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A Survey on Modeling and Simulation of MEMS Switches and Its Application in Power Gating Techniques

Pramod Kumar M.P*, A.S. Augustine Fletcher**
*(PG scholar, VLSI Design, Karunya University, Tamil Nadu, India)
** (Assistant professor, ECE Department, Karunya University, Tamil Nadu, India)

ABSTRACT
Large numbers of techniques have been developed to reduce the leakage power, including supply voltage scaling, varying threshold voltages, smaller logic banks, etc. Power gating is a technique which is used to reduce the static power when the sleep transistor is in off condition. Micro Electro mechanical System (MEMS) switches have properties that are very close to an ideal switch, with infinite off-resistance due to an air gap and low on-resistance due to the ohmic metal to metal contact that is formed. In this paper, we discussed the MEMS switch, its material selection and its working in power gated circuits for the purpose of massive reduction of leakage power. This CMOS- MEMS combination provides high switching speed, very clean contacts, less reliability and less lifetime.

***Keywords* -** MEMS, MTCMOS, RF-MEMS Switch, power gating, Electrostatic MEMS switch, static power

I. INTRODUCTION

Micro Electro Mechanical switches are the switches that operates with the laws of mechanical motion. Main advantages are their zero OFF-current and their fast switching behavior. MEMS switches behaves as perfect switches with very low ON resistance and infinite OFF resistance and hence can be used to power-gate CMOS systems. The cantilever bends when the voltage between the cantilever and the gate-electrode reaches to VPI. The lever bending due to the electrostatic, piezoelectric, thermal or magnetic forces and forms an ohmic contact. CMOS-MEMS integration efforts have focused on capacitive MEMS switches.

Power gating a circuit with transistors reduces the leakage power of the circuit during the idle state. It also introduces a delay due to the voltage drop created by the ON resistance of the power gate. The leakage reduction and delay increase is the characteristic that involves the sizing of the power gates. As the technology is scaled down, the leakage current will be more and hence the power gating takes an important role. Large voltage drop may render the circuit as inoperable.

The advantages of MEMS switches over FET switches are zero power consumption, high isolation, low insertion loss, low cost, low Speed, power handling capacity, high voltage drive, reliability, packaging and cost. The main applications of MEMS switches are in radar systems for defense applications, automotive radars, wireless systems satellite communication systems and instrumentation systems.

The performance of RF-MEMS switches depends on the suitable material to be used for the switch. Several material selection strategies have been developed in the past, the methodology for selecting the materials used in RF-MEMS switches, mainly for reconfigurable antenna, has never been proposed in [1]. The electrostatic switch is composed of a fixed electrode and a movable electrode, forming a parallel plate capacitor. After the application of a specific voltage, the movable electrode bends closing the air gap and turning ON the switch. Series switch and shunt switch are the two different RF MEMS switches [3]. The typical shunt MEMS switch consists of a thin metal membrane suspended over the center conductor of a coplanar waveguide (CPW) and fixed at both ends to the ground conductor of the CPW.

Equation 1 shows the total energy consumption per switching cycle [4]:

$$E_{Tot} = \frac{\epsilon_o * A}{g - g_d} V_{dd}^{\ 2} \quad (1)$$

Where g is the gap between the contacts when the beam is deflected, g_d is the dimple gap thickness and A is the actuation area. The dimple gap is an air gap that separates the source and the drain in the OFF state.

The response time t_{PI} [4] is described in equation 2:

$$t_{PI} \propto \sqrt{\frac{m g_d}{k_{go}}} \left(\frac{V_{PI}}{V_{DD}}\right) \quad (2)$$

Where k is the spring constant, m is the mass and V_{DD} is the supply voltage. The pull in voltage V_{PI} is given by [4]:

$$V_{PI} = \sqrt{\frac{8}{27}\frac{k_{go^3}}{\epsilon_o WL}} \quad (3)$$

Here W is the width of the switch, L is the length of the switch and ϵo is the permittivity of free space

II. RF MEMS SWITCHES [2]

This paper presents an overview of the RF MEMS switches. It also presents a technique for modeling and design of inductively-tuned shunt MEMS switch [5]. An equivalent lumped element model can be determined. The values of the circuit elements are determined based on the physical dimensions of the switch. Analytical form of inductance for inductive-tuned MEMS switch is also presented in this paper.

