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Low frequency noise and complex AC magnetoresistance in superconducting Pb/Ge with square antidot lattice

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Abstract

The low frequency voltage noise and complex AC voltage response to weakly modulated magnetic fields have been studied in a superconducting Pb film with a square lattice of antidots. The temperature was close to T_c and the DC magnetic field was changed between ±1.5 H_1 with $H_1 = 9.2$ Oe corresponding to one vortex per antidot. A narrow band noise near $f \approx 0.55$ Hz has been observed which shows different dependences on the magnetic field in 4- and 5-point probe configurations. In the latter configuration one probes the correlation between the noise voltages in the two parts of the sample. We also measured the resistance when, in addition to the DC field, a small AC field with frequency $f < 177$ Hz was applied. The data showed that the complex magnetoresistance response becomes nonlinear below 1/3 of the first matching field.

Keywords: Superconducting Pb film; Periodic pinning centers; Low frequency noise; Complex low frequency voltage response

1. Introduction

Superconductivity in periodic nanostructures has recently attracted much attention. Previous work on these structures mostly studied DC magnetization and electric transport [1]. It was found that the critical current can be strongly enhanced by nanostructuring [1]. Moreover, anomalies were observed in resistivity and magnetization at special fields, multiples and factors of the first matching field H_1, which corresponds to one magnetic flux quantum per center. We shall denote as $H_m = m \times H_1$ these matching fields. Currently little is known about the low frequency noise and dynamics in such superconducting structures, unlike to systems with random vortex pinning. This manuscript presents the first experimental study of the low frequency voltage noise and some aspects of the low frequency dynamics in a superconducting Pb film with a periodic antidot lattice measured via electron transport with two different methods. In order to get appreciable voltage in the superconducting state we measured the resistive response rather close to T_c ($T/T_c \approx 0.995$ with T_c obtained from the middle of the

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resistive transition at 10 μA). However, such proximity to T_c makes it difficult to estimate the correlation length and the penetration depth.

2. Experimental

Our experiments have been performed on a Pb/Ge superconducting film with a square array of holes (antidots), prepared with electron beam lithography. The Pb layer was 80 nm thick, the period of the square antidot lattice was 1.5 μm and the size of holes 0.5 μm. The sample had 300×300 μm^2 cross geometry. Details of sample characterization have been given before [2].

We have measured the noise power spectrum with two different contact configurations: 4- and 5-point techniques. In the 5-point configuration the current is injected in-between the voltage probes from the contact situated opposite to them, and is split into two identical opposite currents, resulting in zero average voltage [3]. A magnetic field modulation method was used with different bias DC current to provide the in-phase (X) and out-of-phase (Y) contributions to the change of resistivity of the sample.

Since the noise power spectrum (S) is, in general, a relatively flat function of the inverse frequency, it is convenient to characterize the noise level by the mean value of the product $A(H) = f \times S$ between 0.1–1 Hz. This allows us to perform an "express" study of the noise, plotting $A(H)$ as a function of the magnetic field. Simultaneously, we controlled the value of the sample resistance. These results were analyzed in order to reveal characteristic points in the dependence $A(H)$ where the low frequency noise was enhanced or suppressed. Fig. 1 shows magnetoresistance and $A(H)$ obtained in the 4-point configuration. Magnetoresistance clearly shows anomalies at matching fields H_m with $m = 1$, 1/2, 1/3 and 2/3. We note that in all our experiments we had a small remanent field of 0.4 Oe.

We observe that $A(H)$ has minima at matching fields. At the second stage we carried out a detailed investigation of the noise power spectrum at different fixed magnetic fields as follows: we collected 120,000 points (with a time resolution of 60 ms) at each characteristic field and subsequently performed an statistical processing of the noise power spectrum using fast Fourier transform (FFT). We have chosen the following fields: 17 Oe (normal state), residual field $H = 0.4$ Oe (superconducting state), 9.7 Oe (H_1), 5 Oe ($1/2H_1$), 10.9 Oe (the field where $A(H)$ reaches a maximum and the magnetoresistivity had the maximum derivative) and 9 Oe (between matching fields). Before each measurement the sample was turned to normal state by magnetic field $H > H_1$.

