MEMS Electrostatic Vibration Energy Harvester (e-VEH)

P. Basset
p.basset@esiee.fr

Université Paris-Est
ESYCOM lab - ESIEE Paris

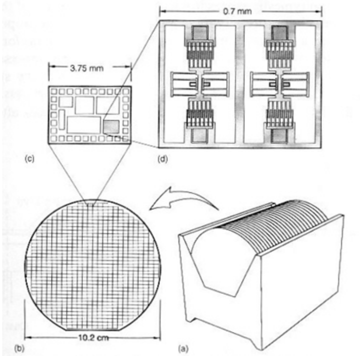
UNIVERSITÉ PARIS-EST
ESYCOM
ESIEE PARIS

Outline

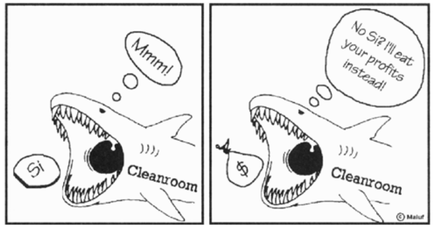
- Introduction to MEMS
- Introduction to VEH
- Electrostatic transducer
- Electrostatic energy conversion
- Example of a e-VEH from ESIEE Paris
- Conclusion

Introduction to MEMS

Batch fabrication from IC technologies

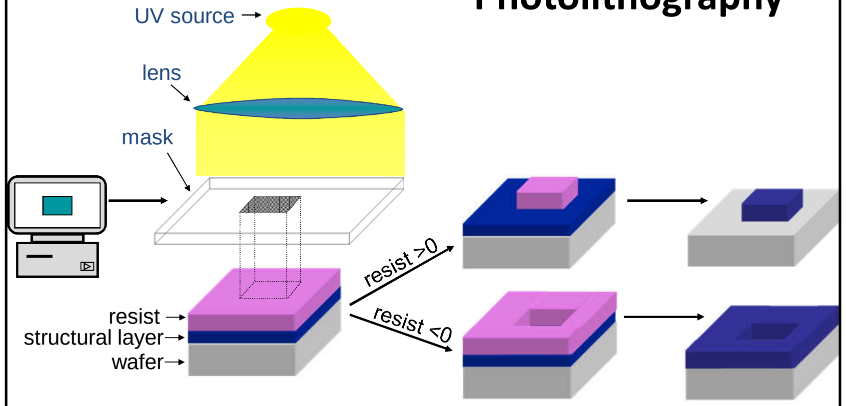


Batch-fabrication process of microelectronic circuits.



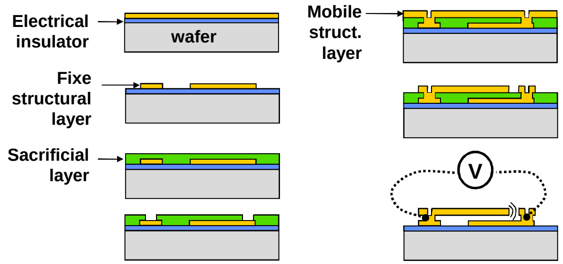
- High cost for low volume / Low cost for high volume (> 1 MU)

Photolithography



- Use of (UV) light to transfer a geometric pattern from a photo mask to a light-sensitive chemical "photo resist"on the substrate

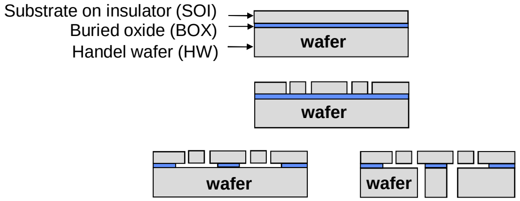
Thin film MEMS



- The silicon wafer is mainly a "handling layer"
- The deposited layers are typically in the µm range

Bulk micromachining

example on a SOI wafer

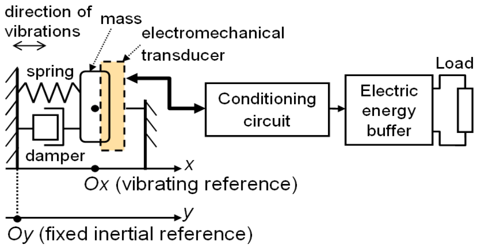


- The mobile parts are in bulk silicon
- Thickness can be in the mm range (typ. tens to hundreds of µm)

→ better reliability

Introduction to VEH

Principle of a typical VEH

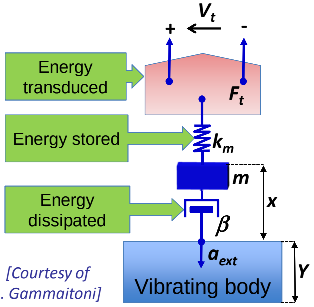


- 2 main steps:

1. Part of the vibration energy is captured by the spring-mass system
   Kinetic energy (mass velocity) & potential energy (spring compression)
   → Determine the maximum amount of energy that can be converted into electricity
2. An electromechanical transducer converts some of this energy into electrical form

→ Some of this energy is also dissipated into heat

Principle of a typ. VEH

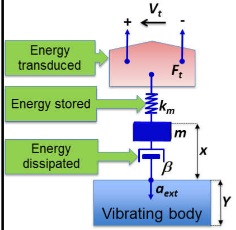


[Courtesy of L. Gammaitoni]

k_m = spring stiffness
m = mass
β = damping coefficient
A_{ext} = external acceleration
F_t, V_t = transducer force and voltage

- Energy conversion
  ⇔ loss of kinetic energy
  (→ damping force)
  ⇔ added electrical power
- The loss of kinetic energy comes from the negative work of an electrical force F_t introduced by the electromechanical transducer

Dynamical model



2nd Newton law:

$$m\ddot{x} = -\frac{d}{dx}E_p + F_{mech\_damp.} + F_t + F_{ext}$$

- $E_p(x)$ = stored energy = $k_m x^2/2$ for a linear spring
- $F_{mech\_damp.}$ = dissipative force = $-\beta.\dot{x}$
- $F_t(x,V_t)$ = force introduced by the transducer
  →opposed to the motion during the energy conversion: $F_t<0$
- F_{ext} = $-ma_{ext}$ = vibration force

Dynamical model

$$\begin{cases} m\ddot{x} + \beta_m \dot{x} + k_m x - F_t(x,V_t) = -ma_{ext} \\ \dot{V}_t = f(\dot{x},V_t) \end{cases}$$

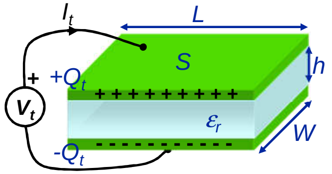
- The transducer force F_t and the function f describing the dynamic of the transducer output voltage V_t are determined by:
  - The transduction mechanism
  - The geometry of the transducer
  - The conditioning circuit of the transducer

→ The transducer can not be studied independently of its conditioning circuit

The electrostatic transducer

The electrostatic transducer

- MEMS capacitive transducers are generally represented by two parallel electrodes



$$C_t = \frac{Q_t}{V_t} = \varepsilon\frac{S}{h} = \varepsilon_0\varepsilon_r\frac{L\cdot W}{h}$$

- ε_0 = permittivity of vacuum
  ε_r = relative permittivity of the dielectric
- S = (effective) facing area of the electrodes
- h = gap between electrodes

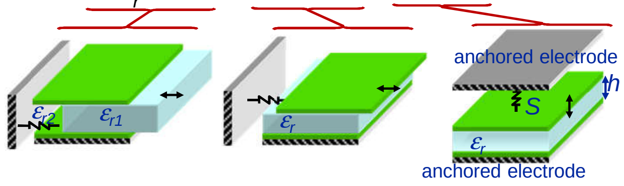
- The capacitance is varying with time:

$$C_t = C_t(t) \Rightarrow I_t = \frac{dQ_t}{dt} = \frac{d}{dt}(C_tV_t) = \underbrace{C_t\frac{dV_t}{dt}}_{\text{electrical}} + \underbrace{V_t\frac{dC_t}{dt}}_{\text{mechanic}}$$

Basic geometries of a capacitive transducer

- If the fringe electric field can be neglected: $C_t = \varepsilon\frac{S}{h}$

$$\Delta C_t = \frac{\partial C_t}{\partial\varepsilon_r}\cdot\Delta\varepsilon_r + \frac{\partial C_t}{\partial S}\cdot\Delta S + \frac{\partial C_t}{\partial h}\cdot\Delta h$$



- Depending on the design, the capacitance variation comes from a change in the gap, the overlapping area or the permittivity

