

Nanotechnology for Astrophysics

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Involved in this project

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National dark matter search program EDELWEISS (CNRS/CEA)

BoloX X-ray detection (CEA)

Hot electron bolometers for 2.5THz detection (Observatoire de Paris)

Sub-THz & THz by submicron Schottky diodes (Observatoire de Paris)

CESAR (Cryogenic Electronics for Space Applications and Research) (FP7-SPACE-2010)



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Outline

- CNRS/LPN
- Introduction - cryoelectronics
- MBE and 2DEG
- Nanofabrication and devices
- 1D ballistic HEMT
- Low-frequency noise LT HEMTs
- LT hot electron bolometers
- Sub-micron Schottky diodes
- Summary



CNRS/LPN – 1/2

one of the key national nanofabrication centers

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 ...



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CNRS/LPN – 2/2

~ 40 permanent researchers, ~ 40 permanent engineers, ~ 40 PhD&postdoc

Research topics

-Nanofabrications

materials by molecular beam epitaxy: quantum dot, quantum wire

nano-lithography

- Physics and nanostructured devices

quantum and coherent electronic transport

high performance cryoelectronics → for astrophysics

- Optoelectronics

- quantum optics and nonlinear optics



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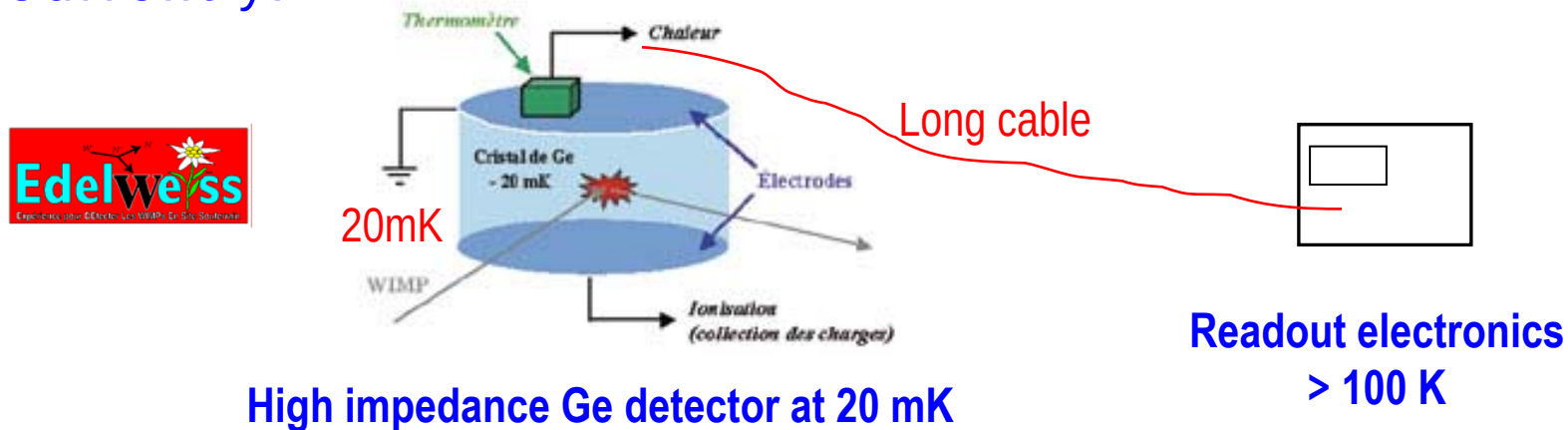


Introduction

Why cryogenic condition

For most ultra-sensitive detectors: low-temperature $\rightarrow$ low thermal noise
 $\sqrt{4kTR} \rightarrow 50\Omega$: at **300 K** $\Leftrightarrow 0.9$ nV/ $\sqrt{\text{Hz}}$; at **4.2 K** $\Leftrightarrow 0.1$ nV/ $\sqrt{\text{Hz}}$

Currently:



due to the long cable:

- High capacitance $\rightarrow$ limit time resolution
- Microphonic noise $\rightarrow$ limit the readable signal level

