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Effect of Schottky Barrier Alteration on the Low-Frequency Noise of InP-based HEMT's

Hans van Meer, Matteo Valenza, Koen van der Zanden, Walter De Raedt, Eddy Simoen, Dominique Schreurs, *Member, IEEE,* and Leon Kaufmann

***Abstract*—For the first time the effect of increasing the Schottky barrier's Al content of InP-based InAlAs–InGaAs HEMT's from 48 to 60% on the low-frequency (LF) drain and gate current noise is investigated. It is shown that the LF gate current noise $S_{I_G}(f)$ for the 60% case decreases by almost three decades, while the LF drain current noise $S_{I_{DS}}(f)$ stays at the same level. From small coherence values, it can be concluded that drain and gate noise sources can be treated separately which facilitates the LF noise modeling of these HEMT's.**

I. Introduction

Up to now, InAlAs/InGaAs high electron mobility transistors (HEMT's) grown on InP substrates have shown to be the best performing three terminal devices in terms of noise figures and gain at frequencies up to 100 GHz and above [1]. However, low-frequency (LF) noise in InP-based HEMT's has shown to be an important limitation of the device performance in nonlinear applications such as mixers and oscillators that suffer from noise up-conversion [2], [3]. This results in undesired amplitude and frequency modulation. Therefore, for the design of nonlinear monolithic microwave integrated circuits (MMIC's) it is desirable to model the LF noise of the HEMT. To obtain correct noise models, a detailed noise analysis has been performed on InAlAs–InGaAs HEMT's [4]–[6]. On the other hand, to improve the LF noise behavior of the HEMT, well selected technological parameters have to be optimized. In this paper, we concentrate on the influence of the Al content of the Schottky barrier layer while the Al content is altered from 48 to 60%. The effect on the LF drain and gate current noise has been examined. Furthermore, the coherence between drain and gate current noise sources has been investigated.

II. Experiment

In this work, two almost identical heterostructures are studied, both grown by MBE on semi-insulating 2-in InP substrates. The growth scheme is depicted in Fig. 1 which represents a conventional InAlAs/InGaAs layer sequence of an

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H. van Meer, K. van der Zanden, W. De Raedt, E. Simoen, and D. Schreurs are with the IMEC, B-3001 Leuven, Belgium.

M. Valenza is with the Centre d'Electronique et de Microoptoelectronique de Montpellier, Sciences et Techniques du Languedoc, 34095 Montpellier Cedex 5, France.

L. Kaufmann is with the Faculty of Electrical Engineering, Electronic Devices Group, COBRA Interuniversity Research Institute on Communication Technology, 5600 MB Eindhoven, The Netherlands.

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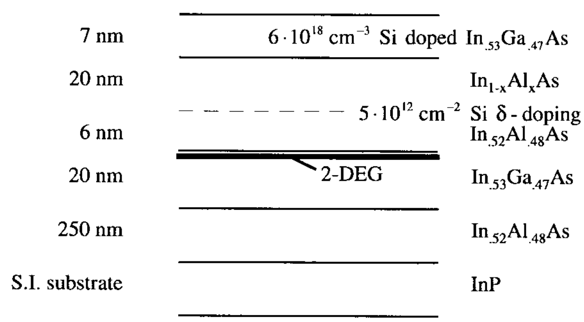


Fig. 1. InAlAs/InGaAs heterostructure with Si-doped cap, Si δ-doping and $In_{1-x}Al_xAs$ Schottky layer ($x = 48\%$ for structure I and $x = 60\%$ for structure II).

