An overview of low noise devices and associated circuits for 100-200 GHz space applications

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Abstract — This paper relates the state of the art of the HEMT low noise technologies for the space applications at millimeter wave and specially for the earth observation in the G-band (140 – 220 GHz). The different III-V technologies (HEMT and LNA) and their associated performance are presented. Parameters limiting the improvement of high frequency characteristics for HEMTs with the downscaling process are studied.

I. INTRODUCTION

MM-wave radiometer space applications like atmospheric sounding needs ultra low noise receivers in order to achieve an excellent radiometric sensitivity (brightness temperature resolution). One of these space applications is the Eumetsat \([1]\) Microwave Humidity Sounder (MHS) (see Fig. 1 photograph of the MHS Receiver built by ASTRIUM France). This instrument looks down into the atmosphere and scans the emitted radiation in various spectral bands (mainly in G-band) to determine the water vapor content or humidity profile of the atmosphere.

Table I shows the performance information for the MHS instrument. The radiometer performance is primarily driven by the radiometric sensitivity which expresses the capability to separate scene (or antenna) temperatures.

<table>
<thead>
<tr>
<th>channel</th>
<th>H1</th>
<th>H2</th>
<th>H3</th>
<th>H4</th>
<th>H5</th>
</tr>
</thead>
<tbody>
<tr>
<td>f(_l)</td>
<td>89</td>
<td>157</td>
<td>183.3</td>
<td>183.3</td>
<td>190.3</td>
</tr>
<tr>
<td>IF (GHz)</td>
<td>0.1 -</td>
<td>1.25</td>
<td>0.75 -</td>
<td>2.5 -</td>
<td>0.1 -</td>
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<td></td>
<td>1.25</td>
<td>1.25</td>
<td>3.5</td>
<td>1.1</td>
<td>0.57</td>
</tr>
<tr>
<td>Temperature sensitivity (K)</td>
<td>0.22</td>
<td>0.52</td>
<td>0.24</td>
<td>0.21</td>
<td>0.57</td>
</tr>
<tr>
<td>Specified DSB equivalent temperature (K)</td>
<td>&lt;920</td>
<td>&lt;1540</td>
<td>&lt;1582</td>
<td>&lt;1763</td>
<td>&lt;1763</td>
</tr>
</tbody>
</table>

TABLE I

THE PERFORMANCE INFORMATION FOR THE MHS INSTRUMENT

It is related to the noise nature of the useful signal after square-law detection:

\[
\Delta T = T_{sy} \sqrt{\frac{1}{B \tau} + \left(\frac{\Delta G}{G}\right)^2} \tag{1}
\]

where: \(T_{sy}\) is the System noise temperature, \(B\) is the RF pre-detection bandwidth, \(\tau\) is the video integration time and \(\Delta G/G\) is the short term overall gain stability.

In the Front Ends design two key performances are therefore to be optimised:
- The noise performance
- The gain stability performance.

Actually, most of the G-band (140 - 220 GHz) receivers are realized using hybrid circuits including Schottky diodes. Fig. 2 represents the state-of-the-art of the noise performance of diodes and SIS based receivers in the G-band. As shown in Fig. 2, the noise performance of the receivers using HEMT LNAs are comparable with uncooled sub-harmonic pumping (SHP) Schottky receivers. Why cannot HEMT-based-receivers get higher performance? We are trying to answer by presenting in a first part the different HEMT technologies and their associated performance. The main intrinsic and parasitic parameters of short gate length HEMTs are analyzed in the second part.
II. HEMT STRUCTURES AND THEIR ASSOCIATED PERFORMANCE FOR MILLIMETER WAVE APPLICATIONS

A. HEMTs structures

The indium phosphide (InP)-based HEMTs has demonstrated its high-speed potentialities for mm-wave applications. A standard layer structure (Fig. 3) is composed of a semi-insulating InP substrate followed by an InAlAs buffer layer, an InGaAs channel layer, an AlInAs spacer, a pulsed-doped donor layer, a Schottky barrier layer and finally an InGaAs cap layer. Using these indium compositions, both layers have same lattice parameter than the InP substrate (Fig. 4). Value of conduction band discontinuity $\Delta E_c$ is close to 0.5 eV and leads a 2DEG carrier density higher than $3 \times 10^{12}$ cm$^{-2}$. One way to improve the performance of HEMT on InP substrate consists to increase the Indium content in the channel that leads better transport properties.

On an other hand, metamorphic HEMTs (MM-HEMTs) using an $\text{In}_{x}\text{Al}_{1-x}\text{As}/\text{In}_{y}\text{Ga}_{1-y}\text{As}$ heterostructure grown on GaAs substrate constitute a good alternative to lattice-matched HEMTs. Compared to using InP substrates, the MHEMT technology is less expensive, taking advantage of the rapidlygrowing size of GaAs wafers, up to 6 inch today. Using the metamorphic concept, the indium content of unstrained heterostructure can be chosen in the range 0.33 – 0.6 and more for pseudomorphic heterostructure; recent results [2] (NF=2.1 dB, $G=13$ dB at 94 GHz) of high performance W-band LNAs have been obtained with an indium content of 80%.