MEMS is a multidisciplinary technology that involves materials and fabrication, process and device engineering, microwave engineering, mechanical engineering etc. The main applications of MEMS switches are in radar systems for defense applications, instrumentation systems, wireless communication systems, satellite communication systems, etc. Two types of MEMS series switches [6] are broadside series switch and inline series switch. The actuation of the broadside switch is in a plane that is perpendicular to the transmission line. The actuation of the inline switch is in the same plane as the transmission line. A series capacitance in the up-state position and a small resistance in the down-state position is the electrical equivalent of the MEMS inline series switch. Fig 1 and 2 shows the MEMS shunt switch and MEMS series switch respectively.

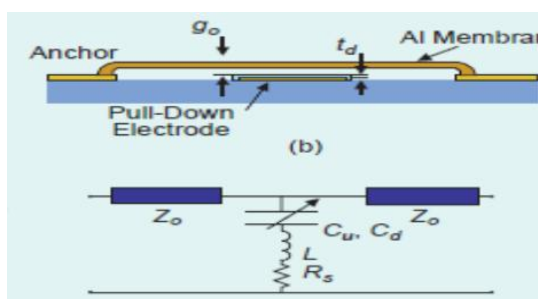

Fig-1: MEMS Shunt switch [2]

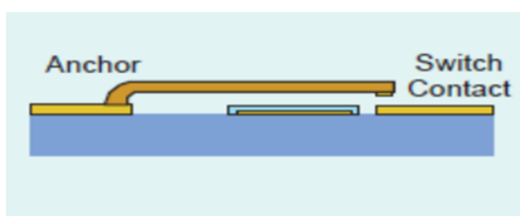

Fig-2: MEMS Series Switch [2]

In the shunt switch, center conductor of the CPW line is biased with respect to the ground to accomplish switch actuation. Resulting electrostatic force pulls the membrane towards the center conductor with a pull-down voltage. Shunt switch in the up position behaves mainly as a small capacitance to ground. In series switch, the movable part touches the fixed electrode if applied voltage reached to V_{PI}. Packaging is the most critical part of MEMS switch design. A large effort was involved in developing wafer scale packaging techniques which are compatible with MEMS switches.

III. RF MEMS SWITCHES AND SWITCH CIRCUITS [6]

This paper presents the new developments in RF MEMS switches and high-isolation switch circuits. The main difference between the broadside and inline designs is that the inline switch passes the RF signal entirely. The inline switches must be fabricated using a thick metal layer (Au, Al, Pt etc.). The analog device MEMS-series inline switch [7] is fabricated using a 7-8 µm thick gold cantilever and is suspended 1 µm above the substrate. The switch is around 75µm long and 30µm wide. Pull-down electrode is defined near the end of the cantilever and is 20 X 35 µm. There are two contact points, each with dimensions 2-m square. The spring constant is 60-100 N/m, which results a switching time of 2-3 µS and pull-down voltage of 60-80 V. The mechanical Q is close to 1, the switch settles quickly upon actuation. The switch resistance is 0.5-1.0Ω and contact force is 100-150 µN. The up-state capacitance is 4-5 fF and measured insertion loss is -0.15 dB up to 20 GHz.

The reliability of the switch is limited by damage, pitting and hardening of the contact area due to the impact force between the beam and the bottom metal. Failure mechanisms are due to organic deposits and contamination in the contact area. Packaging is quite difficult and the only way to limit the cost of RF MEMS switches for applications requiring a large number of units is to develop a wafer-scale solution. Glass-to-glass anodic bondings, epoxy seals, gold-to-gold bonding are several techniques used by industry to package MEMS devices.

