Ultra-Low Power Data Converters with BEOL NEM Relays

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Abstract—With the fundamental limitation on transistor scaling and energy efficiency, Nano-electromechanical (NEM) relays have emerged as a promising alternative solution for ultra-low power integrated circuits due to their zero leakage and steep subthreshold properties. In this paper, we explore the implementation of the I/O interface circuits, namely the analog-to-digital converter (ADC) and the digital-to-analog converter (DAC), with back-end-of-line (BEOL) NEM relays. The proposed design for the ADC comparators eliminates the need for reference generation by utilizing a bank of NEM relays with different pull-in voltages. The decoder and encoder of both data converters are optimized by using a minimum number of devices and exclusive, non-leaking paths for each input and output code. As a result, while the sampling rate and operation frequency of the relay-based converters are inherently lower than CMOS counterparts due to mechanical nature of operation, the proposed data converters can achieve at least one order of magnitude lower energy consumption, which makes them appealing alternatives for ultra-low power VLSI and Internet of Things (IoT) applications.

Keywords—BEOL NEM relay, Ultra-low power VLSI design, Analog-to-Digital converter, Digital-to-Analog converter

I. INTRODUCTION

The NEM relays have been studied and demonstrated extensively in diverse VLSI applications such as logic gates, arithmetic blocks, memory cells and power management [1-5]. The potential of NEM relay technology for low power I/O units and data converters have also been investigated [1-3]. However, no complete circuit implementation of data converters can be found in the previous works, and the proposed schemes suffer from significant static power dissipation.

Recently a CMOS-compatible, vertical NEM relay that utilizes BEOL process and airgap technology has been proposed [6, 7]. In this work, we use a similar structure and customize it to demonstrate a novel implementation of all-NEM relay 4-bit data converters. By minimizing the number of devices for each block, removing the current leakage path and optimizing the operational voltage of relays, the proposed design in this paper can reduce the energy per operation cost significantly. We use Coventor MEMS+ [8] to investigate the electromechanical behavior of the relays and Cadence Virtuoso Spectre for the circuit implementation and simulation with a Verilog-A behavioral description model that we have developed for the BEOL relay.

The rest of this paper is organized as follows. The device structure, operation principles and methods for tuning and customizing the device behavior are presented in section II. The architecture and simulation results of the proposed ADC and DAC, and their corresponding decoder/encoders, are discussed

Fig. 1. BEOL NEM relay (adapted from [6]). (a) 3D illustration of the relay under pull-in state. (b) Technological specifications. (c) Pull-in and pull-out behaviors.

II. DEVICE STRUCTURE, OPERATION AND TUNING

A. Device Structure and Operation

Similar to the CMOS transistor, the NEM relay, depicted in Fig. 1(a), has four terminals: a moving gate beam (G), and fixed source (S), drain (D) and body (B) electrodes, all made of aluminum. The gate spans from M1 to M4 layers and the channel is on the M5 layer. M1 is fixed as an anchor. The VIA between M4 and M5 is inter-metal dielectric made of silicon dioxide and prevents the flow of current from the gate to the channel. The technological specifications are listed in Fig. 1(b).

When a voltage difference is applied between the gate (the free moving beam) and body electrodes, the beam will bend towards the body due to the electrostatic force generated in between. If this force is strong enough to overcome the spring restoring force, the beam “pulls in,” and the channel connects the source and the drain. Now if we reduce the applied voltage, at a certain point, the spring restoring force becomes larger than the electrostatic force and surface contact forces (including Van der Waals’ force between atoms and capillary force due to a certain humidity in the air [9]), thus the beam “pulls out”. As a consequence, the operation is inherently hysteretic, a fact that is reflected by a 0.17 V difference between the pull-out voltage (V_{PO}) and pull-in voltage (V_{PI}), as illustrated in Fig. 1(c).

B. Tuning the Pull-in Voltage

The design of ADC comparators, explained in the next section, requires relays with different V_{PI} . There are a few methods for tuning the spring constant of the beam and thus the V_{PI} . The simplest way to do this without a change in the dimensions and area of the device is by adjusting the inter-metal

TABLE I. VIA ARRANGEMENTS FOR V_{PI} TUNING

$V_{PI}(V)$	1.92	2.02	2.12	2.22	2.32	2.42	2.52	2.62
VIA Arrangements	151	515	154	525	144	412	541	355
$V_{PI}(V)$	2.72	2.82	2.92	3.02	3.12	3.22	3.32	
VIA Arrangements	244	522	431	233	224	444	333	

VIA locations. By doing that, the V_{PI} can be tuned by changing the effective length of the spring (L_{eff}). The serpentine-shaped gate in Fig. 1 (a) represents the largest L_{eff} , hence provides the minimum stiffness and spring constant. Therefore, minimum V_{PI} is obtained with this structure. In this work, we achieve the V_{PI} tuning by varying the location of VIA1 to VIA3 along the beam. We assign the VIA locations to five points along the metal beam, including both ends, to observe distinct shifts in the V_{PI} . We call the possible locations from far left to far right as position “1” to “5” as annotated in Fig. 2(a), and the full arrangement is represented by a three-digit number representing the position of VIA1 to VIA3. As an example, the structure in Fig. 1(a) has the VIA arrangements of “151”.

