iNGage®
Disruptive Navigation Sensors



From Micro to Nano:

Technological breakthroughs and business opportunities

Andrea Buffoli
Cristiano Marra

CEA-Leti

Innovation pioneers





Key Figures

1,900 employees

€ 315 Million budget
(**85%** from R&D contract)

3 200 Patents portfolio
(**40%** under license - **300** patents/yr)

80+ Startups created
(**75%** in activity / **3 500+** jobs created)

8'' AND 12'' WORLD-CLASS FACILITIES



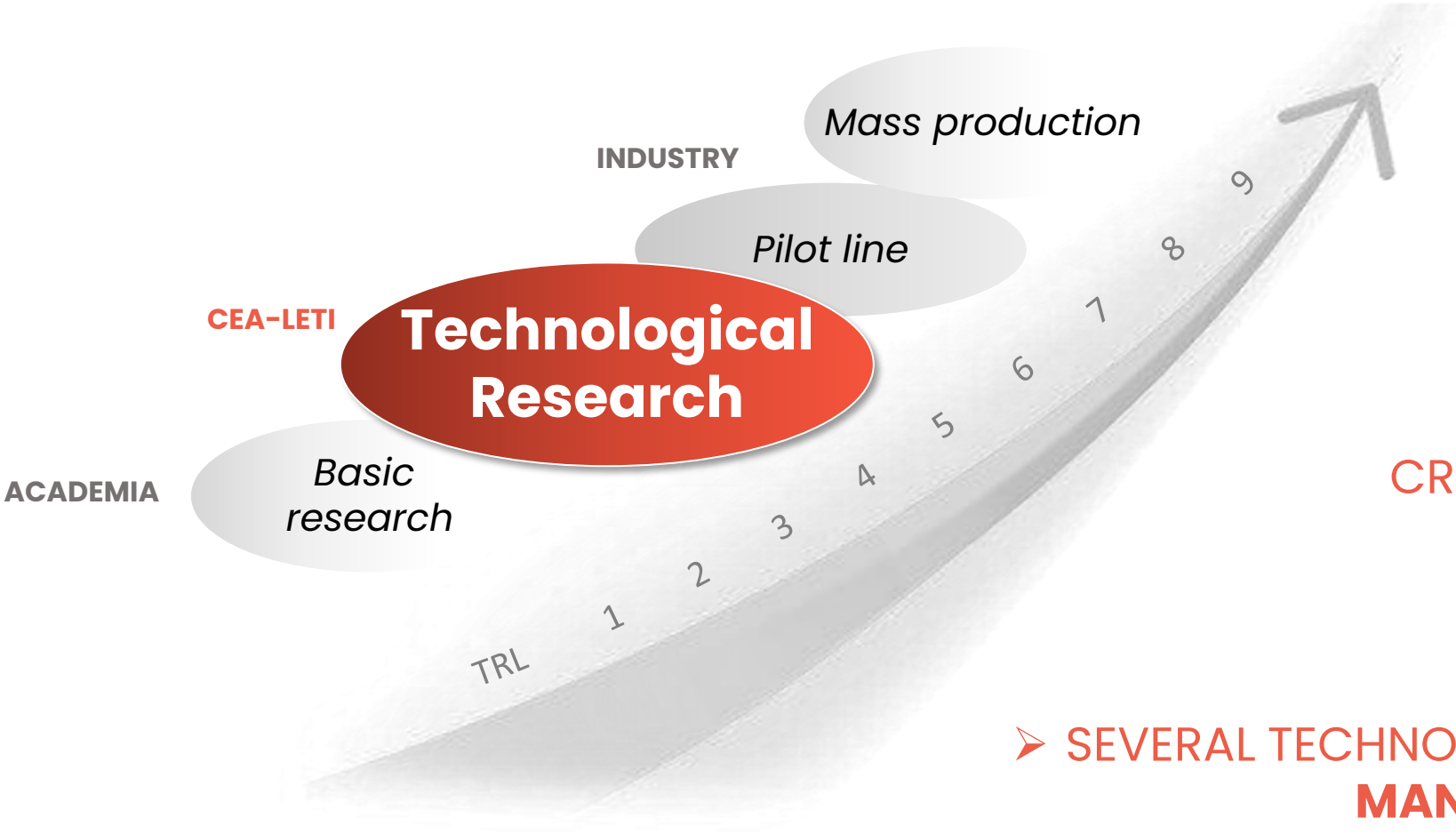
11.000 m² Silicon Platform

Advanced Electronics (sub-20 nm), **MEMS** and **3D**

Working 7days/week – 24h/days

CEA-Leti

Business model



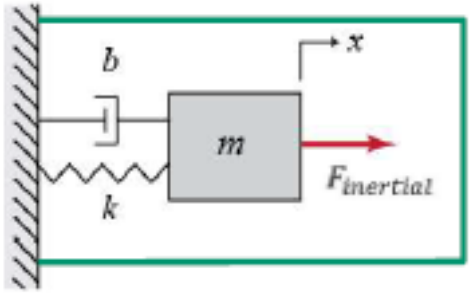
BRIDGING THE GAP BETWEEN ACADEMIA AND INDUSTRY

CREATE AND TRANSFER INNOVATION TO INDUSTRIAL PARTNERS

➢ SEVERAL TECHNOLOGICAL PLATFORMS DEVELOPED, **MANY OF WHICH IN THE MEMS FIELD**!

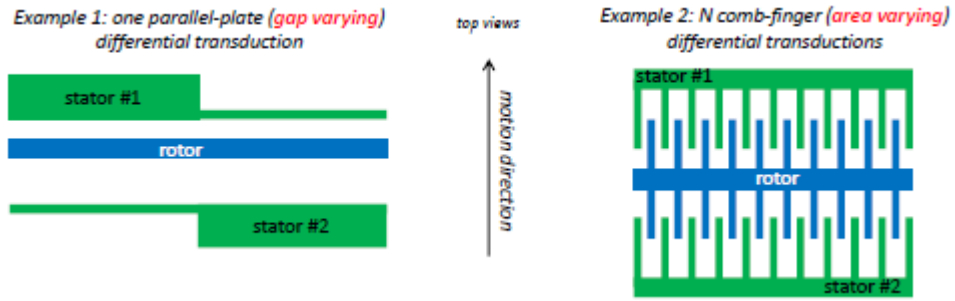
Capacitive MEMS sensors

Something you already know…

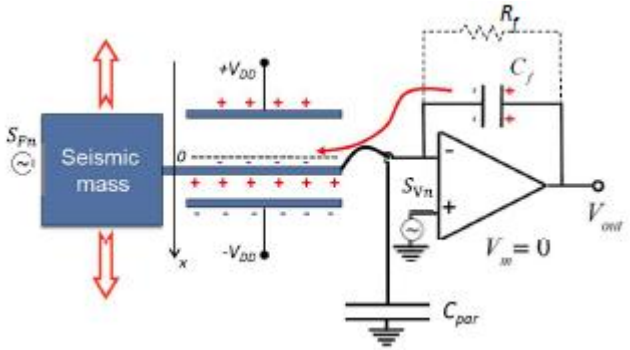


$$m\ddot{x} + b\dot{x} + kx = F_{inertial}$$

$$C = \frac{\varepsilon_0 A N}{g}$$



Accel example:



$$\Delta V_{out} = 2\frac{V_{DD}}{C_f}\frac{C_0}{g}x$$

$$x = \frac{1}{\omega_0^2}\,a_{ext}$$

$$\frac{\Delta V_{out}}{a_{ext}} = 2\frac{V_{DD}}{C_f}\frac{C_0}{g}\frac{1}{\omega_0^2}$$

$$S_{Vn,out} = S_{Vn}\left(1 + \frac{sR_fC_{par}}{1 + sR_fC_{par}}\right)^2$$

- **Capacitive** MEMS sensors are widespread in **consumer** and **automotive** applications nowadays;

BOSCH · life.augmented · SiTime · muRata INNOVATOR IN ELECTRONICS · TDK

- Very competitive **SWaP-C**
  - ✓ Low size
  - ✓ Low power
  - ✓ Low cost
- Anyways, there are some trade-offs affecting the performances:
  - × Area-Sensitivity trade-off
  - × Linearity
  - × Largely affected by capacitive parasitics

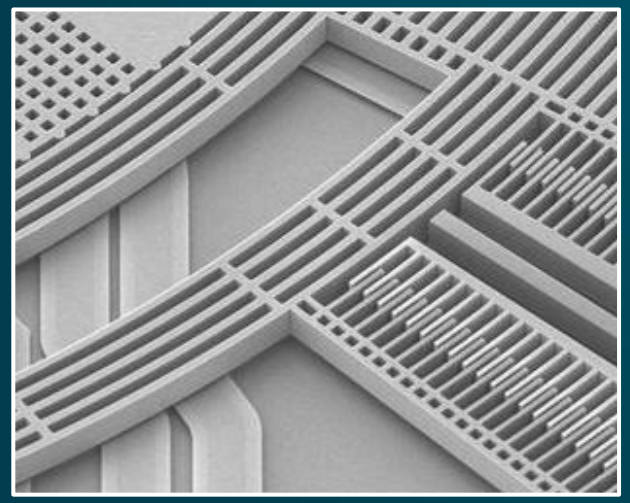
A 40 years' MEMS technology that needs a second wind