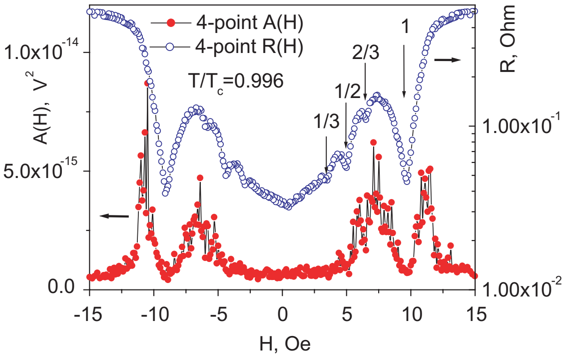

Fig. 1. Magnetoresistance and the "noise level" $A(H)$ for $I = 500$ μA in the 4-point configuration.

Fig. 2 shows the noise power spectrum at these characteristic fields. Reproducible peaks with period 1.83 s and smaller ones with 0.62 s are clearly observed. It seems important that these peaks are absent both in the normal and in the superconducting states, where the voltage noise is

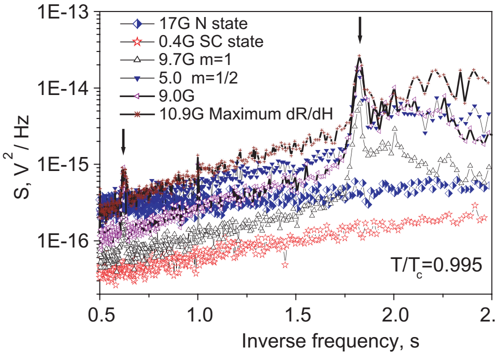

Fig. 2. The noise power spectrum at $I = 500$ μA with 4-point configuration at different fields.

strongly reduced. Let us now discuss the narrow band noise (NBN) anomaly. The height of the main NBN peak at the first matching field H_1 is smaller than those at nonmatching fields. We have measured the noise power spectrum at fixed field $1/2H_1$ for lower current ($I = 250$ μA) and found that reducing the current to one half reduces the amplitude of the NBN, though the characteristic frequency remains almost the same.

Fig. 3 shows $A(H)$ measured using 4096 points with 5-point configuration, and the magnetoresistance, which was measured before starting the experiment with the 4-point technique and with 1/2 of the DC current ($I = 250$ μA). It may be clearly seen that, contrary to what was observed in the 4-point configuration, $A(H)$ shows maxima at the matching fields. The noise power spectrum in 5-point configuration reveals the presence of a peak at 1.83 s, except in the normal and superconducting states. The peak height reaches a maximum when the magnetic field is close to the matching fields. We remind that this tendency is opposite to what we have observed with the 4-point configuration. We verified that the 1.83 s peak is absent not only in the superconducting and normal states but also without electric current. By using the signal from the magnetic coils we have also proved that the observed NBN is not related to the noise spectral density of the magnetic field itself.

Next we present the complex low frequency magnetoresistive response of the vortex system to a periodic change of the magnetic field. The sample was biased by a DC of 500 mA at a fixed temperature close to T_c. The X and Y responses vary linearly with AC except for a range of fields below about 2 Oe.

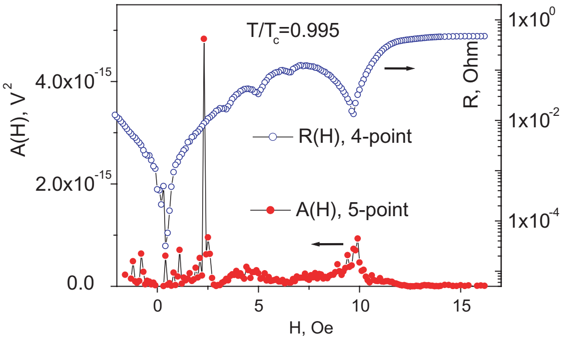

Fig. 3. Magnetoresistance and the "noise level" $A(H)$ for $I = 500$ μA in the 5-point configuration.

