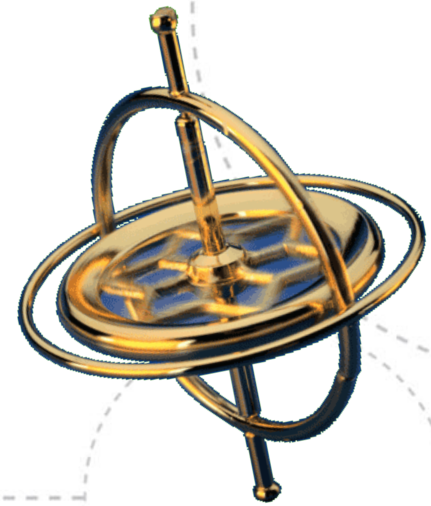
NTNU – Trondheim
Norwegian University of
Science and Technology



Case Study: InvenSense ITG-3200 Gyroscope

Damiano Milani *Alessandro Benedetti* *Davide Vimercati*

Case study: InvenSense ITG-3200 Gyroscope

- single chip, three-axis digital output yaw, pitch, and roll gyroscope
- only one chip, very small package
- 3 independent vibratory MEMS gyroscopes, which detect rotational rate about X, Y and Z axes
- Coriolis effect causes a deflection that is detected by a capacitive pickoff

Electronics:

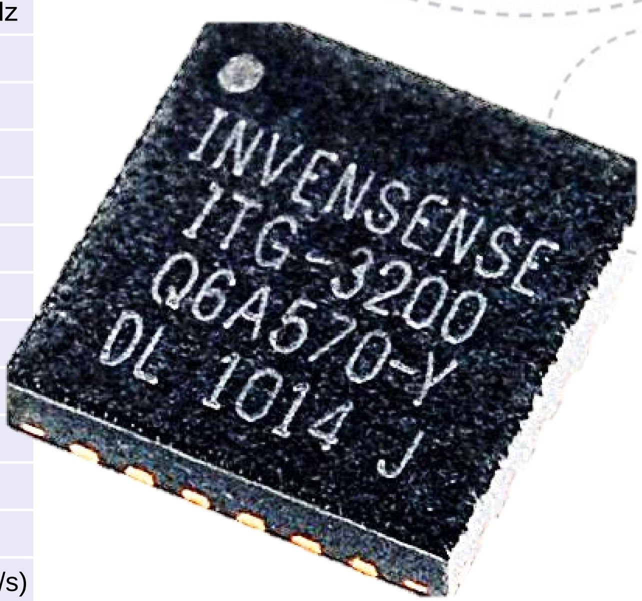
- 3 individual ADCs converters
- output rate: from 8000 down to 3.9 samples/s
- low pass filter
- charge pump to drive the oscillators
- timing generator clock frequency
- digital output temperature sensor
- QFN package
- RoHS and Green compliant

Applications:

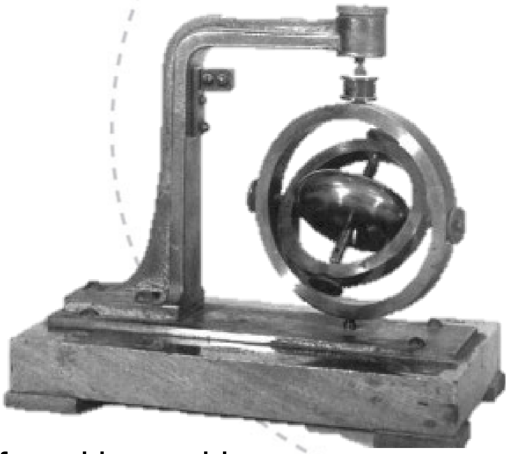
- motion-enabled game controllers
- motion-based portable gaming
- motion-based 3D mice and 3D remote controls
- *No Touch* UI
- health and sports monitoring

