ELECTROMECHANICAL DAMPING IN MEMS ACCELEROMETERS

A WAY TOWARDS SINGLE CHIP GYROMETER ACCELEROMETER CO-INTEGRATION

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Abstract

This work describes a controllable damping source that can decrease the quality factor (QF) of a mechanical resonator by several orders of magnitude. This additional damping mechanism, which is independent of ambient pressure, is expected to allow the co-integration of quasi-static accelerometer with resonant gyrometer inside a same cavity under vacuum.

Single package 9 DOF Context

Inertial Measurement Unit (IMU) requirements for the consumer market :

- Size shrinking (At present : 3x3 mm², in 2016 : 2x2 mm²)
- Cost reduction (<1$)

Combo Accelerometer **3A** / gyrometer **3G** / magnetometer **3M**

One single package 9 Degrees Of Freedom (DOF)

First 9 DOF combo released in 2012
large growth expected within the next few years

Applications : *motion tracking, pedestrian navigation, etc.*

Prospects : *pressure gauge integration* ⟶ *10 DOF*

Sensor Dynamics

2 MEMS dies side by side

on 6 × 6 mm² (system plus consulting)

Invensense MPU-9250 :

2 stacked chips :

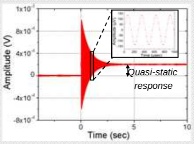
3A3G MEMS chip and Hall sensor chip

on 3 × 3 mm².

Accelerometer Gyrometer co integration issue

Different Quality Factor (QF) requirements for Static and Dynamic sensors

- **Static Accelerometer**



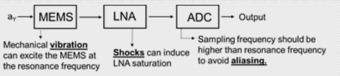
System response to an ideal shock

- Resonance frequency around a few kHz
- Under vacuum, QF=2000 up to 40000

⟶ Sensitivity **x QF** to high frequency mechanical disturbances

Signal filtering not suitable

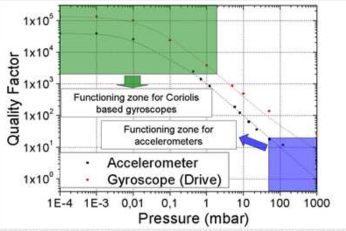
High damping force required $\boldsymbol{QF < 10}$



Mechanical **vibration** can excite the MEMS at the resonance frequency

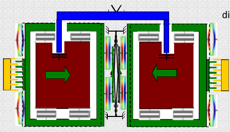
Shocks can induce LNA saturation

Sampling frequency should be higher than resonance frequency to avoid **aliasing.**



Quality Factor as a function of pressure for M&NEMS accelerometers and gyrometers. *The green (blue) zone corresponds to the pressure environment that is compatible with gyrometers (accelerometers)*

- **Coriolis force Gyrometer**



Drive mode operation needs displacement amplitude around **2 µm**

For standard gyrometer QF must be larger than

$$QF_{\text{min}} = \frac{k_x.u}{F_{exc}} \approx 2000$$

Low damping force required **:** $\boldsymbol{QF > 1000}$

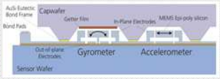
No common pressure range for the two kinds of sensor

- Accelerometer : operation pressure > 0.1-1 bar
- Gyrometer : operation pressure < 1 mbar

Single chip integration
under the same MEMS cavity not suitable

Single package co integration solutions

- **Different MEMS cavities:** Multi Cavity Packaging [7] (Invensense MPU 9250, Sensor dynamic…)



From P. Merz, et al, Proc. of MEMS 2010

- Pressure in 3A cavity : P = 0.1 bar
- Getter required for gyrometer P = 0.25 mbar

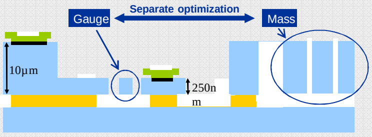
- **Same MEMS cavity: Resistive electromechanical damping** without no active electronic feedback loop (proposed work).

M&NEMS technological platform

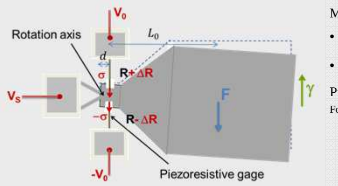
M&NEMS basic concept

Two different thicknesses on the same device [1]:

- MEMS layer for the inertial mass (>10µm)
- NEMS layer for the NEMS part (250 nm)



Suspended piezoresistive nanogauges
etched in the NEMS layer



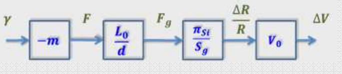
Signal conditioning chain

Mechanical signal amplification through

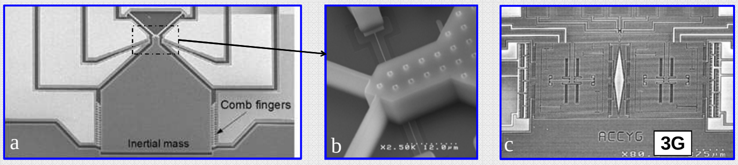
- lever arm effect $\frac{L_0}{d}$
- stress concentration over the small gauge cross section $\sigma = \frac{F_g}{S_g}$