TODAY'S PROBLEM

MEMS capacitive sensors are limited by

- ✗ Small capacitance signal
- ✗ Parasitic capacitance noises

Leads to a <u>limitation on performances</u>



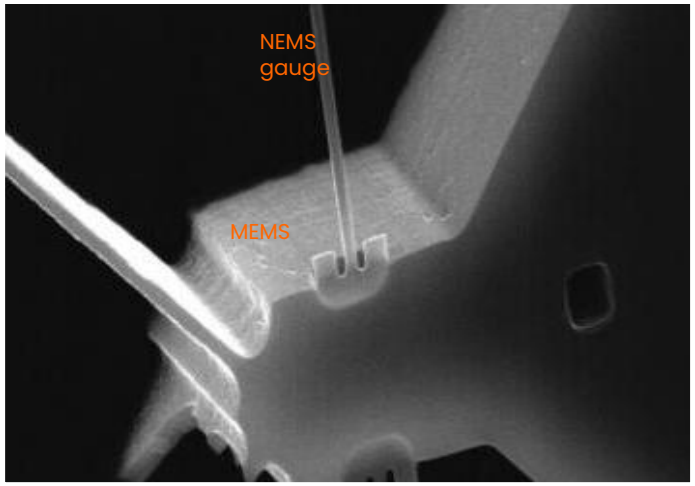
A technological breakthrough expected

OUR SOLUTION

NEMS-gauge coupled with **thick MEMS** structure

- ✓ Very high sensitivity
- ✓ Not sensitive to parasitic capacitance

➢ **M&NEMS technology**

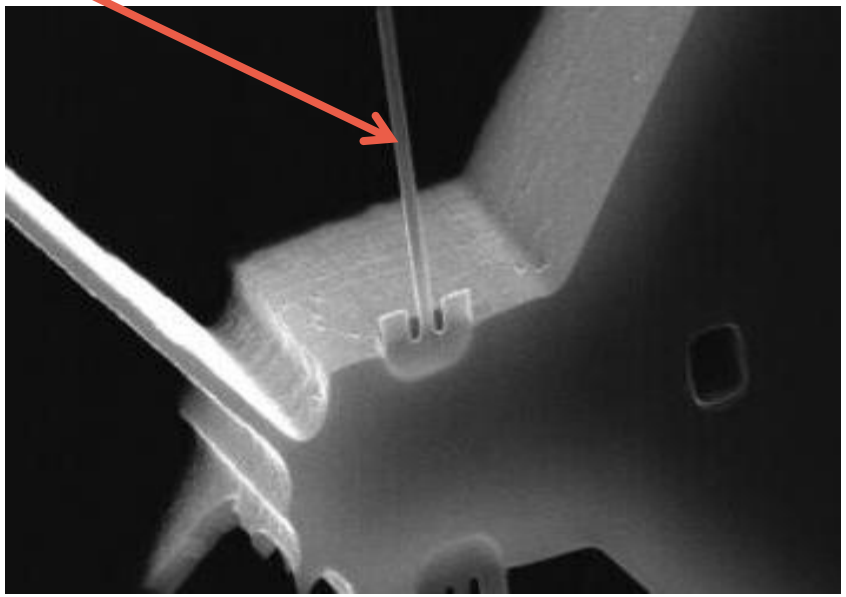


CONFIDENTIAL

M&NEMS

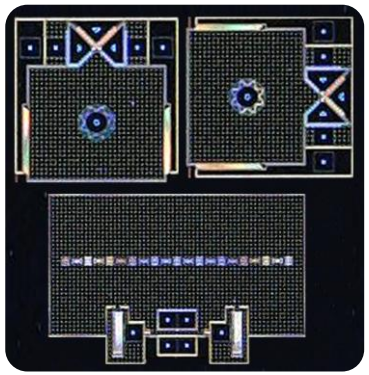
A universal sensor platform

Few $100x100\ nm^2$

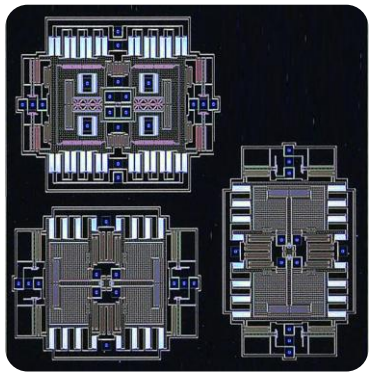


A differentiating and effective solution

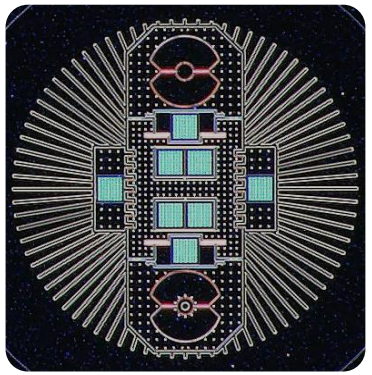
- **Ultra-Sensitive piezoresistive NEMS-gauge** detection (high stress concentration) coupled with thick MEMS structure
- Demonstration of **high performance multi-sensor** co-integration
- Ultra-miniature, compatible with "**High-Volume Market**"



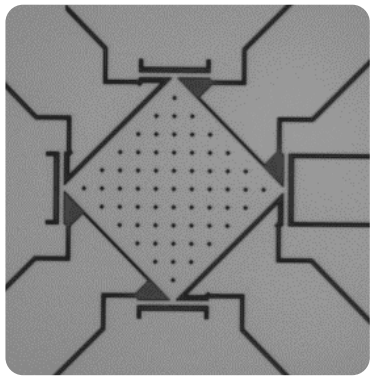
3-axis Accelerometer



3-axis Gyroscope



Pressure sensor



100 MHz Time Reference resonator

SAME TECHNOLOGY

Piezoresistive effect

- Resistance variation of a metal or semiconductor due to compression or elongation:

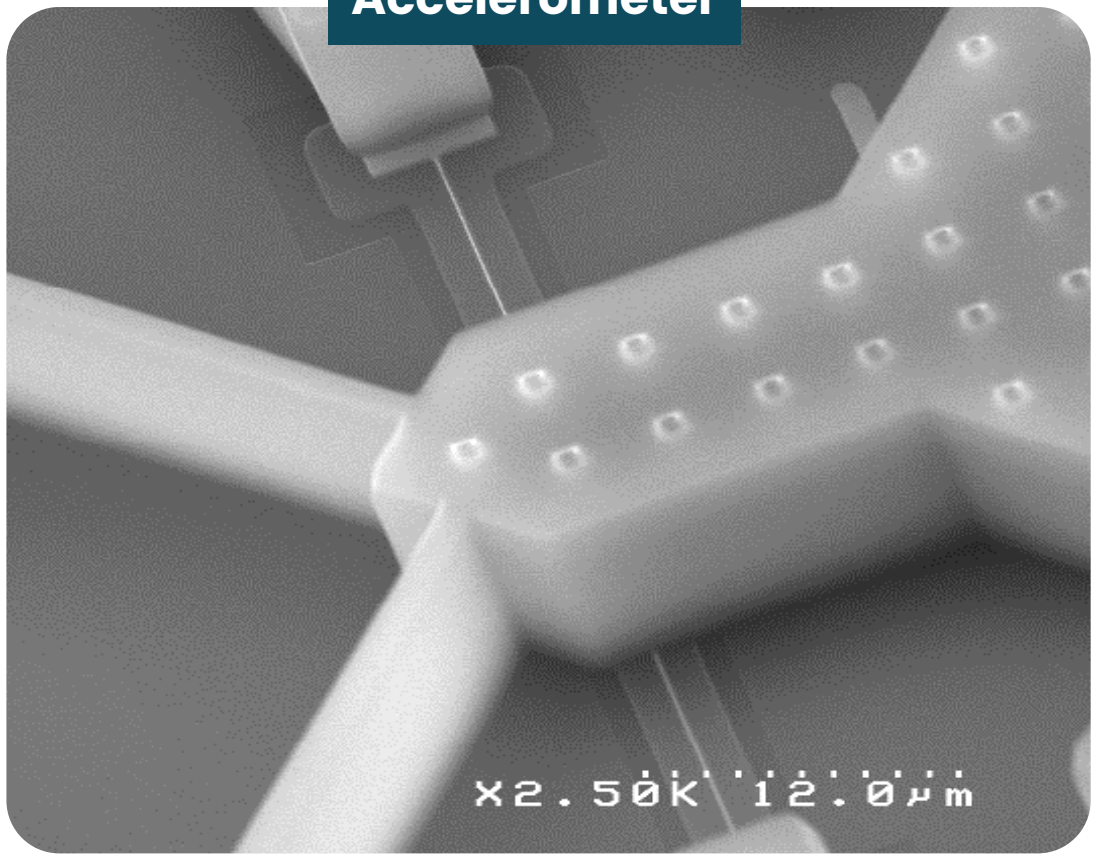
1. Geometrical → metal
2. Resistivity variation → semiconductors

$$R = \rho \cdot \frac{L}{A}$$

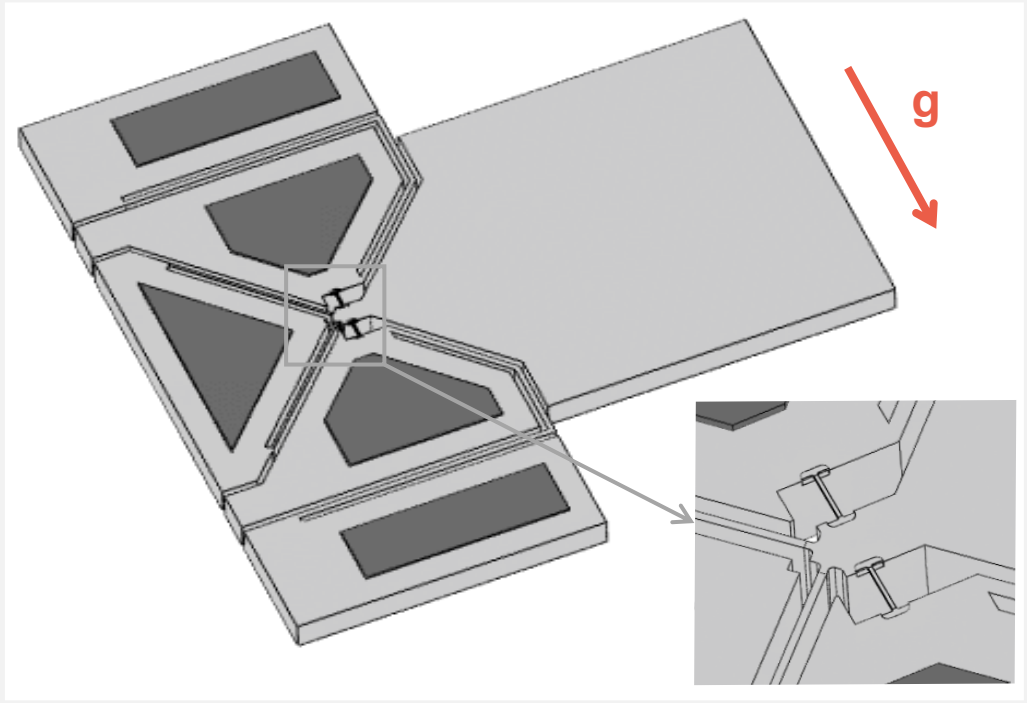
M&NEMS

Working principle

Accelerometer



Working principle

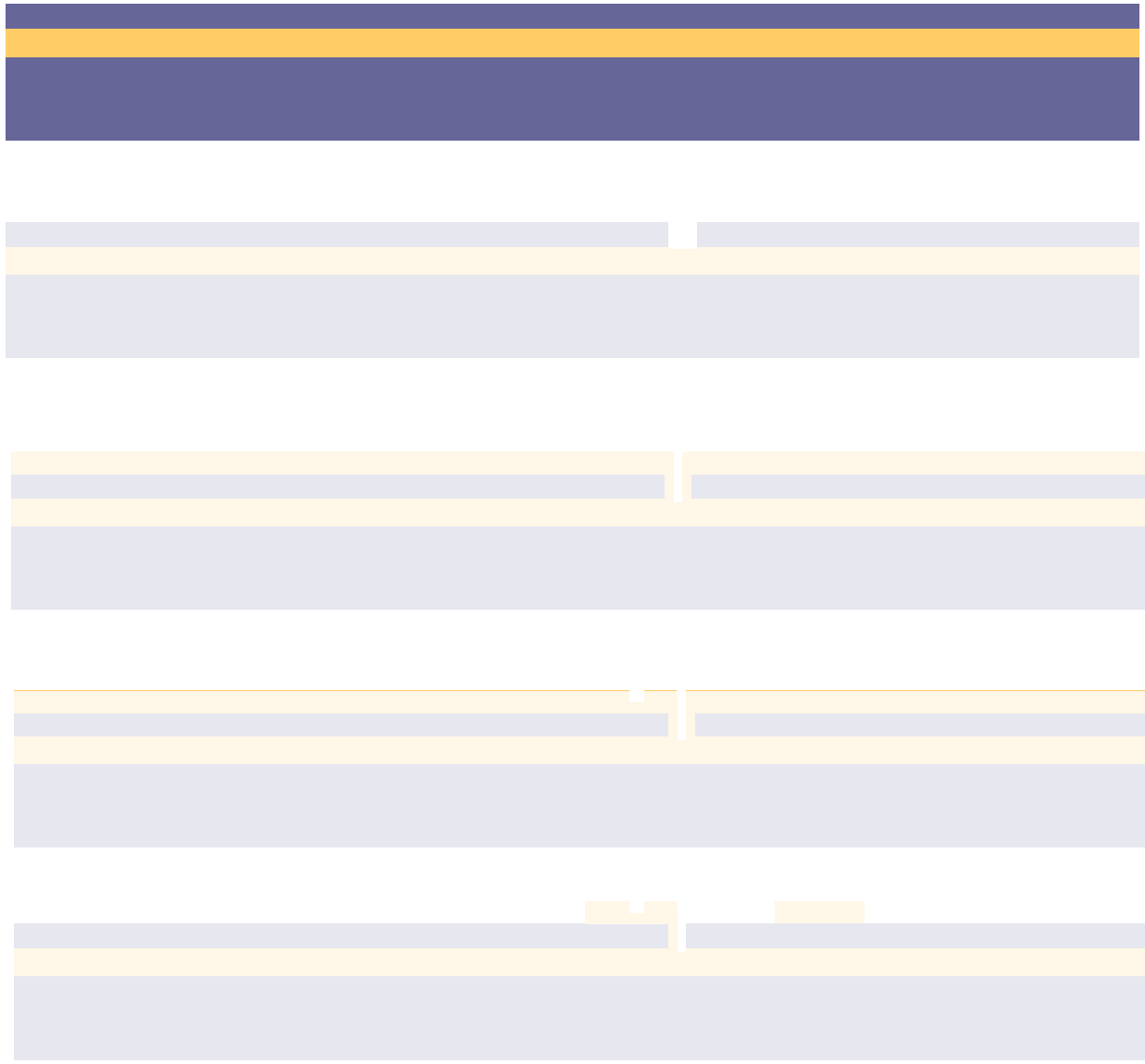


External acceleration → resistance variation $\Delta R/R$

Stress magnification induced by the nano-gauges x100

UNIVERSAL MEMS PLATFORM

Process-flow



SOI substrate + **BOX** : 2µm
NEMS layer: monocrystalline highly p-doped Si (250-500nm)
NEMS silicon implant (Boron) (5E19 at/cm^3)

