding reduction of the damping force above v^* gives rise to the instability of the vortex system and hence to the abrupt transition into the normal state. The energy relaxation time τ_e of the quasiparticle plays a crucial role in this dissipative process. In fact, the vortex velocity should be high enough in order to allow the quasiparticles to escape from the vortex core during their lifetime such that $v\tau_e \gg \xi$. In the hypothesis of a spatially uniform quasiparticle distribution in the superconducting material, the LO model predicts a magnetic-field-independent critical velocity, which, as a function of the reduced temperature $t = T/T_c$, has the following expression:

$$v^*_{LO}(t) = \frac{D^{1/2}[14\zeta(3)]^{1/4}(1-t)^{1/4}}{(\pi\tau_e)^{1/2}} \qquad (1)$$

where D is the quasiparticle diffusion coefficient and $\zeta(x)$ is the Riemann zeta function. A good agreement with experiments has been found in large magnetic fields, when the inter-vortex distance a_0 is smaller than the quasiparticle diffusion length $l_e = (D\tau_e)^{1/2}$, while at lower magnetic fields a power law behavior $v^* \sim B^{-1/2}$ has been reported below a crossover field B_{cr} [9]. However, the behavior of the critical vortex velocity at low magnetic fields, in which the main hypothesis of LO theory fails, has not been deeply investigated. In the limit of a_0 larger than l_e a dependence $v^* \sim 1/B$ has been predicted by Vodolozav *et al* [10] consistent with the experimental field-independent critical voltage V^* reported in [11].

In this work I–V characteristics measurements in the mixed state of niobium thin films strips are reported. Measurements are performed in applied magnetic fields close to the lower critical field B_{c1} and at different temperatures T down to $0.5T_c$. In particular, at sufficiently high bias current, the I–V data exhibit a remarkably steep voltage jump at a critical voltage V^* from the flux flow state to the normal one. On the basis of our experimental data, we exclude the occurrence of other possible mechanisms, so that the critical vortex velocity deduced by I–V data can be analyzed in the framework of LO theory. The study as a function of temperature is performed to evaluate the quasiparticle scattering rate, and in the low applied magnetic field regime a new behavior of critical vortex velocity has been observed.

2. Experimental results and discussion

Thin films of Nb on Si(100) substrates were fabricated by a UHV dc diode magnetron sputtering with a base pressure $P_b = 4 \times 10^{-8}$ mbar and sputtering argon pressure $P_{Ar} = 1 \times 10^{-3}$ mbar. The deposition rate, as controlled by a quartz crystal monitor calibrated by low-angle reflectivity measurements, was $r = 0.3$ nm s^{-1}. The standard photolithographic technique was used to pattern the Nb films in a four-contact geometry. Two strips Nb1 and Nb2 of linewidth $W = 50$ μm and thicknesses $d = 60$ and 135 nm were investigated, with a length $L = 2$ mm. The critical temperatures T_c of the two samples are 8.1 ± 0.2 K and 8.7 ± 0.1 K, respectively, while the resistivity in the normal state $\rho_{10\ K}$ is 17 $\mu\Omega$ cm. A typical value of the superconducting coherence length is $\xi = 10$ nm. The slightly high values of ρ_{10K}, as well as the relatively suppressed T_c values, may be related to the wet etching process applied for the definition of the strip geometry.

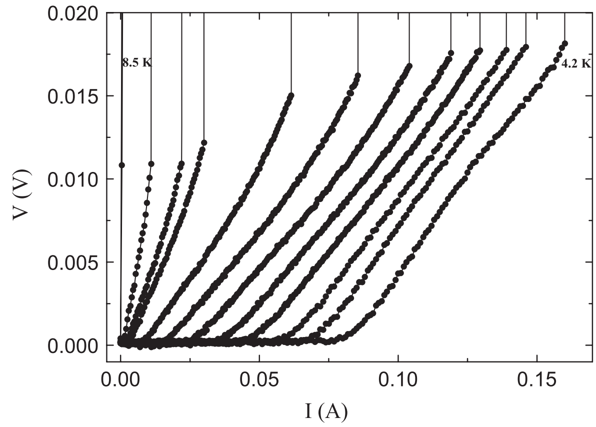

Figure 1. I–V curves at different temperatures in a magnetic field $B = 8.0$ mT for the Nb2 sample. From right to left, the temperature values are: 4.2, 4.6, 5.0, 5.5, 6.0, 6.5, 7.0, 7.5, 8.0, 8.1, 8.3 and 8.5 K.

