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Improvement of the Reliability of Contactless Electrostatically Actuated MEMS through the Control of Dielectric Charging

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Outline

- Statement of the problem
- Multiexponential model: discretization.
- Quasi-differential capacitance measurement
- Experimental results:
    - First order Σ–Δ control
- Bitstream extraction of information
- Conclusions

Statement of the problem

- **The amount of parasitic charge trapped in the dielectric layer of electrostatic MEMS devices after long actuation cycles poses serious reliability problems:**
  - Drift in key parameters: Pull-in and pull-out voltages, rest position.
  - Device destruction due to permanent stiction.
- **Drift in the characteristics of MEMS damages device performance: RF switches change the transmitted or reflected power due to dielectric charging.**
- **Several mechanisms have been identified in the literature explaining dielectric charging**
- **More than one mechanism can coexist at the same time in a device**.

References

- The authors have proposed the control of dielectric charging with closed loop systems based on sigma-delta modulation:

[1] M. Dominguez, D. Lopez, D. Molinero, and J. Pons, “Dielectric charging control for electrostatic mems switches,” in Proc. of SPIE Conf. on Defense, Security and Sensing DSS-2010, vol. 7679, pp. 1-11, Orlando, 2010.

[2] Blokhina, E.; Gorreta, S.; Lopez, D.; Molinero, D.; Feely, O.; Pons-Nin, J.; Dominguez-Pumar, M., "Dielectric Charge Control in Electrostatic MEMS Positioners/Varactors," Microelectromechanical Systems, Journal of , vol.21, no.3, pp.559,573, June 2012

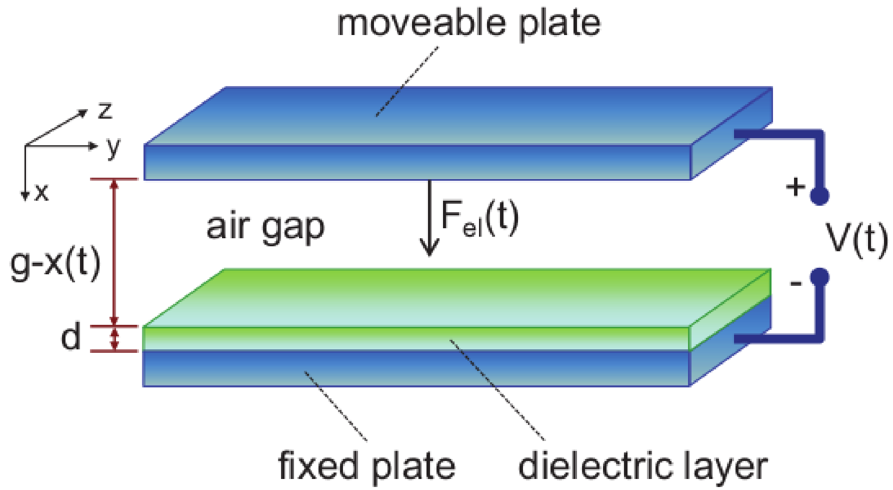
[3] Gorreta, S.; Pons-Nin, J.; Blokhina, E.; Feely, O.; Dominguez-Pumar, M., "Delta-Sigma Control of Dielectric Charge for Contactless Capacitive MEMS," Journal of Microelectromechanical Systems, in press.

- These controls mimic Thermal Sigma-Delta modulation as implemented in thermal anemometers, such as the one of the wind sensors in the REMS instrument of the NASA Curiosity Rover:

[4] M. Dominguez-Pumar, et. al, “A hot film anemometer for the Martian atmosphere”, Planetary and Space Science, vol. 56, pp. 1169-1179, 2008.

[5] J. Gomez-Elvira, et al, “REMS: The Environmental Sensor Suite for the Mars Science Laboratory Rover”, Space Science Reviews, Vol. 170, pp. 583-640, 2012.

Phenomenological model



$$F_{el} = \frac{C(t)^2}{2A\epsilon_0}\left(V(t) - \frac{Q_d}{C_d}\right)^2$$

- 1-D Mass-spring model: simple model where charge implies a shift of the C-V curve.
- Complex physical mechanisms vs. phenomenological models.

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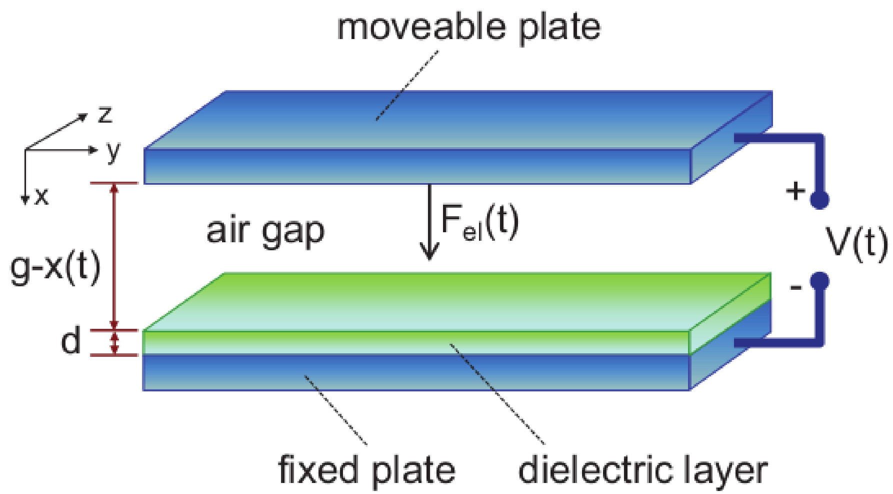
Phenomenological model



- Trapped charge in the dielectric can be positive or negative, depending on the polarity of the applied voltage (contactless case):

  - $V > 0 \rightarrow Q_d < 0$
  - $V < 0 \rightarrow Q_d > 0$

$$V_{sh} \ \alpha \ \overline{Q}_d$$

- Net charge (Q_d) generates an horizontal shift of the C-V curve (V_{sh}).

