Cryogenic Front-end for Astrophysics
analog multiplexers and cryo-electronics

Damien Prêle - APC

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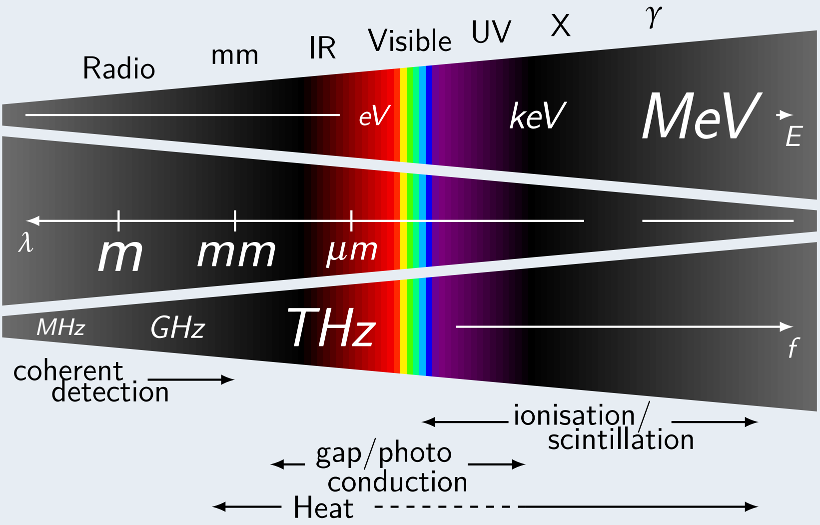
Observational astrophysics and cosmology from radio-astro to hight-energy astro. :

Astronomical sources

	f	λ	E	Astro. sources
Radio	$<$ 300MHz	$>$ 1m	$<$ 1μeV	21cm redshifted
μWave	$\approx$ 3GHz	$\approx$ 10cm	$\approx$ 10μeV	$_1$H (21cm line)
mm	$\approx$ 300GHz	$\approx$ 1mm	$\approx$ 1meV	CMB
IR	$\approx$ 300THz	$\approx$ 1μm	$\approx$ 1eV	interstellar dusts
Visible	$\approx$ 500THz	$\approx$ 600nm	$\approx$ 2eV	stars, planet ...
UV	$\approx$ 1PHz	$\approx$ 300nm	$\approx$ 4eV	Sun, stars
X	$\approx$ 300PHz	$\approx$ 1nm	$\approx$ 1keV	X binaries
γ	$>$ 30EHz	$<$ 10pm	$>$ 100keV	GRB

Arrays of sensors required to **fast and sensitive maps** of the sky.

Development of sensor technologies in manny wavelength range.



"We must be **COOL**ed to be **sensitive**"

$+$

"**Array** are needed to do maps - do **images**

AND

integrate signal - **sensitivity** again"

$=$

Cryogenic Multiplexing

Outline

1. Analog multiplexers
   - Multiplexing as a modulation
   - Time domain multiplexing
   - Frequency domain multiplexing
2. Cryo-electronics
   - Cryogenic electronic devices
   - Semiconductor active devices
   - SQUID a superconducting active device
3. Applications
   - Millimeter domain to IR
   - Visible domain and scintillation
   - X domain

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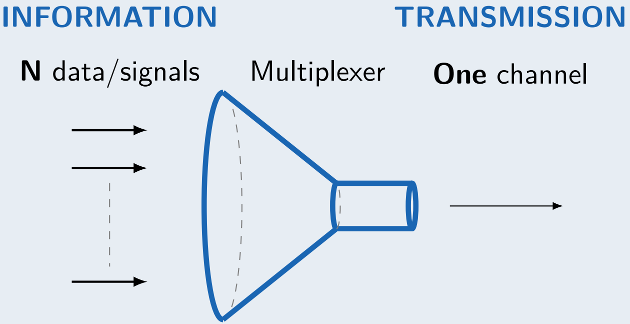
Multiplexing general

Transmission of **N** signals over **1** channel



Introduced for telegraphy at the end of the 19th century and widely applied in **telecommunications** during the 20th century :

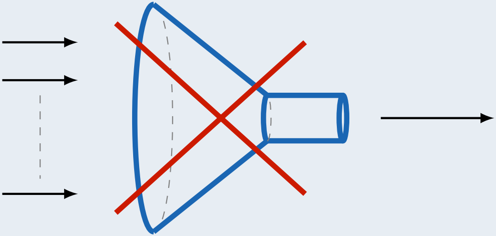
several telephone calls may be carried using one wire

Multiplexing general

Transmission of **N** signals over **1** channel

INFORMATION **TRANSMISSION**

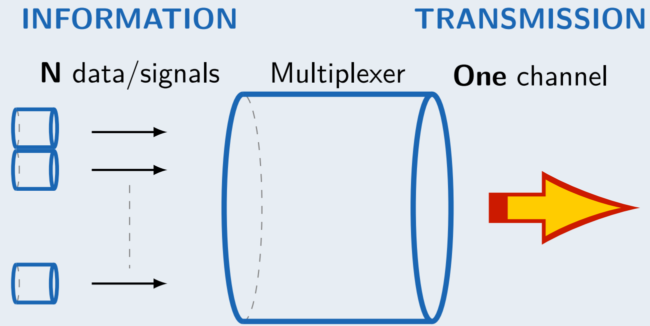
N data/signals Multiplexer **One** channel



That is **not a real multiplexer***, because this need to reduces -* **Data compression** *- the transmitted informations to use the* **same output channel capacity**

Multiplexing general

Transmission of **N** signals over **1** channel with HIGHER "capacity"



⚠ *To transmit N signals via One channel,* **the "channel" must provides better performances** *than for a single signal transmission.*

Multiplexing notice

⚠ To transmit N signals *via* one channel, **the "channel" must provides better performances** than for a single signal transmission.

⇒ The increasing of the required performances are directly linked to the number N of multiplexed signals.

⇒ The affected performances are both :

- Band Width
- Dynamic / Signal to Noise Ratio

the multiplexing **divides the capacity of the high-level communication channel** into several **low-level sub-channels**, one for each message, signal or data to be transmited.

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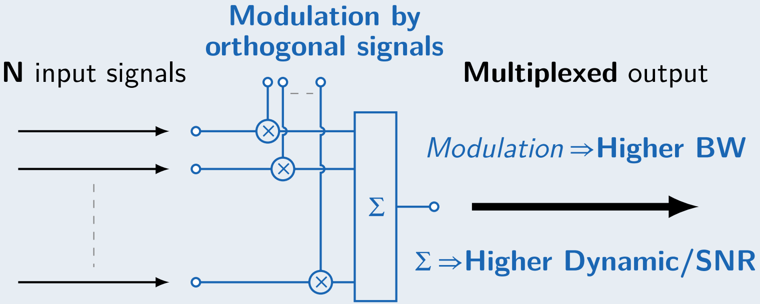
Multiplexing as a modulation

There are intersections between modulation and multiplexing

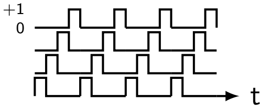
Multiplexing = modulation of input signals by orthogonal signals :



Orthogonal : **boxcar functions** or **carriers at different frequencies**.
Orthogonality ⇒ demultiplexer **able to recover each input signals without interference from the other.**

Orthogonal functions

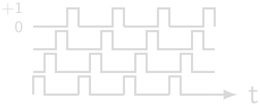
- boxcar functions ≡ **sampling**



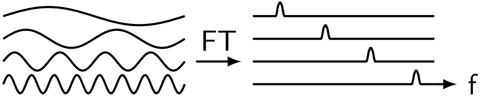
- carriers ≡ **modulation**
- linear codes ≡ **coding**

Orthogonal functions

- boxcar functions ≡ **sampling**



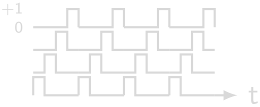
- carriers ≡ **modulation**



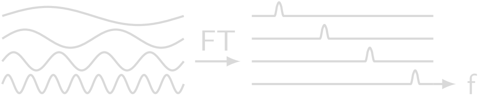
- linear codes ≡ **coding**

Orthogonal functions

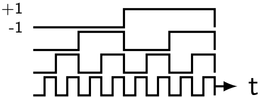
- boxcar functions ≡ **sampling**



- carriers ≡ **modulation**



- linear codes * ≡ **coding**



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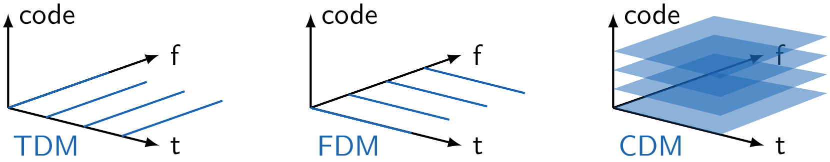
*. as used for error-detection/correction code. Especially, Hadamard/Walsh code could be used for multiplexing.

Multiplexing type *vs* standard modulations

- Multiplexing
  - **Time Domain Multiplexing (TDM)**
  - **Frequency Domain Multiplexing (FDM)**
    - Wave length Domain Multiplexing for optical fiber
  - Coded Domain Multiplexing (CDM)

- Coding
  - Amplitude Shift Keying (ASK)
  - Frequency Shift Keying (FSK)
  - Coded Division Multiple Access (CDMA)

Code as a third dimension ?



Multiplexing ⇒ spread spectrum

- Code is represented as a third dimension even if this is **not necessarily a physical dimension**.
- CDM is usually used to **spread the spectrum** of the multiplexed signal. But the code dimension is often a repartition both in time, in frequency and some times in amplitude.

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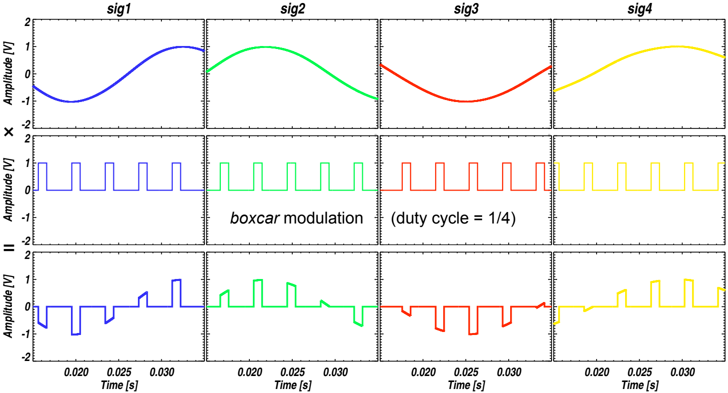
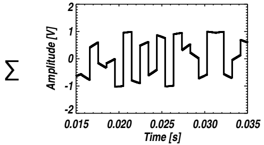
Boxcar modulation + Summing



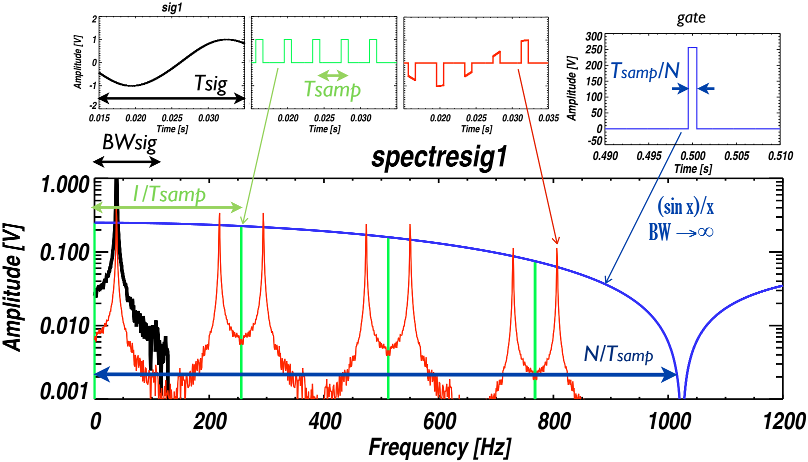


Multiplexed signal

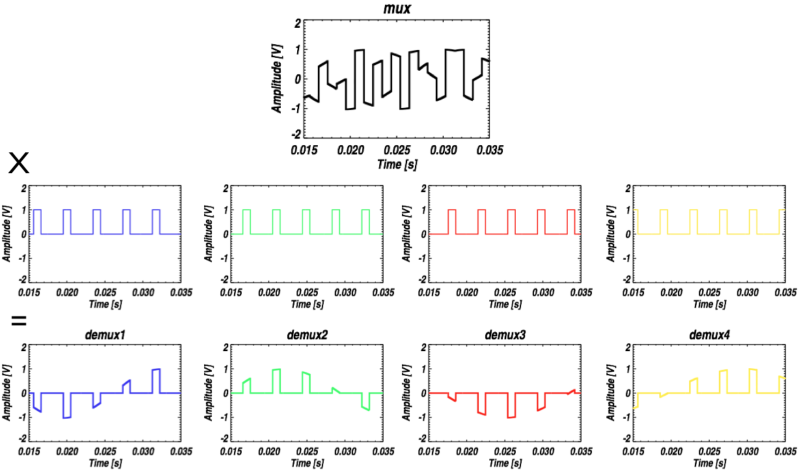
$$\text{duty cycle (DC)} = \frac{T_{ON}}{T_{ON}+T_{OFF}}$$

$$\Rightarrow N\nearrow \rightarrow DC\searrow \rightarrow BW\nearrow$$

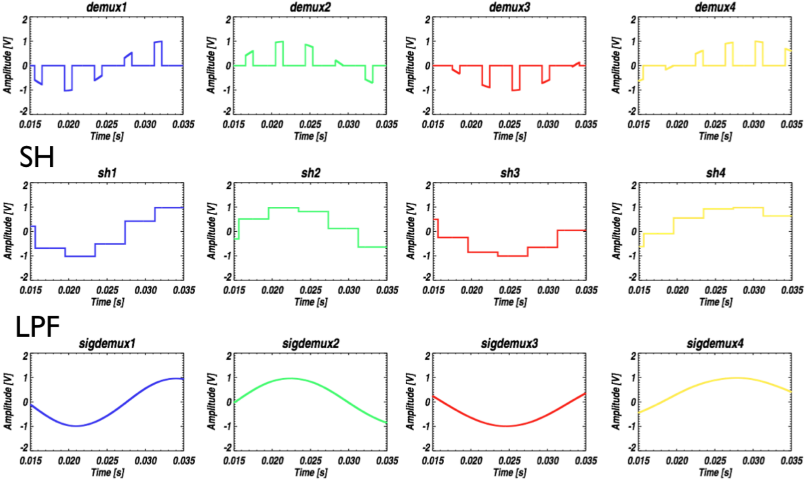
Spectrum of a boxcar modulation



Demultiplexing - Demodulation



Demultiplexing - Sample and Hold



Sample and Hold (SH) + Low Pass Filtering (LPF)