➔ High performance cryoelectronics for high impedance readout electronics

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

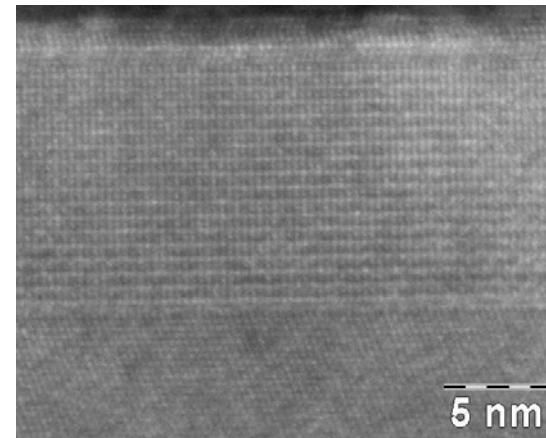
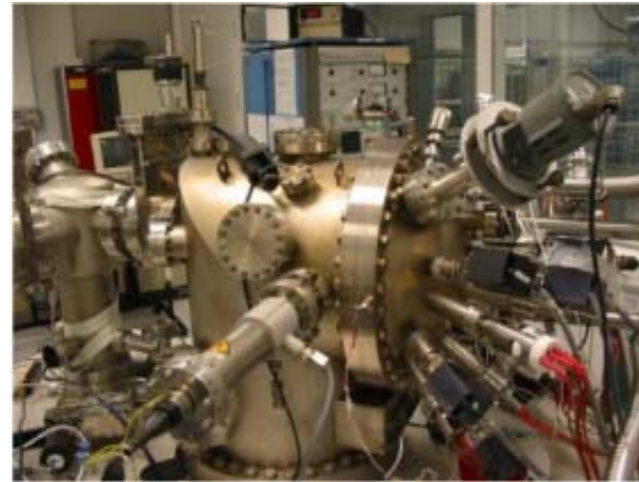
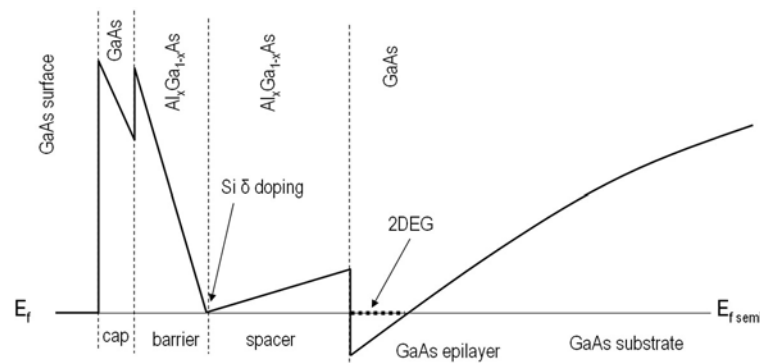
MBE and 2DEG

Initially: improve material quality

MBE (Molecular Beam Epitaxy)

Atomic level quality

Heterojunction AlGaAs/GaAs



2DEG (2-Dimensional Electron Gas)

Free electrons separated from donors

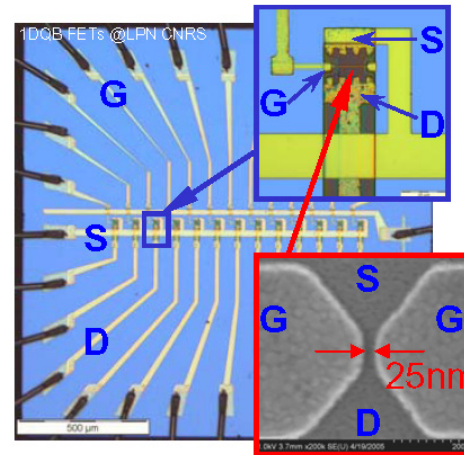
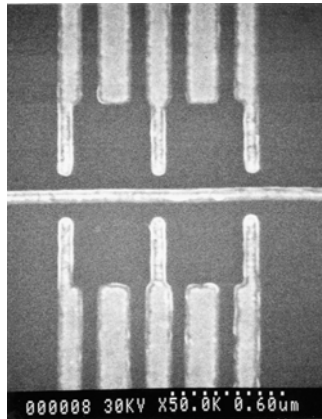
→ **no LT limit**, it can work at mK; very high mobility → mean free path $l > \mu\text{m}$