Capacitive MEMS shunt switches with a nitride dielectric provide excellent isolation at 20-50 GHz. If more isolation is desired, then two switches can be placed in series. Also, one can build tuned capacitive switches with a relatively wideband response and very low loss.

IV. MATERIAL SELECTION OF RF MEMS SWITCH USED FOR RECONFIGURABLE ANTENNA USING ASHBY'S METHODOLOGY [13]

Material selection for RF MEMS shunt switch with the help of Ashby approach has been discussed in this paper. Ashby approach provides an improvised material selection strategy with less computation. Variety of materials are available to a design engineer, best possible material is needed to be selected. Three primary performance indices i.e. pull in voltage, RF loss and thermal residual stress are used to obtain the desired performance. Observed that the possible materials used for fixed-fixed beam capacitive shunt switch are gold, aluminum, platinum, molybdenum, copper, nickel, alumina, and silicon nitride [8],[9]. The selection chart shows that aluminum is the most suitable material for being used as contact material in RF- MEMS switches. Gold is used only for mass production of switches as it is expensive compared to aluminum.

Ashby selection strategy is used to characterize the best material for desired performance depending upon mechanical, electrical and thermal properties of the material. Material selection using performance indices is achieved by plotting one material property on each axis of selection chart. The design of a component is specified by its functional, geometrical and material properties. The performance indices are

1) Pull in voltage: At the time of actuation, the sufficient pull in voltage is applied between the MEMS Bridge and electrode.
2) RF Loss: It can be reduced significantly by selecting suitable contact material having good conductivity.
3) Thermal residual stress: The MEMS Bridge experiences the temperature change due to self-heating which further causes the change in thermal stress.

V. COMPARISON OF Au AND Au–Ni ALLOYS AS CONTACT MATERIALS FOR MEMS SWITCHES [14]

This paper reports on a comparison of gold and gold–nickel alloys as contact materials for MEMS switches. Gold is commonly used as the contact material in low-force metal contact MEMS switches. The top two failure mechanisms of MEMS switches are wear and stiction which may be related to the material softness and the relatively high surface adhesion respectively. New processing options introduced by alloying gold with another metal to strengthen the material against wear. The properties of Au–Ni alloys were investigated as the lower contact electrode was controlled by adjusting the nickel content and thermal processing conditions.

McGruer et al. [10] showed that ruthenium (Ru), platinum (Pt), and rhodium (Rh) were susceptible to contamination and the contact resistance increased after a characteristic number of cycles. But gold alloys with a high gold percentage shows no contact resistance degradation under the same test conditions. Coutu et al. [11], [12] showed that alloying gold with a small amount of palladium (Pd) or Pt extended the micro switch lifetimes with a small increase in contact resistance.At present, comprehensive investigations of the effects of surface topography, alloy composition and material microstructure on contact resistance and lifetime performance are lacking.

The existing tests have difficulty in duplicating the switch and the contact geometry. The contact geometry has a strong influence on the stress and heat distribution across the contacts and thus, on the switch performance and failure mechanism. The switching degradation test facility utilizes the upper cantilevers from commercial RF MEMS switches and test these against alternative bottom contact materials. The emphasis is placed on a comparison of the alloys and correlations between material properties, contact resistance and contact degradation. Information revealed by the test can be summarized below:

1) Low initial contact resistance was achieved for all the tests. After a number of cycles, a slight decrease of the initial contact resistance can be observed.
2) Pure gold has the lowest number of cycles before electrical failure. Solid solution strengthened Au–Ni alloys shows an increased cycles with an increased nickel composition.
3) Two-phase Au–Ni has the largest number of cycles, while providing a stable and acceptable contact resistance. Compared with the solid solution Au–Ni alloys. Two phase Au–Ni films have an intermediate hardness while yielding a much larger contact area due to the film smoothness.

