Noise-induced resonance-like phenomena in InP crystals embedded in fluctuating electric fields

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I. INTRODUCTION

The electron velocity fluctuations during the nonlinear transport of hot electrons in semiconductor structures subjected to static or ciclostationary electric fields, have been extensively investigated during last decades[1–4]. In fact, the presence of intrinsic noise both limits the performance of semiconductor based devices and affects their sensitivity. Furthermore, electronic devices are often imbedded into noisy environments that also can affect their performance. In recent years increasing interest has been directed toward the investigation of noise-induced phenomena in nonlinear systems, with a focus on possible positive cooperative effects between the noise and the intrinsic interactions of the system[5,6]. In particular, theoretical studies have shown that, under specific conditions, the addition of external sources of noise to intrinsically noisy systems may induce an enhancement of the dynamical stability of the system, resulting in a less noisy response[7]. The possibility of suppressing the diffusion noise by the addition of a random fluctuating contribution to the driving periodic electric field, has been previously investigated in GaAs bulks[8,9]. By superimposing an external noise source to the intrinsic one, it has been possible to tune the dynamic electron response and obtain noise enhanced stability phenomena in the electron transport[8,9]. In this study, we employ a semi-classical Monte Carlo (MC) approach to simulate the non-linear transport of electrons inside low-doped n-type InP crystals, embedded in sub-THz electric fields, fluctuating for the presence of an external source of noise. The electronic noise features are statistically investigated by computing the correlation function of the velocity fluctuations, its spectral density and the total noise power. Main aim of this work is to deeply explore the occurrence of a noise reduction effect and the appearance of a stochastic resonance-like phenomenon in the noise spectra. Moreover, we will discuss the dependence of these noise-induced positive effects on the relationship among the characteristic times of the external fluctuations and the temporal scales of complex phenomena involved in the electron dynamics.

II. THE MODEL

The transport of electrons in InP bulks is simulated by using a MC algorithm[10]. In our model the conduction bands of InP are represented by the Γ- valley, by four equivalent L-valleys and by three equivalent X-valleys. All possible scattering events of hot electrons in the medium, the main details of the band structure, as well as the heating effects, are taken into account. The scattering probabilities are calculated by using the Fermi Golden Rule and the scattering events are considered instantaneous. Scattering probabilities are assumed to be field-independent. Accordingly, the influence of the external fields is only indirect through the field-modified electron velocities[10]. The table of parameters used in the present work is given in Ref[11]. All results are obtained for a doping concentration of 10^{19} m^{-3} (non-degenerate n-type), at lattice temperature $T = 77$ K. The fluctuations of the electron velocity around its average value correspond to the intrinsic noise of the system. Therefore, to characterize the stochastic properties of the electron transport, we statistically analyze the velocity autocorrelation function and the mean spectral density of the velocity fluctuations. Since our sample is driven by a periodic electric field, we calculate a two-time symmetric electron velocity autocorrelation function [12], in order to eliminate any regular contribution and describe only the fluctuating part of $v(t)$. The spectral density of the electron velocity fluctuations is then calculated as the Fourier transform of the correlation function. In our simulations the electrons are driven by a fluctuating periodic electric field $E(t) = Ecos(\omega t) + \eta(t)$, where the deterministic term has amplitude E and frequency $f = \omega/2\pi$. The stochastic component $\eta(t)$ is modelled by an Ornstein-Uhlenbeck (OU) process which obeys the following stochastic differential equation:

$$\frac{d\eta(t)}{\mathrm{d}t} = -\frac{\eta(t)}{\tau_c} + \sqrt{\frac{2D}{\tau_c}}\xi(t) \tag{1}$$

where τ_c and D are the correlation time and the intensity of the noise component, respectively[8].

