Micro-Hall devices: a tool for investigating process dependent noise sources in planar III–V heterostructure devices

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Abstract

We promote here the use of cross-shaped 4-terminal devices (Hall crosses) to measure LF noise spectra in planar technologies. The implementation of this method and its advantages over conventional methods are described. The method is then used to extract information on the energetic as well as spatial location of a trap in Metal-Insulator-Semiconductor P-HEMT hetero-structures. This method is also of special interest for the characterization of devices based on less-mature materials such as AlGaN/GaN or SiC, as it provides a robust, simple mean for performing noise spectroscopy.

INTRODUCTION

Low frequency noise (or "excess noise") is a parameter of paramount importance in compound semiconductor devices. First, it directly affects HF device performances due to non-linear up-conversion processes. But in addition, the low frequency (LF) noise spectrum also constitutes a signature of defects that may affect device performance or reliability. Thus, correctly identifying LF noise sources and their location may provide valuable information on process quality.

Unfortunately noise measurements are not easily performed at the wafer level in production environment [1]. Indeed, fluctuations known as "noise" are small as compared to the common-mode potential drop in a biased device. In order to suppress the deterministic common mode voltage due to biasing, it is customary to use either a Wheatstone bridge (differential measurement) or a dedicated electronic circuitry (single-ended measurement). In both cases, the determination of the true noise spectrum is not straightforward, due to both intrinsic and extrinsic reasons detailed below.

We promote here the use of cross-shaped 4-terminal devices (Hall crosses) to perform a differential measurement of LF noise spectra in planar devices.

Indeed, we show that, when investigating LF noise for the purpose of material or process characterization, such a procedure is by far superior to conventional differential noise measurements based on a Wheatstone bridge or single-ended measurements based on proprietary electronic circuitry.

As an example of application, we then use it to extract information on the energetic as well as spatial location of a trap in Metal-Insulator-Semiconductor PHEMT pseudomorphic heterostructures.

LF NOISE IN PLANAR 2DEG DEVICES

LF Noise Spectrum for Conductivity Fluctuation Noise

LF noise in semiconductor devices is known to be due to conductivity fluctuations [2]: the number of free carriers fluctuates, due to trapping/detrapping on localized levels located within a few kT from the Fermi level. As a side effect, the scattering processes (hence the mobility) may also fluctuate, but this effect is believed to be of 2nd order in most situations. These traps can be either interface traps, or bulk traps present in the whole cap layer or buffer layer. However, due to the fact that only traps energetically located a few kT around the Fermi level, and due to the presence of strong band bending and electric field in either the cap layer or buffer layer, even bulk traps active as noise generator are located in a thin slice a material (cf. Fig. 1).

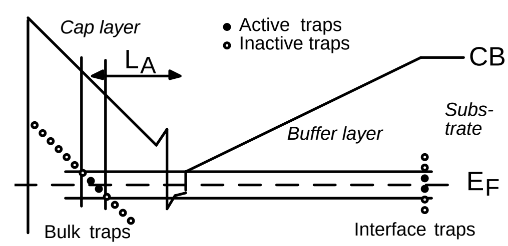

Figure 1. Band diagram of a P-HEMT-like planar device showing hypothetical bulk and interface traps. Only those in the vicinity of E_F are active.

Thus, for a discrete level with sheet density N_T, energy level E_T, mean generation-recombination time τ and occupancy described by the Fermi function $F = F(E_T) = 1/(1+g^{-1}\exp\frac{E_T - E_F}{kT})$, the level capacitance is $C_T = eN_T/kT \cdot F(1-F)$ and the time constant is $\tau = e_{n0}^{-1} \cdot \exp\frac{\Phi_B - E_T}{kT}(1-F)$. The active trap is located in a plane at a distance L_A from the 2D channel, so that the sheet capacitance between these 2 plates is equal to $C_A = \varepsilon_S / L_A$. Under these assumptions, the noise PSD has a Lorentzian behavior [3] which differs from the usual form by the term $(C_T + C_A)^2 / C_A^2$ in the denominator [2]:

$$S_V = \frac{1}{e^4 n_s^4 \mu_n^2} \frac{4kT \quad \tau \; C_T}{\left(\frac{C_T + C_A}{C_A}\right)^2 + \omega^2 \tau^2} \cdot G_N \cdot \frac{I_{DUT}^2}{W^2} \qquad (1)$$

