Correspondence

Comments on "Noise Source Modeling for Cyclostationary Noise Analysis in Large-Signal Device Operation"

S. L. Delage and J. Obregon

***Abstract*—We want to comment on a recent paper by Bonani *et al.* on the noise source modeling in devices driven in large-signal conditions.**

First, we would like to remind the readers that pioneering work was previously carried out based on Monte Carlo analysis together with a study of the impact of a large RF signal on the GR noise modulation. This work was published in two important scientific journals. More recently, two communications were presented on this problem at the 16th International Conference on Noise in Physical Systems and 1/f Noise by others research teams.

Second, we would like to discuss the "system model" applied to homogeneous devices, presented in the discussed paper by Bonani *et al.*, which was constituted by a white noise source driving a lowpass filter followed by a HF modulator.

Third, the results obtained by all the teams were worthy of being carefully considered since they gave a different view on the noise factor stemming from a linear electrical two-port, which was classically viewed as a simple degradation of the signal-to-noise ratio introduced by the circuit.

I. Discussion

In the above letter, [1] the authors showed, using a drift-diffusion modeling, that the generation-recombination (GR) noise sources inside a semiconductor medium could be modulated at the rate of the applied quasiperiodic high-frequency (HF) signals. Then, they derived a "system model" including a white noise source driving a lowpass filter followed by a HF modulator. Finally, the authors concluded that despite the GR process exhibiting a much longer time constant, those sources could be surprisingly modulated by the HF signal. This effect leads to the existence of local noise current sources, which were colored and cyclostationary.

We are in agreement with these general conclusions, which are corroborating our own previous results [2], [3] carried out based on Monte-Carlo analysis.

Besides, we would like to stress that a proper "system model" such as described by Bonani *et al.* does require the implementation of two modulations of the local current sources, as shown in (16) of the discussed paper, instead of a unique one, which applies only to the carrier population. A first modulation would be applied to the fluctuating carrier density $\delta n\ (t)$ since the GR process is a function of the total electric field (DC + HF) present in the sample, whereas the second modulation would modulate the carrier velocity, which is also a function of this total electric field. In homogeneous semiconductors, the carrier velocity is the main parameter that could be modulated by the HF signal. Indeed, the carrier density is modulated very little by the HF signal due to the lowpass nature of the random generation.

Nevertheless, the modulation of the fluctuating carrier density could become important if the frequencies of the applied signals are close to the cut-off frequency of the GR process. This could be quite important for new semiconductor devices under development, where both materials and processes are not mature, leading to rather HF GR noise (up to 1 GHz).

The local equivalent scheme with two modulations is necessary because at the circuit or system level, noise current/voltage sources are used instead of population noise sources. The first modulation applies to carrier population, whereas the second depends on the nature of the convective current (drift or diffusion current) prevailing in the region where the generation takes place.

Finally, the results of the research teams [2]–[5] question the commonly used definition of the spot average noise factor when it is considered as a degradation of a signal-to-noise ratio introduced by linear system since it was demonstrated that the output noise power was depending on the input level. It must be pointed out that the IEEE definition of the noise factor does not take into account the signal level, while this signal with its genuine behaviors (amplitude, phase, envelope) is always present in operating systems. Incidentally, it is interesting to note that a similar (but not strictly identical) problem was discussed in the 1960s. It was further pointed out that the noise figure of low-noise parametric amplifiers turns out to be a function of the input signal level.

These works of [2]–[5] are alerting the RF community to the fact that refined models of semiconductor devices might be necessary in order to determine accurately the noise performance of nonlinear circuits.

II. Conclusion

The GR noise sources of a homogeneous semiconductor were modeled using two different approaches: The first one was based on Monte-Carlo simulation [2], whereas the second used drift-diffusion simulation. Both models showed that the noise current sources were modulated by an HF signal. These works showed that the GR sources were transposed into sidebands of the HF signal components giving rise to cyclostationary local noise current sources. As an extension of these results, it could be expected that the fundamental $1/f$ local noise current sources created by random fluctuations of the low field mobility could be also modulated by the HF signal. Indeed, the product of the low-frequency mobility fluctuations by the applied HF electric field should give rise to HF velocity sidebands, leading to cyclostationary local noise current sources.