III. NUMERICAL RESULTS AND DISCUSSION

With the aim to quantify the noise-induced intrinsic noise suppression, we have calculated the Integrated Spectral Density (ISD), i.e. the total noise power, which corresponds to the variance of the electron velocity. In the left panel of Fig. 1, we show the ISD as a function of the noise correlation time τ_c when E=25 kV/cm, f=500 GHz, $D^{1/2}$=10 kV/cm. In the presence of Gaussian time-correlated fluctuations added to the periodic electric field, it is possible to observe a clear reduction up to

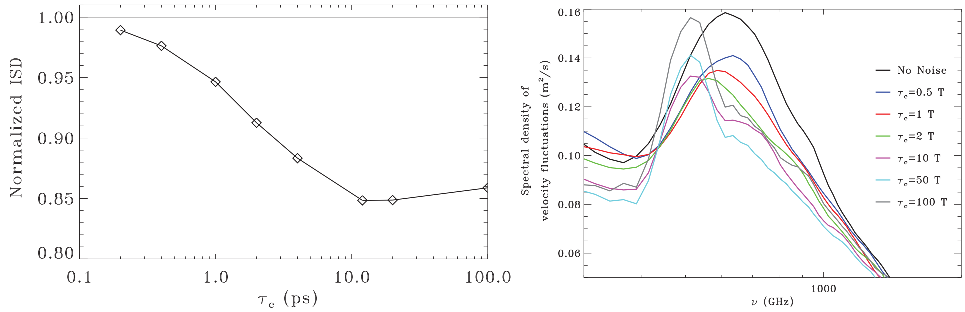

FIG. 1. Left: ISD of the electron velocity fluctuations, normalized to the value obtained in the deterministic case, as a function of the noise correlation time τ_c. Right: Spectral density of the electron velocity fluctuations for different values of the correlation time τ_c. The values of the parameters are E=25 kV/cm, $D^{1/2}$= 10 kV/cm, f= 500 GHz, T=77 K.

15% of the ISD, i.e. a less noisy response. The suppression enhances with the increase of the correlation time of the external fluctuations up to $\tau_c \approx 10$ ps and then stabilizes. Further studies are needed to deeply investigate why under this regime, the external fluctuations constructively contribute to force the electrons to performing a more ordered dynamics (confirmed by a lower total noise power). In the rigth panel of fig. 1 we show how the shape of the spectral density of the electron velocity fluctuations modifies around the frequency of the oscillating field in the presence of Gaussian time-correlated fluctuations. The "effective" electric field experienced by the electrons changes. This implies a modification in the number of intervalley tranfers with respect to the case in which the external noise is negligible. This fact could be responsible of the changes in the height of the peak in the spectral density. The most interesting effect arises for noise correlation times greater than 10 T (2 ps). In fact, in such cases, the presence of time-correlated fluctuations makes the peak strictly resonant at the frequency of the driving periodic field. This resonance-like phenomenon could be an evidence that electrons transfer among the different energy valleys exactly at the same frequency of the applied field, reaching a new more stable equilibrium state.

IV. CONCLUSION

We report the results from a many-valley MC study on the electron non-linear dynamics in low-doped n-type InP crystals operating under a fluctuating sub-Thz electric field. A less noisy response is found, being the correlation time of the electric field fluctuations a crucial quantity for the reduction effect. This noise-induced phenomenon seems to indicate that, under specific time scales, the complex dynamics of electrons in the crystal benefits from the cooperative interplay between the fluctuating electric field and the intrinsic fluctuations of the system itself. Therefore, time-correlated fluctuations on a driving electric field could play a relevant role on controlling and tuning the electronic noise in InP based electronic devices. For noise correlation times greater than 10 T, a resonance-like phenomenon in the noise spectra is found. This response critically depends on the relationship among the characteristic time of the external noise and the time scales characterizing the complex electron dynamics. However, these preliminary findings leave several open problems on the intrinsic physical mechanism beyond this effect, which will be further investigated mainly in terms of (i) different frequencies of the driving field, (ii) different intensities and typologies of the external fluctuations, (iii) different semiconductors materials.

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