Journal of Physics: Conference Series **647** (2015) 012061 doi:10.1088/1742-6596/647/1/012061

Shot-noise suppression effects in InGaAs planar diodes at room temperature

Ó García-Pérez[1], H Sánchez-Martín, J Mateos[1], S Pérez[1], A Westlund[2], J Grahn[2] and T González[1]

[1] Department of Applied Physics, Universidad de Salamanca, Salamanca 37008, Spain
[2] Department of Microtechnology and Nanoscience, Chalmers University of Technology, Gothenburg SE-412 96, Sweden

E-mail: ogarcia@usal.es

Abstract. In this work, the noise characteristics of InGaAs planar diodes are studied. The presence of a recessed region originates a barrier in the potential profile, which can modulate the passage of ballistic carriers along the structure. This effect, in turn, may lead to suppressed levels of noise with respect to the full Poissonian value due to Coulomb interaction. With the aim of evidencing such phenomenon, the noise properties of a set of devices with different dimensions have been measured at room temperature. Some evidence of potential shot-noise suppression is observed in the results, but the undesired effect of resistive contacts and accesses has been found to be a limiting factor to quantify the suppression accurately.

1. Introduction

Noise is usually considered as unwanted fluctuations that appear in any electronic system and distort the processing of information signals. Nevertheless, studies on electronic noise can provide valuable information to better understand the electron transport mechanisms in semiconductor devices. For example, carrier interaction in mesoscopic devices can regulate its propagation statistics, which in turn may lead to suppressed levels of noise [1].

The effect of Pauli principle and/or Coulomb interaction on the carrier statistics in ballistic media, and how it may result in noise levels lower than the full shot noise value ($2qI$), is a field of interest for physicists and electronic engineers [2]-[3]. Pauli principle may have effect on the injecting statistics of the carriers at the contacts, whereas Coulomb interaction may affect the carrier propagation statistics through the device. Therefore, the current spectral density S_I of the device can be written as $S_I = F2qI$, where q is the electron charge, I is the bias current, and F is defined as the Fano factor, which quantifies the aforementioned suppression (or enhancement, which is also possible when positive correlations between carriers exist).

Since shot noise has its origin in the granularity of charge, it plays an important role when lengths are significantly scaled down. Therefore, understanding and characterizing the physics associated to the noise suppression is of great interest. However, the experimental evidence of such effects is not easy to obtain, mainly at room temperature (RT). The aim of this work is to identify suppression effects from the noise measurement of nanoscale InGaAs planar diodes at RT.

2. Device structure and Monte Carlo simulations

The geometry of the diodes, depicted in figure 1, is equivalent to the one of an ungated HEMT with a recess in between the drain and source accesses [4]. The recess-to-source and recess-to-drain distances will be denoted as L_S and L_D, and the length of the slot will be denoted as L_R. The presence of the recess, by removing part of the upper InGaAs layer (cap), allows focusing the electric field in that region. Under this condition, and considering the high mobility in the channel, quasi-ballistic transport of carriers can be expected under the recess even at RT.

In a first step, a set of devices has been simulated using the Monte Carlo particle method. The simulated potential profiles of a device with L_S=200 nm, L_R=160 nm, L_D=300 nm and a cap layer of 4 nm for different drain-to-source voltages are shown in figure 2. As it can be observed, an energy barrier appears under the recess generated from the quasi-ballistic electrons, which is expected to suppress the shot noise due to Coulomb correlations, as it was described in the previous section. The barrier height decreases with increasing bias, but it does not disappear. This is because above around 0.7 V, the value at which inter-valley mechanisms are activated in drain region [4], the increments of voltage are absorbed near the drain contact while the potential profile in the recess remains almost unaltered.

The simulated and measured I-V curves of a set of devices with varying L_R (and L_D=550 nm) and varying L_D (and L_R=160 nm) are represented in figure 3. The cap layer is 4 nm thick, L_S=200 nm, and a contact resistance of $2R_C$=0.35 Ω·mm has been added to the simulations for the direct comparison with the measurements. In all these devices the behavior in the simulated potential profile is equivalent to the case shown in figure 2 and described above.

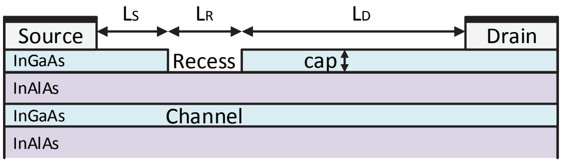


Figure 1. Geometry of the recessed planar diodes.

