Emulation of MEMS Capacitive Sensor for CMOS Interface Circuit Validation

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Abstract—A MEMS capacitive sensor is emulated on a PCB for quick validation of CMOS interface circuit. In capacitive sensor, capacitance changes with external force; to mimic similar changes, controlled magnetic field is applied on emulated PCB capacitor. The dimension optimizations of interdigital capacitor are performed using CST software. The simulated values are milled on a FR4 sheet to make PCB capacitor. The simulated capacitance values are cross checked by making measurement using LCR meter on PCB capacitor and have a deviation of 6.5%. The complete MEMS emulator consists of PCB capacitor, permanent magnet controlled by screw gauge and gauss meter. A minimum change of 50 aF achieved over a base capacitance 1.9 pF.

Keywords— MEMS sensor, CMOS, Interface circuit.

I. INTRODUCTION

Micro Electro Mechanical System (MEMS) technology has gained wide range acceptance in multiple applications like automobile, medical devices, consumer electronics, military etc. Such systems consist of a MEMS/Micro fluidic flow device and sensor interface circuit integrated on a single die or wire bonded on a single package [1-3]. The later approach is widely accepted by commercial sensor manufacturers, majorly due to low fabrication cost. For development of such two chip systems, both sensor and interface circuits will be required. Design optimizations are carried out in two different simulation software tools *i.e.* Coventor-ware and Cadence. During co-simulation the focus is on the impact of package and wire-bond, under ideal conditions, on the overall system performance for system in package (SIP) implementation [4].

Bond wire length, diameter and material play vital role in capacitive sensor system performance. Various interface circuits have been reported to compensate the parasitic effects, majorly using a common clock to operate capacitive sensor and interface circuit [5-6]. For validation of such circuits, on-chip capacitor banks are fabricated [7]. The capacitor bank mimics the functionality of a capacitive MEMS sensor. The above approach has two major drawbacks. First, the fabricated architecture requires array switches and poly-silicon/metal-insulator-metal capacitors. Usage of a switch severely limits the minimum achievable resolution.

Even if the MEMS sensor is capable of generating "aF" range change but the capacitor bank is not capable of achieving such capacitance changes. Therefore the circuit functionality cannot be ratified to its maximum precision. Second, since the capacitor bank and circuit are implemented on a single substrate. The wire-bond related non-linearity creeps in but is not taken into account. Unwanted effects such as substrate capacitance and switch non-linearity's will also add to the interface circuit performance measurement error.

To validate the functionality of an interface circuit, MEMS sensor will be required. So the circuit designer is invariably dependent on a physical MEMS sensor to endorse the fabricated CMOS circuit. Recently, a MEMS signal emulator is reported in literature to validate a CMOS interface circuit [8]. The emulator consists of analog to digital converter (ADC), digital to analog converter (DAC) and digital filters implemented on field programmable gate arrays (FPGA). This emulator is capable of generating voltages but does not support the generation of "aF" range capacitance changes. Similarly validation of bond-wire impact on capacitive sensor with temperature variation is also not possible with the reported emulator.

The current work proposes a MEMS emulator for capacitive sensors. The emulation is done by a parallel plate capacitor and a permanent magnet to generate capacitance change of "aF" range on the "pF" absolute capacitor. The emulator is connected by a bond-wire or by a low capacitance connector. The designed emulated capacitance is measured with the help of evaluation boards (AD7746/MS3110). The results procured from evaluation board with emulated capacitor are in close agreement with those obtained with in-house fabricated MEMS capacitive accelerometer.

II. MEMS CAPACITIVE EMULATOR

Capacitive emulator consists of inter-digital capacitor and permanent magnets. The absolute capacitance specifications are derived from simulated MEMS sensor. The mechanical simulations, for computation of resonance frequency, are carried out using Coventor-ware and the electrical response, for measuring capacitance change is simulated using MEMS+. Fig. 1 shows the capacitive structure chosen for current work. The simulated base capacitance and change in capacitance are mimicked on MEMS emulator.

