BMAS 2007, September 20-21, San Jose, California, USA

Multilevel Modeling of Integrated Power Harvesting System using VHDL-AMS and SPICE

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TIMA micro and nano systems group

Outline

1. Introduction and motivation.
2. Methodology
3. Modeling of the MEMS microgenerator
   a) 1D model for a piezoelectric microgenerator
   b) Enhanced model for resonant piezoelectric microgenerator
4. The Power Management Circuit
5. Global Simulations
6. Conclusion and future work

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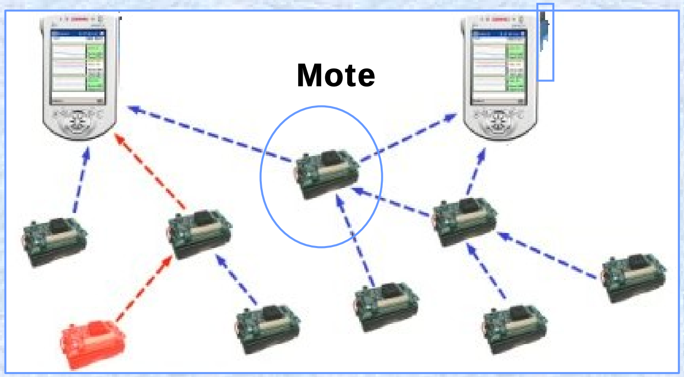
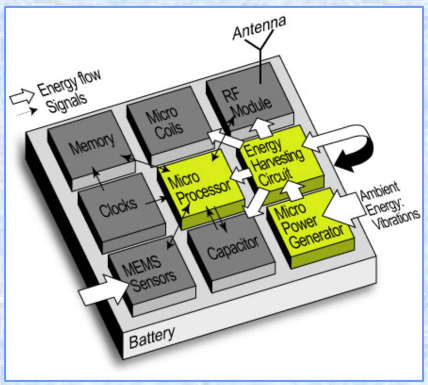
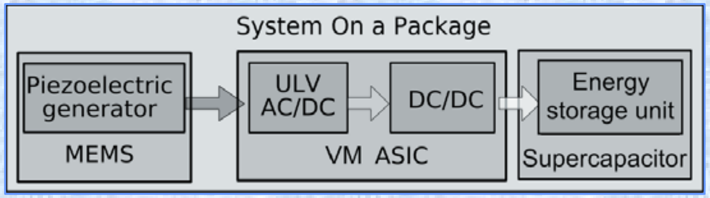
Introduction and motivation

Study case: Integrated Power Harvesting Circuit for motes in Wireless Sensor Networks (WSN).







Challenge :

- Complex MEMS.
- Different physical domains (mechanical and electrical).

»» Language and tool choices are very important in the design optimization process.

Introduction and motivation

Electrical equivalent circuits (SPICE-like simulators).	☺ Can be simulated in any circuit based simulator.	☹ Can lead to neglect cross coupling effects. ➔ unsuitable for systems with considerable coupling effects.
Signal flow approaches (Matlab™ / Simulink™)	☺ Modeling flexibility (LUTs, toolboxs…) .	☹ Allows only unidirectional quantities. ➔ Incompatible with Kirchhoff's law ➔ Leads to complicated models (quantities should be duplicated)[1]. ☹ Models are tool dependent.
FEM modeling (Ansys…)	☺ Accuracy	☹ Very time consuming process. ☹ Active electrical components (diodes, transistors) cannot be modeled with some tools (Ansys)
Analog languages like VHDL-AMS or Verilog-AMS (Cadence AMS, Dolphin…)	☺ Tool independent ☺ Powerful capabilities for modeling components in multiple energy domains.	☹ Tools are not mature enough, some language features are not yet implemented. [1] S. Guessab and al "Modeling of piezoelectric device with shock managements using VHDL-AMS", BMAS 2004

Introduction and motivation

Global simulations of the complete system
using the same environment.

- choice of the languages : VHDL-AMS for MEMS & SPICE for electrical circuit modeling.
  - VHDL-AMS offers more degrees of freedom when writing complex DAEs in a system level modeling.
  - Existing efficient SPICE transistor models in several levels.
- Tool choice: SMASH™ from Dolphin Integration to simulate the global system under the same kernel avoiding slow co-simulations:
  - Direct connection with SPICE netlists.
  - Good implementation of the VHDL-AMS language (especially tolerances subset)