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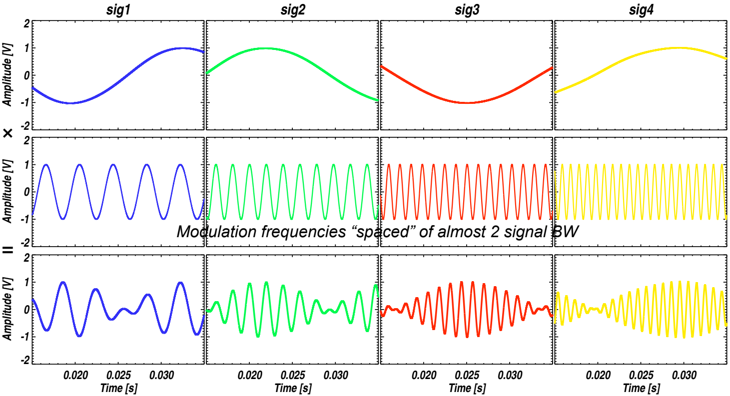
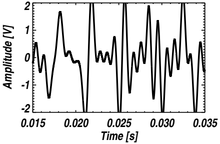
Carrier modulation + Summing



Modulation frequencies “spaced” of almost 2 signal BW

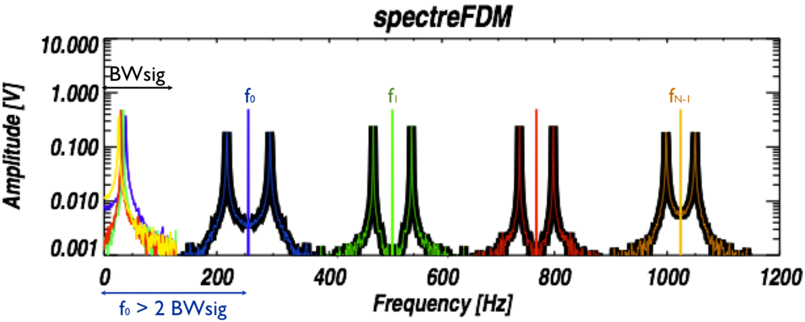
Σ



Multiplexed signal
(dynamique increased)

$$f_n - f_{n+1} > 2 \times Signal_{BW}$$
$$\Rightarrow \mathrm{N} \nearrow \rightarrow MUX_{BW} \nearrow$$

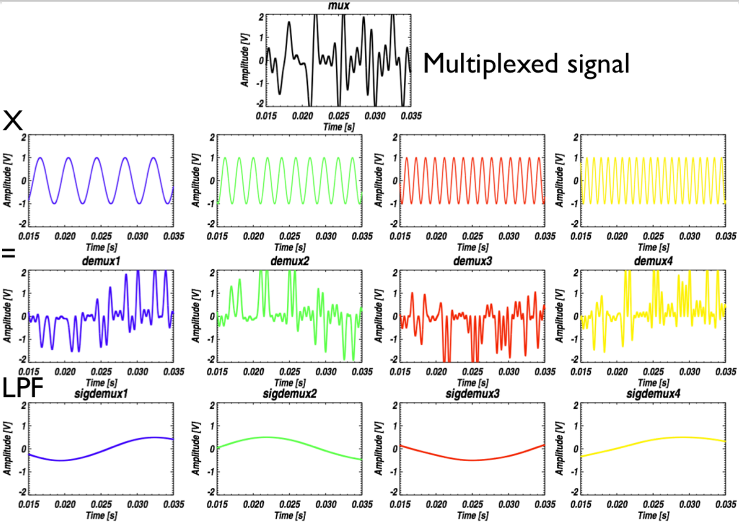
Spectrum of the frequency domain multiplexing



Increasing of the required band width

$$BW_{FDM} > 2 \times N \times BW_{sig}$$

Demultiplexage ≡ Demodulation + filtering



Low Pass Filtering (LPF)

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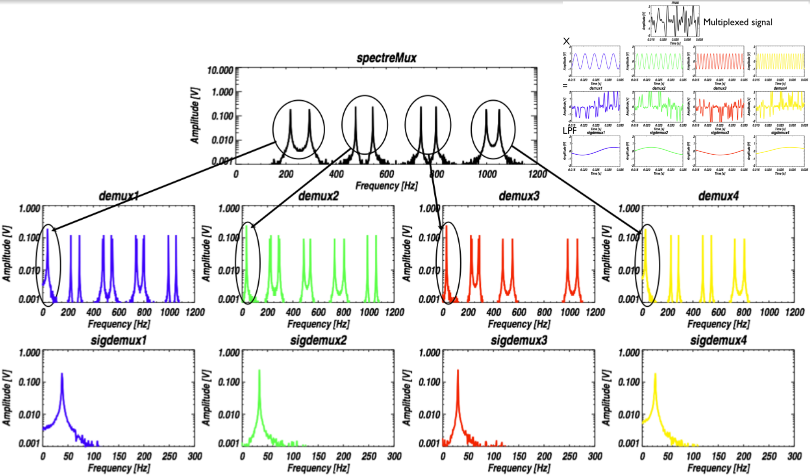
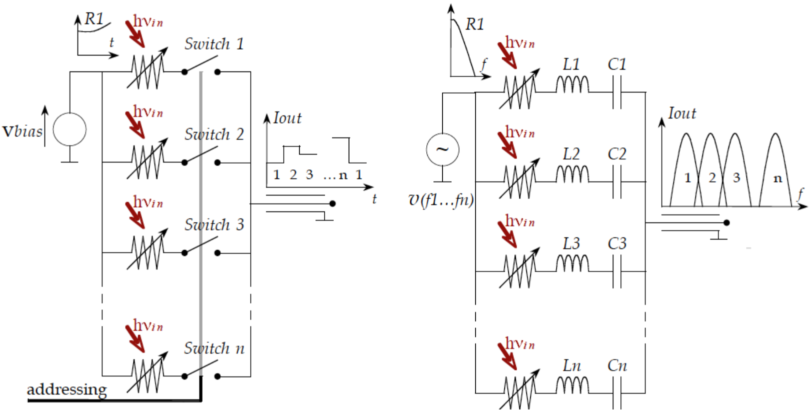


Demodulation of each carrier *ie* each input signal

+ low pass filtering (LPF)

Topologie of a multiplexer



- **N switches or N LC filters**
- **N signals** for the addressing of the switch or the modulation

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Cryogenic electronic devices

- **Linear** amplifier or switches
  - **Passive** devices as **transformers** or resonant circuits
  - **Active** devices → *provide power amplification*
    - **Superconductor** devices as SQUIDs
    - **Semiconductor** devices as transistors

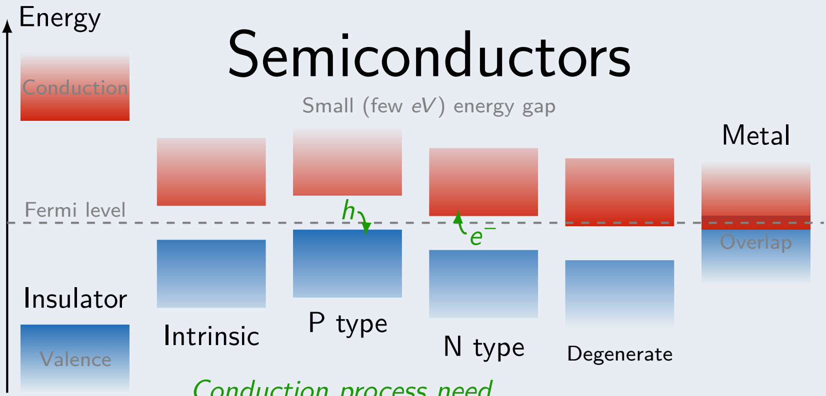
Semiconductor devices for amplification

1. **Field-effect** Transistors - FET
   - standard MOS & JFET
   - Hetero-junction FET *ie* HEMT
2. **Bipolar** transistors
   - Bipolar Junction Transistor - BJT
   - Hetero-junction Bipolar Transistor - HBT

- **Non-linear** amplifier **parametric amplifier** or **mixer**

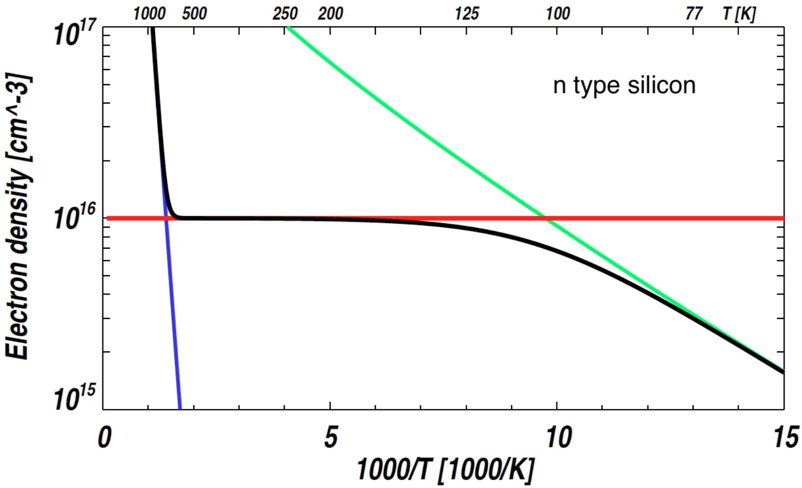
Solid-state physics and semiconductors

Band diagram

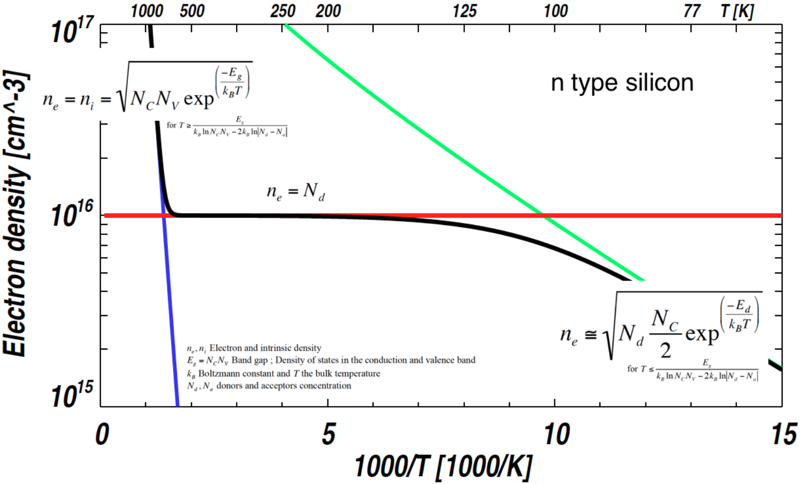


Conduction process need
Thermal activation (kT)

Solid-state physics and semiconductors (carriers density as function of T)



