MEMS-Based Capacitor Arrays for Programmable Interconnect and RF Applications

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Abstract

We describe a programmable capacitor technology under development at NCSU and its potential application in building programmable interconnect devices useful for system level connectivity functions, phased array beam steering, and RF switching. Crossbars are made from arrays of electrostatically controlled bistable MEMS-based capacitors. These new devices allow faster signaling and consume less power than BiCMOS (or even CMOS) cross-bars. We describe the essential elements of these arrays and present results obtained so far.

1. Introduction

Programmable devices have many applications in system level interconnect functions. In DSP arrays, they can be used to reconfigure the array between different tasks, e.g. to change from FFT processing to QR factorization. In programmable logic systems (such as emulation systems based on arrays of FPGAs) they can provide a better means to program the interconnect than the approach of just using an FPGA itself.

Most attempts to provide system level programmable interconnect have relied on using CMOS switches, for example in a crossbar configuration. Unfortunately, CMOS crossbars do not scale very well. With an on-resistance in the kΩ range, the delays in a CMOS crossbar can be quite significant for large crossbars. For example, a leading commercial BiCMOS 16x16 crossbar device runs at 1.5 Gbps and consumes 4.3 W. Simulations show that a three stage 192x192 crossbar based on the MEMS technology will run at 1 Gbps and consume 1.5 W. The basic MEMS switch element also has potential application in RF switching applications.

In this paper, we describe switch operation, applications, and preliminary results.

2. Approach

The elements of our approach are as follows (Figure 1):

- We use a contactless switch, essentially a programmable capacitor with a (modeled) 200:1 on-off ratio built in a surface MEMS process. A “contactless” switch is used due to our experience in past efforts with the ability of “contacting” switches to survive very large numbers of contact cycles and retain a low contact resistance. The capacitive switch is a band-pass switch, whereas a contacting switch is a low-pass device.
- A programming scheme whereby arrays of switches can be programmed with X and Y

addressing only. Normally MEMS actuators require a control line for each device, which makes building arrays difficult. With our control scheme, arrays can be built more easily. A NxN array now requires 2N control lines instead of the former N^2 lines.

- A transceiver circuit design that takes advantage of the band-pass nature of the MEMS switch and does not require signal streams with an equal ratio of 1's and 0's.
- A multi-stage crossbar architecture designed to take advantage of the switches' capabilities.

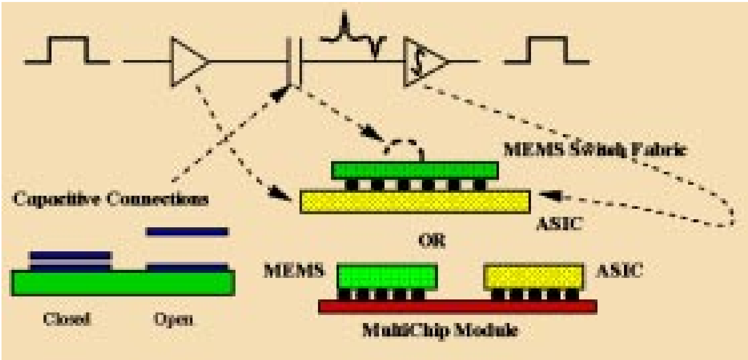

Figure 1. Overall Scheme

Each of these elements will now be explained in turn.

3. MEMS Switch

The cross-section of a single MEMS switch made using MCNC's MUMPS process [2] is shown in Figure 2. The programmable capacitor is formed by the center plates; when they are in close proximity the switch is 'on'. The outer plates form the actuators that pull the capacitor down. A voltage is placed between the actuator plates to form an attractive electrostatic force and thus move the capacitor plate down to the 'on' position. The flexure spring restores the plate up to the 'off' position when the voltage is removed.

In the down 'on' position, the capacitance dielectric consists only of the native oxide of the poly-silicon (about 20 nm). In the up 'off' position, the capacitance dielectric consists of this native oxide and 2um of air gap, forming the 100 times lower 'off' capacitance. The S-parameters obtained from an early switch fabrication, in both the 'on' and 'off' states, are given in Figure 3. These results verify basic functionality, but do not form a satisfactory switch for building large arrays. The results were poor because the MEMS process used to obtain these early switches did not provide sufficiently flat plates and because some of the routing was through high resistance polysilicon. Also, the metal layer provided had poor step coverage. The flatness of the plates greatly affects the 'on' to 'off' ratio of the switch, directly correlating to a small amplitude difference in the obtained S parameters. The routing through high resistance polysilicon produces a large attenuation that is present at all frequencies.