The understanding of the modulation of primary noise sources is therefore crucial in order to explain the noise performance of large signal amplifiers, mixers, and oscillators.

References

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Author's Reply

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In the above paper [1], we presented a discussion on modeling issues concerning generation-recombination (GR) noise source simulation in both physics-based (PB) and compact device modeling making use of a full bipolar drift-diffusion model. The main goal was to describe in a systematic way the system-level techniques used for generating cyclostationary noise sources (originally devised for circuit-level models) starting from available expressions valid in stationary conditions, and using PB models as a validation tool. We considered in particular GR noise because it can be modeled either through fundamental, white stationary sources, or by means of *approximate*, lorentzian current density fluctuations, typically used for monopolar simulations [2].

First of all, we would like to apologize for overlooking some works of the authors [3], [4], of which we were not aware of at the time of writing our paper. In those, the authors (in cooperation with others) presented a Monte Carlo analysis of GR noise, approximated as transitions between conduction band and a trap level, under the effect of time-varying electric fields in a homogenous sample. As stated in the comment, the results of the two groups are in agreement, though in [3,4] only the diagonal elements of the noise sideband correlation matrix are considered.

Furthermore, we would like to point out that the two system models (FM and MF as defined in [1]) yield different results only if the approximate, lorentzian microscopic GR sources in terms of current density fluctuations are employed, since using fundamental sources [1], [5], [6] no ambiguity arises (at least in the RF/microwave frequency range), due to their white stationary spectrum. The lorentzian sources make sense only if diffusion current is neglected and, even if this assumption holds, are in full agreement with fundamental sources only for strictly homogenous samples (see [7] for a discussion).

As a final remark, recent results [8] have shown that, at circuit level, in the case of pn junction diodes GR noise is better described by making use of the MF system approach instead of the FM scheme, in marked contrast with the result obtained for homogeneous resistors [1], [3], [4]. This indicates that cyclostationary noise simulation is extremely sensitive to the physical origin of fluctuations and to the very device structure in which they occur, thus suggesting to make use of white stationary sources whenever possible.

References

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Correction to "Analysis of CMOS Photodiodes—Part II: Lateral Photoresponse"

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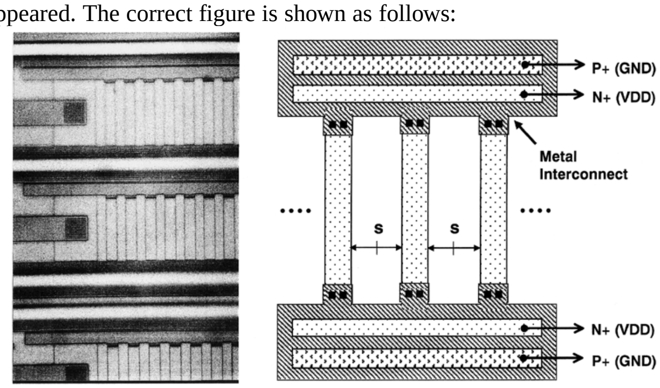
In the above paper [1], an incorrect version of Fig. 1(a) and (b) appeared. The correct figure is shown as follows:



(a) (b)

Fig. 1. (a) Micrograph of the fabricated linear phtodiode array, and (b) an illustration of the layout. Each array consisted of nearly 100 30 μm $\times 5$ μm $n^+ - p_{epi}$ photodiode strips connected in parallel. A guard structure was used to prevent collection of stray photocarriers generated elsewhere in the test chip.

References

[1] J. S. Lee, R. I. Hornsey, and D. Renshaw, "Analysis of CMOS photodiodes—Part II: Lateral photoresponse," *IEEE Trans. Electron Devices*, vol. 50, pp. 1239–1245, May 2003.

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