Ultra-low noise HEMTs for high-impedance and low-frequency preamplifiers: realization and characterization from 4.2 K to 77 K

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Abstract. We report on the experimental results of specially designed HEMTs made at CNRS/LPN. These HEMTs, with a resistance input and different capacitance inputs, have been characterized from 4.2 K to 77 K with a power consumption of 100 µW. At 4.2 K, the lowest input noise voltage, 6 nV/Hz$^{1/2}$ at 1 Hz, has been obtained with the HEMT having the largest input capacitance; the lowest input noise current of about 3 aA/Hz$^{1/2}$ at 1 Hz has been observed with the HEMT with the smallest input capacitance; and the white noise voltage in these HEMTs is of about 0.2 nV/Hz$^{1/2}$. By increasing the temperature from 4.2 K to 77 K, noise voltage and noise current increase, but their values are limited within a factor of about 3 compared with their lowest values at 4.2 K. Our results show that the HEMT can be a promising transistor to fill the gap for FETs below 100 K for high-impedance and low-frequency readout electronics.

1. Introduction

High impedance ultra sensitive sensors operate at few tens of mK in order to avoid the thermal noise perturbation. High performance low-frequency readout electronics have been based for decades on Si JFETs. However, their operating temperature is limited to above about 100 K because of the charge freeze-out. Consequently, a long cable is required between readout electronics and sensors, which degrades the sensors intrinsic performance and the readout rate. From the intrinsic point of view, the charge freeze-out can be avoided by using a degenerate electron gas. Currently, there are two types of FETs available to operate at very low-temperature: MOSFETs and HEMTs. It is well known that the MOSFET suffers from the effects of an extremely high low-frequency noise due to the oxide layer between the metal gate and the active conducting channel [1].

The HEMT is based on a 2DEG (Two Dimensional Electron Gas), which is realized in a heterostructure with a high purity material interface. In particular at cryogenic conditions, high electron mobility can be obtained and it has been widely used for mesoscopic field-effect devices operating at tens of mK for quantum coherent electron transport investigations, as well as for the demonstration of a fully ballistic FET [2]. However, for cryogenic readout electronics, commercially available HEMTs are used in a frequency range above a few hundreds of kHz, and suffer a relatively high noise current and especially a large low-frequency noise or an 1/f noise. Based on our early investigations [3], one 1/f noise source in the HEMT at low temperature has been found out [4]. In this work, we show that specially designed HEMTs can reach unprecedented low noise values at low frequencies and deep cryogenic conditions [5].
2. Experiments

The HEMTs in this work are based on an AlGaAs/GaAs heterostructure grown by MBE (Molecular Beam Epitaxy). It consists of a GaAs buffer layer, a 20 nm AlGaAs spacer layer, a Si δ-doping layer, then a 15 nm undoped AlGaAs barrier layer, and finally a 6 nm undoped GaAs cap layer. At 4.2K, the 2DEG carrier concentration and mobility are $4.5 \times 10^{12}$ m$^{-2}$ and $29$ m$^2$V$^{-1}$s$^{-1}$, respectively. HEMTs with various gate lengths and gate widths are fabricated and individually packaged in ceramic SOT23 as shown in figure 1. In this work, experimental results are based on the HEMTs with three gate surfaces of $6.4\times10^4$, $2.0\times10^4$ and $2.0\times10^3$ µm$^2$, respectively.

Details of the characterization method can be found in [5]. As usual, a real FET is considered as a noiseless transistor with two noise sources in its input, i.e., the noise-voltage $e_n$ which is the lowest noise level of a FET, and the noise-current $i_n$ (see figure 1). With an input impedance $z$, $i_n$ induces a noise voltage $e_{ni} = i_n \times |z|$. In practice, only the equivalent total input noise voltage $e_{in}$ can be measured directly. By supposing that $e_n$ and $i_n$ are uncorrelated, $e_{in}$ can be expressed as:

$$e_{in} = \sqrt{e_n^2 + e_{ni}^2} = \sqrt{e_n^2 + i_n^2 z^2}.$$  

(1)

$e_n$ can be obtained with a sufficiently small input resistor $R_{input}$ or a large enough input capacitance $C_{input}$; $i_n$ can thus be grounded, and consequently $e_{ni} \ll e_n$, and $e_{in} = e_n$. The determination of $i_n$ needs an $|z|$ big enough to have $e_{in} > e_n$ and then $i_n$ can be deduced from:

$$i_n = \sqrt{e_{in}^2 - e_n^2} |z| = e_{in} |z|$$  

(2)

Figure 1. Fabricated HEMT, equivalent input noise voltage $e_{in}$, noise current $i_n$ and the common-source voltage amplifier at 4.2 K (in the frame with black dashed line) based on the HEMT, $R_{input} = 50$ Ω and $R_L = 300$ Ω for $e_{in}$ characterization.

