Micromotors unit based on CMOS-MEMS technology integrated on a single chip

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Abstract— ***This paper shows the design for MEMS linear and rotary micromotors including their respective control circuits, elevation voltage stage and sensors, all together in a single chip. They were designed under the rules of the standard 0.5-micron CMOS technology of On Semiconductor. With simulations carried out in OrCAD PSPice, the designed control circuits of both linear and rotary micromotors were tested; the simulation helps us to verify their correct operation. Finally, the elevation voltage stage between control circuit and electrodes allows the application of the necessary voltage to drive the micromotors.***

Keywords— ***MEMS, micromotor, CMOS technology, FGMOS.***

I. Introduction

A continuous and extensive development in microelectromechanical systems (MEMS) has taken place since 1980s. The area of micromachining has made progress thanks to the advancement of technology and research; due to these improvements, it is possible to design devices that are more complex. This work is focused on the design and integration of different types of micromotors MEMS (linear and rotary) whose dimensions are in the range of microns to millimeters. This type of devices are important in the development of micro-scale systems.

In the case of micromotors, some of their applications can be in miniaturized robotics and other devices such as micropistons or electrovalves; for example, it can be used in medical instruments such as microvalve control [1].

Some works [2] [3] [4] [5] [6] discuss the design of the mechanical structure of micromotors manufactured under the rules of CMOS technology or dedicated technologies for MEMS (such as MEMSCAP [7] [8]). The dedicated technologies have specific layers for manufacturing each mechanic piece; on the other hand, the 0.5-micron CMOS technology of On Semiconductor [9] is not intended for MEMS devices design.

Hence, it can be said that there is a low number of micromotor designs compatible with the standard CMOS technology. This compatibility is very important since in an application it is desirable that both the mechanical structure and the control circuit are within the same chip, therefore both the area occupied by the entire system and its cost are reduced.

Considering this, the present work develops the design of a chip that contains both a linear and a rotary micromotors, with their mechanical structure, control circuit and sensors, as well. These micromotors work with low voltage and they are designed under the rules of the 0.5 micron CMOS technology of On Semiconductor; that is, it is the first complete system designed with this technology.

A. Micromotor MEMS

The driving forces of micromotors that generate a movement are fundamentally of electrostatic nature. The tangential force generated in parallel pairs of misaligned and electrically energized plates, provides the movement required in a micromotor [10].

Fig. 1 exemplifies the operating principle of a linear micromotor, in which there is a movement between two sets of parallel plates. The mobile electrodes are aligned with a constant separation between them. The fixed set electrodes is positioned in front of the moving set electrodes with a constant gap, in such a way that they are out of phase with the mobile electrodes. Therefore, an electrostatic force appears when a potential difference between both electrodes is applied. This phenomenon moves the motor one-step horizontally and it is repeated sequentially for the next pair of electrodes, in this way the motor moves gradually until reaching the final position.

On the other hand, Fig. 2 shows a schematic of a rotary micromotor. In an alternating sequence, a potential difference is applied (control voltage) to the stator poles, so they are connected to three electrical phases (φ_1 is connected to E1, φ_2 is connected to E2 and φ_3 is connected to E3). So by applying these potential differences to the misaligned poles, an electrostatic force is generated between them, which causes a rotor movement of one-step. Repeating this process in an appropriate sequence and periodically, the rotor can rotate at a certain speed in a clockwise or counterclockwise direction [10].

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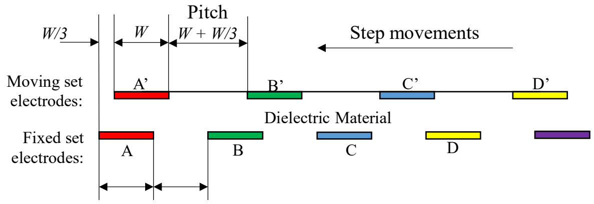

Fig. 1. Principle of operation of a linear electrostatic micromotor.

