MEMS gyroscopes
Design overview and market trends

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Analog, MEMS and Sensors Group

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Who am I

M.Sc. in Electronics Engineering
Politecnico di Milano, 2009

Ph.D. in Information Technology
Politecnico di Milano, 2012

Visiting Ph.D. student
Lawrence Berkeley National Lab, 2011

Master of Business Administration
MIP Politecnico di Milano Business School, 2019

Analog designer and MEMS System Architect
STMicroelectronics, since 2012

Member of Technical Staff
STMicroelectronics
Seminar outline

- STMicroelectronics overview
- The MEMS gyroscope: design considerations
- Integrating gyroscopes into final products
STMicroelectronics overview
Who We Are

- Among the world’s largest semiconductor companies
- Serving over 100,000 customers across the globe
- 2018 revenues of $9.66B, with year-on-year growth of 15.8%
- Listed: NYSE, Euronext Paris and Borsa Italiana, Milan
- Signatory of the United Nations Global Compact (UNGC), Member of the Responsible Business Alliance (RBA)

- Approximately 46,000 employees worldwide
- Approximately 7,400 people working in R&D
- 11 manufacturing sites
- Over 80 sales & marketing offices
# Financial results

## Q3 2019 Financial Results

<table>
<thead>
<tr>
<th>Segment</th>
<th>Revenues</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADG</td>
<td>$885 million</td>
</tr>
<tr>
<td>AMS</td>
<td>$694 million</td>
</tr>
<tr>
<td>MDG</td>
<td>$591 million</td>
</tr>
</tbody>
</table>

- **Net revenues**: $2.17 billion
- **Gross Margin**: 38.2%
- **R&D / SG&A expenses**: $650 million

ST Confidential
AMS – Analog, MEMS and Sensors

PORTFOLIO

MOTION SENSORS
Accelerometer, gyroscope, Magnetic sensor

MICROPHONES
Analog & Digital

ENVIRONMENTAL SENSORS
Pressure, UV

ACTUATORS
Fluidics MEMS, Micro-Mirror

TOUCH
FingerTip

LOW POWER ANALOG
Standard Analog, High-end Analog

RF
Bluetooth, SubGhz, Wi-Fi

Personal Electronics
1 ST MEMS every 2 phones

Automotive
1 ST MEMS every 2 car navigators

Industry
Leadership in WP and Harsh environment pressure sensor

Computing
1 ST Temperature Sensor every 2 DRAM

ST Confidential
AMS customers across Markets

Serving with excellence >30k customers across ST focus markets

<table>
<thead>
<tr>
<th>Personal Electronics</th>
<th>Computing</th>
<th>Automotive</th>
<th>Industry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Huawei</td>
<td>HP</td>
<td>Magneti Marelli</td>
<td>ABB</td>
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<tr>
<td>Samsung</td>
<td>Dell</td>
<td>Continental</td>
<td>Enel</td>
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<tr>
<td>oppo</td>
<td></td>
<td>Delphi</td>
<td>Milwaukee</td>
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<tr>
<td>Garmin</td>
<td></td>
<td>Denso</td>
<td>Siemens</td>
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<tr>
<td>Google</td>
<td></td>
<td>HARMAN</td>
<td>Avantech</td>
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<tr>
<td>fitbit</td>
<td>Micron</td>
<td>Panasonic</td>
<td>WEG</td>
</tr>
<tr>
<td>vivo</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Motion MEMS, continued innovation

New applications driving accuracy requirements in motion sensors

IMU / components specs convergence

Accuracy

Screen Rotation
2005

Gaming
2008

Infotainment
2012

Mobile
2014

Mobile AR
2016

Autonomous Drive
VR/AR / Navigation
OIS
The MEMS gyroscope: design considerations
What is a gyroscope?

Despite years of studying physics, I still find gyroscopes a little freaky.

It’s an ACCELEROMETER…

…to measure the Coriolis acceleration…

…induced by a rotation
The Coriolis force

Apparent force arising in rotating (non-inertial) frames

Example #1:
A cannon is placed on a rotating disc. The cannonballs fly in straight lines since no forces act on them.

Example #1: Cont’d
We will now switch to the disc’s frame of reference. The cannonballs path will now seem curved.

