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Electromechanical design space exploration for electrostatically actuated ohmic switches using extended parallel plate compact model

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ABSTRACT

The nanoscaled electrostatically actuated electromechanical ohmic switch is an emerging device with advanced performance in terms of I_{ON}/I_{OFF} ratio. It is imperative that compact models accompany such novel devices in order to fully evaluate their potential at the circuit-level. A minimal, yet, adequate compact model is developed and analyzed in this work. Further, the model is used as a compass for switch design space exploration and, simultaneously, a corresponding parameter extraction methodology is compiled. The application on data from numerical simulations and on measurements of fabricated devices, verifies the potential of the model, while circuit-level simulations validate its robustness within an industrial IC design environment.

1. Introduction

Modern electronics suffer from a bottleneck regarding the optimum switch performance they can offer. Novel devices and techniques are investigated in order to surpass this limitation and boost technological evolution on the tracks projected by the Moore's law [1–8]. Among these, there is the electrostatically actuated cantilever implemented as an electromechanical ohmic switch with an actuating gap downscaled into the nanometers range (henceforth: NEM relay) [9–14]. Power management, logic applications and memory cells are of particular interest for such devices because of their energy efficiency [15–23].

It is imperative that adequate compact models accompany such novel devices in order to evaluate their potential at the circuit-level and in order to bring the experimental devices within the industrial circuit design environment that is used for the evaluation and characterization of state-of-the-art technologies [24–35]. In this work, a simple, yet adequate, compact model is developed, implemented and analyzed. The model is written in Verilog-A and, thus, it has an easy portability to IC software environments [36–39], while being numerically robust it creates no convergence issues to circuit-level simulations [40]. Further, the model is used as a compass for switch design space exploration and, simultaneously, for the compilation of a parameter extraction methodology.

The simplest structure of a NEM relay is a three terminal switch, as drawn in Fig. 1. Borrowing the terminology from the MOSFET, there is an unmovable gate (G) facing a movable cantilever (beam), whose one fixed side is the source node (S). The other end of the beam (tip) is extended further than the gate and faces another immovable part of the device, the contact node or drain (D). Under no bias ($V_{GS} = 0$ V), the tip is separated from D and there is a highly resistive gap between S and D (state: OFF). The increment of the gate potential (V_{GS}) results into an attractive electrostatic force on the beam towards the gate, which can be high enough to surpass the mechanical resistance of the deformed beam and allow the tip to touch D, forming a conductive path between D and S (state: ON) [41–45].

2. Extended parallel plate model

The physics that regulate such a device is the parallel plate model. The capacitive load between the gate and beam (C_{GS}), if

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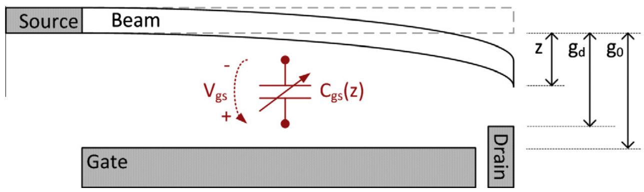

Fig. 1. An annotated, simplified sketch of the 3-terminal NEM relay. g_0 is the nominal gate to beam gap, g_d is the nominal drain to beam tip gap and z is the displacement of the beam. C_{GS} is the capacitance between the gate and beam which is modulated by the position. The dashed, gray lines show the nominal position of the beam with no deformation ($V_{gs} = 0$ V).

biased, results into an attractive force due to the charges of opposite sign that accumulate at the two sides,

$$F_{el} = \epsilon \cdot C_{GS} \cdot \frac{V_{GS}}{2}, \quad (1)$$

where ϵ is the electrical permittivity of the medium between the gate and the beam. However, C_{GS} is a position dependent quantity inversely proportional to the distance between the surfaces, as annotated in Fig. 1. If g_0 is the nominal gate to beam gap and the displacement of the beam is z then a linear approach yields $C_{GS}(z) = C_{GS,0} \cdot \frac{g_0}{g_0 - z}$, with $C_{GS,0}$ being the capacitance when beam is at rest. On the other hand, this simplification assumes the perpendicular displacement of the beam with respect to the axis of movement. A first order extension of this simplified model may be implemented by adding a multiplying factor in front of z, with a value in $[0,1]$, to mitigate the aforementioned overestimation. If the gap between the tip and the drain is g_d, which will be also the maximum displacement possible before contact takes place, then $C_{GS}(z)$ may be expressed as:

$$C_{GS}(z) = C_{GS,0} \cdot \left(1 - \frac{z}{g_d}\left(1 - \frac{C_{GS,0}}{C_{GS,ON}}\right)\right)^{-1}, \quad (2)$$

where $C_{GS,ON}$ is the gate to beam capacitance when the switch is ON. The parallel plate approximation would provide $C_{GS,ON} = C_{GS,0} \cdot \frac{g_0}{g_0 - g_d}$, which in real designs would be the maximum possible value, but here it is treated as an fitting parameter that depends on the exact geometry of the switch allowing it to take smaller values as well.

