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Real-Time Characterization of Dielectric Charging in Contactless Capacitive MEMS

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Abstract This paper presents a new method to characterize the dynamics of the charge trapped in the dielectric layer of contactless microelectromechanical systems (MEMS). For sampled-time systems, this allows knowing the state of the net charge at each sampling time without distorting the measurement. This approach allows one to model the expected behaviour of dielectric charging as a response to a sigma–delta control of charge. The goodness of the proposed approach is obtained by matching the experimentally obtained closed loop response with the one predicted using the proposed characterization method. The characterization method also provides a criterion to avoid nonlinear effects, such as fractal-like behaviour, in charge control.

Keywords MEMS reliability · dielectric charge dynamics · dielectric charge characterization · dielectric charge control

1 Introduction

Electrostatically actuated microelectromechanical systems (MEMS) have many advantages since they consume less power, have high quality and isolation factors, integration capabilities, etc. They have been used as resonators, varactors and switches in a growing set of applications during the last decade. Nevertheless, some reliability problems [1,2] are still hindering a more massive use of these devices. In this way, the main research interest is focused on the parasitic charge trapped in the dielectric layers of electrostatic MEMS. Although the study of its effects on device performance and the proposal of mitigation techniques have received considerable attention in the literature, the characterization

of the dynamics of charge trapped in dielectric layers is a still-pending issue [3].

Several different methods to characterize the charge dynamics have been proposed, but they are not compatible with normal use of the device. For instance, in the case of switches and varactors it is well known that accumulation of parasitic charge implies a shift in the capacitance-voltage (C - V) curve of the device, and thus a shift in the value of the pull-in voltage [4,5]. Then, iterative measurements of such voltage have been used to monitor the charge evolution with time [6,7]. Unfortunately, each measurement of the pull-in voltage implies applying a voltage stress to close the device, so it takes a relatively long time and also alters the amount of charge trapped. One can conclude that this strategy is strong distorting and thus not compatible with normal operation of the devices.

To avoid the problem of closing the device, an alternative strategy is proposed in [8,9]. It is based on applying small voltage steps to locate the minimum of the C - V curve, which is a parabola function for voltage ranges below pull-in. There, the evolution of the parasitic charge is monitored through shifts in the voltage corresponding to the minimum of the C - V curve. Even it strongly reduces the charge injection effects due to voltage stressing, this method is still incompatible with the normal operation of the device.

This paper presents a new method to characterize the charge dynamics that allows us to monitor the shifts of the C - V curve through what has been termed as quasi differential capacitance measurements: the difference of the capacitance measurements obtained by the successive application of two voltages of different polarity. By using a smart predetermined sequence of these measurements it is possible to obtain numerically the parameters of the multi exponential model associated

Fig. 1 Generic geometry of a two-parallel plate capacitive MEMS.

with the actuation of the device by the applied voltages. This actuation principle is compatible with the sigma-delta control proposed in [10], where a smart actuation with two voltages has allowed a control of the trapped charge. Previous control methods have been presented in [11, 12].

With the proposed characterization method, it is possible to obtain the amplitudes and time constants of the charging dynamics for two different voltages. To check the validity of the proposed approach a matching is obtained between the average bitstream provided experimentally by the charge control method, with the one obtained by simulating the device considering the charging dynamics obtained with the charge characterization method. Moreover, the time constants provided by the proposed characterization method allow to establish a criterion to select parameters to prevent nonlinearities in the charge control method. This is also demonstrated through comparison of simulations and experimental results, where a fractal-like behaviour appears for a sampling rates that do not meet the criterion.

2 Charge characterization method

In order to study the evolution of the trapped charge in the dielectric layer of a MEMS device, one can consider the generic two-plate geometry shown in Figure 1, where the voltage applied between the top and the bottom plates generates an electrostatic attraction force. The deflection of the top electrode x can be described by a mass-spring-damper ordinary differential equation:

$$m\ddot{x}(t) + b\dot{x}(t) + kx(t) = F_{el}(V, x) \quad (1)$$

where m is the mass of the movable electrode, b is the damping factor, k is the spring coefficient and F_{el} is the electrostatic force applied to the top plate. This force can be written as:

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

where $C(t)$ is the total MEMS capacitance as a function of time, Q_d the total amount of charge trapped in the dielectric layer, ϵ_0 the air permittivity and $C_d = A\epsilon_0\epsilon_d/d$ the dielectric capacitance, being ϵ_d the relative dielectric constant, A the device area and d the thickness of the dielectric layer. Since the term Q_d/C_d is widely defined as V_{sh} (voltage shift), the electrostatic force F_{el} is proportional to the square of $(V - V_{sh})$ and the C - V characteristic of the device is an even function centred at $V = V_{sh}$. Then, the net charge Q_d can be inferred from the horizontal shift of the C - V curve, that is from the value of V_{sh} .

Since the electrostatic force is proportional to $(V - V_{sh})^2$, then the C - V curve for the state below pull-in can be approximated by a parabolic function [9, 13]:

$$C(V, t) = \alpha(V - V_{sh}(t))^2 + C_0 \quad (3)$$

where the α parameter must be fitted for each device and C_0 is the minimum capacitance value of the curve. Then, in principle the dynamics of the trapped charge can be studied by applying a voltage during a certain time and monitoring the capacitance between the plates of the device. This way, it would be possible to extract the $Q_d(t)$ values from the measured $C(t)$.

However, changes in temperature or humidity, or changes in the uniformity of charge distribution, among other processes, generate vertical displacements in the C - V curve [6, 9, 14]. This means that the constant term in equation (3) may easily present a slow time dependence $C_0(t)$, as shown in Figure 2. It is observed there that both V_{sh} and C_0 exhibit noticeable variations after a voltage stress has been applied, but both curves can still be fitted with the same value of α .

2.1 Sensing charge through quasi differential capacitance measurements

To avoid the above mentioned vertical drift, this work focuses on obtaining the dynamics of the trapped charge by measuring the capacitance of the device at two points of the C - V curve in two consecutive and close instants of time t and $t \pm \Delta t$. For instance, let us suppose that $C^+(V^+)$ for $V^+ > 0$ is obtained at the instant t and that $C^-(V^-)$ for $V^- < 0$ is obtained at the instant $t + \Delta t$. Assuming that α is constant and a slow drift in the charge dynamics, that is $V_{sh}(t) \simeq V_{sh}(t + \Delta t)$ and $C_0(t) \simeq C_0(t + \Delta t)$, then the value of V_{sh} can be extracted from the following equation:

$$\begin{aligned} \Delta C(t) &= C^+(t) - C^-(t \pm \Delta t) = \\ &= C(V^+, t) - C(V^-, t \pm \Delta t) = \\ &= \alpha[(V^+)^2 - (V^-)^2] - 2\alpha V_{sh}(t)[V^+ - V^-] \end{aligned} \quad (4)$$

Fig. 2 Experimental C - V curves of an electrostatic MEMS before and after a voltage stress is applied. The continuous line corresponds to the initial-discharged device ($V_{sh} = 0$), while the dashed line was obtained after applying $V = -4V$ for 40 hours ($V_{sh} = 2.5V$).

According to this, periodic measurements of the quasi differential capacitance $\Delta C(t)$ allow to monitor the amount of net charge in the dielectric. If we consider a sampled-time system, then two capacitance measurements to obtain C^+ and C^- should be performed at the end of each sampling period. This implies that the bipolar voltages V^+ and V^- must be applied within a sampling period. On the other hand, we would like to have actuation waveforms such that, while having the capability of monitoring $\Delta C(t)$, they would also serve to increase, or decrease, the amount of charge in the dielectric.

Let us now consider the periodic bipolar waveforms shown in Figure 3. In waveform (a) the negative V^- is being applied to the MEMS during most of the time, whereas in waveform (b) V^+ is applied most of the time. Both waveforms include short times δT_s on which opposite voltage values are applied. This allows to ob-

tain the value $\Delta C = C^+ - C^-$, and thus the voltage shift V_{sh} due to the charge stored in the dielectric, at sampling times kT_s . Additionally, for appropriate values of V^+ , V^- and δ , the application of waveform (a), in the contactless case, increases the positive charge and reduces the negative charge in the dielectric. On the other hand, applying waveform (b) to the same case has the opposite effects on the charge components injected/extracted into/from the dielectric.