Example #1: Cont’d
Here’s the same scene again with the forces visualized as arrows:
- Coriolis
- Centrifugal
- Total
Three axis Beating Heart gyroscope

Driving concept

- The Drive mode is kept in oscillation close to resonance
  - Comb actuation is normally used

**Driving: X axis**
- Sensing: Y-axis (Roll)
- Sensing: Z-axis (Yaw)

**Driving: Y axis**
- Sensing: X-axis (Pitch)
- Sensing: Z-axis (Yaw)

**Driving: X-Y axis**
- Sensing: X-axis (Pitch)
- Sensing: Y-axis (Roll)
- Sensing: Z-axis (Yaw)
The signal is Amplitude Modulated at the Drive frequency.
MEMS drive section

- The movable mass (or rotor) is biased at voltage $V_{rot}$
  - To readout the capacitance, a voltage difference is superimposed between stators
- Electrostatic force is applied via driving pads $D_1$-$D_2$ and MEMS movement is readout through sensing pads $I_1$-$I_2$
  - Note that the Drive frame does not move in the sense direction

\[
F_{\text{ele}} = \frac{1}{2} \frac{dC}{dx} [(V_{\text{rot}} - V_{D1})^2 - (V_{\text{rot}} - V_{D2})^2]
\]

\[
F_{\text{ele}}^{\sim} \approx \frac{1}{2} \frac{dC}{dx} 2V_{\text{dc}} v_{ac} \sin(\omega_D t)
\]

\[
x_d = F_{\text{ele}} \frac{1}{m s^2 + s \omega_d / Q + \omega_d^2} \frac{1}{s}
\]

\[
x_d(\omega = \omega_d) = F_{\text{ele}} \frac{Q}{k}
\]

\[
\left( \frac{\Delta C}{\Delta x} \right)_{SD} \sim 10 \frac{fF}{\mu m}
\]

\[
\Delta C_{SD}(t) = \Delta C_{SD} \cdot \cos(\omega_D t)
\]
Drive loop design

Phase and Amplitude loops

• Drive chain designed to respect Barkhausen criteria
  • ASIC phase delay designed to have $\omega_d \approx \omega_n$ (usually >20kHz, why? 😊)
  • Remember, it is the $\angle G_{loop} = 2\pi$ condition that fixes the oscillation frequency $\omega_d$!
  • Amplitude controlled by an Automatic Gain Control (AGC) block so that $|G_{loop}| = 1$

$$i_{SD} = (V_{ROT} - V_{CM}) \cdot \frac{dC_{SD}}{dt}$$
Gyroscope startup time

• Startup time is one of the main specifications of gyroscope products
  • State-of-the-art devices guarantee startup times well below 50ms (typ. 35ms)
  • Assuming $Q \ddot{x} \gg x_r$, for a given forcing voltage we can write:
    \[ t_{\text{startup}} = \frac{x_r - x_0}{Q \ddot{x}} \tau = \frac{x_r}{Q \ddot{x}} \frac{2Q}{\omega} = 2 \frac{x_r}{\ddot{x} \omega} \]

  • It does not depend on $Q$
    • Conversely, the ring-down time can be used to measure $Q$
  • Startup must be actively initiated
    • It is not safe to rely on startup from noise conditions
    • We need to ensure the spec R&R (Repeatibility and Reproducibility)
Startup waveforms

- Amplitude growth is stopped by the AGC when $V_{C2V}$ approaches $V_{ref}$.
- The final value of $V_{CTRL}$ is inversely proportional to the quality factor $Q$. 

![Graph showing amplitude and control voltage over time](image)
4.2 Electrical characteristics

@ $V_{dd} = 1.8 \text{ V}, \; T = 25 \degree \text{C}$, unless otherwise noted.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter</th>
<th>Test conditions</th>
<th>Min.</th>
<th>Typ. (1)</th>
<th>Max.</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{dd}$</td>
<td>Supply voltage</td>
<td></td>
<td>1.71</td>
<td>1.8</td>
<td>3.6</td>
<td>V</td>
</tr>
<tr>
<td>$V_{dd_IO}$</td>
<td>Power supply for I/O</td>
<td></td>
<td>1.62</td>
<td></td>
<td></td>
<td>V</td>
</tr>
<tr>
<td>IddHP</td>
<td>Gyroscope and accelerometer current consumption in high-performance mode</td>
<td></td>
<td></td>
<td>0.55</td>
<td></td>
<td>mA</td>
</tr>
<tr>
<td>LA_IddHP</td>
<td>Accelerometer current consumption in high-performance mode</td>
<td></td>
<td></td>
<td>170</td>
<td></td>
<td>$\mu$A</td>
</tr>
<tr>
<td>LA_IddLP</td>
<td>Accelerometer current consumption in low-power mode</td>
<td>$ODR = 52 \text{ Hz}$, $ODR = 1.6 \text{ Hz}$</td>
<td>26</td>
<td>4.5</td>
<td></td>
<td>$\mu$A</td>
</tr>
<tr>
<td>LA_IddULP</td>
<td>Accelerometer current consumption in ultra-low-power mode</td>
<td>$ODR = 52 \text{ Hz}$, $ODR = 1.6 \text{ Hz}$</td>
<td>9.5</td>
<td>4.4</td>
<td></td>
<td>$\mu$A</td>
</tr>
<tr>
<td>IddPD</td>
<td>Gyroscope and accelerometer current consumption during power-down</td>
<td></td>
<td>3</td>
<td></td>
<td></td>
<td>$\mu$A</td>
</tr>
<tr>
<td>Ton</td>
<td>Turn-on time</td>
<td></td>
<td>35</td>
<td></td>
<td></td>
<td>ms</td>
</tr>
</tbody>
</table>
Startup time measurement results

