A Study of Current Stability in the Dissipative Flux Flow State of Superconducting Films

Gaia Grimaldi, Antonio Leo, Angela Nigro, Elena Bruno, Francesco Priolo, and Sandro Pace

Abstract—**In several superconducting applications low energy losses are strictly demanding. In superconducting films the dissipative flux flow state plays a role in the stability of the superconducting state in those devices which can operate just above the critical current (I_c). Therefore details of the current-voltage (*I-V*) characteristics and in particular of current instabilities from the flux flow state to the normal one can become significant. We study current stability in the flux flow dissipative state by a proper current-voltage measurement mode. Low temperature superconducting films have been investigated to demonstrate that the current stability range above I_c can be increased by light ion irradiation.**

Index Terms—**critical current, current-voltage characteristics, instability mechanisms, superconducting films**

I. Introduction

THE STABILITY of current carrying superconducting films, wires and tapes has been studied so far in view of applications, mostly focusing on thermal and magnetic induced effects due to flux motion [1]-[3]. Flux jumping [4] and self-field instability [5] have been investigated to avoid overheating and thermal runway capable to break down the superconducting state and driving it into the normal one. Electronic instability mechanisms can also become crucial to ensure a wider control above the critical current, so that low flux flow dissipations can be sustained in the presence of high transport current [6]. Generally speaking, to achieve higher critical currents below which no dissipations exist, a fine and not trivial control of pinning mechanisms is necessary, by looking for intrinsic or artificial pinning centers in a complex combined way [7]-[9]. Nevertheless it is remarkable that maximum pinning does not always correspond to the highest stability [10]. Indeed in type-II superconducting materials the physics of instability should deal with a dynamical aspect of

strong pinning [11], that is which mechanisms imply the possibility for the Abrikosov vortex lattice to reach the highest velocity, i.e. the vortex critical velocity (v^*), related to the flux flow critical voltage V^*. Thus above this limiting velocity the flux flow dissipative state changes abruptly into the normal state, and this occurs at the instability point (I^*, V^*) in the current-voltage (*I-V*) characteristics. On the other hand there's always the well-known stability problem related to methods of preventing flux propagation at all, but this is focused on optimizing the value of the critical current I_c, that is the highest current before the superconducting system may turn into a dissipative flux flow state or even directly to the normal one [12]. Therefore the current stability range can be improved by studying mechanisms and criteria to control I^* rather than I_c, especially for technological applications which require very low dissipations just above I_c [13]-[15].

Very recently we have investigated the influence of artificial pinning on vortex lattice instability [6], and by tuning the effective pinning strength we succeeded in reducing V^* without a significant change of I^*. Here we study the possibility to extend the current stability range, i.e. increasing I^*, by changing the intrinsic pinning with a random distribution introduced by bombarding the samples with Ar^{++} ions of energy above 0.5 MeV with several doses. The ion irradiation damage on the superconducting properties has been investigated with a special focus on the comparison between the instability point before and after irradiation. The induced disorder effect has been analyzed in several Nb strips of different thickness previously characterized by a moderately strong pinning behavior [16]-[17]. Finally, we suggest how to enhance the stability of the Abrikosov vortex lattice, which can improve the stability of the superconducting device as well.

II. Experimental Procedures

A. Samples preparation

Superconducting Nb thin films of different thickness have been used to test transport properties as a function of magnetic field and temperature before and after irradiation damage. Details of the physical parameters of the measured samples are summarized in Table I. Standard UV photolithographic technique was used to define the strip geometry of the samples, whose width varies between 50 and 100 μm, with a fixed length l = 2 mm. Disorder was introduced in these films by bombarding the samples with 600 keV Ar^{++} at ambient temperature with doses ranging from $4 \cdot 10^{10}$ ion/cm² to $4 \cdot 10^{13}$ ion/cm². The ion energy was chosen to ensure that the

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G. Grimaldi is with CNR SPIN Salerno, via Ponte Don Melillo Fisciano 84084 (SA), Italy (corresponding author: 39-089-969494; fax: 39-089-969659; e-mail: gaia.grimaldi@spin.cnr.it).