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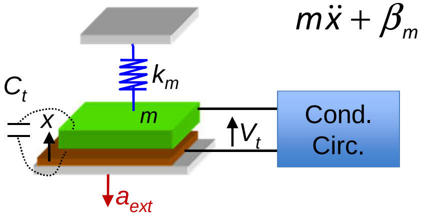
The transducer's force (1)

$$m\ddot{x} + \beta_m\dot{x} + k_m x - F_t(x,V_t) = -ma_{ext}$$



- The energy transducer is a variable capacitor C_t

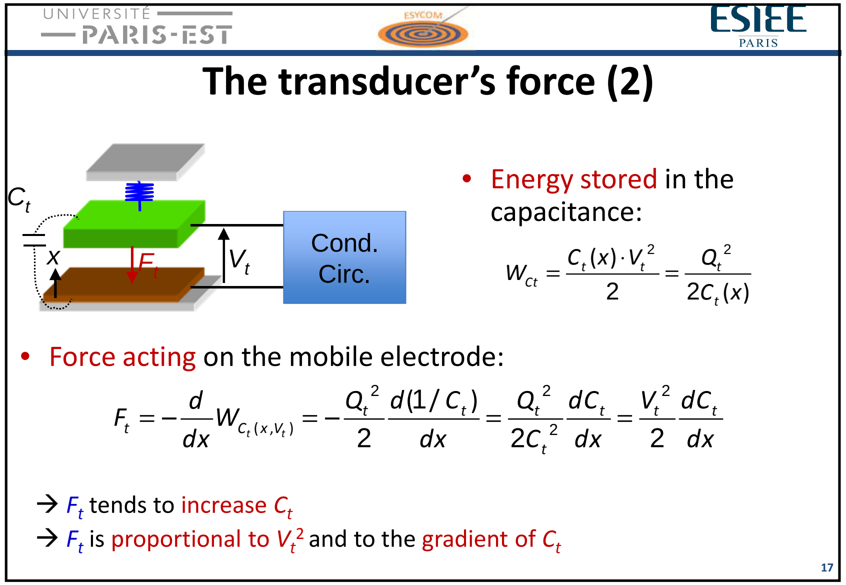
→ The transducer force F_t is an electrostatic force

- F_t derives from the potential energy of C_t

→ F_t depends on the voltage V_t across C_t and on the mobile mass position x

$$\boxed{F_t = -\frac{d}{dx}W_{C_t(x,V_t)}}$$

- V_t is generated by the conditioning circuit (C.C.)



The transducer's force (2)

- Energy stored in the capacitance:

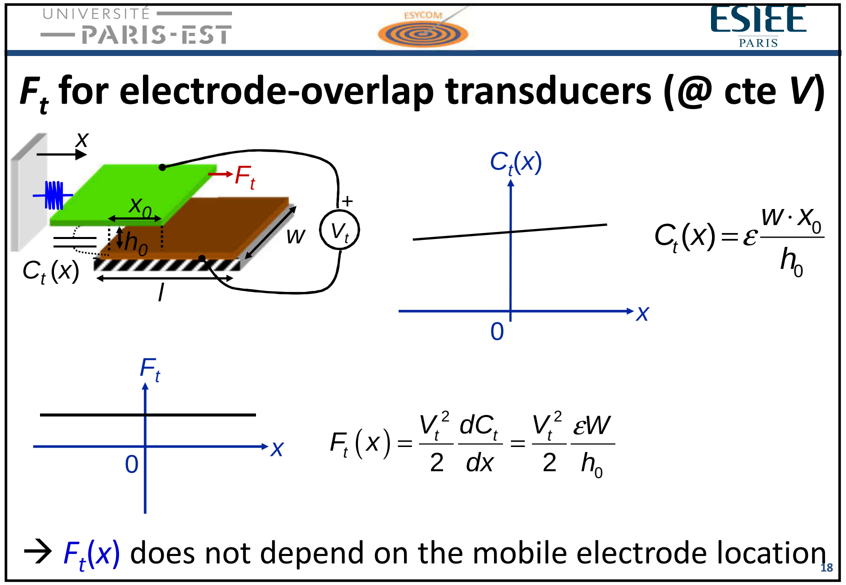
$$W_{Ct} = \frac{C_t(x)\cdot V_t^2}{2} = \frac{Q_t^2}{2C_t(x)}$$

- Force acting on the mobile electrode:

$$F_t = -\frac{d}{dx}W_{C_t(x,V_t)} = -\frac{Q_t^2}{2}\frac{d(1/C_t)}{dx} = \frac{Q_t^2}{2C_t^2}\frac{dC_t}{dx} = \frac{V_t^2}{2}\frac{dC_t}{dx}$$