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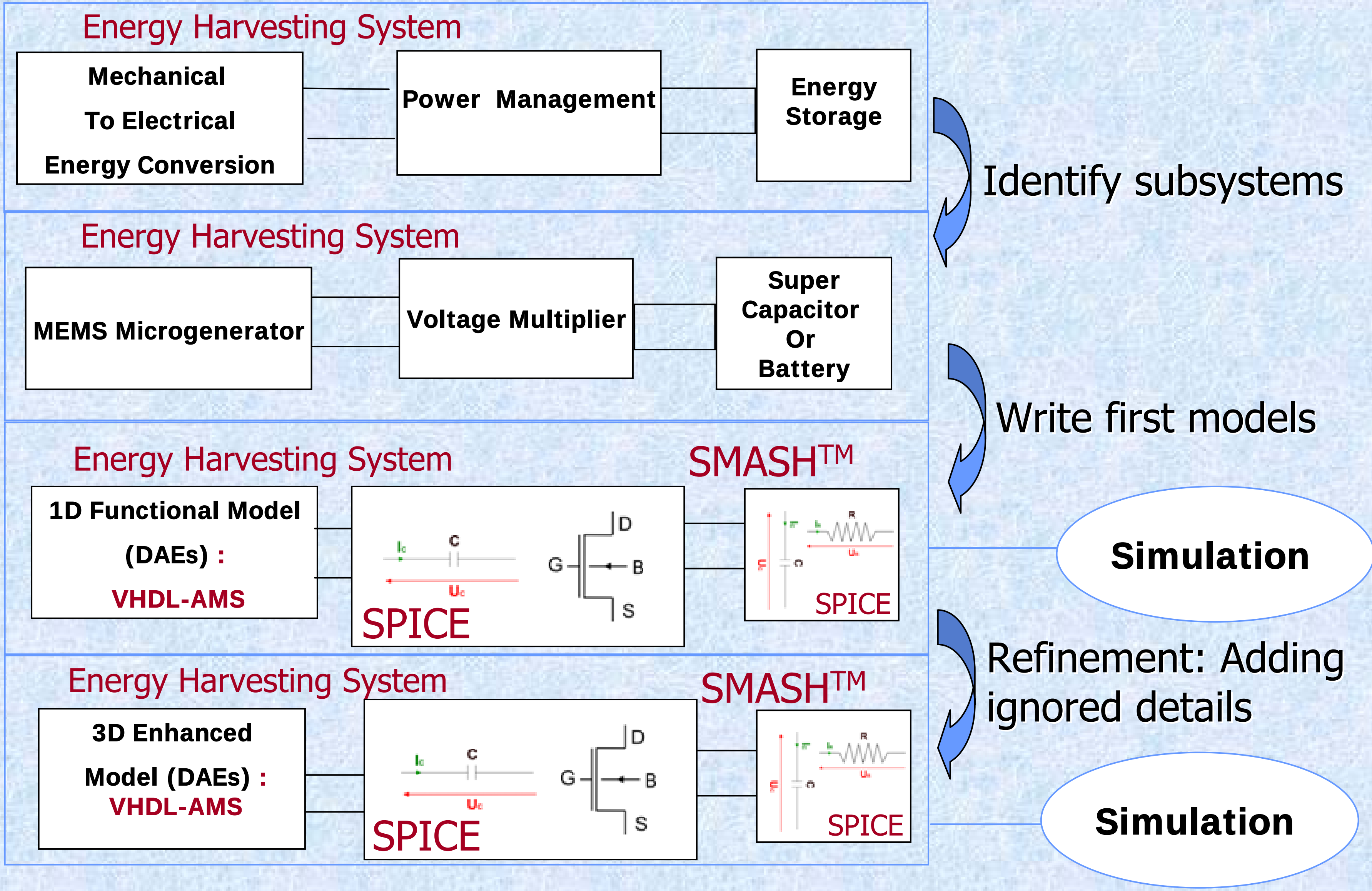
Methodology



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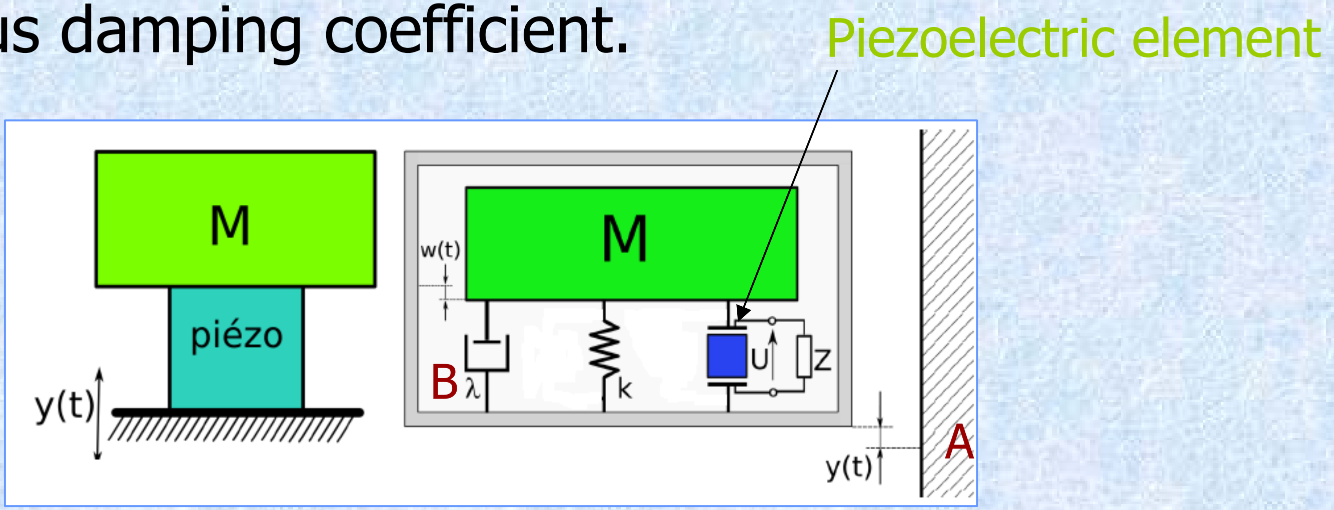
Modeling of the MEMS microgenerator

Top-Down approach:
1D simple model to validate transduction approach.
»» To be refined into an accurate 3D model.

- M is the seismic mass.
- The cage B is subjected to the sinusoidal vibrations y(t).
- w(t) is the displacement of the mass.
- k is the mechanical stiffness.
- λ is the viscous damping coefficient.