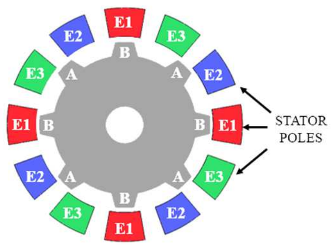

Fig. 2. Schematic of a rotary micromotor.

II. Design of Micromotors

It is important to clarify that in order to move the rotary or the linear micromotors designed in the present work, a minimum control voltage $V_{o_{min}}$ must be applied (18V for rotary micromotor and 16V for linear micromotor [11] [12]).

In addition, it was taken into consideration that there are three metal and two polysilicon layers of different thicknesses available in On Semiconductor 0.5 micron CMOS technology [9]. All the layers are separated by silicon oxide and they can be electrically connected through metal contacts as shown in Fig. 3.

On Semiconductor 0.5 micron CMOS technology is not intended to design MEMS devices, therefore a micro-machining process with TRANSENE Silox Vapox III is needed, in which the silicon oxide is removed only in the area where the mobile structures are located, not affecting the integrity of the metal used as structural layer (aluminum in this case).

A. Rotary micromotor

1) Structure

An area of 500µm × 500µm is assigned for the micromotor structure.

The rotor is manufactured using the Metal1 and Metal2 layers. On the other hand, the stator is built using Metal1, Metal2 and Poly2 layers. All the layers used in the stator and rotor structures are joined by means of metal contacts. The shaft cap of the micromotor is constructed using the Metal3 layer (for more details see [12]).

2) Speed sensor

A floating-gate MOS transistor (FGMOS) is used to estimate the turning speed of the rotary micromotor.

It is well known that the control gate (CG) and the floating gate (FG) of an FGMOS form a parallel plate capacitor. If the capacitance formed by the two gates of the FGMOS varies, the floating gate voltage changes, which causes the transistor current to vary [13].

The speed sensor is constructed in such a way that the control gate is attached to the rotor structure. When the rotor rotates, there are periodic variations in the transistor current that allow obtaining the rotation speed (for more details of the speed sensor see [13]).

The floating-gate MOS transistor is built as shown in the schematic in Fig. 4. A schematic of the cross section of the rotary micromotor structure and the floating gate and control gate are shown in Fig. 5.

1) Control circuit

The first element of the control circuit is an oscillator based on a Schmitt trigger inverter as shown in Fig 6. Both the resistor and the capacitor are external devices of the chip, whose values determine the frequency of the oscillator.

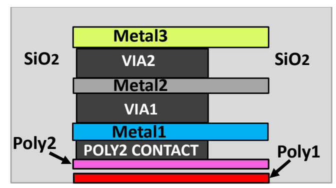

Fig. 3. Schematic of the layers available in On Semiconductor 0.5 micron technology.

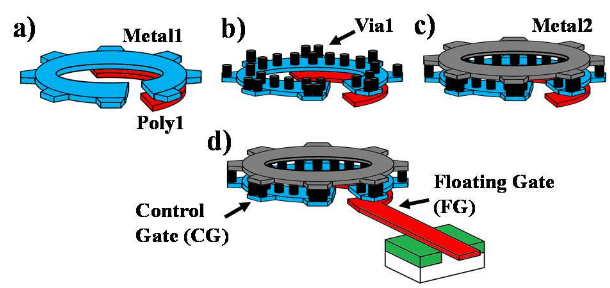

Fig. 4. (a) Capacitor formed by floating gate and control gate (b) Metal contacts on the CG plate (c) The rotor (Metal2) is fixed to the CG plate by means of metal contacts. (d) The FG plate extends and forms the floating gate of the FGMOS.