Solid-state physics and semiconductors (carriers density as function of T)



$$n_e = n_i = \sqrt{N_C N_V \exp^{\left(\frac{-E_g}{k_B T}\right)}}$$

$$\text{for } T \geq \frac{E_g}{k_B \ln N_C N_V - 2k_B \ln|N_d - N_a|}$$

$$n_e = N_d$$

$$n_e \cong \sqrt{N_d \frac{N_C}{2} \exp^{\left(\frac{-E_d}{k_B T}\right)}}$$

$$\text{for } T \leq \frac{E_g}{k_B \ln N_C N_V - 2k_B \ln|N_d - N_a|}$$

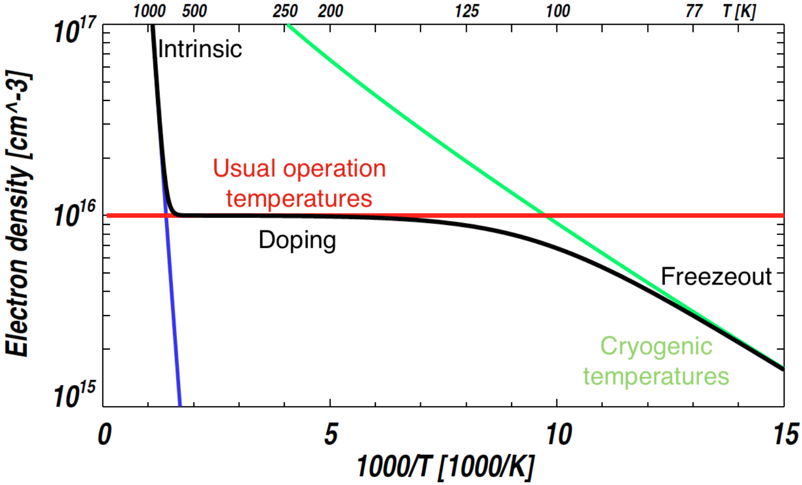
n_e, n_i Electron and intrinsic density

$E_g = N_C N_V$ Band gap ; Density of states in the conduction and valence band

k_B Boltzmann constant and T the bulk temperature

N_d, N_a donors and acceptors concentration

Solid-state physics and semiconductors (carriers density as function of T)



Outline

Field-effect transistor technologies

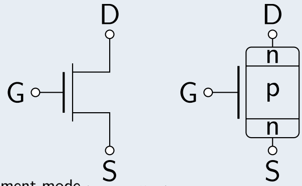
Field Effect Transistor - FET

Field effect transistor uses **ELECTRIC FIELD** to **control** the output current

Different ways to **isolate** the grid

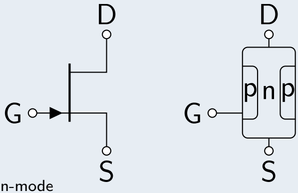
1. **INSULATOR** (as SiO2)
   → MOSFET (Metal Oxide Semiconductor FET)
2. **Depleted region** of a reverse biased **pn JUNCTION**
   → JFET (Junction FET)
3. **Depleted wide band-gap** of an **HETEROSTRUCTURE** (as GaAs/AlGaAs)
   → HEMT (High Electron Mobility Transistor)

nMOS nodes & topology



enhancement-mode (depleted-mode MOS exists)

nJFET nodes & topology



depletion-mode

Parameters :

- **transconductance** $g_m = \frac{\partial I_D}{\partial V_{GS}}$
- capacitive input impedance → close to ∞ at low freq.
- current gain not defined → Z_{IN} too large
- output impedance depends on the circuit (what the output is)

MOS and JFET transconductance

2 different operation modes for amplification

1. weak-inversion for low consumption ; $I_D = I_{D0} \exp \frac{V_{GS}-V_{th}}{\eta V_T} \Rightarrow g_m = \frac{I_D}{\eta V_T}$

   $I_{D0} = I_D$ and $V_{GS} = V_{th}$, $\eta = 1 + \frac{C_D}{C_{ox}}$ at $V_T = \frac{k_B T}{q}$

2. the **active mode** for low-noise analog amplifier

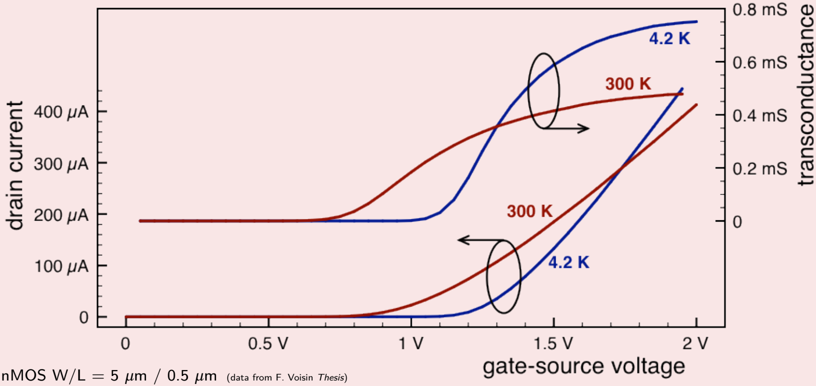
Linear low noise amplification → *pinch-off* and **active mode** (saturation)

- $\boxed{I_D(V_{DS}) \approx \kappa\,(V_{GS} - V_{th})^2}$ with $\kappa = \begin{cases} \frac{\mu C_{ox}}{2}\frac{W}{L} & \text{for MOS} \\ \frac{I_{DSS}}{V_{th}} & \text{for JFET} \end{cases}$
- $|g_m| = \left|\frac{\partial I_D}{\partial V_{GS}}\right| \approx \boxed{2\kappa(V_{GS} - V_{th})} \propto \sqrt{I_D}$
  - $\mu(T) \propto T^{-\alpha} \rightarrow \mu \nearrow$ at low temperature $\Rightarrow \boxed{g_m \propto \frac{\sqrt{I_D}}{T^{\alpha}}}$

Cryogenic measurement of MOS transconductance

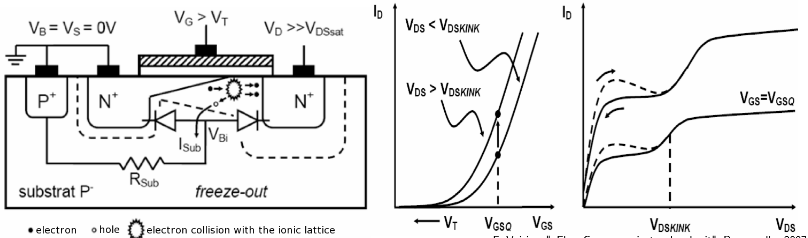
$$I_D(V_{DS}) \approx \frac{\mu C_{ox}}{2}\frac{W}{L}(V_{GS}-V_{th})^2$$

$$\Rightarrow |g_m| \approx \mu C_{ox}\frac{W}{L}(V_{GS}-V_{th}) \propto \frac{\sqrt{I_D}}{T^{\alpha}}$$



nMOS W/L = 5 μm / 0.5 μm (data from F. Voisin *Thesis*)

MOS output characteristic and *kink effect*



F. Voisin - "uElec. Cryo. pour instru. bas bruit", Porquerolles 2007

At high V_D, e^--hole pairs created by impact ionization mechanism.

- $e^- \rightarrow$ drain
- holes stay in the freezed-out bulk (increasing the bulk potential) $\Rightarrow$ add a "potential control" in addition to V_{GS}

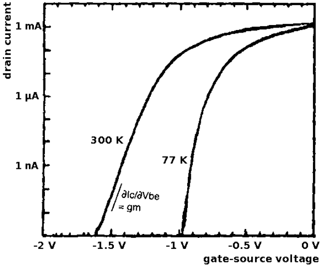
Kink effect is stronger in nMOS as compared to pMOS

Solution : adding many bulk contact around the MOS

Cryogenic measurement of JFET transconductance

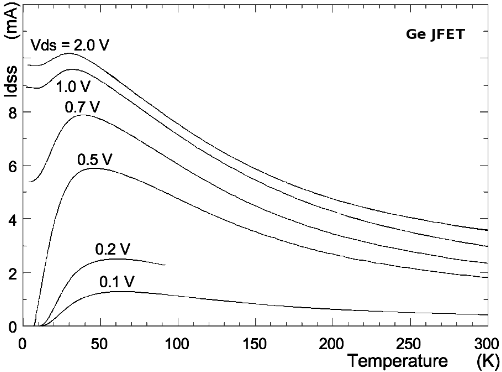
$$I_D(V_{DS}) \approx I_{DSS}\left(1-\frac{V_{GS}}{V_{th}}\right)^2$$

$$\Rightarrow |g_m| \approx 2I_{DSS}\left(1-\frac{V_{GS}}{V_{th}}\right) \propto \sqrt{I_D}I_{DSS}$$



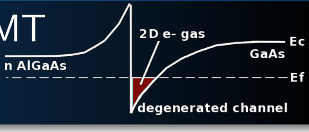
Goldberg et al - Characterization of cryo Si JFET

Ward et al - Dev. of Cryo Ge JFET ->



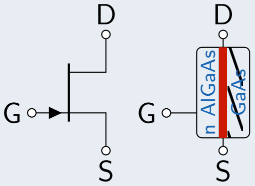
Si JFET for 77 K applications and Ge JFET for 4 K (but there are very few Ge commercial technology)

High Electron Mobility Transistor - HEMT



Charge carriers are "induced" to 2D layer rather than created by dopants

AsGa HEMT nodes & topology



2D electron gas (typ. 100Å)

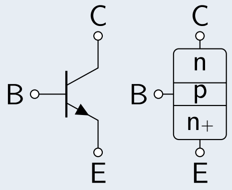
HEMT technologies (JFET with heterojunction)

- **Very high e^- mobility → high g_m**
- **High operation frequency up to mm wavelengths**
- e^- conduction spatially separated from donor impurities → **no ionized scattering** (collisions with impurities)

- Allows operation down to **sub-Kelvin temperatures** (degenerated)
- Suffer from **1/f noise** (crystal defects in interface and residual doping → traps and G-R noise)

Bipolar transistor technologies

Nodes & topology



Bipolar transistor technologies

Thin semiconductor material common to 2 junctions :

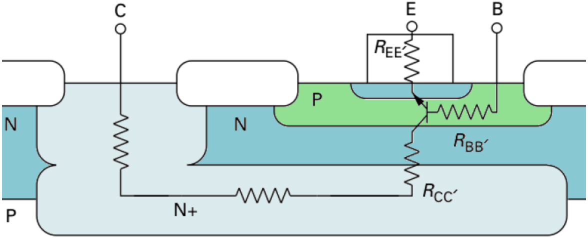
- **Homojunctions** Si/Si
  → Bipolar Junction Transistor - **BJT**
- **Heterostructure** III/V as InP/InGaAs or IV/IV as Si/SiGe
  → Heterojunction Bipolar Trans. - **HBT**

Parameters :

- **transconductance** $g_m = \frac{\partial I_C}{\partial V_{BE}}$
- **current gain** $\beta = \frac{\partial I_C}{\partial I_B}$
- **input impedance** $h_{11} = \frac{\partial V_{BE}}{\partial I_B} = \frac{\beta}{g_m}$
- output impedance depends on the circuit (not an issue)

Bipolar access resistances R’

At cryogenic temperatures, weakly doped semiconductor suffer from freeze-out ⇒ **increasing of the access resistances**

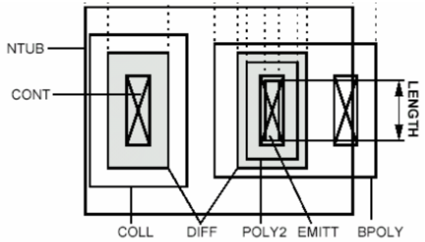


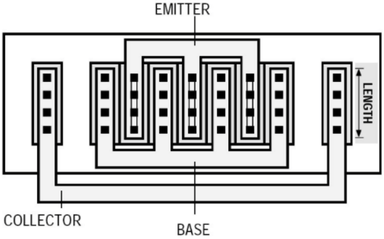
$R_{BB'}$ and $R_{EE'}$ access resistances are **combine in a unique R’**

$$R' = \frac{R_{BB'}}{\beta} + \frac{(\beta+1)R_{EE'}}{\beta}$$

Multiple access to reduce parasitic resistances

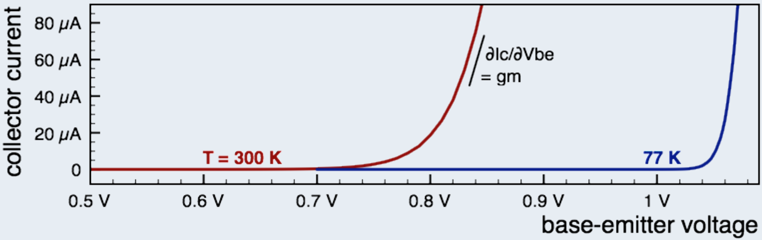
Single *vs* multiple (NPN243) B, E and C acces :





Transconductance - g_m

Drift diffusion theory $I_C = I_{C0} \exp \frac{V_{BE}}{V_T}$ **with** $V_T = \frac{k_B T}{q}$



recombinations, carrier mean free path, thermal decoupling and R'

$$g_m = \frac{\partial I_C}{\partial V_{BE}} = \frac{I_C}{V_T} = \frac{qI_C}{k_B T} \qquad \Longrightarrow \qquad g_m\Big|_{T_{cryo}} = \frac{\frac{qI_C}{\eta k_B T_e}}{1+R'\frac{qI_C}{\eta k_B T_e}}$$

Current gain β and input impedance

Degraded BJT current gain at low temperatures

$$\boxed{\beta \propto \exp\frac{\Delta E_g}{k_B T} \quad with \quad \Delta E_g = E_{g_E} - E_{g_B} < 0}$$