NEMS lithography and **etching**

NEMS protection oxide deposition

Stopper lithography
(Oxide partial etching)

Protection lithography
(Oxide etching)

UNIVERSAL MEMS PLATFORM

Process-flow



Bulk contacts lithography
(NEMS layer + BOX etching)

MEMS layer: Doped **Silicon epitaxial growth** (Boron - <25µm)

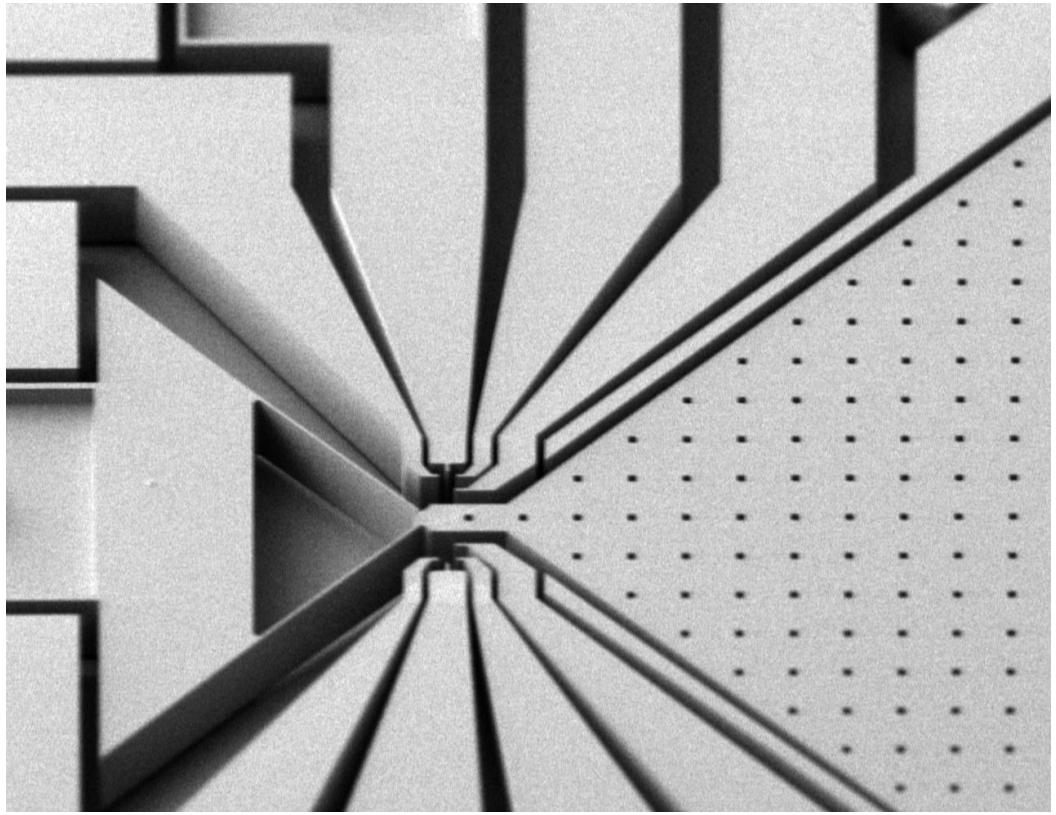
Silicon planarization
To grant uniform thickness