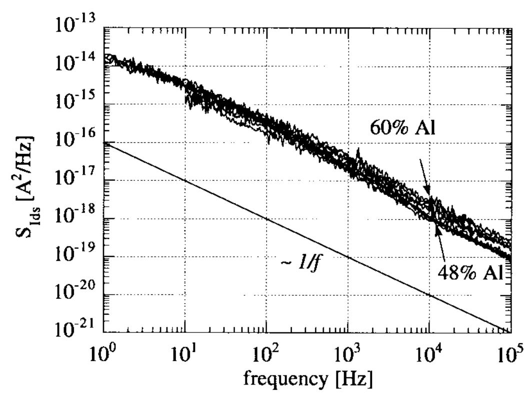
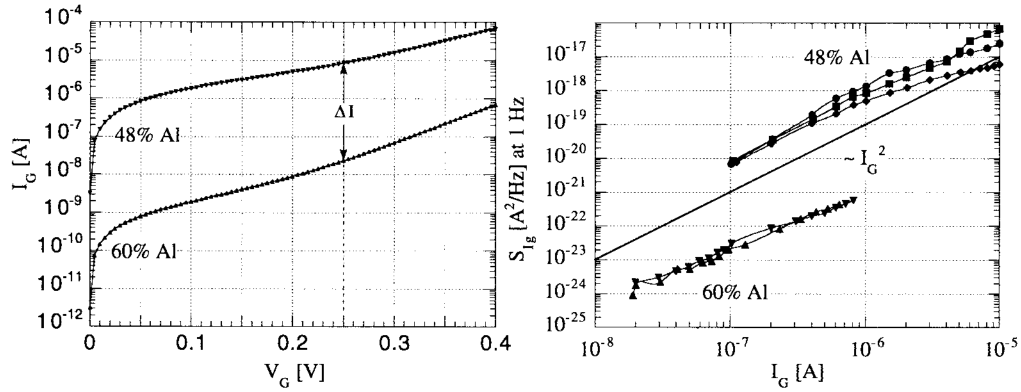


Fig. 2. Spectral drain current power densities of four HEMT's with 48% Al (structure I), respectively, 60% Al (structure II) in the Schottky barrier.

InP-based HEMT. The 20-nm $In_{0.52}Al_{0.48}As$ layer (structure I) can be grown lattice-matched on the Si δ-doping layer and will act as the Schottky barrier for the gate metal. For structure II, the Al content in the Schottky layer is increased to a content of 60% at which a 20-nm pseudomorphic $In_{0.40}Al_{0.60}As$ layer can be grown on top of the Si δ-doping layer. If higher Al contents are applied, disadvantageous effects occur like for example an indirect bandgap in the Schottky layer [7], more severe oxidation of Al and introducing dislocations when exceeding the critical thickness. The higher Al content yields an increase of the energy bandgap of approximately 0.15 eV, which results in a lower gate leakage current in the HEMT. Finally, for both structures a Si-doped $In_{0.53}Ga_{0.47}As$ cap layer is applied to facilitate the forming of ohmic contacts. At room



(a) (b)

Fig. 3. (a) I_G–V_G characteristics of Schottky gates with 48% Al (structure I) and 60% Al (structure II) in the Schottky barrier layer. The dc measurements have been carried out on HEMT's at $V_{DS} = 0$ V and (b) spectral gate current power densities at 1 Hz of a HEMT structure with 48% Al (structure I), respectively, 60% Al (structure II) in the Schottky barrier at $V_{DS} = 0$ V.

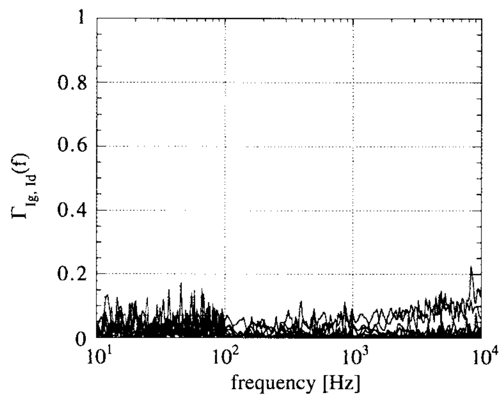


Fig. 4. Coherence measurements at several operation points within the region 50 mV ≤ V_{DS} ≤ 1.5 V and 0.12 ≤ V_G ≤ 0.52 where $V_G = V_{GS} - V_T$.

temperature these epitaxial sequences have a similar sheet resistance of 236 Ω/□ (structure I) and 229 Ω/□ (structure II) because the relevant layers (channel, spacer, and δ-doping) are kept constant for both structures. After mesa isolation, ohmic contacts (Ni–Au–Ge–Ni–Au) are applied and alloyed, followed by an interconnect metallization. Definition of the 0.2-μm T-shaped gates is done by e-beam exposure in a two-level resist with a high-dose single scan (footprint definition) and a low-dose rectangular exposure (top definition). Device processing is described in more detail in [8].