The routing problems have been resolved in current designs and results will be obtained when these samples arrive from fab. The final switches, with an expected 200:1 capacitor ratio and low insertion losses, are in fabrication now using the SUMMiT process[3]. A larger gap is used and the device moves upward to contact plates positioned above in order to decrease the influence of the substrate on device operation.

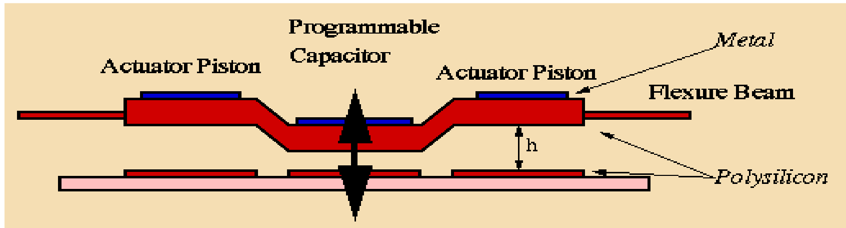

Figure 2. Cross-Section of an individual switch.

The switch which we present results for here each fit in a 50um by 130um region without routing. The bistability property discussed in later sections allows it to be fabricated in processes without active circuitry, allowing lower production cost. Because all signals must travel off-chip, there are significant signal integrity issues raised by the poor electrical properties of the interconnect possible in MEMS processes without multiple metal layers. The interconnect for the devices currently under fabrication in the SUMMiT process will be added as a post-processing step in order to deal with this problem.

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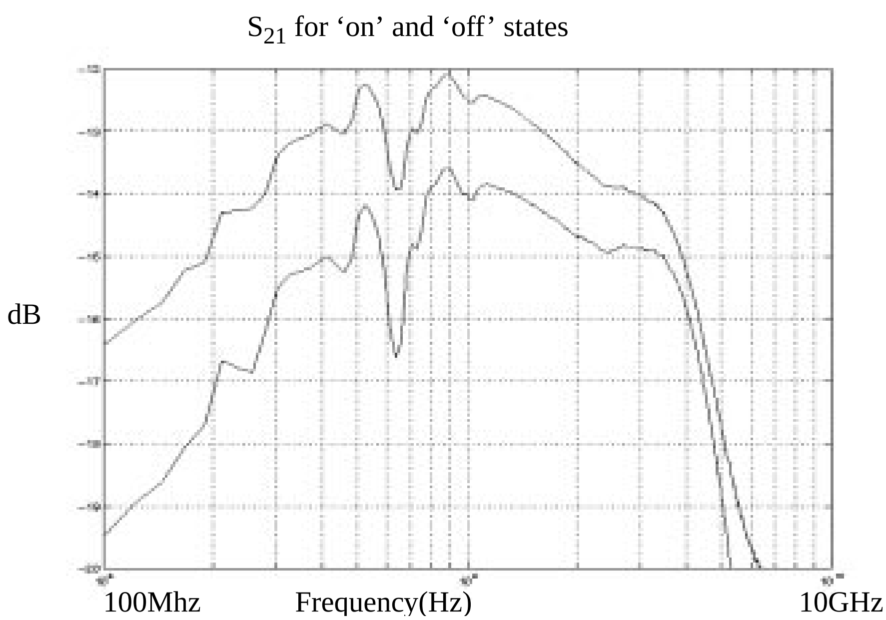

Figure 3. S-parameters of an early switch design, indicating basic functionality. These are NOT indicative of expected final capabilities. The fabrication process and design used for this measurement has evolved considerably.

