Ultra-low noise HEMTs for deep cryogenic low-frequency and high-impedance readout electronics

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- Why cryoelectronics
- Why HEMT
- Noise characterization
- Previous results
- Input noise voltage
- Input noise current
- Noise and input capacitance
- Applications
- Conclusions and perspective
CNRS/LPN  (http://www.lpn.cnrs.fr)

one of the key national nanofabrication centers in France

Fabrication
Clean room : 1000m²

Molecular Beam Epitaxy  III-V : AlGaAs/GaAs, (Al,In)GaAs/GaAs, InGaAsP/InP

Lithography : e-beam nanolithography, Optical, Focused Ion Beam nanolithography

Etching : Ion Beam Etching, Reactive Ion Etching

Metal film deposition : Au, Ni, Co, Pt, Ti, W, Nb, Cr, Al …

Dielectric film deposition : Si, SiC, Si3N4, SiO2, Al2O3 …

Packaging : MCP, bonding

Analysis and e-transport characterization

Transmission Electron Microscopy, X ray microscopy, STM, AFM, Low temperature and high vacuum STM, dilution cryostat with magnetic field, Hall effect, I-V, C(V), Noise spectrum analyzer …
Why low-temperature electronics or cryoelectronics

For most ultra-sensitive detectors: low-temperature → low thermal noise

\[(4kT)^{1/2} \rightarrow 50\Omega: \text{at } 300K \leftrightarrow 910nV/\text{Hz}^{1/2}; \text{at } 4.2K \leftrightarrow 108nV/\text{Hz}^{1/2}; \text{at } 20mK \leftrightarrow 7.4nV/\text{Hz}^{1/2}\]

• **Currently:**

![Diagram of a high impedance Ge detector at 20 mK](image)

Readout electronics > 100 K

- High impedance Ge detector at 20 mK

**High performance cryoelectronics for high impedance readout electronics**

Low-temperature, low-power consumption and low-frequency noise

- High capacitance → limit time resolution
- Microphonic noise → limit the readable signal level
Why HEMT - comparison JFET, MOSFET and HEMT

gate // P-N
low 1/\textit{f} noise
non degenerate e^{-}
freeze-out at L.T
condition: T > 100K

gate // oxide layer
high 1/\textit{f} noise
degenerate e^{-}
no T limit

gate // large gap
1/\textit{f} noise ?
Degenerate e^{-}
no T limit

small band gap
δ doping
large band gap

δ doping

2DEG

S
G
D
n^+
in+
Noise characterization

Channel voltage PSD

\[ S_{v-drain} \]

Voltage gain

\[ A_v = \frac{\delta V_{out(ds)}}{\delta V_{in(gs)}} \]

Equivalent input voltage PSD

\[ e_{nt}^2 = \frac{S_{v-drain}}{A_v^2} \]

Channel effective impedance

\[ R_e = \frac{\delta V_{out}}{\delta I_{ds}} \]
**Total equivalent input noise voltage**

\[ e_{nt} = \sqrt{e_n^2 + e_{ni}^2} \]

**Noise current induced noise voltage**

\[ e_{ni} = \sqrt{e_{nt}^2 - e_n^2} \]

**Equivalent input noise current**

\[ i_n = e_{ni} / z \]
Previous results

- **Mesoscopic devices at few tens mK for quantum ballistic transport investigation**

- **Fully ballistic 1D FET**

- **Un of the 1/f noise sources in HEMTs at 4.2K: gate leakage current**

- **Input 1/f noise voltage in HEMTs at 4.2K ~ 1/(C_{gs})^{1/2}**

- **Input white noise voltage in HEMT at 4.2K ~ 2eF I_{ds}/(g_m)^2**
**Input noise voltage (92 pF)**

**Noise voltage**

HEMT with $C_{gs} = 92$ pF, $C_{gd} = 7.8$ pF

$I_{ds} = 1$ mA and $V_{ds} = 100$ mV

Gate Leakage current: $I_{gs} = -0.6$ aA

General: few tens of aA down to < 1 aA (aA=10^{-18} A)

