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Dual stage resistive transition of MgB_2 evidenced by noise analysis

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The resistive transition of polycrystalline superconducting MgB_2 films is studied by means of an extensive set of stationary noise measurements, going from the very beginning of the transition to its final point, where the normal state is reached, either with and without magnetic field. The experimental results, taken at low current density and close to the critical temperature T_c, show very clearly the existence of two different dissipative processes at the different stages of the transition. An extended analysis proves that, at the beginning of the transition, when the resistance is below ten percent of normal value, the specimen is in a mixed state and dissipation is produced by fluxoid creation and motion. At higher temperature the specimen is in an intermediate state, constituted by a structure of interleaved superconducting and resistive domains. Such a situation occurs in type II superconductor when the transition temperature is very near to T_c and the critical field H_c for fluxoid penetration tends to zero. It is found that in the intermediate state, the power spectrum of the relative resistance fluctuations, is independent of the average resistance value and is unaffected by the magnetic field. As shown in the paper, this means that the noise is generated by density fluctuation of the normal electron gas in the resistive domains, while the contribution of the superconducting ones is negligible. The reduced noise amplitude does not depend on the steepness of the transition curve, thus adding further evidence to the above interpretation. The noise is thus related to the film impurities and can be investigated when the specimen is in the normal state, even at room temperature. The occurrence of a different dissipative process at low resistance is clearly evidenced by the experimental results, which show that the amplitude of the reduced power spectrum of the noise depends on magnetic field and resistance. These results are consistent with the assumption of fluxoid noise as shown by the model for the calculation of the noise developed in the manuscript. © *2011 American Institute of Physics*. [doi:10.1063/1.3605533]

I. INTRODUCTION

Electrical noise, observed either in stationary or non-stationary conditions during the transition process, can be used to investigate many important physical properties of superconductors.[1–4] In particular, the dynamics of the resistive transition plays an important role in many applications, as, for instance, in the development of transition edge sensors (TES), used as radiation detectors.[5,6] The electrical noise is detected in specimens brought to a resistive state by varying temperature, current density with or without an applied magnetic field. Depending on the type of superconductive materials and on the experimental conditions, a stationary voltage noise can be generated either by magnetic flux flow under the action of a transversal current density, or by resistance fluctuation of the specimen brought to an intermediate state, constituted by a mixture of superconducting and resistive domains. The intermediate state, characteristic of type I superconductors, may also occur in type II superconductors when the transition takes place at low current densities and at temperature near to the critical value T_c, where the critical field H_c vanishes, and the distinction between the two types of superconductors disappears. A controversial case is MgB_2, which exhibits aspects of types I and II even at temperatures much lower than T_c.[7,8] Since for many applications, superconductors are used to carry high current densities at low temperature, most of the existing literature is concerned with the noise produced by fluxoids motion, both in metal and in high-T_c superconductors. Such noise can be detected by measuring the induced voltage fluctuations at the ends of the specimen connected to a constant current generator,[9,10] or as a magnetic noise, by means of a superconducting quantum interference device (SQUID).[11–14] Different geometries and structures of the fluxoids pinning centers are considered to evaluate the frequency behavior of the noise power spectrum.[15–17]

A completely different approach is required to explain the voltage noise in the intermediate state. In this case, the noise is generated by resistance fluctuations in the normal domains, while the superconducting ones simply act as

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noiseless shunt reducing the electrical resistance of the whole specimen.

The present paper is aimed at studying the noise at low current density and at temperature close to T_c in MgB_2. This condition allows one to explore the evolution of fluctuation process, from the beginning to the end of the transition.

The intermediate state has been observed in superconducting polycrystalline MgB_2 films by measuring the power spectrum of the non-stationary noise during the resistive transition process.[18] The experimental results were interpreted by means of a simplified model, assuming that, during this process, the resistance increase is generated by the formation of resistive layers across the specimen. These assumptions were confirmed by modeling the polycrystalline film as a network of superconducting grains, characterized by a random distribution of critical currents.[19] By solving the Kirchoff equations for this network of strongly non-linear elements, it was evidenced that resistive layers formation occurs along the steepest part of the transition curve. Advancing with the transition up to its end, the layers mix up and create a more disordered structure of resistive and superconducting regions.