<table>
<thead>
<tr>
<th></th>
<th>STD AMP.</th>
<th>-30% AMP.</th>
<th>-50% AMP.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average startup time</td>
<td>55.8</td>
<td>43.1</td>
<td>37.1</td>
</tr>
<tr>
<td>(ms)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard deviation (ms)</td>
<td>2.97</td>
<td>2.83</td>
<td>2.35</td>
</tr>
</tbody>
</table>

Negligible spread
Drive charge amplifier

Capacitor and resistor value

\[ V_{out} = 2 \frac{[V_{ROT} - V_{CM}]}{C_f} \left( \frac{\Delta C}{\Delta x} \right)_{SD} x_{dr} \ast \cos(2\pi f_{dr} t) \]

- Target: 5\(\mu\)m peak movement
- \(V_{ROT} - V_{CM} \sim 10V, \left( \frac{\Delta C}{\Delta x} \right)_{SD} = 10 \frac{fF}{\mu m}\)
- Supply: 1.6V, pMOS input: \(V_{out} = 0.8V\)

\[ C_f = 2 \frac{[V_{ROT} - V_{CM}]}{V_{out}} \left( \frac{\Delta C}{\Delta x} \right)_{SD} x_{dr} = 1.25pF \]

- \(f_p = \frac{1}{2\pi R_f C_f} \ll f_{dr} = 20kHz\)
- \(f_p = 100Hz\)

- \(R_f = \frac{1}{2\pi f_p C_f} = 1.27G\Omega\)

(\textit{note: }R_f \text{ sets the input common mode to be equal to the output common mode)}

Not an open choice…

\(~ 0.6V\) (pMOS-input stage)

\(V_{DD} \sim 0.6V\) (pMOS-input stage)
### 4.1 Mechanical characteristics

@ $V_{dd} = 1.8$ V, $T = 25$ °C, unless otherwise noted.

#### Table 3. Mechanical characteristics

<table>
<thead>
<tr>
<th>Symbol</th>
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<th>Min.</th>
<th>Typ.$^{(1)}$</th>
<th>Max.</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>G_So</td>
<td>Angular rate sensitivity$^{(2)}$</td>
<td>$FS = \pm 125$ dps</td>
<td></td>
<td>4.375</td>
<td></td>
<td>mdps/LSB</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$FS = \pm 250$ dps</td>
<td></td>
<td>8.75</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$FS = \pm 500$ dps</td>
<td></td>
<td>17.50</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$FS = \pm 1000$ dps</td>
<td></td>
<td>35</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$FS = \pm 2000$ dps</td>
<td></td>
<td>70</td>
<td></td>
<td></td>
</tr>
<tr>
<td>G_So%</td>
<td>Sensitivity tolerance$^{(3)}$</td>
<td>at component level</td>
<td>(\pm 1)</td>
<td>(%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LA_SoDr</td>
<td>Linear acceleration sensitivity change vs. temperature$^{(4)}$</td>
<td>from $-40^\circ$ to $+85^\circ$</td>
<td>(\pm 0.01)</td>
<td>(%/^\circ C)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>G_SoDr</td>
<td>Angular rate sensitivity change vs. temperature$^{(4)}$</td>
<td>from $-40^\circ$ to $+85^\circ$</td>
<td>(\pm 0.007)</td>
<td>(%/^\circ C)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Amplitude control loop