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**Graph**

$e_n (V/\text{Hz}^{1/2})$

$e_n (V/\text{Hz}^{1/2})$ simulat. at 4.2 K

$e_{ni} = \sqrt{e_{ni}^2 + e_n^2} \approx e_n$

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**Noise voltage**

- 6.3 nV/Hz$^{1/2}$ at 1 Hz
- 2.1 nV/Hz$^{1/2}$ at 10 Hz
- 0.74 nV/Hz$^{1/2}$ at 100 Hz
- 0.32 nV/Hz$^{1/2}$ at 1 kHz
Input noise voltage: comparison

Noise voltage: comparison with Si JFET

InterFET JFETs at 300K
- NJ450L $C_{gs} = 100\,\text{pF}$
- NJ1800DL $C_{gs} = 160\,\text{pF}$

CNRS/LPN HEMT at 4K
- $C_{gs} \approx 92\,\text{pF}$
**Noise current**

HEMT with $C_{gs} = 92$ pF, $C_{gd} = 7.8$ pF  
$I_{ds} = 1$ mA and $V_{ds} = 100$ mV  
Gate Leakage current: $I_{gs} = -0.6$ aA  
Measured with different $C_{input}$

\[
\frac{e_{ni}}{Z} = \sqrt{e_{ni}^2 - e_n^2} / Z = i_n
\]

Noise current induced noise voltage with  
$C_{input} = 10$ pF at 1 Hz $\rightarrow$ 20 nV/Hz$^{1/2}$  
the total input capacitance  
$(C_{gs} + C_{input} + (1 + A_v)C_{gd}) \rightarrow 150$ pF $\leftrightarrow$ impedance  
of 1 GΩ  
$\Rightarrow$ 20 aA/Hz$^{1/2}$ at 1 Hz
**Input noise charge (92 pF)**

**Equivalent Noise Charge**

HEMT with $C_{gs} = 92$ pF, $C_{gd} = 7.8$ pF

$I_{ds} = 1$ mA and $V_{ds} = 100$ mV

Gate Leakage current: $I_{gs} = -0.6$ aA

Measured with different $C_{input}$

\[
\text{ene} = e_{nt} \left[ C_{in} + C_{gs} + (1 + A_{v})C_{gd} \right]
\]

Equivalent noise charge with $C_{input} = 10$ pF

- $5$ e/Hz$^{1/2}$ at $10$ Hz
- $0.5$ e/Hz$^{1/2}$ at $1$ kHz
### Input noise voltage at 4.2 K and gate configurations

(with $I_{ds}=1\text{mA}$, $V_{ds}=100\text{mV}$)

<table>
<thead>
<tr>
<th>Gate surface</th>
<th>For Ge detector</th>
<th>For microcalorimeter</th>
<th>For mesoscopic sys.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gate surface</td>
<td>$6.4\times10^4\mu\text{m}^2$</td>
<td>$2.0\times10^4\mu\text{m}^2$</td>
<td>$2.0\times10^3\mu\text{m}^2$</td>
</tr>
<tr>
<td>$g_m$ (mS)</td>
<td>35</td>
<td>110</td>
<td>44</td>
</tr>
<tr>
<td>$g_d$ (mS)</td>
<td>0.75</td>
<td>1.27</td>
<td>1.27</td>
</tr>
<tr>
<td>$A_v$</td>
<td>8.7</td>
<td>23</td>
<td>10</td>
</tr>
<tr>
<td>$e_{n-1/f}$ (nV/Hz$^{1/2}$)</td>
<td>$6.3 @1\text{Hz}$</td>
<td>$12 @1\text{Hz}$</td>
<td>$30 @1\text{Hz}$</td>
</tr>
<tr>
<td></td>
<td>$2.1 @10\text{Hz}$</td>
<td>$4.5 @10\text{Hz}$</td>
<td>$11.7 @10\text{Hz}$</td>
</tr>
<tr>
<td></td>
<td>$0.73 @100\text{Hz}$</td>
<td>$1.5 @100\text{Hz}$</td>
<td>$4 @100\text{Hz}$</td>
</tr>
<tr>
<td></td>
<td>$0.32 @1\text{kHz}$</td>
<td>$0.54 @1\text{kHz}$</td>
<td>$1.4 @1\text{kHz}$</td>
</tr>
<tr>
<td>$e_{n-white}$ (nV/Hz$^{1/2}$)</td>
<td>0.22</td>
<td>0.15</td>
<td>0.23</td>
</tr>
</tbody>
</table>

\[
e_{n-1/f} \sim \frac{1}{(C_{gs})^{1/2}}
\]
**Input noise current at 4.2 K and gate configurations**