2.2 Modelling the charge dynamics

Now the objective is to apply the actuation and sensing strategy introduced above to predict the evolution of the net dielectric charge for a contactless MEMS. For the sake of generality, let us name each period of waveform (a) in Figure 3 as voltage symbol BIT0, name each period of waveform (b) as voltage symbol BIT1, and suppose that the waveform applied to the MEMS is any arbitrary sequence of symbols BIT0 and BIT1. Note that both symbols have the same time length, T_s , and the same values of V^+ , V^- and δ .

Regarding the above assumptions, we introduce here an analytical model for the dynamics of the dielectric charge. Equations (5) and (6), taken from [12], model a multi-exponential time evolution of the dielectric charge for the contactless case, when a positive or a negative voltage is being applied.

$$Q^p(t) = \begin{cases} Q_{\max}^p \sum_i \zeta_i^p e^{-t/\tau_{D_i}^p} & V > 0 \\ Q_{\max}^p (1 - \sum_i \zeta_i^p e^{-t/\tau_{C_i}^p}) & V < 0 \end{cases} \quad (5)$$

$$Q^n(t) = \begin{cases} Q_{\max}^n (1 - \sum_i \zeta_i^n e^{-t/\tau_{C_i}^n}) & V > 0 \\ Q_{\max}^n \sum_i \zeta_i^n e^{-t/\tau_{D_i}^n} & V < 0 \end{cases} \quad (6)$$

Fig. 3 Periodic voltage waveforms for MEMS actuation and sensing. On each period T_s of (a), a negative voltage V^- is applied during $(1 - \delta)T_s$ and the value of C^- is measured at the end of this time, then a positive voltage V^+ is applied for a short time δT_s and the value of C^+ is measured. On each period of waveform (b), V^+ is applied during $(1 - \delta)T_s$ and then C^+ is measured, next V^- is applied for δT_s and then C^- is measured. In both cases, a new value of $\Delta C(t)$ is obtained at times kT_s .

In general, the application of a voltage across a metal-dielectric-air-metal structure (MEMS in contact-less mode) or across a metal-dielectric-metal structure (MEMS in contact mode) will result in an electric field in the dielectric. A number of processes then occur that can be classified into polarisation and charge injection processes [2, 15]. Polarisation processes include dipolar polarisation, 'free charge' displacement and interfacial polarisation [16], while charge injection is the transfer of charge carriers from the metal to the dielectric. It is known that dipolar polarisation origins from the orientation of the dipoles of the dielectric material, while the polarisation due to free charge transfer may arise from the displacement of 'free' charges in the dielectric (such as ions left from the deposition process or injected charges). The injection of charges from the contact with the metal occurs, for example, through trap assisted tunnelling of Schottky emission. It is usually the dominant process if relatively high fields are applied to dielectric layers, and it has been shown as the primary charging mechanism in RF MEMS switches [3, 17]. The charges injected from the metal participate then in the Pool – Frenkel conduction mechanism and/or free charge polarisation [18]. By introducing the model given by (6), we assume that there are a number of independent mechanisms responsible for dielectric charging and charge relaxation, and each of these processes is described by its own characteristic time.

The total amount of net charge trapped in the dielectric can be obtained as the addition of both contributions $Q_d(t) = Q^n(t) + Q^p(t)$. The charging and discharging time constants for each charge component $Q^n(t)$ and $Q^p(t)$ are, respectively, τ_{Ci} and τ_{Di} . $Q_{\max}^n$ and $Q_{\max}^p$ are the maximum values of negative or positive net charge, respectively, and the coefficients ζ_i specify how these total charges are distributed along all the exponential. Therefore we have $\sum_i \zeta_i^n = \sum_i \zeta_i^p = 1$ and $0 \leq \zeta_i^n, \zeta_i^p \leq 1$. The maximum amount of charge of each exponential is then defined as $Q_{\max}^{p,i} = Q_{\max}^p \zeta_i^p$ and $Q_{\max}^{n,i} = Q_{\max}^n \zeta_i^n$.