The simulated MEMS structure is mimicked by an air gap parallel plate capacitor. The impact of magnetic field generated by permanent magnet on the capacitance of parallel plate capacitor is analyzed through Computer simulation technology tools (CST). The analytical formulation regarding design of inter-digital capacitance is well established and can be found in [1]. Initial geometrical parameters of an inter-digital capacitor for a given value of capacitance can be extracted using the formulations of [9].
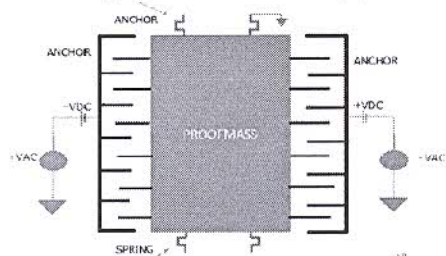

Fig. 1 Capacitive sensor structure.

The geometry of the inter-digital capacitor is created in the CST EM studio software [10] considering loss-free FR4 as the dielectric substrate and the thickness of the fingers of the inter-digital capacitor is taken as 0.1 mm. A potential of 5 V is applied between two electrodes of the capacitor. The low frequency electrostatic solver is used for numerical computation of the electric field distribution and evaluating capacitance matrix between the two terminals of the capacitor. The whole computation boundary was terminated with the open space boundary condition to evaluate free space around the capacitor. Hexahedral meshing with adaptive mesh refinement has been used to eliminate any computation inaccuracy related to the meshing scheme of the capacitor. The layout of the simulated capacitor, applied potential between the electrodes and calculated electric field distribution is shown in Fig. 2. The capacitance value calculated from the postprocessor is 2.034 pF.
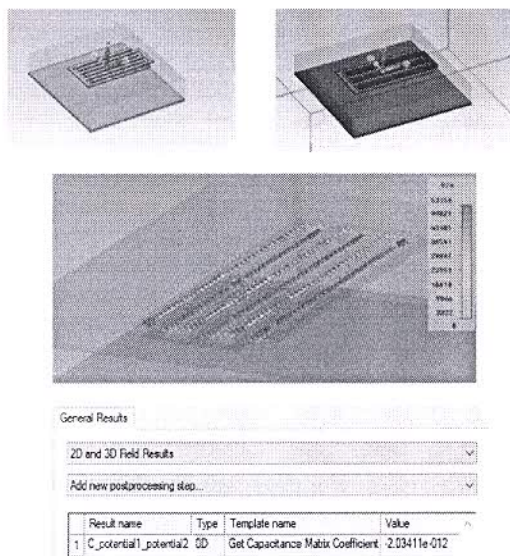

Fig. 2 3D Geometry of the inter-digital capacitor, applied potential between the terminals and corresponding electric field distribution and the capacitance value.

The simulation of the structure having dimension 5mm X 10mm derived from calculation had a base capacitance of 2.034 pF. The calculated and simulated data are in close proximity. The simulated dimensions are milled on a FR4 sheet with a copper thickness of 75μm. The milled capacitor and its dimensions are shown in Fig. 3. The value of milled capacitor is measured using a LCR meter (Model No–Agilent-E4890A). The measured base value of capacitance after probe parasitic compensation was found to be 1.9 pF. The measured value showed a deviation of 6.5 % from CST simulated results. A similar capacitor was used as reference capacitor.

The variation in capacitance is achieved by to and fro movement of neodymium permanent magnets from milled capacitor. Fig. 4 shows the orientation of the milled capacitor and the direction of the movement of the magnet. The screw arrangement helps in generating varying magnetic field strength. Magnetic field interaction with capacitor alters the capacitance value.
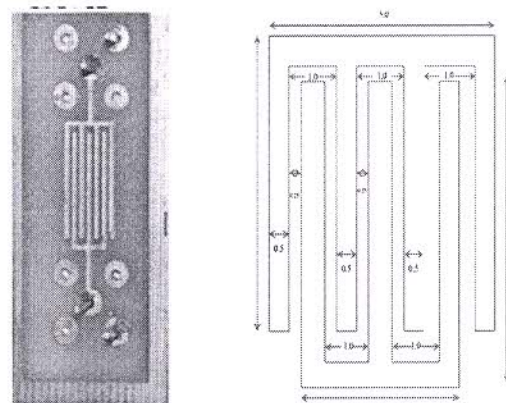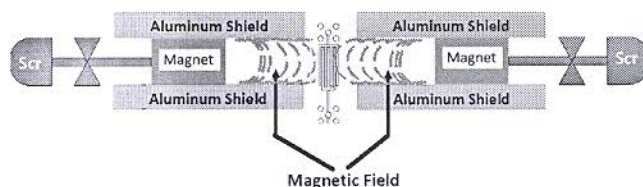

Fig. 3 Milled capacitor on FR4 PCB.

