Ultra-low noise and low-temperature readout electronics $f<1\text{GHz}$ based on cryoHEMTs made at C2N (formerly LPN): performance and applications

Y. Jin, Q. Dong, L. Couraud, A. Cavanna, U. Gennser, C. Ulysse, E. Cambril

C2N, CNRS, Univ. Paris-sud, Univ. Paris-Saclay, Marcoussis, France

moving to:

C2N, CNRS, Univ. Paris-sud, Univ. Paris-Saclay, Palaiseau, France
Outline

- Introduction
  
  Motivation
  
  Low temperature and low noise vs FETs
  
  From HEMT to cryoHEMT

- Performance
  
  Noise voltage: sub-nV/$\sqrt{Hz}$
  
  Noise current: aA/$\sqrt{Hz}$

- Applications

- Conclusions and further developments
Why low-temperature electronics and the challenge 1/2

- For most ultra-sensitive detectors: low-temperature → low thermal noise
  
  \[(4kT_R)^{1/2} \rightarrow 50\Omega: \text{at } 300K \Leftrightarrow 910\text{nV/Hz}^{1/2}; \text{at } 30\text{mK} \Leftrightarrow 9.1\text{nV/Hz}^{1/2}\]

- Due to the long cable:
  - High capacitance → slow down the data acquisition rate
  - Microphonic noise
  - Triboelectricity
  - Capacitive coupling → degrade the intrinsic detectors’ performance

- High performance electronics for high-impedance cryogenic readout electronics
- Low temperature, low power and low-frequency noise

CDMS
Cryogenic Dark Matter Search
weakly interacting massive particle: WIMP

High impedance Ge detector at 20 mK

\[\text{Readout electronics at 150 K}\]
Why low-temperature electronics and the challenge 2/2

Present Low Noise Electronics & Operating Conditions

<table>
<thead>
<tr>
<th>Condition</th>
<th>Low Frequency</th>
<th>High Frequency</th>
<th>High Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low Impedance</td>
<td>High Impedance</td>
<td>Low Impedance</td>
</tr>
<tr>
<td>Room Temperature</td>
<td>HEMTs</td>
<td>JFETs</td>
<td>HEMTs</td>
</tr>
<tr>
<td>BJTs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low Temperature</td>
<td>HEMTs</td>
<td></td>
<td>HEMTs</td>
</tr>
<tr>
<td>(T &lt; 100 K)</td>
<td>$f \geq$ MHz</td>
<td>$f &gt; 1$ GHz</td>
<td></td>
</tr>
</tbody>
</table>

The challenge is to fill the above gap:

High performance electronics for high-impedance cryogenic readout electronics
Low temperature, low power and low-frequency noise
Low temperature (LT) and low-frequency (LF) noise vs FETs

- comparison JFET, MOSFET and HEMT

- non degenerate e-freze-out at LT
  - limit: T>100K
  - gate // P-N
  - low 1/f noise

- degenerate e-
  - no LT limit
  - gate // oxide layer
  - high 1/f noise

small band gap

large band gap

δ doping

1/f noise?
From HEMT to cryoHEMT

During a long period:
The input noise voltage > 1 nV/√Hz @ 1kHz and 4.2 K
From HEMT to cryoHEMT

More than 10 years collective efforts for optimizing:

**Heterostructures by Molecular Beam Epitaxy:**
A. Cavanna; U. Gennser  
several tens of heterostructures tested

**Ohmic and Schottky contacts:**
L. Couraud, L. Leroy, A. Durnez, C. Ulysse

**EBL (Electron Beam Lithography) and IBE (Ion Beam Etching):**
E. Cambril, S. Guilet  
several thousands of HEMTs with 4 to 6 steps of EBL

**Characterization and simulation:**
Q. Dong (PhD & Postdoc since 2009),  
YX. Liang (Postdoc 2007-2012), E. Grémion (PhD 2005-2008),  
M.C. Cheng, Clarkson Univ. NY (visiting scientist 2007)  
several hundreds transistors measured from 300 K to 4.2 K
From HEMT to cryoHEMT

The breakthrough was achieved in 2012 and since then: the input noise voltage can be « 1 nV/√Hz @ 1kHz and 4.2 K
Outline

- Introduction
  Motivation
  Low temperature and low noise vs FETs
  From HEMT to cryoHEMT

