Low Frequency Noise Deviation from Schottky theory in p-n junctions

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***Abstract*— Theories on linear white noise sources such as thermal noise or shot noise are well established and massively used for low noise device modeling and circuit design. However, it has been experienced that diffusion noise in a large variety of pn diodes (transistors) can deviate from the expected value given by the Schottky theorem or by the Van der Ziel representation commonly used. In this work, more than ten types of pn junctions have been investigated, all featuring an increase of the diffusion noise floor in the low frequency band when operated under low d.c current conditions. These specific conditions certainly explain why such phenomenon has not been reported earlier; however, this noise degradation becomes a problem as many systems make use of pn diodes for low signal photodetection (PPD or CCD), operating at very low (dark) current. For the first time, we report current spectral densities deviations from the Shottky theorem at low frequency; a focus on the experimental workbench is given to remove any doubt regarding the opportunity to analyze data under concern. Then, low frequency noise spectra are presented for various diodes and pn junctions, and a model is proposed. Impedance spectroscopy is also used to support this study.**

Keywords—Low frequency noise, diffusion noise, noise frequency dispersion.

I. INTRODUCTION

Low frequency noise of junctions is still of great interest as it is massively used for the noise modelling of solid state devices such as diodes and transistors. The well-established theory formulated by W. Schottky one hundred years ago (and first demonstrated in ideal vacuum tubes [1]) still applies and lays down the basic principles of electronic sensitivity for receivers, detectors or any electronic system facing the case of minimum detectable signal. From this theory, a d.c current I flowing through a barrier of potential will generate a current noise spectral density as $S_i=2q(I+2I_s)$, as established by Van der Ziel [2]. In this equation, the contribution of saturation current I_S is added to the main d.c current I initially considered by Schottky in its formulation. Some exceptions have been investigated, due to generation-recombination processes occurring in the space charge region. This mechanism can be expressed by the Fano factor $\gamma = S_i/(2q(I+2I_s))$ where $0.5 \leq \gamma < 1$, depending on the overall current, on the frequency and on the temperature. In this paper, a new low frequency spectral signature is presented, never previously reported to the authors' knowledge. Still using the normalized γ expression of the noise floor (but not referred to as Fano factor), this factor deviates from unity beyond a given frequency, and stabilizes at a value ranging from one to more than six as depicted in figure 1 (and more than ten in specific conditions). This noise degradation phenomenon has only been observed on silicon p-n diodes at low frequency and for very low biasing conditions. Various emitter-base or collector-base junctions have been investigated in silicon transistors such 2N2222, 2N2905, BC557 for the most commonly used devices. In section 2, the Low Frequency Noise (LFN) experimental workbench is presented, and measurements are performed with various pre-amplification schemes in order to validate reported data. Given the very low noise spectral densities involved, particular attention is paid to the instrumentation used for the characterization of the LFN, and to the deembedding of the diode noise from various contributions (amplifiers termination versus frequency, noise contribution and correlation of amplifier noise sources) to the total noise. This warrants a rigorous characterization of the Devices Under Test (DUT) noise. Calibration steps and measurements are presented in this section. The third section is dedicated to the modeling and analysis of the observed phenomenon versus d.c current. Diode impedance spectroscopy is used in order to substantiate LFN data from a newly proposed model.

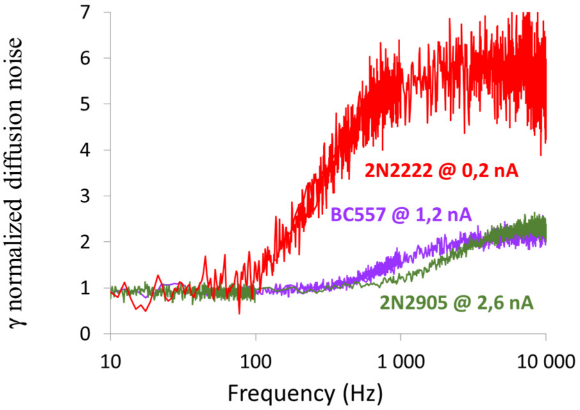


Fig. 1 : Evidence of the diffusion noise floor increase at low frequencies (deviation of the normalized representation from unity), for three various silicon technologies. *Nota: emitter-base diodes (collector open) are investigated*