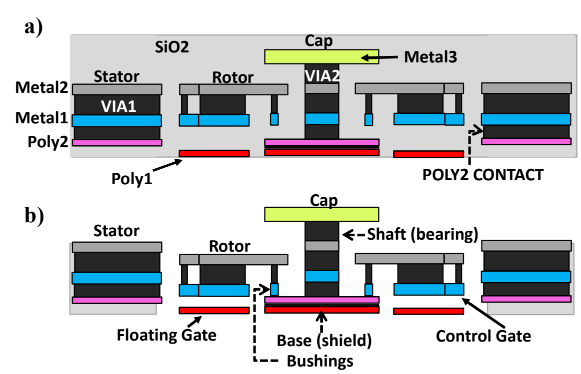

Fig. 5. Schematic of micromotor cross section with On-Semi 0.5 micron CMOS technology layers (a) before micromachining (b) after micromachining.

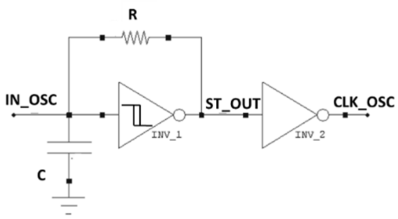

Fig. 6. Oscillator circuit based on a Schmitt trigger inverter.

The oscillator is used as clock signal of a sequential circuit based on D-type flip-flops. This circuit generates the signals (P1, P2, P3) that indicate the order of excitation of the stator poles (signals in an alternating sequence of three electrical phases that determines the direction of the micromotor rotation). When the frequency of the oscillator varies, the frequency of P1, P2 and P3 changes (Fig. 7(a)), which will cause the micromotor rotation speed to change.

An external signal x is used to select the order of generation of P1, P2 and P3. If x=0 the micromotor rotates in a clockwise direction. If x=1 the motor rotates in a counterclockwise direction (Fig. 7(b)).

B. Linear micromotor

1) Structure

The linear micromotor occupies a total area of 649µm × 597µm. A characteristic of this micromotor is the use of springs as a support of the mobile electrodes, which is not common in this type of devices. These springs will be the support of the arrangement of capacitive plates and their guide in the moving axis. Another function is to avoid the friction between the moving part and the lower layers. The structure has an arrangement of springs at each end of the actuator as shown in Fig. 8.

Since the structure is suspended in the air, it is necessary to overcome the force to move the springs and not that due to friction in order to achieve the micromotor movement. Because of this consideration, it was calculated the electrostatic force required to move the springs and then the voltage (V_{motor}) to obtain this force. With the purpose to define the dimensions of the springs, it was necessary to analyze their deflection and take into consideration the electrostatic force and the voltage. Finally, the layer in which the springs and the actuator will be manufactured is Metal1 (aluminum) having a thickness (h) of 0.64µm.

2) Position sensor

As shown in the rotary micromotor design, the FGMOS transistor in this case is used as a position sensor of the micromotor. The FGMOS correlates the position of the moving set electrodes with the current delivered by the transistor, therefore the changes of the coupling coefficient can be used by adding a movable control gate as shown in Fig. 9. This change allows the variation of overlap with the floating gate. When the micromotor is displaced by applying an electrostatic force due to the interaction between the electrodes, the area of overlap between the control gate and the floating gate varies (as shown in Fig. 10).

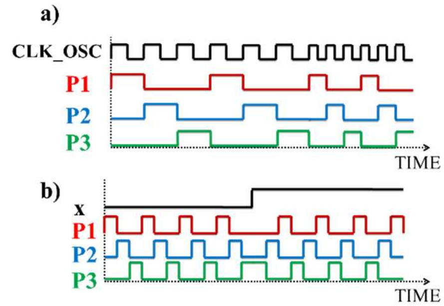

Fig. 7. Control circuit signals (a) the frequencies of P1, P2 and P3 change with CLK_OSC (b) The order of P1, P2 and P3 is given by the value of x.

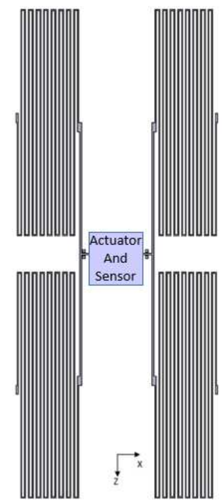

Fig. 8. Mechanical structure of the linear micromotor.