Modeling of the MEMS microgenerator

Piezoelectric transduction:

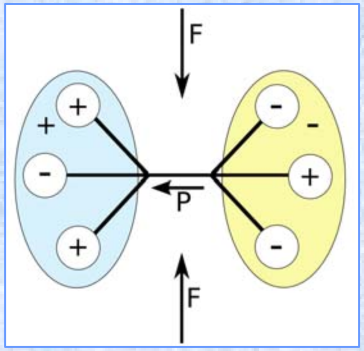
Deformation of a piezoelectric material

Hooke's law

$$T = c^E \cdot S$$

Maxwell's law:

$$D = \varepsilon^S \cdot E$$

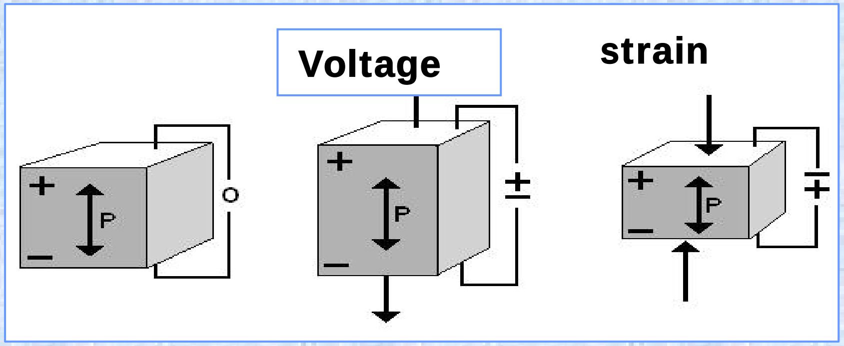


Constitutive equations of piezoelectricity

$$T = c^E S - e\, E$$

$$D = \varepsilon^S E + e\, S$$

Piezoelectricity coupling matrix



Constraint ➔Charge

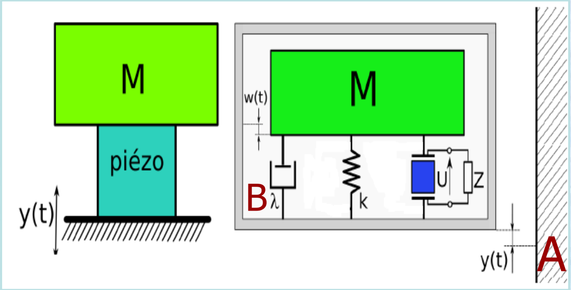
Modeling of the MEMS generator

The constitutive equations of piezoelectricity can be written in 1 dimension as:

$$T_3 = C_C S_3 - e_{33} E_3$$
$$D_{33} = e_{33} S_3 + \epsilon_c E_3$$

with

$$F_p = T_3 A$$
$$U = -E_3 L$$
$$w = S_3 L$$



***Fp* represents the force introduced by the piezoelectric element, linked both with the stiffness and with the piezoelectric coupling.**

The viscous damping coefficient λ is taken into account. This coupled electromechanical structure can be modeled as a damped harmonic oscillator.

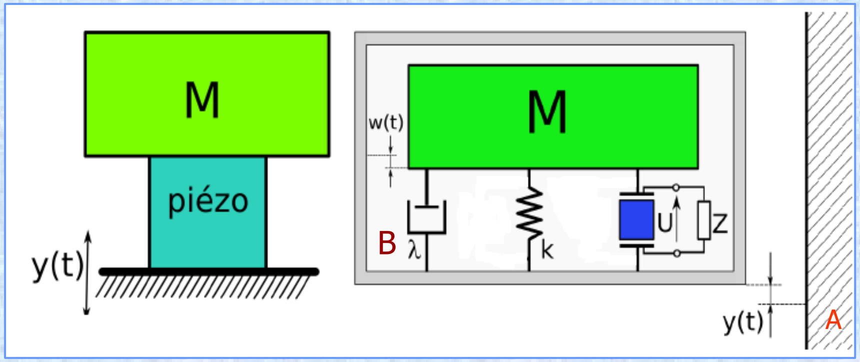
Extracting of DAEs to be used in VHDL-AMS model.

Modeling of the MEMS generator

$$M\ddot{w}+\lambda\dot{w}+F_P+M\ddot{y}=0$$

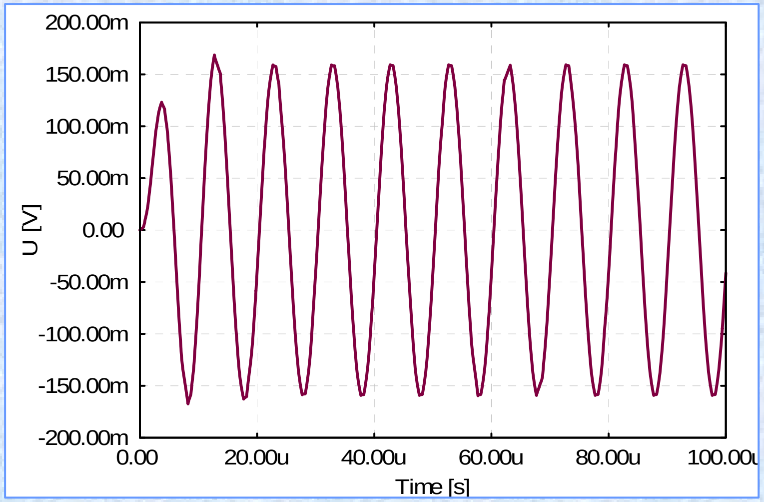
$$F_P=k_c w+\alpha U$$

$$\frac{U}{Z}=\alpha\dot{w}-C\dot{U}$$



To validate the MEMS microgenerator model. We have used a sinusoidal acceleration of 1g amplitude and a frequency equal to resonance frequency.