VI. POWER GATING OF VLSI CIRCUITS USING MEMS SWITCHES IN LOW POWER APPLICATIONS [4]

This paper proposes a combination of CMOS- MEMS switch to power gate VLSI circuits, such that leakage power is effectively reduced. As a result of implementing this power gating method, a standby leakage power reduction of 99% and energy savings of 33.3% are achieved. MTCMOS (Multiple Threshold CMOS) is the most commonly used technique to power-gate low throughput devices even though MTCMOS unfolds many drawbacks such as inefficiency in down-scaling of the technology. The contributions of this paper are as follows:

1) Designing, modeling and simulating an electrostatic MEMS switch using materials that are compatible with CMOS processes.
2) Adapting the actuation voltages of this MEMS switch with CMOS circuit's voltages.
3) Studying the effects of the insertion of the modeled MEMS switch on ground bounce and surge currents.
4) Comparing the leakage savings using MEMS power gating with other leakage reduction techniques.

Copper is selected as contact material. If the applied voltage reaches V_{PI}, the cantilever bends down and touches the fixed contacts. If we release the voltage, it moves up. Calculate the switching time. Obtained 0.1876Ω ON resistance and 1.967nF OFF capacitance from this model [4].

COMSOL Multi-physics software is used for MEMS switch modelling. Three ISCAS benchmarks circuits were selected for these simulations and constructed using 65nm transistors. The circuits are 32 bit parity checker, 4 bit CLA adder (74182) and 4 bit ALU (74181). Compared the leakage power with and without MEMS switch and other power gating techniques too. During these tests, we found many additional parameters such as delay, ground bounce noise, and dynamic power consumption. Table 1 shows the parameters which are used for modeling.

Table-1: Parameter Table [4]

Parameter	Value
Cantilever Length L	430 µm
Dimple gap g	0.9 µm
Air gap g0	2 µm
Width W	20 µm
Thickness t	2 µm
Contact Length L_c	50 µm
Contact Thickness t_c	13.1µm
R_{ON}	0.1876Ω
C_{OFF}	1.966746 nF
V_{PI}	4.5V

VII. FROM TRANSISTORS TO MEMS-THROUGHPUT-AWARE POWER GATING IN CMOS CIRCUITS [15]

In this paper, compared the efficiency of transistor switches and MEMS switches power gating methods, in reducing the power consumption of a design with a certain target throughput. For instance, transistor switches favor smaller and slower architectures and the MEMS switches favor faster and larger designs when the target throughput is low. Compared four different FFT designs with varying complexity in terms of their suitability for throughput-aware design. Experimental results showed that an FFT architecture with 16 parallel units is able to cut the power almost in half compared to a nonparallel architecture, when using MEMS switches in low-throughput applications.

With a MEMS-switched design, a substantial decrease in power is shown. After the comparison, the curves for the parallel architecture and the low-complexity architecture using the transistor switches are also shown as dashed lines in Fig 3. With a very small exception in the high throughput region, the MEMS-switched parallel architecture is the clear winner in terms of power consumption.

As the design gets faster and more complex, the energy efficiency increases and the optimal supply voltage decreases. With the parallel design, the optimal supply voltage is pushed even further lower and power is reduced by 40% across all throughputs. With transistor-switched design, parallelization only increased power in the low throughput range and decreases power at high throughputs.

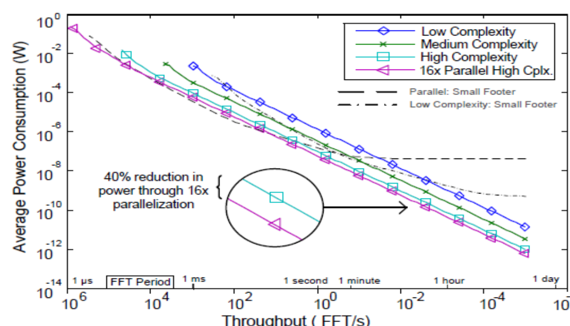

Fig.-3: Average power consumption of MEMS switched FFT architectures

Four FFT architectures that vary in speed and complexity will be investigated. Each performs a 1024 point radix 2 FFT with 32 bit complex numbers. The low and medium complexity implementations use a single real valued 16 bit ALU with a multiplier and an adder, a register bank, and a simple micro program to implement the FFT. The low complexity design uses a 16 bit add/shift multiplier that takes 16 clock cycles, while the medium complexity design uses a high speed booth multiplier that takes a single clock cycle. Finally, a parallel architecture with 16 high complexity core is implemented. As the complexity of the designs increases, the energy per FFT decreases mainly due to the fact that the smaller designs must save intermediate operands in registers and have lower activity factor. The aim of throughput aware power reduction is to maximize power efficiency of a design for a certain target throughput.