- Performance
  Noise voltage: sub-nV/$\sqrt{Hz}$
  Noise current: aA/$\sqrt{Hz}$

- Applications

- Conclusions and further developments
Characterization: Noise voltage & noise current

Directly measurable parameters:

Channel voltage PSD
\[ S_{v-drain} \]  
(Power Spectral Density)

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

Deduced parameters:

Equivalent input voltage PSD
\[ e_{nt} = \sqrt{e_n^2 + e_{ni}^2} \]

Total equivalent input noise voltage
\[ e_{nt} = \sqrt{e_n^2 + e_{ni}^2} \]

Input noise voltage (with R input)
when \( e_{ni} \ll e_n \)
\[ e_n = e_{nt} \]

Input noise current (with R & C input)
\[ i_n = \sqrt{e_{nt}^2 - e_n^2} / |z| = e_{ni} / |z| \]

\[ \text{4.6 pF cryoHEMT} \]

\[ \text{Appl. Phys. Lett. 105, 013504 (2014)} \]
**Characterization: Noise voltage & noise current**

Directly measurable parameters:

Channel voltage PSD

\[ S_{\text{v-drain}} \]

(Power Spectral Density)

Voltage gain

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

Deduced parameters:

Equivalent input voltage PSD

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

Total equivalent input noise voltage

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

Input noise voltage (with R input)

when \( e_{ni} \ll e_n \)

\[ e_n = e_{nt} \]

Input noise current (with R & C input)

\[ i_n = \sqrt{e_{nt}^2 - e_n^2} / |z| = e_{ni} / |z| \]

Characterization: Noise voltage & noise current

Directly measurable parameters:
- Channel voltage PSD $S_{v\text{-}drain}$
- Voltage gain $A_v = \delta V_{out(ds)}/\delta V_{in(gs)}$

Deduced parameters:
- Equivalent input voltage PSD $e_{nt}^2 = S_{v\text{-}drain}/A_v^2$
- Total equivalent input noise voltage $e_{nt} = \sqrt{e_n^2 + e_{ni}^2}$
- Input noise voltage (with R input) when $e_{ni} \ll e_n$
  $e_n = e_{nt}$
- Input noise current (with R & C input)
  $i_n = \sqrt{e_{nt}^2 - e_n^2/|z|} = e_{ni}/|z|$

Characterization: noise current measurement

Comparison of capacitor and resistor input

Noise current induced noise voltage

With two different $C_{\text{input}}$

The deduced noise current
**Characterization: gate leakage current measurement**

Using a follower configuration, the gate leakage current can be deduced by measuring the variation of the source voltage

For the working point

\[ V_{ds} = 100 \text{ mV}, \quad I_{ds} = 1 \text{ mA} \]
\[ V_{gs} = -90 \text{ mV} \]

Using \( C_{\text{input}} \) setup,

- \( C_{\text{input}} = 5 \text{ pF} \)
- \( \delta V_{\text{input}} = \delta V_s = 0.5 \text{ mV} \)
- \( \delta t = 480 \text{ s} \)

\[ I_{gs} = \frac{\delta V_{\text{input}}}{\delta t} \approx 5.2 \text{ aA!} \]

Input impedance \( V_{gs}/I_{gs} \approx 17 \text{ P}\Omega! \)

Understanding (1/3): noise voltage spectrum compositions

Noise voltage spectrum = 1/f noise + white noise

PSD: Power Spectrum Density

Noise voltage PSD:

1/f noise component:

White noise component:

\[ e_{n-1/f}^2 = 4.0 \times 10^{-17} / f^{0.95} \]

\[ e_{n-white}^2 = 4.8 \times 10^{-20} \]

APL 105, 013504 (2014)
Understanding (2/3): input 1/f noise voltage

Input noise voltage $e_n$ vs. gate capacitance $C_{gs}$

fundamental of the 1/f noise voltage in field-effect devices: standard deviation of the average value $\langle N \rangle$ in an open system $N$ (grand canonical ensemble) - central limit theorems
Reduced thermal shot noise

\[ e_{n-white}^2 \approx \frac{F 2eI_{ds}^2}{g_m^2} \]

\textbf{F: Fano factor which depends on the gate length}

\textit{APL} 105, 013504 (2014)
Performance: Input noises vs. gate capacitance $C_{gs}$