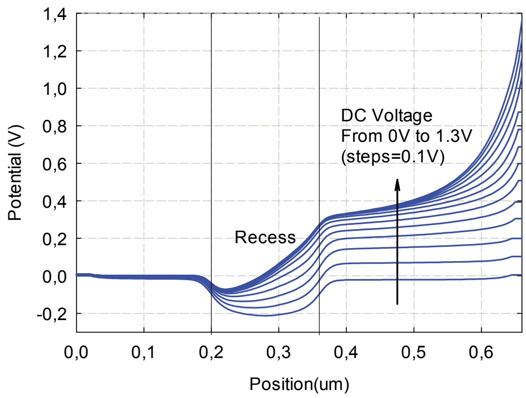


Figure 2. Simulated potential profile along a device with L_S=200 nm, L_R=160 nm and L_D=300 nm.

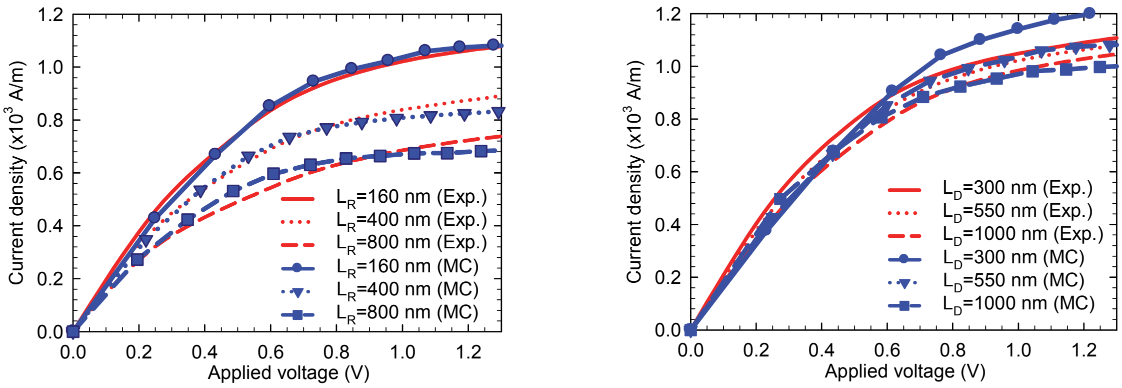


Figure 3. Simulated (MC) and experimental (Exp.) current-voltage curves.

3. Experimental results

For the measurement of the noise spectral density of the diodes, a PNA-X N5244A with Option 029 from *Agilent Technologies* has been used. This equipment allows the simultaneous acquisition of the noise power density and the complex impedance of a device with higher levels of accuracy and sensitivity. With both magnitudes, the conversion into current spectral density is straightforward. For each bias point, the spectral density value has been calculated averaging data between 20-30 GHz, ensuring that we are in the high-frequency white-noise plateau above 1/*f* noise.

The noise measurements were performed in the set of devices whose I-V curves were presented in figure 3, with: varying L_R (and L_D=550 nm), and varying L_D (and L_R=160 nm). The source access length is L_S=200 nm, the cap layer is 4 nm thick and the width is 10 µm. Additionally, a non-recessed device of 1300 nm length and 10 µm width has been characterized for comparison. The current spectral density S_I as a function of the bias current is shown in figures 4(a) and (c). When the current begins to saturate, there is a significant increase of S_I, which is not observed in the non-recessed device. The flat noise density of the non-recessed device indicates that thermal noise dominates in that case, due to the diffusive nature of the transport in the long structure. Also, as it is observed from the plots, the measured values of S_I are well below the full shot noise value $2qI$. Consequently, the values of F remain lower than one [figures 4(b) and (d)].