Compact dynamical model

$$Q^p(t) = \begin{cases} Q^p_{\max} \sum_i \zeta_i^p e^{-t/\tau^p_{Di}} & V > 0 \\ Q^p_{\max}(1 - \sum_i \zeta_i^p e^{-t/\tau^p_{Ci}}) & V < 0 \end{cases}$$

$$Q^n(t) = \begin{cases} Q^n_{\max}(1 - \sum_i \zeta_i^n e^{-t/\tau^n_{Ci}}) & V > 0 \\ Q^n_{\max} \sum_i \zeta_i^n e^{-t/\tau^n_{Di}} & V < 0 \end{cases}$$

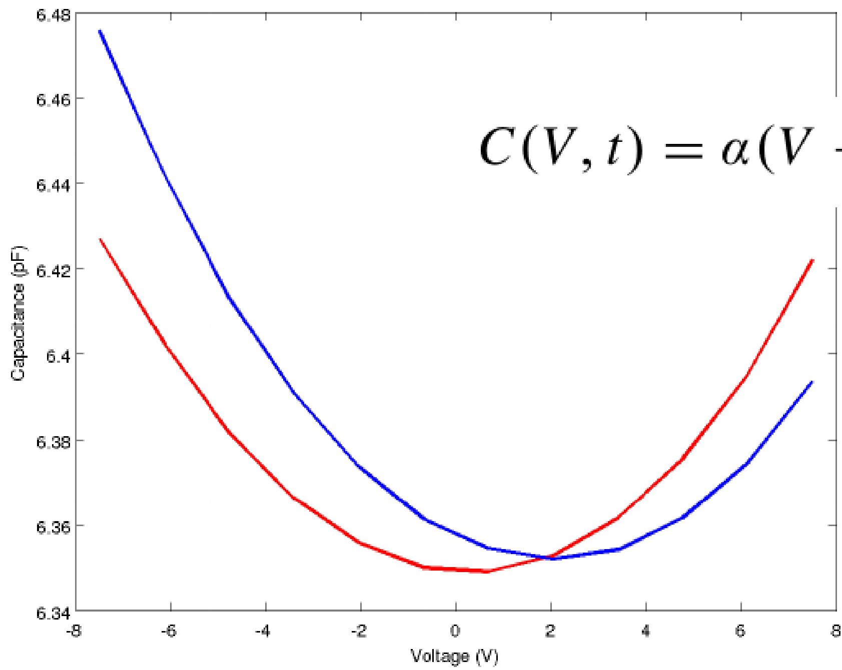
$$\sum_i \zeta_i^n = \sum_i \zeta_i^p = 1$$

$$0 \leq \zeta_i^n, \zeta_i^p \leq 1$$

- **Charge characterization**:
  - Objective: compact dynamical model obtained from measurements.
  - Characterization compatible with dielectric control: only two different voltages will be applied.
    - Outcome: for two voltages, V^+, V^-, amplitudes and time constants

$$Q^p{}_{max}, Q^n{}_{max}, \zeta_i{}^p, \zeta_i{}^n$$

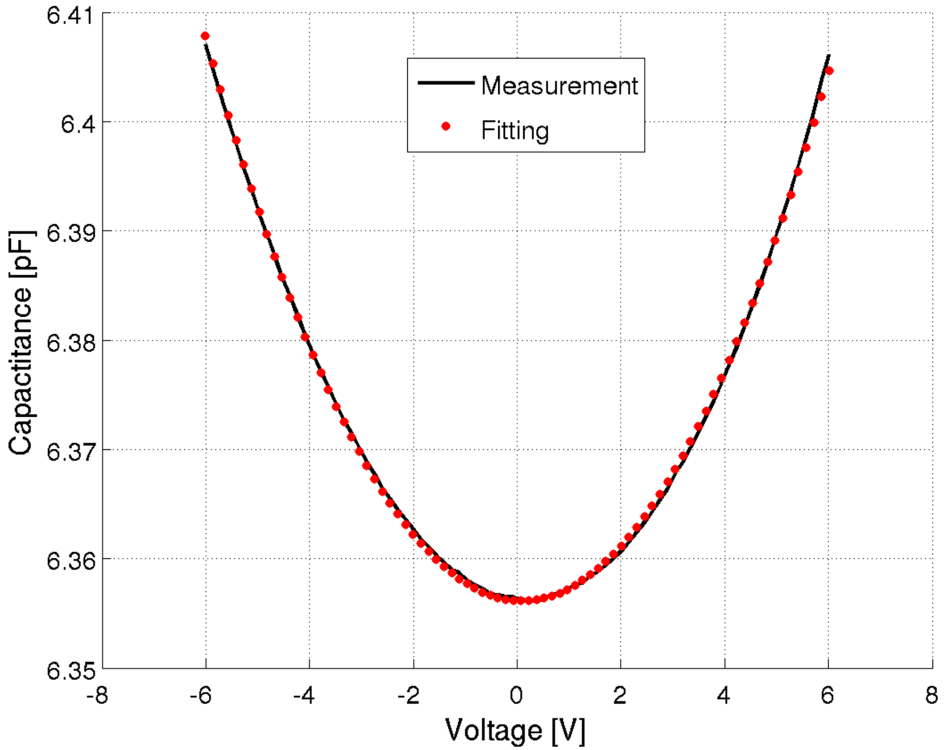
Phenomenological model



$$C(V,t) = \alpha(V - V_{\mathrm{sh}}(t))^2 + C_0$$

- Red line: discharged device (V_{sh} = 0),
- Blue line: after applying V = −8V during 30 minutes (V_{sh} = 2V).
- In general even swift and small range C-V measurements distort the amount of charge present in the dielectric.
- We will consider that a measure of net dielectric charge is the placement of the bottom of the C-V curve (V_{sh}).
- Vertical displacements are also possible: C_0(t) function of time.

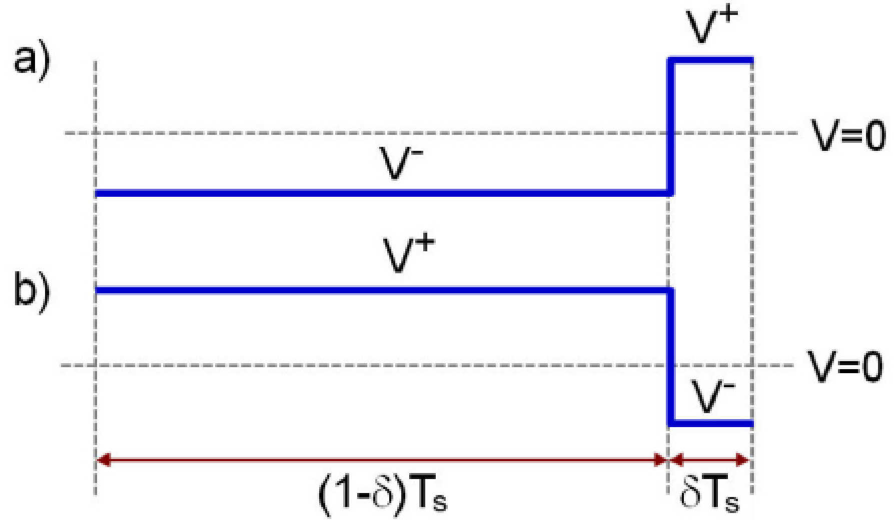
Obtaining α



- C-V measured from -6V to 6V
- α is quite constant in time.