InvenSense ITG-3200 Gyro: Specifications

	minimum value	typical value	maximum value	unit
Operating voltage range	2,1		3,6	V
Normal operating current		6,5		mA
Rate noise spectral density		0,03		°/s/√Hz
Mechanical frequencies:				
X-axis	30	33	36	kHz
Y-axis	27	30	33	kHz
Z-axis	24	27	30	kHz
Initial ZRO tolerance		±40		°/s
Full-scale range		±2000		°/s
Start-up time ZRO setting		50		ms
Specified temperature range		-40 to 85		°C
Temperature sensor range		-30 to 85		°C
Storage temperature range		-40 to 125		°C
Standby current		5		μA
Sensitivity scale factor		14,375		LBS/(°/s)
Nonlinearity		0,2		%
Cross-axis sensitivity		2		%
Noise tolerance		0,03		°/s/√Hz
Shock tolerance		10000		g
Package dimension		4x4x0.9		mm

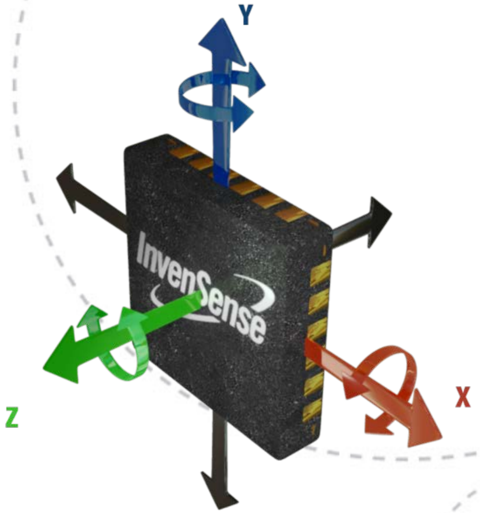


Brief history of Gyroscopes



- At the beginning they used the mechanical principle of the **conservation the angular momentum**, and they were mostly diffused in maritime applications (gyrocompass)
- After that, due to the high productive costs, only military applications were developed (guidance mechanism for missiles, gyrostabilizer for automatic pilot)
- MEMS: around 1980s new kinds of principles were applied, the quartz tuning fork is the first architecture that takes advantage of the **Coriolis force** to sense a rotation in a vibrating structure
- MEMS technology made everything much cheaper, high-efficient and small, so nowadays gyros are present in a wide variety of fields (automotive ambit, motion sensing gaming devices, human-computer interfaces, camcorder stabilization, smartphones, laptops)
- The future development of the gyroscopes will go in the direction of decreasing the costs, and improving the packaging technologies and processes, the two main issues of this kind of device.

MEMS Gyroscopes



- MEMS Gyroscopes design and production are the most challenging among the MEMS devices, and that is because they need both a *sensing* and a *driving* systems that have to work together with high performances.

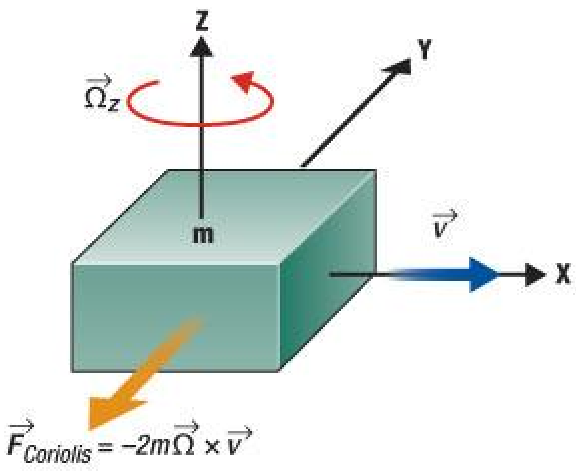
- Furthermore Gyroscope performance is very sensitive to all potential manufacturing variations, for instance packaging, linear acceleration, temperature, etc.

- To achieve **high performance** and **low cost**, lots of care must be taken during the initial design, in order to simplify the process and all these uncertainties.

- In addition to this technological difficulties there is an intrinsic limitation: the quantity detected (the effect of the Coriolis Force) is many magnitude orders smaller than any other quantity involved in MEMS measurement technology.