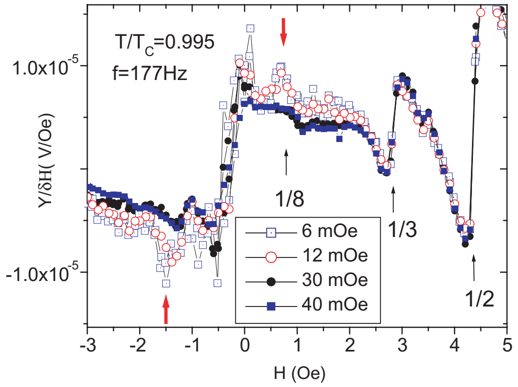

Fig. 4. Normalized Y response for different AC drives.

With the aim of a clearer understanding of the observed nonlinear behavior at fields lower than 2 Oe, we carried out a series of experiments where the AC drive was changed at different magnetic fields from below to above $H = 2$ Oe, while frequency and temperature were fixed. Fig. 5 shows such curves obtained for six different fields from 0.8 to 2.3 Oe. The span of the AC drive amplitude was from 3 to 80 mOe. For 2.3 Oe almost linear dependences of the in-phase and out-of-phase responses are clearly visible (we only show the Y component). However, for the magnetic field range where a nonlinear behaviour of the out-of-phase response was found ($H < 2$ Oe), we confirmed a strongly nonlinear dependence of both X and Y responses. The general trend is that the out-of-phase response is enhanced for the lowest AC field drives, which correspond to measurements with varied magnetic fields and fixed drives (Fig. 4).

3. Discussion and conclusions

Let us discuss the maximum with period of 1.8 s observed in the noise power spectrum. It is likely that collective pinning plays a critical role in the generation of this NBN. Similar low frequency NBN features but at frequencies around 10^1–10^3 Hz have been detected in transport and magnetic noise measured on YBCO [4] and BSCCO [5]. In

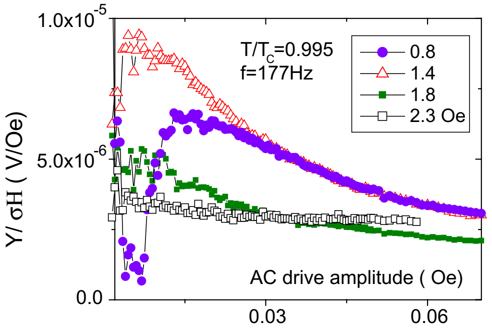

Fig. 5. Normalized Y response at ($0.8 < H < 2.3$ Oe).

both systems the vortices move in the disordered potential created by natural pinning centers. For YBCO the magnetic field configuration (both current and field in the sample plane) differed from ours, while for BSCCO was similar. Previously [4] the NBN frequency was shown to be controlled by the vortex velocity. However, in our experiments the independence of the NBN frequency on magnetic field indicates that individual vortex velocity has no relation to NBN. By using values of the magnetic field B and voltage U between contacts at a distance L, we may estimate the lower limit for the vortex velocity v from relation $U/L = v \times B$. Supposing that the measured voltage is due to the movement of all vortices, we obtain $v > 40$ m/s for $B = 10$ Oe. The characteristic frequencies of this individual movement, related with crossing the distance between two pinning centers (50 MHz) or the whole sample (20 kHz), are too high compared to those experimentally measured (around 1 Hz).

While in the 4-point configuration one measures the noise associated with the vortex lattice movement in one direction, in the 5-point configuration the direction of the movement of the vortices is opposite in the two parts of the sample. Therefore, the first experiment probes fluctuations in the sum of the voltages $V_1 + V_2$ in the two parts of the sample, while in the second their difference $V_1 - V_2$ is probed. A clear difference in behaviour of the NBN in 4- and 5-point configurations at rational matching fields may reflect some correlation between voltages V_1 and V_2 i.e. that $\langle V_1 \times V_2 \rangle \neq 0$. Our experiments, which probe the vortex dynamics via the flux resistance have found a nonlinear behavior of the resistive response vs. applied magnetic field excitation amplitude for magnetic fields only below approximately $1/3H_1$. The crossover from nonlinear to nearly linear vortex response occurs above approximately 30 mOe. We tentatively interpret this observation as a reconfiguration of the vortex matter induced by the AC magnetic field. The possibility of metastable vortex states is also corroborated by the apparent hysteretic response for low AC drives which disappears at larger field excitations. Another interesting (indirect) indication on a possible change in the local vortex structure is a strong enhancement of the noise level $A(H)$ visible between $1/4H_1$ and $1/3H_1$ (5-point measurements, Fig. 3).

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