Investigation of the resistive transition of MgB$_2$ thin film through current noise

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Abstract. In this paper we present measurements concerning the current noise produced during the resistive transition in a MgB$_2$ polycrystalline thin film. The power spectrum of the current noise, observed when the temperature is slowly changed across its critical value, presents a large electrical noise of the $1/f^n$ type ($n \approx 3$) over a quite wide range of frequencies. This noise may be considered as generated by the abrupt creation of resistive strips across the specimen constituted by grains which have undergone the resistive transition. A computer model that takes into account fluctuations of the grain critical currents and of the number of grain per strips, has been developed to simulate the resistive transition and to evaluate the noise power spectrum. When the temperature is increased and reaches its critical value, resistive strips are formed according to a percolative process, giving rise to resistance steps which are at the origin of the noise. The theoretical results obtained by this model are in good agreement, concerning both the shape and intensity of the noise power spectrum, with the experimental data directly measured on the specimen.

1. Introduction

Noise measurements are an important complement to the understanding of transport properties in complex systems, like superconductors. In particular, current noise measurements taken in non stationary conditions during the transition from the superconductive to the resistive state in granular films can highlights information on the film properties responsible of the percolative processes [1].

In this paper we study the current noise during the superconductive transition of a nanocrystalline films of MgB$_2$. A slow change of the temperature across the transition induces a sequence of discrete rearrangements of the internal distribution of the current density, giving rise to abrupt conductance changes and consequently to a large noise. The experimental results are interpreted on the basis of a model which gives the correct slope and amplitude of the power spectrum of the noise.

2. Experimental results

The MgB$_2$ film investigated in this paper has been prepared at IEN Laboratories by an in-situ growth process on silicon nitride (SiN) substrate[2]. Mg and B were simultaneously evaporated from a Mo resistive heater and from Mo crucible by e-beam heating, respectively. The deposition rates are such to obtain an excess of Mg in the film. To obtain MgB$_2$ thin films with good structural and electrical
properties, we carried out the thermal annealing of the Mg and B precursor in a quartz tube at 620 °C for 600 s in Ar atmosphere (1 mbar).

The measured sample is a thin film 30 nm thick, lithographed to have dimensions 1x1 mm$^2$, placed between two larger areas used to separate current and voltage contacts to avoid contact noise. The grain size, as measured with a STM technique, are about 10 nm. The specimen is sealed within a copper container filled with helium and put in a cryostat with the possibility of slowly changing the temperature across its critical value. The resistance is evaluated using a current source and a nanovoltmeter, canceling the thermoelectric EMFs by the current-reversal method. At a constant current of 10 mA the critical temperature is 30.1 K with a transition width of 2 K.

An extra low noise step-up transformer is used to detect the noise signal and to act as a high-pass filter to suppress the DC component. Its low cut-off frequency is about 4 Hz. A constant current generator is used to bias the specimen and a signal analyzer to obtain the noise power spectrum. In figure 1 the power spectra of the current noise are reported both in the case of thermal equilibrium, with a 1/$f$ type power spectrum, and during the resistive transition of the film, with a 1/$f^3$ type power spectrum, superimposed to the smaller 1/$f$ component.

3. Physical model
To describe the behaviour of the resistive transition process and its noise spectrum we propose a model based on the granular structure of MgB$_2$. The sample, when is in the resistive state, can be represented by a sequence of equipotential zones separated by resistive strips crossing the whole sample [3]. Each strip is formed by a series of grains. When the current crossing a grain becomes larger than its critical current a resistive transition occurs. The assumed V-I characteristic of the single grain is similar to the characteristics of a Josephson junction: there is a current that can flow with a zero potential up to a critical current value, a resistive region for currents higher than the critical value, and an intermediate state where the current crossing the grain is equal to the critical current and the potential drop is between zero and the value corresponding to the normal state [3].

We assume that both the number of grains for the single strip and the critical currents of the grains are not constant, but are distributed in a gaussian mode. The two variances of these distributions are taken as free parameters to match the experimental data. The results of computer simulations for a single strip are reported in figure 2. The curves represent the temperature behaviour of the strip resistance around the critical temperature. The trailing edge of the resistive step is not square owing to

**Figure 1.** Power spectrum of the current noise (curve 3) measured at I=10 mA during the temperature change of 1K across the transition. Curve 1 is the background noise and curve 2 is the power spectrum in stationary conditions at T=29.5 K.

**Figure 2.** Computer simulation of the resistance vs. temperature of a single strip during the superconductive transition. The effect of the variance on the gaussian distribution of the grain critical currents is shown for two values.

the presence of grains in the intermediate state. We also show the effect of the variance of the gaussian
distribution of the grain critical currents. To obtain the resistance vs. temperature curve representing the total transition of the sample, it is necessary to consider the behaviour of all the strips. In particular, the resistive transition is generated by the superposition of curves, like the one reported in figure 2, occurring at slightly different temperatures, both because of the grain critical current dispersion and for the fluctuation of the number of grains which constitute the different strips. A model of the sample based on a matrix formed by 100 stripes with 100 grains, with a variance on the number of grains for the strip of 10% is sufficient to obtain a good fit of the experimental data.

Besides the resistive behaviour we consider also the noise power spectrum produced during the transition. The experimental measurements show that the noise is identical either in the case when the transition occurs from the superconducting to the resistive state or when it occurs in the opposite direction. The noise is generated by the superposition of resistive steps of the type shown in figure 2, each one corresponding to the creation of a strip of resistive grains across the specimen. To evaluate the noise power spectrum it is necessary to represent the resistive steps as a function of time. In our experiments the relation between temperature and time is linear and the change of 1 K occurs in 30 sec. With this conversion, the shape of the voltage pulse is similar to that of figure 2. Nevertheless, the low cut-off frequency of the input transformer introduces an exponential decay of the signal as shown in figure 3, where the simulated voltage signal vs. time produced by the transition of a single strip is shown. A poissonian time interval distribution is appropriate to describe these events. This is true when the number of events per unit time is constant, as allowed by the constant rate of change of the temperature during the transition. The assumption of a poissonian distribution allows an analytical calculation of the noise power spectrum whose detailed description will be presented in another paper.

In figure 4 the computed noise power spectrum of a sample with 100 strips of 100 grains, obtained by a critical current variance of 0.4 and grain number per strip variance of 0.25, is shown. The reason of the presence of a $1/f^3$ dependence in the spectrum is the trailing edge of the voltage pulse of figure 3 which is not step like, but is smoothed out as a consequence of the variance of the grain critical currents (figure 2). The simulated power spectrum of figure 4 takes into account also the $1/f$ dependence observed in the stationary conditions and is in good agreement with the experimental noise power spectrum presented in figure 1 (curve 3), which is again reproduced in figure 4 for comparison.

**Figure 3.** Simulated voltage signal produced by the transition of a single strip, taking into account also the effect of the transformer.

**Figure 4.** Power spectrum of the current noise (gray curve) equal to curve 3 of figure 1 and its numerical simulation obtained as described in the text (black curve).

### 4. Conclusion
In this work we have proposed a simple theoretical model to describe the superconductive transition process in a MgB$_2$ film. The model allows to explain both the temperature behaviour of the film resistance around the transition and the noise power spectrum measured during a slow change of the temperature across the transition. The power spectrum has a rather large component of the type $1/f^3$ and the computer simulation based on our model allows to obtain a good agreement with respect to the experimental data both for the shape of the spectrum and its amplitude. It turns out that this result gives information about the distribution of the grain critical currents. The distribution of the grain critical temperatures plays also a role and will be investigated in a future work.

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