Nanofabrication and devices

Initially: for increase IC density and speed

2DEG + nanofabrication → mesoscopic physics: device dimension $L < l$

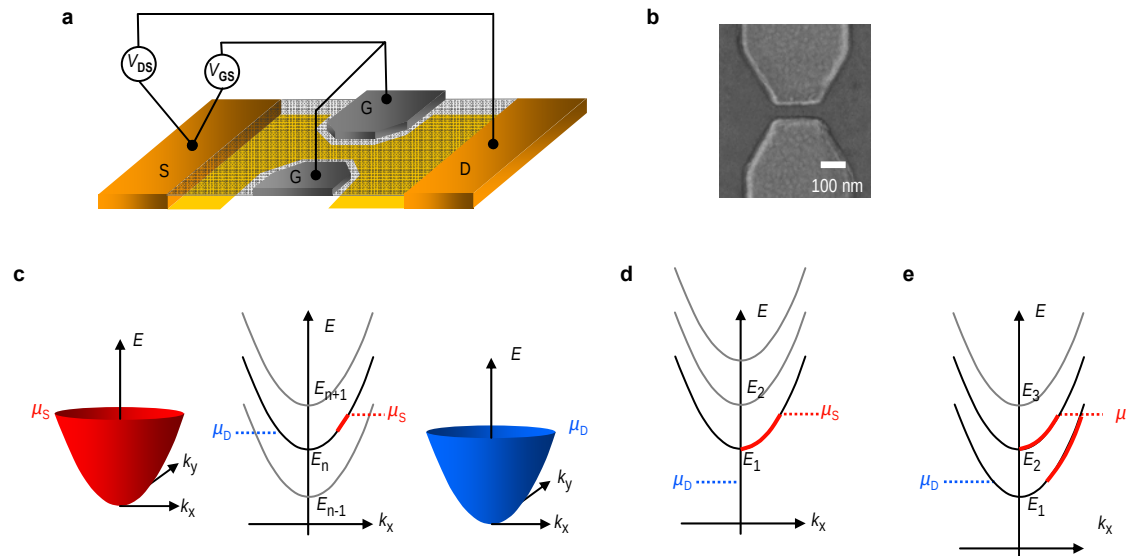
Routinely:



- Mesoscopic physics → New electron transport properties
Science, 313, 499, 2006, *Science*, 316, 1169, 2007
- shot noise reduction *PRL*, 76, 2778, 1996
- New devices for specific applications
currently: for ultra-LT high impedance detectors