Eq. (1) can be rearranged to yield:

$$S_V \propto S_T = \frac{C_T C_A}{C_A + C_T} \cdot \frac{\tau'}{1 + \omega^2 \tau'^2} \qquad (2)$$

where the apparent time constant τ' is related to the true time constant τ through $\tau' = C_A/(C_A + C_T)$. The geometrical factor G_N will be discussed later.

Standard Noise Measurement Methods

The standard setup used to measure LF noise spectra are either differential, based on a Wheatstone bridge (Fig. 2) or single-ended, based on proprietary electronic circuitry (see an example in Fig. 3). The set up configuration is driven by the need to subtract or filter out the DC common mode before amplifying and processing the noise signal [1].

In the Wheatstone Bridge configuration (Fig. 2), there is in principle no need for a low noise source (source in common mode) as long as the bridge is balanced, but practically the bridge balance is difficult to maintain in situations where the device impedance is varied by changing a gate or substrate voltage. Moreover, the voltage noise spectrum measured at the bridge output:

$$S_V^{bridge} = \frac{2R_B^{\,2}}{(R_B + R_{DUT})^2} S_V^{device} + \frac{R_{offset}^{\;2}}{(R_B + R_{DUT})^2} S_V^{source} \qquad (3)$$

is not a straightforward image of noise sources inside the channel. Even when the bridge is matched ($R_{offset} = 0$), the noise spectrum S_V^{device} contains components from the access and contacts regions.

In the single-ended configuration, the common mode has to be cancelled by using a counter voltage or current (as in Fig. 3) or by high pass filtering at the output. Of course excellent noise characteristics of the op amp and source are crucial for ensuring proper measurements, but anyway noise pickup from the environment is a critical point.

Canceling the DC common mode by a countervoltage is a critical issue when the DUT impedance is changing (due to gate bias or temperature ramping), whereas the spectral components under 10 to 100 Hz are lost when filtering out the DC component at the ouput using e.g. a large capacitor.

Noise Measurement using Cross-Shaped Devices

In the proposed method (Fig. 4), a cross-shaped symmetrical 4-terminal device is connected to a commercial current or voltage source and the transverse voltage is amplified by a low noise amplifier whose output is fed to a FFT analyzer. This method is characterized by the following features:

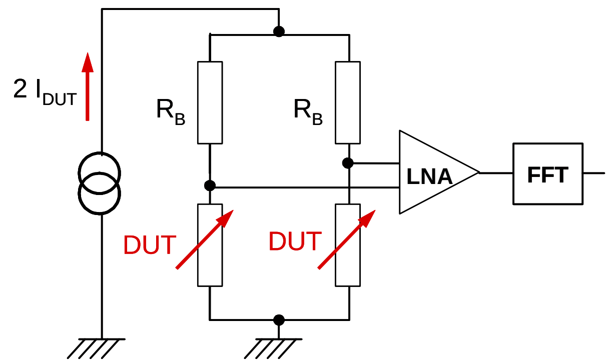

Figure 2. Differential measurement of the noise PSD of a 2-terminal device in a Wheatstone bridge configuration.

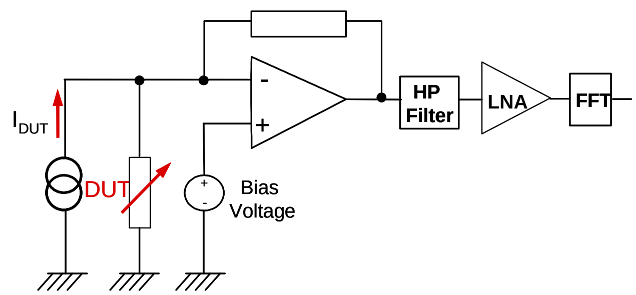

Figure 3. Single-ended measurement of the noise PSD of a 2-terminal device using a dedicated electronic circuitry.