II. LOW FREQUENCY DEVIATION FROM THE EXPECTED DIFFUSION NOISE FLOOR.

A. *Experimental setup*

Various experimental workbenches for LFN measurements have been developed over the past five decades [3][4]; the experimental workbench allows LFN measurement of a 2-port DUT current (or voltage) noise sources from 1 Hz to 1 MHz. For the study case under concern, only diodes are measured; the current spectral density S_i of the DUT is obtained from a transimpedance low noise preamplifier (model 5182 from EG&G Instruments) or also a voltage low noise preamplifiers (model 5184 from Perkin Elmer Instruments or model SR560 from Stanford Research Systems). According to the selected preamplifier, different appropriate noise deembedding techniques are used to get the

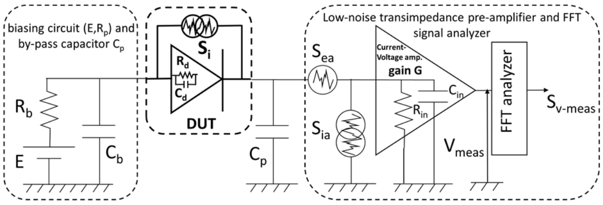


Fig. 2 : LFN experimental setup for diode measurement with current-voltage preamplifier.

S_i current spectral density of the DUT from the overall noise measure $S_{v\text{-}meas}$, as depicted in Figure 2. As long as the DUT is a diode operating at very low current, hence featuring a high dynamic resistance, using a current-voltage preamplifier is more convenient as it presents the lowest impedances to the DUT and therefore sinks most of the DUT noise current. The schematic representation is depicted in Figure 2. On the left part of the figure, d.c biasing battery powered circuit makes use of a by-pass capacitor featuring elevated C_b to consider this circuit as a short circuit over the whole frequency bandwidth of measurement (from 10 Hz to 1 MHz). The DUT (diode) is represented by a parallel association of R_d with C_d. The DUT's package capacitive coupling and the coaxial cable capacitance are accounted for with C_p connected at the output of the DUT. Then the measurement apparatus makes use of a current-voltage preamplifier connected to a Fast Fourier Transform signal analyzer. LFN sources or the preamplifier are represented at the input terminal of the preamplifier (S_{ea} and S_{ia} respectively for the voltage and current noise sources). The parallel association of R_{in} and C_{in} account for the frequency variation of the input impedance of the preamplifier connected to the DUT. The noise voltage spectral density $S_{v\ meas}$ is characterized with the FFT analyzer, according to the contribution of all terms as given in equation 1(assuming $R_{in}C_{in}\omega$<<1).

$$S_{v-meas}(f) = \left(\frac{G^2R_d^2}{(R_d+R_{in})^2+(R_{in}R_dC_d\omega)^2}\right).\left(\frac{S_{ea}[1+(R_dC_d\omega)^2]}{R_d^2} + S_{ia} + \frac{2Re(S_{ea.ia^*})}{R_d} + 2Im(S_{ea.ia^*}).C_d\omega + \boldsymbol{S_i}\right) \qquad \text{Eq. 1}$$

Then it is easy to express S_i as in equation 2.

$$\boldsymbol{S_i(f)} = S_{v-meas}(f)\left(\frac{(R_d+R_{in})^2+(R_{in}R_dC_d\omega)^2}{G^2R_d^2}\right) - \frac{S_{ea}[1+(R_dC_d\omega)^2]}{R_d^2} - S_{ia} - \frac{2Re(S_{ea.ia^*})}{R_d} - 2Im(S_{ea.ia^*}).C_d\omega \qquad \text{Eq. 2}$$

where the noise voltage $S_{ea}(f)$ and the noise current $S_{ia}(f)$ spectral densities of the noise sources contributed by the transimpedance amplifier are correlated as $S_{ea.ia^*}=Re(S_{ea.ia^*})+j.Im(S_{ea.ia^*})$.

It can be noticed that the term in red from equation 1 (and equation 2) corrects the fraction of the current flowing to the DUT instead of the preamplifier (it vanishes if R_{in} is very low).

Finally different challenges must be considered simultaneously in order to be able to observe the frequency deviation from the accepted formulation of S_i derived from the d.c current $I+2I_s$.

1- The 1/f contribution should be negligible or easily corrected at low frequency. This is the reason why we were able to investigate only silicon devices. No GaAs diode has been found sufficiently rid of flicker noise in order to warrant the diffusion noise floor characterization.