As a result, the capacitance formed by the control gate and the floating gate varies, producing a change in the drain current (I_D).

Thus, the position sensor will give different I_D (drain current) values for each position. This sensor is made up of a control gate, a floating gate, drain and source, as shown in Fig. 9.

There must be no obstacles in the path of the mobile electrodes, due to the type of movement of the micromotor. Hence, as shown in Fig. 9 it was chosen to place the control gate and the moving part in the same layer (Metal1-Aluminum in order to have more stiffness of the mobile mechanical structure because of its greater thickness). The same figure illustrates the floating gate made in Poly1 just below the control gate.

With the help of an Overglass window in the chip, there will be no friction between mobile and fixed pieces after the surface micromachining and the MOS transistor stays fixed with the floating gate.

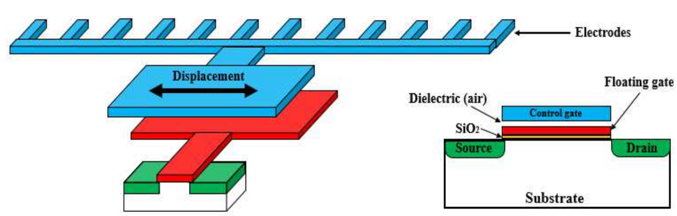

Fig. 9. Position sensor structure.

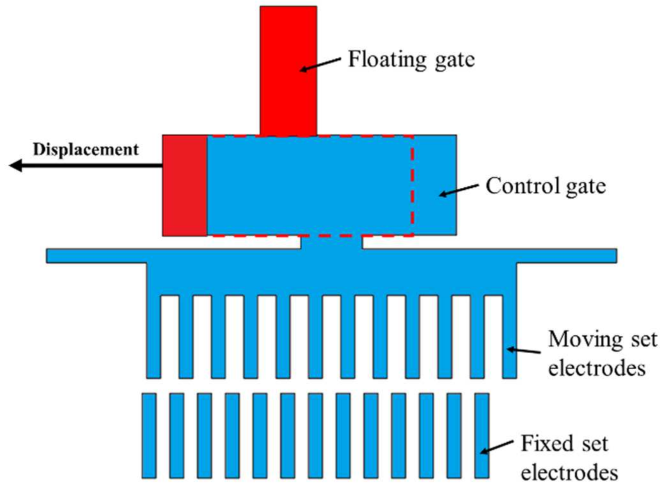

Fig. 10. Overlapping of the position sensor (top view).

3) Control circuit

The elements of the linear micromotor control circuit are:

- An internal or external oscillator, the same of the rotary micromotor, the user decides which of them to use and at what frequency. This signal is used for the clock of the "Phase Generation" stage.
- The stage which is in charge of generating the phases; that is, it generates the necessary signals to move the micromotor forward until final position, stop there and go backward. These phases are applied to the fixed set electrodes, initialized with the clear signal and the x signal selects the direction of movement of the motor (back or forward).

It is needed an up counter in order to enable phases F0 to F5 on the fixed electrodes (Fig. 11) in order to change the potential difference between electrodes (to obtain a forward displacement). To return the motor to the initial position a down counter is needed. Three D-type Flip-Flops were used to obtain the ascending and descending counters, after this stage it was used a combinatorial circuit in order to activate each phase.

It is important to mention that F0 to F5 phases are renamed as F0' to F5' after the elevation voltage stage.

C. Elevation voltage

The signals from the control circuits range from 0 to 5V; these voltages are not capable of driving the micromotors. As previously mentioned, to generate the electrostatic force necessary to drive the linear or rotary micromotor, 16V and 18V are needed, respectively.

In order to use these voltages in On Semiconductor's 0.5-micron CMOS technology, an extended drain MOS transistor is needed [9]. A schematic of this transistor is shown in Fig.12.

The drift region (n-) is an "extension" of the drain, hence it is called an "extended drain", therefore the channel is located between the extended drain and the source.