This work was done by Synopsis Design Compiler using 130nm technology.

VIII. MEMS BASED POWER GATING FOR HIGHLY SCALABLE PERIODIC AND EVENT DRIVEN PROCESSING [16]

For periodic and event driven applications with long standby times, leakage power control is essential. This paper investigates use of MEMS switches for power gating processors, which allows for highly scalable processing and eliminates leakage power. This paper demonstrates a novel method for power gating using MEMS switches, which have a nearly infinite OFF resistance and very low ON resistance. MEMS switches are currently designed for the RF domain, which requires a clean switch and precludes the easy integration and low cost of CMOS compatibility. The following contributions:

1) Investigated the energy efficiency of a MEMS gated 32 bit processor with respect to technology size and threshold voltage and find that when idle state leakage is eliminated, the leakiest process 32nm Zero V_{TH} is the most energy efficient.
2) Compared the 32nm Zero V_{TH} MEMS gated processor to two state of the art low leakage processors and showed that for a variety of embedded benchmarks, the MEMS gated processor consumes the least amount of power and is capable of much higher frequencies.
3) Due to activation energy, very low cycle periods and very small workloads are not well suited for MEMS-gated processors.

The MEMS gated processor is always energy optimal, regardless of the target throughput. In MEMS gated circuits, the average power consumption approaches 0 as RT approaches 0. This is in contrast to a transistor gated circuit, where the power approaches the idle state leakage power. With non-gated circuits, changing the maximum frequency generally has no effect on energy. With MEMS-gated circuits shows that increasing the maximum frequency can potentially decrease the total energy.

In this paper, investigated the technology node and threshold voltage that minimizes total energy for three benchmark circuits. Also, compared the energy optimal MEMS processor to two state of the art low leakage processors. Energy and timing simulations for a 32 bit in order 5 stage pipeline RISC CPU were performed across four technology nodes i.e. 90nm, 65nm, 45nm and 32nm and four threshold voltages (high, medium, low, and zero). The RTL of an open-source 32 bit in order RISC CPU was synthesized, placed and routed and the combinatorial and interconnect energy as well as the operating frequency were determined. Industry standard cell libraries were used for the 90nm and 65nm nodes, while SPICE and PTM models were used to scale results down to 45nm and 32nm.

IX. ADVANTAGES OF MEMS SWITCHES

MEMS switches offer lower insertion loss, zero power consumption and small size, less weight, higher isolation and very low intermodulation distortion compared to other types of switches. The electrostatic MEMS switch has many advantages such as its high energy efficiency and scalability compared to the magnetic, thermal and piezoelectric switches. Other parameters were also considered while studying these switches such as their ON resistance, actuation voltage, response time, size, and ease of manufacturability. Compared to other power gating techniques like single mode and tri-mode techniques, MEMS power gating ensures less static power, less delay and fast response.

X. CONCLUSION

MEMS are the integration of actuators, mechanical elements, sensors, and electronics on a common substrate using integrated circuit process sequences. The electronics are fabricated using standard IC processing. Micromechanical components are fabricated using compatible ‘micromachining’ processes. In order to build a solid material knowledge base for micro switch designers, correlations among material properties, contacting performance, and failure modes need to be built based on systematic experimental data for different materials. Electrical and mechanical characteristics are strongly considered in the MEMS switch material selection. MEMS switch offers less static power, less delay and fast response time compared to the sleep transistors in power gating.

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