»» Sinusoidal voltage can be harvested.

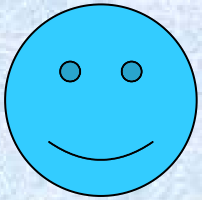


Open circuit output voltage of 1D microgenerator excited at its resonant frequency for an acceleration of 1g.

Modeling of the MEMS generator

The 1D model:

Simple, focuses on the piezoelectric transduction
»» Speed simulation.
»» Perfect for first validation.



Accuracy :
The 1D model is neither accurate nor predictive : The Structure is considered in one dimension and did not take into account all physical parameters and geometric dimensions.

Necessity of an enhanced model.

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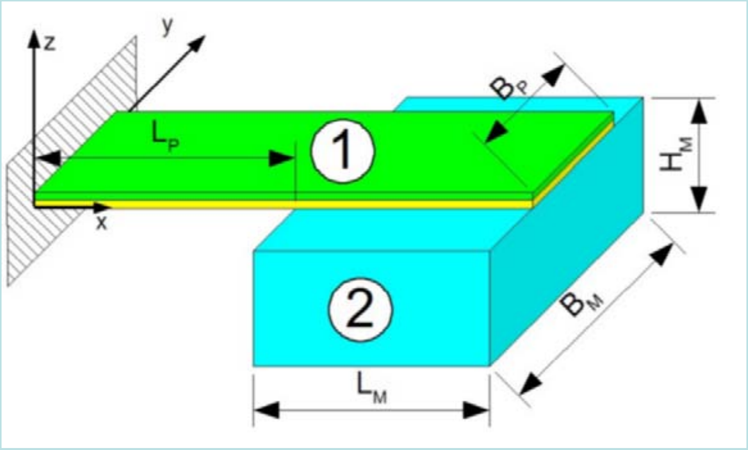
Modeling of the MEMS microgenerator

Structure:

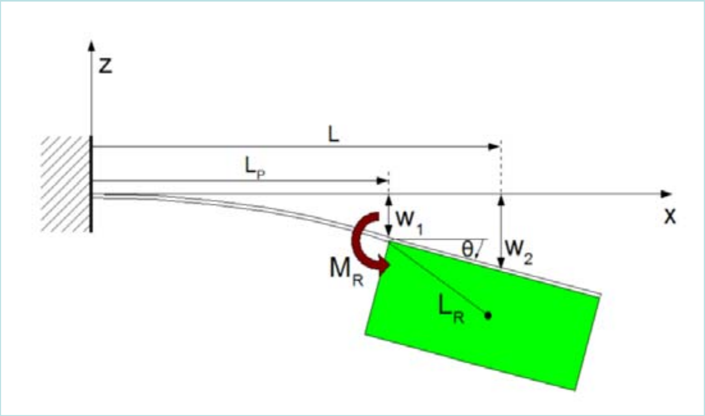
The enhanced model [2] is based on :

- A cantilever beam composed of two layers a pure mechanical layer and a piezoelectric film.
- A big mass attached at the end of the beam.



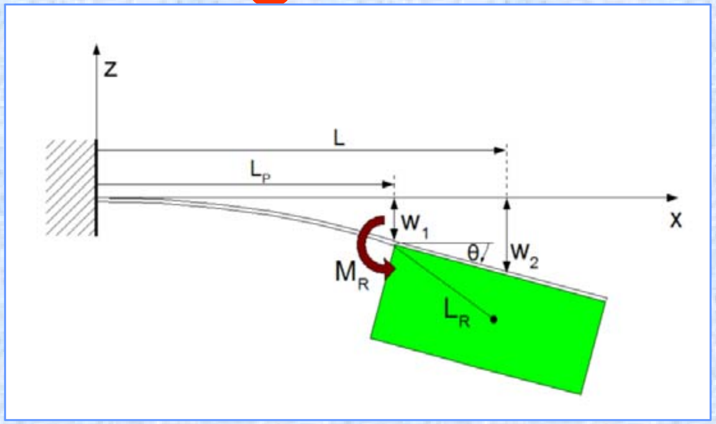
The device is fabricated on SOI substrates

»» An applied acceleration includes the deformation of the beam the displacement w_2 of the centroid of the mass.