III. Results and Discussion

The measured LF drain current noise $S_{I_{DS}}(f)$ of both structures shows a similar gate voltage dependence as reported for example in [9]. The spectral drain current power densities of 4 HEMT's with 48 and 60% Al in the Schottky barrier are depicted in Fig. 2. The gate width (50 μm), drain bias (50 mV) and drain current (1 mA) are the same for both structures. From Fig. 2, it is obvious that no significant change with Al content appears in the LF drain current noise. In first order, only $1/f$ noise was measured in the accessible frequency range. The thermal noise will start to dominate well beyond 100 kHz, which follows from the theoretical value of $S_{I_{DS}}(f) = 4kT/R \approx 3.3 \cdot 10^{-22}$ A^2/Hz for the case shown in Fig. 2.

The dc I_G–V_G characteristics of the HEMT's at $V_{DS} = 0$ V are presented in Fig. 3(a). It can be shown that the ideality factor of the 60% Al containing structure (structure II) is lower than the one of structure I. For example, the ideality factor at $V_{GS} = 0.25$ V is 1.87 for structure II and 3.28 for structure I. Low-frequency gate current noise measurements have been performed on both HEMT's from 1 to 100 kHz, while drain and source contacts were short-circuited. The obtained spectra contained in first approximation, again, only $1/f$ noise. The applied gate voltages lie in the range of 10–270 mV for structure I and 240–400 mV for structure II. Fig. 3(b) shows the spectral gate current power densities at 1 Hz plotted versus I_G. Increasing the Al content to 60% not only decreases I_G considerably, but also reduces $S_{I_G}(f)$ by almost a factor 1000 for similar I_G. The former implies that the gate current shot noise $S_{I_G} = 2qI_G$ is also lower for structure II (60% Al), which is especially of importance at higher frequencies where $1/f$ noise is no longer dominant. In both structures, $S_{I_G}(f)$ is strongly dependent on the operating point [10] and in first approximation proportional to I_G^2 for gate currents from 10 μA down to 20 nA. At higher currents, a deviation of the I_G^2 dependence is observed for the 48% Al containing structure. A similar kind of behavior was observed earlier by Meva'a [11]. The I_G^2 dependence is attributed to the modulation of the barrier height Φ_B arising from fluctuations in the occupancy of traps distributed within the InAlAs layers. For higher currents, an $(I_G)^\gamma$ dependence is observed with $0 < \gamma < 2$ and is explained by the influence of the Schottky barrier's series resistance. Assuming that the LF barrier height fluctuations $\delta\Phi_B$ are caused by trap assisted tunnelling, in analogy with the case of thin silicon oxides [12], we interpret this significant reduction in LF gate current noise as being caused by a strong reduction of the density (or trap parameters) of the effective tunnelling defects. At the same time, the lower ideality factor of the 60% Al containing structure in the Schottky layer also contributes to the reduction of the LF gate current noise.

However, the total noise reduction cannot be explained by the lower ideality factor only [11].

If we measure the coherence

$$\Gamma_{I_G, I_{DS}}(f) = |S_{I_G}, I_{DS}(f)|^2 / [S_{I_G}(f) \cdot S_{I_{DS}}(f)]$$

where $S_{I_G, I_{DS}}(f)$ is the cross spectrum of the drain and gate current noise, at several gate bias points in the ohmic as well as in the saturation region between the LF drain and gate noise sources, we obtain the result of Fig. 4. These coherence measurements were performed on a 48% Al containing HEMT. The low value of the measured coherence indicates that the effect that the electrons which contribute to the channel current can hardly interfere with the electrons contributing to the gate current due to a good electron confinement in the channel of the InP-based HEMT. In addition, it can be stated that the gate and drain are electrically separated. A significant consequence that follows from Fig. 4 is that the LF gate noise sources can be treated separately from the drain noise sources due to this low coherence value. This facilitates the LF noise modeling considerably. From this we can model the LF noise in the HEMT at the drain and the gate side by placing a spectral current noise source parallel to the intrinsic current source as well as parallel to the gate and source contacts. This approach is valid as long as the input impedance of the gate remains negligibly small, which is the case in the linear and saturation regions in which the coherence measurements have been carried out.

IV. Conclusion

We have demonstrated that $S_{I_{DS}}(f)$ is independent on the Schottky layer composition. We have also shown that the spectral gate current power density $S_{I_G}(f)$ is in first approximation proportional to I_G^2 for a wide range of gate currents for Schottky layers containing 48–60% Al. The 60% Al containing structure has shown to produce almost three decades less gate current noise. Finally, from coherence measurements it can be concluded that the drain and gate LF noise sources can be treated separately, which is in agreement with our noise measurements and facilitates the LF noise modeling of these HEMT's.

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