Let us now discretise equations (5) and (6), so that we have the charge evolution in the dielectric for the kT_s and $(k+1)T_s$ sampling times, accordingly to the symbol, BIT0 and BIT1, applied at kT_s :

$$Q^{p,i}(k+1) = \begin{cases} \text{BIT0:} & Q_{\max}^p \zeta_i^p (1 - \alpha_{C_{1-\delta}}^{p,i}) \alpha_{D_\delta}^{p,i} + Q^{p,i}(k) \alpha_{C_{1-\delta}}^{p,i} \alpha_{D_\delta}^{p,i} \\ \text{BIT1:} & Q_{\max}^p \zeta_i^p (1 - \alpha_{C_\delta}^{p,i}) + Q^{p,i}(k) \alpha_{C_\delta}^{p,i} \alpha_{D_{1-\delta}}^{p,i} \end{cases} \quad (7)$$

and

$$Q^{n,i}(k+1) = \begin{cases} \text{BIT0:} & Q_{\max}^n \zeta_i^n (1 - \alpha_{C_\delta}^{n,i}) + Q^{n,i}(k) \alpha_{C_\delta}^{n,i} \alpha_{D_{1-\delta}}^{n,i} \\ \text{BIT1:} & Q_{\max}^n \zeta_i^n (1 - \alpha_{C_{1-\delta}}^{n,i}) \alpha_{D_\delta}^{n,i} + Q^{n,i}(k) \alpha_{C_{1-\delta}}^{n,i} \alpha_{D_\delta}^{n,i} \end{cases} \quad (8)$$

where the following parameters are used:

$$\begin{aligned} \alpha_{C_\delta}^{p,i} &= e^{-\delta T_s / \tau_{C_i}^{p,i}} & \alpha_{D_\delta}^{p,i} &= e^{-\delta T_s / \tau_{D_i}^{p,i}} \\ \alpha_{C_{1-\delta}}^{p,i} &= e^{-(1-\delta) T_s / \tau_{C_i}^{p,i}} & \alpha_{D_{1-\delta}}^{p,i} &= e^{-(1-\delta) T_s / \tau_{D_i}^{p,i}} \\ \alpha_{C_\delta}^{n,i} &= e^{-\delta T_s / \tau_{C_i}^{n,i}} & \alpha_{D_\delta}^{n,i} &= e^{-\delta T_s / \tau_{D_i}^{n,i}} \\ \alpha_{C_{1-\delta}}^{n,i} &= e^{-(1-\delta) T_s / \tau_{C_i}^{n,i}} & \alpha_{D_{1-\delta}}^{n,i} &= e^{-(1-\delta) T_s / \tau_{D_i}^{n,i}} \end{aligned} \quad (9)$$

Equations (7) and (8) imply that, given a set of parameters of the multi exponential model describing the dielectric charging, $\{Q_{\max}^p, \zeta_i^p, Q_{\max}^n, \zeta_i^n, \tau_{C_i}^{p,i}, \tau_{D_i}^{p,i}, \tau_{C_i}^{n,i}, \tau_{D_i}^{n,i}\}$, it is possible to calculate the time evolution of the net dielectric charge if a known sequence of symbols BIT0 and BIT1 is applied to the device. Then, the characterization method consists on finding the set of model parameters that minimize the mean square error between the predicted time evolution and the one experimentally obtained. In our case, these fittings have been carried out using the well known unconstrained nonlinear minimization Nelder-Mead algorithm.

2.3 Obtaining the parameters of the charge dynamics from experimental data

Experimental works have been carried out to corroborate the charge sensing method and the theoretical model for the charge dynamics introduced above. The MEMS used in the experiments reported here is a capacitive switch-like device fabricated with PolyMUMPS technology. The area of the plates is $515 \times 515 \mu\text{m}^2$, the air gap is $2.75 \mu\text{m}$, the thickness of the dielectric (silicon nitride) is $0.6 \mu\text{m}$ and the pull-in voltage is around 14V. All the measurements have been done in ambient conditions using a precision LCR meter controlled from a computer.