ΔE_g : difference in band gap between the emitter and the base regions and induced by **doping** - **band gap narrowing**

Example of common commercial transistor : 2N2222 BJT

measured β go from **225** to **35** from room temperature to 77 K

$\underline{h_{11} = \frac{\beta}{g_m}}$:

Considering $I_C = 1\text{mA} \rightarrow h_{11(\mathrm{T}=300\mathrm{K})} = \frac{225}{39\ mS} \approx 6\ k\Omega$

$h_{11(\mathrm{T}=77\mathrm{K})} = \frac{35}{150\ mS} < 250\Omega \quad \Rightarrow \quad$ fails $\quad Z_{in} > Z_S$ at lower temperatures

Heterojunction Bipolar Transistor - HBT

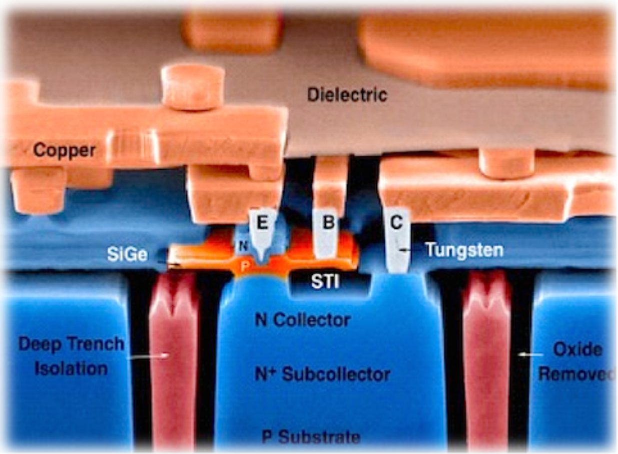
Differing semiconductor materials ⟹ Heterojunction

of one, at least, of the junctions of a bipolar transistor

→ **high frequency performances**

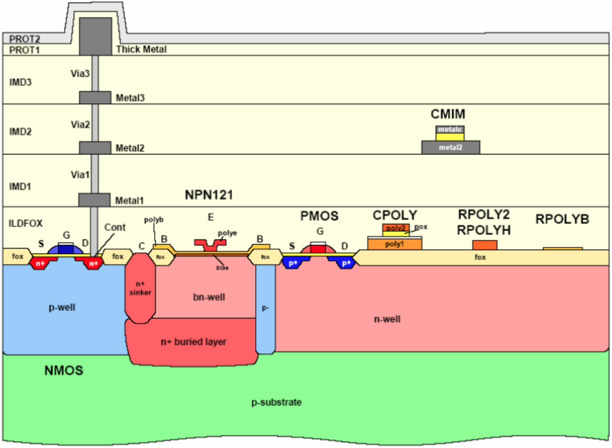
- **III-V or IV-IV hetero-junctions** are used by using InP/InGaAs or **Si/SiGe** for instance.
- Si/SiGe is one of the few hetero-junction **compatible with standard Si based technology**
  SiGe HBT becomes the most popular bipolar technology with competitive speed, and even better, than III-V expensive technologies

HBT planar technology



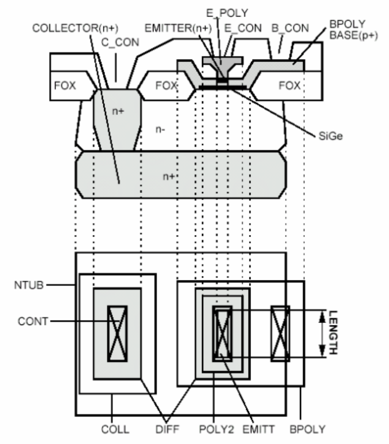
`SiGe HBT - J.D. Cressler - Georgia Tech.`

HBT planar technology



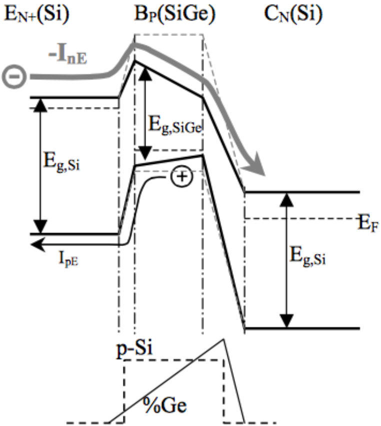
`AMS BiCMOS SiGe` $0.35\mu m$

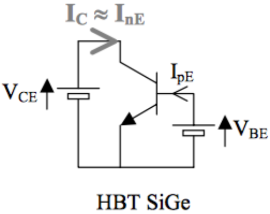
HBT planar technology



`AMS BiCMOS SiGe` 0.35μm

HBT planar technology





`Instru. Cryo. SiGe - PhD D. Prêle`

SiGe and cryogeny

- HBT is usually developed to achieve **high frequencies** perf.
- For **Cryogenic** applications, alloy of silicon and germanium (SiGe)

⇒ $\boxed{\text{Change the } \beta(\mathbf{T})}$

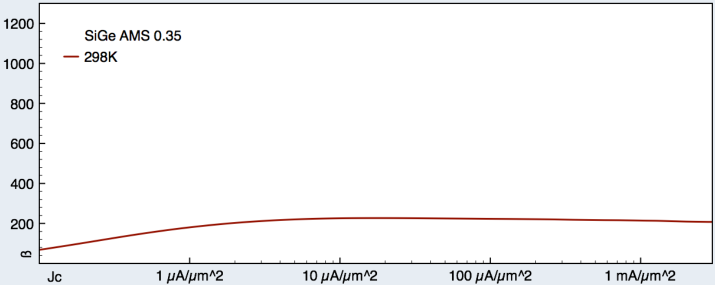
⇒ Pushes the **freeze-out** at lower temperatures

Si/SiGe heterojunction improve the **emitter injection efficiency**, as compare to BJT, so that it is possible to **increase the base doping**
⇒ **SiGe HBT still work at 4.2 K**, far away temperatures where Si BJT is freezed out

HBT current gain could increase exponentially with decreasing temperature

$$\beta_{SiGe} \propto \exp\frac{\Delta E_g}{k_B T} \quad \text{with} \quad \Delta E_g = \underbrace{E_{gE} - E_{gB}}_{<0 \text{ for BJT due to doping}} \approx \underbrace{E_{gE_{Si}} - E_{gB_{SiGe}}}_{\text{could be } >0 \text{ due to Ge}}$$

$\beta(T)$ and "band gap *vs* doping"



- at small J_C : recombinations in the base
- at large J_C : high injection

$$\beta(J_C) \xrightarrow[T\searrow]{} \text{"bell curve"}$$

Transistor geometry → *current density (match the area for a I_C)*

HBT current gain could increase exponentially with decreasing temperature

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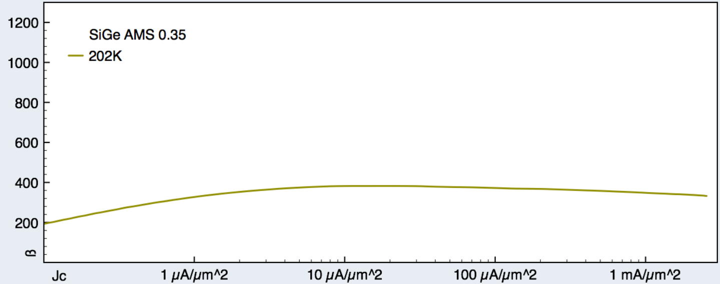

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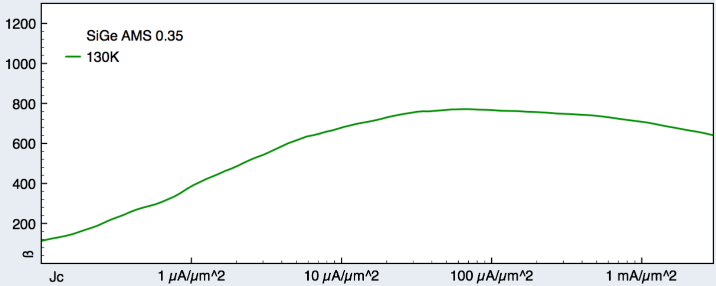

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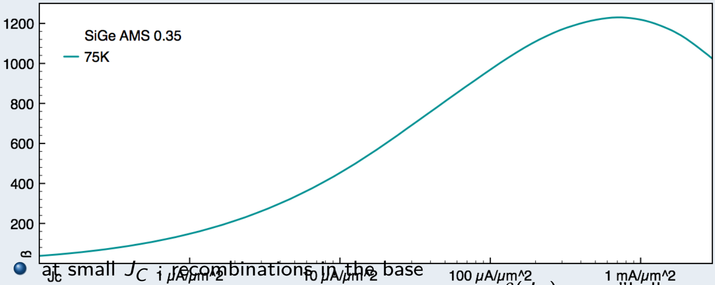

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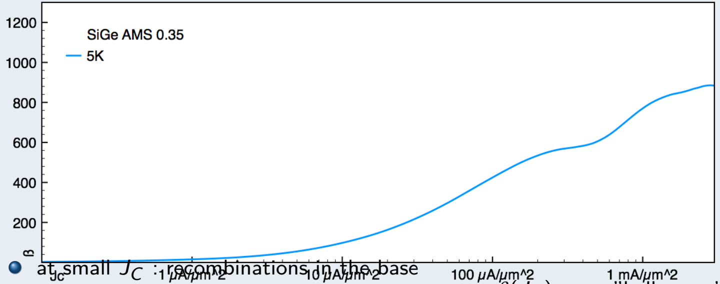

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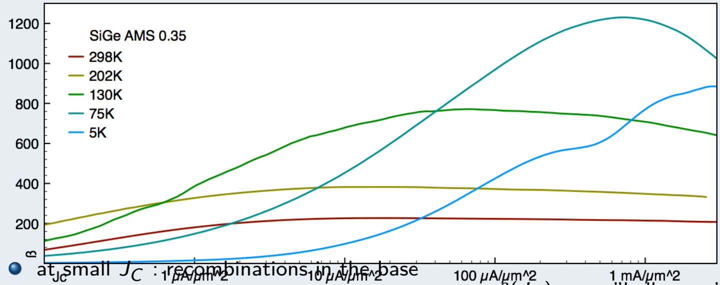

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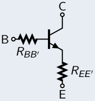
HBT transconductance

As for, BJT, the SiGe HBT transconductance follows

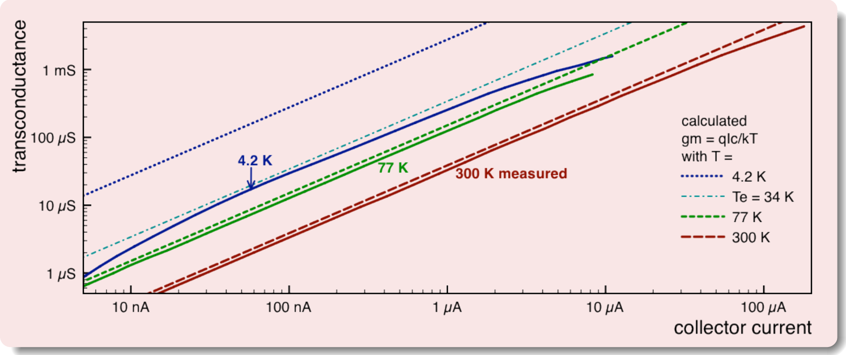
$$\boxed{g_m = \frac{\frac{qI_C}{\eta k_B T_e}}{1 + R' \frac{qI_C}{\eta k_B T_e}}} \quad \text{with} \quad R' = \frac{R_{BB'}}{\beta} + \frac{(\beta+1)R_{EE'}}{\beta}$$



Below 77 K, the HBT still operates ...