B. InP-based HEMTs performance

Figure 5a shows the state of the art $f_t$ values of InP-based HEMTs versus the gate length while Fig. 5b represents the values of $f_{\text{max}}$, $f_{\text{max}}$ and $f_t$ are defined respectively as the transit frequency (i.e. the gain is equal to 0 dB) for Mason’s gain ($U$) and for the Current Gain ($|H_{21}|^2$). $f_t$ continues to increase with the downscaling process and values higher as 562 GHz is obtained in the case of the
70% indium content pseudomorphic heterostructure with a gate length of 25nm [3]. $f_{\text{max}}$ is also a very important criterion for low noise amplifiers and values close to 600 GHz is also obtained by the shortest gate length InP-based HEMTs. Contrary of $f_c$, $f_{\text{max}}$ presents a saturation effect versus the downscaling process (for $L_{g} \leq 100$ nm); the origins of this limitation will be discussed in the next paragraph. Fig. 6 represents the noise performance ($G_{\text{min}}$ versus $\text{NF}_{\text{min}}$) at 60 and 94 GHz of InP-based HEMTs. A value of 1.3 dB of $\text{NF}_{\text{min}}$ with and associated available gain of 8.2 dB at 94 GHz has been reported in [4] for a 100nm gate length pseudomorphic InP-based HEMT. No results of $\text{NF}_{\text{min}}$ in the G-band are reported in literature, simple extrapolation of these 94 GHz results should lead $\text{NF}_{\text{min}}$ close to 3 dB at 200 GHz that is very optimistic as compared to G-band LNA’s results (NF=5 dB at 155 GHz).

![Figure 6. State-of-the-art of the noise performance of InP-based HEMTs.](image)

**III. LIMITING PARAMETERS OF SHORT GATE LENGTH**

$f_{\text{max}}$ is one of the best criterion to compare the mm-wave performance of transistors, for both power and low noise applications. As shown in the approximated expression (2), $f_{\text{max}}$ depends on both extrinsic (access resistances, parasitic capacitances) and intrinsic parameters (gate transconductance, output conductance, intrinsic capacitances). We can also approximate the minimum noise figure as function of $f_{\text{max}}$ (equation 3); this approximated expression of $\text{NF}_{\text{min}}$ is enough accurate even in the mm-wave because $f_{\text{max}}$ includes all the intrinsic and extrinsic contributions.

$$f_{\text{max}} \approx f_c \sqrt{\frac{R_g + R_s + R_i}{g_d + g_m \frac{C_{\text{Miller}}}{C_{\text{gs}}}}}$$

$$NF_{\text{min}} = 1 + \frac{1}{f_{\text{max}}} \sqrt{P + PR - 2\sqrt{PR} + \left(1 + \frac{2}{f_c} \left(\frac{R_g + R_s + R_i}{f_c} \right)^2\right) g_m (R_g + R_s + R_i)}$$

where $P$, $R$ and $C$ are dimensionless Pucel’s noise parameters.

The improvements of $f_{\text{max}}$ by optimizing the HEMT structure and its associated technological processes, are very difficult and depend of several technological trade-offs. For the shortest gate length devices, the optimization window of $f_{\text{max}}$ is very narrow that allows a slowing down of the increase of $f_{\text{max}}$ versus the downscaling process (see Fig. 5b). Nevertheless, by considering the equation 2, it is possible to study the main dependences of $f_{\text{max}}$ which we can classify into three groups:

- The intrinsic elements $g_m$, $g_d$, $R_i$ and $f_c=g_m/2\pi C_{\text{gs}}$; this intrinsic cut-off frequency value keeps on following the conventional downscaling law. Consequently, this term is not a main limiting factor for $f_{\text{max}}$. A second term of equation (2) is the strong contribution of the access resistances $R_g$ (gate resistance) and $R_s$ (source resistance). These access resistances depend directly on the transistor topology; $R_g$ is linear as function of the total gate width while $R_s$ is inversely proportional. $R_s$ depends also on the number of gate fingers ($n_f$) connected in parallel and varies proportionally to $1/(n_f)^2$. Moreover $R_g$ and $R_s$ depend of the downscaling process. Indeed $R_s$ depends of several gate parameters (length, height, Mushroom width and shape, characteristic of the metal, width of the gate finger...). $R_g$ depends also of a lot of technological parameters (gate to source distance, thickness and doping of the cap layer, alloyed or non-alloyed ohmic contacts, sheet resistance of the Schottky layer...). We focus on the dependence of $R_g$ and $R_s$ versus the total gate width only, the minimum value of the sum $R_g + R_s$ (equation 2) is obtained for an optimal total gate width $W_{\text{top}}$.

$$W_{\text{top}} \approx \sqrt{\frac{3R_{m}}{R_m - R_s}} n_f$$

where $R_m$ is normalized source resistance ($\Omega$.mm), $R_s$ the normalized metallic gate resistance ($\Omega$mm) and $n_f$ the number of gate fingers.