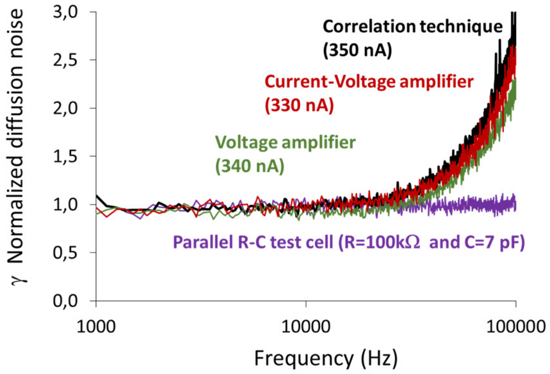
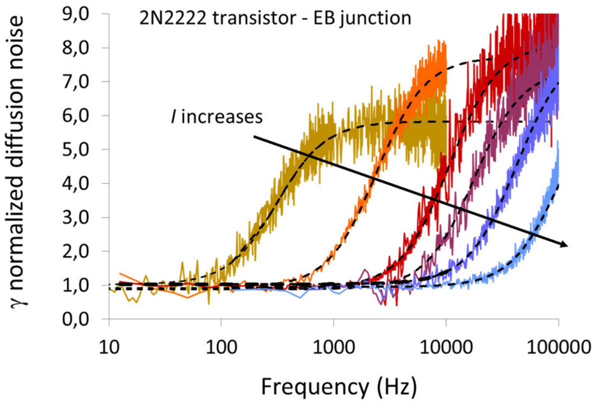


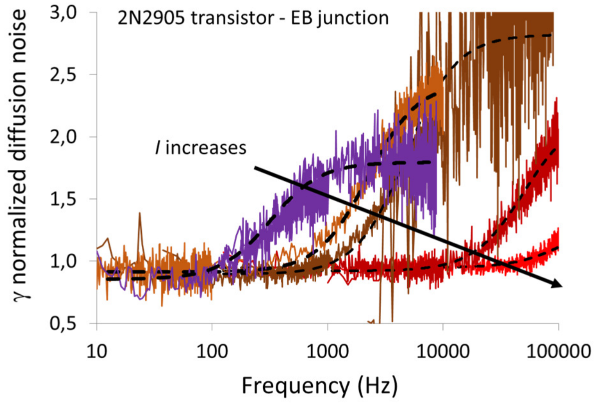
Fig. 3 : LFN spectra of the emitter-base junction of silicon 2N2222 device, making use of 3 different techniques (red transimpedance amplifier, green voltage amplifier, black correlation technique). Purple constant plot over the whole frequency band represent a calibration test with parallel RC discrete elements.

2- The low d.c biasing conditions at which the phenomenon appears implies low S_i noise current levels. Therefore high sensitivity and high gain are needed for the voltage-current preamplifier, at the cost of a reduced bandwidth. Low amplifier noise, that warrants accuracy, and wide frequency bandwidth cannot be achieved simultaneously (as a consequence of the well-known properties of any current amplifier), and tradeoff with various experimental conditions are developed and compared. Moreover, the selection of a high gain (and a high sensitivity that corresponds to a low noise current S_{ia}) is associated with an increase in the input impedance of the preamplifier EG&G 5182. This means that a lower fraction of the diode noise current is collected by the amplifier, but fortunately R_d also increases with I decreasing that makes the measurement still possible. It must be noticed that, even if the amplifier gain selection for the better accuracy over a given bandwidth at a given bias is always a challenge, it can nevertheless be handled (see the recovery of spectra obtained for different frequencies and gains in Figure 1). Figure 3 compares measurements performed with different preamplifier configurations (current amplifier, voltage amplifier and two current amplifiers for cross-correlation measurements) at a not too low current (in order to warrant voltage amplifier measurements) on the same device. Although the DUT noise deembedding from the measurements is very different for each technique, the final results are similar and demonstrate the same noise enhancement. Voltage amplifiers are not suitable for those measurements as the DUT impedance must remain much lower than that of the amplifier, and this is only achieved at elevated d.c current where the investigated phenomenon is no more present. Correlation technique has also been used with no noticeable improvement.

