Observation of stochastic resonance in percolative Josephson media

A. M. Glukhov and A. G. Sivakov
B. Verkin Institute for Low Temperature Physics and Engineering, 61103 Kharkov, Ukraine

A. V. Ustinov
Physikalisches Institut III, Universität Erlangen-Nürnberg, D-91058 Erlangen, Germany

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Measurements of the electrical response of granular Sn-Ge thin films below the superconducting transition temperature are reported. The addition of an external noise to the magnetic field applied to the sample is found to increase the sample voltage response to a small externally applied ac signal. The gain coefficient for this signal and the signal-to-noise ratio display clear maxima at particular noise levels. We interpret these observations as a stochastic resonance in the percolative Josephson media which occurs close to the percolation threshold.

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1. Introduction

The phenomenon of stochastic resonance has been discussed in relation to diverse problems in nonlinear science, physics, chemistry and biology [1]. Generally speaking, stochastic resonance is the enhancement of the output signal-to-noise ratio caused by the injection of an optimal amount of noise into a periodically driven nonlinear system. This kind of behavior is often thought as counterintuitive, since here a stochastic force amplifies a small periodic signal. Its mechanism is usually explained in terms of motion of a particle in a double-well potential subjected to noise, in the presence of a time-periodic force. The periodic forcing leads to noise-enhanced transitions between the two wells and thus to an enhanced output of the forcing signal.

A clear example of nonlinear systems with few degrees of freedom is a superconducting loop with a Josephson junction, well known as a superconducting quantum interference device (SQUID). With a proper choice of the size of the loop, this system undergoes bistable dynamics for magnetic flux trapped in the loop. There have already been experiments that reported operating SQUIDs under stochastic resonance conditions, both with external noise injection [2] and with thermally generated intrinsic noise [3]. The stochastic resonance effect can be considerably enhanced in a system of coupled bistable oscillators (see, e.g., Ref. [4]). Therefore, it is interesting to study stochastic amplification for a Josephson media consisting of many superconducting contours with Josephson junctions.

Earlier we observed quantum interference effects in macroscopically inhomogeneous superconducting Sn-Ge thin-film composites near the percolation threshold [5]. This system exhibits a considerable voltage noise under dc current bias and a rectification of ac current, which arise below the superconducting transition temperature. According to Ref. [6], a dc voltage is observed when an ac current larger than the critical current passes through a system of two superconductors weakly connected by an asymmetric double point contact, i.e., the magnetic flux quantization induces the critical current oscillations and the respective voltage oscillations. We have argued [7], that the oscillatory dependence $V_{dc}(H)$ in Sn-Ge thin-film composites is related to quantum interference in randomly distributed asymmetric superconducting contours interrupted by Josephson weak links.

In Ref. [8] we reported measurements of the $V_{dc}(H)$ dependence for various orientations of the film relative to the field. The scale of the oscillatory structure in $V_{dc}(H)$ is inversely proportional to the cosine of the angle between the applied magnetic field and the normal to the sample plane. The emergence of the normal magnetic field component alone and also the antisymmetry of the oscillatory structure relative to $H = 0$ indicate a quantum-interference origin of $V_{dc}(H)$. Moreover, it appears feasible to relate these active contours to the percolative cluster that has a well-known fractal structure. The existence of a wide and self-similar distribution of Josephson contour areas leads to a fractal character of the dependence $V_{dc}(H)$. We have suggested and verified a model for the origin of the $1/f$ voltage noise by a passive transformation of magnetic field oscillations with a fractal transfer function $V_{dc}(H)$ [9].

In the present paper, we study the noise-induced electrical response of granular Sn-Ge thin-film composites. We argue that a distributed network containing many superconducting loops with Josephson junctions may show a cooperative behavior as stochastically resonating media.

2. Experimental details and results

Josephson networks may occur naturally, e.g., in nonuniform superconducting materials such as granular thin films. We prepare granular Sn-Ge thin-film composites having monotonically varying structure by vacuum
condensation of Sn on a long (60 mm) substrate along which a temperature gradient is created. Sn is deposited on the previously prepared 50 nm thick Ge layer. The thickness of the Sn layer is 60 nm. The metallic condensate is covered from the top with amorphous Ge. The structural change results in variation of the composite properties from metallic to insulating over the substrate. This crossover in properties is observed on a series consisting of 30 samples cut from different parts of the substrate. For the present investigations, we chose samples with properties near the percolation threshold, with a characteristic structure depicted in Fig. 1.