Piezoresistive transduction for p-doped Silicon

For $p = 4 \times 10^{19} cm^{-3}$: $\pi_{Si} \approx 50$, $R_g \approx 2000\Omega$, $s \approx 1\, m\Omega/\Omega/g$



$$\gamma \xrightarrow{} \boxed{-m} \xrightarrow{F} \boxed{\frac{L_0}{d}} \xrightarrow{F_g} \boxed{\frac{\pi_{Si}}{S_g}} \xrightarrow{\frac{\Delta R}{R}} \boxed{V_0} \xrightarrow{} \Delta V$$



A technological platform for 9 DOF combo sensor [1-4]

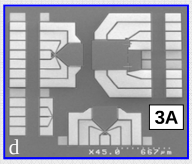
- Common process flow for 9 DOF sensors (10 with pressure sensor under development)
- Reduce the footprint of inertial sensors
- Overcome diffused piezoresistive limitations (suspended nanogauges)

a. M&NEMS Accelerometer (300x300 µm²)

b. Close up on nanogauges
(5 µm long, 250 nm wide and thick)

c. M&NEMS gyrometer

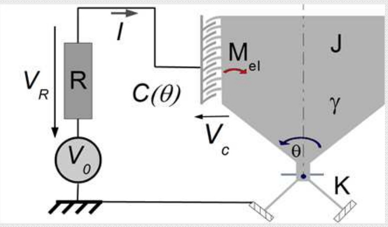
d. 3A accelerometer



Industrial transfer
to TRONICS MICROSYSTEM

Resistive electromechanical damping

Electromechanical coupling between a MEMS resonator and a resistive circuit



Two coupled degrees of freedom for the electromechanical system [5,6]

- In the mechanical domain: the position θ

$$J\ddot{\theta} + J\gamma_0\theta + K\dot{\theta} = M_{el} \qquad M_{el} = -\frac{1}{2}\frac{\partial}{\partial\theta}\left(\frac{Q^2}{C}\right)\Big]_Q$$

- In the electrical domain: the charge Q

$$V_0 = \frac{Q}{C} + R\dot{Q} \qquad Q = CV_c$$

For a constant bias voltage V_0, Q depends only on position θ @ ω:
if $\delta C \ll C_0$

$$\delta Q = \frac{V_0}{1 + jRC_0\omega}\frac{\partial C}{\partial\theta}\theta$$

Back action Momentum exhibits a dissipative term:

$$M_{el} = -J\gamma_{el}\dot{\theta} + \cdots \qquad \gamma_{el} = \frac{RV_0^{\,2}\left(\frac{\partial C}{\partial\theta}\right)^2}{1 + (RC_0\omega)^2}$$

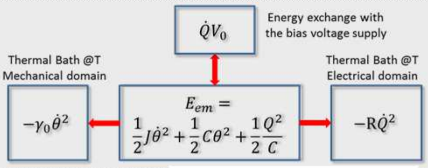
Energy balance: an additional damping source

$$\frac{d}{dt}\left(\frac{1}{2}J\dot{\theta}^2 + \frac{1}{2}K\theta^2 + \frac{1}{2}\frac{Q^2}{C}\right) = -\gamma_0\dot{\theta}^2 - R\dot{Q}^2 + \dot{Q}V_0$$

(no approximation)

The total energy of the system :

- Is dissipated in the mechanical domain through usual channel $-\gamma_0\dot{\theta}^2 < 0$
- **Is dissipated in the electrical resistance through Joule effect** $< -R\dot{Q}^2 > = < -\gamma_{el}\dot{\theta}^2 >$
- Can be exchanged with the voltage supply $< \dot{Q}V_0 > = 0$



$\dot{Q}V_0$

Energy exchange with the bias voltage supply

Thermal Bath @T Mechanical domain

Thermal Bath @T Electrical domain

$$-\gamma_0\dot{\theta}^2 \leftarrow E_{em} = \frac{1}{2}J\dot{\theta}^2 + \frac{1}{2}C\theta^2 + \frac{1}{2}\frac{Q^2}{C} \rightarrow -R\dot{Q}^2$$

Damping force control : quality factor tuning

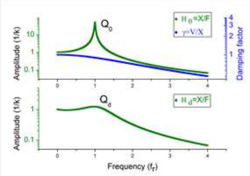
The mechanical resonator experiences a additional damping force that alters the quality factor QF

$$\gamma = \gamma_0 + \gamma_{el} = \gamma_0 + \frac{RV_0^{\,2}\left(\frac{\partial C}{\partial\theta}\right)^2}{1 + (RC_0\omega)^2}$$

The damping factor is maximal if $RC_0\omega$<1 : the low pass filter RC set the limitation of the proposed approach. In practice, the relevant frequency is the resonance frequency of the resonator ω_r