- C_0 =6.36 pF
- V_{sh} =0.1 V
- $\boldsymbol{\alpha = 1.4\ fF/V^2}$

Quasi-differential Capacitance measurement

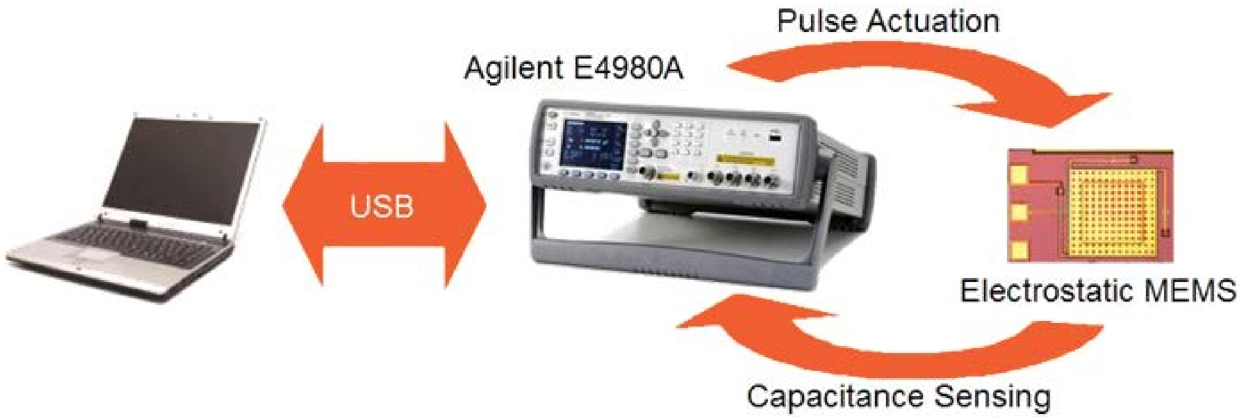


$$C_0(t) \simeq C_0(t + \Delta t)$$

$$\begin{aligned}\Delta C(t) = C^+(t) - C^-(t \pm \Delta t) = \\ C(V^+, t) - C(V^-, t \pm \Delta t) = \\ \alpha[(V^+)^2 - (V^-)^2] - 2\alpha V_{sh}(t)[V^+ - V^-]\end{aligned}$$

- ΔC(t) is an affine function of V_{sh}(t).
- Assuming known α, V_{sh}(t) may be inferred from ΔC(t).

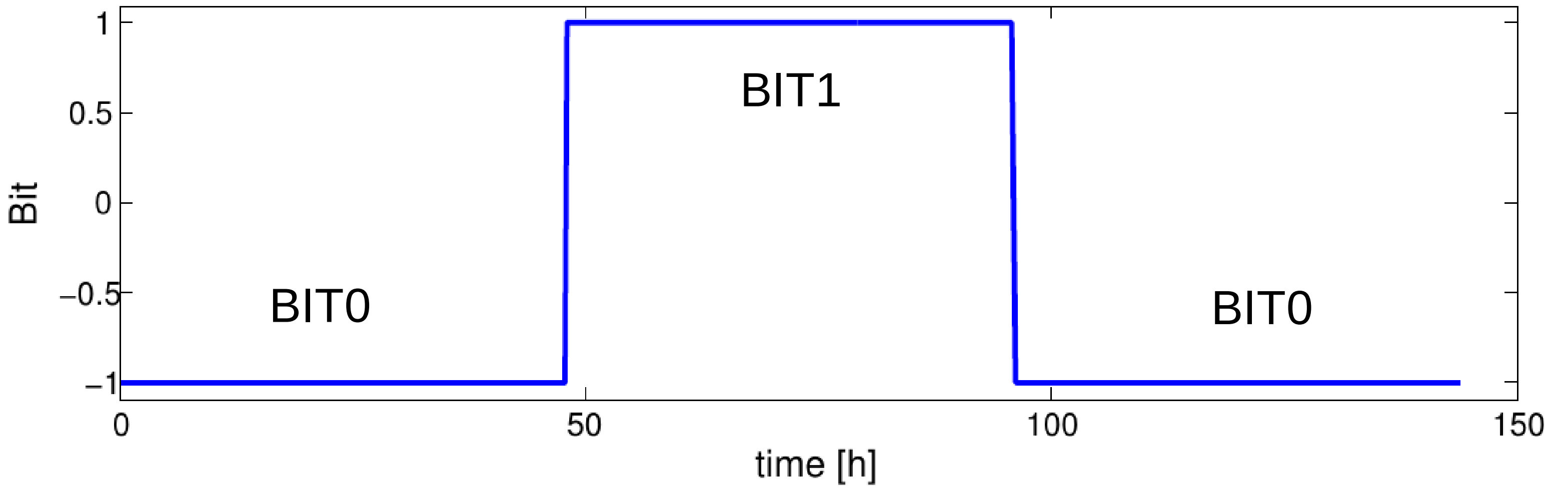
Experimental Setup



- Periodic sampling of the capacitance. Application of different bias voltages.
- This setup allows to implement the characterization and control of the devices.

- Devices: PolyMUMPS technology.
  - Area 515x515μm^2, g=1.75μm, dielectric Si_3N_4 0.6μm.