A thin silicon oxide layer separates the transistor's gate, over the channel region so this one behaves in a similar way as in a low voltage transistor; the gate extends beyond the channel and sits on a thick oxide (FOX) on the side of the drain region to increase the breakdown voltage of the oxide.

This transistor is used as an inverter as shown in schematic in Fig.13 and it is placed as an intermediate stage between each phase of the control circuit and the fixed electrodes of micromotors.

III. Results

In this section it is evaluated the electrical operation of the control circuit. Using the SPICE BSIM3 Version 3.1 transistor model, simulations were performed in OrCAD PSPice to test the performance of the designed control circuits of both linear and rotary micromotors.

The oscillator circuit showed in Fig.6 is simulated using a capacitor C = 10pF and a variable resistor; the signals shown in Fig. 14 were obtained. It is observed that the oscillator has a good behavior for a wide range of frequencies. This will allow to test the mechanical structure in different frequencies.

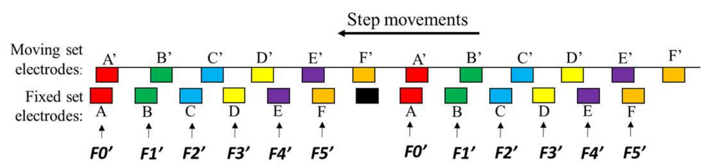

Fig. 11. Phases in fixed set electrodes.

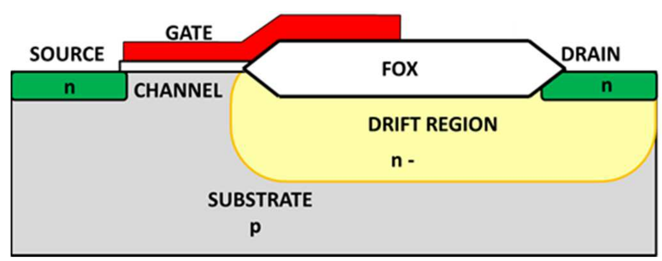

Fig. 12. Extended drain transistor cross section.

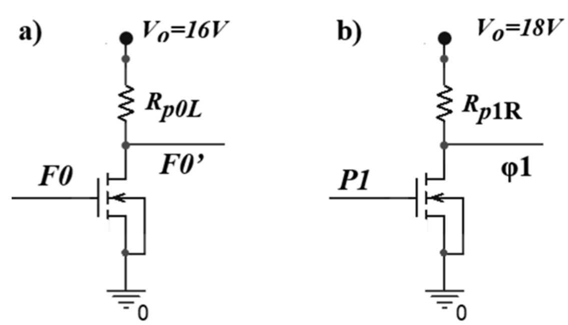

Fig. 13. Inverter using an extended drain MOS transistor. (a) For phase 0 of the linear micromotor. (b) For phase 1 of the rotary micromotor.

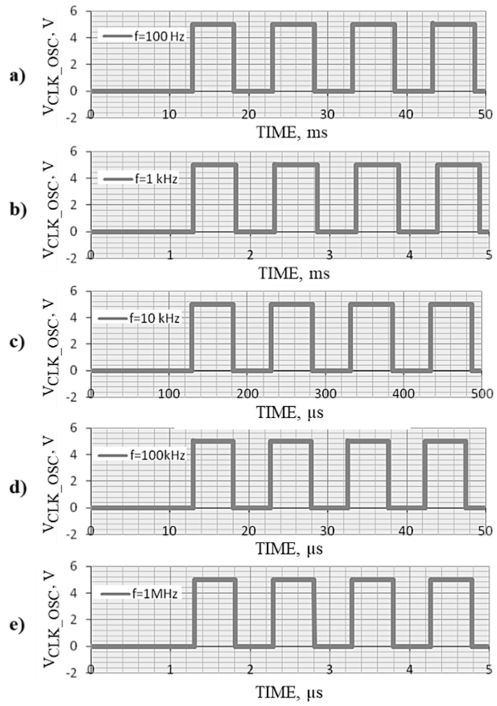

Fig. 14. Signals at the oscillator output using a 10pF capacitor and a variable resistor.

