Stochastic Resonance in Experiment

A. Kittel, R. Richter, M. Hirsch, and G. Flätgen
Physical Institute, University of Tübingen, Tübingen, Germany

J. Peinke
C.R.T.B.T.-C.N.R.S., Grenoble, France

J. Parisi
Physical Institute, University of Bayreuth, Bayreuth, Germany

Z. Naturforsch. **48a**, 633–635 (1993); received February 16, 1993

We observe the phenomenon of stochastic resonance in a semiconductor experiment. Originally, such an effect was predicted for bistable dynamical systems that are influenced by a periodic modulation as well as a random perturbation. In that case, a "resonance" peak can be observed in the power spectrum. The phenomenon investigated is the low-temperature impact ionization breakdown. There, bistability results from the competing states of low and high conductance.

The phenomenon called stochastic resonance was proposed by Benzi et al. [1]. They investigated the transition rates of a bistable dynamical system that is, first, weakly periodically driven and, second, influenced by a stochastic perturbation. The power spectrum of the output signal exhibits a peak at the driving frequency superimposed on a noisy background. It is just the existence of the peak why that effect has got the somewhat confusing name "stochastic resonance". The peak can not be observed for too small amplitudes of the driving force. Surprisingly, this holds also for too small amplitudes of noise. It can be understood by the fact that the system stays in a locally stable state. The periodic forcing is too weak for being able to destabilize the actual state of the system, i.e., it is already bistable. There exists a certain probability that the system obtains a kick from the stochastic perturbation just at the moment the periodic driving has destabilized the system. As a result, the system leaves the state which is unstable at that moment. In detail, a model of this system consists of a pseudo potential of fourth order, while the system itself is overdamped. The potential has the form $U = (1/4)\,a\,x^4 - (1/2)\,b\,x^2 + f(t)\,x$ (a and b are parameters of the potential). The function $f(t)$ consists of two components, $f(t) = \sqrt{D}\,\xi(t) + A\,\sin(\omega_0 t)$, the former being a stochastic term with the intensity D, the latter a small periodic term with the amplitude A and the modulation frequency ω_0. As a consequence, the potential is tilted in time. The so-called Kramers transition rate is defined as $r(t) = (\alpha/2\pi)\exp\{(-\Delta U + A\sin(\omega_0 t))/D\}$, where α depends on the curvature of the potential and ΔU represents the height of the separating barrier. The transition rates determine the characteristic time of the system. There are two distinct phenomena of stochastic resonance. Under variation of the noise intensity D or the modulation frequency ω_0, the signal to noise ratio as well as the amplitude ratio of the correlated output to the modulation signal becomes maximum for certain values of D and ω_0, respectively. In this paper, the second property will be discussed.

There are already some examples of experimental confirmation for stochastic resonance performed on an analog simulator [2] and a ring laser system [3]. We focus on low-temperature impact ionization breakdown in a semiconductor system. The sample, single-crystalline p-type germanium, is surrounded by liquid helium and shielded against radiation. The simple electric circuit consists of a series combination of the sample with a load resistor R_L and a voltage source V_0. The latter is composed of a constant voltage V_{DC}, a sinus voltage V_{AC}, and a noise voltage V_n. For clarity, Fig. 1 shows the time trace of the voltage $V_n + V_{AC}$ (a) and the relating autocorrelation function (b). Note that the autocorrelation function uncovers the periodic modulation signal (with the frequency $\omega_0 = 1$ Hz). Interesting observables are the sample current I_s and voltage V_s, measured as voltage drops

Reprint requests to Prof. Dr. J. Parisi, Physical Institute, University of Bayreuth, P.O. Box 10 12 51, W-8580 Bayreuth, Germany; FAX + +49-921-552621.