The above scenario is, for the largest part of the transition process, confirmed by the extended set of measurements on MgB_2 films reported in Sec. II, concerning the power spectrum of the stationary voltage noise, taken at constant temperature at different points of the transition curve, with and without the application of a magnetic field. At the very beginning of the transition, a quite different transition mechanism is evidenced, corresponding to the creation of a mixed state, where fluxoid motion is responsible for the induced voltage and the noise. In this case, the noise amplitude, at constant resistance, becomes very sensitive to the application of an external field, while at higher resistance values, when the specimen is in the intermediate state, the effect of the field vanishes. In summary, the presence of two different processes characterizing the resistive transition of polycrystalline MgB_2 films, is clearly evidenced by the noise results.

II. EXPERIMENTAL

Polycrystalline MgB_2 thin films were produced at I.N.Ri.M. Institute through simultaneous evaporation of Mg and B on a SiN substrate kept at T = 570 K. Mg and B precursors were annealed *in situ* at 773 K for 300 s in argon atmosphere at a pressure of 1 mbar. Film dimensions were 1×1 mm^2 and thickness 150 nm. Average grain size was estimated to range between 10 and 20 nm by means of Scanning Tunneling Microscopy (STM) and X-Ray Diffraction techniques. The film was sealed within a copper container filled with helium and put in a cry-ocooler that allowed to control and fix the specimen temperature at different stages of its transition process up to the normal resistive state. In order to perform noise measurements at the beginning of the transition, which were not reported in Ref. 20, the wiring of the extra low noise step-up transformer (PAR mod.AM1) has been modified. After the changes, the input impedance of the transformer was 1.25 Ω and the gain 320. An high capacity condenser (75 000 μF) prevented the flow of the bias current through the primary winding of the transformer. The secondary winding was connected to a low noise high impedance differential amplifier (SR mod560), and the output signal fed to dual channel power spectrum analyzer (HP 3562 A). An extra low noise constant current source was used to feed the specimen. Both resistance and noise measurements were performed according to the standard four contact technique.

To exclude the presence of spurious noise due to the current generator or contacts, two different tests were carried on the setup. The first test consists in the substitution of the specimen with a noiseless metallic resistor. No spurious noise was observed. The second test was performed by doubling the internal resistance of the current generator. This should have caused the halving of a possible current noise generated by the current contacts. No change in the noise power spectra was detected.

The set-up was accurately calibrated as a function of frequency by using a white noise source and a voltage divider with the minimum resistor of the same order of the specimen resistance along the transition curve. The sample resistance was measured for each noise power spectrum shown in the figures.

Measurements were performed in a shielded room. Background noise, measured by switching off the bias current, was white with a value of 3×10^{-20} V^2/Hz above 100 Hz, and nearly $1/f^2$ sloped below that frequency. Since for resistance values between R = 0.6 Ω and R = 6 Ω, the absolute spectral density of the noise below 60 Hz was of the same order of the background noise, reliable values of the spectra were limited to the frequency range from 60 to 1000 Hz, as shown in Fig. 2. The reduced power spectra of the resistance noise, in Fig. 3, refer to the relative fluctuations of the specimen resistance, obtained by dividing the voltage noise power spectra reported in Fig. 2 by the square of the voltage drop at the voltage electrodes of the sample.

Figure 1 shows the sample transition curves without magnetic field and with fields of 800 G and 1100 G. The markers represent the value corresponding to the voltage

