Flux Flow Velocity Instability in Wide Superconducting Films

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Abstract. To understand energy losses related to vortex high velocity we study the critical voltage in the current-voltage (I-V) characteristics above which in the flux flow regime a sudden voltage jump appears. Different mechanisms have been proposed to account for the existence of a critical vortex velocity corresponding to the observed instability, such as heating effects or intrinsic non equilibrium phenomena. Nevertheless experimental studies of flux flow instabilities in wide superconducting films have been less investigated. We report on critical voltage measurements in Nb wide superconducting strips. We perform I-V measurements as function of magnetic field by using different bias modes (sweeping, compensated long and short pulsing). The magnetic field dependence of the critical voltage shows different features in the three operation modes. We quantitatively estimate self-heating effects taking into account cryogenic stabilization criteria and thermal diffusion calculations, and we demonstrate that the observed dynamics instabilities are not triggered by Joule self-heating. The Larkin – Ovchinnikov (LO) theory of non linear effects in the vortex motion has been then applied to interpret the critical velocity results. The magnetic field dependence of the vortex critical velocity shows some discrepancies with the LO predicted behaviour.

1. Introduction

Studies about the dissipative regimes in both low- (LTS) and high-\(T_c\) (HTS) superconductors are far to be completed. Current-voltage (I-V) measurements covering the whole range from the zero voltage state to the normal resistive branch have to be carefully analyzed, mainly for high bias currents and in particular for wide superconducting tapes, to be used for large scale applications [1]. In fact, since high power dissipation may damage the superconducting films and affect the superconducting properties, the highly dissipative states have been extensively investigated by I-V measurements on thin microbridges, thus preventing heating effects at all [2]. In these cases, far above the critical current, an intrinsic abrupt transition form the flux-flow regime to the normal conductive state have been analyzed [3]. In wide superconducting films the unavoidable heating effects should be taken into account, and the origin of these instabilities have to be clarified [4, 5]. Several mechanisms have been proposed to explain the observed flux-flow instabilities [6], which first of all have been predicted by Larkin and Ovchinnikov (LO), due to the diffusion of nonequilibrium quasiparticles from the moving...
vortex core. The induced vortex shrinking, corresponding to a critical vortex velocity $v^*$, determines the corresponding voltage jumps at high bias currents [4]:

$$v^* = D^{1/2} \left[ 14 \zeta(3)^{1/4} \right] (1-t)^{1/4} \left( \pi \tau_E \right)^{1/2}$$

where $D$ is the quasiparticle diffusion coefficient, $\zeta$ is the Riemann zeta function, $\tau_E$ is the time of quasi-particle energy relaxation and $t = T/T_c$ the reduced temperature.

The LO model of the electronic instabilities has been extended by Bezuglyi-Shklovskij (BS), by taking into account quasi-particle heating due to the finite heat removal rate of power dissipated in the sample [7]. This approach calculates the heat flow from the film to the substrate as a result of their mutual phonon exchange rather than interface properties. In the electron temperature approximation and in the Joule heating regime, the temperature $T$ of quasi-particles and phonons, which is higher than the substrate temperature $T_0$, that is the bath temperature, can be found from the heat balance equation. The heat flow from the film to the substrate can be written as $Q = h(T_0)(T-T_0)$, with $h$ the heat transfer coefficient. Following a microscopic analysis of the heat removal from a thin film in the resistive state near $T_c$, a macroscopic parameter has been derived which separates the region where non thermal ($B << B_T$) or pure heating mechanisms ($B >> B_T$) of the instability dominates:

$$B_T = \frac{0.374e\tau_E}{k_B\sigma_Nd}$$

where $e$ is the electron charge, $k_B$ is the Boltzmann constant, $\sigma_N$ is the normal conductivity and $d$ is the film thickness.

Due to the large interest in wide samples such as coated conductors, in this paper we analyze I-V instabilities in wide Nb films measured in different biasing modes and we show experimental results on the magnetic field dependence of $v^*(B)$, comparing with the recently modified LO models.

