

Observation of stochastic resonance in percolative Josephson media

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Measurements of the electrical response of granular Sn–Ge thin films below the superconducting transition temperature are reported. 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 as well as the signal-to-noise ratio displays clear maxima at particular noise levels. We interpret these observations as a stochastic resonance in the percolative Josephson media that 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 injection of an optimal amount of noise into a periodically driven nonlinear system. This kind of behavior is often thought as counterintuitive, since a stochastic force amplifies a small periodic signal here. 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.

One of clean examples of nonlinear systems with few degrees of freedom is a superconducting loop with a Josephson junction, well known as a superconducting quantum interferometer (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 been already experiments that reported operating SQUIDs under stochastic resonance conditions, both with the external noise injection [2] and with the thermally generated intrinsic noise [3]. The stochastic resonance effect can be considerably enhanced in a system of coupled bistable oscillators (see, e.g. [4]). Therefore, it is interesting to study stochastic amplification for a Josephson media consisting of many superconducting loops 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 [5], that the oscillatory depen-

dence $V_{dc}(H)$ in Sn–Ge thin-film composites is related to quantum interference in randomly distributed asymmetric superconducting contours interrupted by Josephson weak links. In Ref. 5 we reported measurements of $V_{dc}(H)$ 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 as well as the antisymmetry of the oscillatory structure relative to $H = 0$ indicate the 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 the fractal character of the dependence $V_{dc}(H)$. We have suggested and verified the model of the voltage $1/f$ noise origin by a passive transformation of magnetic field oscillations with the fractal transfer function $V_{dc}(H)$ [5].

In this 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 present investigations, we chose the samples with properties near the percolation threshold, with a characteristic structure depicted in Fig. 1.

During 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 $f_1 = 100$ kHz and amplitude $I_{ac} = 0.8$ mA was produced by an

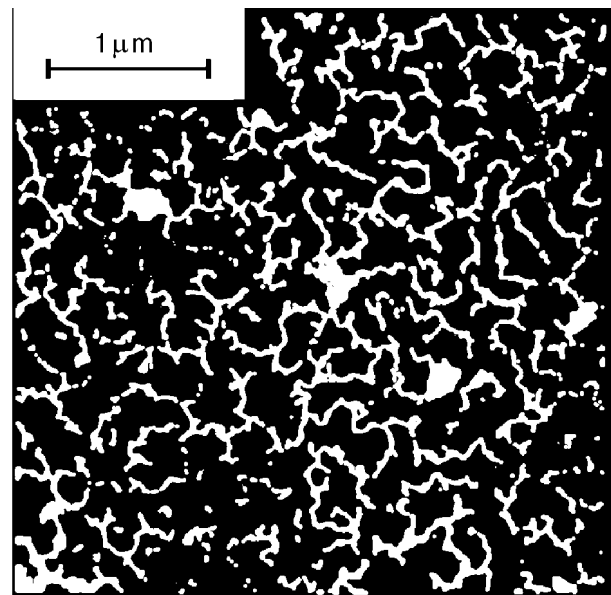


Fig. 1. Electron micrograph of Sn–Ge sample prepared close the percolation threshold. Black regions correspond to the metallic phase.

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 a spectrum analyzer SR770 with Blackman–Harris window function. We used signal-to-noise ratio (SNR) as the major characteristic of stochastic resonance. 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 σ_N of the Gaussian white noise signal, which was supplied by the internal SR770 generator.

The transition of the studied 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} , which magnitude oscillated as a function of dc magnetic field H applied perpendicular to the substrate (Fig. 2,a). 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: (i) dc field H varied in the range between -300 and $+300$ mOe, (ii) small ac