The I–V measurements of the samples are performed by means of a pulsed current technique, in order to prevent undesired Joule heating [12]. Figure 1 displays I–V characteristics of sample Nb2 at different temperatures and in a magnetic field $B = 8.0$ mT. A discontinuous voltage jump is clearly shown with a monotonic decreasing behavior of the instability current I^* as the temperature increases towards T_c. On the other hand, experimental I–V characteristics of sample Nb1 at $T = 5.5$ K, reported in figure 2, display a non-monotonic behavior of I^* as a function of the applied magnetic field in the range $B < 11.0$ mT. A detailed analysis of the dissipated power at the critical point (I^*, V^*) within the BS model has been reported elsewhere [12]. We have found a threshold magnetic field $B_T \approx 0.24$ T below which relevant heating effects can been ignored and hence a pure LO description of the instability can be assumed in the field range investigated in the present work.

From the I–V data the magnetic field and temperature dependences of the vortex critical velocity have been deduced as $v^*(t, B) = V^*(t, B)/BL$ [13].

In figure 3 the magnetic field dependence of the critical vortex velocity has been reported for different temperature values. We found an experimental feature of $v^*(B)$ in the low magnetic field regime investigated, $B < 11.0$ mT, with a new crossover magnetic field $B_{cr1} \approx 5.0$ mT at $T = 4.2$ K, above which the $v^* \sim B^{-1/2}$ dependence is restored [14]. Moreover such crossover field results are temperature-dependent. In

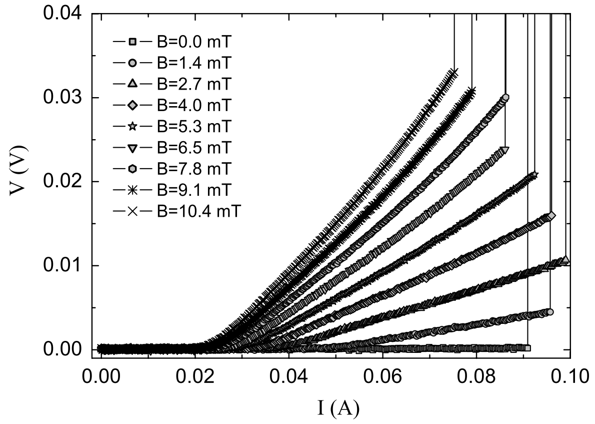

Figure 2. I–V curves at $T = 5.5$ K in different magnetic fields for the Nb1 sample. The value of the fields are reported in the panel.

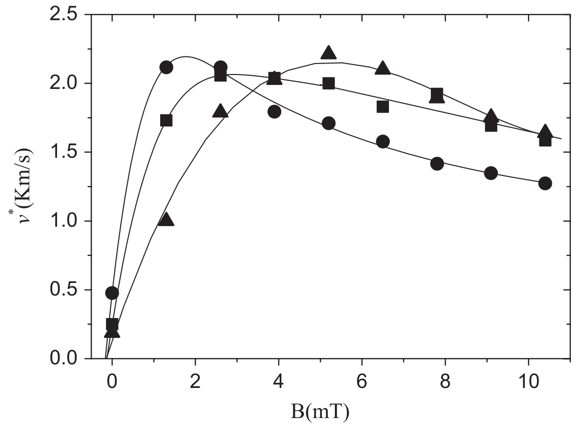

Figure 3. Magnetic field dependence of the critical vortex velocity for the Nb1 sample at different temperatures $T = 4.2$ K (triangles), 5.5 K (squares) and 7.5 K (circles).

particular it is shifted to lower magnetic field values by increasing the temperature as shown in figure 3.

Concerning the temperature dependence, the LO predicted vortex critical velocity of equation (1) has been compared with the experimental results of $v^*(t)$ reported in figure 4. Here, in particular, for the Nb2 sample, the $v^*(t)$ for three values of the external applied magnetic field ($B = 6.0$, 8.0 and 10.4 mT) is shown.

In the magnetic field range investigated v^* increases by decreasing the field with the power law behavior $B^{-1/2}$. In this case a B-dependent pre-factor has been included in equation (1) by [9] to account for the v^* versus B experimental data:

$$v^*(t, B) = \left(1 + \sqrt{\frac{a_0}{D\tau_e}}\right) v^*_{LO}(t) \qquad (2)$$

with $a_0 = \sqrt{2\Phi_0/\sqrt{3}B}$. Although the LO prediction is strictly valid for T close to T_c, the data fitting by equation (2) has been performed for $t > 0.7$, since for Nb it has already verified an extended validity range down to $0.6T_c$ [4]. Assuming a constant value of the inelastic quasiparticle time in equation (2) and a diffusion coefficient $D = 2.0 \times 10^{-10}$ m^2 s^{-1}, the fitting