Each voltage symbol applied to the MEMS, BIT0 or BIT1, has a time length of n clock periods. This means that the sampling period, or symbol time, is $T_s = nT_{\text{clk}}$. During each symbol, the device capacitance is measured at both $(n-1)T_{\text{clk}}$ and nT_{clk} instants, so that a new value of the quasi differential capacitance ΔC is provided. Figure 4 shows the result of applying such voltage symbols for 144 hours: BIT0 is applied during the first 48 hours, then BIT1 for the next 48 hours and finally BIT0 again for the last 48 hours. The parameters used are $V^+ = 4V$, $V^- = -4V$, $\delta = 1/5$ and $T_s = 2.5 \text{ s}$.

The evolution over time of the capacitances C^+ , C^- and C_0 is shown in Figures 4(a) and (b). As it can be seen, C_0 exhibits noticeable variation during the measurement and therefore it is not possible to extract the value of V_{sh} directly from this data. However, as discussed in previous sections, the effects of variations in C_0 can be cancelled by obtaining $\Delta C(t)$ as $C^+(t) - C^-(t)$, as shown in Figure 4(c). Then, it is necessary to know the α parameter in equation (4) to obtain $V_{sh}(t)$. This parameter can be obtained from a single C - V measurement. In our case, it yields $\alpha = 1.4 \text{ fF/V}^2$. The voltage shift associated with the previous measurement is the continuous line shown in Figure 5.

Once $V_{sh}(t)$ calculated from equation (4), it is necessary to fit the model of the charge dynamics given by equations (7) and (8) with the experimental data. A two-exponential model was used and the corresponding result is shown in Figure 5, revealing very good match between model simulation and experimental data. The fitting parameters obtained are shown in Table 1. Note that all time constants reported in Table 1 are far above the clock period $T_s = 2.5 \text{ s}$.

Fig. 4 Capacitance measurements obtained by consecutively applying BIT0, BIT1 and BIT0 during 48 hours each. Curves (a) show the behaviour of $C^+(t)$ (red line) and $C^-(t)$ (blue line), while curve (b) shows the behaviour of $C_0(t)$. Curve (c) shows the evolution of the "quasi differential" capacitance $\Delta C(t)$.

Fig. 5 Fitting of the experimental data (continuous line) through 1D model simulations based on equations (7) and (8) (red ticks), for the experiment shown in Figure 4.

Table 1 Parameters for the negative and positive components of the two-exponential charge dynamics model, obtained from the fittings shown in Figure 5.

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

3 Validation of the characterization method through charge control experiments

The characterization method of the charge dynamics introduced in the previous section opens a door to the application of a closed-loop strategy for real-time control of MEMS dielectric charging [10].

According to this, this section checks and discusses the goodness of the characterization method when using it for such charge control purposes, through comparisons between the experimental behaviour and the behaviour obtained from discrete time simulations of the control system.

3.1 Algorithm for real-time charge control

Since it is straightforward that under some assumptions the quasi differential capacitance ΔC is an affine function of the total dielectric charge Q_d , then it is possible to fix ΔC (and thus V_{sh} or the total charge Q_d) around a desired threshold value, ΔC_{th} . To obtain this, appropriate sequences of positive and negative voltages, V^+

Fig. 6 Curve (a) is a target C - V with $V_{th} = Q_{target}/C_d < 0$. In curve (b) the net charge is not enough negative ($V_{sh} > V_{th}$, so $Q_d > Q_{target}$), then $\Delta C = C^+ - C^- < \Delta C_{th}$ and, according to equation (10), the next symbol is BIT1. In curve (c) the net charge is too negative ($V_{sh} < V_{th}$ so $Q_d < Q_{target}$), then $\Delta C > \Delta C_{th}$ and the next symbol is BIT0.

and V^- , namely of symbols BIT0 and BIT1, must be applied at sampling times.

The main advantage of this charge control strategy is its ability to work with devices suffering from vertical displacements in the C - V curve, alongside with horizontal displacements due to parasitic charging. Moreover, by adjusting the threshold parameter ΔC_{th} it is possible to switch on real-time between target values, even positive and negative, of net charge.