Noise voltage $e_n$, Total noise voltage $e_{nt}$, Noise current $i_n$ (at 4.2 K)

<table>
<thead>
<tr>
<th>$L_g W$ ($\mu m^2$)</th>
<th>$1.5 \times 10^5$</th>
<th>$6.4 \times 10^4$</th>
<th>$2.0 \times 10^4$</th>
<th>$2.0 \times 10^3$</th>
<th>$4.0 \times 10^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{gs}$ (pF); $C_{gd}$ (pF)</td>
<td>236; 8.9</td>
<td>103; 8.9</td>
<td><strong>33; 3.5</strong></td>
<td><strong>4.6; 1.0</strong></td>
<td>1.8; ~0.6</td>
</tr>
<tr>
<td>$V_{ds}$ (mV); $I_{ds}$ (mA)</td>
<td>100; 1.0</td>
<td>100; 1.0</td>
<td>100; 1.0</td>
<td>100; 1.0</td>
<td>100; 0.5</td>
</tr>
<tr>
<td>$g_m$ (mS); $g_d$ (mS)</td>
<td>52; 0.4</td>
<td>40; 1.2</td>
<td>115; 1.3</td>
<td>44; 1.3</td>
<td>15; 0.8</td>
</tr>
<tr>
<td>$f_t = g_m/(2\pi C_{gs})$ (Hz)</td>
<td>$3.5 \times 10^7$</td>
<td>$6.2 \times 10^7$</td>
<td>$5.5 \times 10^8$</td>
<td>$1.5 \times 10^9$</td>
<td>$1.3 \times 10^9$</td>
</tr>
<tr>
<td>$e_n$ (nV/Hz$^{1/2}$)</td>
<td>@1Hz 5.4</td>
<td>6.3</td>
<td>14</td>
<td>30</td>
<td>100</td>
</tr>
<tr>
<td>@10Hz 1.7</td>
<td>2.1</td>
<td>4.5</td>
<td>12</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>@100Hz 0.52</td>
<td>0.76</td>
<td>1.5</td>
<td>4.5</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>@1kHz 0.24</td>
<td>0.34</td>
<td>0.57</td>
<td>1.4</td>
<td>2.7</td>
<td></td>
</tr>
<tr>
<td>$e_{n-white}$ (nV/Hz$^{1/2}$)</td>
<td>0.18</td>
<td>0.22</td>
<td><strong>0.12</strong></td>
<td>0.21</td>
<td>0.4</td>
</tr>
<tr>
<td>$i_n$ (aA/Hz$^{1/2}$)</td>
<td>@1Hz 21</td>
<td>15</td>
<td>9.1</td>
<td>2.2</td>
<td>3.6</td>
</tr>
<tr>
<td>@1kHz 6.8$\times$10$^2$</td>
<td>5.1$\times$10$^2$</td>
<td>2.4$\times$10$^2$</td>
<td>70</td>
<td>57</td>
<td></td>
</tr>
<tr>
<td>$R_n$ ($\Omega$)</td>
<td>@1Hz 2.6$\times$10$^8$</td>
<td>4.2$\times$10$^8$</td>
<td>1.5$\times$10$^9$</td>
<td>1.4$\times$10$^{10}$</td>
<td>2.8$\times$10$^{10}$</td>
</tr>
<tr>
<td>@1kHz 3.5$\times$10$^5$</td>
<td>6.3$\times$10$^5$</td>
<td>2.2$\times$10$^6$</td>
<td>2.0$\times$10$^7$</td>
<td>3.7$\times$10$^7$</td>
<td></td>
</tr>
<tr>
<td>$T_{nt}$ (mK)</td>
<td>@1Hz 4.1</td>
<td>3.4</td>
<td>4.6</td>
<td>2.4</td>
<td>13</td>
</tr>
<tr>
<td>@1kHz 5.9</td>
<td>6.2</td>
<td>5.0</td>
<td>3.6</td>
<td>5.6</td>
<td></td>
</tr>
</tbody>
</table>
Outline

- Introduction
  Motivation
  Low temperature and low noise vs FETs
  From HEMT to cryoHEMT

- Performance
  Noise voltage: sub-nV/$\sqrt{Hz}$
  Noise current: aA/$\sqrt{Hz}$

- Applications

- Conclusions and further developments
**Applications: Mesoscopic Physics - I**

First cryo-preamplifier by F. Pierre, A. Anthore et al at C2N (formerly LPN)