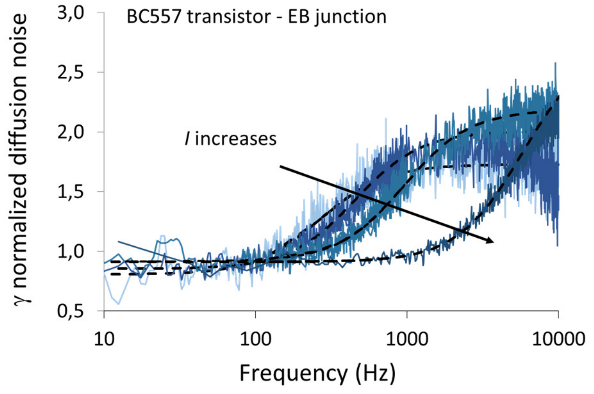
3- The impedances used in equation 1 and 2 must be accurately characterized versus frequency for each gain selection of the preamplifier (R_{in} and C_{in}) or d.c biasing of the DUT (R_d and C_d, obtained from impedance spectroscopy, see section III) in order to warrant a correct noise deembedding. Furthermore, noise of parallel *R-C* cells using discrete elements is measured as a test; resistance and capacitor values are chosen in the range of the measured diode R_d-C_d values. As expected, measured γ normalized values of the R-C cell are nearly equal to unity over all the measured bandwidth, as depicted in Figure 3 for a given *R-C* configuration. This last calibration test gives consistency to the measurements



a) 2N222 emitter-base junction biased at d.c current of 0.18 nA, 1.2 nA, 6 nA, 12 nA, 27 nA and 100 nA.



b) 2N2905 emitter-base junction biased at d.c current of 0.54 nA, 2.6 nA, 7,7 nA, 103 nA and 669 nA.



c) BC557 emitter-base junction biased at d.c current of 0.46 nA, 0.63 nA, 1.2 nA, and 6.2 nA.

Fig. 4 : γ normalized LFN diffusion noise for three different silicon diodes. Dotted lines represent the fitting model for the plateau magnitude and specific corner frequency extraction.

presented in Figure 1 and in Figure 4 where γ is reported versus frequency for three different silicon devices (and for various d.c current in Figure 4).

B. LFN deviation from diffusion noise floor

More than ten silicon devices have been investigated, with a special focus on many 2N2222, 2N2905 and BC557 devices.

Figure 4 plots the evolution of the γ values versus frequency, and for many d.c currents. Whatever the considered DUT, the same trend is observed: the corner frequency shifts towards higher frequencies when increasing d.c current. The plateau magnitude also increases with *I*, but then the frequency band limitation does not allow to develop any conclusions about the probable decrease of this plateau beyond a second frequency corner.

Similar trends on the variation of γ versus frequency have been observed for different technologies. Deviation from the unity expected value can be large (up to more than 10). As a result of this noise increase, significant errors can appear on CCD detector equipment's if this phenomenon is not properly accounted for. In the next section, a model is developed that correctly describes LFN measurements. Junction impedance spectroscopy is performed in order to substantiate this model.

III. BEHAVIOUR VERSUS D.C CURRENT

From the LFN spectra measurements, a model is proposed that fits all the measured noise spectra of the devices under test, as illustrated by the dotted line representation from Figure 4 a) b) c). This model is depicted in Figure 5: serial R_{add}-C_{add} elements are added to the conventional diode equivalent network in order to match both the LFN and impedance spectroscopy measurements. Moreover, the variation of these additional electrical elements with *I* shows similar features for the three devices under test as shown in Figure 6. An inversely proportional relation of R_{add} with *I* for all the tested devices suggests that R_{add} is closely related to the material, as for the main diode resistance R_d ($=nU_T/I$) in figure 5 (crosses in Figure 6).

The capacitances share the same behavior with the biasing d.c current in Figure 6 (in spite of a slightly higher value for the 2N2222 diode): once again, it must be mentioned that the LFN measurements have been performed over different frequency bands, still featuring the same increase from the conventional noise floor (diffusion noise).

Moreover, it must be noticed that R_{add} produces thermal noise in the proposed model. Thus R_{add}-C_{add} cannot be interpreted as a time constant or as a trap. Therefore, the spectral current noise $S_i(f)$ can be modelled by Equation 3:

$$S_i(f) = S_{id}(f) + \frac{(C_{add}\omega)^2 . Se_{add}}{(1+(R_{add}C_{add}\omega)^2)} \qquad \text{Eq. 3}$$

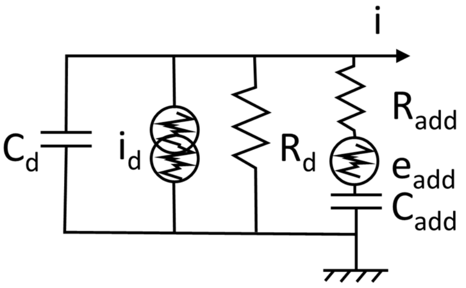


Fig. 5. Electrical representation of the diode (parallel R_d-C_d) with its shot noise current source (i_d) and with the low frequency noise enhancement (e_{add}) associated to the electrical cell (serial association R_{add} C_{add}).