(with \( I_{ds}=1\text{mA}, V_{ds}=100\text{mV} \))

<table>
<thead>
<tr>
<th>Gate surface</th>
<th>For Ge detector 6.4x10^4(\mu)m(^2)</th>
<th>For microcalorimeter 2.0x10^4(\mu)m(^2)</th>
<th>For mesoscopic sys. 2.0x10^3(\mu)m(^2)</th>
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<td>0.75</td>
<td>1.27</td>
<td>1.27</td>
</tr>
<tr>
<td>( C_{input} ) (pF)</td>
<td>10</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>( A_v\text{-capa} )</td>
<td>5.36 @( C_{input} = 10)pF</td>
<td>7.3 @( C_{input} = 10)pF</td>
<td>5.1 @( C_{input} = 5)pF</td>
</tr>
<tr>
<td>( C_{gs} ) (pF)</td>
<td>92</td>
<td>26.5</td>
<td>5.3</td>
</tr>
<tr>
<td>( C_{gd} ) (pF)</td>
<td>7.8</td>
<td>3.7</td>
<td>1.1</td>
</tr>
<tr>
<td>( C_{total} ) (pF)</td>
<td>152</td>
<td>67</td>
<td>17</td>
</tr>
<tr>
<td>((2\pi f C_{total})^{-1} )@1Hz ((\Omega))</td>
<td>1.0x10^9</td>
<td>2.4x10^9</td>
<td>16x10^9</td>
</tr>
<tr>
<td>( i_n ) (aA/Hz(^{1/2}))</td>
<td>20 @1Hz</td>
<td>6.7 @1Hz</td>
<td>3.7 @1Hz</td>
</tr>
<tr>
<td></td>
<td>34 @10Hz</td>
<td>21 @10Hz</td>
<td>11 @10Hz</td>
</tr>
<tr>
<td></td>
<td>105 @100Hz</td>
<td>67 @100Hz</td>
<td>34 @100Hz</td>
</tr>
<tr>
<td></td>
<td>334 @1kHz</td>
<td>209 @1kHz</td>
<td>100 @1kHz</td>
</tr>
<tr>
<td>( e_{ni} ) (nV/Hz(^{1/2})) @1Hz ((\Omega))</td>
<td>20</td>
<td>16</td>
<td>59</td>
</tr>
</tbody>
</table>

\[ i_{n-1/f} \sim (C_{gs})^{1/2} \]
# Applications

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<td>92pF</td>
<td>26 pF</td>
<td>5.3 pF</td>
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For Ge detectors in dark matter search:

**SuperCDMS collaboration:** [http://cdms.berkeley.edu/cdms_collab.html](http://cdms.berkeley.edu/cdms_collab.html)

**EDELWEISS collaboration:** see poster by C. Nones

For microcalorimeter: presentation by X. de la Broïse

For mesoscopic sys.: presentation by A. Anthore for the work on *Quantum Limit of Heat Flow Across a Single Electronic Channel*

Published online 3 October 2013 [DOI:10.1126/science.1241912]

For power below 100μW down to 1nW: see poster by Q. Dong
Conclusions and perspectives
- Specially designed and fabricated HEMTs at or below 4.2 K can replace Si JFETs with a better noise (current) performance
- $1/f$ noise voltage can be reduced by increasing $C_{gs}$
- $1/f$ noise current can be decreased by reduce $C_{gs}$
- White noise below 0.1 nV/$\sqrt{\text{Hz}}$ can be expected
- High impedance cryogenic detectors, FIR, THz, Nuclear Phy. ...

Acknowledgements
This work was supported in part by the Réseau RENATECH, "le RTRA Triangle de la Physique" grants No. 2008-015T and No. 2009-004T and European FP7 space project CESAR grant No. 263455. Q. D. is funded by the BDI CNRS/CEA.
Noise voltage evolution with temperature

Experimental observation

\[ T \rightarrow e_{n-1/f} \]

\[ T \rightarrow e_{n-white} \]