- **Strong T_e decoupling**
- "Start" of freeze-out ⇒ R' ↗
- R' effect if $R' \frac{qI_C}{\eta k_B T_e}$ is comparable or larger than 1
  - Large R'
  - Large I_C
  - Low T

measured SiGe transconductance

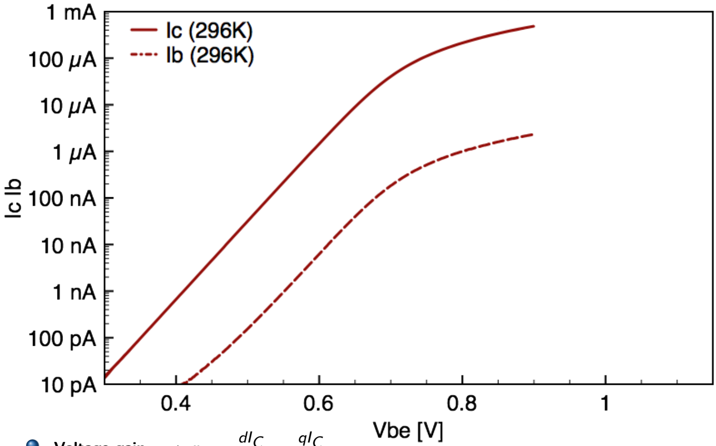


non-idealities

- **T_e → the 4.2 K measurement fit with $qI_C/k_B 34$ K**
- R' reduce the measured g_m (as compare to the ideal law)
- Recombination in the base-emitter depletion region at cryo. T

HBT parameters determined from pummel plots

Gummel plot of a NPN254 SiGe$_{AMS_{0.35\mu m}}$ ($L_E = 50\mu m \rightarrow area = 20\mu m^2$)



- **Voltage gain** $\Rightarrow gm = \frac{dI_C}{dV_{be}} \approx \frac{qI_C}{k_B T}$
- **Input impedance** $\Rightarrow h_{11} = \frac{\beta}{gm}$ **and** $\beta = \frac{I_C}{I_B}$; **Buffer output impedance** $\Rightarrow \frac{1}{gm}$

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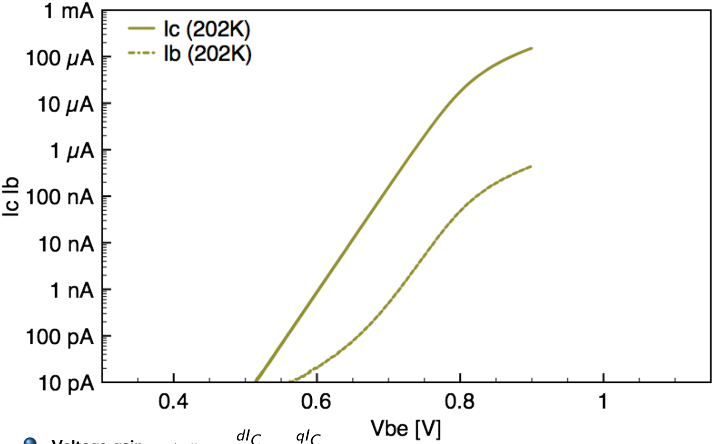

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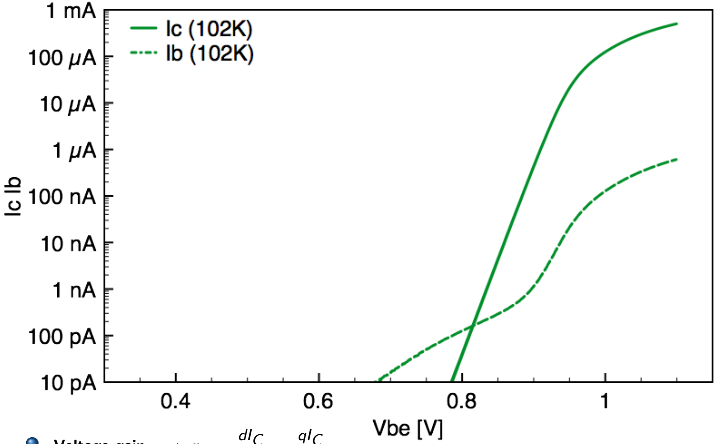

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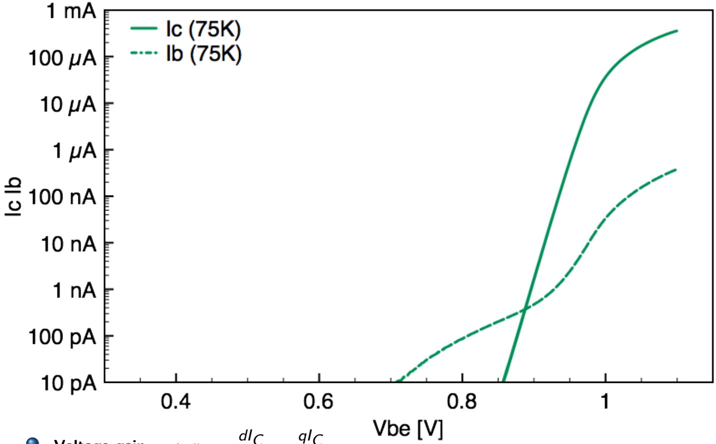

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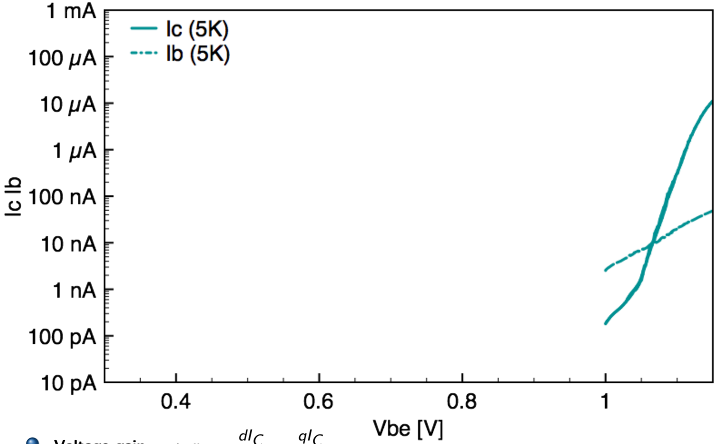

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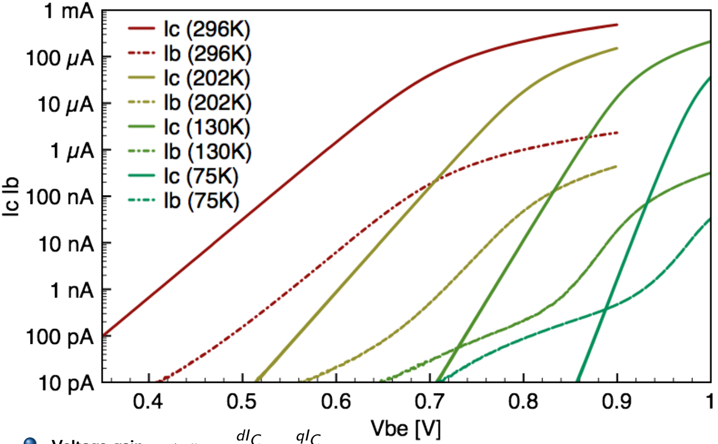

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Calculated h_{11} from β and g_m measurements

input impedance h_{11}

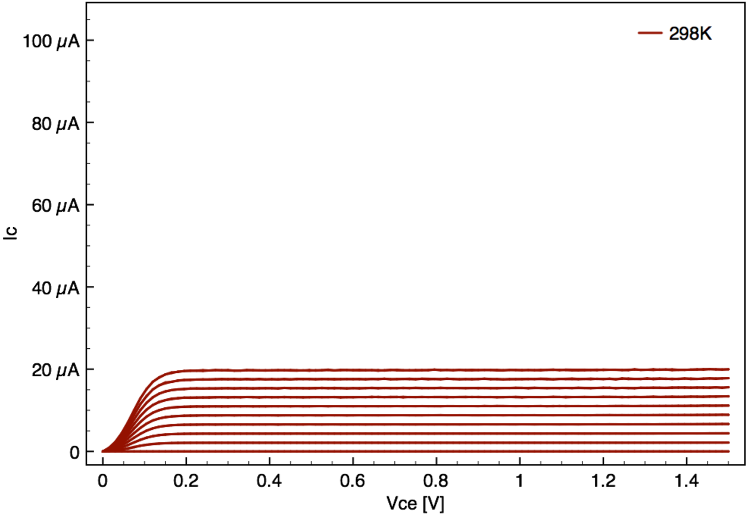
$$h_{11} = \frac{\beta}{g_m}$$

Considering a HBT SiGe with 100 μm^2 area and $I_C = 1$ mA

- J_C is thus equal to 10 μA/μm^2 (1 mA/100 μm^2)

Parameters	300 K	77 K	4.2 K
β	180	1400	900
g_m	30 mS	100 mS	150 mS
h_{11}	6 kΩ	14 kΩ	6 kΩ

HBT Ic(Vce) characteristic → V_{ce} offset



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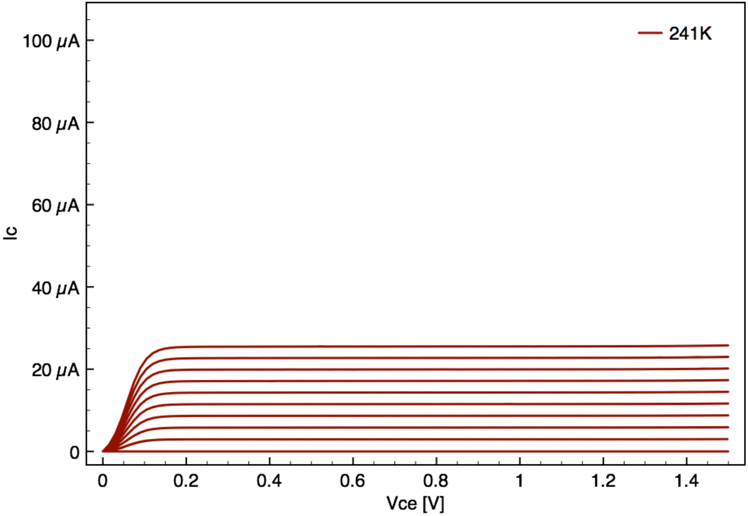

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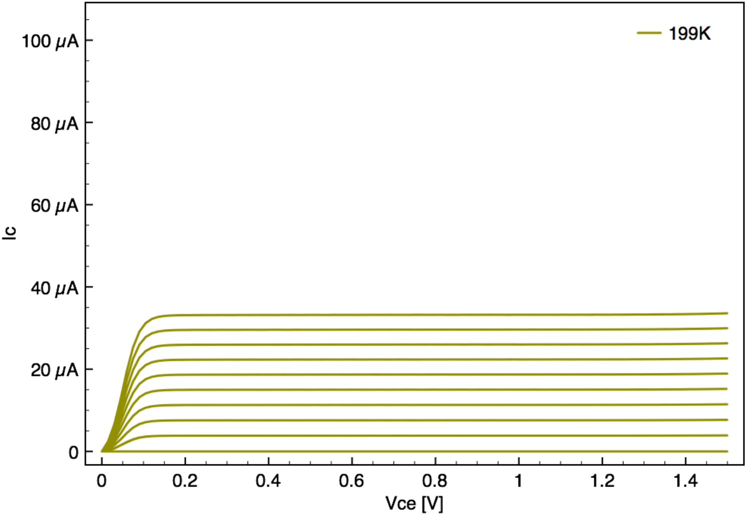

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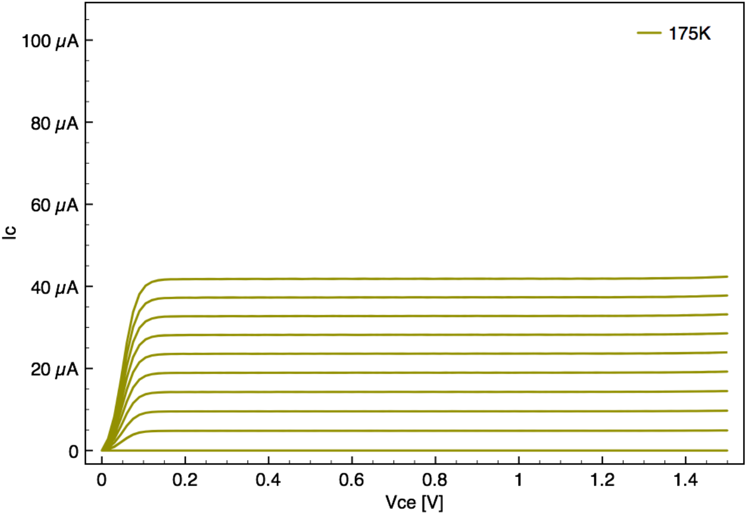

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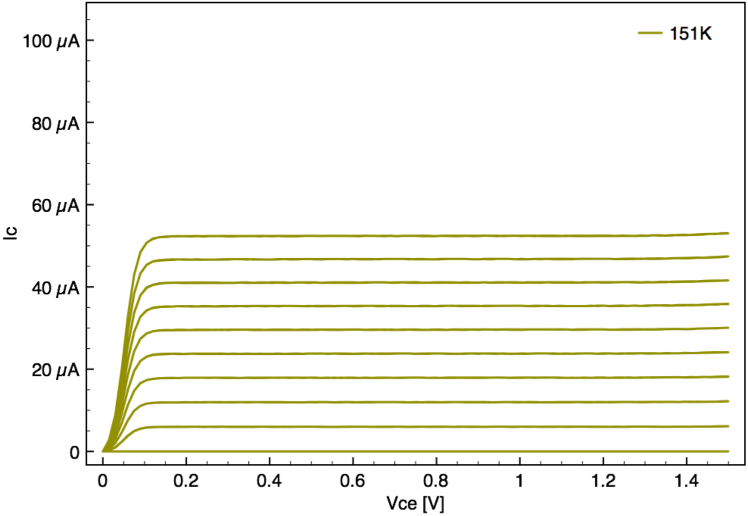