4. Array Addressing

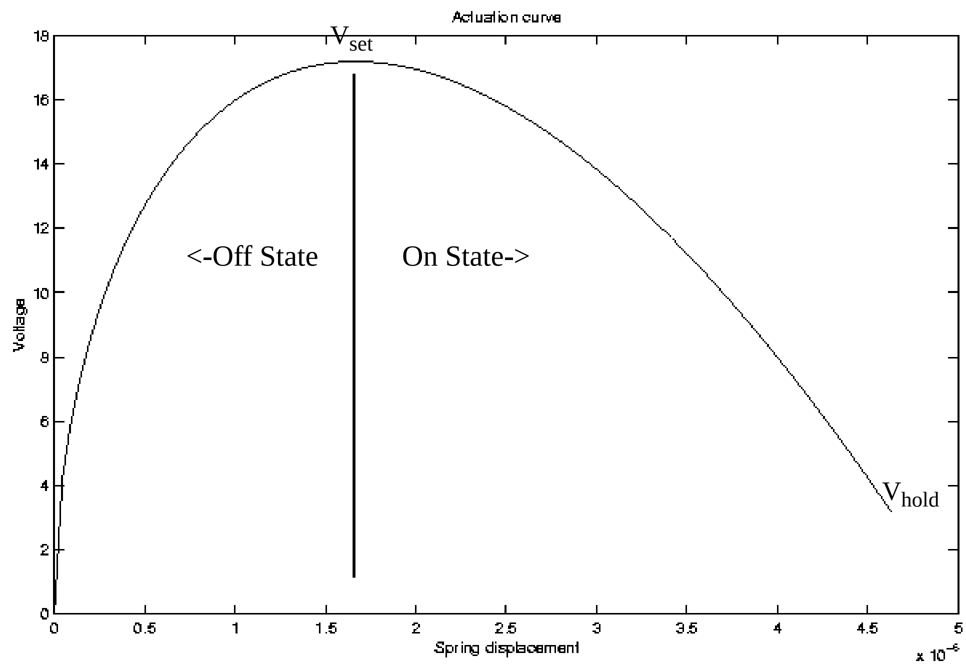

Figure 4. Voltage-Displacement Characteristic using flat-plate model

The relationship between plate displacement and the applied voltage necessary to create a force, balancing the restoring spring force at a given displacement for a basic switch given in Figure 4. It can be observed that for actuation voltages below V_{set} there are two positions. On the right side of the maximum (V_{set}) these positions are not stable; however, the device will move all the way to where physical stops prevent further motion, at maximum displacement. In order to return to the left side of the hump it is necessary to apply a voltage lower than the hold voltage necessary for the maximum displacement ($V_{release} < V_{hold}$). This property can be used to provide array addressability (Figure 5) since applied voltage potential is the difference between the X and Y control voltage levels. For example, control X1 can be set low enough so that all the switches in that row are released (return to their “off” state). The voltage X1 is then set just to a few volts less than V_{set} in Figure 4. Appropriate voltages are then applied to individual columns (Y1 or Y2) so as to bring the desired individual switches down while other switches in the array remain up.

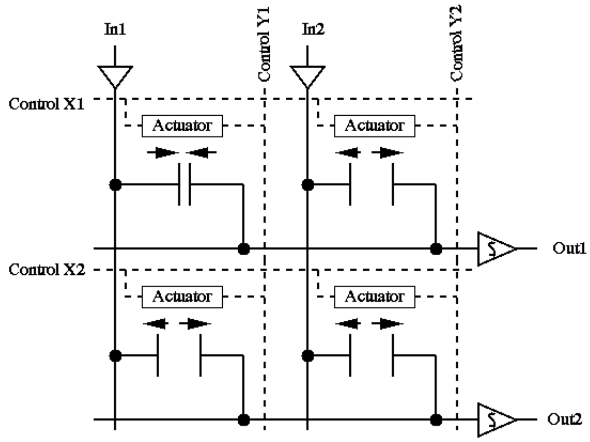

Figure 5. Array Addressing Scheme.

This property has been verified experimentally. Figure 6 shows a optical microphotograph of a the top of 4 switches. The central 'capacitor' plates and the outer 'actuator' plates can be clearly seen on each switch. The restoring springs run parallel to the actuator plates' long edge. This photograph is taken using 546nm light and a Mireau objective lens, resulting in fringe patterns appearing on the sloped spring surfaces for those devices that are 'down'. The corresponding programming voltages are given in Table 1. Since a 5V swing on each line is an appropriate choice, programming can be performed by a 5V capable CMOS process, once a DC bias source of around 20 V is provided. In the photograph on the left in Figure 6 two devices diagonal to each other have been actuated using x-y addressing while leaving the surrounding devices unactuated. Then these devices were released and two neighboring devices on the opposing diagonal were actuated. Optical devices based on the same principles are described in [4], and analog control of device state is described in [5].