2. Heating effects on I-V measurements

A Nb 100nm thick film with a transition temperature $T_c = 8.5$ K was prepared by dc sputter deposition on oxidized Si (100) substrates. By standard UV photolithography a Nb strip of $w = 100 \mu$m width was obtained. The distance between the voltage tips was $L = 2$ mm. The I-V curves were measured by the standard dc four probe technique, with the samples immersed in a liquid helium bath, by performing three different measurement modes (see Fig. 1). A Keithley Source Meter model 2430 (K2430) was employed, both as current source and voltage meter. In the first measurement mode, i.e. the sweeping mode, a current ramp step-like is generated, with a current-on time at each step (step width, SW) of 22ms and a total step number at least equal to 50 according to the fixed maximum current. In the second mode (compensated pulse mode) a couple of long pulses of the same amplitude and opposite sign for every measurement point has been used; the pulse width (PW) was equal to 100ms spaced by a pulse delay (PD) equal to 200ms. Finally, in the third mode (short pulses mode) short current pulses were generated, with a PW equal to 2.5ms and PD equal to 3ms. In Fig. 1 we show the comparison between the I-V curves as resulted by the three measurement modes.
Experimental data show different features in the three current operation modes, in particular the highest voltage threshold values at the instability are achieved in the short pulsing mode, in which no hysteresis was observable. Besides, in the compensated pulses mode, with the PW extremely longer, the critical voltages \( V^* = v^*BL \) [8] are significantly reduced and a thermal hysteresis characterized by a counterclockwise direction was detectable. Moreover, the I-V curves recorded in the sweeping mode also show depressed voltages \( V^* \) at higher magnetic fields.

In any case at these high bias currents, since the high dissipated power in the sample cannot be instantaneously removed, unavoidable self-heating may affect the experimental results, probably even in the short pulses operation mode. For this reason, as a first step, we quantitatively analyze Joule heating by estimating the thermal diffusion characteristic times within the superconducting film and the substrate. Following the so called dynamic stability theories [9], the heat diffusion equation in an homogeneous material can be written:

\[
D_T \nabla^2 T = \frac{\partial T}{\partial t}
\]

where \( D_T = W/\gamma C \) is the thermal diffusivity, \( W \) is the thermal conductivity, \( \gamma \) is the material density and \( C \) is the specific heat. In a slab, large in the y- and z- directions, and of thickness \( d \) in the x-direction, this equation has the following steady state solution with the initial condition of a temperature gradient in the same x-direction

\[
T = \sum_{n=1}^{\infty} A_n \sin \left( \frac{n\pi x}{d} \right) e^{-\frac{D_T n^2 \pi^2 t}{d^2}},
\]

so that the solution will decay with a characteristic time

\[
\tau_T = \frac{d^2}{\pi^2 D_T}.
\]

In the measured Nb strips the thermal diffusion characteristic time results equal to \( \tau_T^{Nb} = 0.04\text{ns} \) with \( D_T = 0.24\text{cm}^2/\text{s} \); in our SiO\(_2\) substrate (\( d = 300\mu\text{m} \)) it is \( \tau_T^{SiO_2} = 100\mu\text{s} \) with \( D_T = 0.9\text{cm}^2/\text{s} \).
Moreover, in the same slab geometry the characteristic time for surface cooling is \( \tau_h = \gamma C_d/2h \), with \( h \) the unitary heat transfer coefficient, that is \( \approx 10^4 \) W/m\(^2\)K for liquid helium surrounding [9]. Therefore it is \( \tau_h^{NB} = 10\mu s \). Since \( \tau_h^{Nb} / \tau_h^{Nb} >> 1 \), the surface cooling is a slower process than heat conduction in Nb thin film, therefore a uniform temperature across the conductor can be assumed.