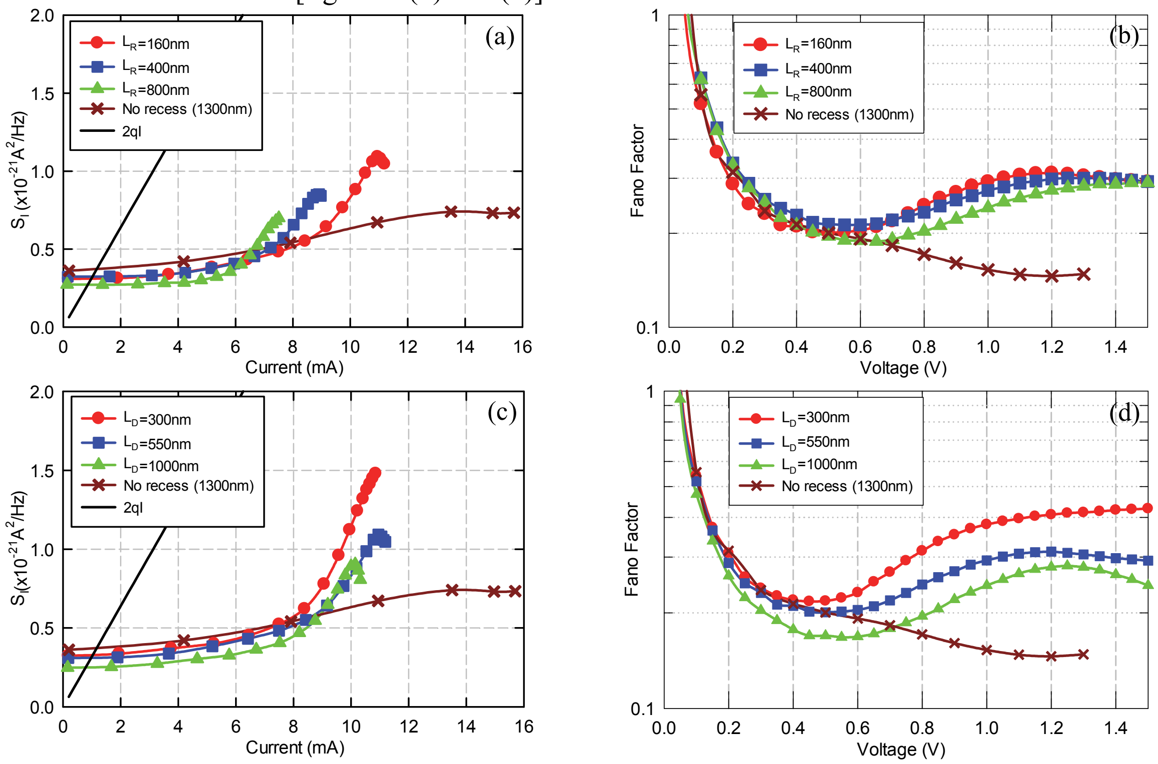
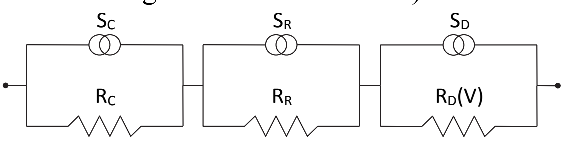


Figure 4. Measured (a)(c) current spectral density, and (b)(d) Fano factor.

4. Noise model and discussion

In order to determine and quantify the noise suppression effects directly attributed to the barrier under the recess, the noise contributions from the drain/source access regions and the contacts should be properly eliminated from the raw measurements presented in figure 4. For this purpose, a simple noise model has been developed based on the scheme shown in figure 5. The first module represents the contact resistance R_C=35 Ω, and its noise contribution is assumed to be thermal $S_C=4kT_0/R_C$, being k the constant of Boltzmann and T_0=300 K. The second module represents the zone of interest, i.e. the region of the barrier under the recess, and its noise contribution S_R is modeled as $S_R=F2qI$, assuming two different scenarios F=1 (full shot noise) and F=0 (fully suppressed noise) for comparison. Finally, the third module represents the drain access region, as a non-linear resistance $R_D(V)$, and its noise contribution is assumed to be thermal as $S_D=4kT_0/R_D(0)$. This strong assumption, which is not completely correct, allows to simplify the noise model and, as we will show later, it does not affect the main conclusions of this work. The values of R_R and R_D, which are bias dependent, are determined from the potential profiles and currents obtained from the Monte Carlo simulations. The resistance of the source region is considered negligible according to the potential profiles shown in figure 2. Finally, the resulting current spectral density S_I can be calculated following the formula shown in figure 5.