For a threshold value ΔC_{th} , which from equation (4) leads to $V_{sh} = V_{th}$ and $Q_d = Q_{target}$, and suitable values for V^+ , V^- , δ and T_s , the control strategy may be implemented as the following algorithm:

1. The MEMS is being actuated with any of the symbols BIT0 or BIT1.
2. Measure the MEMS capacitance at symbol times $(k - \delta)T_s$ and kT_s . For T_s far below the time constants of the charge dynamics, $\Delta C = C^+ - C^-$.
3. The next symbol to apply to the MEMS is decided from the comparison between ΔC and ΔC_{th} , according to the following law:

$$\text{Next Symbol} = \begin{cases} \text{BIT0} & \text{if } \Delta C > \Delta C_{th} \\ \text{BIT1} & \text{otherwise} \end{cases} \quad (10)$$

4. Apply the next symbol and go back to step 2.

Figure 6 illustrates how the decision law (10) works: a target C - V curve is shown in Figure 6(a), whereas Figure 6(b) corresponds to the case $Q_d > Q_{target}$, then BIT1 must be applied to shift the C - V curve to the left, thus decreasing Q_d . Symmetrically, in Figure 6(c) $Q_d < Q_{target}$ and the next symbol, BIT0, would increase Q_d and thus it would shift the C - V curve to the right.

Fig. 7 Implementation of the charge control algorithm. The LCR equipment provides the voltage symbols BIT0 and BIT1. It also measures the values of C^+ and C^- at each symbol. The control subsystem implemented in the computer compares $C^+ - C^-$ with the threshold value ΔC_{th} and, according to equation (10), decides the next symbol to apply.

It has been shown in [10] that, under some conditions, this control algorithm can be described by the equation of a first-order delta-sigma modulator [19]. The dynamical behaviour of this kind of circuit is well known, and therefore this allows one to extract real-time information on the state of the device, from the point of view of dielectric charging, directly from the control bitstream. Such bitstream is the sequence of symbols BIT0 and BIT1 applied, thus it is provided at the sampling rate by the decision law (10).

3.2 Comparison between simulations and experimental results

To validate the characterization method proposed in this paper, a long-time charge control experiment has been carried out. The experiment consists on applying the control algorithm to consecutively fix three different target values of the quasi differential capacitance ΔC_{th} , corresponding to three values of the target voltage shift -first 0.5V, then -0.75V and finally 0V-, to the MEMS whose charge dynamics was characterized in the previous section. The whole experiment lasts for 6 days and the target value is changed each 48 hours.

Figure 7 depicts the implementation of the control method. As in the characterization experiments reported above, the LCR equipment is used both to excite the device with either a BIT0 or a BIT1 symbol and to measure the device capacitances C^+ and C^- at the appropriate symbol times. A computer controls the LCR equipment and decides the next symbol to apply, accordingly to (10). The parameters used for the BIT0 and BIT1 symbols are the same used to obtain the fit-

ting values reported in Table 1: $V^+ = 4V$, $V^- = -4V$, $T_s = 2.5s$ and $\delta = 1/5$.

The evolution of the voltage shift V_{sh} with time, obtained from the measurements of the quasi differential capacitance ΔC at sampling times kT_s , is shown in Figure 8. Note that such experimental voltage shifts match fairly with the target ones, thus true control regimes are achieved at each 48-hour time segment.

Fig. 8 Results of the control method, applied to obtain a specific sequence of target voltage shift values. These values are 0.5V, -0.75V and 0V. The symbol parameters used are $V^+ = 4V$, $V^- = -4V$, $T_s = 2.5s$ and $\delta = 1/5$.

As commented above, the bitstream used to obtain the voltage shifts of Figure 8 consists on a sequence of symbols BIT0 and BIT1 determined by the control method. Each time a symbol BIT0 or BIT1 is applied to the device, a certain amount of positive or negative charge is injected into the dielectric. The average number of symbols BIT1 in the output bitstream is then a measure of the amount of time a positive voltage V^+ must be applied, with regard to the amount of time V^- is applied, to have a net injection of charge compensating the charge continuously being leaked out of the dielectric [10].

To corroborate the goodness of the characterization method, a comparison between the simulated behaviour of the device using the parameters obtained in the previous section, and the experimental control bitstream is shown in Figure 9. Both signals have been obtained by filtering the bitstream with a window composed of 1000 samples. As it can be observed, very good match exists between both signals. With this regard, not only the asymptotic values but even the dynamic evolution near the switching between target voltage shifts is remarkably close when comparing experimental and simulation values.