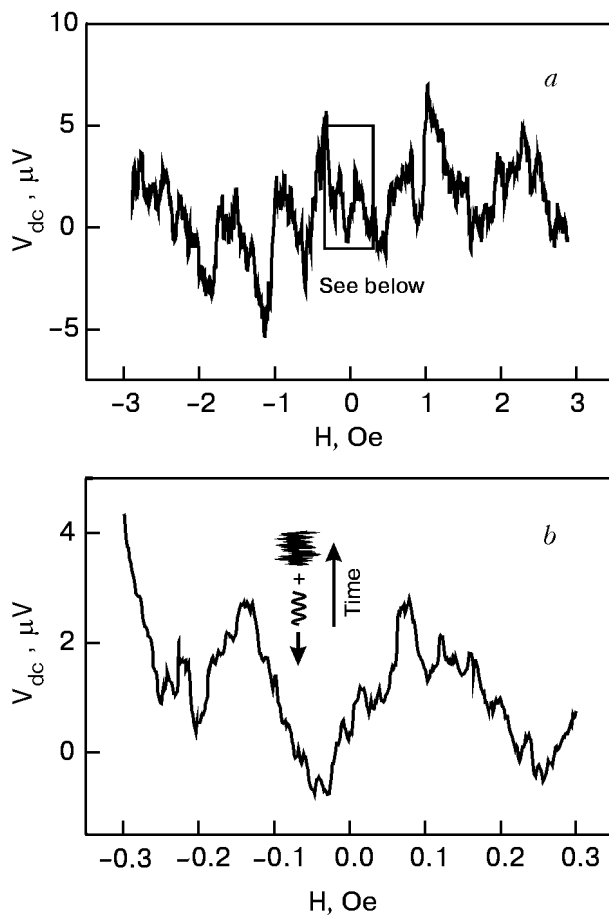


Fig. 2. *a* – Oscillatory behavior of the rectified voltage across Sn–Ge sample versus dc magnetic field: $T = 3.0$ K, $f_1 = 100$ kHz and $I_{ac} = 0.8$ mA. *b* – Illustration of the stochastic resonance detection scheme. Magnetic field components H_{ac} and H_{noise} are added to dc magnetic field H .

component with the frequency f_H between 5 and 60 Hz and amplitude $H_{ac} = 20$ mOe, and (iii) white Gaussian noise H_{noise} with the intensity σ_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_{noise} . One can see that increasing the noise amplitude at first increases 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. 5.

3. Discussion

In summary, our experiments demonstrate the characteristic feature of the phenomenon of stochastic resonance, namely the nonmonotonic behavior of

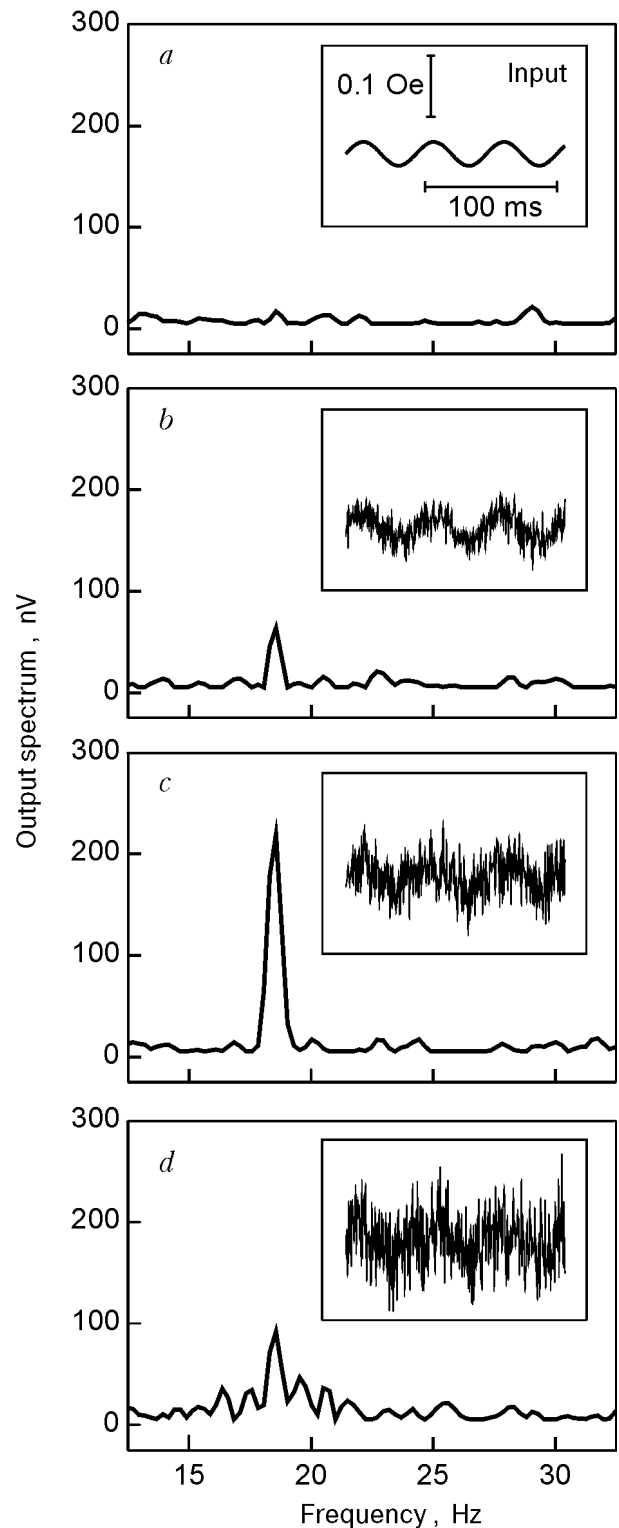


Fig. 3. Input signal $H_{ac} + H_{noise}$ (insets) and the Fourier spectrum of the output voltage for different levels of input noise H_{noise} : $\sigma_N = 0$ (*a*); $\sigma_N = 16$ mOe (*b*); $\sigma_N = 31$ mOe (*c*); $\sigma_N = 47$ mOe (*d*). The input signal amplitude remains constant $H_{ac} = 20$ mOe. Signal frequency $f_H = 18.5$ Hz, dc magnetic field $H = 0.17$ Oe.