DC working point analysis

- The movement approaches the desired set-point with a precision that depends on the amplitude control loop gain.
- The value of the gain is mainly impacted by variations of the $dC/dx$ of the drive sensing and the quality factor of the gyro.

$$V_{C2V} = V_{ref} \frac{T_0}{1 + T_0}, T_0 = G_{AGC} G_{C2V} h(t) = G_{AGC} G_{C2V} \frac{Q}{k_1} \frac{dC}{dx}$$
MEMS drive section

Biasing and forcing choice

\[
F_{\text{elett}} \sim \frac{1}{2} \frac{dC}{dx} 2V_{dc} v_{ac} \sin(\omega_D t), x_d(\omega = \omega_d) = F_{\text{elett}} \frac{Q}{k}
\]

Given the necessary force to be applied, is it better to have a large DC biasing or a large AC signal?

Forcing signal:
- at the drive frequency
- same phase of the Coriolis signal

\[
i_c = (V_{\text{rot}} - V_{\text{stat}}) \frac{\partial C_S}{\partial t}
\]

\[
i_{\text{par}} = C_{\text{par}} \frac{\partial V}{\partial t}
\]

- \((V_{\text{rot}} - V_{\text{stat}}) = 10V\)
- \(\Delta C_S = 0.4 \, \text{fF}/300 \, \text{dps}\)
- \(\Delta V = 1V\)

1dps with \(C_{\text{par}} = 1.3aF\)
In any case, be very careful when implementing a 6x IMU because of possible Gyro-to-XL couplings:

- The sinusoidal forcing would continuously inject charge into the XL
- With the square wave and if a switched cap XL is used, edges can be properly placed in the XL reset phases
Sensor transfer functions

- The modulation of the angular rate creates two sidebands around the drive oscillation frequency

\[ F_c = -m\Omega_0 v [\cos(\omega_d + \omega_{in}) t + \cos(\omega_d - \omega_{in}) t] \]

- The output signal is Amplitude Modulated
- Sensitivity is proportional to the Drive displacement
  (but pay attention to nonlinearities!)

Mode split operation:

Gain

Drive transfer function

Sense transfer function

\( \omega_d - \omega_{in} \)

\( \omega_d \)

\( \omega_d + \omega_{in} \)

Frequency (rad/s)

S: Sense electrodes
M: Proof mass
D: Drive electrodes
SD: Sensing drive electrodes
S: Sense electrodes
Sense chain design

- The movable mass (or rotor) is biased at voltage $V_{rot}$
  - To readout the capacitance, a voltage difference is superimposed between stators
- Coriolis movement is readout through sensing pads $S_1$-$S_2$
  - Input nodes are biased at $V_{CM}$ by the Fully Differential Charge Amplifier

$\Delta C_S \approx 0.4 \, fF / 300 \, dps$

Self-clocked system
\[ V_{out} = 2 \frac{[V_{ROT} - V_{CM}]}{C_f} \left( \frac{\Delta C}{\Delta \Omega} \right)_S \Omega_{in} * \sin(2\pi f_{dr} t) \]

- \( V_{ROT} - V_{CM} \approx 10V, \left( \frac{\Delta C}{\Delta x} \right)_{SD} = 10 \frac{fF}{\mu m} \)
- \( \left( \frac{\Delta C}{\Delta \Omega} \right)_{S, max} = 2 \left( \frac{\Delta C}{\Delta \Omega} \right)_S = 0.8 \frac{fF}{300 \text{ dps}} \)
- Supply: 1.6V, pMOS input: \( V_{out} = 0.8V \)

\[ C_f = 2 \frac{[V_{ROT} - V_{CM}]}{V_{out}} \left( \frac{\Delta C}{\Delta \Omega} \right)_{S, max} \Omega_{in} = 150fF \]

Take spreads into account!
How many Coriolis electrons?

- Let's consider $V_{ROT} - V_{CM} \approx 10V$ and calculate the number of electrons induced by the Coriolis force for 1dps of angular velocity.

$$\#el = (V_{ROT} - V_{CM}) \cdot \frac{\Delta C_s}{300 \text{dps}} \cdot \frac{1}{q} \approx 83 \text{el/dps}$$

$\Delta C_s \sim 0.4 \text{fF}/300 \text{dps}$

Note that the actual resolution is way smaller than 1dps!!
• Mechanical quadrature signal (anisoelasticity): when the primary resonator movement couples directly to the secondary resonator
  • It is in phase with the Drive position, so in quadrature w.r.t. Coriolis signal
  • Quadrature can be 10 times greater than the signal full scale (2kdps)

Ideal structure

M: Proof mass
D: Drive electrodes
SD: Sensing drive electrodes
S: Sense electrodes

Real structure

M: Proof mass
D: Drive electrodes
SD: Sensing drive electrodes
S: Sense electrodes
What about quadrature electrons?