As the comparator bank of the 4-bit flash ADC in this paper requires 15 devices with uniform changes on V_{PI} , the tuning method stated above is implemented on the structure. Fig. 2 displays four examples of the device variations and the resulting V_{PI} . TABLE I summarizes simulated V_{PI} for all desired devices.

C. Tuning the Operating Voltage with Body Biasing

The NEM relay is actuated by the electrostatic force generated between the moving gate and the fixed body, conventional way of implementing this is applying V_{PI} on the gate while the body is grounded. However, biasing the body with a negative voltage while keeping the voltage difference identical can lower the required input voltage on the gate. When the body is biased at $-V_{PO}$, the relay can be switched on with only $(V_{PI} - V_{PO})$. If this method is applied to the structure in Fig. 1(a), it results in a V_{PI} of 0.17V and V_{PO} of 0V, which is the minimum operating voltage achievable as described in Fig. 3(a).

In addition to more freedom on the circuit design, this method also saves more than one order of magnitude dynamic energy for most cases, as a direct result of operating in lower voltage domain. A practical operating point to ensure safe functioning is suggested in Fig. 3(b) with the simulated results from Cadence Virtuoso pointing out an abrupt switching behavior in the I-V curve.

III. BEOL NEM RELAY FLASH ADC

An overview of the ADC design is illustrated in Fig. 4. The analog input (V_A) goes through a standard sample and hold (S/H) sub-circuit[1], then it is picked up by the comparators. The

Fig. 2. Showcase of VIA arrangements to obtain different V_{PI} . (a) Arrangement “151” (b) Arrangement “541” (c) Arrangement “231” (d) Arrangement “333”.

Fig. 3. (a) Body biasing scheme. (b) Practical operating point adopted, the inset shows the corresponding pull-in and pull-out behavior.

outputs of comparators are then converted from thermometer coded (TC) to standard binary output. The comparators utilize a variety of relay structures mentioned in TABLE I. The details of the design will be discussed in this section.

A. Design Methodology for ADC Core

The schematic block diagram in Fig. 4 exhibits the architecture of the all-relay flash ADC. The body of the comparators and the decoder is biased with a negative voltage, V_{NEG} , to enable the operation of the circuits with an independent low voltage supply (V_{LOW}) thus reducing the total energy consumption. The control signals used in the circuit include the sample signal (SAMP) and the hold signal (HOLD) to guarantee a valid and fixed analog input for the comparators, V_{HOLD} , during each conversion. V_{HOLD} , the shared input among all comparators, is effectively compared with the V_{PI} of various relays simultaneously, deciding the switching behavior of those relays. Each comparator’s output (OUT_n) is first pre-discharged to GND when the evaluation signal (EVAL) is 0. When EVAL becomes 1, OUT_n is evaluated (charged) to V_{LOW} only if V_{HOLD} is large enough to turn on that specific comparator relay (with a unique pull-in voltage of $V_{PI,n}$), otherwise OUT_n remains 0.

Note that only the comparators utilize relay structures with various V_{PI} . All other relays have the same structure (“151”) which exhibits the minimum V_{PI} and optimal energy and speed.

B. 15-line to 4-line TC to Binary Relay Decoder

The 15-bit TC output needs to be converted to its standard 4-bit binary equivalent. We designed a relay-based decoder that generates the final output $D_3D_2D_1D_0$ based on the truth table in Fig. 5(a). The TC output, OUT in Fig. 5(a), contains consecutive 1’s and 0’s. This property can be used to simplify the decoder with a methodology shown in Fig. 5(b). The implementations

Fig. 4. Design flow of the proposed ADC with circuit implementation illustration of sample/hold block and comparators.

Fig. 5. (a) Truth table of the 15-bit to 4-bit decoder. (b) Design methodology. are demonstrated in Fig. 6. The circuit is optimized to implement the decoder with as few as 68 NEM relays and only incurs one mechanical delay ($\sim 20\text{ns}$), the total delay of the ADC is approximately two mechanical time constants. Fig. 7 reveals the Spectre simulation results of the NEM relay ADC with a sampling rate of 2.5MHz. The TC output plots are replaced with binary blocks for better visualization.