- For all this reasons MEMS Gyroscopes are not cost-competitive yet, and it is a field that still need important technological improvement.

Working principle



The most part of the MEMS gyroscopic devices is based on sensing the oscillations of a proof mass vibrating at a known frequency.

If we consider a rotating reference frame, every object moving at a velocity $\boldsymbol{v}$ will undergo the **Coriolis acceleration**.

This is an apparent acceleration proportional to the rate of rotation, and the subsequent force will be:

$$\boldsymbol{F_c} = m\boldsymbol{a_c} = -2m\,\boldsymbol{\omega} \times \boldsymbol{v}$$

In the Gyroscopes a pair of proof masses are driven to oscillate with a fixed and know frequency. When the device is rotating, the Coriolis force results in an orthogonal vibration that can be sensed. The sensing task is often performed by **capacitive electrodes**.

NTNU – Trondheim
Norwegian University of
Science and Technology

The Gyro: Analysis of the dynamic system

Every single axis of ITG-3200 device can be seen as as a **dynamic system** with 2 degrees of freedom.

Along the *driving axis*: the proof mass is excited in x direction, with a sinusoidal force; the differential equation that describes the motion is

$$m\ddot{x} + c_x\dot{x} + k_x x = F\sin\omega t$$

If the sensor is rotating, there will be a Coriolis force; this force is detected along the *sensing axis*:

$$m\ddot{y} + c_y\dot{y} + k_y y = F_{Cor} = 2m\Omega\,\dot{x}$$

The natural resonant frequency is different for each axis, because the spring constants are usually different

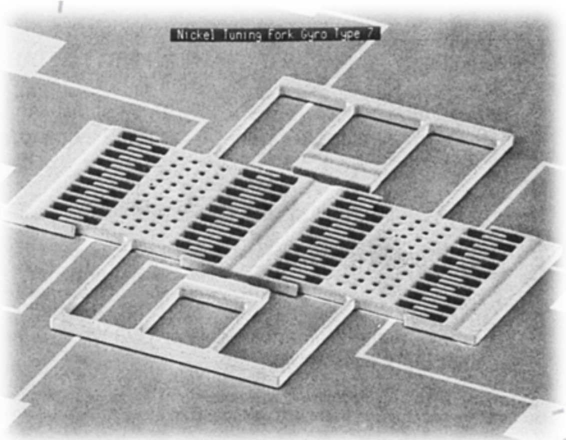
$$\omega_{rx} = \sqrt{\frac{k_x}{m}} \qquad \omega_{ry} = \sqrt{\frac{k_y}{m}}$$

The driving is actuated at the **resonant frequency**, in order to:

- maximize the displacement, thus increasing the range of actuation. It could also lead to self-destruction of mechanical elements
- minimize the power input, thus decreasing the power consumption (extend battery life for portable devices)

The equation of motion becomes:

$$m\ddot{x} + c_x\dot{x} + k_x x = F \sin \omega_{rx} t$$



Hence the force generate a sinusoidal displacement $x(t)$ and velocity $\dot{x}(t)$

$$x(t) = -x_m \cos \omega_{rx} t \qquad \dot{x}(t) = x_m \omega_{rx} \sin \omega_{rx} t$$

that causes the Coriolis force on the y axis:

$$F_{Cor} = 2m\Omega\, \dot{x} = 2m\Omega x_m \omega_{rx} \sin \omega_{rx} t$$

Eventually the module of the **Transfer Function** at the frequency ω_{rx} can be evaluated:

$$|Y(\omega_{rx})| = \frac{2m\Omega x_m \omega_{rx}}{\omega_{ry}^2 \sqrt{\left(1 - \left(\frac{\omega_{rx}}{\omega_{ry}}\right)^2\right)^2 + \left(\frac{2\xi\omega_{rx}}{\omega_{ry}}\right)^2}}$$

Using this function is possible to relate the motion along the two axes, hence obtaining the intended measure.