A. Leo, is with CNR SPIN Salerno and Department of Physics, Salerno University, Fisciano, SA 84084 Italy (e-mail: antoleo@sa.infn.it).

A. Nigro is with CNR SPIN Salerno and Department of Physics, Salerno University, Fisciano, SA 84084 Italy (e-mail: nigro@sa.infn.it).

S. Pace is with CNR SPIN Salerno and Department of Physics, Salerno University, Fisciano, SA 84084 Italy (e-mail: pace@sa.infn.it).

E. Bruno is with Matis IMM-CNR and Physics-Astronomy Department, Catania University, CT 95123 Italy (e-mail: elena.bruno@ct.infn.it).

F. Priolo is with Matis IMM-CNR and Physics-Astronomy Department, Catania University, CT 95123 Italy (e-mail: francesco.priolo@ct.infn.it).

projected range of the ions was greater than the film thickness, minimizing the implantations of Argon in the films. An EDS analysis confirmed no detectable Argon in any region of any of the prepared films. With these doses the minimum matching field can be inferred, assuming $a^2 = \Phi_0/B$ with $N \cdot a^2$ the total hit area (N is the total ions number, Φ_0 is the flux quantum), it is found $B_\Phi \cong 800$ mT. We present measurements at very low fields compared with this magnetic field value. Here we show results on three Nb strips, namely N1, N2, N3, with thickness $t = 60, 135, 150$ nm, respectively, which were subjected to the same Ar^{++} ion energy (600 keV) and dose ($4 \cdot 10^{10}$ ion/cm^2), and renamed as N1i, N2i, N3i. Successively, the same Ar^{++} irradiation energy but at an increased dose ($4 \cdot 10^{13}$ ion/cm^2) was applied on the N2i sample, which is then identified as N2i2.

Table I: Physical parameters of the samples.

Sample	Status	d (nm)	T_c (K)	ΔT_c (K)	w (μm)	ρ_{10K} (μΩ·cm)
N1	bare	60	8.2	0.2	50	16
N2	bare	135	8.8	0.1	100	15
N3	bare	150	9.0	0.1	50	10
N1i	irrad.	60	8.2	0.3	50	17
N2i	irrad.	135	8.8	0.2	100	15
N2i2	2nd ir.	135	8.8	0.3	100	16
N3i	irrad.	150	9.0	0.2	50	11

B. Measurements technique

Temperature dependence of the resistance R has been checked for each level of ion damage for each sample by a standard four probe technique with a fixed bias current of 100 μA. The critical temperature T_c has been estimated as the temperature at the midpoint of the transition. We performed direct transport measurements in the four probe configuration using a pulsed-current technique in order to avoid heating effects [18]. Current-Voltage characteristics have been acquired for different temperatures in the range from $0.5 \cdot T_c$ to T_c, and in the presence of a low magnetic field, up to 10 mT. The magnetic field was applied perpendicularly to the film surface for all measurements.

C. Flux-Flow Instability

We used the flux flow instability as a tool to investigate the high velocity regime of vortex dynamics [16]. In terms of current carrying capability of the superconducting material this means to bias the sample with increasing current up to the instability value (I^*), at which suddenly the system undergoes an abrupt transition to the normal conducting state. The corresponding value of the critical voltage V^* states the upper limit to the flux flow dissipative regime. This is strictly related to the limiting vortex velocity, i.e. vortex critical velocity v^*, by Maxwell equations [19]: $v^* = V^*/(B \cdot l)$, where B is the applied magnetic field and l is the distance between voltage contacts.

Despite the fact that there are several theories and mechanisms which give an enriched scenario dealing with different explanations for the observed voltage jumps [20]-[24], we remark that our present analysis can be done regardless of the intrinsic mechanism responsible for such instability.