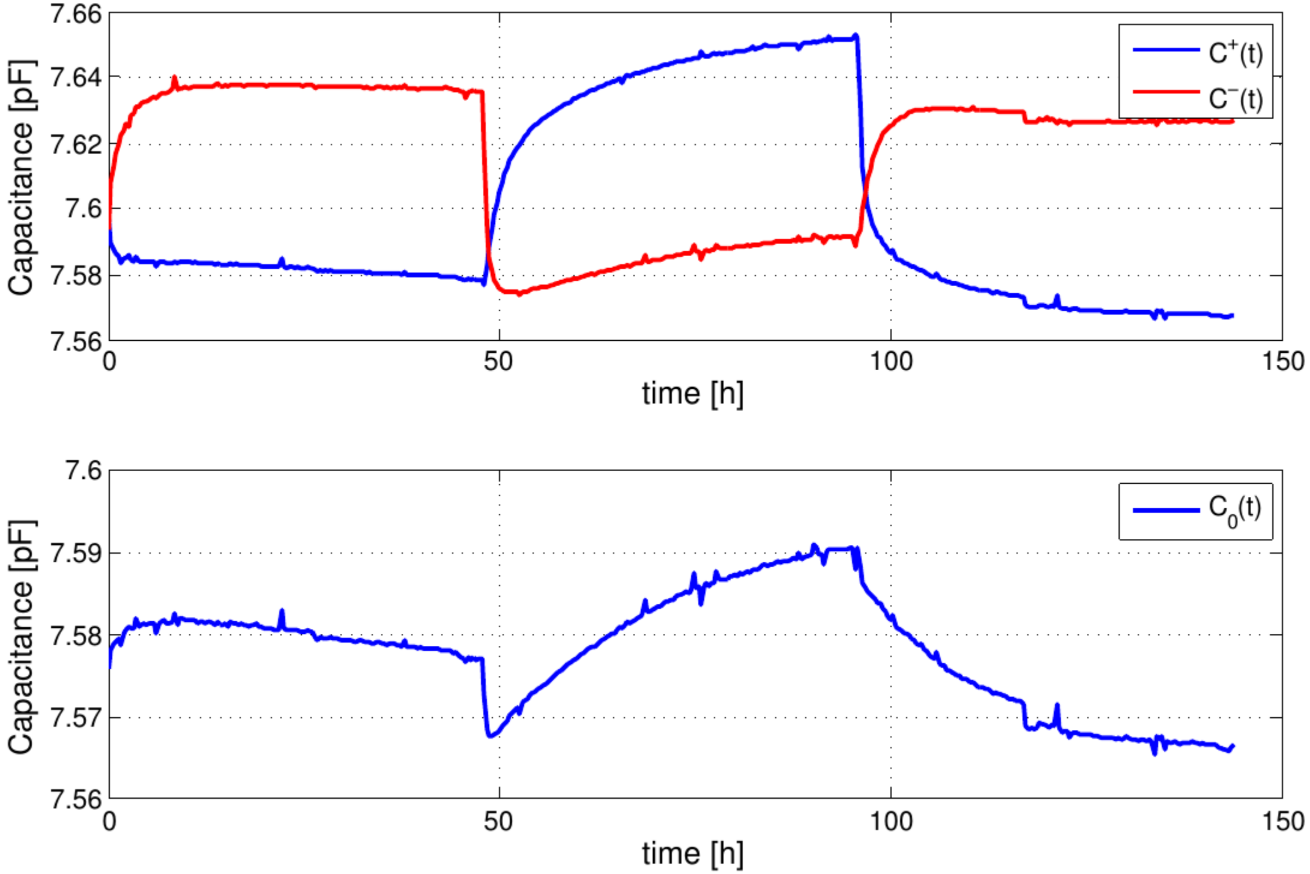
Charge dynamics characterization



- Excitation waveform composed of:
  - 48 hours of BIT0, 48 hours of BIT1, 48 hours of BIT0
- Quasi-differential capacitance measurement allows charge inference
- The function to minimize:

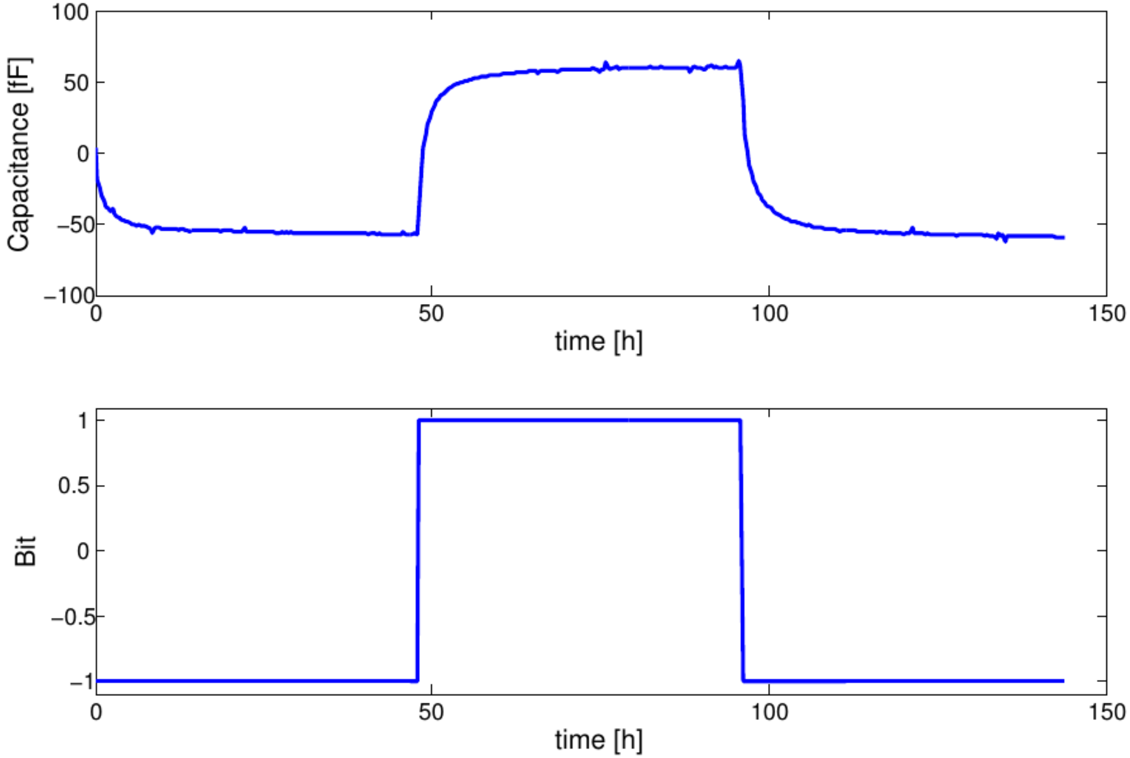
$$\Delta E = \sum_n \left(\Delta C(nT_S)|_{measure} - \Delta C(nT_S)|_{model} \right)^2$$

Measurements



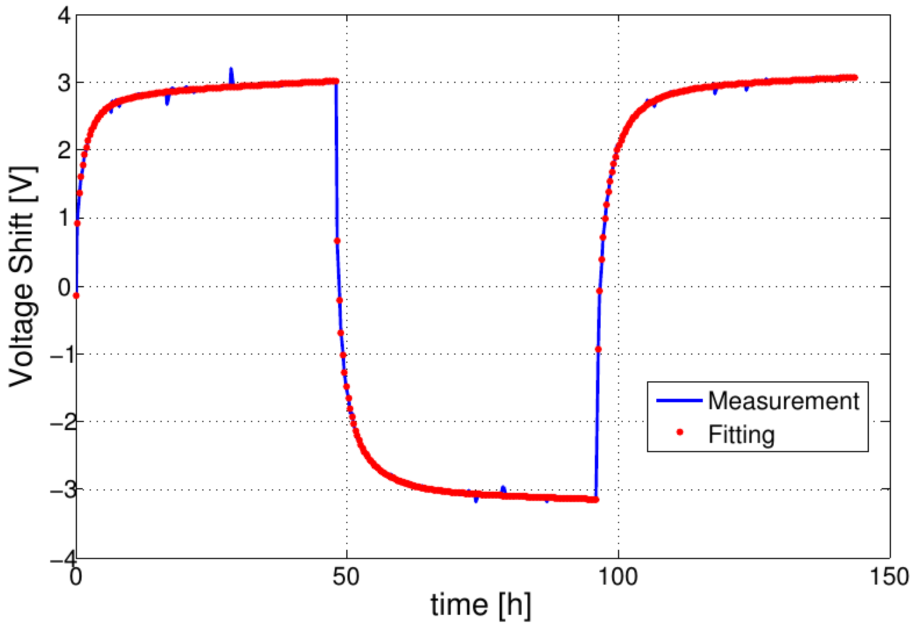
- $C_0(t)$ presents variations due to environmental parameters, it also has a correlation with the applied excitation.