A. Rotatory micromotor

Fig.15 shows the results of the simulation of the control circuit (using an oscillator frequency of 1MHZ) that generates the phases P1, P2 and P3 to move the rotary micromotor; clear initializes the phases and, subsequently, when x = 0 the circuit generates the sequence P1-P2-P3 and when x = 1 the sequence is P3-P2-P1. It is also observed that in each sequence 11 pulses are generated, which will cause the micromotor to rotate 11 steps.

B. Linear micromotor

The control circuit is tested in order to move the micromotor forward and backward, which requires a three-bit up counter that counts from zero to five and thus activates the phases from F0 to F5 on the fixed electrodes to change the potential difference between the electrodes. In addition, a down counter of three bits is needed for a count from F5 to F0, in order to return the micromotor to the initial position.

When clear signal changes its state to low then all the phases are initialized, that is, the counters are initialized. The signal x is used to decide which of the two directions will be active (x = 0 forward, x = 1 backward). Both the x and clear signals are generated by emulating user interaction. In this way, the phase signals are obtained as shown in Fig. 16.

C. Elevation voltage

The extended drain MOS transistor shown in Fig. 13 is simulated; after this stage, it is obtained a higher voltage (from 0 to 18V) as shown in Fig. 17.

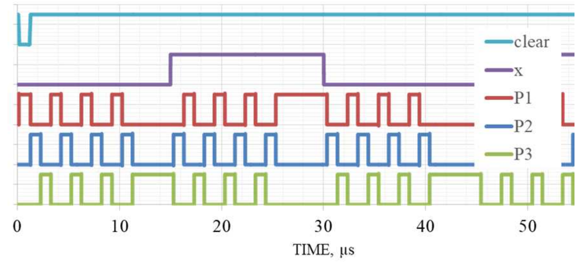

Fig. 15. Control circuit signals for the rotary micromotor.

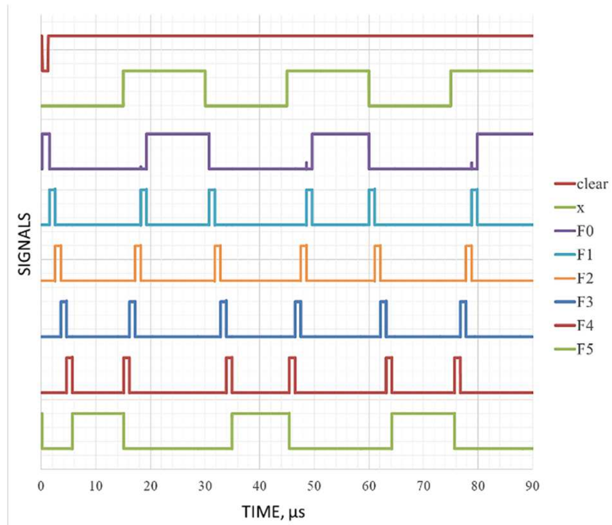

Fig. 16. Control circuit signals for the linear micromotor.

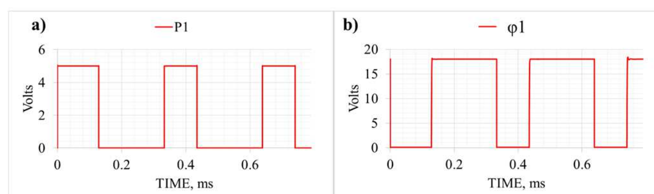

Fig. 17. Signals for the extended drain transistor (a) input (0-5V), (b) output (0-18V).

D. Topological design

The topological design was made in L-Edit software under the rules of On-Semi technology of 0.5µm. The design process of the extended drain MOS transistor is shown in Fig 18.

Finally, in Fig. 19 it can be seen the chip with both linear and rotary micromotors, with their respective control circuit and sensor.