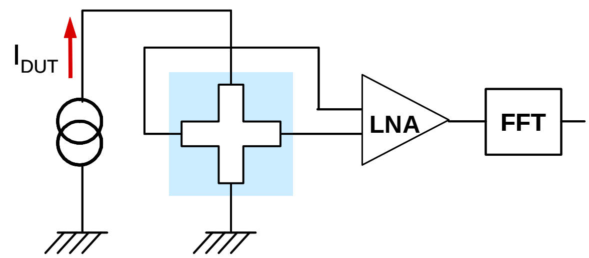

Figure 4. Differential measurement of the noise PSD using a cross-shaped device.

1. The observed noise originates from a small, well defined region of the channel at the intersection of the cross [4]. This brings two advantages:
   - One gets access to the direct noise spectrum of the channel, without any need for de-embedding from series resistance of access regions, nor parasitic contribution of contact noise or access region noise. This improvement over the bridge configuration is demonstrated in Fig. 5.
   - The noise is measured under well defined potential conditions, i.e. without spreading of emission activation energies that would be caused by the voltage drop in the channel.
2. A Hall cross forms by itself an intrinsic, perfectly balanced differential bridge, with following advantages:
   - The noise of the biasing source is fully rejected, since it is common mode. There is no need for a battery powered or extremely low-noise bias.
   - The bridge remains perfectly balanced when applying a gate or substrate voltage, or varying the temperature.

3. In addition, the area of the measurement loop can be made extremely small, in contrary to the case of a Wheatstone bridge using external resistors. This makes the measurement much less sensitive to electromagnetic perturbations (external noise), as seen in Fig. 6, where the ambient 50 Hz and harmonics is not seen in the Hall cross configuration.

The same constraints as for designing Hall effect devices are relevant for the design of devices relevant for noise investigations. As a rule of thumb, the aspect ratio L/W should be equal to at least 4, for avoiding parasitic conduction in the voltage probe contact. More details are given in Ref. [5].

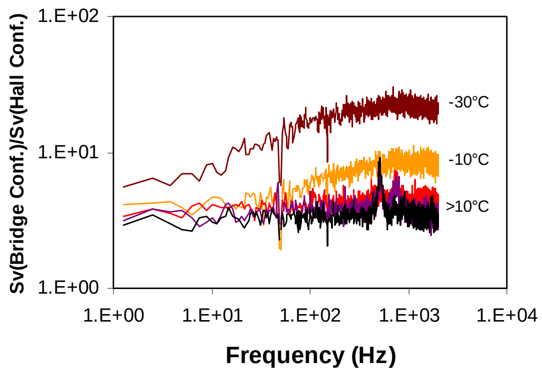

Figure 5. Ratio of the noise PSD of the same given device measured in the Wheatstone bridge and cross configuration. An additional noise contribution from the ohmic contact region perturbs the noise spectrum at low temperature in the former case, but not in the cross configuration.

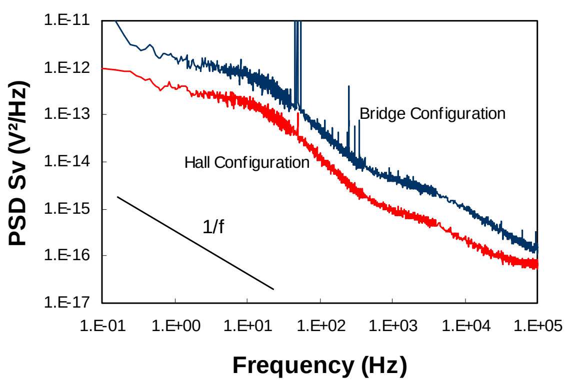

Figure 6. Comparison of the noise PSD of the same device measured either using 2 terminals in a Wheatstone bridge configuration or using all 4 terminals in the cross configuration.