III. RESULTS AND DISCUSSION

Here we present results on the effects of ion damage on transport properties of Nb. First of all we noted that the normal state properties are only slightly modified by the ion irradiation used. On the contrary a very profound effect on the superconducting behavior in a low magnetic field was observed. We also compared some of our results with previous studies performed on both Nb and NbN samples [25]-[26].

A. Temperature dependence of the resistance: $R(T)$

The superconducting transitions have been recorded before and after irradiation for each sample, as reported in Fig. 1. The general trend is that the critical temperature values do not change significantly, although the transition widths of the disordered samples increase. This is a well known effect due to disorder, indeed non magnetic impurities do not reduce T_c. The robustness of T_c in our thin films is also comparable to previous results on low temperature superconducting films exposed to a similar light ion irradiation [9]-[26].
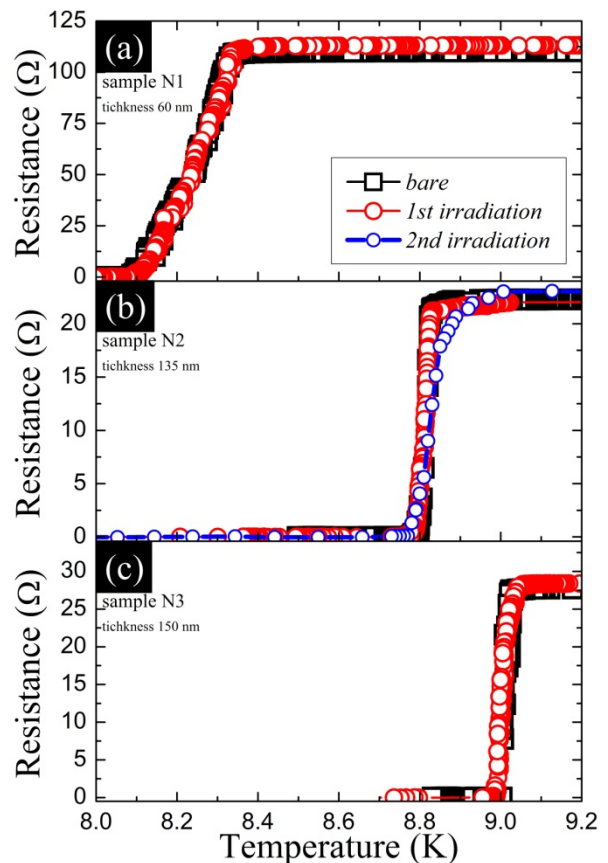

Fig. 1. Resistance as a function of temperature for the three samples of different thickness: (a) upper plot refers to the thinnest sample N1. (b) In the middle one there's the N2 sample of intermediate thickness. (c) In the lower plot results are reported for the thickest sample N3. All measurements were performed in zero external applied magnetic field.

I-V measurements were performed by carefully taking into

account self-heating effects, since this is a not trivial problem and is related to the observations of voltage jumps [27]. Moreover we have recorded the time dependence of the temperature on the sample during each single *I-V* curve measurement at a fixed magnetic field and temperature. This can give roughly an estimate of the effective temperature variation during the *I-V* measurement, which always results less than 0.1 K. In Fig. 2 there are two examples of *I-V* curves recorded with the rising temperature. The temperature remains constant during the whole measurement, there's an increase only corresponding to the high voltage state, i.e. the normal state, after voltage jumps occur.
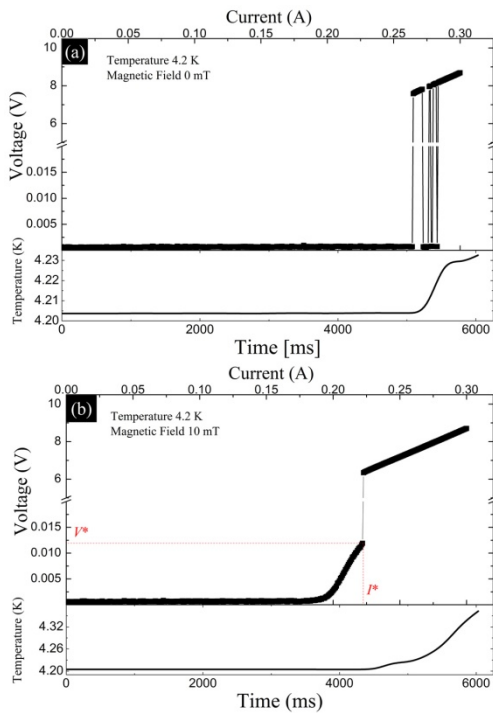