The deformation of the beam results into an opposing spring resistance force

$$F_s(z) = -K \cdot z, \quad (3)$$

with K symbolizing the spring coefficient [46]. These two forces, for small enough V_{GS}, counterbalance each-other. Yet, there is a gate potential value (V_{pi}) above which the mechanical spring resistance cannot be as large as the attractive force, hence the beam is pulled-in towards the contact. The movement of the beam is blocked by the contact force (F_c) applied between the drain and the tip, where a highly nonlinear spring is assumed, which minimizes the penetration of the tip in the drain.

2.1. Adhesive forces

Upon contact, van der Waals adhesive forces (F_a) appear between the tip and the drain. Physics define such forces as inversely proportional to third power of the distance between the two surfaces [47–50]. However, this is a numerically problematic definition in terms of compact modeling, and a simplified expression shall be used instead, which still maintains the order of dependency on the position of the beam:

$$F_a(z) = A_{adh} \cdot (\max(z - g_d, 0))^3, \quad (4)$$

where the max function allows F_a to be non-zero only upon contact ($z > g_d$) and A_{adh} is an empirical model parameter.

The above set of equations covers the static electromechanical behaviour of the beam. To go into the transient domain one has to add the mass of the movable cantilever (m) and the damping coefficient (b) [51,52]. The positional problem of the beam is expressed as:

$$\sum_{i=el,s,c,a} F_i - b \cdot \dot{z} = m \cdot \ddot{z}. \quad (5)$$

2.2. Contact resistance

To complete the core of the model, it is required to include an expression for tip to drain resistance that becomes non-infinite upon contact [53–59]. This resistance (R_c) depends on the force between the two surfaces, thus, a dependence on F_c is foreseen. Further, R_c is inversely proportional to the contact area (A_c).

$$R_c \propto A_c^{-1} \cdot F_c^{-n_f}, \quad (6)$$

where n_f is a fitting parameter, with a nominal value of $\frac{1}{3}$.

2.3. Electromechanical parameters and geometrical expressions

The above set of equations describes the smallest possible compact model for the NEM relay, which covers all the core functionality of the device and holds all flexibility required in order to be adjusted on any particular switch design. The model-card used covers the essential electromechanical properties of the switch and it is physically connected to the material properties and the geometry of the device, as shown in Table 1.

3. Electromechanical design space exploration

The above described model has been developed and implemented in Verilog-A, which is compatible with the majority of circuit simulators, including the Cadence design platform, which was used for this study [36–39]. The compact model has been used as a compass in order to chart the switch design space. The exploration is also describing a straight-forward parameter extraction methodology. For the parameters that are not explicitly defined below in the various steps of the analysis, the following values are used: $C_{GS,0} = 0.5$ pF, $C_{GS,ON} = 1$ pF, $K = 1$ N/m, $A_{adh} = 0$ N/m^3, $m = 10$ pg, $b = 0$ N s/m, $K_R = 10^{-15}$ Ω m^2 N$^{\frac{1}{3}}$, $n_f = \frac{1}{3}$.

Table 1
Model parameters and their geometrical correlations

Model parameter	Geometrical scaling	Unit
$C_{GS,0}$	$\epsilon \cdot \frac{W \cdot L}{g_0}$	F
$C_{GS,ON}$	$\epsilon \cdot \frac{W \cdot L}{g_0 - g_d}$	F
K	$E \cdot \frac{t^3 \cdot W}{4 \cdot L^3}$	N m^{-1}
A_{adh}	$\propto L_{cs} \cdot W$	N m^{-3}
K_R	$R_c = \frac{K_R}{L_c \cdot W \cdot F_c^{n_f}}$	Ω m^2 N^{n_f}
n_f	–	–
m	$\rho \cdot W \cdot L \cdot t$	Kg
b	$\frac{2}{3 \cdot \pi} \cdot \frac{\mu_u \cdot (W \cdot L)^2}{g_0^3}$	N m^{-1} s

Note: W, L and t are the width, the length and the thickness of the beam assuming a simple parallelepiped shape for the beam, E and ρ is the Young's modulus and the density of the material of the beam, L_c is the length of the contract area, K_R is a fitting parameter, μ_u is the viscosity of the medium between the gate and the beam.