An other main limiting parameter of the increase of $f_{\text{max}}$ is the ratio $C_{\text{gin}} / C_{\text{Miller}}$ (see equation 2) where $C_{\text{gin}} \sim C_{gs} + C_{pd}$ and $C_{\text{Miller}} \sim C_{gd} + C_{p} + C_{po}$ (symmetric source-gate-drain structure). $C_{gs}$ and $C_{gd}$ are the intrinsic charge control capacitances, $C_{p} + C_{po}$ is a parasitic capacitance distributed along the source and gate metallization (see figure 7); $C_{p}$ is assumed to be dependent with the finger width while $C_{po}$ (1-2 IF typical) is assumed to be independent. These parasitic capacitances are almost in parallel with the intrinsic capacitances $C_{gs}$ and $C_{gd}$ and directly contribute to the degradation of the mm-wave performance.

® SILVACO simulations show that these parasitic capacitances are mainly located between the cap layer region (if not depleted) and the bottom of the mushroom. Then the value of $C_{p}$ is strongly dependent of the gate foot height, the doping and thickness of the cap layer. For
a 6 × 10^{18} \text{cm}^{-2} \text{ doping cap layer with a thickness of 10 nm,}
this region is depleted due to the surface potential and the calculated value (® SILVACO) of \(C_p\) is close to 40 fF/mm. With a silicon nitride passivation, \(C_p\) increases to 170 fF/mm.

![Image](image_url)

**Fig. 7.** Photography (MEB) of the cross section of a 60 nm gate length LM-HEMT.

Using a simple calculation, Fig. 8 shows the variation of \(R_g + R_s\) and the \(C_{gs}/C_{Miller}\) versus the total gate width for a two fingers 70nm gate length LM-HEMT \(R_m = 480 \Omega \text{mm}, R_{so} = 0.35 \Omega \text{mm}, C_{gs} = 720 \text{fF/mm}, C_{gd} = 90 \text{fF/mm}, C_{p,\text{air}} = 40 \text{fF/mm and } C_{p,\text{Si3N4}} = 170 \text{fF/mm, } C_{po} = 1 \text{fF}.\) The minimum value of \(W_t\) is strongly related both to the increase of \(R_g + R_s\) and the decrease of the capacitance ratio. The maximum value of \(W_t\) is chosen to minimize the effect of the output conductance \(g_d\) (proportional to the gate width). For mm-wave applications with such device, the minimum value of the total gate width \(W_t\) is close to 70 µm while its maximum value is about 100 µm for a two fingers HEMT.

Otherwise some intrinsic parameters in equation 2 contribute to decrease \(f_{\text{max}}\). The intrinsic resistance \(R_r\) associated with \(C_{gs}\) in a conventional equivalent circuit, also should be influential on the decrease of \(f_{\text{max}}\). Physical based simulations and experimental results demonstrated that this resistance is inversely proportional to the intrinsic transconductance. Consequently, this intrinsic resistance cannot be, from theoretical point of view, a limitation to increase \(f_{\text{max}}\) along with the downscaling process of channel gate length. Finally, the increase of the output conductance \(g_d\) with the reduction of gate channel length is one of the well known short channel effect of FET devices. The origin of the increase of \(g_d\) is due to numerous parameters. Many solutions to improve the efficiency of the channel control by the gate have been proposed. One of them [5] consists to optimize the epilayer structure along the downscaling of the gate by reducing the thickness of Schottky, spacer and active layers to increase the aspect ratio. The window of such optimization for sub-70nm node is very narrow. Indeed the decrease of the EPI layers induces several parasitic effects (Tunnel conduction, modulation of the channel by the surface charges, direct injection into the buffer...).

**VI. CONCLUSION**

The key performance of a G-band receiver for atmospheric sounder applications is the low noise and high gain stability. Short gate length InP-based HEMTs are a good alternative to conventional Schottky-diodes-based down converters. Nevertheless the performance \((f_{\text{max}}, \text{gain}, T_{\text{min}})\) of InP-based HEMTs tend to saturate with the downscaling process. \(f_{\text{max}}\) is one of the best criteria to compare the microwave performance of transistors, for analog applications. The first limiting parameter of \(f_{\text{max}}\) is the access resistances, the second limiting parameter is the \(C_{gs}/C_{Miller}\) ratio and the third ones is the intrinsic output conductance \(g_d\). Solutions of optimization to improve the performance of both active and passive devices in G-band for the realization of MMIC will be presented.

This work is performed under ESA contract – TENDER AO/1-4060/01/NL/DC- “MMIC Technology for Future Atmospheric Sounders”.

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