At this point, the thermal exchanges between the Nb film with the liquid helium bath, and the Nb film with the substrate can be analyzed. Concerning the first contribution, following the cryogenic stabilization criterion, a necessary condition should be verified to determine significant Joule self-heating [5, 9]. From the steady-state heat balance equation of an homogeneous current-carrying material, in the case of hard superconductor in thin film geometry, the Stekly parameter has been deduced [5, 9]:

\[
\alpha = \frac{\rho_N j_c^2 d}{h(T - T_0)}
\]

where \( \rho_N \) is the electrical resistivity in the normal state, \( j_c \) is the superconducting critical current density, \( d \) is the Nb film thickness, \( T_0 \) is the liquid helium bath temperature and \( T \) is the sample temperature. The parameter \( \alpha \) characterizes the role of Joule self-heating contribution, so that self-heating is important if \( \alpha > 1 \) and negligible if \( \alpha << 1 \). Since in our measurements a minimum measurable temperature range of \( \Delta T \approx 10\)mK can be retained, it results \( \alpha \approx 0.002 \), so that it seems that the Joule self-heating cannot be responsible of the nonlinearity of the I-V characteristics at high driving currents. Therefore, if the sample is in the liquid helium bath, the self-heating can be neglected also in the flux flow regime for currents well above \( j_c \), independent of the current bias mode.

In the absence of the liquid bath the thermal exchange between the film and the substrate has to be analyzed. In this case some authors suggested that the \( h \) heat transfer coefficient is not a constant value and a decreasing up to two orders of magnitude with the increasing of the bias current pulse duration was claimed [6]. Since our experimental data in the short pulsing current mode are less sensitive to the heating effects, a quantitative estimate of the temperature rise in a thin strip of length \( l \) can be deduced during the pulse measurement [10]. The total temperature rise can be separated into two parts: \( \Delta T_1 \) across the thermal boundary resistance between film and substrate \( \Delta T_1 = R_{bd}P/A = 0.27 \) K, where \( P = IV \) is the dissipated power \( (P_{max} = I_c^2R_N = 0.8W) \) during the pulse time \( t_0 \), \( A = lw \) is the strip area and \( R_{bd} \) is the thermal boundary resistance \( (R_{bd} = 10^{-3} \) Kcm\(^2\)/W) [10]. The second term \( \Delta T_2 \) is a temperature rise at the top surface of the substrate due to heat flow from the film into the substrate. In a time \( t \) after the application of the current pulse, heat diffuses a distance \( d_s \) in the substrate \( d_s = 2(Dt)^{1/2} \). The volume in which heat diffuses is \( V = (2d_0 + w)d_s l \). The average temperature rise \( \Delta T_2 \) of this volume is \( Pt/VC \) (heat balance equation):

\[
\Delta T_2 = \frac{\beta Pt}{2l(Dt)^{1/2}C[4(Dt)^{1/2} + w]} = 0.45K ,
\]

where \( \beta \) is a corrective factor of the order of unity. Finally, the total temperature rise is about 0.7 K in our short pulse operation mode. We note that this temperature rise is an overvalue with respect the experimentally observed value.
To further exclude that the observed instabilities are triggered by heating effects, we also check the magnetic field dependence of the dissipated power $P^* = I^*V^*$ taken just below the voltage jumps where the instabilities occur. In fact, if self-heating effects were relevant a magnetic field independent behavior of $P^*$ should be expected [6]. In Fig. 2 the experimental curves $P^*(B)$ are presented. We note that it is almost $B$-independent only for $B > 0.4$T in the short pulse mode and $B > 0.6$T in both the sweeping and compensated pulse modes, but with lower $P^*$ values. The $P^*$ increasing with the field decreasing proves the absence of relevant heating effects at low fields and even more at high fields.

Moreover, following the BS theoretical approach [7], inserting the actual values of the measured sample, we found a threshold magnetic field $B_T \approx 0.24$T, whose physical meaning is that heating effects should be taken into account for explaining flux flow instabilities only above $B_T$.