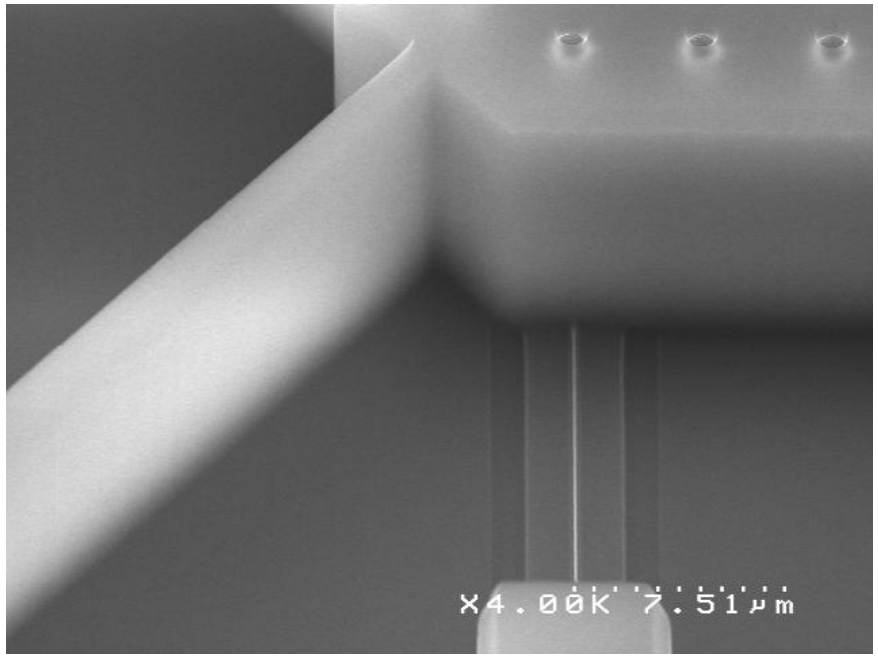
UNIVERSAL MEMS PLATFORM

Process-flow



MEMS lithography
Photoresist mask
Deep Reaction Ion Etching (DRIE) of silicon



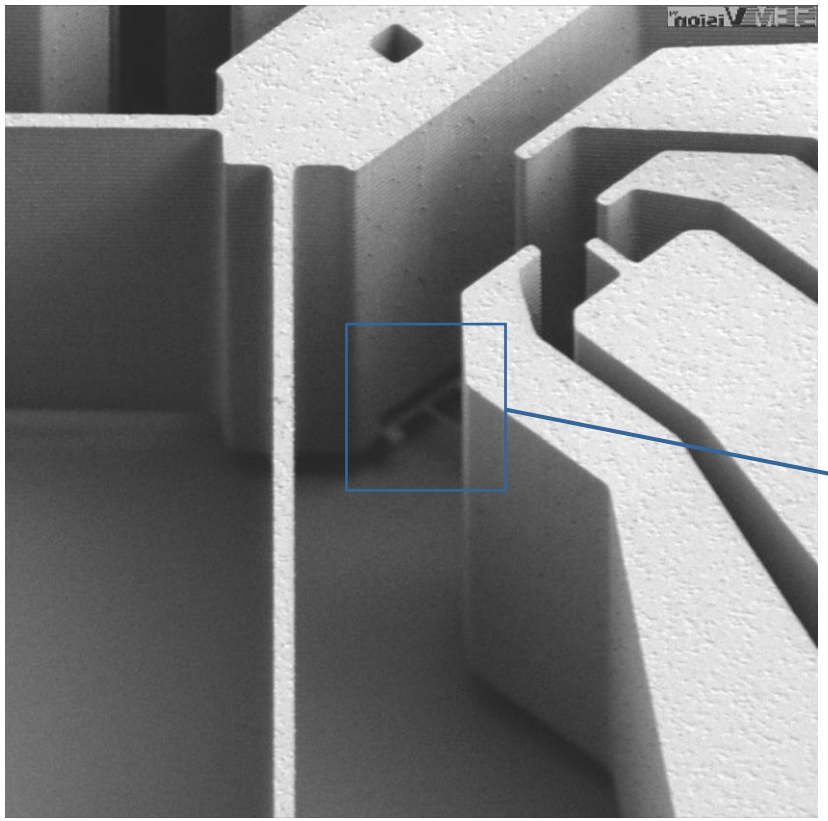


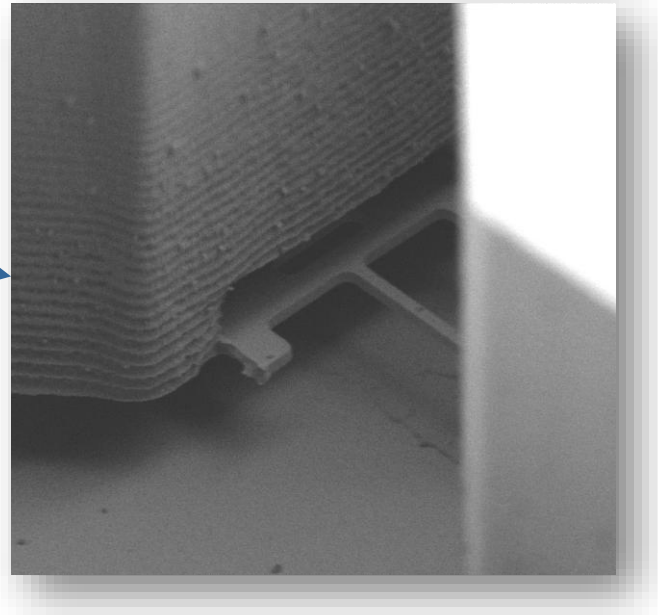
UNIVERSAL MEMS PLATFORM

Process-flow



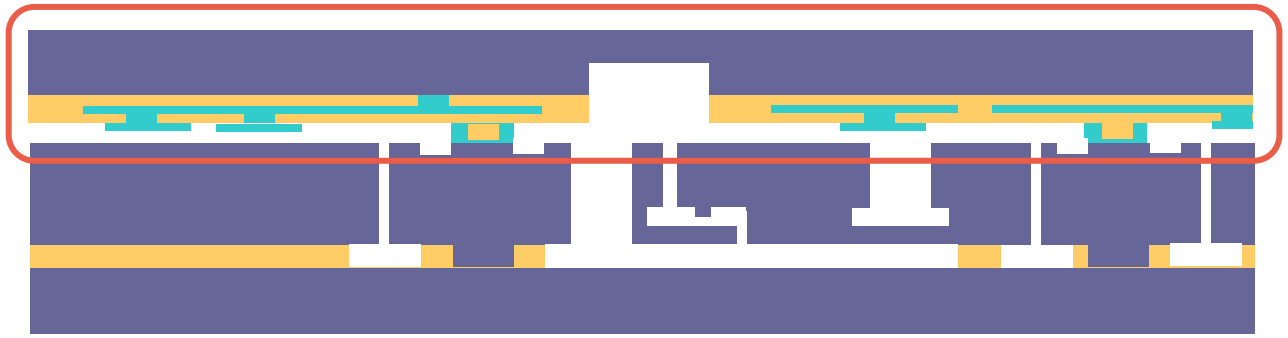
Vapor HF release





UNIVERSAL MEMS PLATFORM

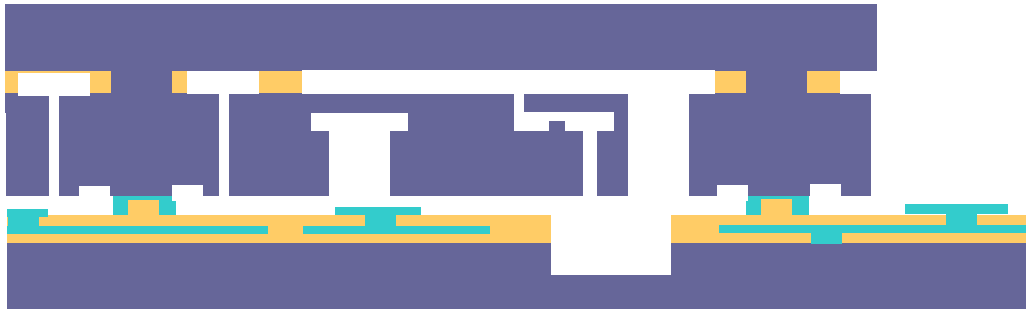
Process-flow

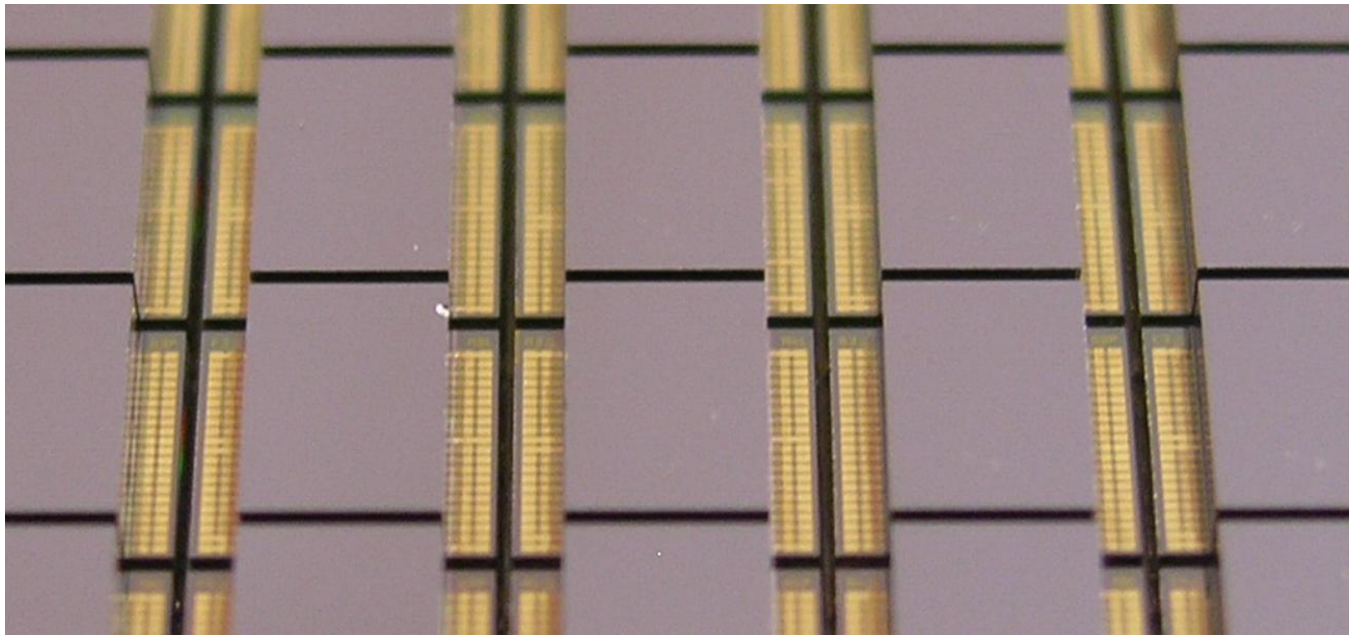


CAP wafer: polysilicon substrate; 2 metallic (Alu) levels (one buried, one exposed); cavity+getter

CAP/MEMS Wafer Level Packaging: AlGe eutectic bonding

Flip Wafer
Saw To Reveal process to reveal bonding pads

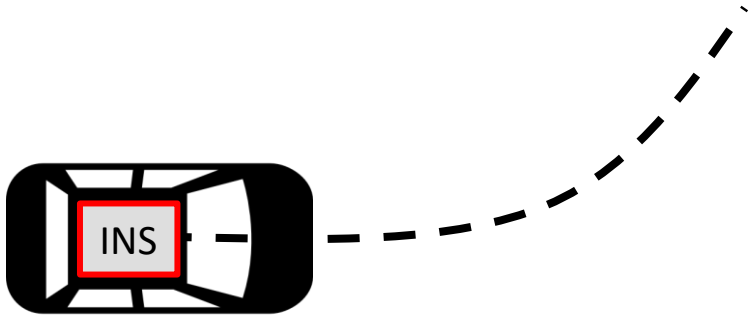




Why MEMS inertial sensors?

- **Inertial Navigation System (INS)** → exploit accelerometers and gyroscopes (i.e. **inertial sensors**) to calculate position, orientation and velocity (direction and speed) of a moving object, starting from its initial location (**dead reckoning**), and provide estimate future positioning, without the need for external references (GNSS/GPS);

- Gyroscopes, accurately sense the **angular velocity** Ω of an object, and are typically classified depending on their working principle and their **noise (ARW)** and **stability (BI)** performance



Grade	Angle Random Walk	Bias Instabilty
Consumer	$> 5\ °/\sqrt{h}$	$> 10\ °/h$
Automotive	$< 0.5\ °/\sqrt{h}$	$< 10\ °/h$
Industrial	$< 0.5\ °/\sqrt{h}$	$1 - 10\ °/h$
Tactical	$0.05 - 0.005\ °/\sqrt{h}$	$0.01 - 1\ °/h$
Navigation	$< 0.005\ °/\sqrt{h}$	$< 0.01\ °/h$
Strategic	$< 0.0003\ °/\sqrt{h}$	$< 0.001\ °/h$

FOG

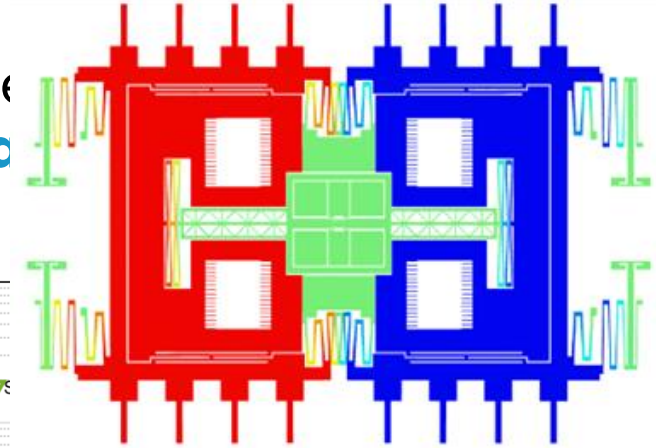


Volume $> 20{\times}20{\times}10\ cm^3$
Weight $> 5\ kg$
Power $> 10\ W$

HRG

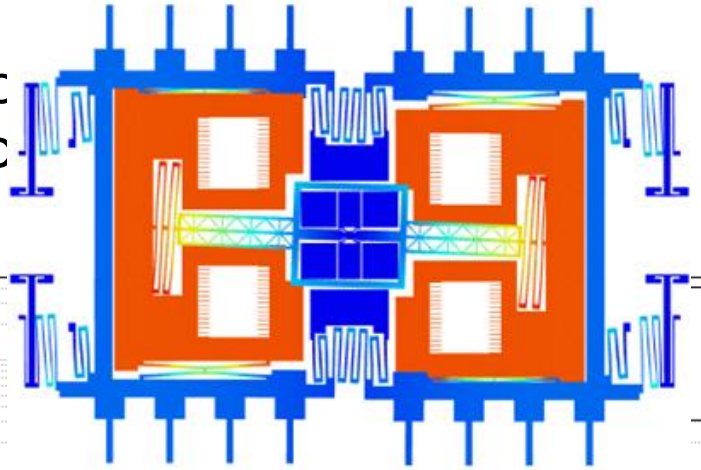


Towards navigation grade MEMS gyroscopes



➢ In the gyroscope market experienc
expo being MEMS navigation comp

$$\overrightarrow{F_{COR}} = -2m\overrightarrow{v_D}\times\overrightarrow{\Omega_Z}$$



$t_{NG} = (250\ nm)^2$
$L_{NG} = 5\ \mu m$
$R_{NG} = 2.4\ k\Omega$

Nano-gauge

Lever

- Drive and sense motions are deamplified, through apposite levers by a factor Γ, and transferred to PZR nanogauges.
- The gauges are thus elongated/compressed by ΔL_{NG} at frequency ω_D, resulting in a resistive variation induced by the stress.

$$\frac{\Delta R_S}{R_S} = GF\frac{\Delta L_{NG}}{L_{NG}} = GF\frac{\Gamma_S}{L_{NG}}y_0(\Omega)\sin(\omega_d t)$$

M&NEMS gyrosocopes

Basics

- Several **advantages** over the capacitive counterpart:

$$\begin{bmatrix} m_x & 0 \\ 0 & m_y \end{bmatrix}\begin{bmatrix} \ddot{x} \\ \ddot{y} \end{bmatrix} + \begin{bmatrix} b_x & b_{xy} \\ b_{xy} & b_y \end{bmatrix}\begin{bmatrix} \dot{x} \\ \dot{y} \end{bmatrix} + \begin{bmatrix} k_x & k_{xy} \\ k_{xy} & k_y \end{bmatrix}\begin{bmatrix} x \\ y \end{bmatrix} = -2\alpha\Omega_Z \begin{bmatrix} 0 & -m_x \\ m_y & 0 \end{bmatrix}\begin{bmatrix} \dot{x} \\ \dot{y} \end{bmatrix} + \begin{bmatrix} F_{dx} \\ F_{dy} \end{bmatrix}$$

angular gain → $\alpha = \frac{m_{Cor}}{\sqrt{m_x m_y}}\sqrt{\frac{k_x}{k_y}}$

1) Low capacitive feedthrough and parasitics/drifts;
2) Low operating voltages (max. 5 V);
3) High sensitivity through **piezoresistive NEMS sensing elements**;
4) Same readout elements for both drive and sense;
5) Larger area available for quadrature compensation electrodes

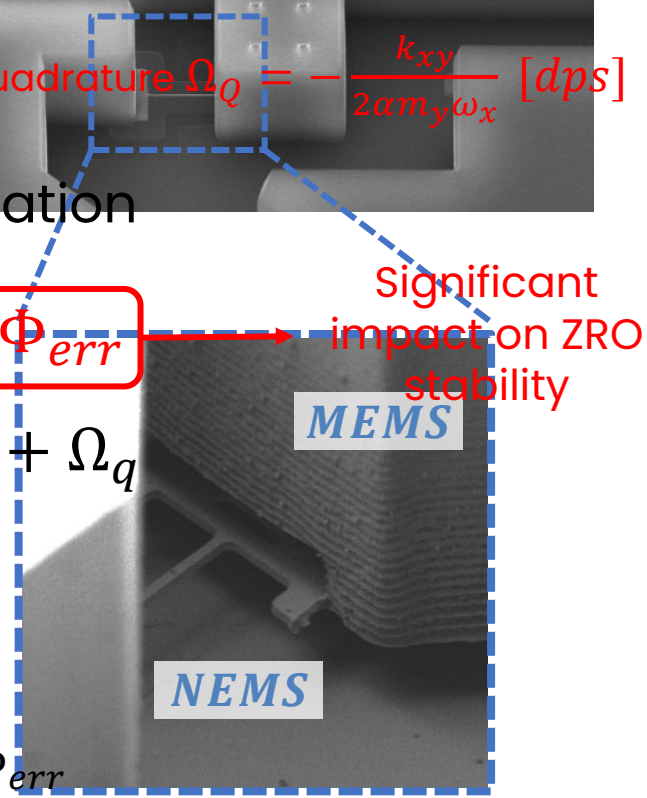
Cross-axis stiffness → quadrature $\Omega_Q = -\frac{k_{xy}}{2\alpha m_y \omega_x}\ [dps]$

- Output signal is modulated at the drive frequency → I/Q demodulation

$$I = \Omega_{in} \cdot \cos(\Phi_{err}) + \Omega_q \cdot \sin(\Phi_{err}) \approx \Omega_{in} + \Omega_q \Phi_{err}$$

$$Q = \Omega_{in} \cdot \sin(\Phi_{err}) + \Omega_q \cdot \cos(\Phi_{err}) \approx \Omega_{in}\Phi_{err} + \Omega_q$$