→ F_t tends to increase C_t

→ F_t is proportional to V_t^2 and to the gradient of C_t

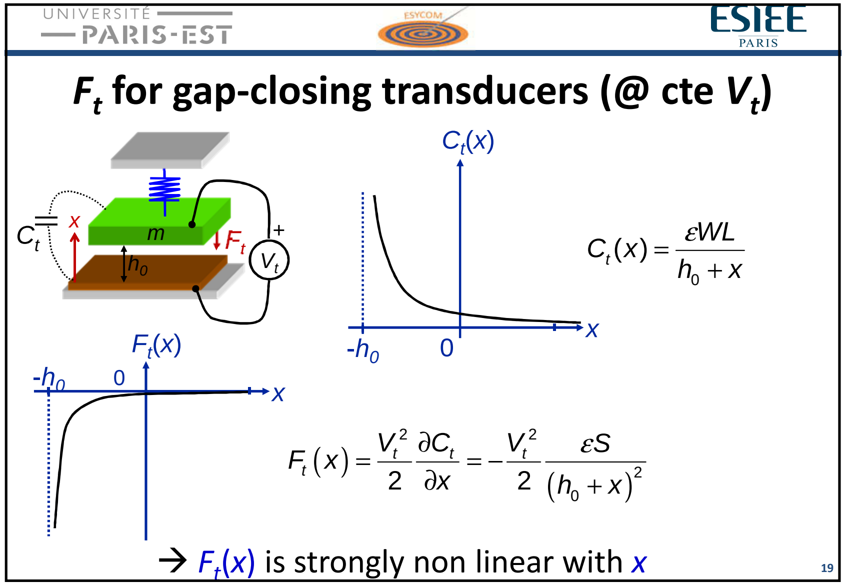


F_t for electrode-overlap transducers (@ cte V)

$$C_t(x) = \varepsilon\frac{w\cdot x_0}{h_0}$$

$$F_t(x) = \frac{V_t^2}{2}\frac{dC_t}{dx} = \frac{V_t^2}{2}\frac{\varepsilon W}{h_0}$$

→ $F_t(x)$ does not depend on the mobile electrode location

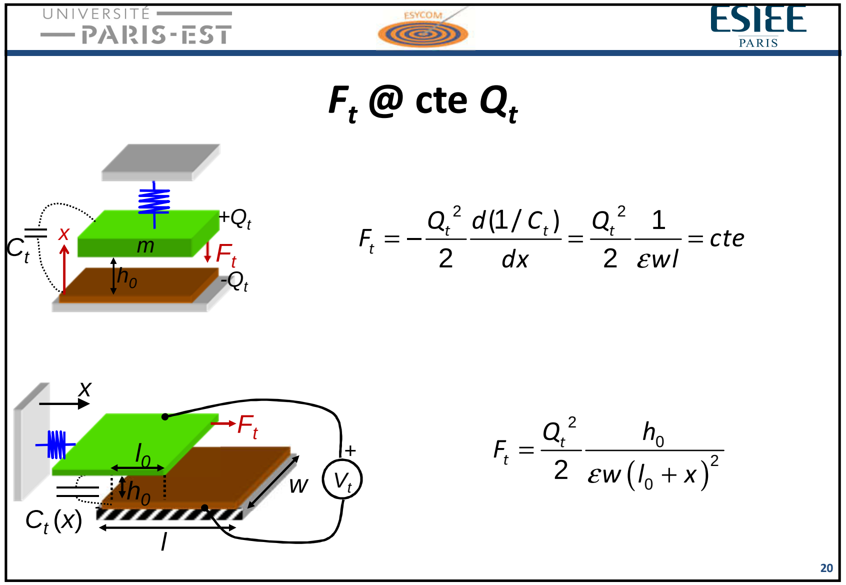


F_t for gap-closing transducers (@ cte V_t)

$$C_t(x) = \frac{\varepsilon WL}{h_0 + x}$$

$$F_t(x) = \frac{V_t^2}{2}\frac{\partial C_t}{\partial x} = -\frac{V_t^2}{2}\frac{\varepsilon S}{(h_0+x)^2}$$

→ $F_t(x)$ is strongly non linear with x

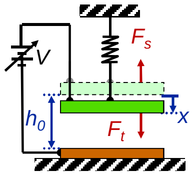


F_t @ cte Q_t

$$F_t = -\frac{Q_t^2}{2}\frac{d(1/C_t)}{dx} = \frac{Q_t^2}{2}\frac{1}{\varepsilon wl} = cte$$

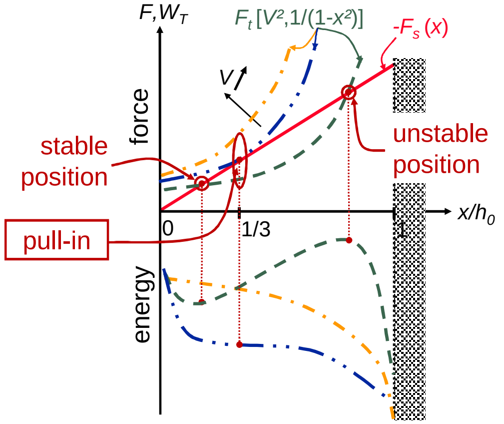
$$F_t = \frac{Q_t^2}{2}\frac{h_0}{\varepsilon w(l_0+x)^2}$$