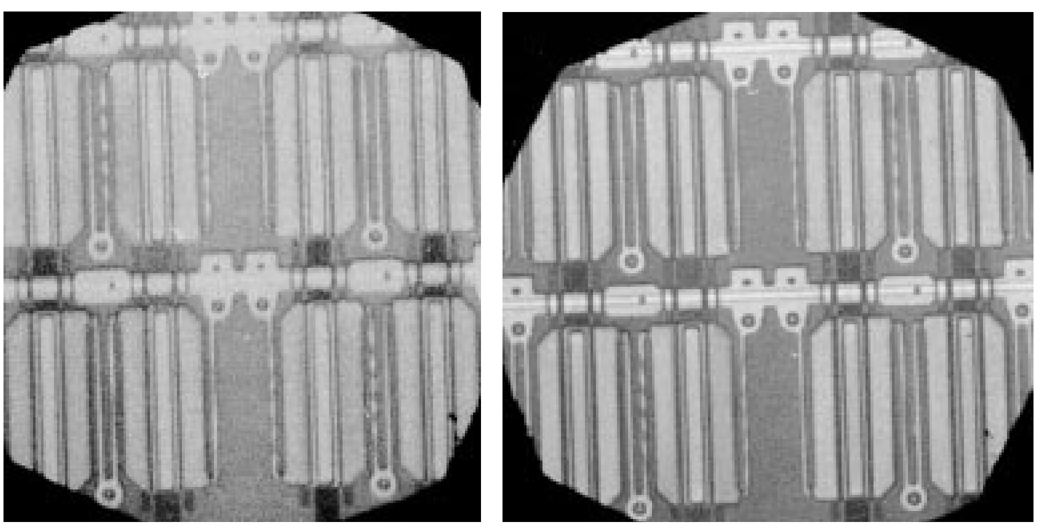

Figure 6. Microphotographs demonstrating array addressability. The vertical springs for the 'down' switches show fringe lines.

Table 1: Control for Figure 6 Devices

Pull-in/Release (Volts)	Column 4	Column 5
Row G	29.7/20.6	29.1/22.9
Row H	30.0/22.6	29.7/22.3

5. Substrate Effects and Differential Signaling

In a case where differential signaling is used, a pair of devices is used at each crosspoint instead of a single device.

If the substrate is left floating, induced charges on it will prevent consistent device operation. Therefore, a bias is applied to the substrate. This can be used to adjust the Pull-in and Release voltages on a chip-wide level. In Figure 7, the pair of curves which slopes upward from left to right are the pull-in and release voltages when the fixed actuation plates are held at 0V and the actuation voltage is applied to the top plate; in the other pair of lines the top plate is held at zero while the bottom plate has the actuation voltages applied. The substrate is biased so that distance between the lower of the upper pair of lines (the pull-in voltages) and the upper of the lower lines (the release voltages) is maximized. This region is the range of voltages at which both devices will retain their state if one pair of control signals has the higher voltage on the moving acutation plates, while the other has the higher voltage on the fixed actuation plates.