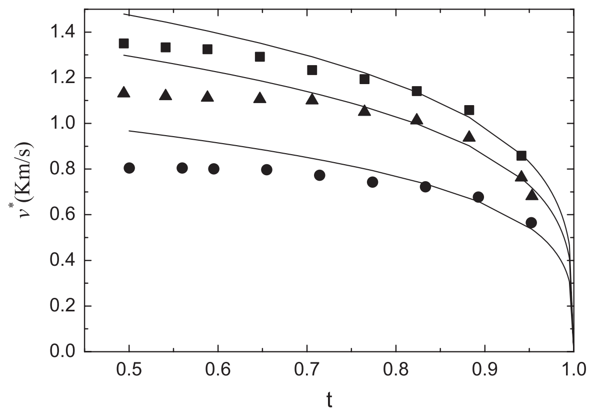

Figure 4. Temperature dependence of the critical vortex velocity at different magnetic field values $B = 6.0$ mT (squares), 8.0 mT (triangles) and10.4 mT (circles) for the Nb2 sample. The solid lines are data fitted by equation (1).

procedure gives for τ_e values of the order of 5×10^{-10} s. The obtained results are slightly larger compared with the reported values on Nb thin films in the dirty limit regime [4]. On the other hand, in order to account for the low temperature behavior of the critical velocity v^* in figure 4 the temperature dependence of the inelastic scattering time, $\tau_e(t)$, has to be considered [4, 7, 14, 15]. In particular, for $t < 0.7$ our data display an almost constant behavior of $v^*(t)$, which has been previously observed but in the whole temperature range investigated ($t > 0.6$) for the clean limit case [4]. The quasi-constant v^* at $t < 0.7$ can be described in terms of a saturation of the relaxation time at low temperatures, suggesting the presence of a temperature-independent scattering time of the quasiparticle at energies larger than the energy gap $\Delta(0)$, as reported elsewhere [4, 16].

3. Conclusions

We perform I–V measurements on wide thin Nb strips as a function of temperature and applied magnetic field. The intrinsic flux flow electronic instabilities of vortex motion predicted by the LO theory have been observed. Vortex critical velocity results show the temperature dependence of v^* in good agreement with the LO prediction for T close to T_c, while at lower temperatures the presence of a second relaxation channel can be inferred. On the other hand, a new feature in the magnetic field dependence $v^*(B)$ has been observed. In particular, the heuristics power law behavior $v^* \sim B^{-1/2}$ has been reproduced only at sufficiently high fields, but in the low field range, the observed $v^*(B)$ dependence shows a new crossover field B_{cr1} of a few mT which also becomes temperature-dependent.

References

[1] Blatter G, Feigel'man M V, Geshkenbein v B, Larkin A I and Vinokur V M 1994 *Rev. Mod. Phys.* **66** 1125
Brandt E H 1995 *Rep. Prog. Phys.* **58** 1465

[2] Larkin A I and Ovchinnikov Yu N 1986 *Non Equilibrium Superconductivity* ed D N Langenberg and A I Larkin (Amsterdam: Elsevier) p 493
[3] Klein W, Huebener R P, Gauss S and Parisi J 1995 *J. Low Temp. Phys.* **61** 413
[4] Peroz C and Villard C 2005 *Phys. Rev.* B **72** 014515
[5] Ruck B J, Trodahl H J, Abele J C and Geselbracht M J 2000 *Phys. Rev.* B **62** 12468
[6] Xiao Z L, Voss-de Haan P, Jakob G, Kluge Th, Haibach P, Adrian H and Andrei E Y 1999 *Phys. Rev.* B **59** 1481
[7] Angrisani A A, Bell C, Aarts J and Attanasio C 2007 *Phys. Rev.* B **76** 054502
[8] Bezuglyi A I and Shklovskij V A 1992 *Physica* C **202** 234
[9] Doettinger S G, Huebener R P and Kuhle A 1995 *Physica* C **251** 285
[10] Vodolozav D Y and Peeters F M 2007 *Phys. Rev.* B **76** 014521
[11] Chiaverini J, Eckstein J N, Bozovic I, Doniach S and Kapitulnik A 2000 arXiv:cond-mat/0007479v1
[12] Grimaldi G, Leo A, Nigro A, Pace S, Angrisani A A and Attanasio C 2008 *J. Phys.: Conf. Ser.* **97** 012111
[13] Tinkham M 1996 *Introduction to Superconductivity* 2nd edn (Singapore: McGraw-Hill)
[14] Grimaldi G, Leo A, Nigro A, Pace S, Cirillo C and Attanasio C 2008 *Physica* C **468** 765
[15] Doettinger S G, Huebener R P, Gerdemann R, Kuhle A, Anders S, Trauble T G and Villegier J C 1994 *Phys. Rev. Lett.* **73** 1691
[16] Kaplan S B, Chi C C, Langenberg D N, Chang J J, Jafarey S and Scalapino D J 1976 *Phys. Rev.* B **14** 4854