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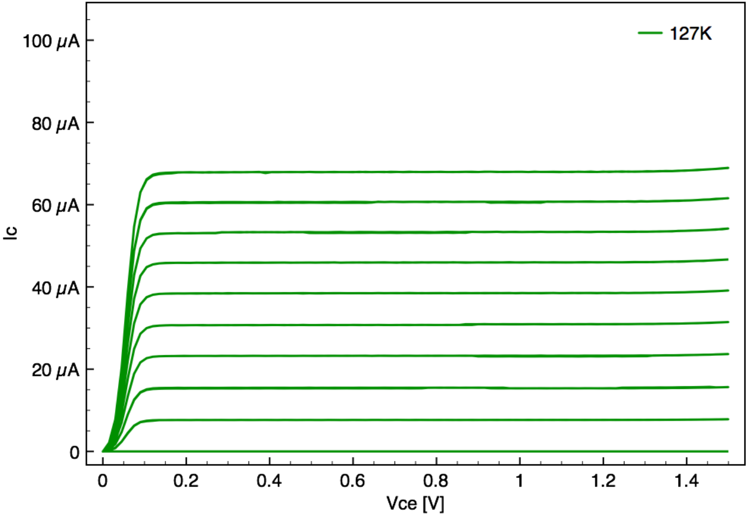

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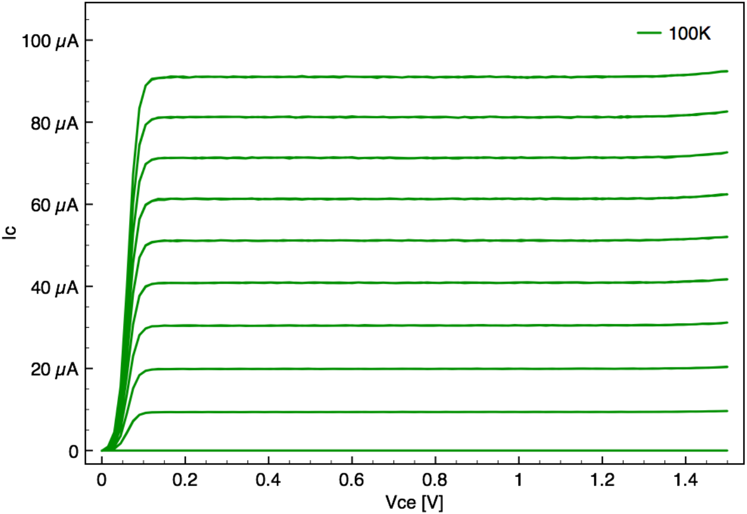

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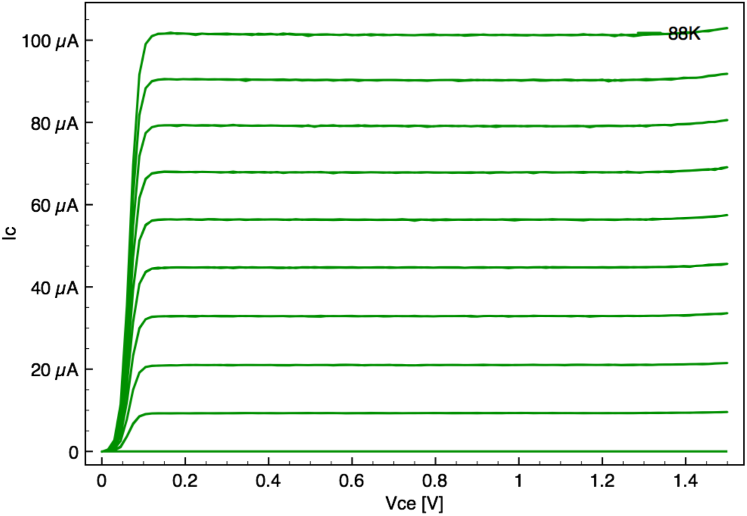

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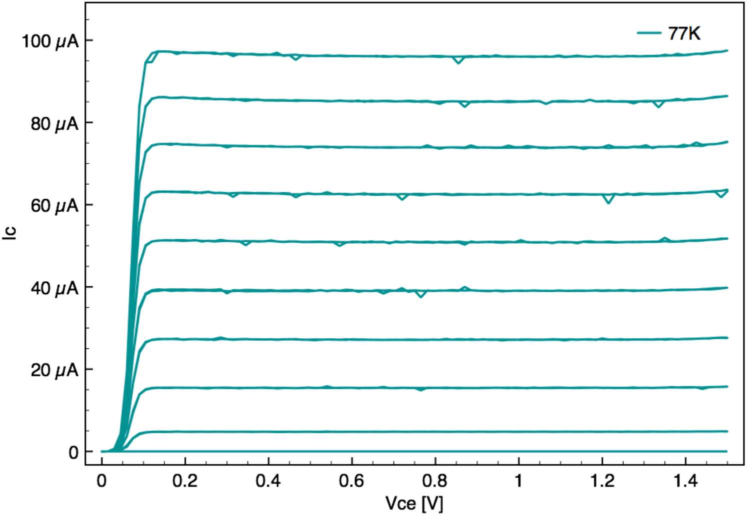

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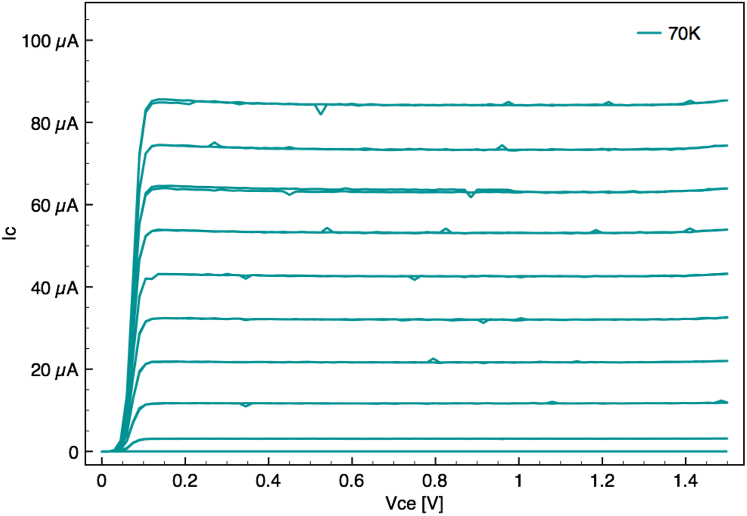

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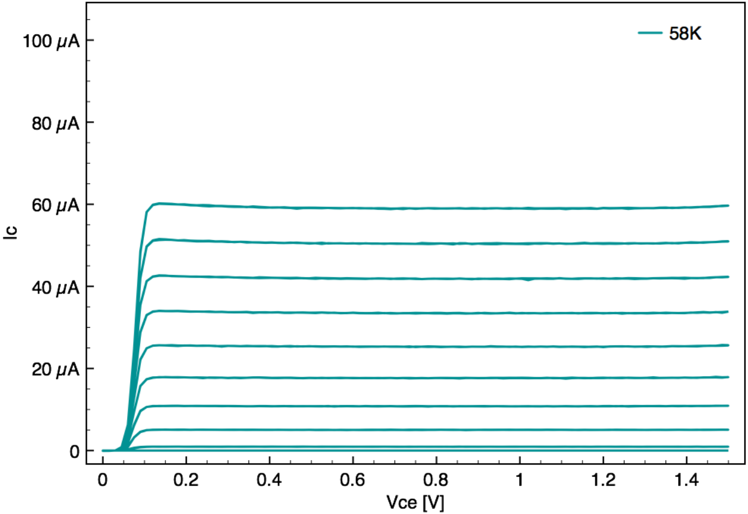

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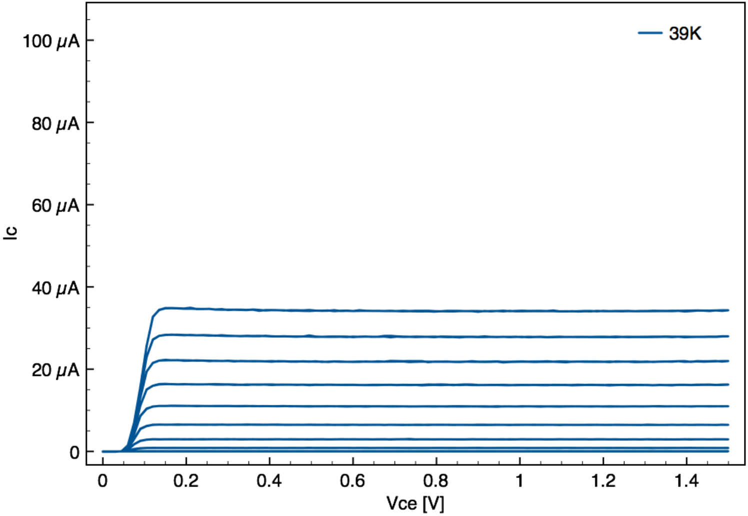

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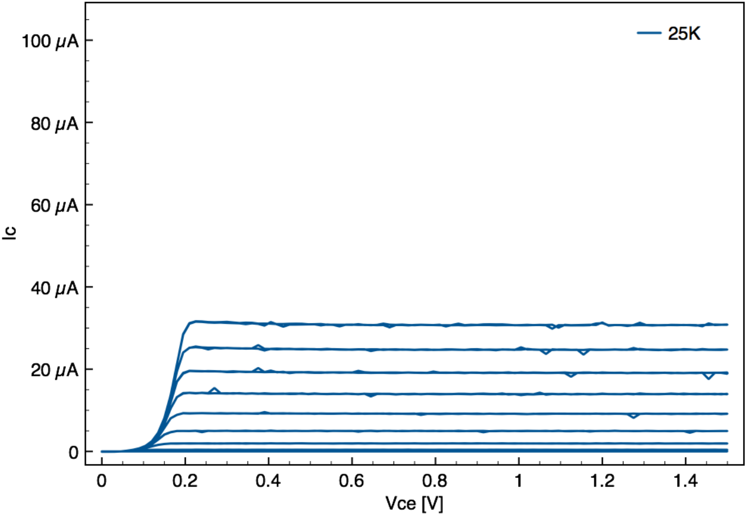

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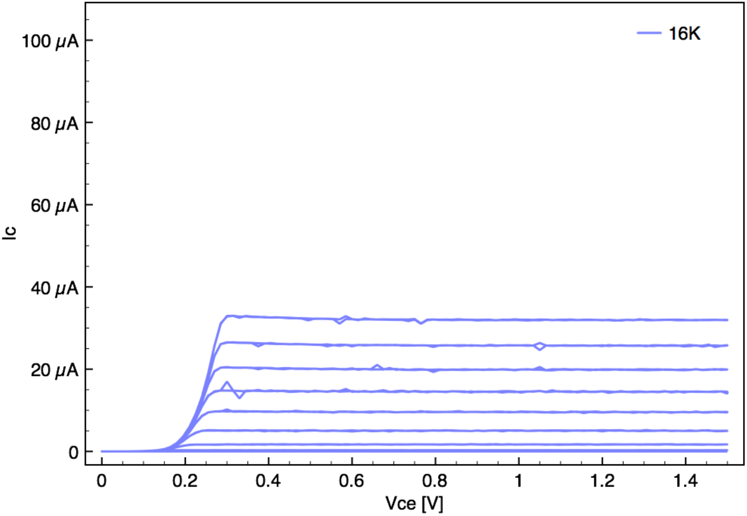

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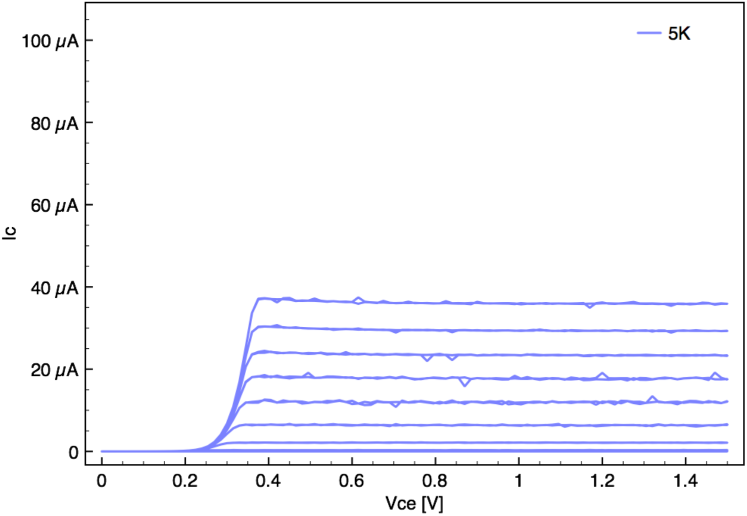


Noise discussion - on the benefit to have the larger g_m

FET noise = **THERMAL** noise of the channel resistance

- Output current noise : $S_{i_D} = 4k_B T \frac{2g_m}{3} + K \frac{I_D^{\alpha\approx 2}}{f^{\gamma\approx 1}}$
- **Input voltage noise :** $S_{v_{GS}} = \frac{S_{i_D}}{g_m^2} = \frac{8k_B T}{3g_m} + \frac{K}{g_m^2}\frac{I_D^{\alpha\approx 2}}{f^{\gamma\approx 1}}$

Bipolar noise = **SHOT** noise of the junctions

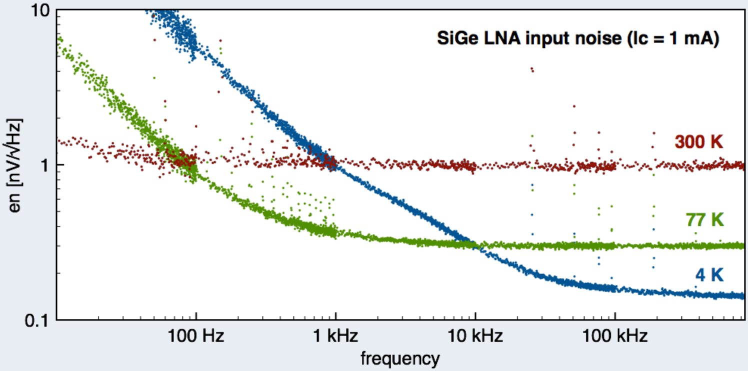
- **Input voltage noise** $S_{v_{BE}} = 4k_B T R_{BB'} + \frac{2qI_C}{g_m^2} + K\frac{R_{BB'} I_B^{\alpha\approx 2}}{f^{\gamma\approx 1}}$

$$\approx \frac{4k_B T}{2g_m} + K\frac{R_{BB'} I_B^{\alpha\approx 2}}{f^{\gamma\approx 1}}$$

- Input current noise $S_{i_B} = 2qI_B + K\frac{I_B^{\alpha\approx 2}}{f^{\gamma\approx 1}}$

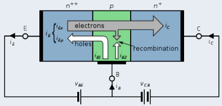
SiGe HBT Shot noise and 1/f (?) noise at cryo. T

1/f noise or sensitivity to the thermal fluctuations ?