A HEMT based common-source amplifier can be used to determine $e_n$ and $i_n$. For $e_n$ measurement, the HEMT, $R_{input} = 50$ Ω and the load resistance $R_L = 300$ Ω, are mounted in a cryogenic insert as illustrated in figure 1. Using a lock-in amplifier, the voltage gain $A_v$ and the output impedance or the channel impedance $R_C$ can be measured in-situ. The signal at the drain of the HEMT is amplified once more by a low-noise amplifier with a voltage gain $A_{v-amp}$. The output voltage noise spectrum $e_{measured}$ is recorded by a vector signal analyzer. The noise voltage spectrum at the drain $e_{drain}$ is deduced directly from $e_{measured}/A_{v-amp}$ and $e_n$ is obtained from $e_{drain}/A_v$. For $i_n$ characterization, to avoid the thermal noise perturbation, we use a $C_{input}$ common-source voltage amplifier as shown in figure 2. In this configuration, the effective voltage gain $A_{v-cap}$ cannot be measured directly due to the feedback effect induced by $C_{input}$, the gate-source capacitance $C_{gs}$, the gate-drain capacitance $C_{gd}$ and the Miller effect. The detail of the determination of $A_{v-cap}$ and $C_{total}$ is described in [5]. By neglecting the real resistance due to the gate leakage current, $|z|$ can be simply expressed as $(2\pi f C_{total})^{-1}$, where $f$ is the frequency. $i_n$
can be deduced from the results on the $R_{\text{input}}$ (see figure 1) and the $C_{\text{input}}$ (see figure 2) according to equation (2).

3. Results
We report measured $e_{\text{in}}$ at a chosen working point of $V_{\text{ds}} = 100$ mV and $I_{\text{ds}} = 1$ mA. This choice is in order to have sufficient large values of the transconductance $g_m$. Corresponded $C_{\text{gs}}$ under the chosen working point, according to the measurement method described in [5], are of about 92, 26.5 and 5.3 pF, respectively. Our experimental results show that $e_{\text{in}}$ is approximately inversely proportional to the square root of $C_{\text{gs}}$ [6]; on the other hand, using capacitance input measurement method, $i_{\text{n}}$ increases with the increase of $C_{\text{gs}}$. Therefore, both $e_{\text{in}}$ and $i_{\text{n}}$ must be taken into account for designing readout electronics.

3.1. HEMT with $C_{\text{gs}} = 92$ pF
We plot $e_{\text{in}}$ spectra in figure 3 with different input configurations at 4.2 K. At the chosen working point, $g_m$ and the output conductance $g_d$ are 35 mS and 0.75 mS, respectively. $e_{\text{in}}$ with 50 Ω input (see figure 1) and 1 nF input (see figure 2) show the lowest noise spectra. $e_{\text{in}}$ reaches a value of $6 \text{nV/Hz}^{1/2}$ at 1 Hz, and about 0.3 nV/Hz$^{1/2}$ at 1 kHz. The corner frequency (at which the $1/f$ noise value = the white noise value) is 1.2 kHz and the white noise is 0.22 nV/Hz$^{1/2}$ [5]. With the decrease of $C_{\text{input}}$ from 300 pF to 10 pF, $e_{\text{in}}$ increases and reaches its maximum value of about 20 nV/Hz$^{1/2}$ at 1 Hz. At 1 Hz, the highest input impedance equals about 1 GΩ with $C_{\text{input}} = 10$ pF and $C_{\text{total}} \approx 150$ pF [5]. We have $i_{\text{n}} \approx 19$ aA/Hz$^{1/2}$ at 1 Hz according to equation (2). It is interesting to notice that the maximum $e_{\text{in}}$ is about 3 times larger than $e_{\text{in}}$ at 1 Hz even $C_{\text{input}}$ being almost zero.

At 77 K, only $R_{\text{input}} = 50$ Ω and $C_{\text{input}} = 100$ pF are used for the noise characterizations, $e_{\text{in}}$ spectra are plotted in figure 4, in the same figure $e_{\text{in}}$ at 4.2 K are reported for comparison. At 77 K and 1 Hz, $e_{\text{in}}$ is around 20 nV/Hz$^{1/2}$ and $i_{\text{n}}$ (with $C_{\text{total}} \approx 240$ pF) can be estimated at 52 aA/Hz$^{1/2}$. Each $e_{\text{in}}$ component increases with the increase of temperature from 4.2 K to 77 K: $e_{\text{in}}$ and $i_{\text{n}}$ increase about three times.