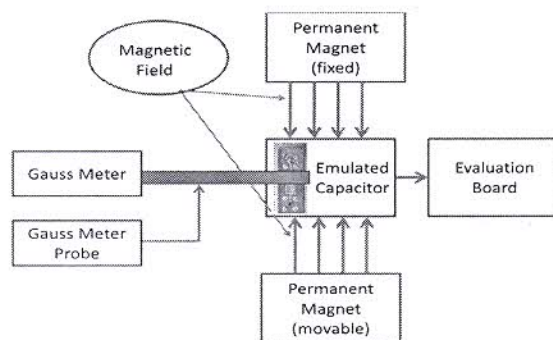Fig. 4 Milled capacitor with permanent magnets.

Fig. 5 Block diagram of complete setup.

The magnetic field reaching the capacitor is measured by a hall sensor. The relative placement of capacitor/emulated sensor, hall sensor and permanent magnet are shown in Fig. 5.

It may be noted here that changes in the capacitance value may also be achieved by insertion of metallic objects in its vicinity and changing the distance of the objects from the capacitor. The change in the capacitance with metallic objects of similar dimensions of the magnets and with similar distance can be experimentally observed and compared. However, this experimental study is being planned to be executed in near future.

For validation of MEMS capacitive emulator, two different commercial interface circuits are selected. The two IC's used are MS3110 and AD7746. MS3110 is a universal capacitive readout IC which is general purpose, ultra-low noise CMOS IC intended to support a variety of MEMS sensors that require a high resolution capacitive readout interface. The MS3110 consisting of a front-end trans-impedance amplifier is capable of sensing capacitance change as low as $4aF/\sqrt{Hz}$. AD7746 is a high resolution, Σ-Δ capacitance-to-digital converter IC. Both circuits are capable of measuring single ended and differential capacitances. On-chip capacitors are used to trim the offset values. AD7746 has on-chip clock to compensate bond-wire related errors. The full scale testing of emulator is possible with the selected two IC's.

III. MEASURMENT OF EMULATOR WITH INTERFACE CIRCUIT

The emulator is placed as shown in Fig. 5. All the measurements are done at room temperature. As the capacitor is placed in open environment, external interference may induce unwanted charges on the capacitor. During measurement, no motors/transformers/high frequency switching devices were kept in close proximity.

Fig. 6 shows AD7746 interfaced with MEMS emulator for measurement. Setup consists of aluminum assembly with fixed permanent magnet. The position of permanent magnet position is controlled with the help of screws. Additionally, notches are made for the placement of the probe of gauss meter, multi-plate capacitor and evaluation board are attached. The developed setup generates approximately 100 Gauss to 2000 Gauss of magnetic field. The emulator and board are connected by a co-axial cable. For parasitic capacitance minimization, on chip oscillator is used to excite the emulator. The output is displayed in-terms of capacitance on a computer. By placing a gauss meter in parallel with emulator, a direct co-relation between applied magnetic field and change in capacitance is established. Fig. 7 shows the variation of capacitance with respect to a decreasing and increasing magnetic field strength.

The result of the assembly is cross verified by same permanent magnet assembly setup with universal capacitive readout IC MS3110IC as shown in Fig. 8 the capacitor is placed in between the permanent magnet setup in differential topology mode for minimization of parasitic capacitance. Measurement of this setup is done using Gauss meter and LCR meter, Fig. 9 show the output of this setup in the form of capacitance.

The Output of MS3110 is given by (1)

$$V_o = Gain * V2P25 * 1.14 * \left(\frac{CS2_T - CS1_T}{C_f}\right) + V_{ref} \quad (1)$$

Where, V_{ref} is a reference voltage 2.25V, $CS2_T - CS1_T$ is a total change in capacitance and C_f is the feedback capacitance [5].

The magnetic field is applied on the multi-plate capacitor than change in capacitance is increase and voltage is also increase with respect to change in capacitance [11-12], Fig. 10 shows the output of MS3110IC assembly and Fig. 11 show the increasing capacitance and voltage with increasing magnetic field.