Fig. 2. *I-V* characteristics at a fixed temperature *T* = 4.2 K with the corresponding time dependence of sample temperature (a) in zero magnetic field and (b) in the presence of applied external magnetic field. The instability point (*I**, *V**) is marked.

B. Magnetic field dependence: I-V, v*(B, T)

I-V curves are reported in Fig. 3 for the three samples before and after the irradiation damage took place. Depending on the film thickness, the ion damage has a different effect: an increase of the instability current value *I** is observed for the intermediate thick sample N2. Such enhancement is less pronounced for the thickest sample N3 at low fields. On the other hand, for the thinnest sample N1, a decreasing *I** occurs only at very low fields with a saturation at higher fields. On the contrary, the critical current values show a behavior mostly insensitive to the first irradiation dose. This experimental observation can be quantitatively stated that any variation of the current value I_c between the bare sample and the first irradiated one is within few percent.
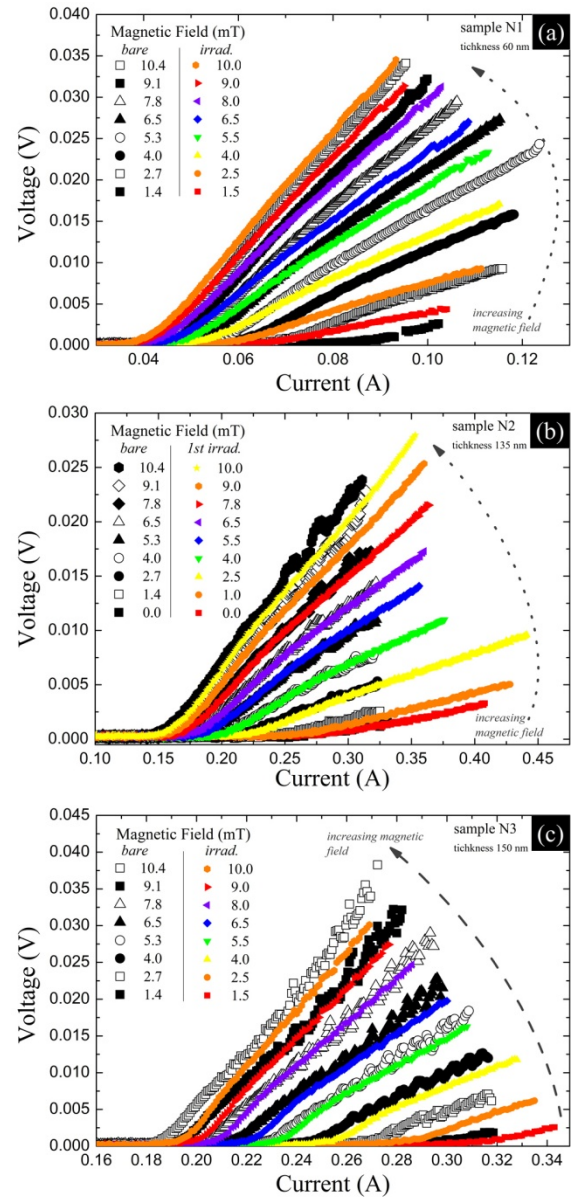

Fig. 3. *I-V* curves at different magnetic field values and at *T* = 4.2 K in the pristine and irradiated states for each of the three samples. The arrows indicate the increasing direction of the magnetic field. (a) in the upper plot the *I-V* belong to the thinnest sample (N1). (b) In the middle plot *I-V* are shown for the N2 sample of thickness 135 nm. (c) In the lower plot there's the thickest sample N3.