1D ballistic HEMT 1/3

1 Dimensional HEMT (High Electron Mobility field-effect Transistor)



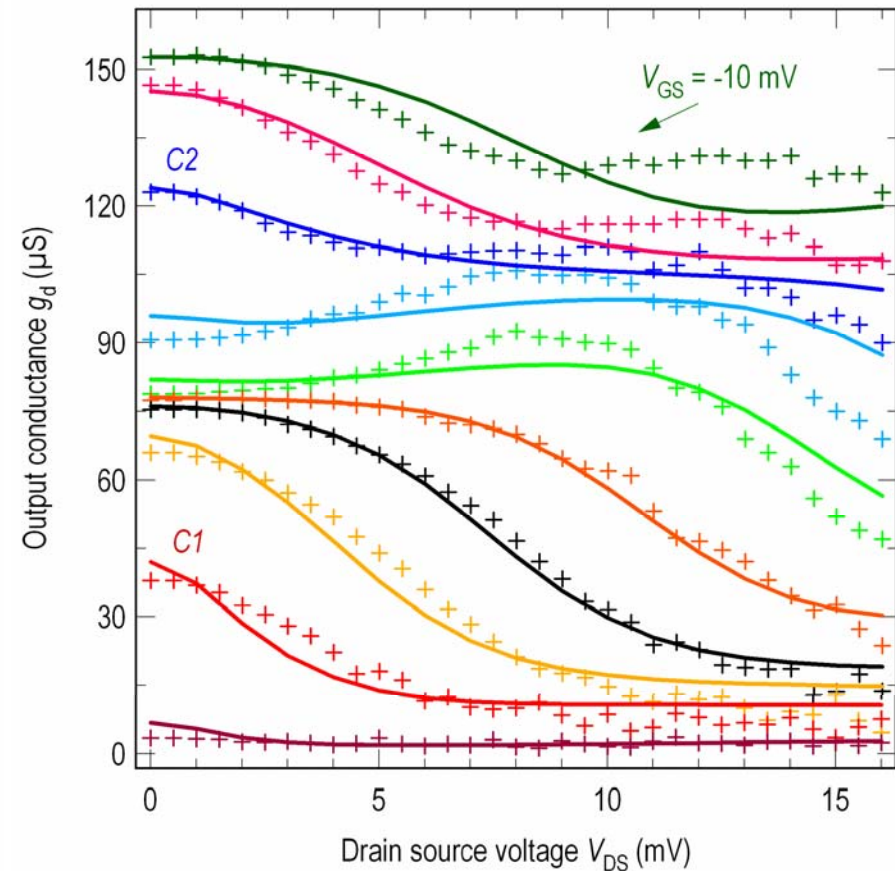
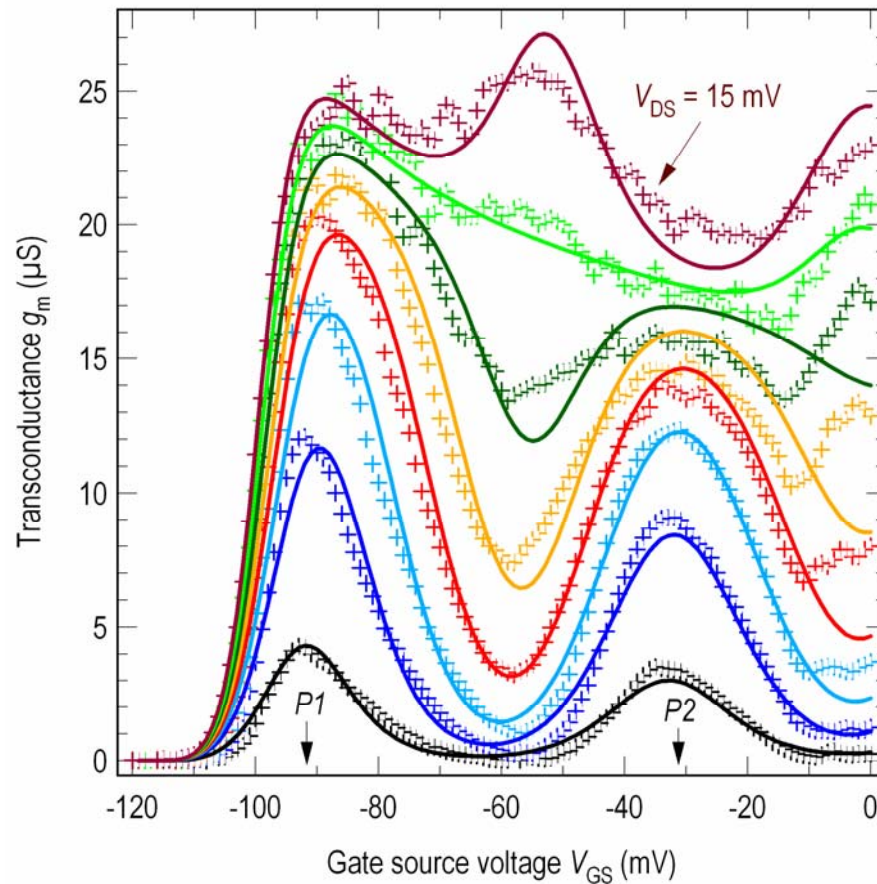
Mesoscopic physics: Landauer-Büttiker formalism

$$I_{DS} = \frac{2e}{h} \sum_n \frac{\hbar \omega_X}{2\pi} \ln \left(\frac{1 + \exp(2\pi(\mu_S - E_n)/\hbar \omega_X)}{1 + \exp(2\pi(\mu_D - E_n)/\hbar \omega_X)} \right)$$