Electrostatic instability: pull-in phenomena

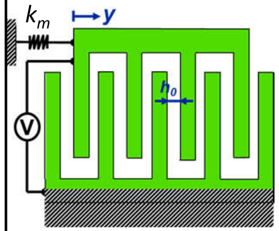


$$x_{pi} = \frac{h_0}{3}$$

$$V_{pi} = \sqrt{\frac{8kh_0^3}{27\varepsilon S}}$$



Electrostatic spring softening



$$C(y) \approx N\varepsilon S\left(\frac{1}{h_0+y}+\frac{1}{h_0-y}\right)$$

$$F_{e,y} = \frac{V^2}{2}\frac{\partial C}{\partial y} = \frac{N\varepsilon SV^2}{(h_0-y)^2} - \frac{N\varepsilon SV^2}{(h_0+y)^2} \underset{y<<}{\approx} N\overset{-k_e \geq 0}{\frac{2\varepsilon SV^2}{h_0^3}}y$$

$$k_e = -\frac{V^2}{2}\frac{d^2C}{dy^2} \rightarrow \omega_0 = \sqrt{\frac{k_m+k_e}{m}} = \sqrt{\frac{k_m}{m}}\sqrt{1+\frac{k_e}{k_m}}$$

- A gap-closing interdigited-comb transducer acts as negative spring
- This electrostatic spring is strongly non linear with y

→ voltage dependence of the mechanical resonance frequency

The electrostatic mechanical → electrical energy conversion

Scaling

- m scales as L^3
- X_{max} scales as L

→ Power scales as L^4

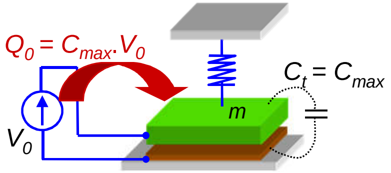
$$P_{\max\_avail.} = \frac{2}{\pi}\underbrace{mX_{\max}}_{\text{design driven}}\underbrace{A_{ext}\omega}_{\text{application driven}}$$

Power density falls drastically as size reduces

In vibration energy harvesting, size matter!!!

Principle of the electrostatic energy conversion (ex. of constant-charge operation)

Step 1



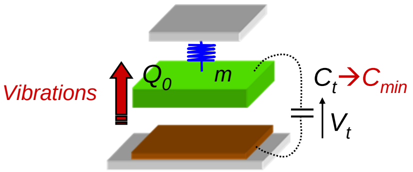
- A charge Q_0 is applied on C_t when its value is maximal (C_{max})

- The energy stored in C_t is: $$W_0 = \frac{1}{2}\frac{Q_0^2}{C_{max}}$$

Principle of the electrostatic energy conversion (ex. of constant-charge operation)

Step 2

- The voltage source is disconnected
- The external vibrations bring C_t to itsminimum value C_{min}



$$Q_0 = cte = C_{max}V_0 = C_{min}V_t$$
$$\Rightarrow V_t \to V_0\frac{C_{max}}{C_{min}} = V_{t\_max}$$

- The energy stored in C_t is now : $$W_1 = \frac{1}{2}\frac{Q_0^2}{C_{min}} > W_0$$

Principle of the electrostatic energy conversion (ex. of constant-charge operation)

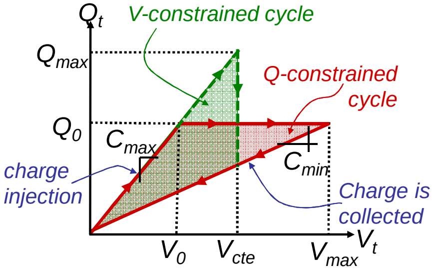
- Between *step1* and *step2*, the difference of energy in the capacitance equals :

$$\boxed{\Delta W = W_1 - W_0 = W_0\left(\frac{C_{max}}{C_{min}} - 1\right) > 0}$$

→ The energy in C_t has increased by a factor (C_{max}/C_{min}-1)

- This increase of energy comes from the mechanical domain → ***step3*** consists in storing ΔW

The *QV* diagram



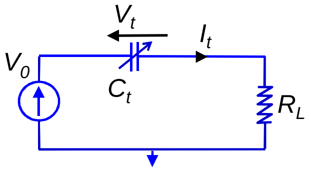
- Ideally, the *QV* diagram of the conversion cycle is triangular
- The area of the triangle corresponds to the harvested energy [=$W_0(C_{max}/C_{min}$-1) for the cte Q cycle]
- This is the highest energy per cycle that can be harvested for a given transducer using electrostatic conversion and a given mass displacement amplitude
- However increasing W_0 does not allow to harvest beyond the maximal power defined previously (→ *why?*)

The conditioning circuit

The Conditioning circuit

- Two main roles :
  - Ensure the charge-discharge flow on the variable capacitor, required by the mechanical energy conversion principle
  - Provide the interface with the load

The simplest conditioning circuit (C.C.)