The total number of relays used to implement the ADC is 102, and the energy consumed during each conversion step is 0.74 fJ on average. This low energy consumption behavior is attributed to the absence of static direct current, e.g., voltage reference level provided by resistor string in traditional flash ADCs, and low swing of operational voltage (V_{LOW}). The energy/op consumed in this circuit shows more than 96.6% reduction compared to the flash relay ADC proposed in [1]. The comparison between this work and state of the art relay ADC as well as a few CMOS ADCs are listed in TABLE II. The figure of merit used in this paper is Walden FOM [13], $\text{FOM} = \text{Power} / (2^n \cdot \text{Sampling Rate})$, where n is the resolution of the ADC.

IV. BEOL NEM RELAY DAC

In this section, we describe the implementation of all-relay DAC. Fig. 8(a) illustrates the schematic of the proposed DAC. Here we follow a design flow that is the reverse of the ADC, where we encode the 4-bit input into a 15-bit TC output via a dedicated relay encoder and then convert it to the final analog output using a bank of relay buffers. Each buffer is driven by one of the TC input lines and followed by a terminating resistor. This topology can generate the output voltage with a fixed step increment of V_{LOW}/N , where $N=2^k-1$ and k is the bit resolution

Fig. 6. The circuit implementation of the all-relay TC to binary decoder. Only one mechanical delay is introduced by this block. (a) D₀ bit. (b) D₁ bit. (c) D₂ bit. (d) D₃ bit, a buffer is introduced for an identical delay with other bits.

Fig. 7. Simulation results of the NEM relay-based ADC, $V_{\text{LOW}} = 1\text{V}$, $V_{\text{DD}} = 2\text{V}$, $V_{\text{NEG}} = -1\text{V}$, $C = 500\text{fF}$.

of the DAC. The analog output voltage V_A is determined by the number of 1's in the encoder's output, or $V_A = (D/15) \cdot V_{\text{LOW}}$.

We use the reverse of the truth table in Fig.5(a) to extract the expressions for the binary to TC encoder. The algorithm is summarized in Fig. 8(b). Since many of the TC bits share similar expressions, we share some relays in the main path for multiple outputs. The constructed circuit is shown in Fig. 8(c), in which 11 out of 15 outputs reuse some relays, resulting in minimized device count of 84. The devices used in the DAC have identical V_{PI} with body biased at V_{NEG} . The encoder operates at the same independent I/O voltage V_{LOW} as well for energy saving.

Similar to the ADC, the full DAC circuit incurs two mechanical delays, so we operate it at the same frequency as the ADC. The simulation results are shown in Fig. 9, where the analog output accurately represents the digital input. The DAC consumes 5.82 fJ/conversion while the encoder itself consumes a negligible amount of energy of 0.03 fJ/conversion. The comparison of the results with state of the art CMOS DACs is summarized in TABLE III.

V. CONCLUSION

This paper introduces the design methodology for all-NEM relay based data converters, customized for predictive vertical relays fabricated in BEOL process. The reference generation unit traditionally implemented by resistor strings or similar methods in flash ADCs has been removed by tuning the operational voltage of each NEM relay in the comparator bank. The decoder of the ADC and the encoder of the DAC are

TABLE II. COMPARISONS OF THE ADCs

	VLSI'13 [10]	TVLSI'14 [11]	VLSI'17 [12]	ICCAD' 08 [1]	This Work
Device /Technology	CMOS /22nm	CMOS /65nm	CMOS /65nm	NEM Relay /90nm	NEM Relay /22nm
Architecture	$\Delta\Sigma$	Flash	Flash	Flash	Flash
Resolution (bit)	8	4	8	6	4
Sampling Rate	240 MS/s	10 GS/s	2 GS/s	10 MS/s	2.5 MS/s
Power (mW)	12.7	104	21	3.5×10^{-3}	2.97×10^{-5}
FOM (fJ/Conv.step)	259.6	880	109.4	5.5	0.74

Fig. 8. (a) The architecture of the proposed all-relay DAC. (b) Encoder output expressions and (c) encoder circuit implementation.

optimized to remove recurring current paths and achieve the minimum number of devices for each function. The operational voltage of the relays has been reduced to a minimum which is

Fig. 9. The simulation results of the proposed DAC.

TABLE III. COMPARISONS OF THE DACS

	[14]	[15]	[16]	[17]	This Work
Device /Technology	CMOS /65nm	CMOS /90nm	CMOS /40nm	CMOS /0.13 μm	NEM Relay /22nm
Resolution (bit)	4	5	6	6	4
Sampling Rate	10 GS/s	2 GS/s	4 GS/s	2.7 GS/s	2.5 MS/s
Power (mW)	30	12	13	5.4	1.064x10 ⁻³
FOM (F/Conv.step)	190	187.5	50.8	31	5.82

enforced by the inherent hysteresis between V_{PI} and V_{PO}. The energy efficiency is significantly improved for both DAC and ADC as a result of these optimizations. While the conversion speed of relay-based data converters is considerably lower than the CMOS counterparts due to the mechanical nature of their operation, the superior energy per conversion proves the feasibility of this technology for ultra-low power applications with modest performance requirement, such as IoT and biomedical applications.

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