0932-0784 / 93 / 0500-0633 $ 01.30/0. – Please order a reprint rather than making your own copy

Dieses Werk wurde im Jahr 2013 vom Verlag Zeitschrift für Naturforschung in Zusammenarbeit mit der Max-Planck-Gesellschaft zur Förderung der Wissenschaften e.V. digitalisiert und unter folgender Lizenz veröffentlicht: Creative Commons Namensnennung-Keine Bearbeitung 3.0 Deutschland Lizenz.

Zum 01.01.2015 ist eine Anpassung der Lizenzbedingungen (Entfall der Creative Commons Lizenzbedingung „Keine Bearbeitung") beabsichtigt, um eine Nachnutzung auch im Rahmen zukünftiger wissenschaftlicher Nutzungsformen zu ermöglichen.

This work has been digitalized and published in 2013 by Verlag Zeitschrift für Naturforschung in cooperation with the Max Planck Society for the Advancement of Science under a Creative Commons Attribution-NoDerivs 3.0 Germany License.

On 01.01.2015 it is planned to change the License Conditions (the removal of the Creative Commons License condition "no derivative works"). This is to allow reuse in the area of future scientific usage.

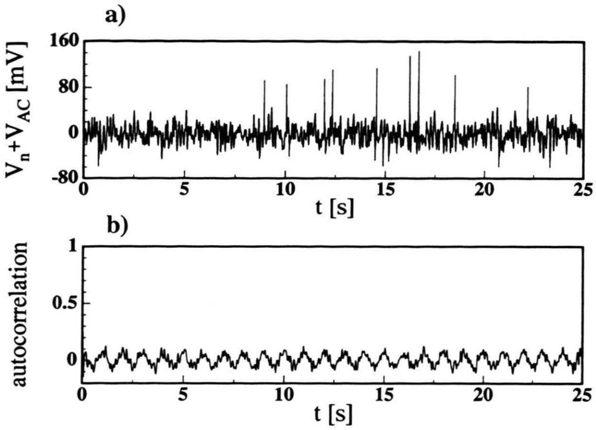

Fig. 1. Time trace (a) and autocorrelation function (b) of the sum of the external noise and sinus voltage at the constant parameters noise intensity 70.63 mV and sinus amplitude 10 mV.

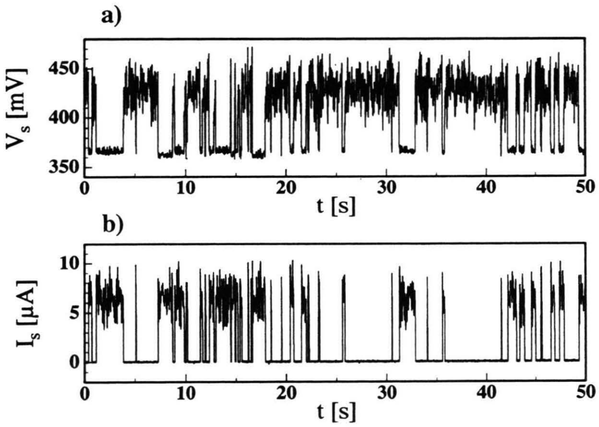

Fig. 2. Time traces of the sample voltage (a) and the sample current (b) obtained at the constant parameters noise intensity 70.63 mV, sinus amplitude 10 mV, bias voltage 430 mV, load resistance 10 kΩ, and temperature 1.9 K.

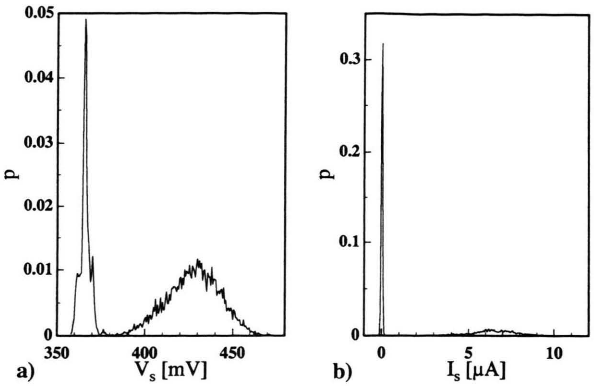

Fig. 3. Probability density of the sample voltage (a) and the sample current (b) obtained at the constant parameters of Figure 2.