TABLE I
GEOMETRIC FACTOR IN THE NOISE PSD.

Device type		Configuration; # of terminals	Geometrical factor G_N for noise PSD: General	Case L/W=4
Rectangular		Wh. bridge; 2T	L/W	4
Greek cross with sharp corners		Wh. bridge; 2T	L/W-0.5259	3.4741
		Cross; 4T	0.3248	0.3248
Greek cross with cut corners		Cross; 4T	0.12 to 0.3 depending on shape	

Quantitative exploitation of LF noise spectra

We recently showed [3] that the LF noise spectrum of any planar device can be in a very general way expressed as:

$$S_V = S_\rho \; G_N \; \frac{I_{DUT}^2}{W^2} \qquad (4)$$

In this equation, the term S_ρ is representative of the noise generating processes in the structure, and is fully independent of the bias, shape and size of the device. It may contain e.g. the Lorentzian spectral dependence due to a discrete trapping center. The term W denotes a characteristic length representative of the width of the active region. It would be the device width for a rectangular device, or the width of the cross arms for a Greek cross shaped device. The term I_{DUT}^2 / W^2 describes the bias and size dependence of the noise. Finally the term G_N denotes a geometrical factor which doesn't depend on the size, but is fully determined by the device type (2 or 4 terminals) and geometry. Apart from the trivial case of a rectangular bar, the geometric factor cannot be calculated by elementary methods, but has to be determined using e.g. Finite Elements calculations. General expressions of G_N in different cases have been given elsewhere [3]. Some useful values are given in Table I.

In addition, the mobility μ_n and channel carrier density n_S appearing in Eq. (1) or hidden in S_ρ in Eq. (4) can be directly obtained from Hall measurements in the same cross-shaped device. Knowing G_N, n_S and μ_n, the quantity defined as S_T in Eq. (2) can be calculated from the experimental spectra.

APPLICATION: NOISE SOURCE IN A PHEMT LIKE STRUCTURE

Gated Hall crosses can be used to vertically localize the traps responsible for the excess noise. Indeed, when applying a DC gate voltage, the variation of the channel electron density is a direct image of the variation of the electric field F_A in the cap layer. According to Gauss' theorem:

$$\delta F_A = e/\varepsilon_S \cdot \delta n_S \qquad (5)$$

and the change of the activation energy in the expression of the cutoff frequency is in first approximation given by

$$\delta \Phi_B = e/\varepsilon_S \cdot \delta n_S \cdot L_A . \qquad (6)$$

If the LF noise source is a defect located between channel and surface, its cutoff frequency will shift due to the related energy shift and hence its distance to the channel can be determined. Similarly a backside voltage will allow to probe defects underneath the channel.

This was probed with MIS-Hall crosses patterned using a standard process from heterostructures as shown in Fig. 7, with a Ti/Pt/Au gate deposited above the 200 nm thick silicon oxide passivation layer.