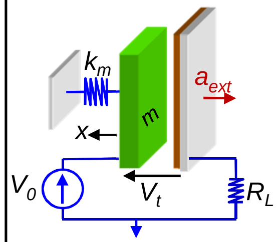


$$V_0 = V_t + R_L I_t$$

$$\rightarrow V_0 = V_t + R_L \frac{d}{dt}[C_t(x)\cdot V_t(x)]$$

- V_0 can be a battery, an electret, a rectenna, a piezoelectric element…
- Typically used to test the mechanical transducer

Basic C.C.

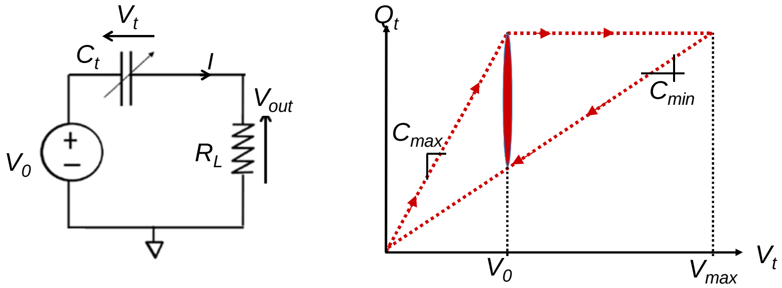


- Any C.C. impacts the system
  → there is an optimal value of R_L

Energy stored in the transducer capacitance

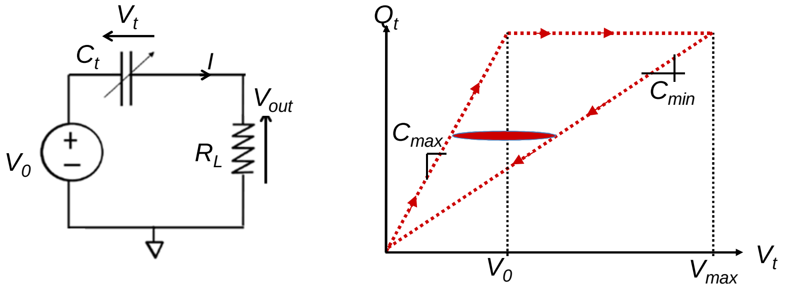
$$\begin{cases} m\ddot{x}+\beta_m\dot{x}+k_m x-\dfrac{d}{dx}\left[\boxed{\dfrac{V_0^2}{2}C_t(x)}\right]=-ma_{ext} \\ R_L\dfrac{d}{dt}[C_t(x)\cdot V_t(x)]+V_t(x)=V_0 \end{cases}$$

Prediction of the optimal load (1)



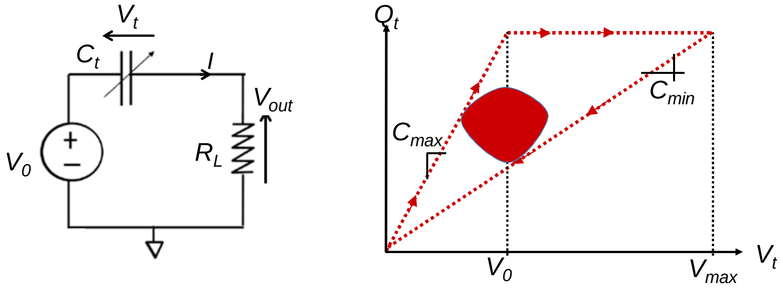
- If R_L is small → $I_{av}.R_L << V_0$
  - ~ constant voltage operation with low voltage variation across C_t during the cycle
  - → low harvested power

Prediction of the optimal load (2)