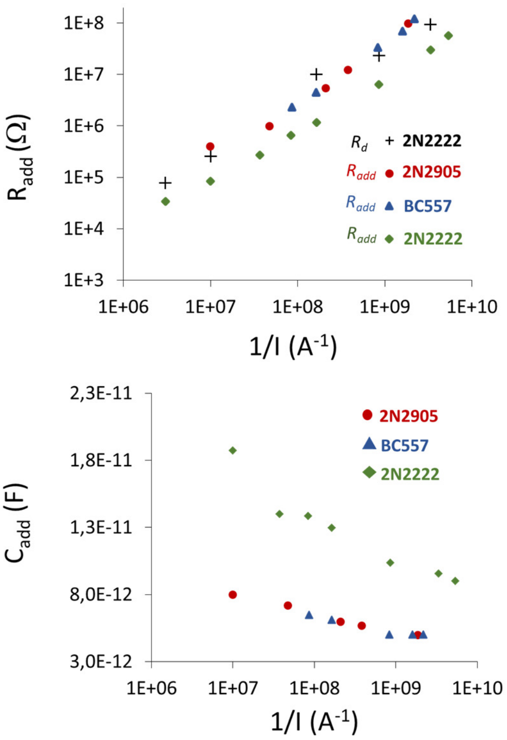


Fig. 6 : R_{add} C_{add} variations versus d.c current I for three silicon E-B diodes (from 2N222, 2N2905, BC557 transistors). The diode resistance R_d for the emitter-base diode of 2N222 is also reported for comparison (+).

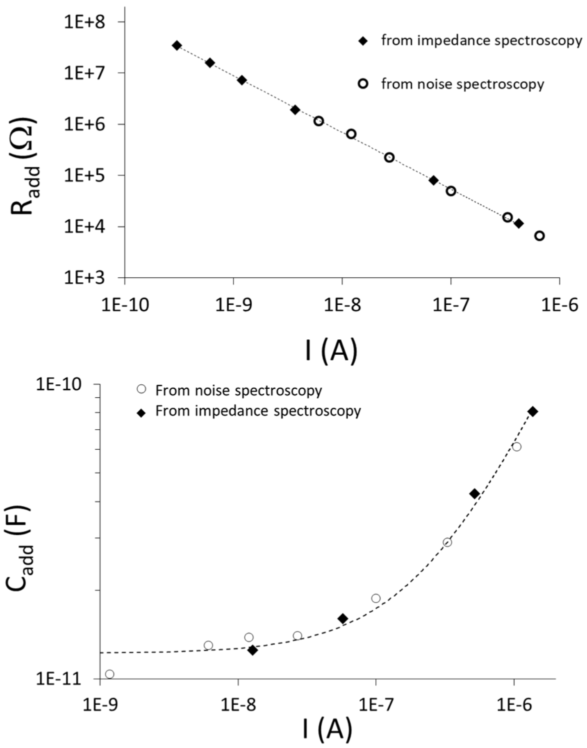


Fig. 7 : Comparison of R_{add} and C_{add} variation either derived from noise (data from Fig. 4) or from impedance spectroscopy data.

Figure 7 compares R_{add} and C_{add} versus I, either obtained from noise measurements or from impedance spectroscopy measurements, for the emitter-base diode of the 2N2222 transistor. Good agreement is found between the two techniques. It validates the proposed model of Figure 5 that can therefore be used to describe accurately the diffusion noise enhancement in silicon diodes, even if no data allows us to conclude about the higher frequency behavior (as a decrease of γ is expected!).

IV. CONCLUSIONS

In this paper, a deviation from the conventional diffusion noise theory has been evidenced below 1 MHz in various silicon junction devices operating below 1 µA. As the noise level under consideration is very low, its measurement needs special considerations that have been evoked in this paper. An electrical and noise model is proposed for this noise floor degradation. The model is well substantiated since elements provided by the diode impedance spectroscopy closely fit those obtained from noise data. This newly observed excess white noise can be of great impact on the noise floor of photodetectors considering that the dark current in silicon devices range between 0.001 and 100 nA, i.e. within the biasing range under concern in this study. However, some issues still need to be solved; if the excess diffusion noise grows up from a specific frequency, it should be expected to return to the conventional level above a second specific frequency. Despite sustained efforts, no experimental result has been obtained on this last point so far.

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