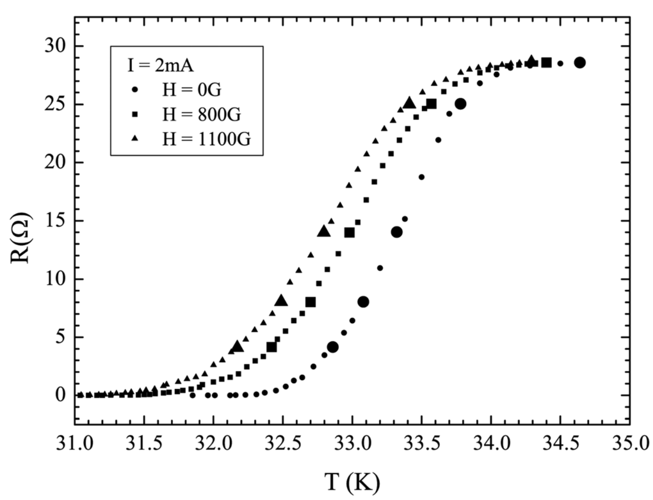

FIG. 1. Transition curves R vs T of the specimen with magnetic field of 0 G, 800 G, and 1100 G, orthogonal to the film surface. Points mark the resistance values corresponding to the noise power spectra, reported in Figs. 3 and 4.

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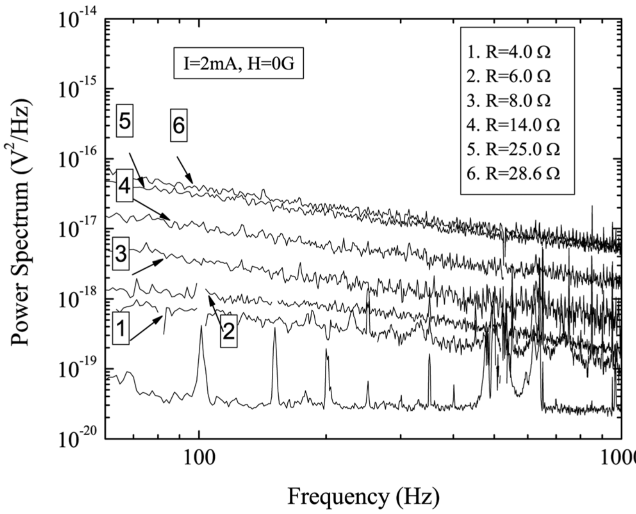

FIG. 2. Voltage noise power spectra detected at zero magnetic field in the range of resistance values from 4 up to 28.6 Ω, corresponding to the normal state of the specimen. Background noise power spectrum was subtracted to all the reported spectra. As the curves reported in Fig. 5 show, these power spectrum spectra and the ones reported in Fig. 3 are not influenced by the magnetic field.

noise power spectra and the reduced noise power spectra reported, respectively, in Fig. 2 and Fig. 3. These results show that the reduced spectra are coincident for specimen resistances varying from 4 to 28.6 Ω.

As Fig. 5 shows, they are also not influenced by the presence of a magnetic field if the specimen resistance is kept constant by adjusting the temperature when the field is changed, and are also independent of the intensity of the bias current, as expected when the voltage noise is generated by spontaneous resistance fluctuations. As discussed in Sec. III, these results are consistent with the assumption that the specimen is in the intermediate state and that the noise is generated in the resistive regions, without any detectable contribution from the superconducting ones, which simply act as a shunt to the specimen resistance.

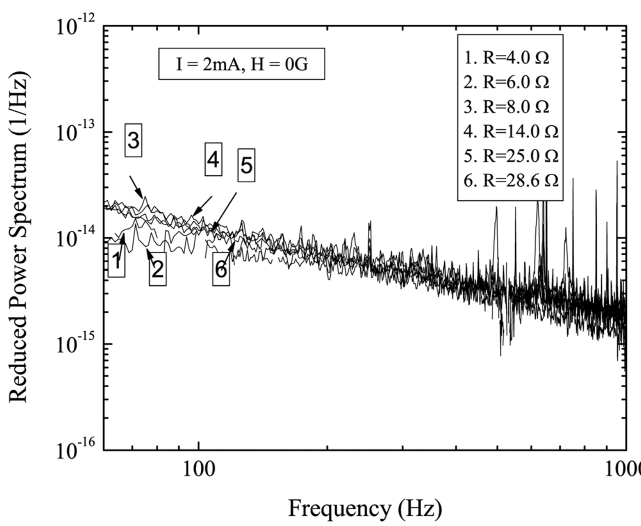

FIG. 3. Reduced power spectra of the resistance noise, obtained by dividing the spectra reported in Fig. 2 by the square of the specimen resistance. All the spectra of Fig. 2, corresponding to resistance values from 4 Ω up to 28.6 Ω, are reported. Apart from disturbances, all the spectra become practically coincident.