Although, the interface circuit has a 24-bit ADC at the front end but detection of "aF" range change is not possible due to large absolute error added during conversion. Therefore, an analog output interface circuit i.e. MS3110 is used to measure the change in capacitance. Fig. 8 shows MS3110 interfaced with MEMS emulator, rest of the measurement arrangement remains same as in Fig. 6. The mismatch between the emulator and reference capacitor is compensated by the on-chip capacitor of MS3110 IC. The variation of emulator capacitance with magnetic field is shown in Fig. 9. A large variation of in capacitance is observed over a magnetic field variation of 1000 Gauss. By combining the results of AD7746 and MS3110, a direct co-relation between applied magnetic field strength, change in capacitance and amplified output voltage is obtained. The combined graph is shown in Fig. 10.
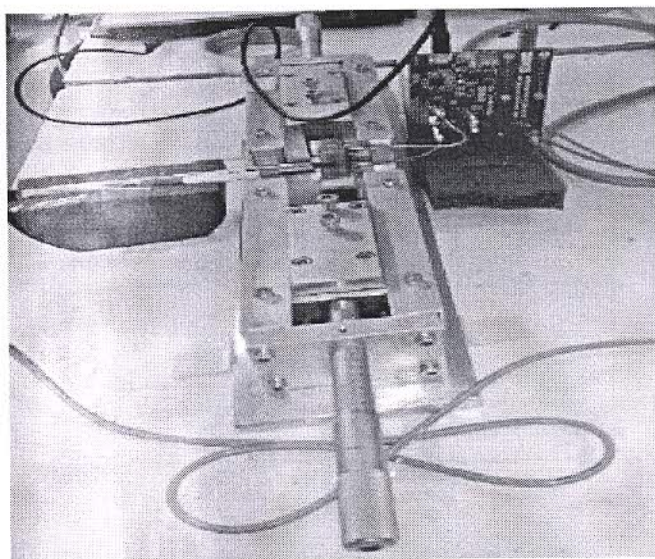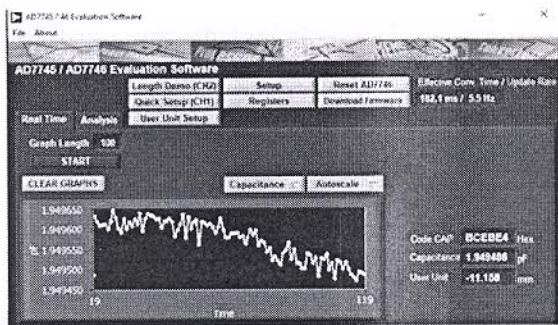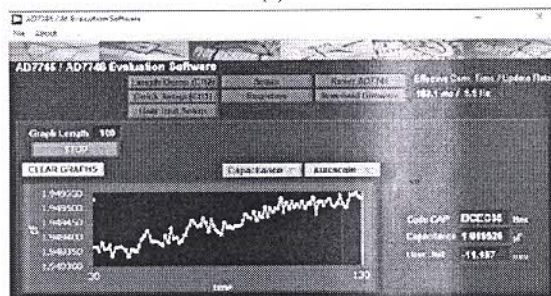

Fig. 6 AD7746 interfaced with MEMS emulator.

(a)

(b)