In a mK dilution refrigerator, to readout signals at ~ 1 MHz:
- Capacitance of the cable from mK to K: 100 pF
- Impedance of to be measured system: 10 kΩ
- At 1 MHz, signal gain < 0.2

To avoid signal loss at high $f$:
- Introducing an inductor $L$ for a chosen $f$
- At 1 MHz, signal gain $\approx 1$

CryoHEMTs based cryogenic amplifier facilitates:
- Quantum limit of heat flow across a single electronic channel *Science* 342, 601 (2013)
- Primary thermometry triad at 6mK in mesoscopic circuits *Nature Commun.* 7, 12908 (2016) $\pm 9 \times 10^{-32}$ A$^2$/Hz
Applications: Mesoscopic Physics - II
Based on the work by F. Pierre, A. Anthore et al @ LPN
G. Fève et al at LPA, ENS Paris

Comparisons: NF LI-75A and cryoHEMT (from V. Freulon thesis at LPA, ENS Paris)

Signal-to-noise ratio $SNR$: \[ SNR = \frac{\int_{f_{\text{min}}}^{f_{\text{max}}} du S_v^p(u)}{\left[\int_{f_{\text{min}}}^{f_{\text{max}}} du (S_v^a)^2/2\right]^{1/2}} \sqrt{T_{\text{meas}}}, \]

PSD of the measured voltage: $S_v^p$; PSD of the amp input noise voltage $e_n$: $S_v^a = e_n^2$ and measurement duration $T_{\text{meas}}$ ⇒ For a fixed SNR: $T_{\text{meas}} \sim e_n^4$

By NF LI-75A at 300 K,
for one point: $2.56 \times 10^4 s \approx 7$ hours!
$SNR = 10!$

By cryoHEMT preamplifier at $\leq 4.2$ K,
for one point: $2.25 \times 10^2 s \approx 4$ minutes!
$SNR = 30!$

Hong-Ou-Mandel experiment for temporal investigation of single-electron fractionalization,
### Comparisons: NF LI-75A at 300 K and cryoHEMT amplifier at 4.2 K

<table>
<thead>
<tr>
<th></th>
<th>According to NF Corporation</th>
<th>4.6 pF cryoHEMT Made at CNRS/LPN</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Operating temperature</strong></td>
<td>300 K</td>
<td>0 K to 77 K</td>
</tr>
<tr>
<td></td>
<td>NF LI-75A</td>
<td>CryoHEMT amplifier</td>
</tr>
<tr>
<td></td>
<td>Data obtained @ 300 K</td>
<td>Data obtained @ 4.2 K</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Power consumption: 0.25mW</td>
</tr>
<tr>
<td><strong>Input impedance</strong></td>
<td>100 MΩ // 50 pF</td>
<td>10 PΩ* // 15 pF</td>
</tr>
<tr>
<td></td>
<td>Voltage gain of 100</td>
<td>Voltage gain of about 10</td>
</tr>
<tr>
<td><strong>Noise voltages</strong></td>
<td>2 nV/Hz$^{1/2}$ at 1 kHz</td>
<td>1.42 nV/Hz$^{1/2}$ at 1 kHz</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.3 nV/Hz$^{1/2}$ at 100 kHz</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.24 nV/Hz$^{1/2}$ at 1 MHz</td>
</tr>
<tr>
<td><strong>Noise currents</strong></td>
<td>$14 \text{ fA/Hz}^{1/2}$ *</td>
<td>60 aA/Hz$^{1/2}$ at 1 kHz</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.7 fA/Hz$^{1/2}$ at 100 kHz</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2 fA/Hz$^{1/2}$ at 1 MHz</td>
</tr>
</tbody>
</table>


cryoHEMT input impedance > 10 PΩ: $10^{16}$ Ω

Invited talk at WOLTE13, Sorrento, 2018
Applications: Astrophysics CDMS

B. Sadoulet team at UC Berkeley

- Comparison of the input noise voltage between cryoHEMT and JFETs (by the C2N)