Design considerations:

- x axis is driven sinusoidally, amplitude and speed must be repeatable; amplitude must be insensitive to environmental factors
- y axis displacement should be as large as possible to increase sensitivity, but however not too high, because it is related with the Coriolis force
- cross-sensitivity: suppression of the rotation in the other axis, and linear accelerations → mechanical decoupling, electrostatic force compensation, mechanical trimming

Sensing and actuation principle: Electrostatic

The characteristics that make **electrostatic forces** suitable for driving micro devices are

- surface forces: micro devices have large surface-to-volume ratio and small mass
- simplicity: only 2 conductive surfaces, no specific materials and doping
- low power (low current, but high voltage)
- high dynamic response speed

Devices based on electrostatic forces measure **capacitance changes**:

$$C = \frac{Q}{V} = \frac{Q}{Ed} = \frac{Q}{\frac{Q}{\varepsilon A}d} = \frac{\varepsilon A}{d}$$

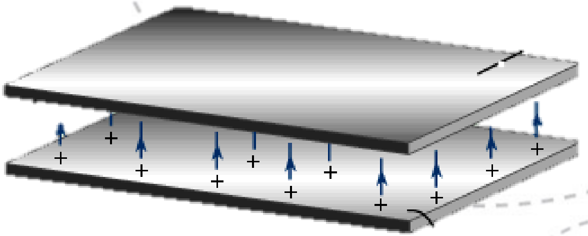
By sensing the changes in capacitance, it is possible to measure changes in

- permittivity
- overlapping area
- distance between surfaces

Sensing: Parallel-plate sensors

A **parallel-plate sensor** consists in a deformable plate supported by elastic elements.
Knowing the expression of the capacitance, it is possible to evaluate the amount of static displacement:

$$d = \frac{\varepsilon A}{C}$$



For design purposes, two parameters must be considered:

- considering the electro-mechanical model, the **equilibrium distance** under a specific biased voltage can be calculated solving the equilibrium equation between:

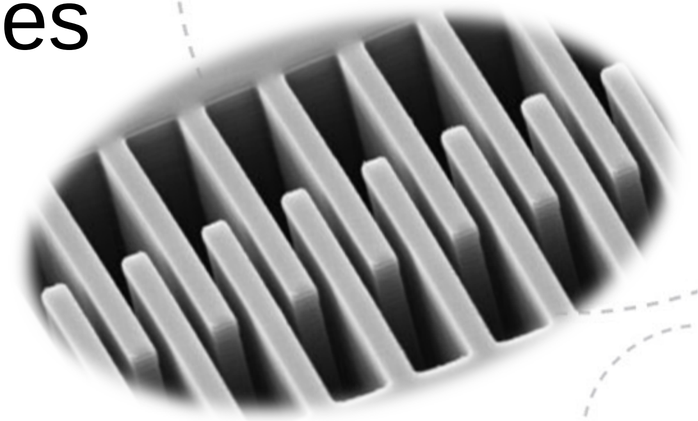
$$F_{electric} = \frac{1}{2} k_e (y + y_0) = \frac{1}{2} \frac{CV^2}{(y_0 + y)^2} (y + y_0) \qquad F_{mechanical} = -k_m y$$

- There is a threshold bias voltage called **pull-in voltage**, when $k_e = k_m$ and the total spring constant is zero (very soft). The two plates will be pulled against each other rapidly until they make contact: irreversible damage due to short circuit, arcing and surface bonding will occur.

  It is a very important issue, mostly for the performances of the high frequency devices.

NTNU – Trondheim
Norwegian University of Science and Technology

Actuation: Comb-drive devices



Interdigitated fingers or **comb-drive** devices:

- fingers structures are made in order to increase the edge coupling length
- one set of finger-like electrode is fixed on chip, while a second set is suspended and free to move in one or more axes

The capacitance between two immediate neighboring fingers is

$$C = \varepsilon \frac{l_0 t}{d}$$

that consider the capacitance related to the vertical surfaces in the overlapped region (l_0 is the overlapping distance, t the thickness, d the distance). In the design of the capacitor it is mainly important that the values of t and d are well defined.