Fig. 7 Change in capacitance with (a) Decreasing magnetic field strength, (b) Increasing magnetic field strength.
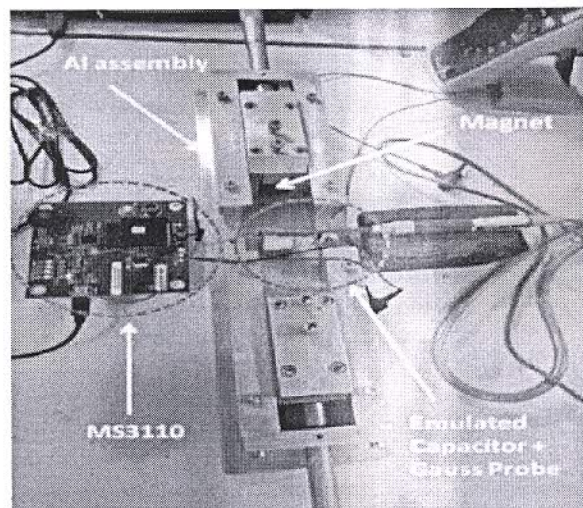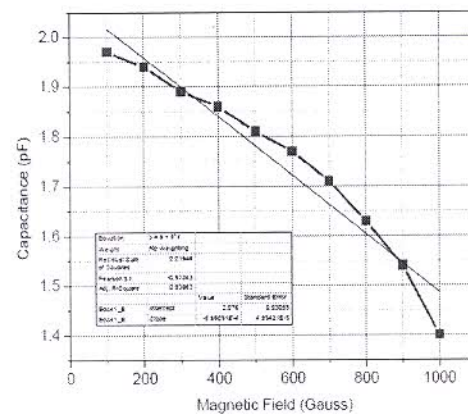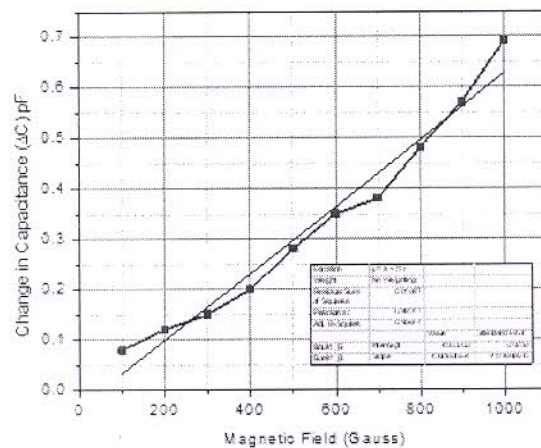

Fig. 8 MS3110 interfaced with MEMS emulator.

(a)

(b)

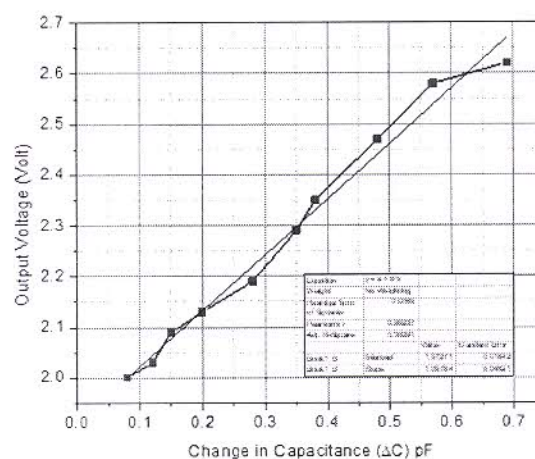Fig. 9 Variation of emulator capacitance with (a) increasing and (b) decreasing magnetic field.

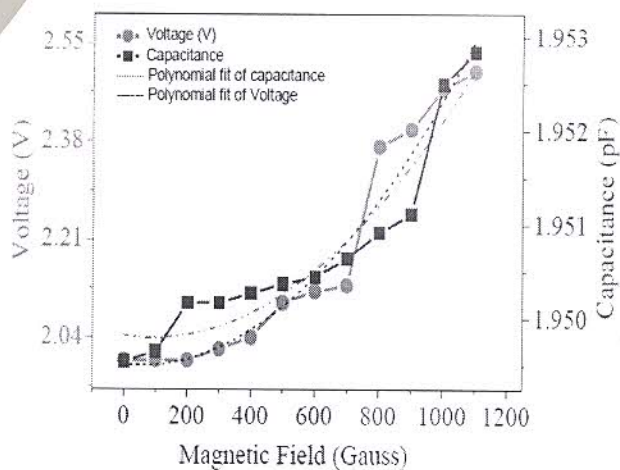Fig 10 Voltage variation with change in capacitance.

Fig. 11 Voltage & Capacitance variation with respect to magnetic field.

IV. CONCLUSION

A MEMS capacitive sensor emulator is developed by milling readily available FR4 sheet. The functional testing of the developed emulator is carried out using commercially available AD7746 and MS3110 IC. The emulator is capable of generating 50 aF range capacitance changes, a range widely used for the validation of CMOS capacitive interface circuits, thereby eliminating the dependency on a physical MEMS sensor. Also, any alteration in the physical sensor is accommodated in the emulated sensor by playing with the area and the strength of the magnets used.

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