- Let’s repeat the same calculation done before, considering an input quadrature of 15k dps

\[
\#el = (V_{ROT} - V_{CM}) \cdot \frac{\Delta C_S}{300\text{dps}} \cdot \frac{1}{q} \cdot Quad \approx 1.25 \cdot 10^6 \text{el}
\]

\[\Delta C_S \approx 0.4 \cdot \frac{f F}{300\text{dps}}\]

- ...and only 83 Coriolis electrons per dps!
Is coherent demodulation enough?

- What about input gain and dynamic range?

\[ V_{\text{OUT}}^{\text{max}} = 1.8V \leftrightarrow 20\text{kdps} \]
\[ V_{\text{OUT}}^{\text{Coriolis}} = \frac{1.8V}{10} = 180mV \leftrightarrow 2\text{kdps (FS)} \]

- What about demodulation errors and drifts?

\[ V_{\text{OUT}}^{\text{err}} = QUAD \cdot \sin(\varphi_{\text{err}}) = 15\text{kdps} \cdot \sin(1\text{mrad}) \approx 15\text{kdps} \cdot 1\text{mrad} = 15\text{dps} \]

- What about demodulation phase noise?

\[ V_{\text{OUT}}^{\text{noise}} = QUAD \cdot \sin(\varphi_{\text{noise}}) = 15\text{kdps} \cdot \sin \left( 1\text{\mu rad}/\sqrt{\text{Hz}} \right) \approx 15\text{mdps}/\sqrt{\text{Hz}} \]
How to cope with quadrature?

MASS

Drive
C2V

Sense
C2V

15k dps

QUADRATURE
CORIOLIS

2 k dps
Let’s remove the problem at its origin

\[
\text{MASS}
\]

\[
\text{Drive C2V}
\]

\[
\text{Sense C2V}
\]

\[
\text{QUADRATURE}
\]

\[
\text{CORIOLIS}
\]

\[
2\text{kdps}
\]
Integrating gyroscopes into final products
Six axis IMUs – Gyro and XL

MEMS technology

- **ST standard technology:**
  - ST ThELMA process with Epi-poly Si structural layer
  - Glass Frit W2W bonding
  - Getter integration to have two cavities with different, tunable bonding pressures for Gyro and XL (XL Q ≤ 1 achievable, overdamped transfer function)
Packaging and assembly example

**ST LSM6DS3**
- Package: LGA 14 pin
- Dimensions: 2.5 x 3.0 x 0.85mm

**INVENSENSE MPU-6500**
- Package: QFN 24 pin
- Dimensions: 3.0 x 3.0 x 0.9mm
Main sources of drift in inertial devices

- MEMS accuracy is mainly affected by stress-induced phenomena

- For consumer applications, MEMS inertial sensors and ASIC are packaged together with low-cost LGA full-molded technique

- The stack-up of this package is composed by many materials characterized by different CTE and Young’s Modulus values

Output parameters affected

AXL
- Differential gap change between Stator-Rotor
  → 0-g level drift, Sensitivity drift

GYRO
- Gap change between Stator-Rotor, Q-factor, Resonance frequency, Quadrature
  → ZRL drift, Sensitivity drift
What Defines Sensor Accuracy

Sensor Value = Accuracy + Screening + HW

Accuracy = \([C_1 + C_2] + [C_3 + C_4 + C_5]\)

System level calibration:
- \(C_3 \rightarrow\) temperature
- \(C_4 \rightarrow\) post solder parameters (sens, off, CX, NL)
- \(C_5 \rightarrow\) software

Sensor level calibration:
- \(C_1 \rightarrow\) Single point calibration \((T_{\text{ambient}})\)
- \(C_2 \rightarrow\) Multi point calibration

The problem is making millions of parts working as expected!
Sensor Accuracy in Manufacturing Technology & Equipment

**MANUFACTURING EQUIPMENT**

Precise geometries, etching, assembly

Enabling sensor accuracy at yields suitable for high volume manufacturing

**TEST & CALIBRATION EQUIPMENT**

Accurate stimuli, Multi-calibration points, Multi DOF-tests, high parallelism

Enabling accurate sensors at high volume
ST stands for life.augmented

Thank you