The total capacitance is the sum of capacitance contributed by neighboring fingers (pairs connected in parallel).

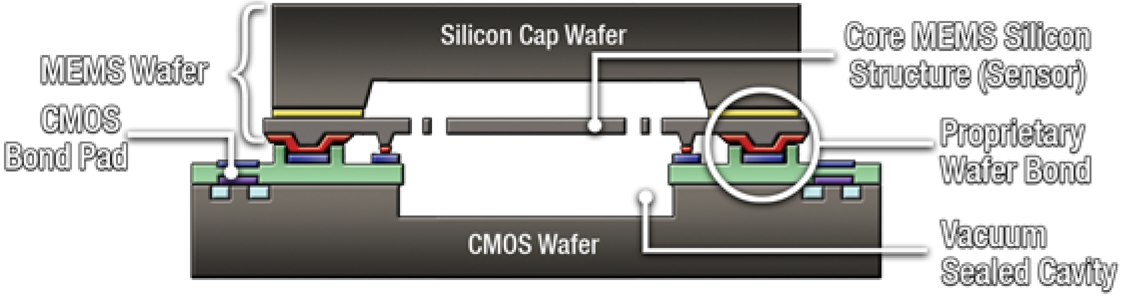
The fringe capacitance is difficult to estimate analytically, it could be calculated with FEM simulations.

The actuator adopted in the gyro is a **longitudinal** comb-drive. The lateral movement x is allowed by suspension along the longitudinal axis of the fingers; due to Coriolis force there is also a displacement in y direction, so the capacitance for each finger becomes:

$$C = \varepsilon \frac{(l_0 - x)(t - y)}{d}$$

NASIRI Fabrication Process

It is a standard MEMS-specific bulk silicon fabrication process that enables direct bonding of MEMS components with electronic circuitry, fabricated using **standard CMOS processes**.



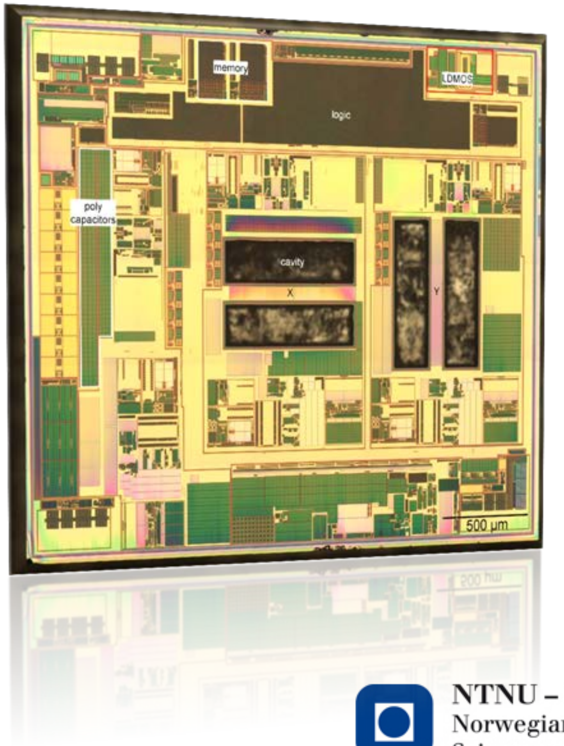
The main process characteristics are:

- the sensing elements are made in a thin silicon substrate and are protected by a silicon cap
- the ASIC wafer is etched to let the sensing elements free, and then bonded with the sensor and the cap compound
- the sensor is protected and thus can be packaged using a standard assembly process

NASIRI Fabrication Process

The important advantages in integrating a MEMS wafer with an industry standard CMOS wafer are:

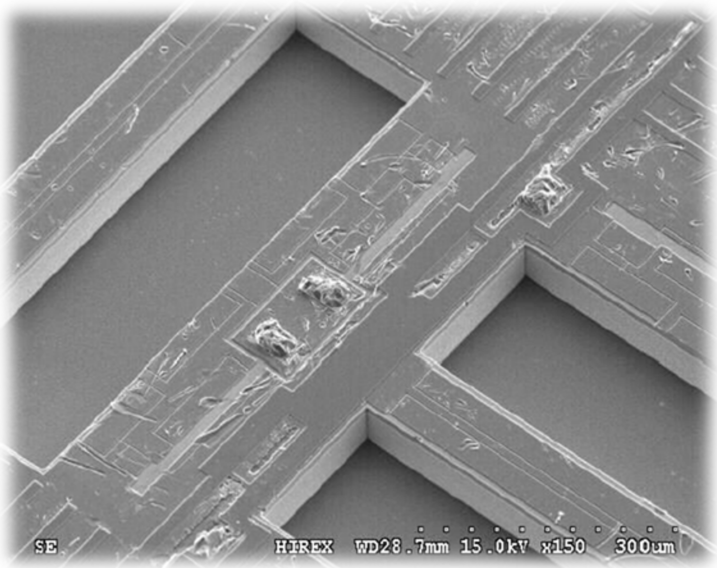
- a small, cost effective standard package
- reduced number of MEMS manufacturing steps
- chip-scale packaging available
- reduced back-end costs
- improved overall yield
- low cost, high throughput wafer-level testing



Fabrication of suspended beams

The three wafers (cap, MEMS and CMOS) are etched by Deep Reactive-Ion Etching (DRIE).

This is a highly anisotropic etch process used to create deep penetration. It is capable of producing deep and high aspect ratio features with near vertical sidewalls.



Some of the interesting feature of this technology are:

- fast and uniform etch rate
- vertical sidewall profiles
- high cost equipement
- good material selectivity
- optimal integration with other processes

Packaging and integration

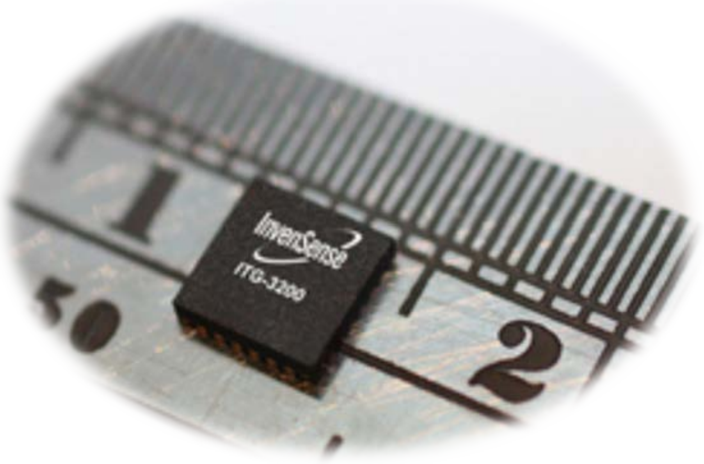
The CMOS and MEMS are bonded using eutectic metal bond at a wafer-level integration.

Using the aluminum metallization already present on CMOS wafers as a bond pad, it is possible to add a single layer of germanium to MEMS wafers.

This enables the formation of a highly reliable aluminum-germanium (Al/Ge) eutectic metal seal that protects the internal MEMS structures and provides a hermetically sealed vacuum cavity (critical for the operation of the MEMS sensors).

Aluminum-germanium bonding allows for precise control of the sealing material in terms of both width and height, enabling an efficient seal ring space and precise gap control.

Thanks to the NASIRI fabrication process the IGT-3200 package size has been reduced to a innovative footprint of 4x4x0,9 mm, and high volume production is ensured.



Conclusions

The ITG-3200 Gyroscopes is a cutting edge technology in its field, the **innovative features** are:

- 3-axial sensitivity
- digital output
- high operating range
- competitive price
- much reduced dimensions

This is thanks to two aspects:

- an **excellent design**: the silicon cap wafer protects the vibrating frame and the three bonded wafers can be packaged with standard procedures
- a cheap and efficient **fabrication process**: NASIRI platforms ensures a high-volume production and the chip-level integration allows the employment of proven and optimized CMOS processes