Significant impact on ZRO stability

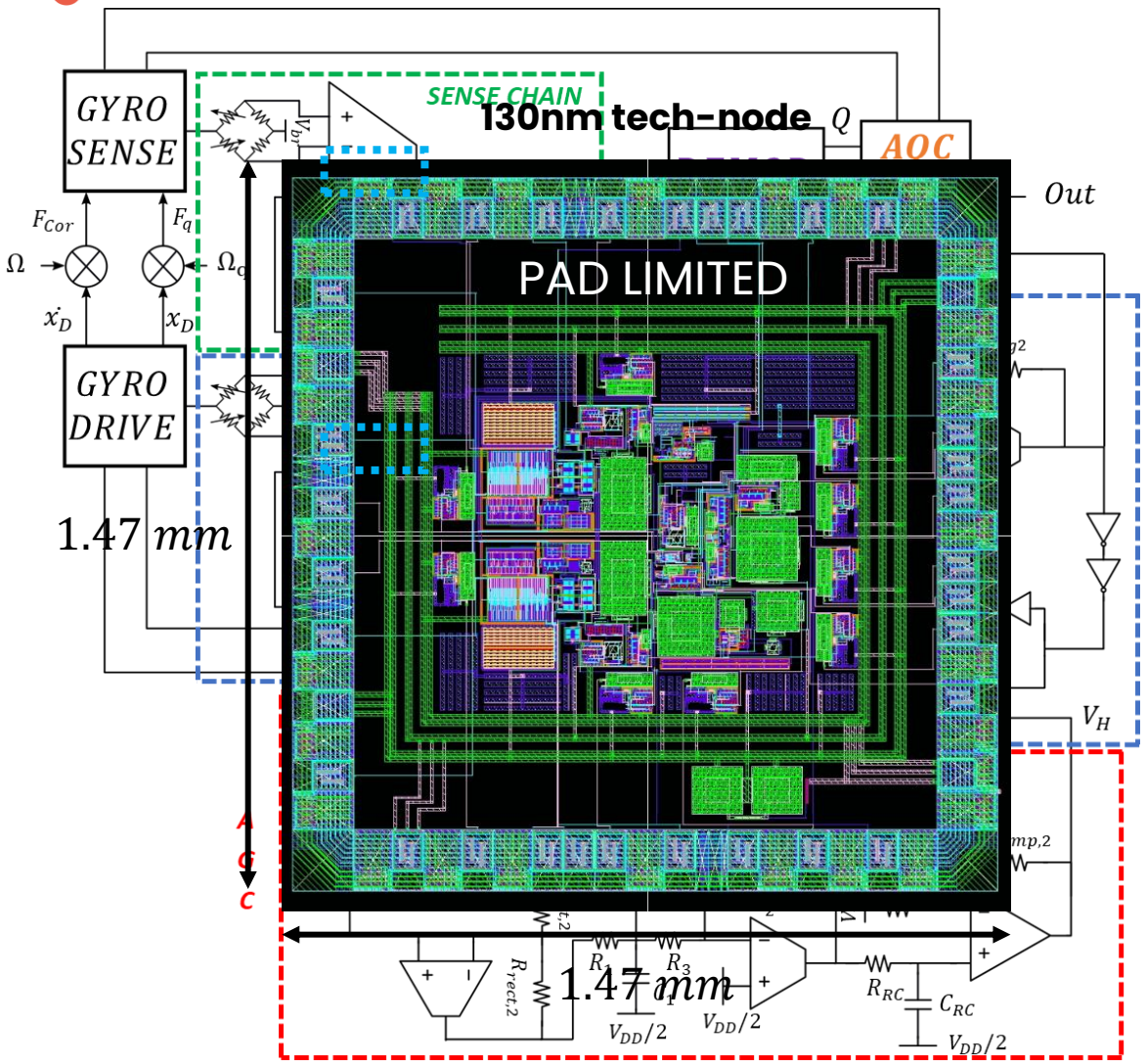


- Thus, for high-end application requiring long-term accuracy:
  1. Quadrature compensation;
  2. Demodulation phase trimming;

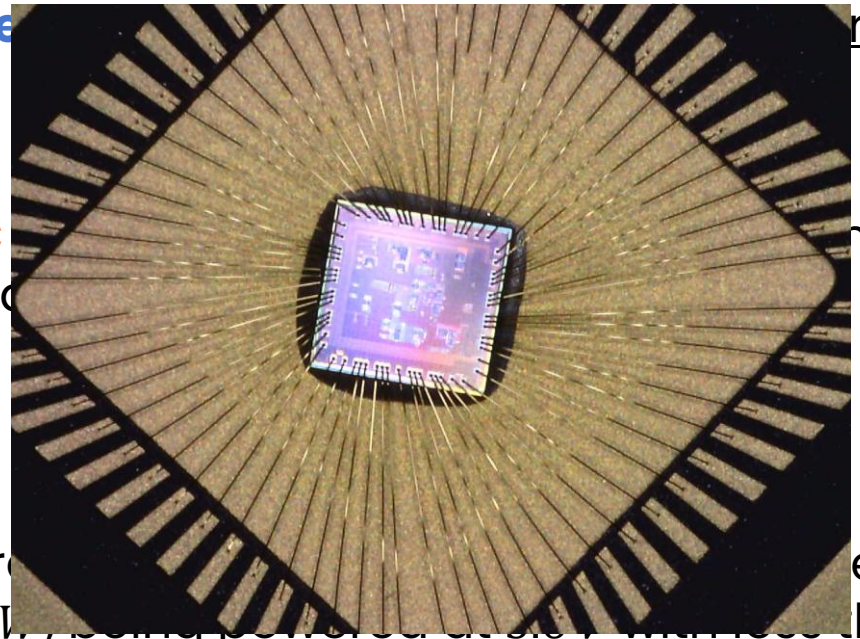
} To minimize both Ω_q and Φ_{err}

M&NEMS gyroscopes

System - Analog

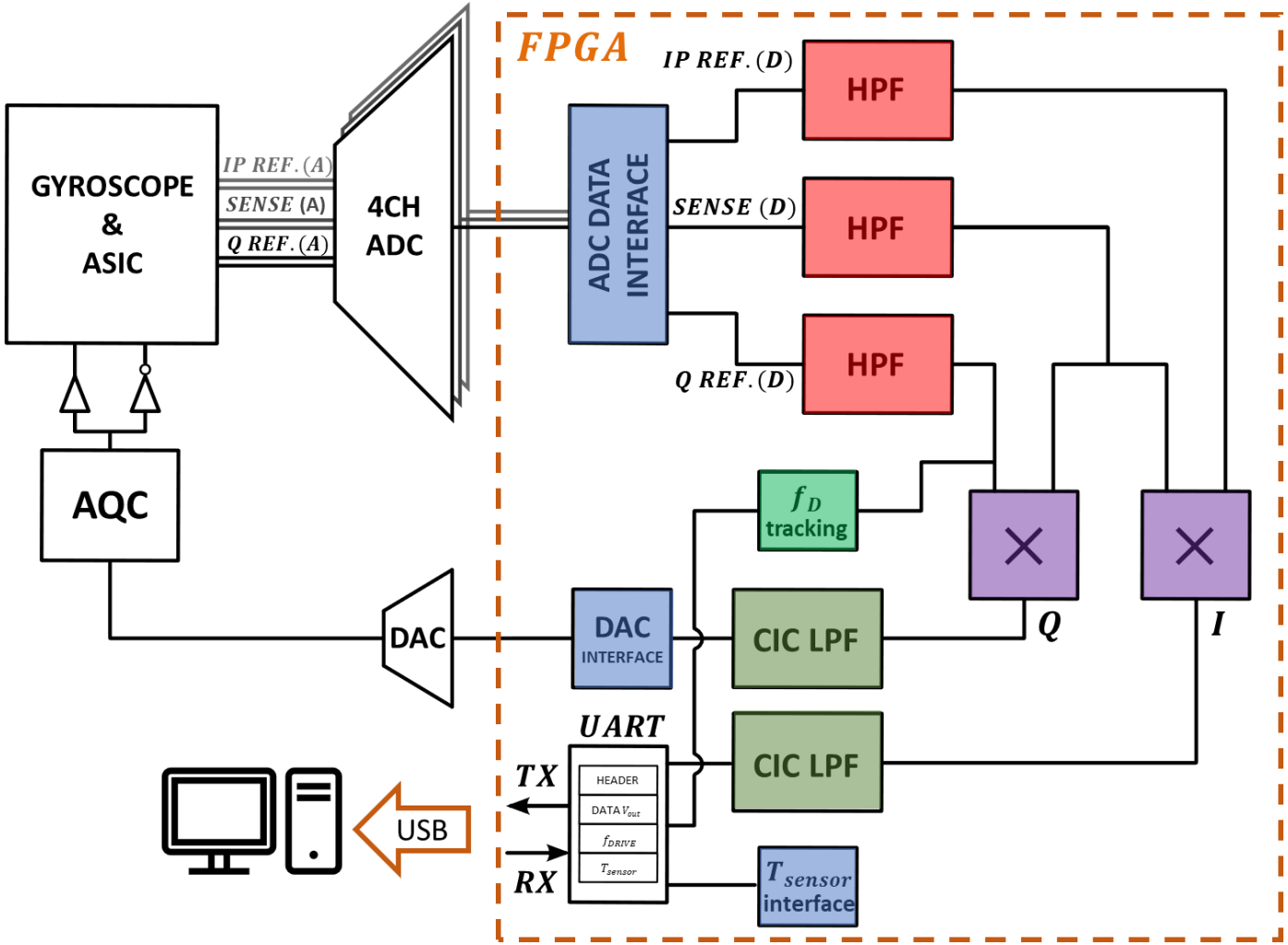


- **Ultra-low noise CFIA (analog front-end)**
- **Drive** rated
- **AQC** n the digit
- Over ess 40 mW, han 7 mA drawn current (comprising the guages current) → for navigation-grade single axis gyroscope current consumption > 25 mA