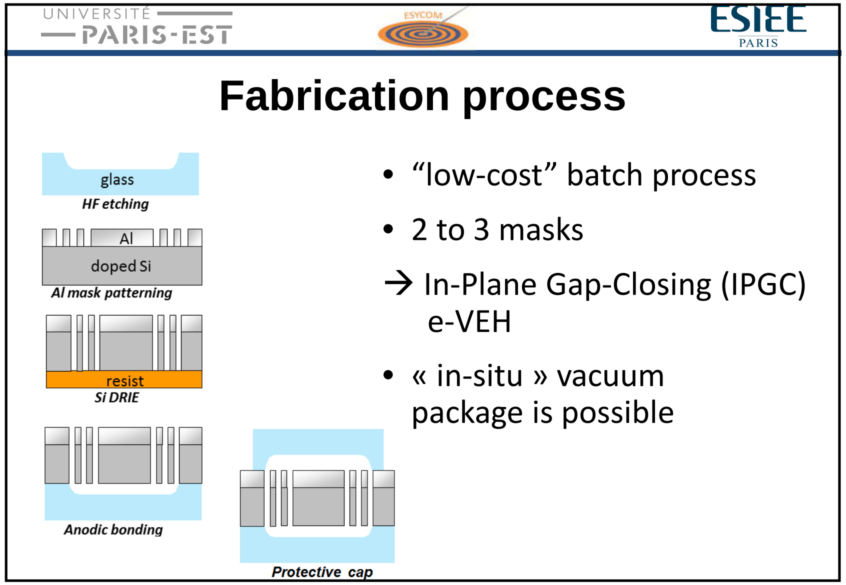
- If R_L is high →I_{av} << → $I_{av}.R_L << V_0$
  - ~ constant charge operation with low charge variation in C_t during the cycle → low harvested power
  - Frequency shift toward low frequencies

Prediction of the optimal load (3)



- If $I_{av}.R_L \sim V_0$
  - Good electromechanical coupling → “impedance matching”
  - Frequency shift toward low frequencies
  - →region of interest