During the measurements, the samples were kept in exchange gas inside a superconducting solenoid. The electrical measurements were carried out according to the standard four-probe technique. A sinusoidal ac current of frequency $f_I = 100$ kHz and amplitude $I_{ac} = 0.8$ mA was produced by an HP3245A universal source connected to the current leads through a dc-decoupling transformer. Fast Fourier transformation spectra of the output voltage are measured by using an SR770 spectrum analyzer with a Blackman-Harris window function. We used the signal-to-noise ratio (SNR) as the major characteristic of stochastic resonance. The SNR was measured as the ratio of the voltage amplitude of the spectral line to the voltage noise level below it. The noise background in the signal bin is estimated by performing a linear fit to the peak clipped spectrum. The noise intensity (noise level) denotes the standard deviation $\sigma_N$ of the Gaussian white noise signal, which was supplied by the internal SR770 generator.

The transition of a sample into the superconducting state is smeared over 1.0 K with the center of the resistive transition at $T_0 = 3.8$ K. At temperatures below $T_0$ and with ac current $I_{ac}$ applied through the sample, we observed a rectified dc voltage $V_{dc}$, the magnitude of which oscillated as a function of the dc magnetic field $H$ applied perpendicular to the substrate (Fig. 2a). The amplitude and frequency of the current $I_{ac}$ did not significantly affect the general features of the $V_{dc}(H)$ dependence. The results could be always readily reproduced.

To observe the phenomenon of stochastic resonance, we study the rectified voltage dependence on magnetic field. The applied magnetic field consisted of three components (Fig. 2b): (i) a dc field $H$, which varied in the range between $-300$ and $+300$ mOe, (ii) a small ac component with a frequency $f_H$ between 5 and 60 Hz and an amplitude $H_{ac} = 20$ mOe, and (iii) Gaussian white noise $H_{noise}$ with the intensity $\sigma_N$ ranging up to 70 mOe. The Fourier spectra of voltage response are shown in Fig. 3 together with oscillograms of the input signal $H_{ac} + H_{noise}$. Figure 4 shows the dependence of the output SNR for the first harmonic of $f_H$ on the intensity of input noise.
H_{\text{noise}}. One can see that increasing the noise amplitude at first increases the SNR and then decreases it. Such maxima are rather characteristic for the phenomenon of stochastic resonance. Similar measurements taken at different magnetic fields and frequencies often showed multiple maxima such as those shown in Fig. 3.

3. Discussion

In summary, our experiments demonstrate the characteristic feature of the phenomenon of stochastic resonance, namely the nonmonotonic behavior of the SNR. At the optimum noise level the SNR increases up to 40. The presence of multiple maxima (Fig. 3 and 4) can be due to the effect of different Josephson contours in our structure, which is operated at the border of the percolation threshold.

We suppose that the nonmonotonic dependence of the SNR on frequency $f_H$ (Fig. 5) excludes other possible explanations (such as, e.g., a simple rectification effect due to a nonlinearity of the response) for the observed gain of a small input signal.

Detailed measurements taken at different frequencies, shown in Fig. 5 indicate, at least in some ranges of the dc magnetic field, the existence of parameter regions characterized by a significant gain for a relatively broadband signal. We interpret this behavior as a property of percolative Josephson media with a wide range of self-similar loops. The SNR gain in our system can be tuned to a desired operation frequency $f_H$ by changing the dc magnetic field $H$.

The nature of the stochastic resonance in the system studied can be related to the commonly known bistable oscillator behavior of the magnetic flux quantization loops. Moreover, in the presence of current bias...
$I_{ac}$ at relatively high frequency (at $f_I$ about 100 kHz) with amplitude larger than critical, our samples exhibit dynamical chaos. Such a regime is commonly characterized by a coexistence of multiple attractors in the phase space. Indeed, calculation of Lyapunov exponents from the time evolution of the voltage measured at constant current indicates presence of chaos in our system $I$. In this case, the “phase trajectory” of the system may stay long time in any of the attractors and perform irregular transitions between them. Synchronization of such intermittent transitions by a small input signal may lead to stochastic resonance as well $\text{[8]}$. Yet, these speculations require further investigations to be firmly justified.

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* Electronic address: glukhov@ilt.kharkov.ua

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