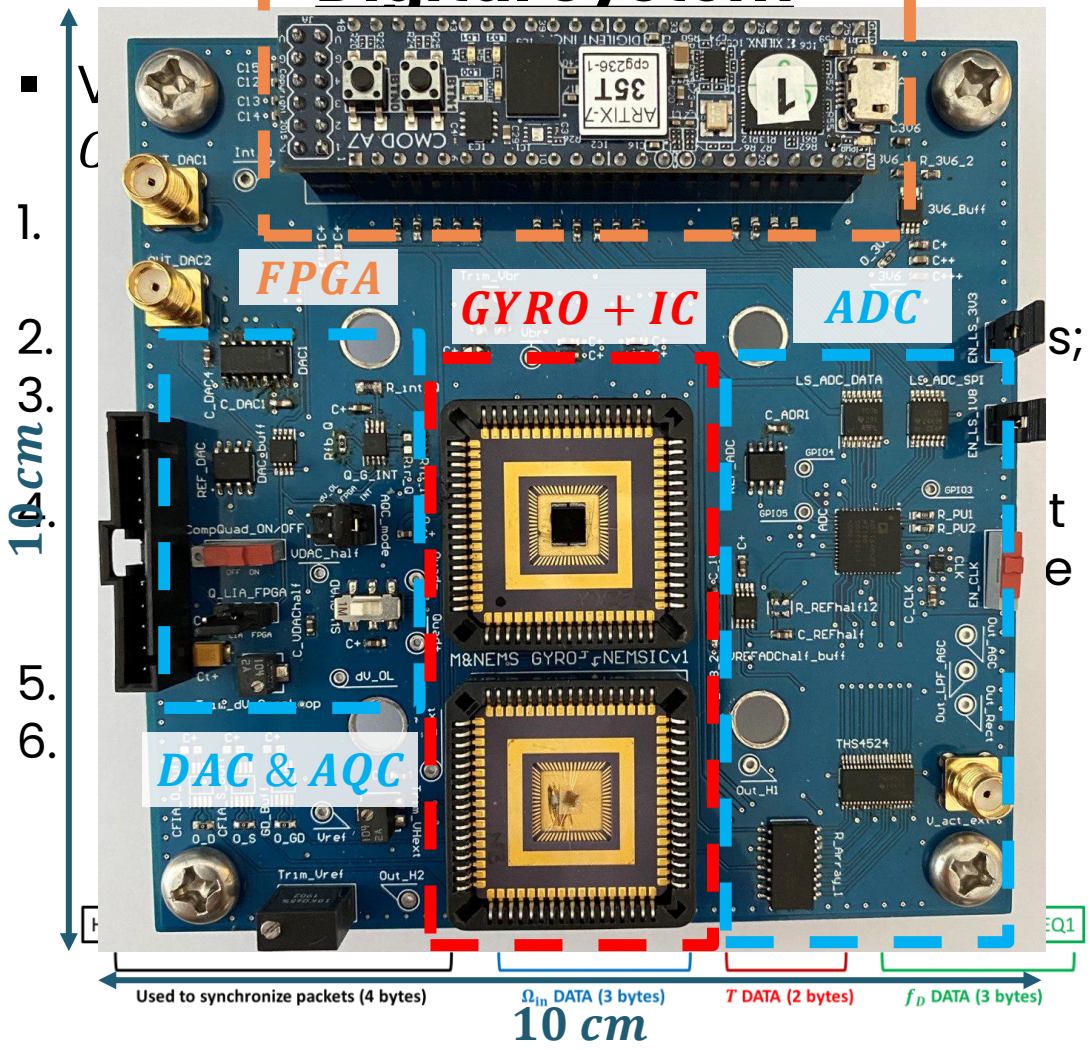


M&NEMS gyroscopes

System – Digital

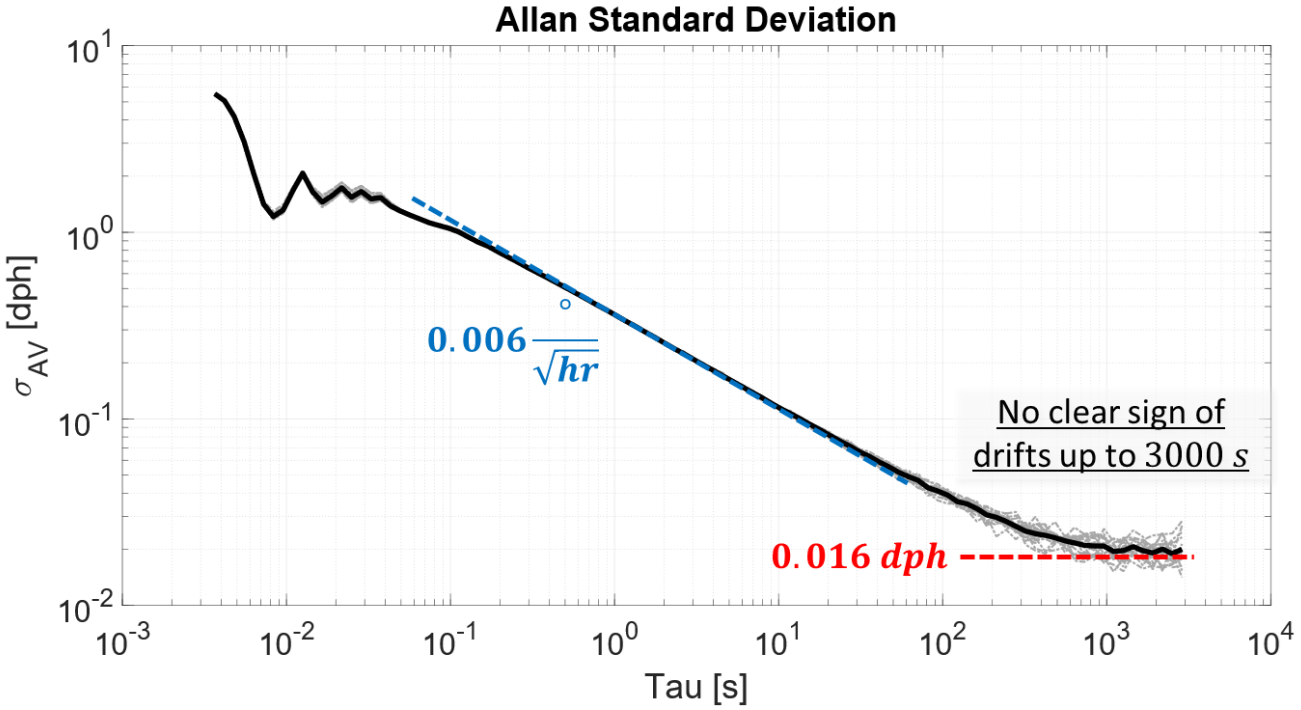


Digital System



M&NEMS gyroscopes

Performance



Allan Deviation tests show near navigation grade performance

- 5 days of consecutive measurement segmented into 8-hours acquisitions

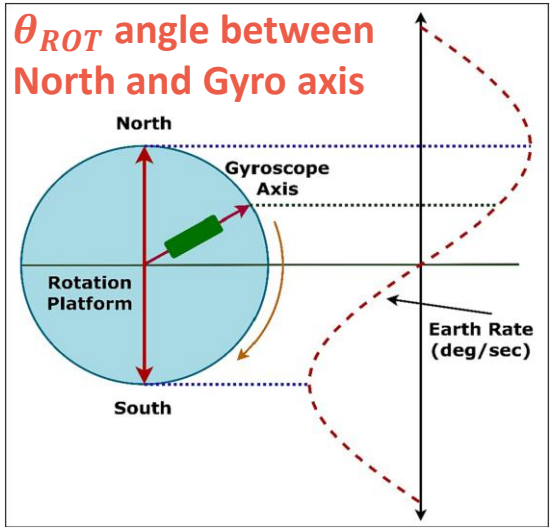
Table on the right showing that our solution compares with the best products/prototypes in the market/literature

- Validated by a key navigation player

		ARW [°/√hr]	BI (25°C, 1000 s) [°/hr]	T.O.T.O. [°/hr rms]	ZRO Temperature Residual [°/hr rms]
Tronics GYPRO 3300 (product)		0.14	0.8	10	70
Safran STIM300 (product)		0.15	0.4	4	9
Honeywell HG7930 (prototype)		0.0035	0.01	±0.1	0.2
This work (prototype)		0.006	0.02 (uncalibrated)	1	6

M&NEMS gyroscopes

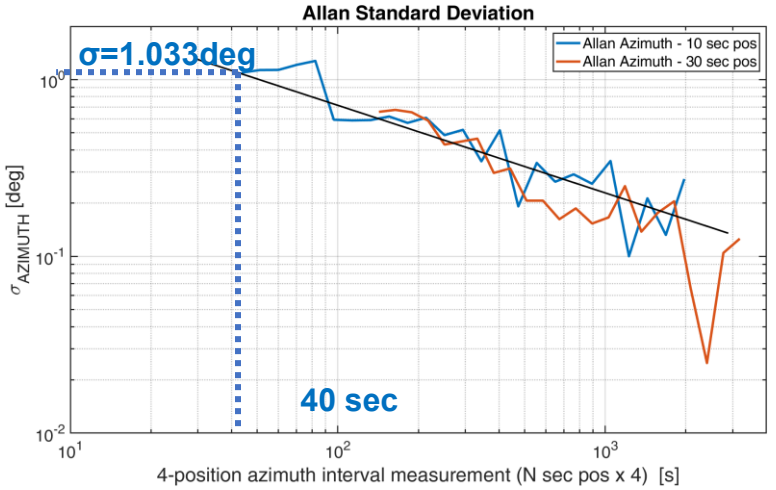
An application example: North-finding



$$GYRO_{OUT} = \Omega_{EARTH} \cdot \cos(\theta_{LAT}) \cdot \cos(\theta_{ROT})$$

- **North-finding** is a key application in navigation (autonomous mobility, …) and exploration (drilling, mining, oil and gas exploration). The **need** is for precise and robust inertial sensors.
- Currently, **FOG** and analog **quartz accelerometers** are used.
  - constrained dimensions (vehicles, drones, drilling tubes, …) and cost-efficiency raise a demand for a **low SWaP-C alternative**.

- MEMS technologies are now demonstrating challenging performances at a fraction of the price, size and power.
- **M&NEMS technology being among the most promising.**
  - ≈ 1 deg azimuth accuracy in 40 sec acquisition



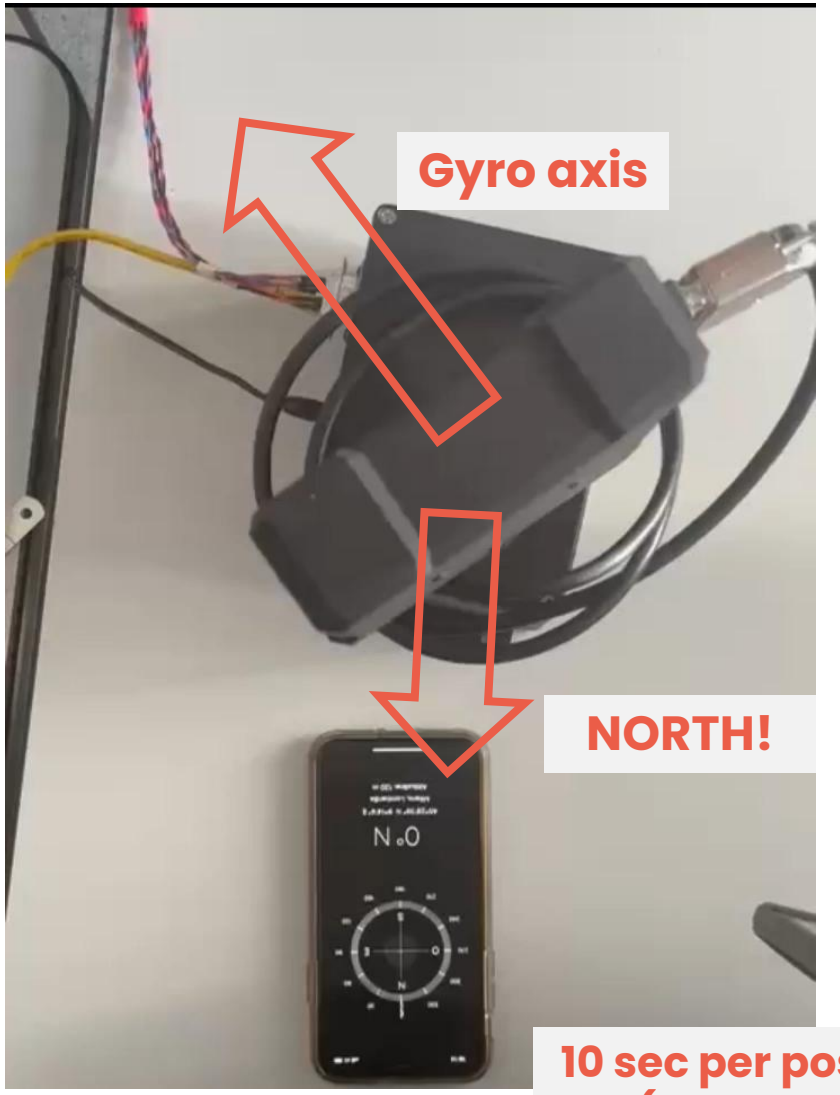
M&NEMS gyroscopes

Maytagging experiment



$20\times 10\times 10\ cm^3$

Maytagging experiment



10 sec per position (sped up…)

What's needed to launch a startup?

1. Technology readiness



M&NEMS: A new generation of sensors

The path to reach technology maturity

2014

INVESTIGATION OF THE FATIGUE ORIGIN AND PROPAGATION IN SUBMICROMETRIC SILICON PIEZORESISTIVE LAYERS

Giacomo Langfelder[1], Stefano Dellea[1], Patrice Rey[2], Audrey Berthelot[2], and Antonio Longoni[1]
[1]Politecnico di Milano, Milano, ITALY
[2]CEA-Leti, Grenoble, FRANCE

- From the **study** of piezoresistive phenomena…

Development at cea leti and POLITECNICO MILANO 1863

2025

REDUCING DRIFTS OF MEMS PIEZORESISTIVE GYROSCOPES IN UNCONTROLLED ENVIRONMENT

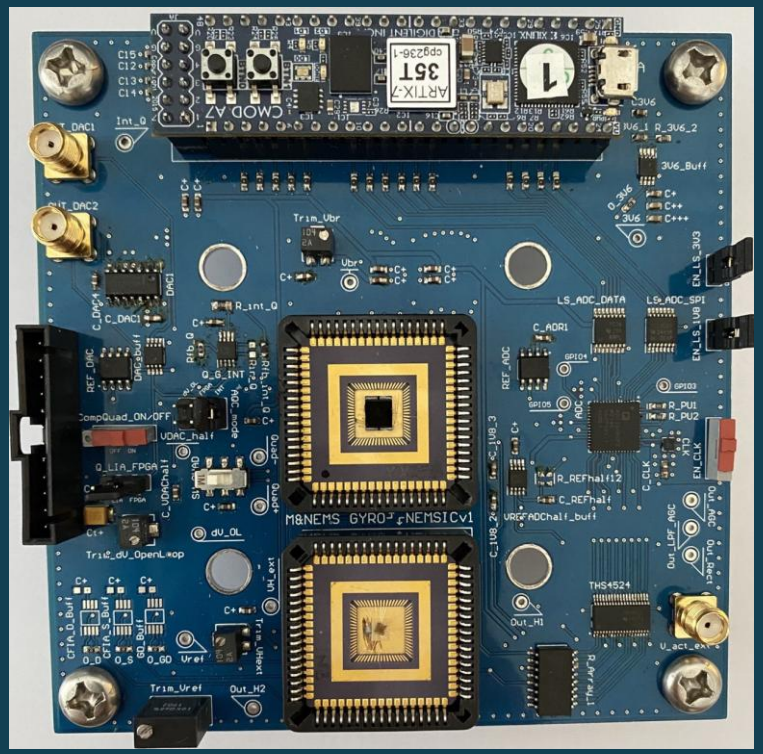
Gabriele Laita[1], Francesco Tubaro[1], Andrea Buffoli[2], Philippe Robert[2], and Giacomo Langfelder[1]
[1]Politecnico di Milano, Dipartimento di Elettronica, Informazione e Bioingegneria, Milan, Italy and
[2]CEA-Leti, Université Grenoble Alpes, Grenoble, France

- To the **optimization** of a near-nav grade gyroscope!