Quasi-differential capacitance measurement



- $\Delta C(t)$ presents a much better behaviour than any component C^+ or C^-.
- Inference of dielectric charge from absolute capacitance measurements does not work.

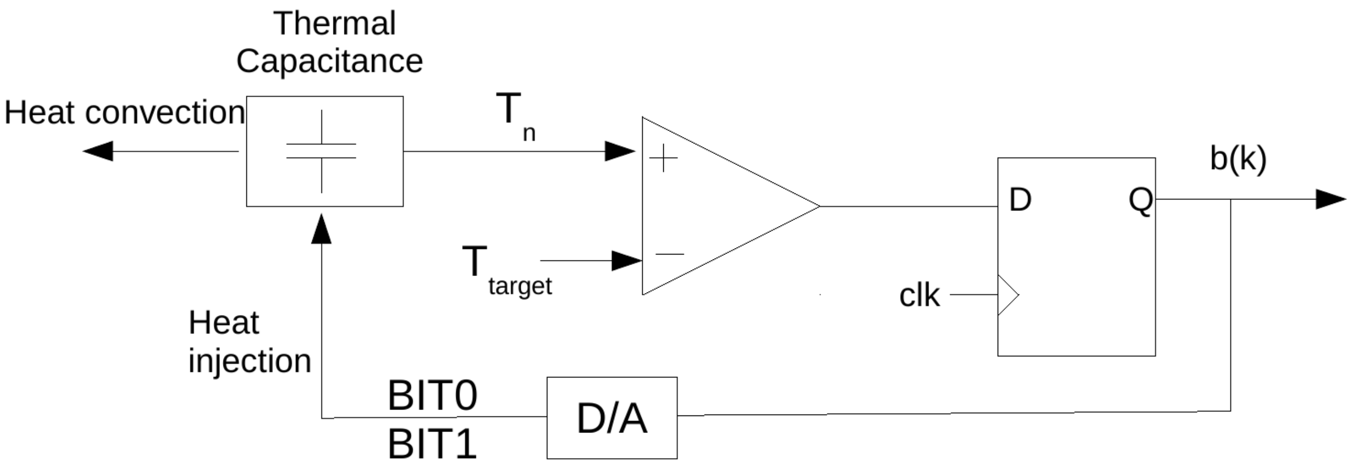
Voltage shift (Q_d/C_d)



Parameter	n	p
$Q_{\max}/C_d$ [V]	-5.3	5.3
$\tau_{C,1}$ [min]	13	113
$\tau_{C,2}$ [min]	509	2369
$\tau_{D,1}$ [min]	11	87
$\tau_{D,2}$ [min]	483	5567
ζ_1	0.68	0.94
ζ_2	0.32	0.06

- Compact dynamical model of dielectric charging can be obtained.
- Accurate simulations can be made and compared with closed-loop control waveforms.

Thermal Σ–Δ modulator



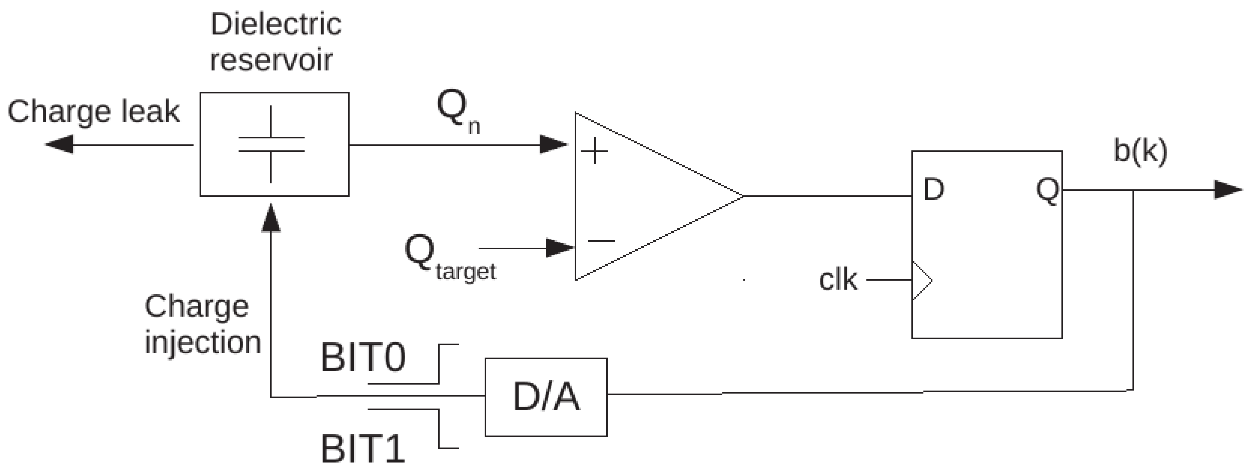
- Similar control implemented in anemometers:

  Mars wind sensor of the REMS instrument:
  NASA Curiosity Rover

- Constant temperature operation: heat loss to wind is compensated by heat injection by the controller

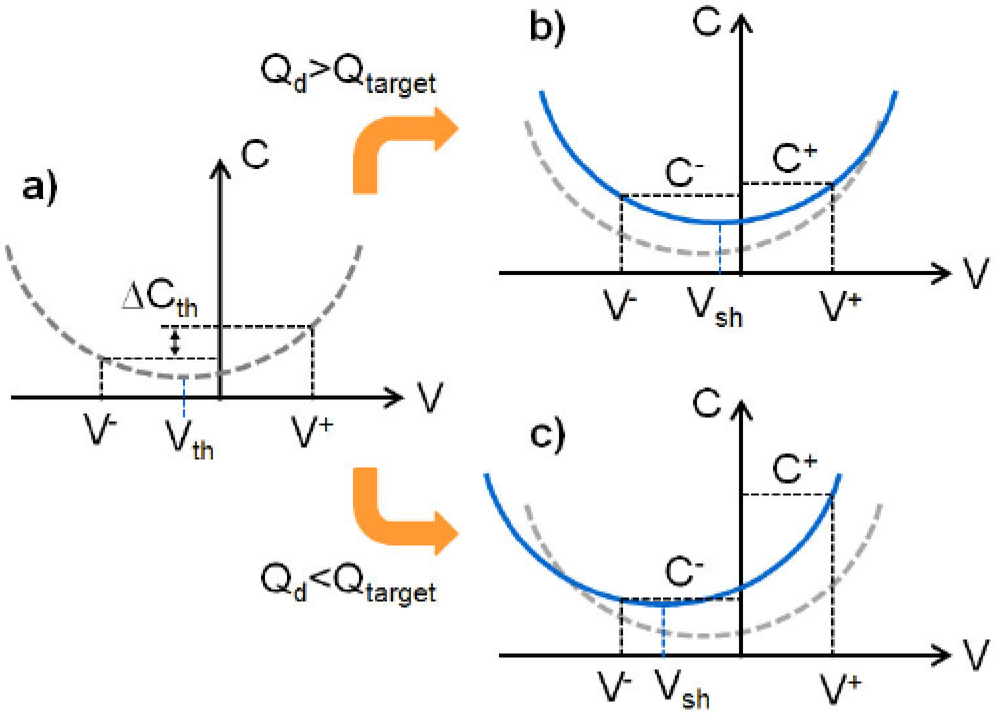
- Output of the sensor: filtered bitstream -> average injected power