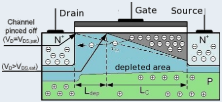


$$\boxed{e_n \approx \frac{\sqrt{2qI_C}}{g_m}}$$ with $g_m \approx \frac{qI_C}{k_B T} \Rightarrow I_C$ fixed by the required input noise

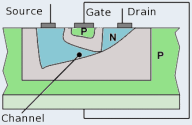
1/f noise and transistor topology



1/f noise is essentially due to the **non-ideal base current** in bipolar technologies



for MOS its cause come from the **trap on the oxide/channel interface** at the surface of the substrate



JFET channel is geometrically limited only by depleted regions → Less trap than near the surface → **Low 1/f noise**

+ effect of the size → $1/f \propto 1/Area$

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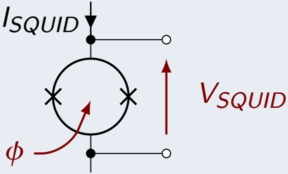
Superconducting QUantum Interference Device

SQUID = **Magnetic flux transducer ⇒ Voltage**

The "DC SQUID" is composed of one superconducting ring (*Washer*) interrupted by two Josephson junctions (×).



Very sensitive magnetometer which combine two physical phenomena :

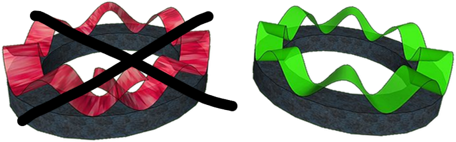
1. **Magnetic flux quantization** ($\phi_0 = \frac{h}{2e} \approx 2.10^{-15}\,Wb$ ou $[T.m^2]$ ou $[V.s]$) **in a superconducting loop**
2. **Josephson tunneling effect**

$h \approx 6{,}6.10^{-34}\,J.s$ or $[W.s^2]$ Planck constant ; $e \approx 1{,}6.10^{-19}\,C$ or $[A.s]$

Magnetic flux quantization in a superconducting ring

Quantum properties of the superconductivity : $q = 2e$ (charge of the Cooper pair)
Superconductor is described by a **quantum wave function** ψ.

In superconducting ring, phase of ψ continuously change but **must comes to the same value around a turn** → magnetic flux screening can only compensates n magnetic flux quanta ϕ_0 :

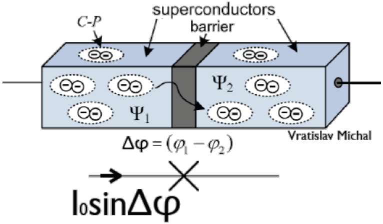


$$\boxed{\phi = n\frac{h}{2e} = n\phi_0}$$

$\phi_0 = \frac{h}{2e} \approx 2.10^{-15}\,Wb$ ou $[T.m^2]$ ou $[V.s]$ le quantum de flux magnétique

Josephson junction

2 superconductors separated by a thin $(\approx 10nm)$ non-superconducting barrier.



Josephson tunneling effect : Cooper pairs of electrons pass through the barrier by tunneling effect, maintaining phase coherence in the process.

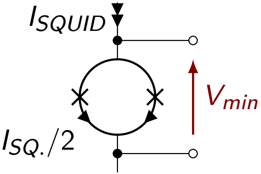
Current biasing controls **phase difference $\Delta\phi$ between the two superconductor** according $I = I_0 sin\Delta\phi$ leading to superconducting **phase modulation**.

Interferences

For $I > I_0$ ⇒ **voltage across the junction became >0**
Superconducting phase difference evolves evolves with time at the → **Josephson frequency :**

$$I \approx I_0 \sin\left(2\pi \frac{V}{\phi_0} t\right) \Rightarrow \frac{f}{V} = \frac{1}{\phi_0} \approx 500 MHz/\mu V$$

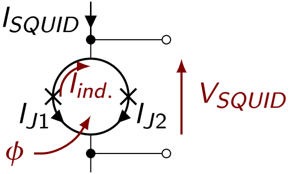
SQUID provides at low frequency, average value of interferences.



With no magnetic flux, the 2 junctions oscillate in phase
⇒ destructive interference.

Flux and superconducting phase shift

Magnetic flux leads to an additional phase shift $2\pi\frac{\phi}{\phi_0}$



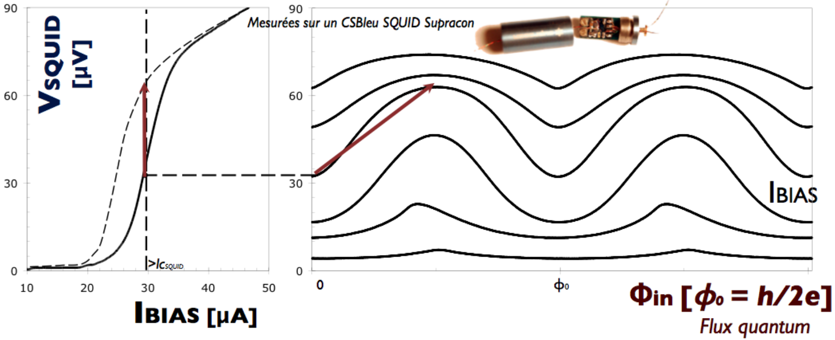
$$I_{J1} \approx I_0 \sin\left(2\pi\frac{V}{\phi_0}t - 2\pi\frac{\phi}{\phi_0}\right)$$

$$I_{J2} \approx I_0 \sin\left(2\pi\frac{V}{\phi_0}t + 2\pi\frac{\phi}{\phi_0}\right)$$

The two junctions are not in phase for $\phi \neq n\phi 0$ *(periodicity)*

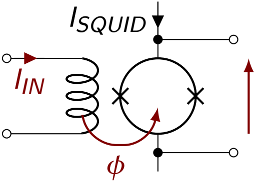
I(V) and V(ϕ) characteristic SQUID (Magnetometer)

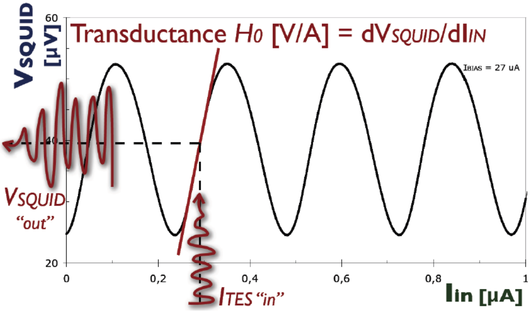
- Bias $< 2I_0$: no voltage
- Bias $> 2I_0$: SQUID has periodic (ϕ_0) characteristic V(ϕ)



SQUID as a trans-impedance amplifier

An input loop is used to convert I_{IN} in flux $\phi = \frac{I_{IN}}{M_{IN}}$:



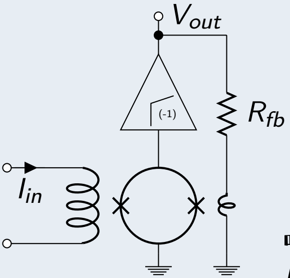


- Input impedance $= 0\ \Omega$
- Input noise $\approx$ pA$/\sqrt{Hz}$
- Trans-impedance gain $\approx$ 100 V/A

A flux feedback to linearize the SQUID characteristic

An other loop is usually used to compensate magnetic flux induced by I_{in}.

Flux Loked Loop

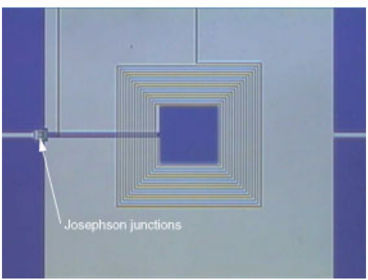


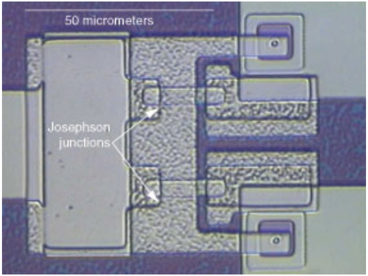
$$|H_{open}| = \left.\frac{V_{out}}{I_{in}}\right|_{open} = H_{0_{SQUID}} G_{Amp}.$$

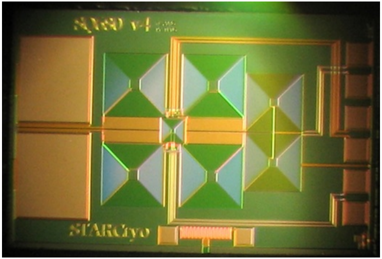
$$|H_{FLL}| = \left.\frac{V_{out}}{I_{in}}\right|_{close} = \boxed{\frac{M_{in}}{M_{fb}} R_{fb}}$$

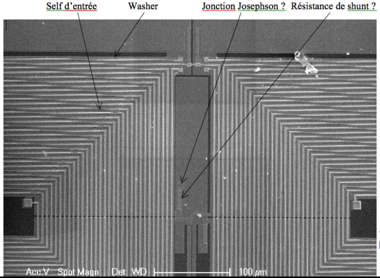
☞ Don't worry about the loop gain sign, H_0 is periodic !

Planar technology and gradiometry









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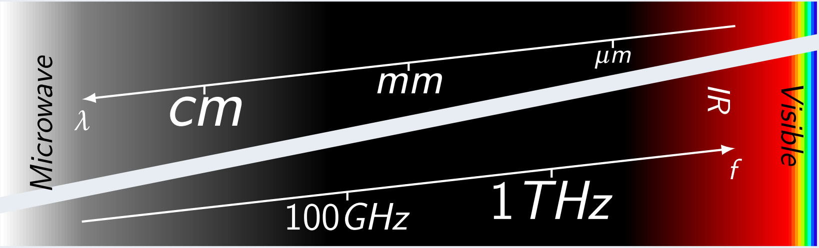
_mm_ domain corresponds to frequencies around 300 GHz ($\lambda = 1mm$)



coherent detection → ← Bolometry & Kinetic inductance → ← photo conduction

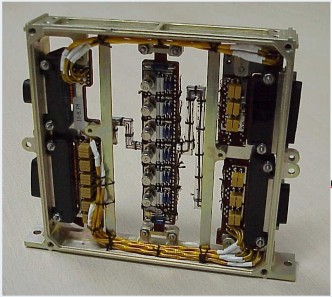
Main interest of the *mm* domain in cosmology :

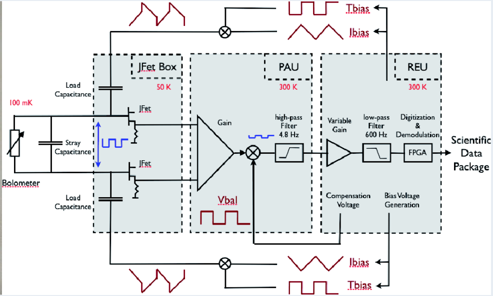
- Observation of the cosmic microwave background (CMB) thermal black body spectrum at a temperature of 2.7 K

The instrument is usually cooled to 100-300 mK ! !