- A considerable number of **researchers**, **professors**, **PhD** and **MSc students** contributed to this development!
- **30+** Patents filed during this period.

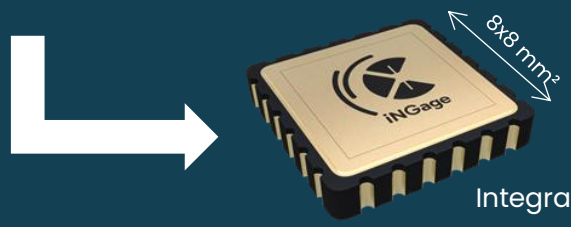
First demo with integrated ASIC

Demonstration of navigation grade performance



Performance in line with autonomous vehicle expectations (<<1.5°/h stability)

Validated by a leading inertial navigation player



Integrated MEMS-IMU

What’s needed to launch a startup?

2. Market and competitor analysis



Autonomous Navigation Everywhere

Need for High-Perf Sensors



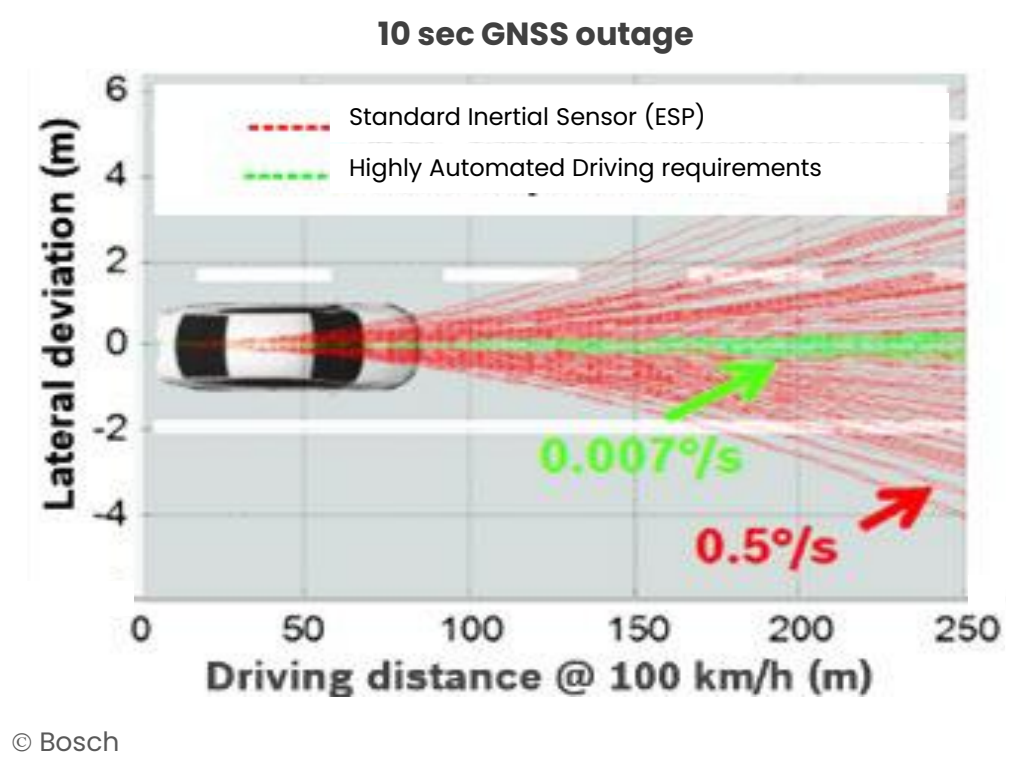
In the absence of GPS localization systems need high performance **Inertial Measurement Unit (IMU)**



Current Accuracy Limits of MEMS Sensors

In automotive

Car positioning error using MEMS sensors when GPS outage occurs



© Bosch

TODAY

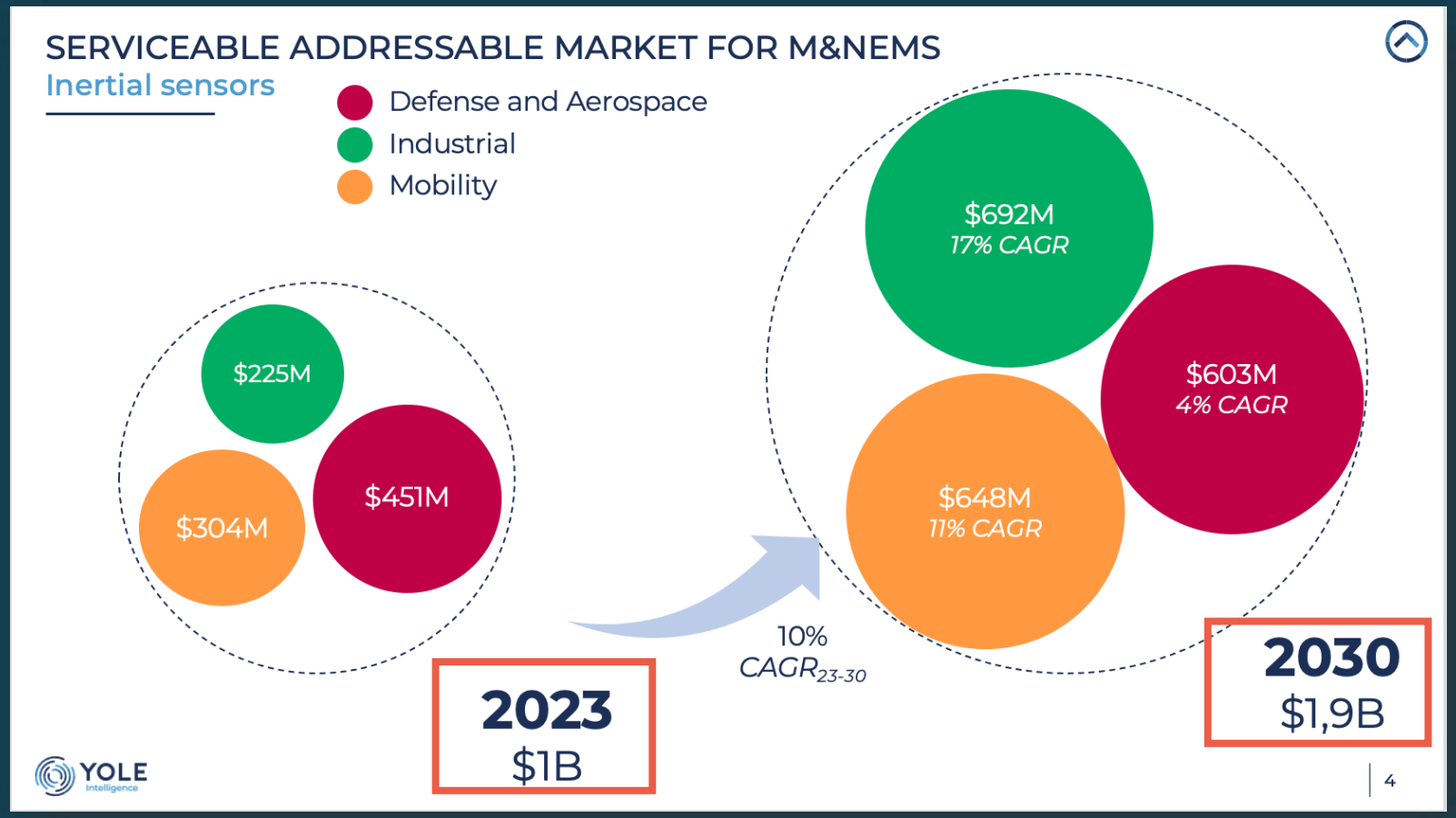
Positioning errors of up to **4 m** after just **10 sec** of use

REQUIRED

Ensuring **< 1 m positioning accuracy** for over **10 min**

Reachable Market (SAM)

Outcome of YOLE market analysis



Strategic Markets Targets

1. **Aerospace/Defense**
2. **Industrial**
3. **Mobility**

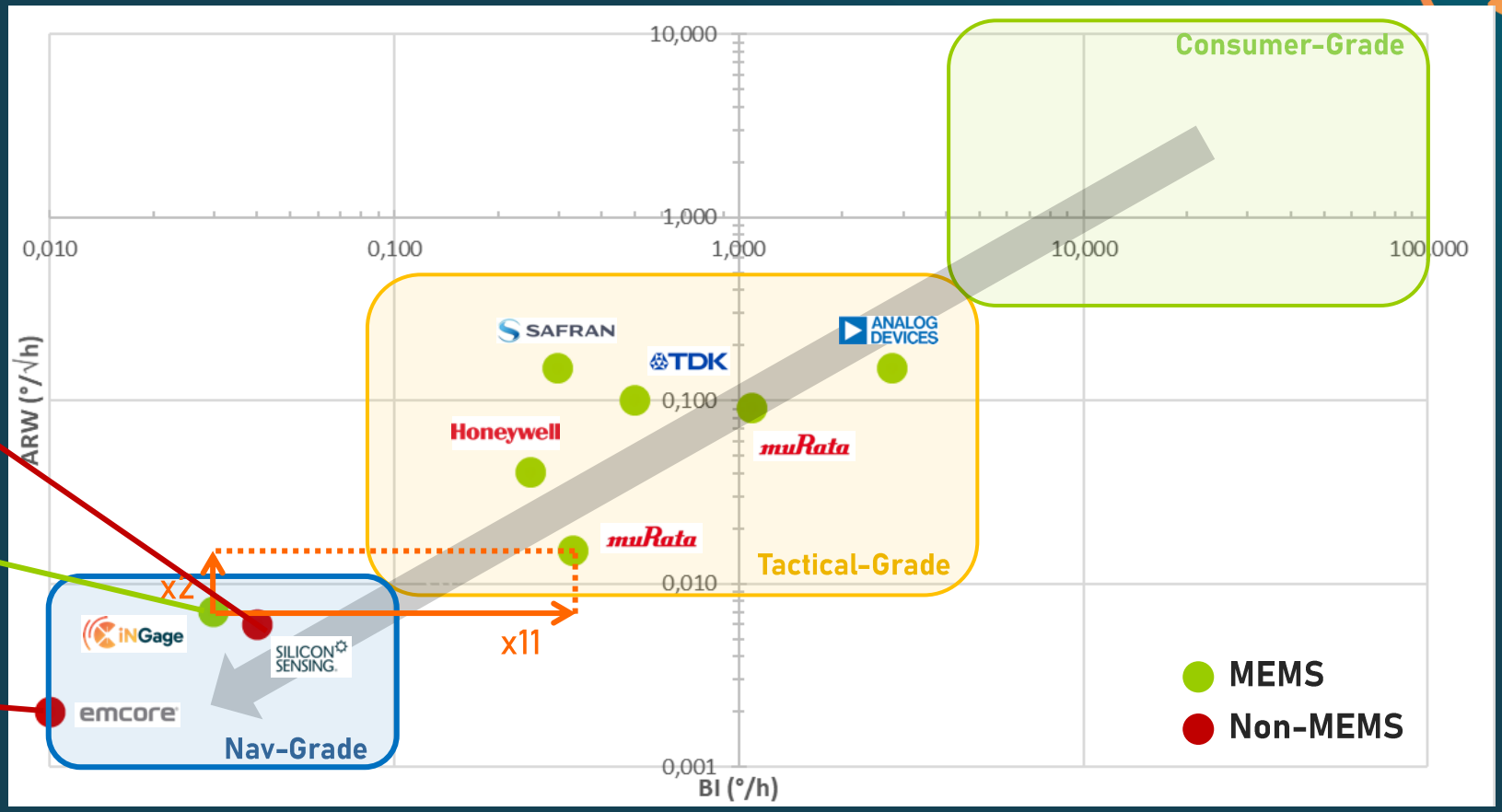
Targeting 50+ M€ revenues by 2035

Performance Comparison Against Competitors









One order of magnitude better than the best existing Inertial MEMS sensor

The Only Inertial MEMS sensor component with Navigation-Grade Performance

CONFIDENTIAL

Market Advantage Over Competitors

High-end inertial sensor

	FOG	Tactical Capacitive MEMS	Integrated FOG	Opto-mechanics	M&NEMS
	emcore, Honeywell, exail	TDK, ANALOG DEVICES, muRata	ANELLO	zeropoint motion	iNGage
Performance	+++	-	+	+	++
Miniaturization	-	++	-	+	+++
3-axis	-	-	-	-	++
Technology for mass production	-	+++	+	+	+++
Cost	-	++	-	+	+++

Defense

Automotive & Industry

Startup with differentiating technology

Founded: 2018

$28M in Series A (2021)

Founded: 2020

$3.22M in Seed (2023)

The only **ultra-compact** and **cost-effective alternative** to FOG, unlocking IMU adoption in high-volume markets

What’s needed to launch a startup?