Example of MEMS e-VEH

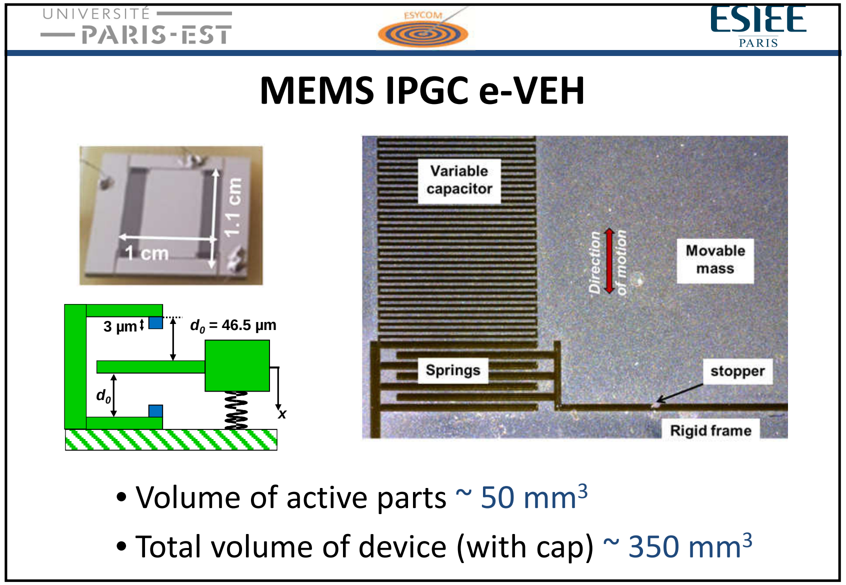


Fabrication process

- “low-cost” batch process
- 2 to 3 masks

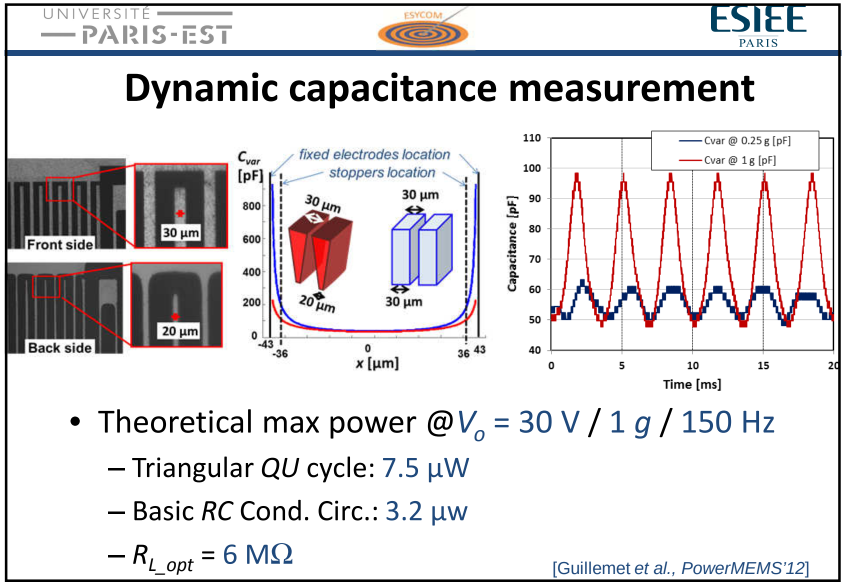
→ In-Plane Gap-Closing (IPGC) e-VEH

- « in-situ » vacuum package is possible



MEMS IPGC e-VEH

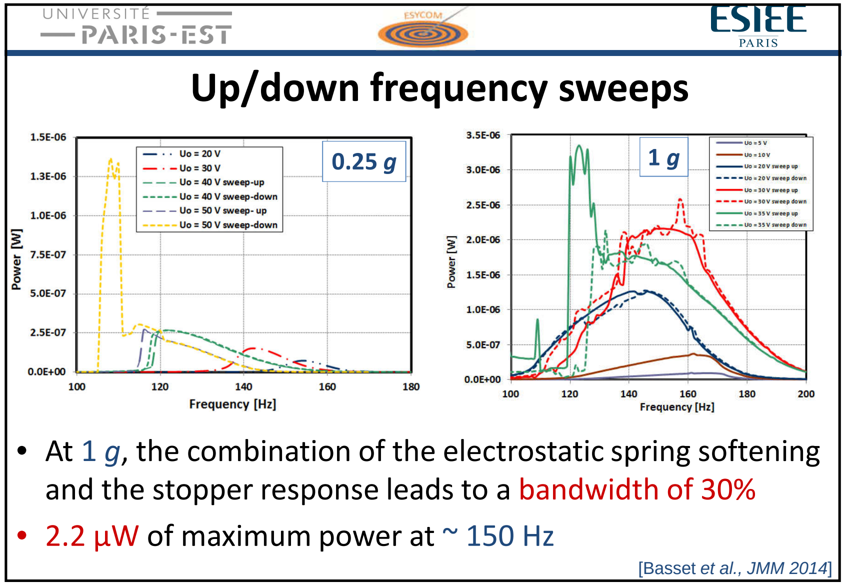
- Volume of active parts ~ 50 mm^3
- Total volume of device (with cap) ~ 350 mm^3



Dynamic capacitance measurement

- Theoretical max power @V_o = 30 V / 1 *g* / 150 Hz
  - Triangular *QU* cycle: 7.5 µW
  - Basic *RC* Cond. Circ.: 3.2 µw
  - R_{L_opt} = 6 MΩ

[Guillemet *et al.*, *PowerMEMS’12*]

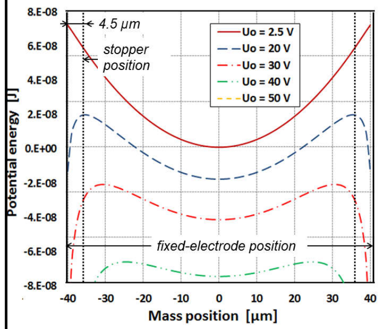


Up/down frequency sweeps

- At 1 *g*, the combination of the electrostatic spring softening and the stopper response leads to a bandwidth of 30%
- 2.2 µW of maximum power at ~ 150 Hz

[Basset *et al.*, *JMM 2014*]

Electrostatic control of the potentiel energy

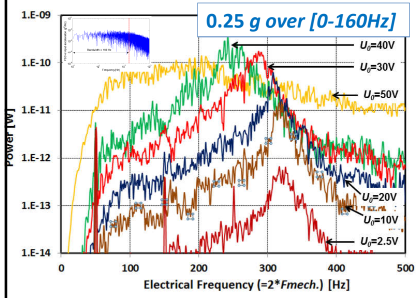


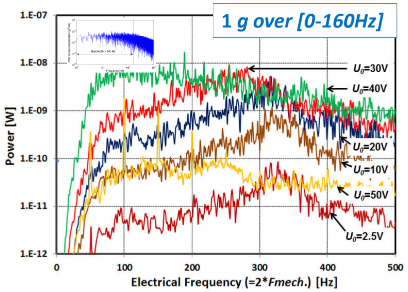
- The potential barriers are tunable through the bias voltage V_0
- Around $V_0 = 20$ V the system changes from monostable to multistable behavior

→ For a given acceleration, there is an optimum V_0 maximizing the harvested power under stochastic vibrations

[Cottone *et al.*, *Transducers'13*]

Stochastic noise excitation





- 0.25 & 1 *g* of input acceleration distributed over the natural bandwidth of the transducers (160 Hz)

➔Very low acceleration input PSD (~10^{-3} g^2/Hz @ 1 *g*) in the bandwidth → only electrostatic non-linearities

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Conclusion

- MEMS e-VEH are complex but full of promises
  - There are mechanically reliable, low-cost if mass-production, smart electronic can be implemented
- Mechanical and electrical non-linearities can be combined to either
  - enlarge the bandwidth,
  - create a multi-stable system
  - or tuned the resonant frequency