Fig. 9 Comparison between the filtered control bitstream as function of time, extracted from the experiment reported in Figure 8, and the control bitstream obtained through simulations of the control system using the characterization method and the model parameters summarized in Table 1.

It is also noticeable that for a target voltage shift equal to zero (i.e. to discharge the device), an "almost zero" control must be applied. This means that if we apply V^+ 50% of the time and V^- the other 50%, the charge being stored into the dielectric would still present some small voltage shift. In other words, although the average bitstream is close to zero, it is not identically zero and therefore there is an slight difference in the percentage of time that both voltages must be applied to completely remove the dielectric charge.

3.3 Non linear effects in charge control

The goodness of both the characterization method and the charge control strategy has been demonstrated in the previous subsection. There, the values of the time parameters T_s and δT_s used (2.5s and 0.5s, respectively) satisfy the criterion of being much less than the time constants of the charging dynamics of the device (11 minutes in the worst case).

Now the objective is to check, both experimentally and through discrete time simulations, the performance of the control method when the above criterion is not satisfied, for instance when T_s becomes closer to the time constants of the charge dynamics. Accordingly to the classic sigma-delta theory, nonlinear effects such as a fractal-like behaviour similar to that observed in thermal sigma-delta sensors [20] are expected for this case.

To reduce both the overall time length of the experiments and the CPU time spent in the simulations, a MEMS that exhibits noticeable fast charging/discharging is used in this section. The device is from the same Poly-

MUMPS batch than the one used in previous sections, but it has $360 \times 360 \mu\text{m}^2$ of plate area and a pull-in voltage around 24V. By applying the same fitting procedure to the values of a "BIT0, then BIT1, then BIT0" experiment as in section 2.3, the charge model parameters listed in Table 2 are obtained for this device.

Table 2 Parameters for the negative and positive components of the two-exponential charge dynamics model, obtained from fittings of experimental data.

Parameter	n	p
$Q_{\max}/C_d$ [V]	-4.67	3.85
$\tau_{C,1}$ [s]	39.54	26.94
$\tau_{C,2}$ [s]	322.4	1.65
$\tau_{D,1}$ [s]	19.89	50.33
$\tau_{D,2}$ [s]	9992	2.17
ζ_1	0.81	0.35
ζ_2	0.19	0.65

The first experiment consists on applying real-time charge control to obtain a given set of increasing values of ΔC_{th} , ranging from -5fF to +5fF in 1fF steps. Each step lasts for 3 hours, time enough to reach a stable regime, according to the maximum time constants reported in Table 2. The parameters of the BIT0 and BIT1 symbols used are $V^+ = 10V$, $V^- = -10V$, $\delta = 1/7$ and $T_s = 270\text{ms}$. The value chosen for T_s is close but still well below the minimum time constant of the charge model of the device, which is 1.65s.

Figure 10 reports the comparison between the experimental averaged bitstream and the same result obtained from discrete time simulations of the control system. It can be concluded that both results denote that fair charge control is achieved in all cases.

In a second version of the experiment, the sampling time T_s is increased up to 820ms, a value noticeable closer to the minimum time constants of the device. For this case, the average bitstreams obtained both from simulations and from experiments, shown in Figure 11, lead exactly to the same conclusion: a fractal-like behaviour is observed for the target capacitances $\Delta C_{th} = -2\text{fF}$, -1fF and 0fF . That is, for this case an output bitstream with the same average number of ones and zeros is provided for the discharged state and also for some low negative values of the target charge. Such loss of resolution implies that, for slow sampling rates that do not fulfil the criterion used in all the previous examples, the control method becomes unable to distinguish among a range of target values.

The characterisation/control method displays specific nonlinearities typical for sigma-delta modulators that appear due to piecewise nature of the method (i.e. the decision made in eq. (10)). To explain these nonlin-

Fig. 10 Comparison between the filtered control bitstream as function of time obtained experimentally and that obtained from simulations of the control method with the fitting parameters reported in Table 2. The symbol parameters used are $V^+ = 10V$, $V^- = -10V$, $\delta = 1/7$ and $T_s = 270\text{ms}$.