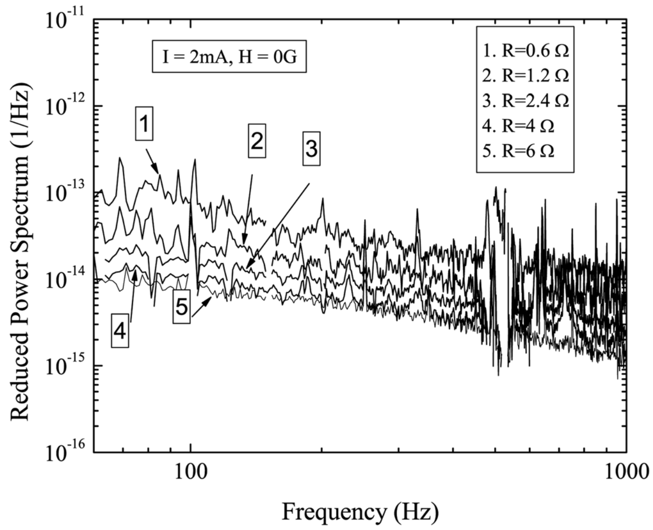

FIG. 4. Reduced power spectra of the resistance noise for resistance values of the specimen from 0.6 to 6 Ω without magnetic field. Contrarily to the reduced spectra reported in Fig. 3, the amplitude of these spectra increases when the specimen resistance decreases, nearly with an inverse proportionality at the lowest resistance values.

Figure 4 shows that, contrarily to the results shown in Figs. 2 and 3, the amplitude of the reduced power spectra of the noise for resistance values smaller than about 4 Ω increases on the resistance value approximately with an inverse proportionality. Furthermore, a strong dependence of the noise on the magnetic field H is also observed. In Fig. 5, the spectral power density of the noise is shown for different values H.

To keep the resistance constant when H increases, the temperature is varied. The set of curves shown in Fig. 6 represents the initial part of the resistive transition, with different values of the magnetic field. The markers indicate the

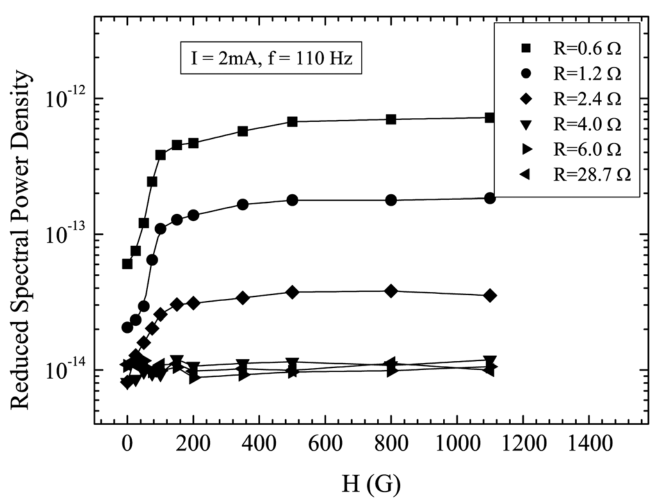

FIG. 5. Reduced noise spectral power density as a function of the magnetic field for different resistance values. For each curve, the resistance is kept constant by adjusting the temperature when the field is changed, according to the data reported in Fig. 6. These results show that, for resistance values larger than 4 Ω, the noise is not influenced by the magnetic field. At the lowest value of 0.6 Ω, the reduced spectral density becomes about one order of magnitude larger than the zero field value. Data refer to a frequency of 110 Hz.