The use of a cryogenic JFet stage for *mm* detection

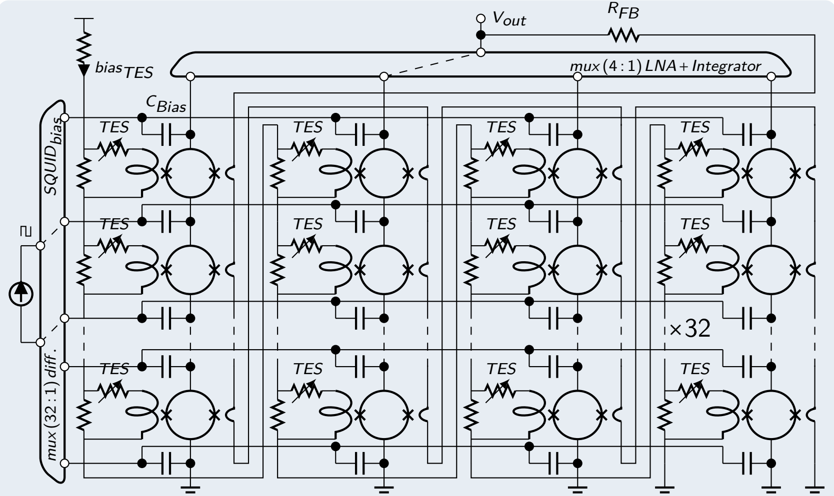
Planck-HFI JFet Box (Semicon. bolo. readout chaine) - NOT multiplexed





- JFET source followers to reduce the semicond. bolo impedance
- JFETs thermally insulated to keep the **optimal temperature of 110 K**
- 240 mW, mainly produced by the JFETs and the source resistors
- 3 $nV/\sqrt{Hz} \Longrightarrow$ less than 5% of the total readout noise

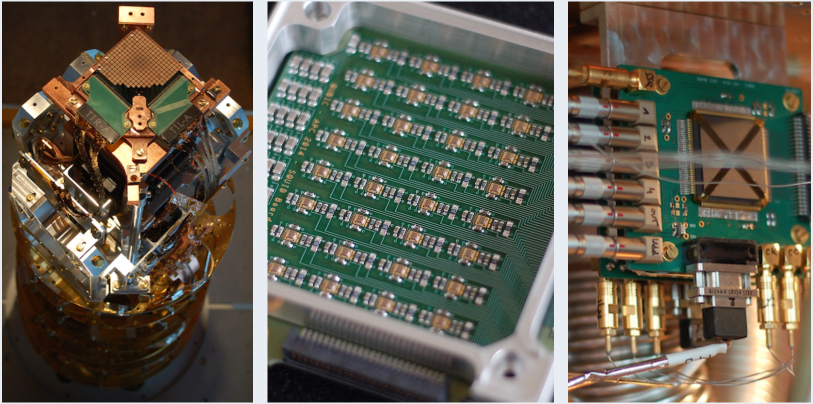
Cryogenic TES time domain multiplexer - QUBIC



D. Prêle, F. Voisin et al, "Capacitively-coupled SQUID Bias for Time Division Multiplexing", Journal of Low Temperature Physics, 2014

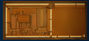
Cryogenic TES time domain multiplexer - QUBIC

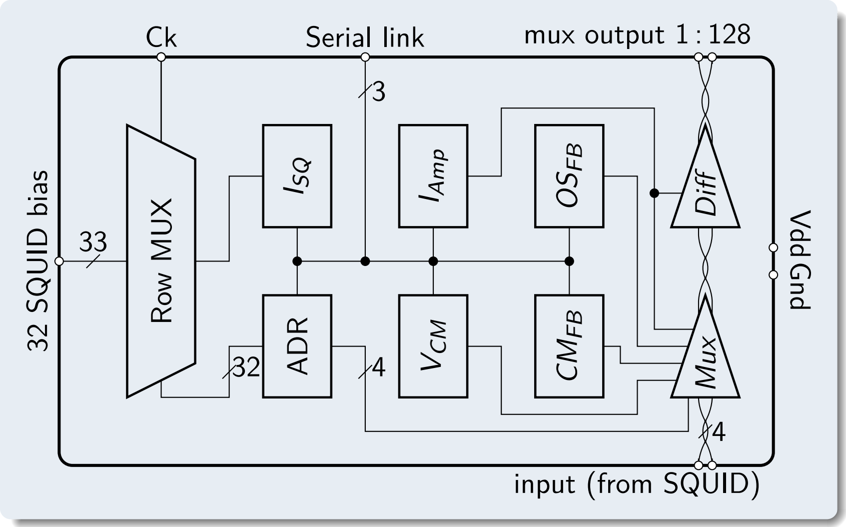
QUBIC readout chaine : TES (300 mK) + SQUID (1K) + ASIC (77K)



Correlated sampling on blind thermometers to remove 1/f noise

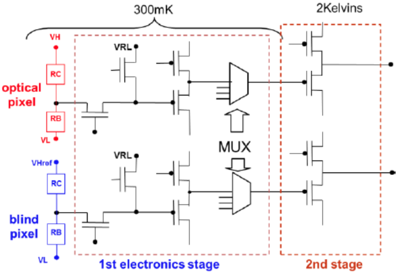
SiGe ASIC for cryogenic 1 :128 TDM

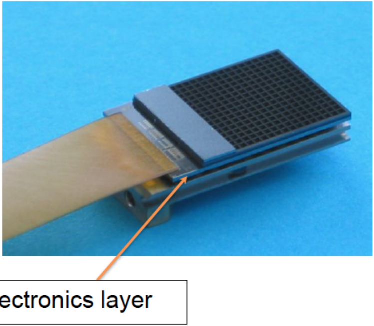




300 mK CMOS 1 :16 TDM - PACS/Herschel satellite

- **Double correlated sampling** to remove 1/f readout noise
- **Differential** measurement with blind pixels to remove the external collective perturbations.





P. Agnèse, L. Rodriguez, L. Vigroux et al. - CEA

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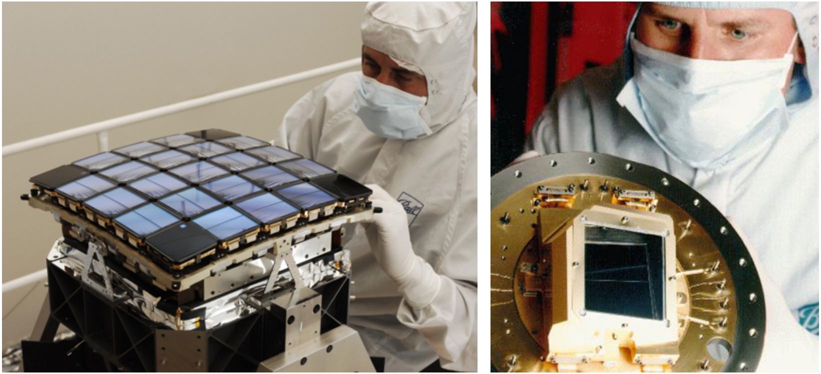
CCD (Charge Coupled Device) in astronomy

CCD is widely used in astronomy (examples : Kepler  and Hubble )

to achieved high-quality image despite a low photon flux

- high quantum efficiencies.



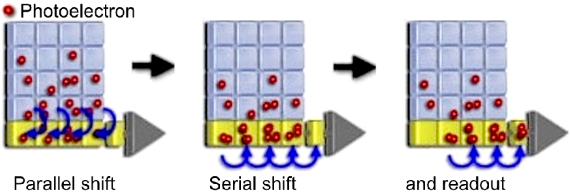
NASA/ESA and Ball Aerospace

CCD - Charge-Coupled Device : Charge Transfert ≡ TDM

- **CCD** was **invented in 1969** by Boyle & Smith - Bell Labs
- They were **Physics Nobel Prize 2009**, for the CCD concept

CCD technologies are based on array of sensors using photoelectric effect. However, **discovery of the law of the photoelectric effect** (photon to e^- conv.) is the **"Einstein Nobel Prize 1921"**

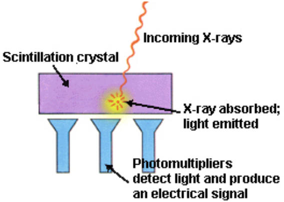
⇒ Reconised as new in the CCD, is the readout technic based on the **charge transfer** : *Parallel-in Serial-out shift register*

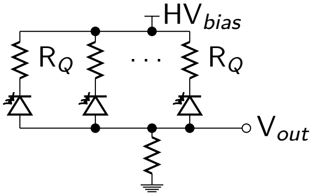


Photon sensitive detectors for "calorimetry"

Ultra sensitive detection and high energy astrophysics indirect detection

Solid state photomultiplier (SiPM) used for high energy calorimetry (measure of the energy of the high energy photon). SiPM are the **summation, with no modulation** of photon sensitive sensors.





SiPM cryogenic operation down to 77 K - D. Prele et al

Cooling required to decrease the noise (DCR)

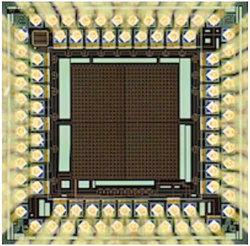
Some time due to natures of scintillators (Liquid xenon or argon for dark matter direct detection)

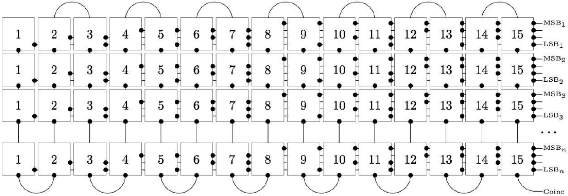
Photon sensitive imager

Gamma astro need to have the direction of the gamma sources.

A way to do that is proposed by the "gamma cube" concept The Gamma Cube : a novel concept of gamma-ray telescope - F. Lebrun et al..

A photon sensitive imager = a coding in the SiPM concept :





Sub array coding allows to determine what is the hit pixel. Operate with a very low photons flux The Gamma Cube : a new way to explore the gamma ray sky - F. Lebrun, R. Terrier, D. Prêle, D. Pellion et al

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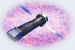
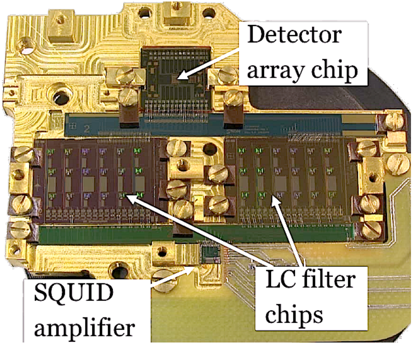
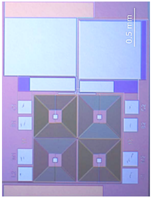
TES Frequency Domain Multiplexing

- Array of TESs (**Transition Edge Sensors**) are used in astronomy (mm and X-ray)
- Athena is a proposed ESA X-ray observatory



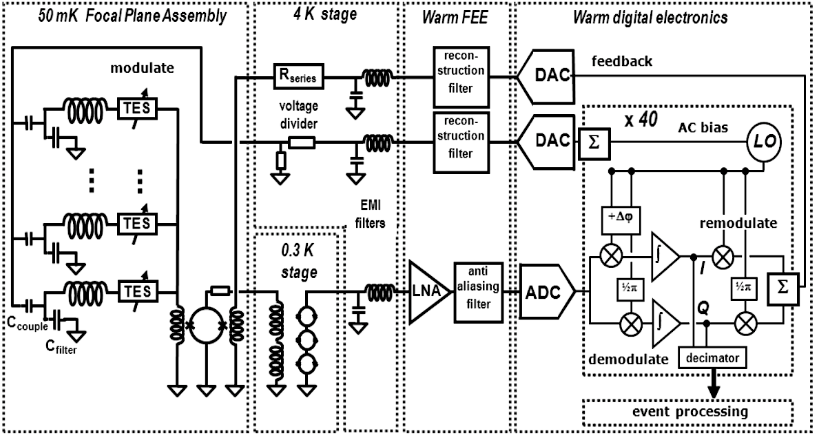
One of the instrument is based on **TES array + FDM** :





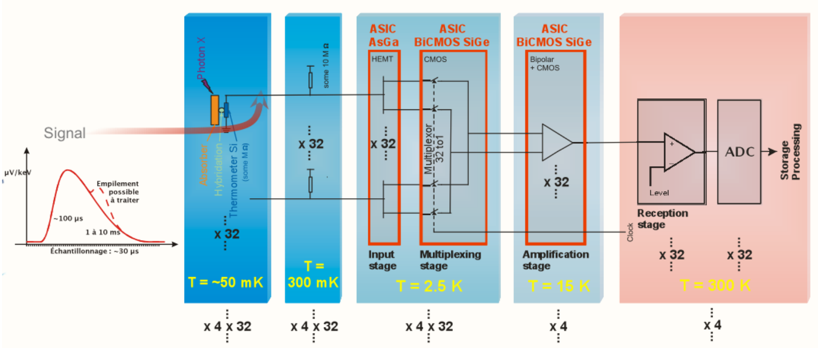
`SRON - Safari & Athena FDM demonstration`

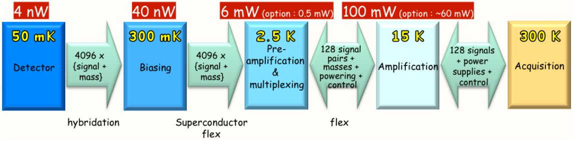
TES Frequency Domain Multiplexing - LC resonators

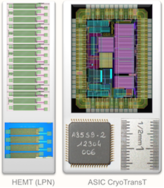


Athena XIFU BBFB - Hartog et Al

Xray microcalorimeter + TDM (HEMT + SiGe)







HEMT (LPN) ASIC CryoTransT

X. de le Broïse et al. - CEA SEDI

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