[2] Marcin Marzencki (TIMA, MNS group) PhD thesis, UJF Grenoble, France 2007

Modeling of the MEMS microgenerator



The VHDL-AMS model:

»» Two coupled DAEs:

$$m\ddot{\boldsymbol{w}}_{\boldsymbol{2}} + \frac{B_P D''_G}{L_P L_{eq}^2}\boldsymbol{w}_{\boldsymbol{2}} - \frac{\zeta B_P D''_G}{L_{eq}^2}\left(L - \frac{L_P}{2}\right)\boldsymbol{U}_{\boldsymbol{0}} + \frac{J_0}{L_{eq}^2}\ddot{\theta}\left(L - \frac{L_P}{2}\right) = m\boldsymbol{A}_{\boldsymbol{in}}$$

$$\dot{\boldsymbol{U}}_{\boldsymbol{0}} L_P + \frac{\beta}{\zeta B_P Z D''_G}\boldsymbol{U}_{\boldsymbol{0}} + \beta\dot{\theta} = 0$$

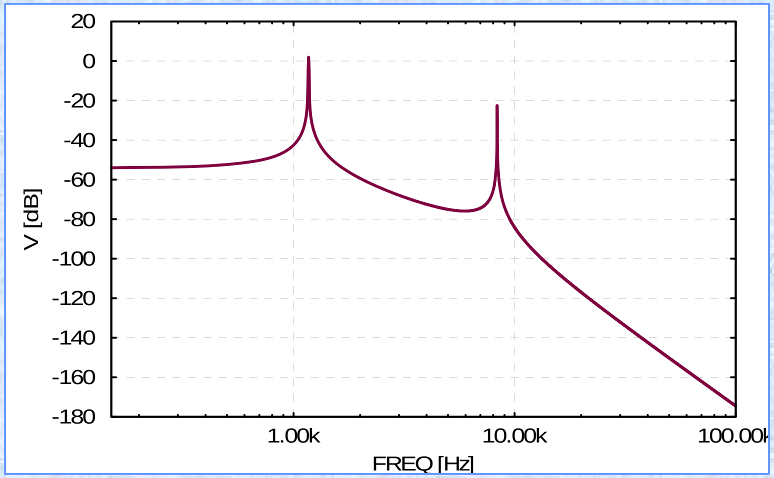
»» Long and slender beam »» Euler-Bernoulli convention used.

»» Beam composed of two layers: a pure mechanical layer and a piezoelectric film.

»» Rotational mass inertia M_R is taken into account.

Modeling of the MEMS microgenerator

- A seismic mass of 400 µm by 400 µm and a beam of 400 µm length in an SOI wafer (410 µm thick) were used.
- A sinusoidal acceleration of 1g amplitude excites the system.
- An AC analysis was first carried out to study the behavior of the system versus frequency.



For the PZT layer, we note a first peak at 1170Hz. The second pick observed corresponds to the resonance introduced by the rotational mass inertia M_R considered in this work.

Modeling of the MEMS microgenerator

Parameterized models using generic interfaces
lists containing geometric and physical parameters

»» Several analysis possibilities such as :

1. The impact of the piezoelectric properties of the material.
2. The impact of the geometric properties of the device.

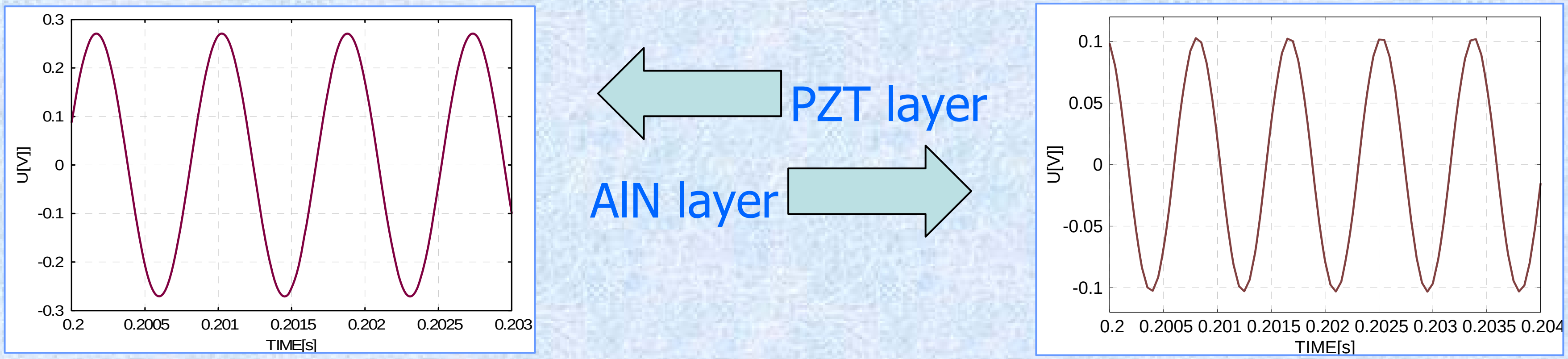
```
--- Entity Declaration piezo_beam ---
ENTITY   enhanced_piezo IS
Generic
        ( --geometric parameters
         Lp=>400.0e-6,--Beam length
          ................
        -- Physical parameters
        --Compliance Matrix
        C11s=> 166.0e9;
        ......................
        -- -Piezoelectric layer thickness
       Hp=> 1.0e-6,
       - --Piezoelectric coefficients
        ..............);
PORT (
     TERMINAL p_mec_out,p_mec_in :  translational;
      TERMINAL p_elec1,p_elec2:  electrical
             );
END ENTITY enhanced_piezo;
```

Modeling of the MEMS microgenerator

- The impact of the piezoelectric properties of the material:

The used piezoelectric materials : Aluminum Nitride (AlN) or Lead zirconate Titanate (PZT) thin layers.

»» Substitute the generic parameters responsible of physical properties of the used material (PZT) in the entity declaration of the previous model by AlN ones.