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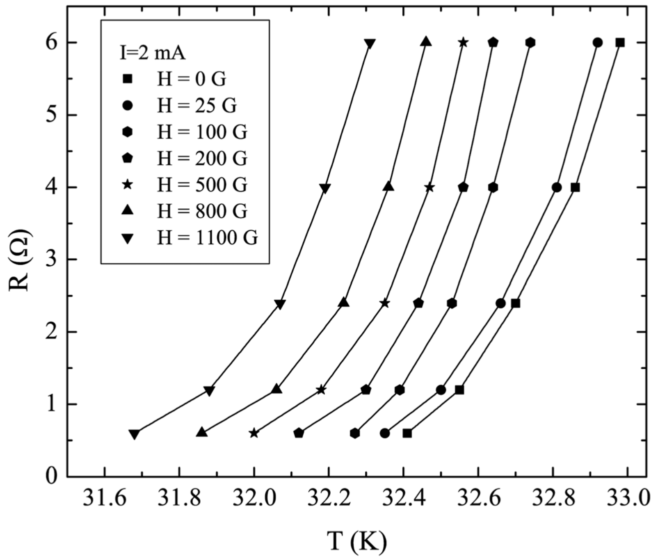

FIG. 6. Initial part of the R vs T transition curve for different values of the applied magnetic field. The points give the temperature values to keep the resistance constant when the magnetic field is changed.

temperature variation corresponding to the data reported in Fig. 4.

As discussed in the next section, all these effects are consistent with the assumption that, at the very beginning of the resistive transition, the noise is generated by fluxoid motion in the fully superconducting state.

III. DISCUSSION

From the analysis of the experimental results reported in the previous section, two different noise processes characterizing the different stages of the resistive transition in MgB_2 have been evidenced:

(i) At the beginning of the transition, when the resistance is well below 10% of its value at the transition end, the amplitude of the reduced noise power spectrum increases approximately inversely proportional to the resistance value. Furthermore, it presents strongly increases when an external magnetic field is applied and the specimen resistance is kept constant by suitable temperature variation.

(ii) For larger resistance values, corresponding to the steepest part of the transition curve, up to the end of the transition, the reduced power spectrum of the noise turns out to be completely independent of the resistance value. It is also not influenced by the application of a magnetic field.

In both cases the frequency behavior of the spectrum is approximately of the $1/f$ type.

We begin the discussion starting from case (ii), which has a simple interpretation.

The specimen behaves exactly as a film made of MgB_2 in its normal state, shunted by a noiseless resistance, which changes its resistance from zero to infinite along the transition curve. The specimen is assumed to be in the intermediate state, as the experimental results on the transition noise reported in Ref. 18 suggest. In a simplified picture, the specimen can be represented as a series of resistive layers separated by superconducting regions that shrink during the transition, to disappear at its end. The reported experimental results clearly show that at the transition end, when the specimen has reached its normal state, the relative resistance fluctuations is the same as in all the other situations where an intermediate state is reached.

The simplest interpretation of these results is the following:

(i) The noise is generated in the resistive layers and there is no contribution of the superconducting regions, as, for instance, thermally activated motion of the interface between resistive layers and superconducting regions. This fact would also explain why the noise does not depend on the steepness of the transition curve nor is it influenced by the magnetic field. Since the spatial distribution of superconducting and resistive domains corresponds to local minimum of the free energy, each distribution is little influenced by temperature fluctuations.

(ii) The fluctuations at different resistive layers are coherent, meaning that resistance fluctuations sum up in phase as their resistances.

These assumptions explain the results concerning the noise in the intermediate state. It should be pointed out, however, that the assumption (jj) is not immediately obvious. If, for instance, the superconducting regions could be assimilated to a metal having a high density of states at the Fermi level, without an energy gap, then the resistance fluctuations would be uncorrelated. In this case the amplitude of the reduced noise power spectra would scale with an inverse proportionality to the number of the layers. This is what actually happens when a number of noisy resistors are connected in series or, in general for a network.[21]

The main difference, in the present case, concerns the infinite conductance of the superconducting regions, due to Cooper electron pairs, and thus, lacking a high density of normal electrons to smooth out the propagation of the fluctuations of the thermally excited electron gas in the resistive layers. The electrons in the resistive layers must be excited above the superconducting gap in order to flow through the superconducting regions, where, approximately, the same density of quasi-particles is present. In this simplified model, borrowed from the semiconductor theory, the excited electron gas covers all the specimen surface, but contributes to the resistivity only in the nonsuperconducting layers. It is as if the superconducting regions between layers would not exist, at least for what concerns the electrical resistance of the specimen, and the resistive layers connected to form a single resistor whose resistance fluctuations scale according to its resistance value. Figure 7 gives a sketch of the interface between normal and superconductive domains. For what concerns the origin of the $1/f$ noise in the resistive regions, it is related to the impurities of the film, which act as a trapping medium for the normal electrons with a large distribution of trapping times.