![Figure 3. $e_{\text{in}}$ spectra of the HEMT with $C_{\text{gs}} = 92$ pF at 4.2 K, with different $C_{\text{input}}$ from 10 pF to 1 nF and $R_{\text{input}} = 50$ Ω.](image1)

![Figure 4. $e_{\text{in}}$ spectra of the HEMT with $C_{\text{gs}} = 92$ pF at 4.2 K and 77 K, with $C_{\text{input}} = 100$ pF and $R_{\text{input}} = 50$ Ω.](image2)

3.2. HEMT with $C_{\text{gs}} = 26.5$ pF
In Figure 5, we plot $e_{\text{in}}$ spectra of the HEMT with $C_{\text{gs}} = 26.5$ pF at 4.2 K with different $C_{\text{input}}$ and $R_{\text{input}}$. At the chosen working point, $g_m$ and $g_d$ are 110 mS and 1.3 mS, respectively. The input noise voltage $e_{\text{in}}$ is of about 15 nV/Hz$^{1/2}$ at 1 Hz and 0.54 nV/Hz$^{1/2}$ at 1 kHz. The corner frequency can be estimated at 13 kHz and the white noise is only 0.15 nV/Hz$^{1/2}$. Such a low white-noise value is owing to the high
$g_m$ value [5]. At 1 Hz with $C_{\text{input}} = 10$ pF, $e_{\text{in}}$ is around 30 nV/Hz$^{1/2}$ and $C_{\text{total}}$ is about 67 pF, the assessed $i_n$ is thus of about 10 aA/Hz$^{1/2}$. At 77 K, only $R_{\text{input}} = 50$ $\Omega$ is chosen for the noise characterizations, $e_m$ spectrum is plotted in figure 6, in the same figure $e_{\text{in}}$ at 4.2 K is reported for comparison. Again, $e_n$ increases about three times from 4.2 K to 77 K.

**Figure 5.** $e_{\text{in}}$ spectra of the HEMT with $C_{gs} = 26.5$ pF at 4.2 K, with $C_{\text{input}}$ from 10 to 47 pF and $R_{\text{input}} = 50$ $\Omega$.

**Figure 6.** $e_{\text{in}}$ spectra of the HEMT with $C_{gs} = 26.5$ pF at 4.2 K and 77 K, only with $R_{\text{input}} = 50$ $\Omega$.

3.3. **HEMT with $C_{gs} = 5.3$ pF**

In Figure 7, we plot $e_{\text{in}}$ spectra of the HEMT with $C_{gs} = 5.3$ pF at 4.2 K with different $C_{\text{input}}$ and $R_{\text{input}}$. At the chosen working point, $g_m$ and $g_d$ are 44 mS and 1.3 mS, respectively. The input noise voltage $e_{\text{in}}$ is of about 30 nV/Hz$^{1/2}$ at 1 Hz and 1.4 nV/Hz$^{1/2}$ at 1 kHz. The corner frequency can be estimated at 55 kHz and the white noise is 0.23 nV/Hz$^{1/2}$. By contrast, no significant increase of $e_{\text{in}}$ values can be found with $C_{\text{input}} = 5$ pF compared to $e_{\text{in}}$ obtained with $R_{\text{input}} = 50$ $\Omega$.

**Figure 7.** $e_{\text{in}}$ of the HEMT with $C_{gs} = 5.3$ pF at 4.2 K, with $C_{\text{input}}$ of 5 and 100 pF, and $R_{\text{input}} = 50$ $\Omega$.

**Figure 8.** $e_{\text{in}}$ of the HEMT with $C_{gs} = 5.3$ pF at 4.2 K and 77 K, with $C_{\text{input}} = 100$ pF and $R_{\text{input}} = 50$ $\Omega$. 
At 1 Hz with $C_{\text{input}} = 5$ pF, $e_{\text{nt}}$ can be estimated at 40 nV/Hz$^{1/2}$ and $C_{\text{total}}$ can be found of about 17 pF (its equivalent impedance at 1 Hz is 9.4 GΩ), the assessed $i_n$ is only 2.8 aA/Hz$^{1/2}$. Indeed, the 5.3 pF HEMT shows an extremely low $i_n$, however, its total input noise $e_{\text{nt}}$ is higher than that can be obtained with the 92 pF HEMT. Obviously, 5.3 pF HEMT is more favorable compared to 92 pF HEMT for increasing the operating frequency of the readout electronics.

In Fig. 8, we report $e_{\text{nt}}$ spectra with $R_{\text{input}} = 50$ Ω and $C_{\text{input}} = 100$ pF at 77 K and 4.2 K. Again, $e_{\text{nt}}$ increase of about three times from 4.2 K to 77 K. $e_{\text{nt}}$ remains almost the same with $C_{\text{input}} = 100$ pF and with $R_{\text{input}} = 50$ Ω at a given temperature. It is worthy to note that the input impedance at 1 Hz with $C_{\text{input}} = 100$ pF ($C_{\text{total}} = 112$ pF) is of about 1.4 GΩ. So, $e_{\text{nt}}$ is dominated by $e_n$, and the $i_n$ contribution is negligible even the input impedance is in the giga-ohm range.

The results of this work provide a useful basis to design HEMTs for each specific application, i.e., to find the best compromise between $e_n$ and $i_n$ at a chosen operating frequency.

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