From these *I-V* curves the critical currents and the instability currents as a function of field have been obtained. Critical currents have been estimated by a 10 µV/cm criterion. Typical uncertainties on any current value determination, i.e. I_c and *I**, are less than 1%. Data are shown in Fig. 4 for the sample of intermediate thickness N2. The *I** enhancement is evident after the first dose of $4 \cdot 10^{10}$ ion/cm^2, when *I** increases of about 20%. After the second dose of $4 \cdot 10^{13}$ ion/cm^2 the enhancement is less pronounced. In any case, the I_c variations between the bare sample and the first irradiated one, as well as

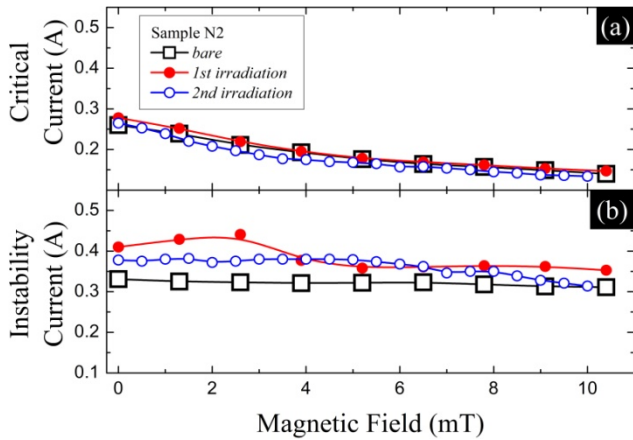between the first irradiated sample and the second irradiated one are less than 7%.

Fig. 4. (a) Critical current and (b) instability current as a function of magnetic field at $T = 4.2$ K in the bare, first irradiated state and second irradiated one, for the sample of intermediate thickness, namely N2 sample.

From the $I^*(B)$ behavior, in the whole field range, it is evident that either after the first irradiation dose and after the second one, the current values increase first, reaching a maximum, and then decrease. In particular it is remarkable that those values remain always above the I^* values achieved in the bare sample. On the other hand, the critical currents are only slightly increased after the first irradiation, but the second dose has a detrimental effect thus reducing the critical current below the values of the bare sample. Although the second dose is 1000 times larger than the first one, it seems that the pinning properties of the sample are only slightly affected, whereas a more disordered system is reached, since the superconducting transition width increases.

The combination of a moderately strong intrinsic pinning in Nb films with a random disorder induced by such Ar^{++} ion irradiation seems to help the vortex lattice to flow to higher velocities, pushing the instability point to higher values, although this effect can be related to the specific order-disorder realization in these thin films. This feature indeed changes from sample to sample, e.g. depending on the sample thickness, but it is well reproducible for each sample, e.g. see the results on the N2 sample. Therefore the observed increase of I^* can be ascribed to the light ion irradiation.

IV. CONCLUSION

The introduction of a random distribution of defects due to Ar^{++} ion irradiation indeed is able to change the intrinsic pinning distribution in Nb samples. Recently, we found that due to the intrinsic moderately strong pinning of our Nb thin films, the vortex lattice prefers to dynamically reorganize before the transition to the normal state occurs, so reaching higher velocities [16]. On the contrary, a different pinning landscape can make the vortex lattice motion unstable, so that the system prefers to jump immediately to the normal state, without rearranging itself. Here the light ion irradiation has the effect of changing the distribution of the pinning centers without changing their pinning strength, so that a final increase of I^* can be reached, with a corresponding increase of V^* and the related vortex lattice velocity. Therefore the system results more stable, even after the irradiation with larger ion doses. Finally our study suggests that to increase current stability a combination of different types of defects is necessary to optimize the pinning landscape both in terms of pinning strength and distribution of pinning centers.

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