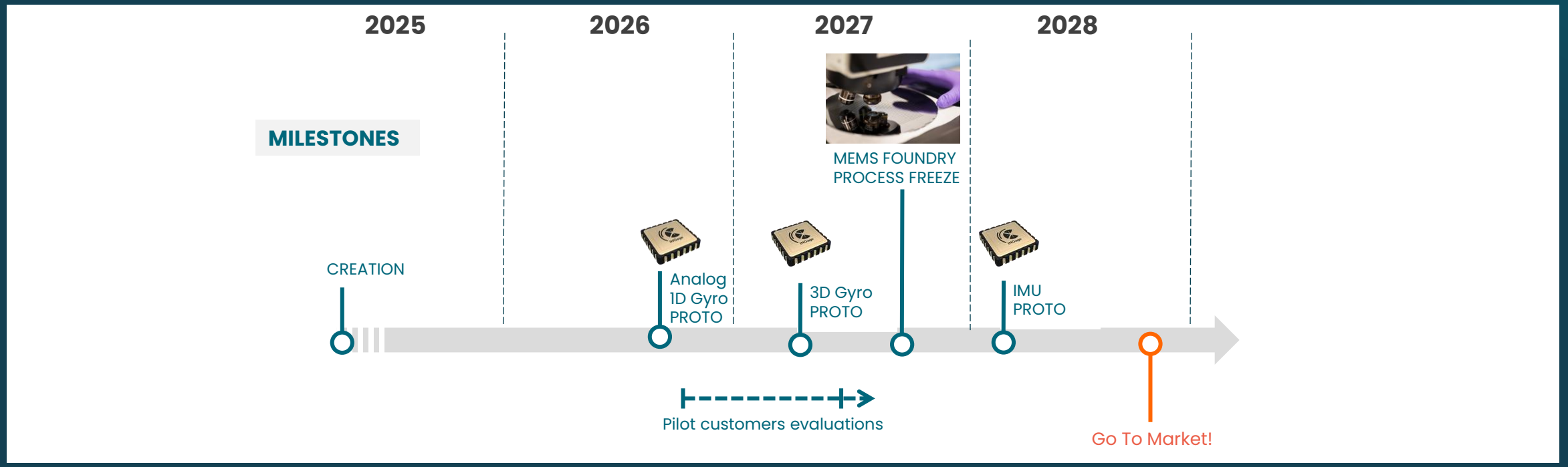
3. Business Plan and Funding



Product Development

Roadmap and planning

- As common in a deep tech startup, during the first years the engineering team is working at full speed to create **prototypes** to engage **pilot customers** evaluations.
- ASIC and MEMS development requires **time and iterations.**

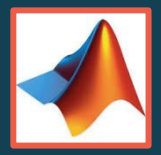


- First product on the market is scheduled for end of **2028**.
- So, how a startup could survive without revenues for 3 years?

Expenses

- **Simulations tools:**

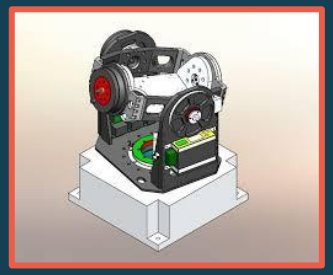








- **Office rent and Lab setup:**





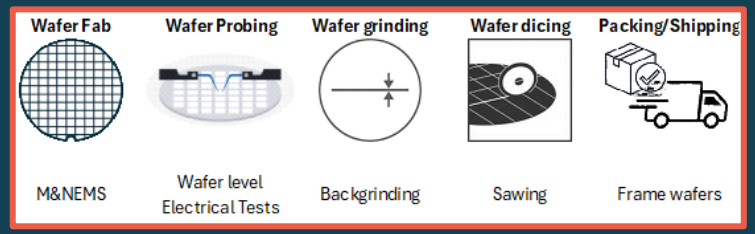
- **Foundry for ASIC/MEMS manufacturing:**



- **Employees salaries:**



- **Supply chain management:**



SEED FUNDING

iNGage®
Disruptive Navigation Sensors

Raises €6M Funds

SUPER NOVA INVEST

360 CAPITAL

BNP PARIBAS DÉVELOPPEMENT

CRÉDIT AGRICOLE ALPES DÉVELOPPEMENT

cea | investissement
AMORÇAGE TECHNOLOGIQUE

30 months Milestones

- First MVP (Minimum Viable Product)
- Feedback from evaluation by pilot customers.
- MEMS technology **transfer validation**

Closed: Sept. 2025

Sept. 2026 update:

Following its €6M funding round in 2025,
iNGage has secured an additional €4M
in grants and loans from Bpifrance and banks
to accelerate the development and industrialization
of its deeptech technology

bpifrance
SERVIR L'AVENIR

What’s needed to launch a startup?

4. A strong team!



Pioneering Team Driving iNGage's Vision

Experienced and Complementary



Philippe Robert
CEO/CTO & Co-founder



Bertrand Gautheron
COO & Co-founder



Vincent GAFF
CBO & Co-founder



Andrea Buffoli
MEMS & Analog designer



Cristiano Marra
Design Architect Leader



Pr. Giacomo Langfelder
Scientific Advisor

+ Independent board member(s)

ENGINEERING RESOURCES

iNGage team growth and collaborations

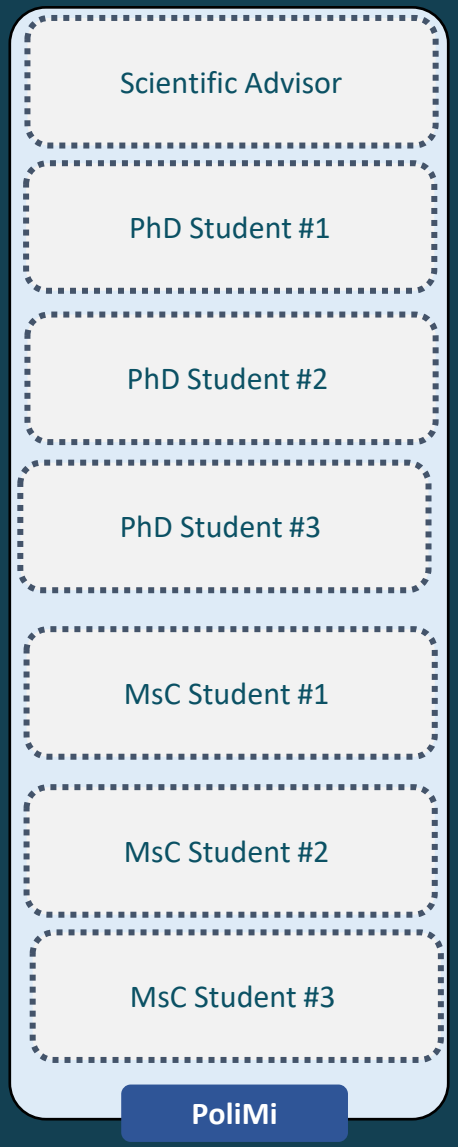


SLIDE FROM LAST YEAR LESSON

- Engineering team is growing with new hires.
- Collaborations with **University and Research Institutes** is key to keep high **innovation** levels while iNGage team is focused on execution.

ENGINEERING RESOURCES – 2026 UPDATES

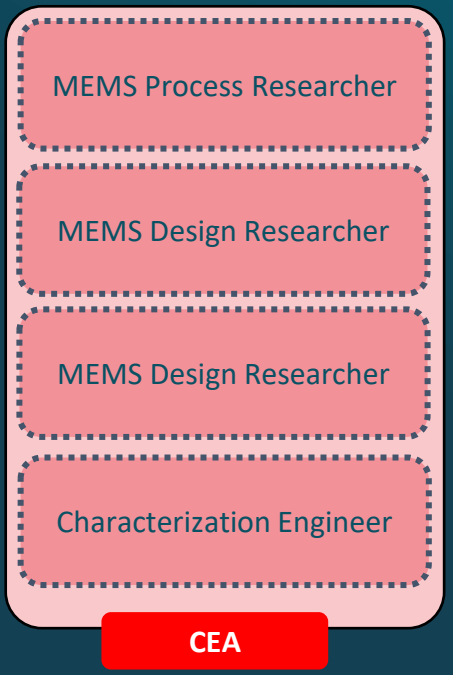
iNGage team growth and collaborations



collab



collab



collab

External consultants for specific tasks (e.g. layout, verification…)

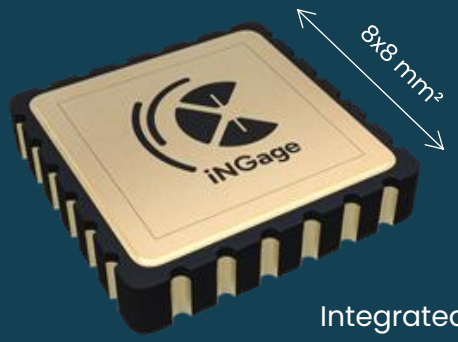
What's needed to launch a startup?

5. A clear mission

iNGage®
Disruptive Navigation Sensors

Our Mission

- Becoming the **Fabless Leader** in Navigation MEMS-IMU
  - **Affordable**
  - **High-Accuracy**
  - **Ultra-integrated**
- Scalable to **mass-production**



Integrated MEMS-IMU

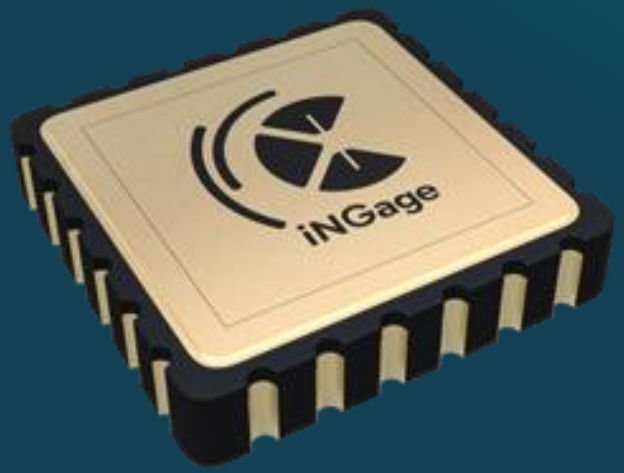
Why Now

🔬 Recent breakthrough performance

- **Validated** by a top global inertial player
- Entering **pre-production** with a world-class industrial company

📈 Market Opportunity

- **Strong demand** for high-performance MEMS
- High-potential **emerging markets** (auto, consumer)



🚀 Business Traction

- **Pilot customers** ready to test our sensors
- Roadmap **aligned with upcoming market** trends (auto…)

🌍 Macroeconomic & Geopolitical Trends

- Rising interest in **sovereign** solutions (and to maintain Europe's MEMS leadership)
- Unique **funding opportunities**

iNGage®
Disruptive Navigation Sensors

Thank you !

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