As already stated in the Introduction, the most interesting aspect evidenced by this study is the presence of two

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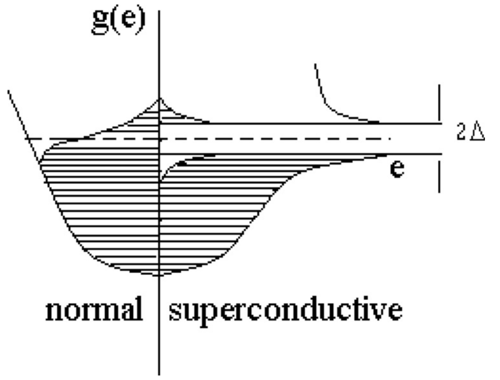

FIG. 7. Scheme of the energy density of states between normal and superconducting domain interface. Electrical conductance in the normal domain is due to the electrons gas above the gap, created by thermal excitation. The gas can be seen as covering the whole specimen surface, and its fluctuations are the origin of the resistance noise generated in the normal domains. In this simplified picture, quasi-particles are assimilated to normal electrons.

different mechanisms of dissipation according to the stage of the transition in polycrystalline MgB_2.

By considering that MgB_2 is a superconductor of the type II, it seems quite reasonable that at the beginning of the transition, the specimen reaches a mixed rather than an intermediate state. Dissipation in this case occurs by fluxoid motion and the observed voltage drop is an induced emf. As we shall show in the following, the experimental results are in agreement with this interpretation when the specimen resistance is below 4 Ω. This fact does not contradict the assumption regarding the noise observed at a higher temperature, corresponding to the steepest part of the transition, since the distinction between type I and II superconductors vanishes at T_c. Let us consider first the results in the absence of magnetic field, reported in Fig. 4. Since the temperature is close to T_c, it may be assumed that fluxoids are created by the bias current and move to opposite direction at the two sides of the specimen.[22] Their motion would be toward the center of the specimen, where they annihilate or are pinned. Even if the magnetic flux through the specimen surface remain unchanged, a voltage is generated to compensate the power dissipation due to moving fluxoids within the specimen, which behaves as a viscous medium.

The simplest approach to characterize the noise due to fluxoid motion is to assume that the voltage pulses obey the Poisson statistics. Furthermore, it can be assumed that every fluxoid $\Phi_i = \Phi$ is constituted by the same number of quantum flux lines and moves, when depinned, under the action of the bias current I_b, with the same velocity v_0, perpendicularly to the current direction.

The amplitude of the fluxoids displacement in the superconducting medium, hosting different types of pinning centers, will be indicated with l_i and the corresponding time with $\tau_i = l_i/v_0$ (see Fig. 8).

During motion, the fluxoid generates a voltage pulse $\delta V_i(t)$, represented in Fig. 9, defined as:

$$\delta V_i(t) = \frac{\Phi v_i(t)}{l_2}, \tag{1}$$

where the velocity $v_i(t)$ can be expressed as

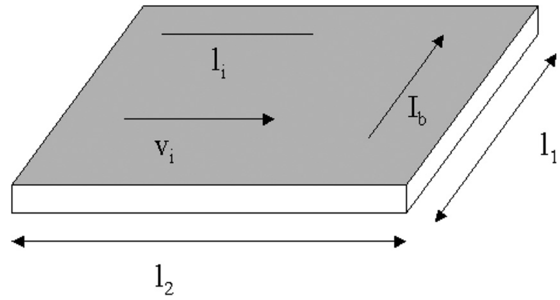

FIG. 8. Scheme of a fluxoid traveling over the distance l_i with velocity v_i under the action of the current I_b. The quantities l_1 and l_2 represent the film dimensions. If the fluxoids are generated by the field due to the current I_b, a second fluxoid would move in the opposite direction from the right side of the film.