$$E_n = E_{n0} + f(V_{GS}, V_{DS}) + g(V_{GS})$$

1D ballistic HEMT 2/3

Experimental and simulated results



1D ballistic HEMT 3/3

Application: multiplexing bolometers array

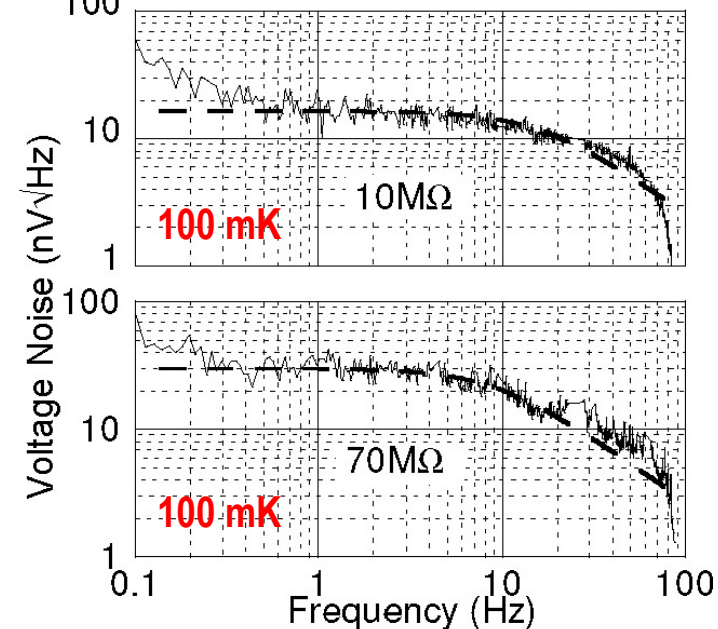
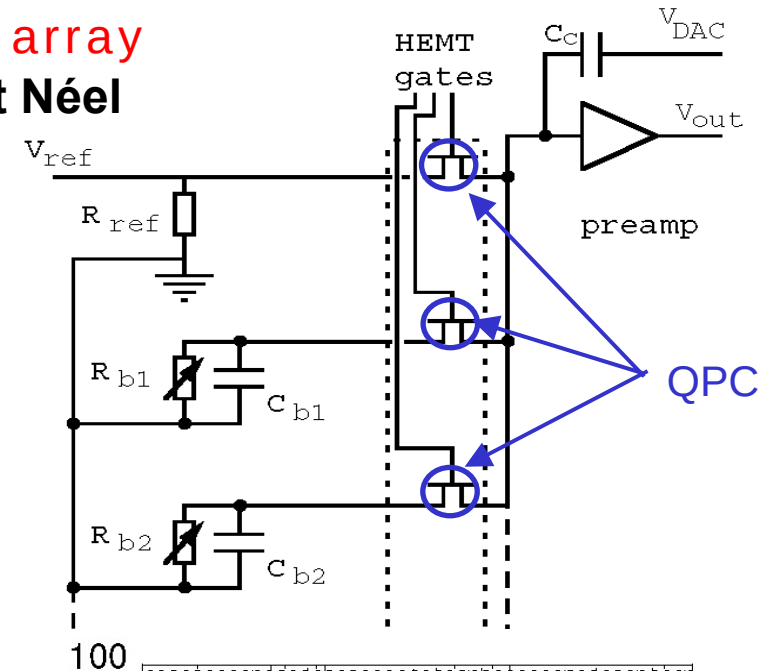
Collaboration : Alain BENOIT, CNRS/Institut Néel

• required specifications:

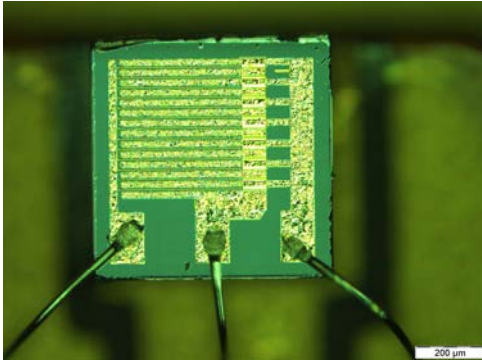
- Low capacitance $C_{GS} < 1$ fF
- Low open R_{DS} resistance ~ 10 k Ω
- Low I_{GS} (shot noise) < 1 pA
- Low power consumption $< \text{nW}$

$T = 4.2$ K	HEMT FHX35LG Fujitsu	MESFET CF739 Infineon	QPC CNRS/LPN
V_{GS-ON}	- 0.2 V	- 1.5 V	+ 100 mV
V_{GS-OFF}	- 0.7 V	- 2.3 V	- 100 mV
R_{ON}	< 10 k Ω	< 10 k Ω	~ 10 k Ω
I_{GS-ON}	X	X	< 0.1 pA
I_{GS-OFF}	~ 10 pA	~ 30 pA	< 0.1 pA
C_{GS}	0.1/0.3 pF	X	< 1 fF