First-order Σ–Δ control of charge



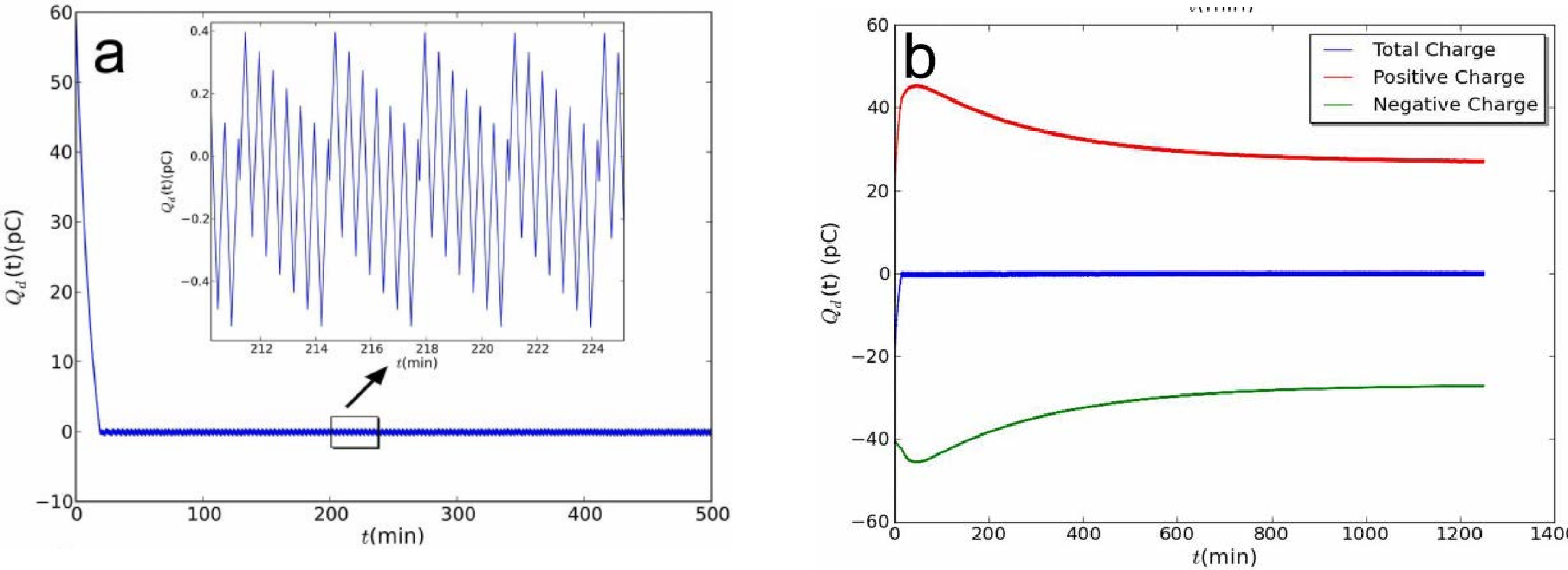
- Dielectric reservoir acts as integrator.
- Charge injection by the controller compensates charge leak from the dielectric
- Q_{target} specifies the desired net charge.

Expected evolution of C-V under control



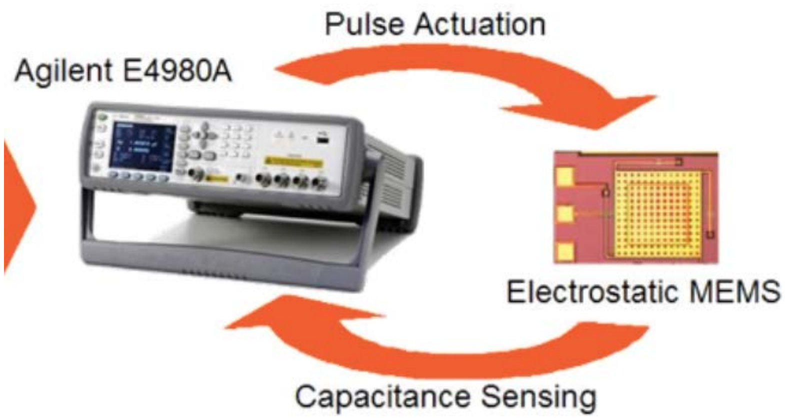
- The C-V is displaced to the right or left (negative or positive charge).
- C-V may also suffer vertical shifts ($C_0(t)$ variations). We assume that aperture is almost constant (α).

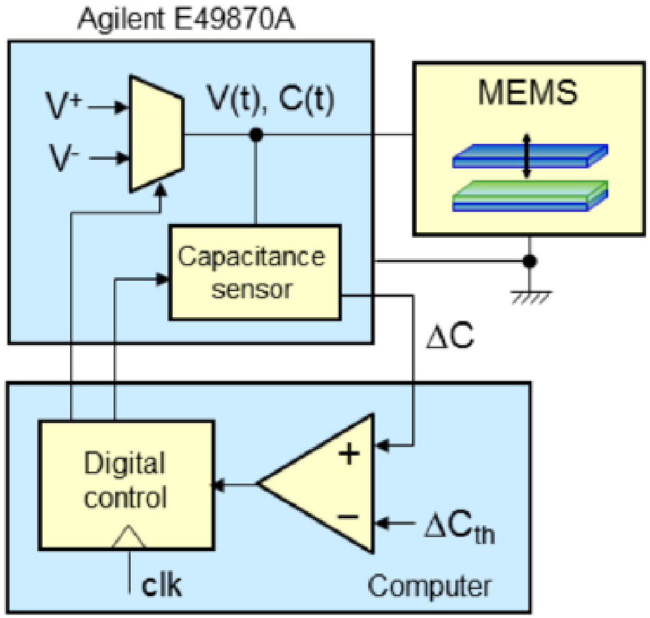
Simulation of the control method



- Control surface with zero net charge is quickly reached.
- Positive and negative components have their own dynamics, but the net charge, after a short transient, is zero.

