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Noise-induced effects in nonlinear relaxation of condensed matter systems

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ABSTRACT

Noise-induced phenomena characterise the nonlinear relaxation of nonequilibrium physical systems towards equilibrium states. Often, this relaxation process proceeds through metastable states and the noise can give rise to resonant phenomena with an enhancement of lifetime of these states or some coherent state of the condensed matter system considered. In this paper three noise induced phenomena, namely the noise enhanced stability, the stochastic resonant activation and the noise-induced coherence of electron spin, are reviewed in the nonlinear relaxation dynamics of three different systems of condensed matter: (i) a long-overlap Josephson junction (JJ) subject to thermal fluctuations and non-Gaussian, Lévy distributed, noise sources; (ii) a graphene-based Josephson junction subject to thermal fluctuations; (iii) electrons in a *n*-type GaAs crystal driven by a fluctuating electric field. In the first system, we focus on the switching events from the superconducting metastable state to the resistive state, by solving the perturbed stochastic sine-Gordon equation. Nonmonotonic behaviours of the mean switching time versus the noise intensity, frequency of the external driving, and length of the junction are obtained. Moreover, the influence of the noise induced solitons on the mean switching time behaviour is shown. In the second system, noise induced phenomena are observed, such as noise enhanced stability (NES) and stochastic resonant activation (SRA). In the third system, the spin polarised transport in GaAs is explored in two different scenarios, i.e. in the presence of Gaussian correlated fluctuations or symmetric dichotomous noise. Numerical results indicate an increase of the electron spin lifetime by rising the strength of the random fluctuating component. Furthermore, our findings for the electron spin depolarization time as a function of the noise correlation time point out (i) a nonmonotonic behaviour with a maximum in the case of Gaussian correlated fluctuations, (ii) an increase up to a plateau in the case of dichotomous noise. The noise enhances the coherence of the spin relaxation process.

1. Introduction

The nonlinear relaxation process in many condensed matter systems proceeds through metastable states, giving rise to nonmonotonic behaviours of the lifetime of the metastable state as a function of the noise intensity or some external

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driving frequency. Moreover, the noise can enhance the electron spin lifetime in semiconductor crystals for an initial metastable state with all spin aligned. Metastability, in fact, is a generic feature of many nonlinear systems, and the problem of the lifetime of metastable states involves fundamental aspects of nonequilibrium statistical mechanics. Nonequilibrium systems are usually open systems which strongly interact with the environment and this interaction can be modelled as a noise source. The investigation of noise induced phenomena in far from equilibrium systems is one of the approaches used to understand the behaviour of condensed matter complex systems.

In this paper we shortly review three noise induced effects in condensed matter systems, namely the noise enhanced stability and the stochastic resonant activation in JJs and the noise-induced coherence of electron spin in a spintronic system. Specifically we will consider the nonlinear relaxation process of long and short JJs and spin transport in GaAs. Moreover, new results concerning the out of equilibrium dynamics of graphene-based JJ and the spin depolarisation process are presented.

1.1. Long JJ

A Josephson junction (JJ) is a device realised by sandwiching two superconducting plates on a interlayer of non-superconducting material. In this mesoscopic device, macroscopic quantities as voltage and current are directly related to a microscopic order parameter φ, representing the phase difference between the wavefunctions of charge carriers in the two superconducting electrodes. In fact, great attention has been paid to JJs as superconducting quantum bits [1–4], nanoscale superconducting quantum interference devices for detecting weak flux changes [5,6], and threshold noise detectors [7–10]. Moreover JJs are typical out of equilibrium systems characterised by tilted or switching periodic potentials [11,12], and the effects both of thermal and non-thermal noise sources on the transient dynamics of JJs have recently attracted considerable interest [13–23]. In the last decade, theoretical progress has allowed to calculate the entire probability distribution of the noise signal and its cumulants, performing a *full counting statistics* of the current fluctuations [14]. Moreover, the presence of non-Gaussian noise signals has been observed experimentally in several systems [13,17,24–27]. As an example in a wireless ad hoc network with a Poisson field of co-channel users, the noise has been well modelled by an α-stable distribution [27]. Non-equilibrated heat reservoir can be looked as a non-Gaussian noise sources [24–26]. In particular, the effects of non-Gaussian noise on the average escape time from the superconducting metastable state of a biased junction coupled with nonequilibrium current fluctuations, has been experimentally examined [13,17].

Recently, the characterisation of JJs as detectors, based on the statistics of the escape times, has been proposed [7–10,19–23]. Specifically, the statistical analysis of the switching from the metastable superconducting state to the resistive running state of the JJ has been proposed to detect weak periodic signals embedded in a noisy environment [9,10]. Moreover, the rate of escape from one of the metastable wells of the tilted washboard potential of a JJ encodes information about the non-Gaussian noise present in the input signal [7,8,19–23].

Here, the theoretical results for nonmonotonic behaviours of the mean switching time (MST) in a long JJ as a function of the noise intensity, frequency of the external driving current, and junction length are shown and analysed. Specifically, we try to understand how non-Gaussian noise sources affect the switching times in long JJs. The model and the results are presented in Section 2.

1.2. Graphene JJ

The Josephson effect came to light also in a particular kind of JJs, in which the interlayer is a graphene sheet. The resistance of the graphene to the surface oxidation makes this material a good candidate for the realisation of high quality junctions. These devices seem indeed good candidates for the realisation of gate-tunable phase qubits [28,29]. The current-phase relation (CΦR) for superconductor – graphene – superconductor (SGS) devices, composed by two electrodes “suspended” over a graphene substrate (see Fig. 6a), was deeply studied in Refs. [30,31]. Moreover, noise signatures in the behaviour of graphene junctions characterise many experimental and theoretical works [28,32–36]. Here we analyse the transient dynamics and the escape process from metastable states in a SGS device. The model and the results are discussed in Section 3.

1.3. Spin polarised transport

In recent years, diffusion in heterostructures [37] and transport in semiconductors [38] have been increasingly investigated. In particular, the interest in developing spin-based devices gave rise to a huge number of investigations on spin phenomena in semiconductors, with the aim to control the electron spin polarisation by means of electric currents or gate voltages [39–44]. Nevertheless, a drawback of the use of the electron spin is the fact that the magnetic polarisation relaxes over time during the transport because of spin–orbit interactions or scattering events.

Since the spin lifetime could be too short to enable the entire execution of the necessary spin manipulations, the investigation of the spin relaxation processes in the spintronic device design is a crucial point [40,41]. In the last decades, great interest has been oriented towards the noise-induced phenomena in nonlinear complex systems, such as conduction electrons inside semiconductor structures [45]. Noise enhanced stability [46–48] in the electron transport inside GaAs bulks, caused by the addition of external fluctuations to the driving oscillating electric field, has been reported in Refs. [49–51]. Recently, in semiconductor quantum wells and quantum wires the possibility of exploiting random Rashba spin–orbit interaction to generate spin currents has been found [52]. Specifically, Monte Carlo simulations have evidenced that the spatial variation of the Rashba electric field along the quantum wire length yields the spatial spin depolarisation process random, non-monotonic and chaotic [53]. Previous studies of the electron spin decoherence process in GaAs crystals have revealed that a Gaussian random contribution added to the static driving field can change both the spin depolarisation time and length