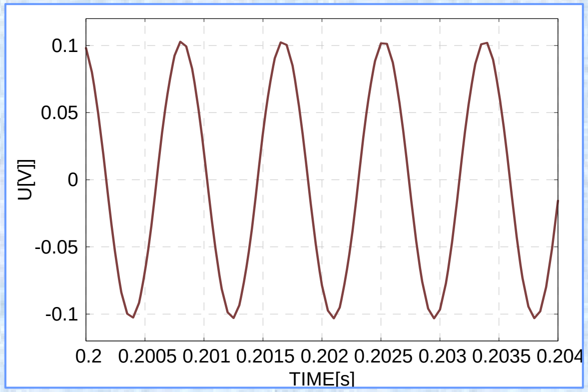
For a given structure, the PZT solution allowed us to harvest a greater voltage. This result was expected because of the poor coupling coefficient of AlN material compared to PZT one.

Modeling of the MEMS microgenerator

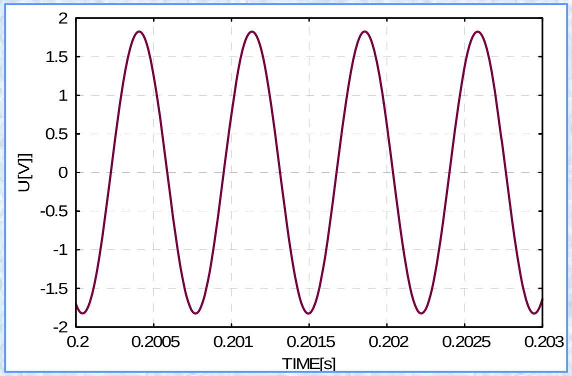
AlN Microfabrication process by sputtering techniques is easier than for PZT ones, the deposition of AlN is relatively simple, compatible with CMOS process and does not require post process polarization.

»» Continue investigating structures based on AlN by changing the dimensions of the structure: we used twice the dimensions for the mass (800µm by 800µm) with a SOI wafer (525 µm thick).

The impact of the geometric properties of the device



A seismic mass of 400 µm by 400 µm



A seismic mass of 800 µm by 800 µm

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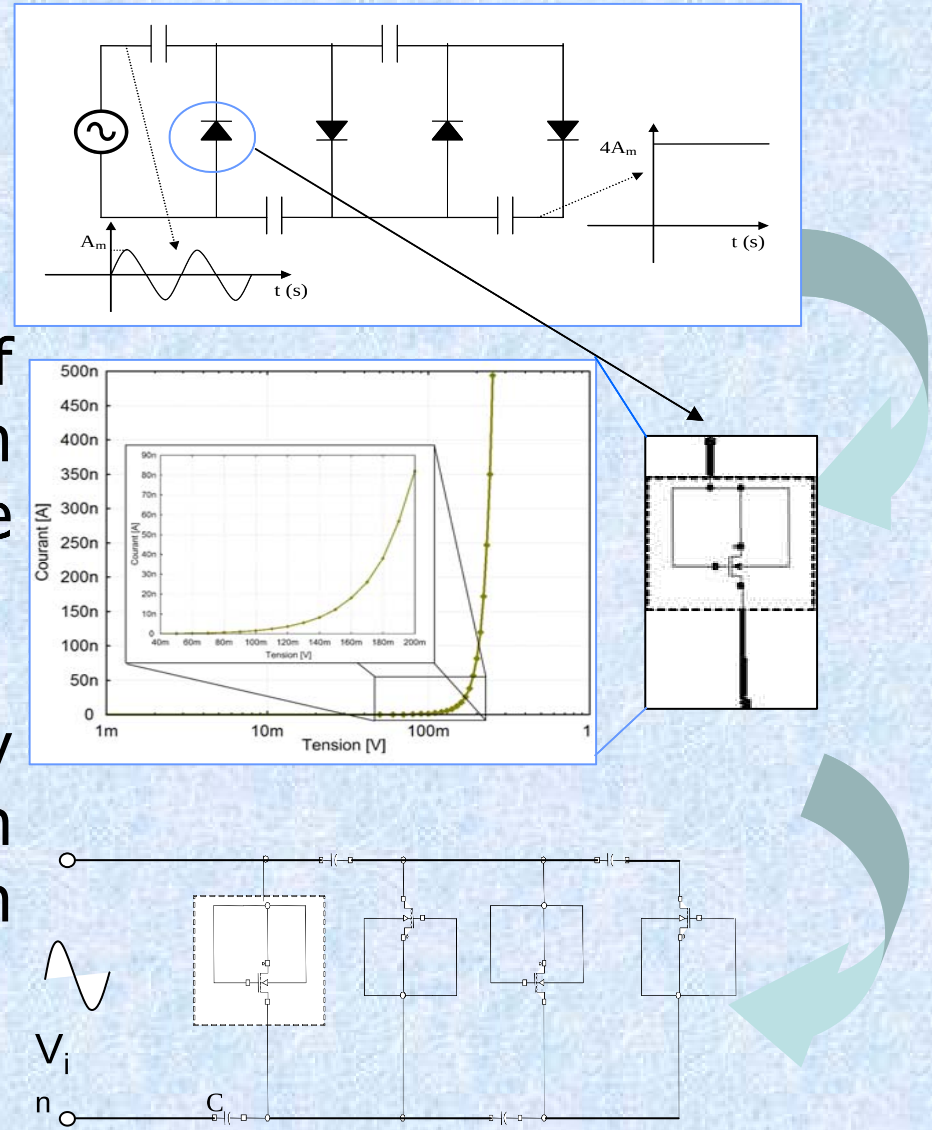
Power Management Circuit

• A voltage multiplier based on conventional structure (Villard): composed of capacitors and diodes.