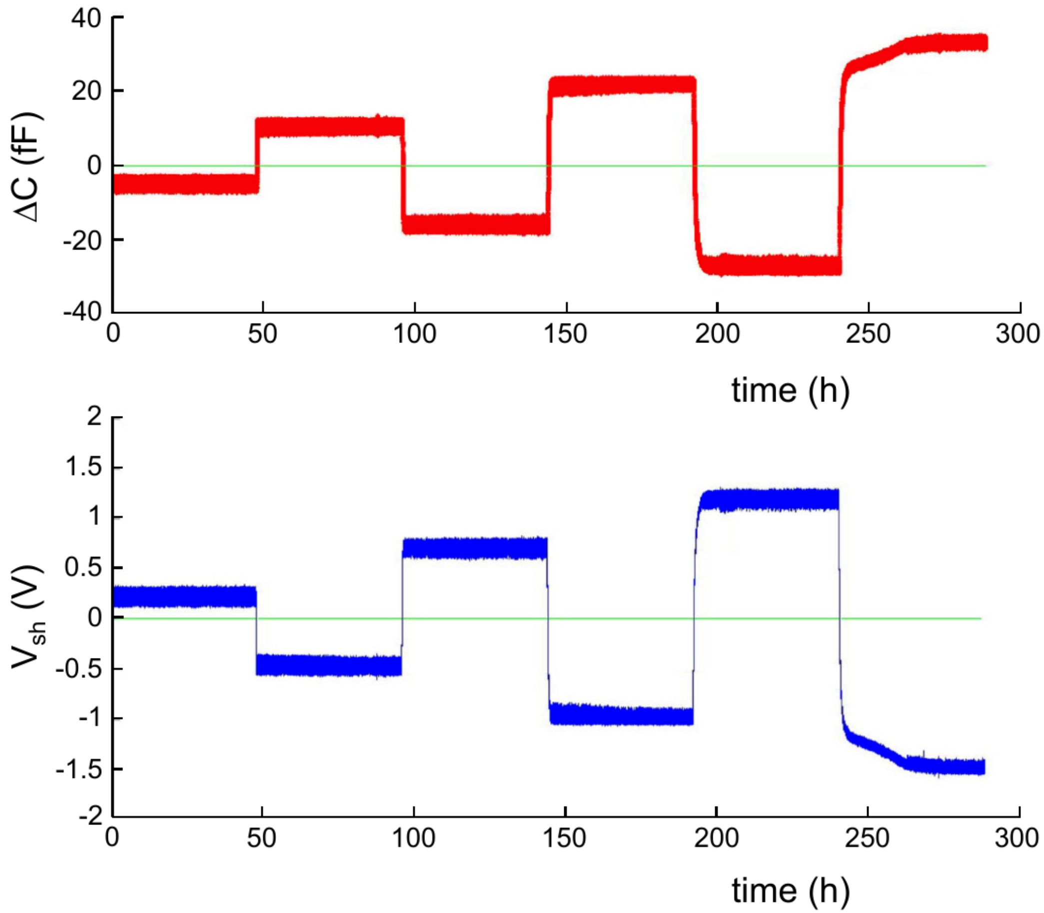
Experimental Setup for dielectric charge control





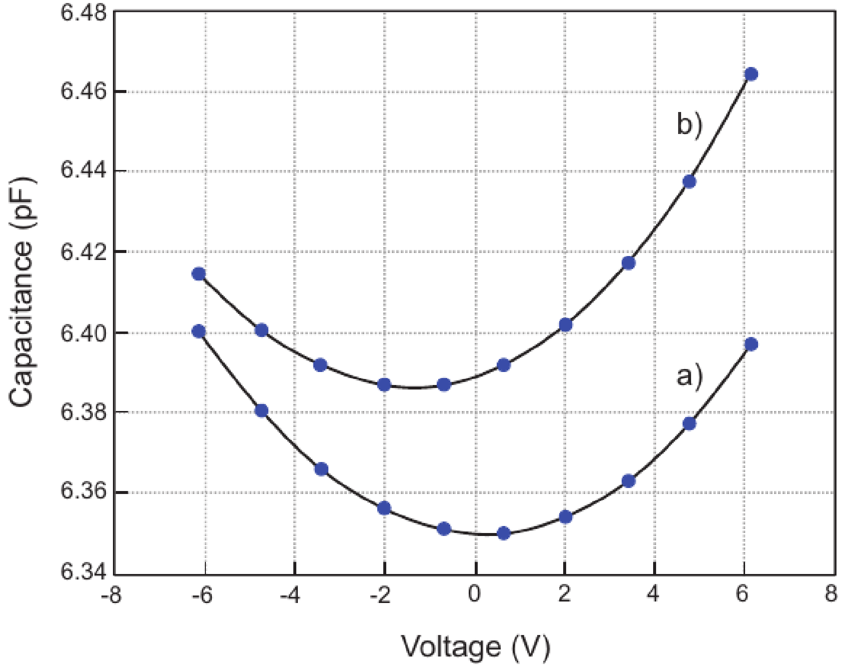
- Same experimental setup as before.
- Sampling period (sigma-delta clock): 2.5s.

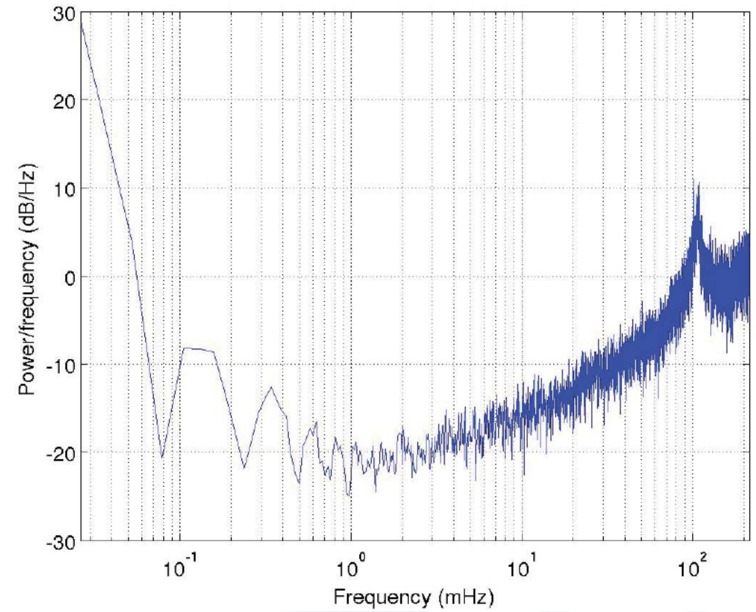
Experimental control



- 6 successive voltage shift targets: {0.25, -0.5, 0.75, -1, 1.25, -1.5V}
- Switching each 48 hours approximately.
- Control voltages: +4V, -4V, δ=0.2, T_s=250 ms.