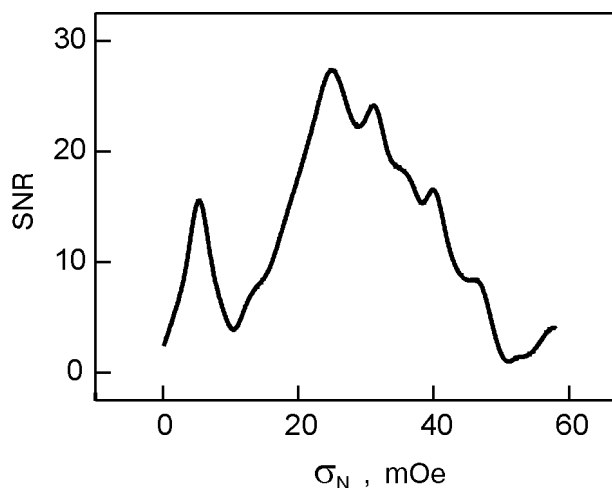


Fig. 4. Output signal-to-noise ratio (SNR) versus input noise level σ_N for the first harmonic of the input signal frequency $f_H = 18.5$ Hz. Magnetic field $H = 0.17$ Oe.

SNR. At the optimum noise level SNR increases up to 40. The presence of multiple maxima (Figs. 4 and 5) can be due to the effect of different Josephson contours in our structure that is operated at the border of the percolation threshold.

We suppose that the nonmonotonic dependence of 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 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 contours. 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 studied system can be related to the commonly known bistable oscillator behavior of the magnetic flux quantization contours. Moreover, in the presence of current bias I_{ac} at relatively high frequency (at f_1 about 100 kHz) with amplitude larger than critical, our samples show a 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 [7]. In this case, the «phase trajectory» of the system may stay long time in any of the attractors and

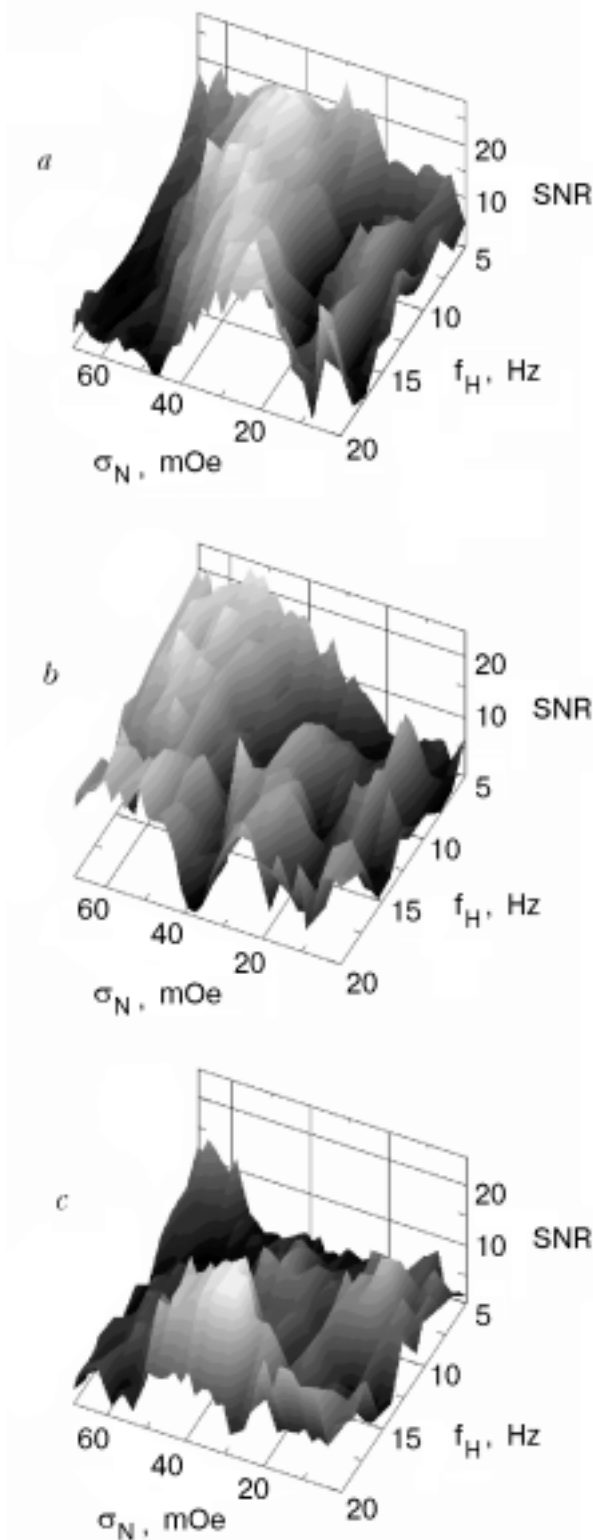


Fig. 5. SNR dependence on input noise level σ_N and input signal frequency f_H at different dc magnetic fields H , Oe: 0.17 (a); 0.18 (b); 0.19 (c).

perform irregular transitions between them. A synchronization of such intermittent transitions by a small input signal may lead as well to stochastic resonance [8]. Yet, these speculations require further investigations to be firmly justified.

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