$$v_i(t) = v_0\theta_i(t). \tag{2}$$

The quantity $\theta_i(t)$ is the unit function with $\theta_i(t) = 1$ when $t_{1i} < t < t_{2i}$ and $\theta_i(t) = 0$ elsewhere. Introducing the pulse amplitude $a = \Phi v_0/l_2$ one gets

$$\delta V_i(t) = a\theta_i(t). \tag{3}$$

Let ν be the number of pulses generated by all the fluxoids in the unit time. As already stated, the pulses are distributed according to a Poisson statistics, then the voltage noise power spectrum $W(\omega)$ can be expressed by

$$W(\omega) = \nu a^2\left\langle |S_i(\omega)|^2\right\rangle = \nu\left(\frac{\phi v_0}{l_2}\right)^2\left\langle |S_i(\omega)|^2\right\rangle, \tag{4}$$

where $|S_i(\omega)|^2$ is the square modulus of the Fourier transform of $\theta_i(t)$, i.e.:

$$|S_i(\omega)|^2 = \frac{2\sin^2\omega\tau_i}{\omega^2\tau_i^2}. \tag{5}$$

The brackets $\langle\cdots\rangle$ in Eq. (4) mean an averaging operation over the pulse ensemble performed over the distribution function $Q(\tau)$ of the pulse lifetime.

It should be noticed that the quantity $\langle |S_i(\omega)|^2\rangle$ determines the frequency behavior of the power spectrum and a^2 its amplitude. If the assumption that Φ and v_0 are equal for all the fluxoids removed, then a should be considered as an average of $\Phi v_0/l_2$ over the pulse ensemble. This would not

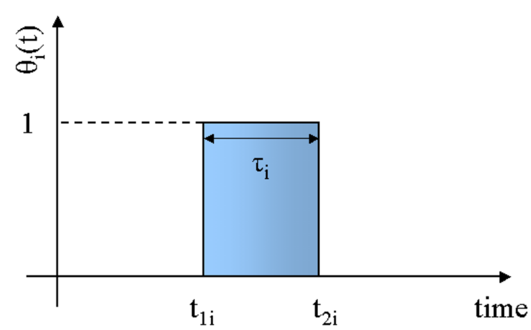

FIG. 9. (Color online) Unitary voltage pulse generated by the fluxoid i during its motion at constant velocity from time t_{1i} to time t_{2i}. In the model, all the pulses have the same amplitude a and move with the same velocity v_0.

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change the conclusion reported below. If $Q(\tau)$ is assumed to be proportional to $1/\tau$ and normalized in the interval between τ_1 and τ_2, then the power spectrum is approximately $1/f$ sloped between $\omega_1 = 1/\tau_1$ and $\omega_2 = 1/\tau_2$.

In order to evaluate the reduced noise power spectrum, $W(\omega)$ is divided by the average voltage $\langle V(t)\rangle^2$, induced by fluxoids motion, given by

$$\langle V(t)\rangle = \left\langle \sum_i \frac{\phi v_0}{l_2}\theta_i(t)\right\rangle = \frac{\phi v_0}{l_2}\left\langle \sum_i \theta_i(t)\right\rangle. \quad (6)$$

The average $\left\langle \sum_i \theta_i(t)\right\rangle$ must be evaluated on the basis of the Poisson distribution $P(t) = \nu[exp(-\nu t)]$ where t is the time interval between subsequent pulses. We notice that $\left\langle \sum_i \theta_i(t)\right\rangle$ is proportional to the average number of voltage pulses per unit time ν. Moreover, it can be reasonably assumed that $Q(\tau)$ remains approximately unchanged during the transition, since the force acting on a fluxoid depends only on I_b, which is constant. Thus the increase of $\langle V(t)\rangle$ and R along the transition curve must be produced by the increase of the average number of fluxoids per unit time generated by the bias current. According to Eq. (4) and Eq. (6) the reduced power spectrum of the noise becomes

$$W_R(\omega) = \frac{W(\omega)}{\langle V(t)\rangle^2} = \frac{\nu\left\langle |S_i(\omega)|^2\right\rangle}{\left\langle \sum_i \theta_i(t)\right\rangle^2} \sim \frac{1}{\nu}. \quad (7)$$