Rev. Sci. Instrum. 78, 035104 (2007)



Low-frequency noise LT HEMTs 1/2



At 4.2 K

Input capacitance: 45 pF

Power supply: 36 μW

Load resistance: 301 Ω

Voltage gain: 7

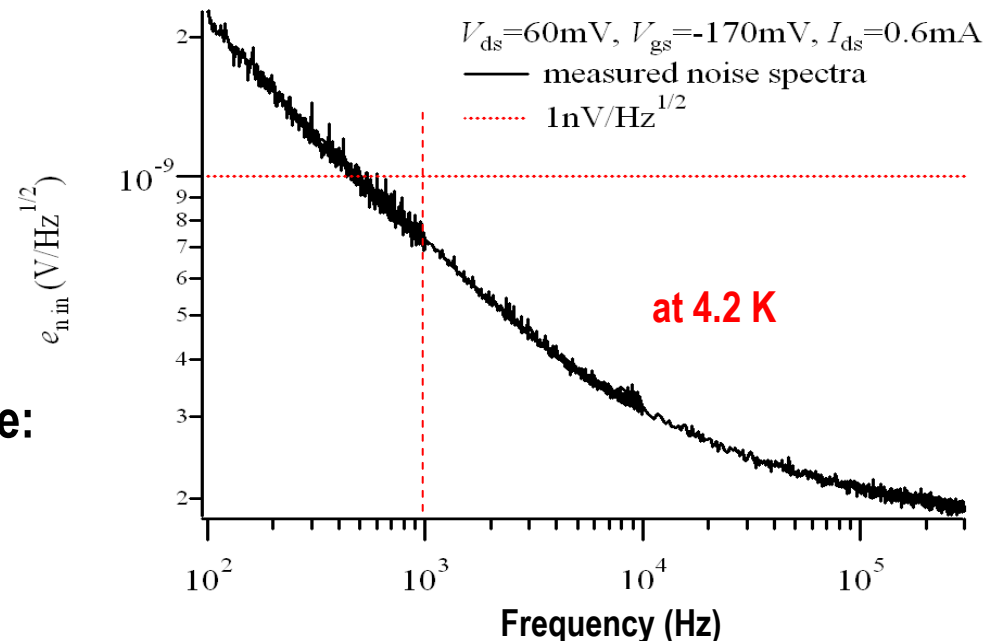
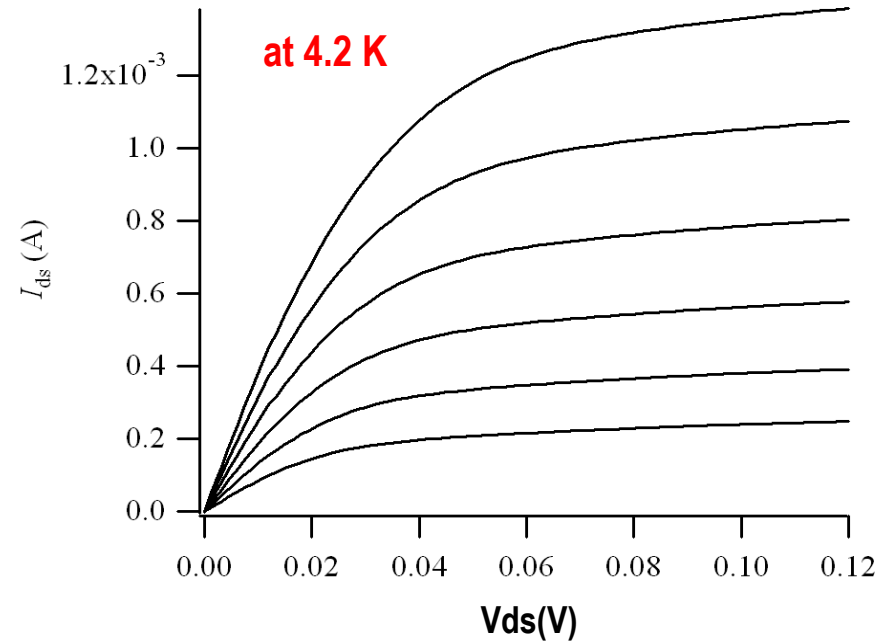
Gate leakage current: < 0.1 pA

Input voltage noise:

0.7 nV(Hz)^{-1/2} at 1 kHz

Minimum input noise - white noise:

< 0.2 nV(Hz)^{-1/2} for > 100 kHz



Low-frequency noise LT HEMTs 2/2

State of the art different high impedance FETs

FET	working Temperature	Power consumption	Input capacitance	Input noise at 1kHz	white noise	Gate leakage current	Current noise
Si JFET InterFET	> 100K	20 mW	~ 10 pF	$0.8 \text{ nV(Hz)}^{-1/2}$	$0.8 \text{ nV(Hz)}^{-1/2}$ $f > 100 \text{ Hz}$	10 pA	$1.5 \text{ fA(Hz)}^{-1/2}$
HEMT Agilent	4K	500 μ W	20 fF	$16 \text{ nV(Hz)}^{-1/2}$	$0.7 \text{ nV(Hz)}^{-1/2}$ $f = 1 - 3 \text{ MHz}$	~ 2 nA	$25 \text{ fA(Hz)}^{-1/2}$
HEMT LPN	$\leq 4\text{K}$	$\leq 100\mu\text{W}$	23 pF	$0.9 \text{ nV(Hz)}^{-1/2}$	$0.2 \text{ nV(Hz)}^{-1/2}$ $f > 100\text{kHz}$	< 0.1 pA	$< 0.18 \text{ fA(Hz)}^{-1/2}$

Deep cryogenic preamplifiers for high impedance detectors:
wimps, photons, particles...

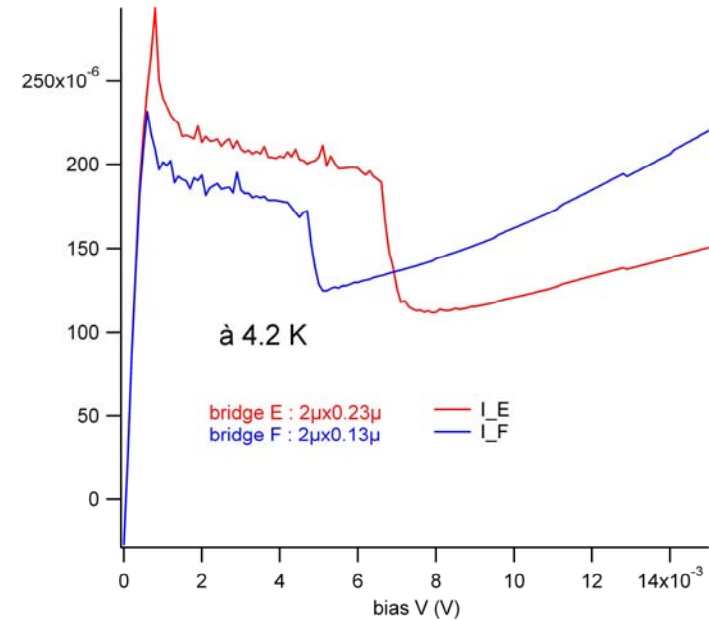
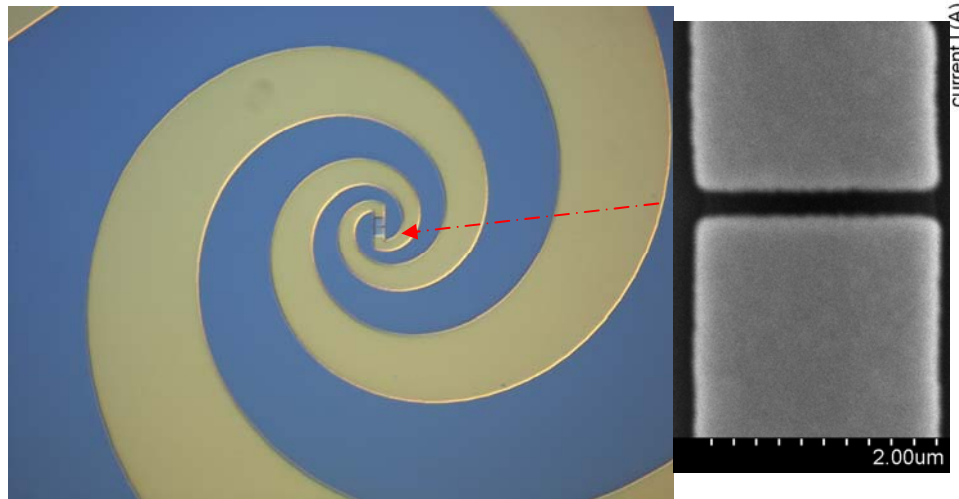