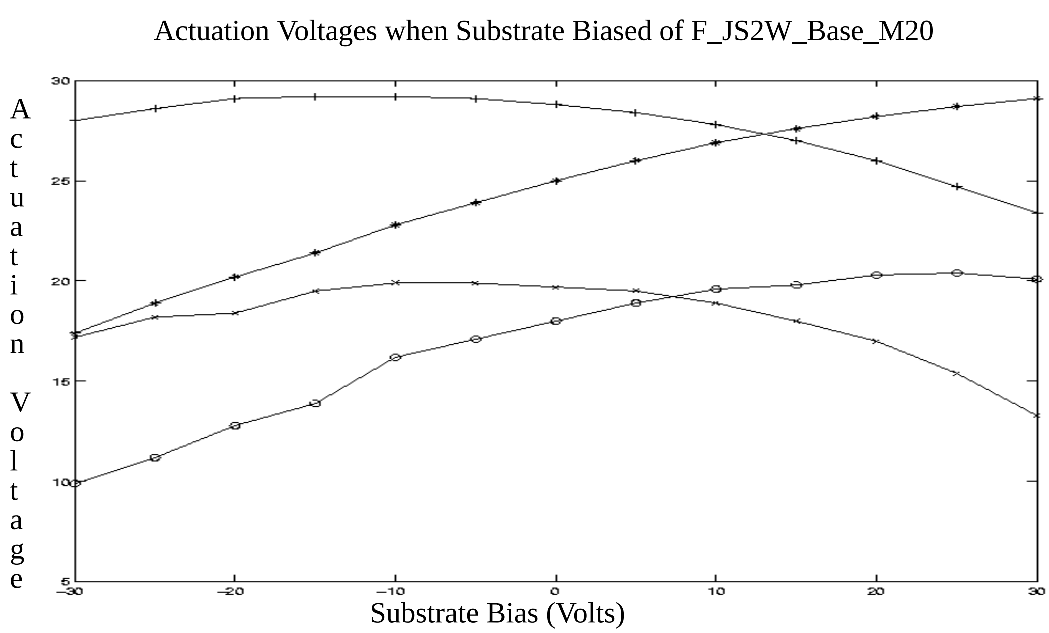

Figure 7. Substrate Effects on Pull-in and Release voltages

6. Transceiver Circuits

The receiver circuits are single-sided circuits, adapted from differential circuits originally designed for capacitively coupled applications [1]. The differential topology used in [1] requires no encoding of the signal because it uses quantized feedback to counteract the “dc wander” effect of a high-pass circuit. The single-sided version that we have developed has the advantage of lower power consumption and, most importantly, a smaller MEMS array with half the devices otherwise required. The first design, simulated in a 0.5um CMOS process, and nominal process conditions, shows a maximum data rate of 1.2Gb/s for NRZ data patterns greater than 500 mV_{pp}. This receiver requires no encoding, and has a power consumption of 2.5 mW. Eventually this design will be modified for a 0.35um process, in an effort to further decrease power consumption and increase speed. An example of the single-sided receiver developed is shown in Figure 8.

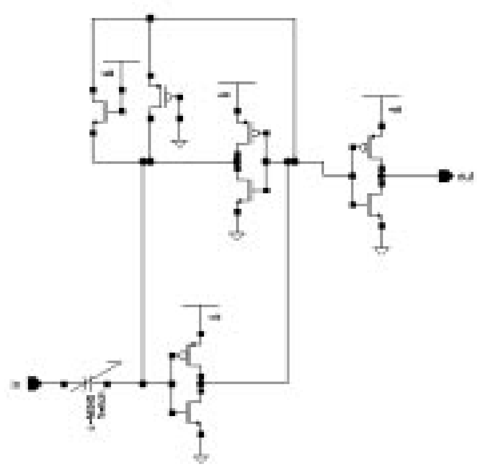

Figure 8. Single-sided Receiver Circuit Topology

Current driver topologies are simple inverters with fast edge rates in an effort to transmit as much energy as possible across the coupling capacitor.

7. Switch Architecture

The switches can be used in many ways. For example, they may be used singly, as with antenna duplex circuits; in small arrays, for phased array systems; or in large arrays to form a crossbar for digital signals. A three stage CLOS network [6] makes most sense for the crossbar because large arrays will most likely exhibit high loss characteristics at the expected on-off ratios and due to the parasitic capacitances of the actuation controls. We have modeled and simulated a 3-stage 192x192 crossbar based on the designs above using stages of 6x11, 32x32, and 11x6. The simulations predict a data rate of 1 Gbit/s, and a power consumption of 1.5 W, and a latency of 1.5ns using a 0.35um CMOS process at 3.3V for active circuitry. This is considerably better than the best commercial BiCMOS 32x32 crossbar.

8. RF Applications

Several MEMS-based architectures are possible at RF frequencies [7]. The devices can be used to build switched attentuators, phase shifters, analog single multiplexers, and high-Q programmable capacitors. The main advantages of MEMS-based devices are their extremely low power consumption (zero after actuation) and their inherent linearity. When the power consumption of MEMS based switches is compared to PIN diodes the differences are impressive, but our demonstrated MEMS switches still need performance improvements to be a practical substitute for PIN diodes.