Where $R_{pi\,L}$ and $R_{pi\,R}$ are the resistors for the elevation voltage stage of the linear and rotary micromotor, respectively. V_0 is connected to 16V or 18V depending on which micromotor is used. V_{DD} is connected to 5V. Considering the voltage applied at V_0, it is necessary to remove the protection devices specifically in this I/O Pad, which can allow application of this voltages.

Fi_in and *Pni* are the inputs of the extended drain transistors used for the linear and rotary micromotors, respectively. *Fi* and

Pi are the outputs of the control circuits for the linear and rotary micromotors, respectively.

clk and *clear* are the clock and clear inputs of the flip-flops, respectively. If the clock generated by the oscillator based on Schmitt trigger is used, it is necessary to connect the *clk* and *CLK_OSC* pins.

I_D and I_{OUT} are the outputs of the sensors of the linear and rotary micromotors, respectively.

Finally, *IN_OSC*, *ST_OUT* and *CLK_OSC* are the oscillator based on a Schmitt trigger inverter signals shown in Fig. 6.

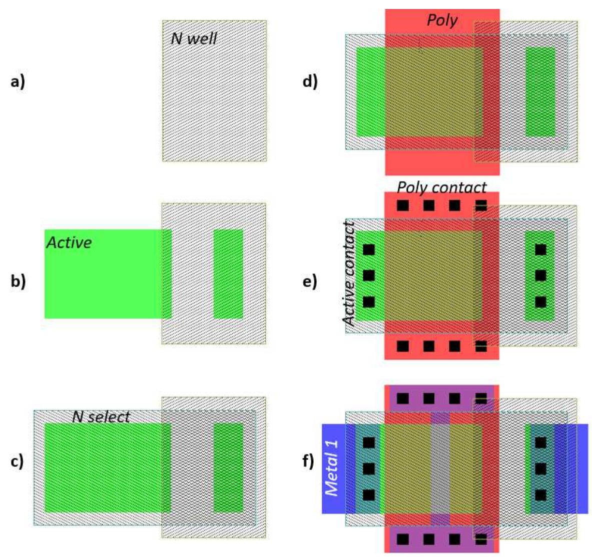

Fig. 18. Extended drain MOS transistor topologycal design.

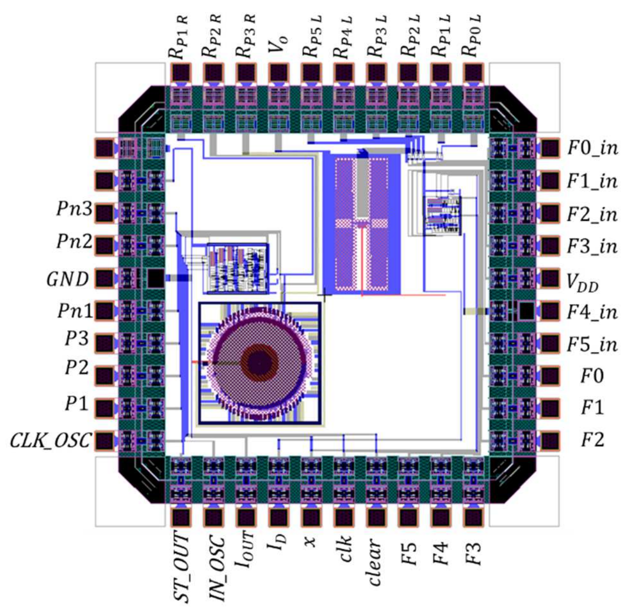

Fig. 19. Chip topologycal design.

IV. Conclusions

Based on the reviewed micromotor literature, this work is the first to integrate two different types of micromotors (linear and rotary) within a single chip.

Another advantage of this work is that it is considered a low voltage system, since it operates with voltages from 0 to 20V.

On the other hand, despite the existence of works that integrate the micromotor, its control circuit and the elevation voltage stage, this work is the first to integrate position and speed sensors within the same chip based on 0.5 micron CMOS technology of On Semiconductor, and an FGMOS.

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