Fig. 11 Comparison between the filtered control bitstream as function of time obtained experimentally and that obtained from simulations of the control method with the fitting parameters reported in Table 2. The symbol parameters used are the same as in Figure 10, but $T_s = 820\text{ms}$.

earities in detail we will use a simulation model developed in [12] for a parallel-plate device as shown in fig. 1, with the expansion that allows to include nonuniform charge distribution [14] that is responsible for vertical displacement of the C - V characteristic:

$$F_{el}(t) = \frac{C(t)^2}{2A\epsilon_0} \left[(V - \bar{V}_{shift})^2 + \sigma_{V_{shift}}^2 \right] \quad (11)$$

Here $\bar{V}_{shift}$ and $\sigma_{V_{shift}}$ are the average voltage 'shift' and the voltage 'variance' created by a non-uniform charge distribution.

Assuming that ΔC_{th} is related linearly to the net charge in the dielectric, let us plot, using this model, the

actual dielectric charge Q_d controlled by the method as a function of ΔC_{th} . Figure 12 shows two lines with one of them simulated at $T_s = 270\text{ms}$ and the other at $T_s = 820\text{ms}$ for the device described in this section with the charging dynamics parameters given in Table 2. In the ideal case, this must be a straight line. The plot at $T_s = 270\text{ms}$ is fairly close to the straight line, while the plot at $T_s = 820\text{ms}$ resembling a devil's staircase-like fractal. This means that the control method is not able to fix the charge with a precise accuracy, and to increase such accuracy one must decrease T_s . Figure 13 shows a similar result for the case when a non-uniform charge distribution is taken into account. The devil's staircase is a known output characteristic of sigma-delta modulators with a leaky integrator [21] and it has also been observed in other systems like MEMS oscillators [22]. In this system, the sampling time T_s can be seen as an analog for a dissipation or leaking parameter in MEMS and sigma-delta modulators correspondingly.

Fig. 12 Simulation results of $Q_d(\Delta C_{th})$ dependence for the device of this Section with charging characteristics described in Table 2, $T_s=270\text{ms}$ and $T_s=820\text{ms}$.

In the steps seen in Figure 12 and Figure 13 the value of the average fixed charge Q_d remains the same. As sampling time is smaller, the line $Q_d(C_{th})$ is smoother. However, as sampling time increases, there is a range of ΔC_{th} where the value of fixed charge Q_d does not change. We denote that behaviour as 'charge locking' similarly to the phenomenon of mode locking of sigma-delta modulators and the frequency locking of MEMS oscillators.

The output of the control method is a cycle that contains repeating sequence of the decision bits $\{b_n\}$. Each step of the devil's staircase shown in Figure 12 corresponds to such a cycle. If we carry out a two-parameter analysis of the system, we can find selected low-period

Fig. 13 Simulation results of $Q_d(\Delta C_{th})$ dependence for the device of this Section with charging characteristics described in Table 2, $T_s=270\text{ms}$ and $T_s=820\text{ms}$. In this case, a large variance $\sigma_{V_{shift}}^2 \neq 0$ of charge distribution is added to include the effect of charge non-uniformity.

Fig. 14 Simulation results presented in the plane $(T_s, \Delta C_{th})$ there each colour denotes a particular cycle of the decision bit sequence $\{b_n\}$. The grey area corresponds to high-period cycles.

cycles in the plane of the parameters $(T_s, \Delta C_{th})$. Such a plane is shown in Figure 14 where each colour denotes the domain of existence of a specific cycle. The staircase shown in Figure 12 is a vertical slice of the plane from Figure 14 at the corresponding value of T_s .

4 Conclusions

A new method for the purpose of characterizing the dynamics of the charge trapped in the dielectric layer of MEMS devices has been presented. This method is based on quasi differential capacitance measurements:

by measuring only two points of the C - V curve, it is possible to extract the V_{sh} value and therefore obtain the net trapped charge Q_d . For sampled systems, the method allows knowing the state of the charge at each sampling time without distorting the measurement nor affecting the normal operation of the device.

The characterization method has been applied successfully in a closed-loop method that provides real-time control of dielectric charge. Both experimental and simulation results have been provided to demonstrate this. The method also provides a criterion to select the timing parameters of the control method to avoid non-linear effects. A fractal-like behaviour has been demonstrated for sampling rates that do not satisfy such criterion.

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