Experimental control

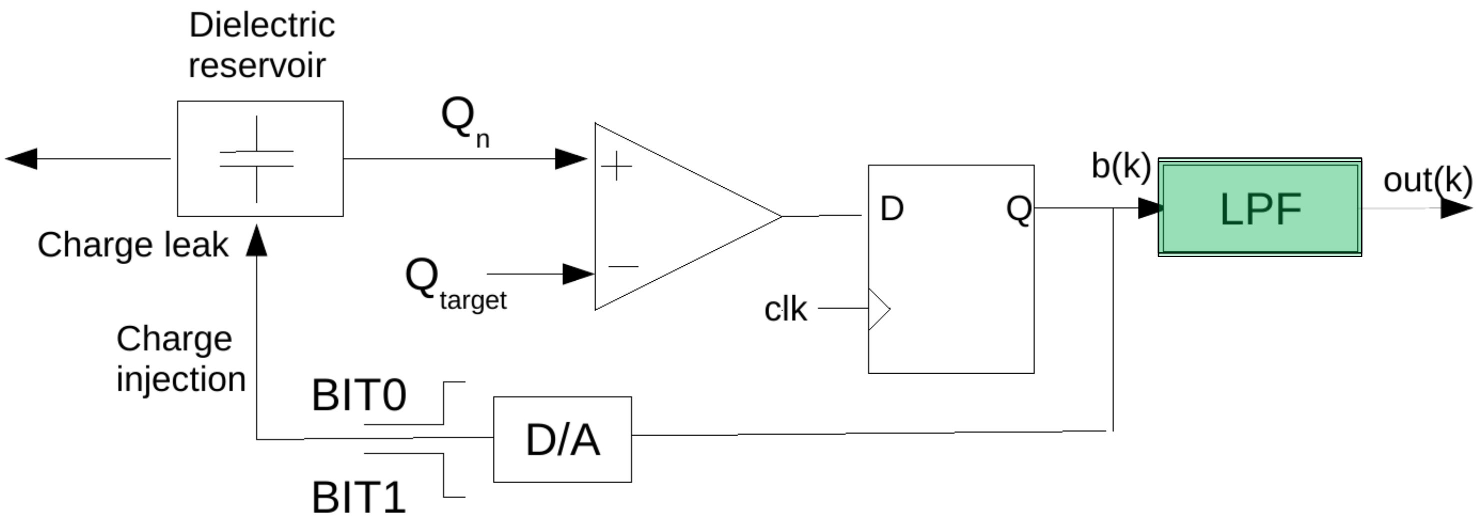




- Left:
  - a) C-V for the discharged device, prior to the beginning of the experiment,
  - b) end of the same experiment, being V_{sh}=-1.47V.

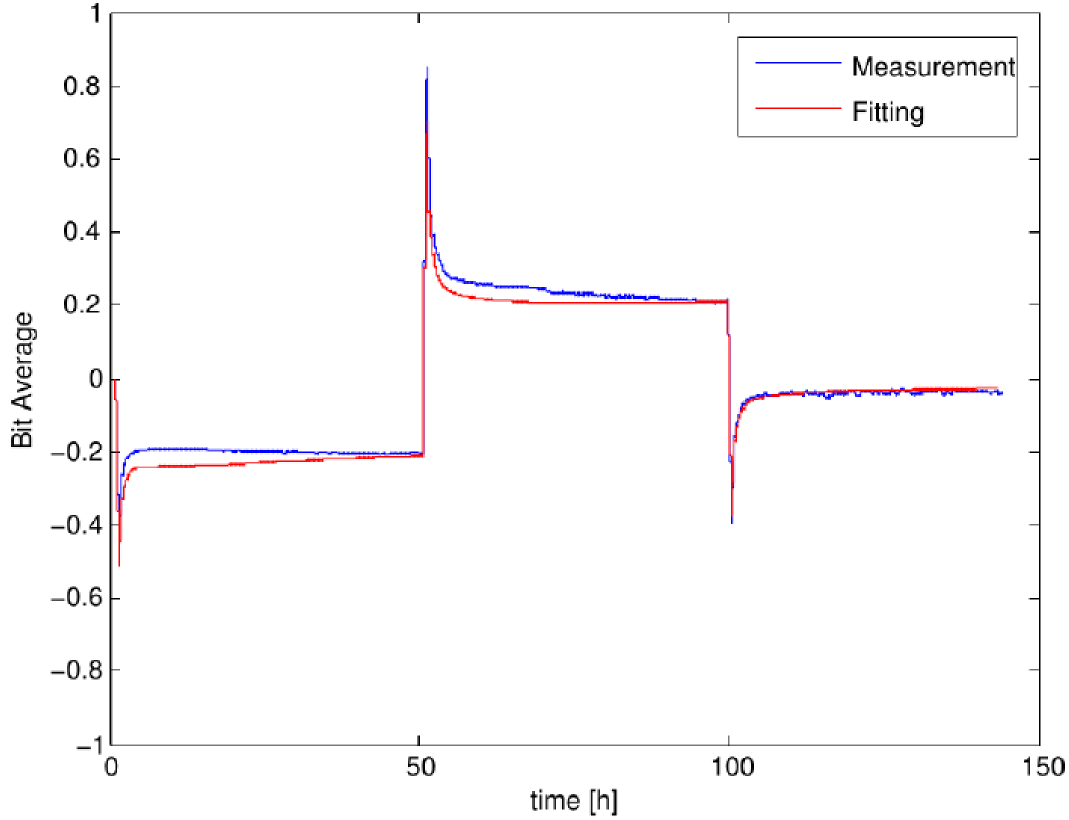
- Right:
  - Power spectral density of the control bitstream.

Information extraction: bitstream



- Output bitstream: control sequence generated by the circuit to enforce the target charge.
- Anemometer controlled in closed-loop mode (constant temperature) to increase sensor bandwidth:
  - Output: average power needed in the sensor to keep the desired temperature
  - This is used to infer convective loss -> wind velocity.

Output Bitstream: 1^{st} order Σ–Δ



- Filtered output bitstream in the experiment for three different target voltage shifts.
- Transient in bitstream is due to separate evolution of charge components within the control surface $Q=Q_{target}$.

Conclusions

- First order Sigma-Delta control of dielectric charging for contactless MEMS have been demonstrated.

- The use of the quasi-differential capacitance measurement allows to improve the inference of the charge in the dielectric.