Qualiy factor $Q_d = \frac{\omega_r}{\gamma(\omega_r)}$

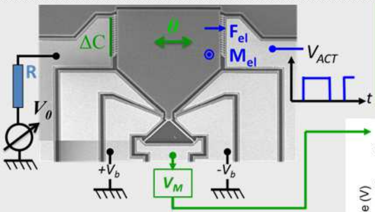
Quality factor can be lowered for large bias voltage V_0, large electromechanical coupling $\frac{\partial C}{\partial\theta}$ and large resistance R. However, these two conditions have to be met: $RC_0\omega_r$<1 and $\delta C \ll C_0$



Experimental analysis

Experimental analysis: response to a step

Response time can be tuned by changing he bias voltage $\boldsymbol{V_0}$ demonstration with the response to a step



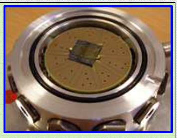
MEMS Parameters

From the setup @ 10 µBar

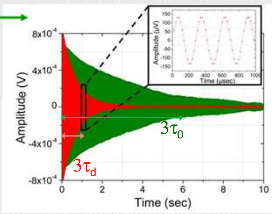
- $C_{comb} = 50fF$ << setup capacitance
- $J = 1.07\ 10^{-16} kg/m^4$
- R from 1kΩ up to 1GΩ

From fit (good agreement with theory)

- $f_r = 3530\ Hz$
- $Q_0 = 41800$
- $C_0 = 20.4\ pF$ (setup parasitic capacitance)
- $C' = \frac{\partial C}{\partial\theta} = 1.14 \frac{pF}{rad}$



Setup: the MEMS sample bonded to the stage and inside a vacuum chamber

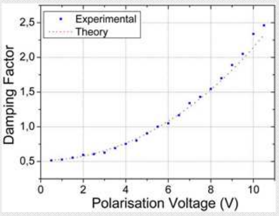


Position of the resonator $\boldsymbol{V_M}$ for two bias voltages

- $V_0 = 0$: mechanical damping alone
  τ_0=1.9 s
- $V_0 = 10$V : with resistive damping
  τ_d=0.4 s

With the resistive damping, the response time τ is divided by 5

Effective Damping factor as a function of the bias voltage $\boldsymbol{V_0}$



Quadratic dependence on bias voltage ⟵

$$\gamma = \gamma_0 + \alpha V_0^{\,2}$$

Quadratic dependence on bias voltage ⟶

$$\gamma = \gamma_0 + \alpha\frac{R}{1 + (RC_0\omega_r)^2}$$

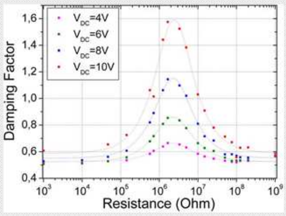
$R_{optimum} = 2.25\ M\Omega$

Limitations set by the parasitic capacitance of the experimental setup

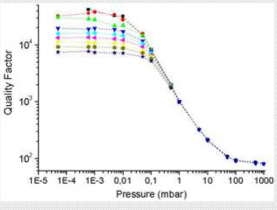
cutoff frequency ~ resonance frequency

Cut off frequency tuning

variable resistance R, constant capacitance C_0



Resistive damping as a function of pressure



Pressure dependency of Quality factor ⟵

$$\gamma = \gamma_0(P) + \gamma_e(V_0)$$

γ_e independent of ambient pressure

Above 0.1mbar the damping factor is dominated by air friction mechanism

Conclusion

- Quality factor control through V_0 √
- For the present MEMS design, Q / 5 demonstrated: Q from 41000 down to 8000 (for $R_{optimum}$ and $V_0 = 10V$) √
- Dedicated MEMS design in prospect √
- Parasitic capacitance to be reduced ⚠

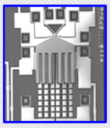
Electromechanical damping prospect

Electromechanical damping provides solutions:

- For Accelerometer and Gyrometer co integration inside a same MEMS cavity. The QF of the accelerometer can be tuned down to 1-10, while keeping the QF of the gyrometer high, above 50000 under vacuum (see below).
- For QF control in gyrometer or for mechanical response control of MEMS devices through the bias voltage V_0

Dedicated accelerometer MEMS designs under development:

- Resistance etched on chip in a low doped silicon layer: $R = 50M\Omega$: total capacitance can be set at 1 pF thus $f_c = 3.2\ kHz$. Comb capacitance can provide $C' = 40pf/rad$. For $V_0 = 3.3\ V$, the damping gain is improved by 30000 : QF drop off from 40000 down to 2-3.
- Resistance etched on chip in a low doped silicon layer: $R = 250M\Omega$: total capacitance can be set at 0.2 pF thus $f_c = 3.2\ kHz$. Comb capacitance can provide $C' = 10pf/rad$. For $V_0 = 3.3\ V$, the damping gain is improved by 10000 : QF drop off from 40000 down to 6-10



MEMS device in prospect

Reference / Acknowledgement

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