There are also some uses at lower frequencies for analog applications [7]. Banks of MEMS devices can be used to build programmable filters for portable communications applications. In this application, again because of their extremely low power consumption, MEMS switches can extend the operating period of battery powered transceivers. Figure 9 provides an example of how MEMS based actuators can be used to build switched attenuators [8].

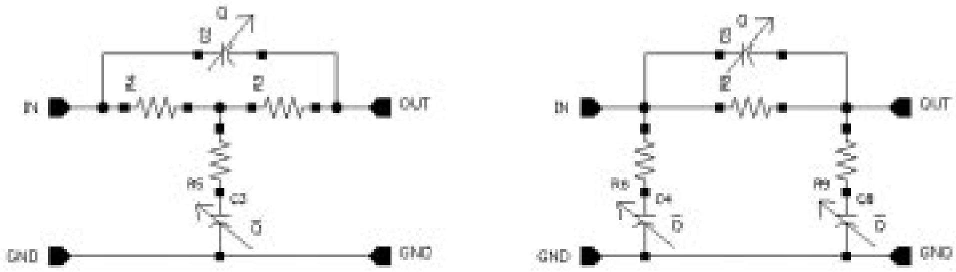

Figure 9. Switched T- or Pi-attenuator configuration.

Switches operating on slightly different principals, mainly conductive coupling, have been developed [9]. These devices perform extremely well, but they don’t operate with the bistability necessary for the reasonable control of a large array.

9. Reliability

The reliability of MEMS devices may seem a concern because of the mechanical element. However, in the case of our devices, where capacitive coupling is used, the fatigue exhibited by MEMS devices using conductive coupling is not an issue. Mechanical reliability tests of other MEMS devices have exceeded 65 billion cycles without fatigue [9]. However, no mention of AC signal performance was mentioned after this high duration of cycles. Tests of mechanical contacting relays in the past have consistently exhibited degradation in AC performance after high cycling. Currently our tests have been limited to approximately 50 million cycles with no mechanical fatigue. AC performance tests have not yet been performed, but due to the contactless nature of the devices no AC performance degradation is expected.

10. Conclusions

An approach to building arrays of ‘contactless’ MEMS switches is described and early results indicated. These switches can be used individually in duplex circuits, in small arrays, for phased array applications, and in large arrays for digital crossbar switching. Currently, prototype switches are being fabricated that should provide a 200:1 capacitance ratio in the frequency range of interest.

Acknowledgments

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References

[1] Gabara and Fischer, Capacitively Coupled and Quantized Feedback Applied to Conventional CMOS Technology, IEEE JSSC, Vol. 32, No. 3, March 1997.

[2] http://mems.mcnc.org/mumps.html

[3] http://www.mdl.sandia.gov/Micromachine/

[4] D. A. Winick, B. E. Duewer, S. Palchaudhury, and P.D. Franzon, "Performance evaluation of micromechanical binary phase-only holographic optical elements," *47th Electronic Components and Technology Conference*, pp. 419-424, Components, Hybrids, and Manufacturing Technology Society, IEEE, (San Jose, CA), May 1997.

[5] David Winick, Bruce Duewer, Som Chaudhury, John Wilson, John Tucker, Umut Eksi, Paul Franzon, "MEMS-Based Diffractive Optical Beam Steering Technology" *Miniaturized Systems with Micro-Optics and Micromechanics III*, Vol. 3276. January 1998.

[6] C. Clos, "A Study of Non-Blocking Switching Networks", *Bell System Tech.* J 32, 406-424 (1953).

[7] J.M. Wilson, B.E. Duewer, D.A. Winick and P.D. Franzon, "Tunable Capacitor Arrays", *Proceedings IMAPS Wireless Communications Conference*, Nov. 1998.

[8] J.S. Joshi, "Switches and attenuators", *MMIC Design*, Chapter 8, IEEE Press, 1995.

[9] M.F. Chang, Y. Qian, T. Itoh, P.D. Tseng, J.J Yao and R. Mihailovich, "Micro-Electro-Mechanical Systems (MEMS) for RF and Microwave Applications", *Proceedings IMAPS Wireless Communications Conference*, Nov. 1998.