• Problem: the output voltage of the microgenerator is often smaller than the threshold voltage of the standard diode.

• Solution [3] :
conventional diodes replaced by low threshold diodes based on DTMOS transistors (PMOS with gate, drain and bulk connected).



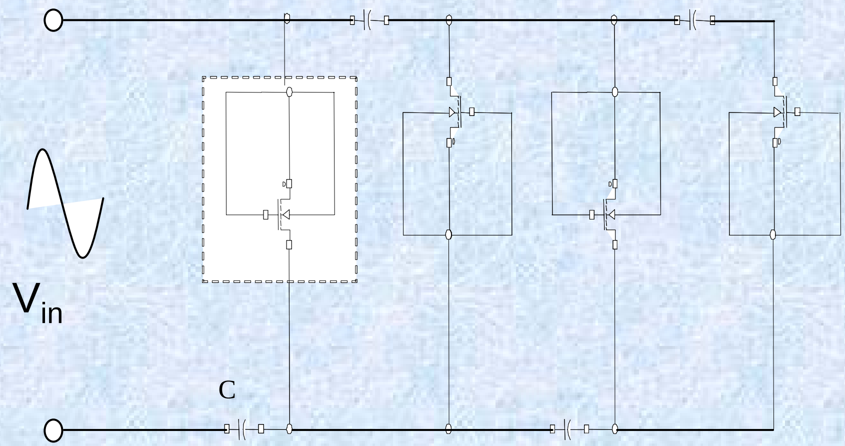
[3] Yasser AMMAR (TIMA, MNS group) PhD thesis, UJF Grenoble 2007, France

Power Management Circuit

- The voltage multiplier model is a structural model obtained by an assembly of SPICE models.

»» Instead of trying to equal SPICE compact models [4], we decided to use parameterized SPICE transistor models given by the tool.

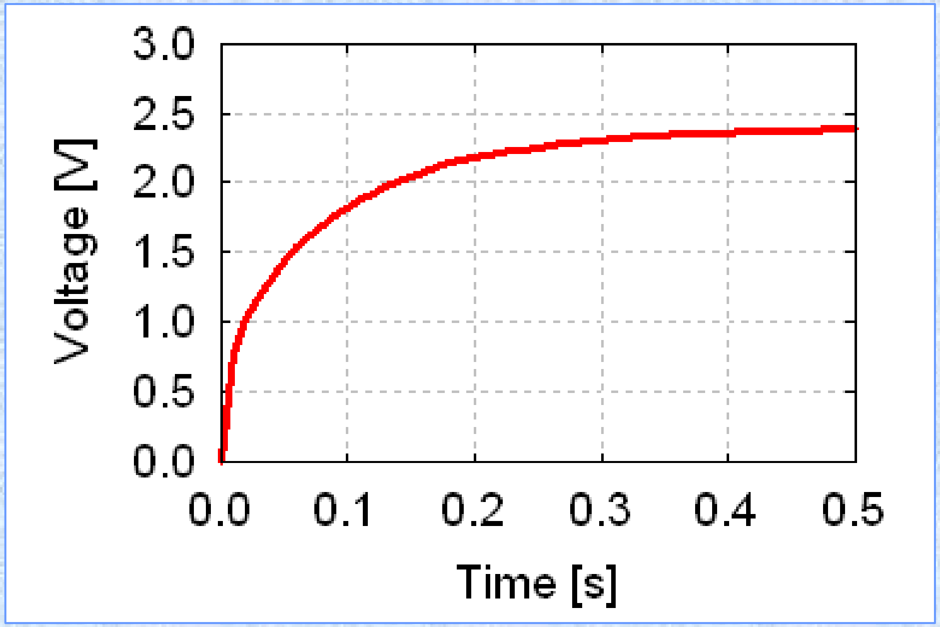
»» For a first validation of the circuit, we have used a level 1 SPICE model.



[4] E. Hessel and al "Model Exchange Process in Automotive Industry with VHDL-AMS" Aachen Electronics Symposium 2004

Power Management Circuit

As a first validation a six stage voltage multiplier was tested with a sinusoidal voltage source V_0 of 0.2 V amplitude and a frequency equal to the resonance frequency of the piezoelectric microgenerator (1500 Hz).