- Comparison of the heat dissipation and the sensibility threshold

<table>
<thead>
<tr>
<th></th>
<th>Temperature</th>
<th>Heat dissipation</th>
<th>Sensibility threshold</th>
</tr>
</thead>
<tbody>
<tr>
<td>JFET</td>
<td>150 K</td>
<td>5.5 mW</td>
<td>133 electrons</td>
</tr>
<tr>
<td>CryoHEMT</td>
<td>4.2 K</td>
<td>0.1 mW</td>
<td>35 electrons</td>
</tr>
</tbody>
</table>

Applications of cryoHEMTs and Publications in

- **Mesoscopic Physics:** C2N, Palaiseau; LPA ENS Paris; IN, Grenoble

- **Low Temperature STM:** LPS, Orsay; Leiden Univ.
  Atomic scale shot-noise using cryogenic MHz circuitry
  Amplifier for scanning tunneling microscopy at MHz frequencies
  Charge trapping and super-Poissonian noise centers in a cuprate high-temperature superconductor

- **Low Temperature Nano-mechanical Resonators:** ICFO, Barcelona
  Ultrasensitive displacement noise measurement of carbon nanotube mechanical resonators
  Improving the read-out of the resonance frequency of nanotube mechanical resonators
  *Nano Letters* 18, 5324 (2018)

- **Low Temperature Detectors:** IRFU, CEA-Saclay
  Toward large μ-calorimeters x-ray matrices based on metal-insulator sensors and HEMTs/SiGe cryo-electronics
  High impedance TES with classical (cryogenic HEMTs) readout electronics: a new scheme toward large x-ray matrices

- **Superconductor Circuits:** LPS, Orsay; Collège-de-France, Paris

- **Cryogenic Dark Matter Detection:** Edelweiss III: IPNL, Lyon; Super-CDMS: SLAC-Stanford, Berkeley; Tsinghua Univ. Beijing

- **CryoHEMTs Based Amplifiers**

*Invited talk at WOLTE13, Sorrento, 2018*
Outline

- Introduction
  Motivation
  Low temperature and low noise vs FETs
  From HEMT to cryoHEMT

- Performance
  Noise voltage: sub-nV/√Hz
  Noise current: aA/√Hz

- Applications

- Conclusions and further developments
## Conclusions

### High impedance and low frequency cryoelectronics

<table>
<thead>
<tr>
<th></th>
<th>Low Frequency</th>
<th>High Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low Impedance</td>
<td>Low Impedance</td>
</tr>
<tr>
<td><strong>Room Temperature</strong></td>
<td>JFETs, BJT</td>
<td>JFETs, HEMTs</td>
</tr>
<tr>
<td><strong>Low Temperature</strong></td>
<td>HEMTs $f \geq MHz$</td>
<td>CryoHEMTs, HEMTs $f &gt; 1GHz$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tested up to 150MHz</td>
</tr>
</tbody>
</table>

Commercially available devices
Made at CNRS/C2N
Formerly: CNRS/LPN

Our cryoHEMTs facilitate the following accomplishments:
- Reaching unprecedented low noise current and decrease significantly noise voltage
- Attaining unrivaled readout rates and improve the *Signal-to-Noise Ratio*
- Realizing novel experimental observations

Their implementation has already resulted in the publications of

Invited talk at WOLTE13, Sorrento, 2018
**Further Developments: LT and LF amplifier**

- Follower + Amplifier: low input capacitance and low noise voltage at LF

\[ g_{m1} R_S > 100 \rightarrow C_{in} \approx C_{gd1} \text{ instead of } C_{gs1} \]

**Benefits of the follower:**
- enabling cryoHEMTs with very large \( C_{gs} \) (to reduce LF noise)
- minimizing feedback effect
- having low output impedance \( 1/g_{m1} \)

**Disadvantage of “follower + amplifier”:**
- minimum input noise voltage \( e_1 \) increases to \( \sqrt{e_1^2 + e_2^2} \)

Using two \( C_{gs} = 236\text{pF} \) cryoHEMTs:
\[ C_{input} = 10\text{pF} \text{ and } R_{input} > 10^{15}\Omega \]
\[ e_n = 1\text{nV/Hz} @60\text{Hz} \]

---

**Graph: Input noise voltage \( (V/\text{Hz})^{1/2} \) vs. Frequency (Hz)**

- input noise voltage
- voltage gain: ~ 5 to 20
- 1 nV/Hz\(^{1/2}\) @ 60Hz
- input capacitance: ~9pF
  no feedback

---

**Invited talk at WOLTE13, Sorrento, 2018**