The proportionality with $1/\nu$ is due to the quantity $\left\langle \sum_i \theta_i(t)\right\rangle^2$ proportional to ν^2, while $(|Si(\omega)|^2)$ does not depend on ν if the assumptions concerning $Q(\tau)$ hold. The reduced noise power spectrum is thus inversely proportional to the resistance, a fact that is verified on the spectra reported in Fig. 4 for the lowest values of R. Let us now consider the noise behavior in the presence of magnetic field, with the resistance kept constant by reducing the temperature, as shown in Fig. 6. In this case, all the fluxoids have the same sign and move in the same direction. The experimental results, reported in Fig. 5, show that the reduced noise power spectral density exhibits a strong increase with the field when the specimen resistance is well below 4 Ω, while, when the resistance is larger, up to the end of the transition, the magnetic field does not affect the noise.

The results at low resistance values can be still explained in terms of fluxoid motion by assuming that the application of the external field increments the number of flux lines forming a single fluxoid.

If R and thus $\langle V(t)\rangle$ are kept constant by decreasing the temperature when the field is applied, according to Eq. (6) an increase of Φv_0 should be balanced by a reduction of $\left\langle \sum_i \theta_i(t)\right\rangle$.

By assuming that the distribution $Q(\tau)$ remains unchanged when the field is applied, then $\left\langle \sum_i \theta_i(t)\right\rangle$ and $W_R(\omega)$ are proportional, respectively, to ν to $1/\nu$. The increase of $W_R(\omega)$ with the magnetic field is thus explained by considering that the average number of pulses per unit time ν must decrease to keep $\langle V(t)\rangle$ constant. The assumption that $Q(\tau)$ remains approximately unchanged when Φ increases can be justified by the fact that the distribution of velocity $v_i(t)$ of the fluxoids remains also unchanged, since both the force on the fluxoid and the viscosity coefficient of the medium are proportional to Φ. According to this interpretation, the saturation of the reduced noise power spectral density with H ~ 200 G would imply that, above this value, a saturation of the number of quantum flux lines forming the fluxoid occurs. The interpretation of this effect, which is also well evidenced by the experimental results reported in Fig. 5, would certainly require a more extensive analysis of the stochastic processes at the beginning of the resistive transition.

IV. CONCLUSION

In this paper the occurrence of two completely different fluctuation mechanisms underlying dissipative processes in MgB_2 has been demonstrated. The investigation has been carried out when the transition occurs at a temperature close to T_c, at low current density and magnetic field. The implications of these different findings are relevant for the optimization, for instance, of superconducting bolometric sensors based on MgB_2 films, which operate at a given point of the transition curve. When the specimen is brought to the intermediate state, the noise is related to the impurities of the film and can be conveniently studied, in order to improve the signal to noise ratio, in the normal state, even at room temperature, as the study reported in Ref. 20 suggests. The presence of fluxoid noise, at low resistance values, is more difficult to characterize. It depends on several properties of the film, like the distribution of pinning centers, making the choice of the working point in that region difficult. Cross-correlation measurements of the noise detected on different points of the same specimen, brought to the intermediate state, compared with the same type of measurements when the specimen has completed its resistive transition, could possibly confirm or reject this simple interpretation.

The results reported in this paper show that noise analysis is a powerful technique to investigate the dynamics of the transition in superconducting materials. More difficult would be the answer to this question when the resistive transition of type II superconductors occurs well below the critical temperature by effect of a high current density. It is well known that the transition begins when the fluxoids created by the current move out from their pinning centers, but as soon as the resistive state is reached, heating effects prevent the analysis of the remaining transition process. This is the reason why, in this case important for the design of superconductive magnets, the papers found in the literature are all concerned with the fluxoid dynamics without considering the possibility of an intermediate state before the fully resistive state is reached at the end of the transition.

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