$$V_{out} = 12\,V_0 - \Delta U$$

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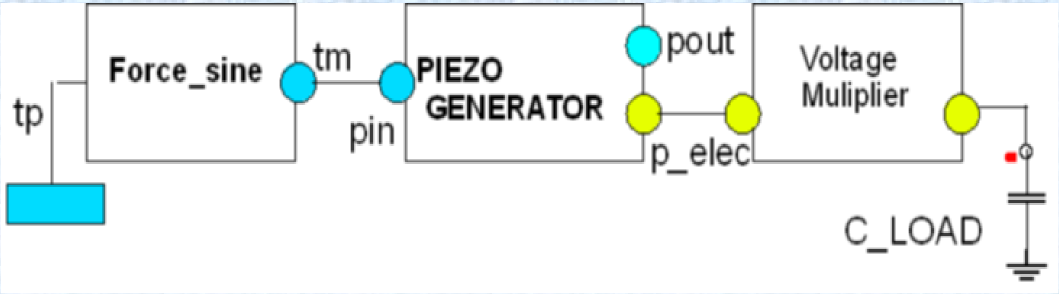
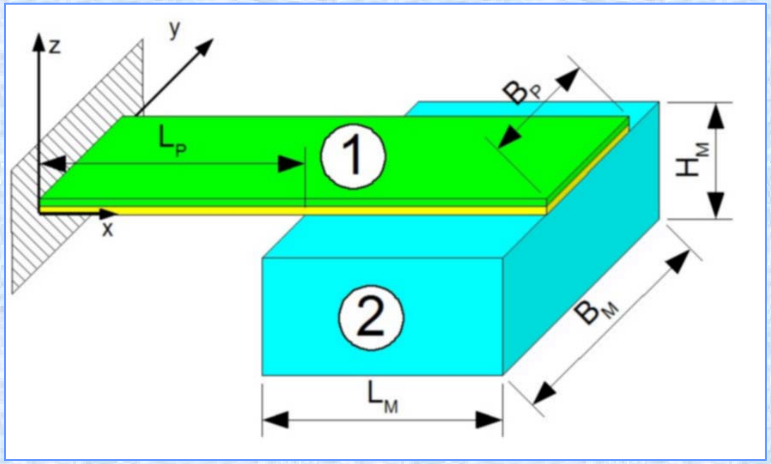
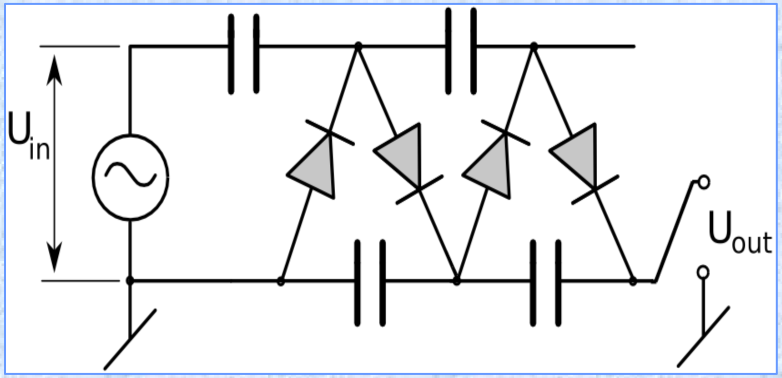
Global Simulations



Synoptic view of the modeled harvesting system

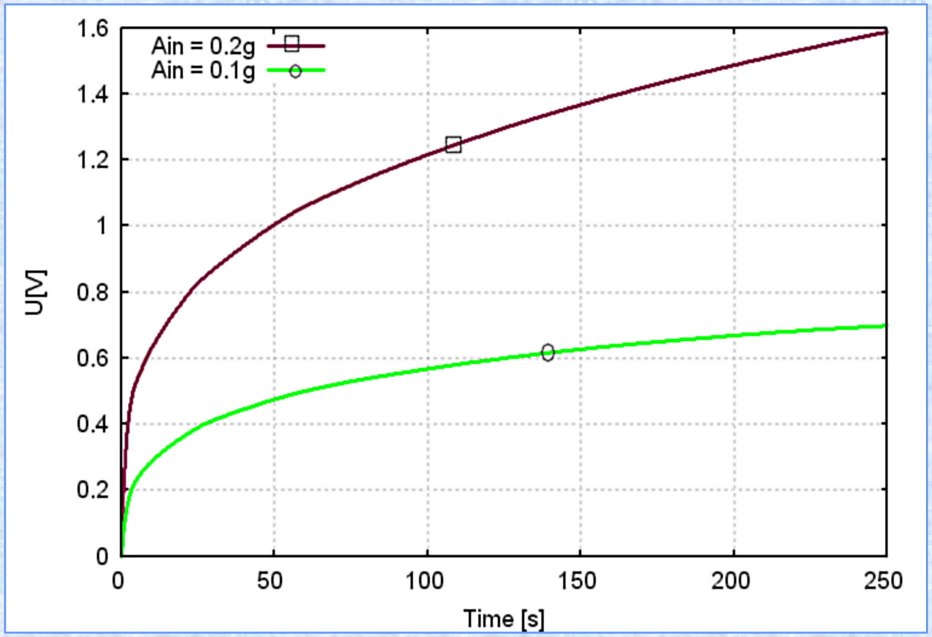




Multi-domains simulations under the same tool: Smash™/Dolphin Integration

Global Simulations

The behavioral microgenerator with AlN layer connected with a structural model of a six stages voltage multiplier.



Simulation results curves of 1µF capacitor charge for two different values of input acceleration amplitude.

Simulation Time: 45”32s to simulate 250s for Ain = 200 mg.

With a low excitation of 0.2g at resonance, we can harvest 1.6V which is sufficient for our application (Wireless Sensor Networks)

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Conclusion

- The reusable aspect of our models offers to the designers the opportunity to select and use their suitable configurations without having to understand the details of blocks, just by changing some parameters.
  - The piezoelectric microgenerator model remains valid for other materials.
  - The voltage multiplier circuit is extensible to other technologies.
- We demonstrate that using VHDL-AMS, we can not only model a system in a descriptive behavior, but also in physical level that can better predict the experimental results.

On going work

The use of Verilog-A for circuit level approach in multi-domain simulations will be proven in future work:

- On going simulations consist in validating the complete system under the same AMS Cadence environment with the voltage multiplier designed in HCMOS9 Design Kit (130nm) from STMicroelectronics cascaded with the low level VERILOG-A description of a piezoelectric MEMS microgenerator that takes into account the three types of damping (viscous, dielectric and structural) .

Thank you for your attention