LT Hot Electron Bolometer NbN

R. Lefèvre (Observatoire de Paris) with technical supports of LPN

Submicron structured bridge on a thin NbN film of ~5 nm

For THz detection, especially, 2.5THz

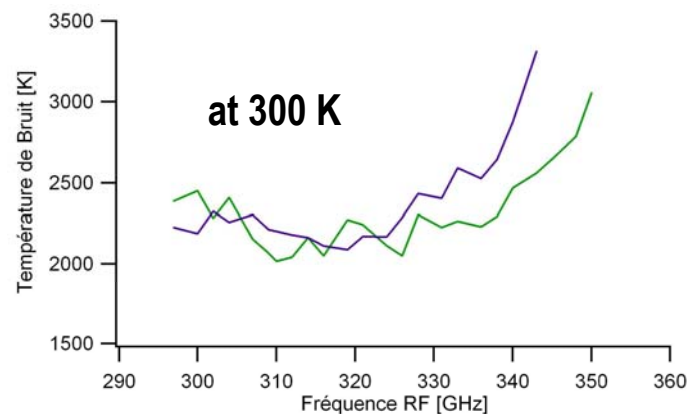
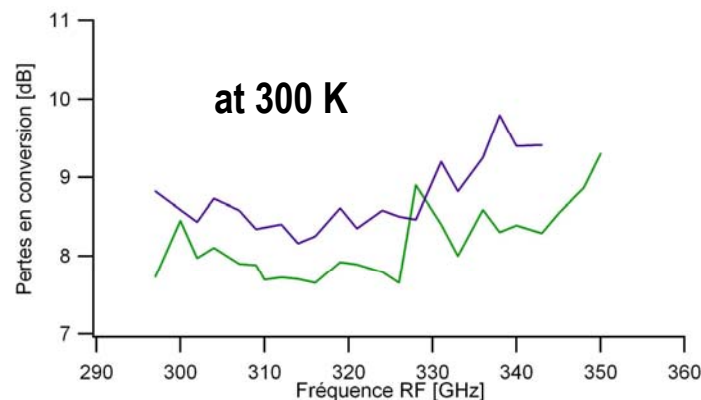
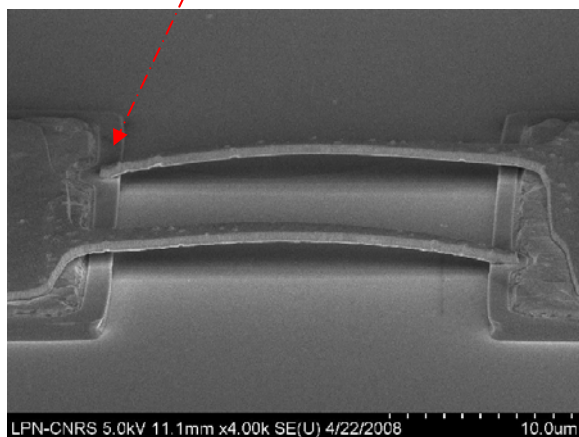
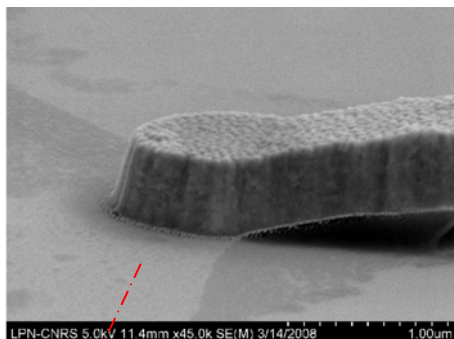


Noise temperature 600K @ 600GHz

Mesured by Y. Delorme *et al*,
Observatoire de Paris

Sub-micron Schottky diodes

C. Jung PhD thesis at LPN, currently Postdoc at JPL



Mesured by A. Maestrini et al,
Observatoire de Paris



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Summary

2DEG + nanofabrication

⇒ High performance cryoelectronics (from 100K down to mK)

for high (or low) impedance readout:

multiplexing or preamplifier at cryogenic condition

Developed technology

⇒ Various devices and detectors

based on semiconductor or supraconductors