We conclude that in the short pulsing I-V measurements the observed instabilities are not driven by heating effects.

3. Critical voltage measurements
Although the LO predicted vortex critical velocity results $B$ independent [4], there is the experimental evidence of a strong magnetic field dependence, widely confirmed in the literature [11]. Here, in particular, the $I^*(B)$ have been measured in the three operation modes, as reported in Fig. 3.

Fig. 2 – Dissipated power just below the instability occurs as a function of the magnetic field up to 1T at $T = 4.2$K in the Nb sample for the three different measurement modes.

Fig. 3 – $I^*$ as function of the magnetic field up to 1T at $T = 4.2$K in the Nb strip for three bias modes.
Fig. 4 – $I^*$ as a function of $B^{1/2}$, up to $B = 1$T at $T = 4.2$K, measured in Nb strip by short pulses mode. Inset: critical velocity as function of the magnetic field.

In Fig. 4 the critical voltages measured by short pulsed I-V are presented as function of $B^{1/2}$. The presence of a crossover between two different dynamic regimes has been observed (see also inset of Fig. 4): an original experimental behavior of $I^*(B)$ in a very low magnetic field range, below 0.01T, with a new cross-over magnetic field $B_{c1} \approx 9$ mT, above which the $I^* \approx B^{1/2}$ ($v^* \approx B^{-1/2}$) dependence is restored, as reported elsewhere [12].

4. Conclusions
I-V measurements on wide thin Nb strips show the abrupt voltage jumps that can be ascribed to the electronic instabilities of the flux flow vortex motion predicted by the LO theory. By using three current biasing modes (sweep, compensated pulses and short pulses), the Joule self-heating influence on the observed dynamics instabilities has been analyzed. Critical voltages measurements in the three current modes show different features. In particular in the short pulsing technique the vortex dynamics instabilities are not triggered by thermal effects. In the short pulsing mode the vortex critical velocity results show the well known power law behavior $v^* \approx B^{1/2}$ at high fields, and in a low field regime, an original $v^*(B)$ dependence was observed with a new cross-over field $B_{c1}$ of few mT between two opposed dependences of $v^*$ above and below $B_{c1}$.

References
[1] V. M. Dmitriev and I. V. Zolochevskii, Supercond.. Sci. Technol. 19 (2006) 342; B. J. Ruck, H. J. Trodahl, J. C. Abele, M. J. Geselbracht, Phys. Rev. B 62 (2000) 12468
[2] W. Klein, R. P. Huebener, S. Gauss, and J. Parisi, J. Low Temp. Phys. 61, 413 (1995)
[3] C. Peroz and C. Villard, Phys. Rev. B 72, 014515 (2005)
[4] A. I. Larkin and Yu. N. Ovchinnikov, J. Low Temp. Phys. 34, 409 (1979)
[5] A. V. Gurevich and R. G. Mints, Rev. Mod. Phys. 59, 941 (1987)
[6] Z. L. Xiao, P. Voss-de Haan, G. Jakob, Th. Kluge, P. Haibach, H. Adrian, E. Y. Andrei, Phys. Rev. B 59, 1481 (1999)
[7] A. I. Bezuglyi and V. A. Shklovskij, Physica C 202, 234 (1992)
[8] M. Tinkham, “Introduction to Superconductivity”, McGraw-Hill, Inc. (1996) Singapore, 2nd ed.
[9] M. N. Wilson, “Superconducting Magnets”, ed. R. G. Scurlock (1983) Oxford Univ. press
[10] S. K. Gupta, P. Berdahl, R. E. Russo, G. Briceno, A. Zettl, Physica C 206, 335 (1993)
[11] S. G. Doettinger, R. P. Huebener, A. Kuhle, Physica C 251, 285 (1995)
[12] G. Grimaldi, A. Leo, A. Nigro, S. Pace, C. Cirillo, C. Attanasio, Thickness dependence of vortex critical velocity in wide Nb films, Physica C: Superconductivity, in press