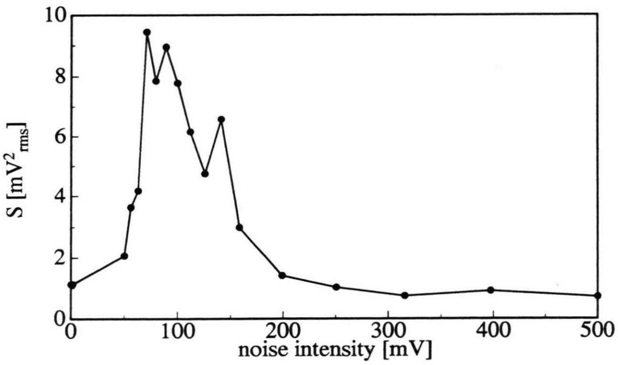

Fig. 4. Amplitude of the coherent part of the sample voltage versus noise intensity obtained at the constant parameters sinus amplitude 10 mV, bias voltage 430 mV, load resistance 10 kΩ, and temperature 1.9 K.

across the load resistor and the sample, respectively. Such kind of electric breakdown is nondestructive, i.e., completely reversible. The system exhibits an S-shaped current-voltage characteristic with a negative differential conductance. Associated with the breakdown phenomenon is a formation of current filament structures. Nucleation of the first filament as well as the transition from the one- to a two-filamentary state and all further transitions at higher currents coincide with the negative differential conductance branch of the current-voltage characteristic [4]. In the vicinity of these transitions, the system undergoes a multistable behavior for certain values of the load resistor. Therefore, there exist different working conditions to observe stochastic resonance. The transition from the weakly conducting state (furtheron called off-state) to the one-filamentary state (on-state) is the subject of this paper.

Figure 2 shows the time traces of the sample voltage V_s (a) and the sample current I_s (b). Obviously, the on-state results in a higher current level and a lower voltage drop (due to the restriction of the load line). Another special feature of the experimental system arises. The voltage (current) fluctuations observed in the on-(off-)state are weaker than those in the off-(on-) state. That means that the system has no symmetrical potential. This assumption is substantiated by the distribution of the probability density p shown in Figure 3. The histograms of the sample voltage (a) and the sample current (b) exhibit an asymmetrical shape. On the l.h.s., there is a narrow and steep peak, contrasting with the smooth peak on the r.h.s. What is the consequence for the behavior of the system? The rates for backward and forward transitions are not equal because the parameter α depends on the curvature of the potential, as mentioned above. In Fig. 4, the amplitude of the coherent signal is plotted versus the noise intensity. The graph possesses a maximum and, therefore, obeys the characteristic predictions of stochastic resonance.

The present experimental system turns out to be very sensitive against changes of external disturbances, like magnetic field, temperature, and irradiation. So it might be possible to apply the stochastic resonance for detecting fluctuations of these quantities. Another use is to gain more detailed physical information about the semiconductor system (for example, the transitions between two different filamentary states).

We want to thank all members of ENGADYN, furthermore, L. Schimansky-Geier and P. Jung for helpful discussions. Paper presented at the 3rd Annual Meeting of ENGADYN, Grenoble, 1992.

[1] R. Benzi, A. Sutera, and A. Vulpiani, J. Phys. A **14,** L453 (1981). – R. Benzi, G. Parisi, A. Sutera, and A. Vulpiani, Tellus **34,** 11 (1982).
[2] S. Fauve and F. Heslot, Phys. Lett. A **97,** 5 (1983).
[3] B. McNamara, K. Wiesenfeld, and R. Roy, Phys. Rev. Lett. **60,** 2626 (1988). – G. Vermuri and R. Roy, Phys. Rev. A **39,** 4668 (1989).
[4] K. M. Mayer, J. Parisi, and R. P. Huebener, Z. Phys. B – Condensed Matter **71,** 171 (1988).