With the model described above, the theoretical values of S_I and F have been calculated for the same set of devices considered for the experiments in section 3, and the resulting plots are shown in figure 6. The calculated results reasonably reproduce the shape of the measured results in figure 4. As it was mentioned before, two extreme conditions are assumed in the recess (F=0 and F=1). However, its effect on the overall noise response is weak. Moreover, any change in the noise of the recess region is indistinguishable above 0.7 V due to the predominance of the drain resistance. Therefore, the signature of shot noise suppression would only be visible from the total noise at intermediate voltages. Nevertheless, even in those cases accurately quantifying the suppression is still challenging. Devices with reduced access and drain resistances should be fabricated in order to obtain more conclusive results (apart from complex low temperature measurements, where the thermal noise of the contacts and drain region would be lowered).



$$S_I = \frac{S_C R_C^2}{(R_C + R_R + R_D)^2} + \frac{S_R R_R^2}{(R_C + R_R + R_D)^2} + \frac{S_D R_D^2}{(R_C + R_R + R_D)^2}$$

Figure 5. Proposed noise model for the recessed diodes.

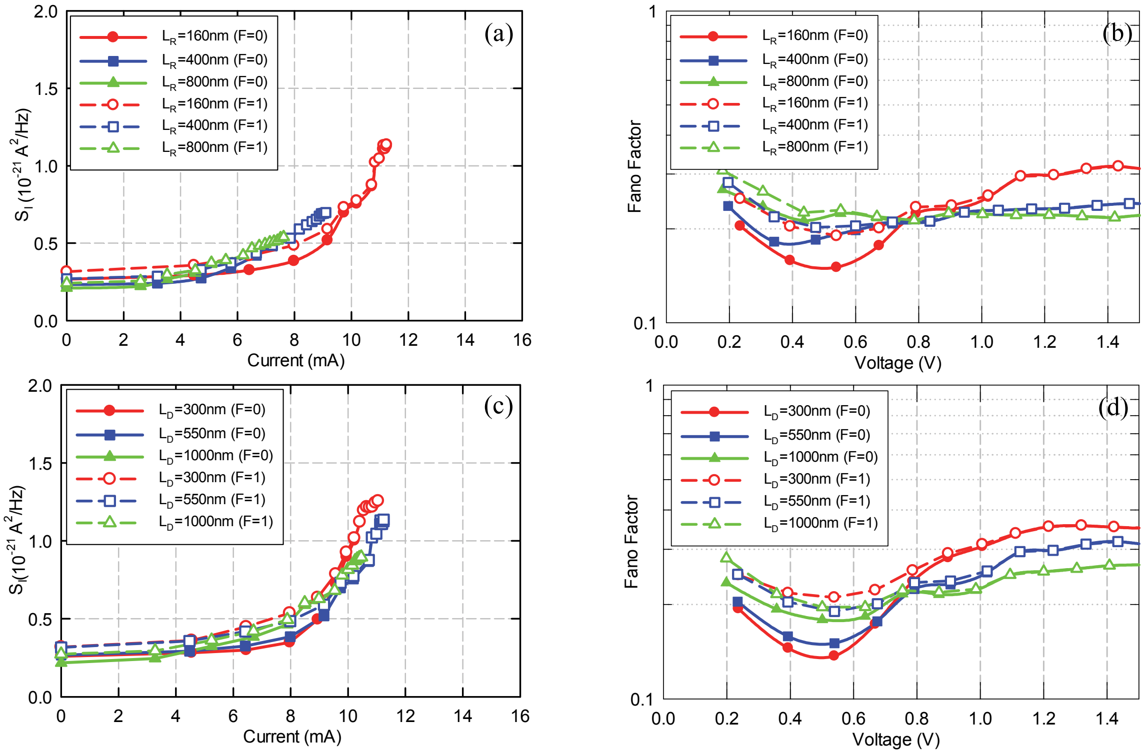


Figure 6. Calculated (a)(c) current spectral density, and (b)(d) Fano factor, using the model of figure 5.

Acknowledgements
This work has been partially supported by the Spanish MINECO through project TEC2013-41640-R, by the Consejería de la JCyL through project SA052U13, and by the European Social Fund (ESF).

References
[1] Landauer R 1998 *Nature* **392** 658-659
[2] Gomila C, Cantalapiedra I, Gonzalez T and Reggiani L 2002 *Phys. Rev. B* **66** 075302
[3] Naveh Y, Korotkov A N and Likharev K K 1999 *Phys. Rev. B* **60** 2169-2172
[4] Perez S, Gonzalez T, Pardo D and Mateos J 2008 *J. Appl. Phys.* **103** 094516