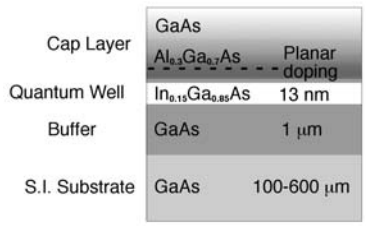

Figure 7. Pseudomorphic heterostructure used in the present study

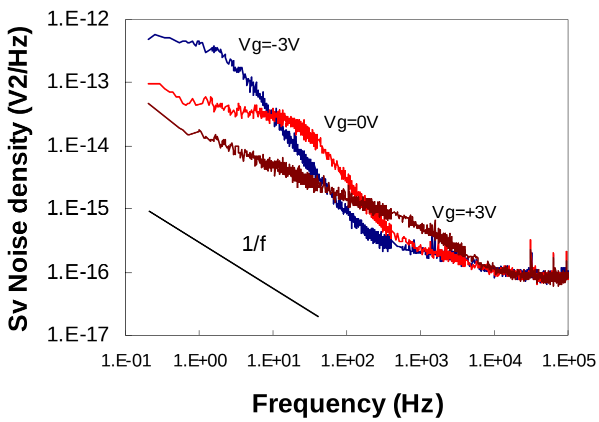

Figure 8. Evolution of the noise spectrum when varying the gate voltage in a cross-shaped MIS device. For the sake of clarity only 3 spectra were drawn.

The evolution of the noise spectrum when varying the gate voltage is shown in Fig. 8. It contains several Lorentzian contributions. Their behavior is highlighted by plotting $f.S_T(f)$, as in Fig. 9. The position of the maximum provides the cutoff frequency $f_c = 1/2\pi\ \tau$ whose evolution as a function of the electron density n_S in the channel (as measured by the Hall effect) is plotted in Fig. 10. The cutoff frequency of the slowest peak varies, as expected, exponentially with the channel electron density:

$$f_c \propto \exp(eL_A \delta n_S / \varepsilon_S kT) \qquad (7)$$

The distance between the related trap and the 2DEG is found to be 240 nm, i.e. the trap is located slightly below the semiconductor surface. This is in agreement with the activation energy of 760 meV found in thermally activated studies.

Conclusion

We propose a LF noise measurement method that is more robust, compact and straightforward to implement than standard methods. It is especially well-suited for the material and process characterization of planar devices such as FET and analog devices.

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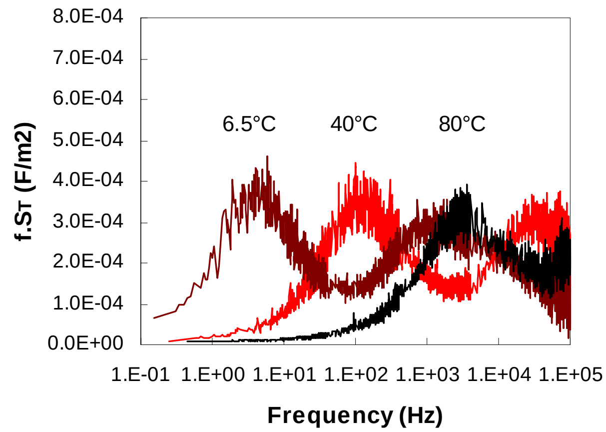

Figure 9. Evolution of the $f S_V$ noise spectrum with temperature in a cross-shaped MIS device, highlighting the individual Lorentzian contributions.

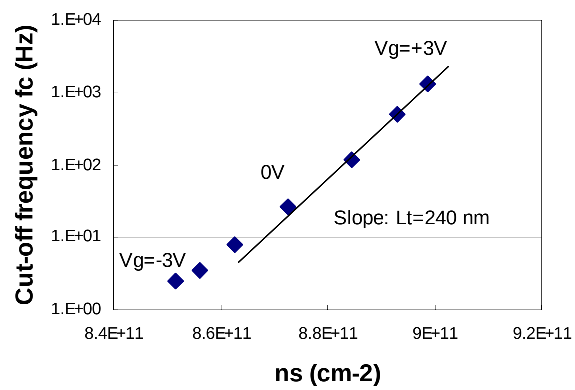

Figure 10. Drift of the cutoff frequency of the low-frequency peak in Fig. 9 as a function of the electron concentration in the channel. The slope provides the distance between the channel and the trap, according to Eq. (7).

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Acronyms

2DEG: 2-Dimensional Electron Gas
FET: Field-Effect Transistor
FFT: Fast Fourier Transform
LF: Low-Frequency
LNA: Low-Noise Amplifier
MIS: Metal-Insulator-Semiconductor
P-HEMT: Pseudomorphic High Electron Mobility Transistor
PSD: Power Spectral Density