Design of MEMS Based XOR and AND Gates for Rad-Hard and Very Low Power LSI Mechanical Processors

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Abstract— Design and calculations for a novel MEMS based logic gate (XOR and AND) is presented. Applications include computational circuits that require low operational power consumption (leakage current & power <10⁻⁹ A, <1μW), low operational voltage (~2V), and harsh environment (radiation hard and high temperatures) operations. The device relies on an innovative Si₃N₄/PolySi cross-bridge platform with patterned metal (W) contacts to form single device logic gates. These functional structures reduce device count (6-14 for a single logic gate in the preceding configuration) leading to denser circuits, improved reliability, better speed and fabrication yield. We examine Si₃N₄, PolySi, and W as bridge materials and the resulting gate speed and transition voltages. XOR and AND gates are specifically discussed.

I. INTRODUCTION

NEMS switches have found interesting applications in a wide gamut of areas ranging from processors, power management in scaled VLSI, programming interconnects in FPGA’s to biomedical devices prolonging implanted battery life and other applications in harsh environments where CMOS based devices cannot operate [1-10]. One such case includes that in the presence of ionizing radiation (I-R) in troubled reactors like Chernobyl and Fukushima or high temperatures. The need for specialized electronics in these cases is paramount as in typical cases the silicon channel in CMOS becomes highly conductive due to lattice defect generation caused by I-R radiation over prolonged exposure [4]. Space applications also require radiation-hard devices and materials. In some electronic materials such as SiC, the energy required to produce lattice defects is high enabling these materials to withstand I-R longer than Si. In other materials such as InP, defects heal at relatively low temperatures enabling them to recover quickly.

NEMS/MEMS devices are based on mechanical switches that are inherently insensitive to I-R. The ionizing radiation causes lattice defects in these devices but these defects do not alter their characteristics the way they affect channel resistance in CMOS. Eventually large defect densities created over extended I-R exposure leads to embrittlement and changes in mechanical properties that may affect NEMS/MEMS electrical characteristics. NEMS/MEMS devices also have very low leakage power making them very desirable in biomedical implant devices or other applications requiring very long battery lifetime.

At the very core of MEMS based devices are circuits based on MEMS switches. Here we discuss the design of a single device MEMS-based logic gate that reaps the benefits of MEMS switches with the existing functionality of combining logic gates creating a scope for improved density, reliability, speed and fabrication yield. The devices are based on a Si₃N₄/PolySilicon cross-bridge platform with metal contacts designed to provide AND or XOR capability from a single actuating structure.

II. FUNCTIONAL STRUCTURE

The cross-bridge platform shown in fig. 1 forms the basis for both XOR and AND gates. Fig. 1 illustrates the electrode design for an XOR gate. Metal traces overlap at the intersection area of the bridges and the bridges are attracted by electrostatic actuation between the gate electrodes.

![Fig. 1: Schematic of MEMS based single device XOR gate](image)

With reference to fig. 1, when both gates are low (“00”), or when both gates are high (“11”) there is no electrostatic attraction. When either one of the gates are high (“10” or “01”) electrostatic attraction causes the drain and source to collapse towards each other and thereby form a contact. This is the XOR function. A minor modification of the electrode design produces similar functionality corresponding to AND gates.
gate (fig. 2 and 3). The fabrication procedure of these devices are discussed in [4]. Other gates such as NAND and NOT can also be realized in a similar manner. An XOR gate can be converted to NOT gate by fixing one of its inputs at “1”. A NAND gate can be produced by NOT(AND) or by using different device structure.

This type of single device logic structure reduces the device count by a factor of 8 for XOR (fig. 4). This results in a reduction in the number of moving parts, and thereby 8 times better reliability, at least 4 times faster gate and proportionately higher fabrication yields.

### III. CALCULATIONS

Based on mathematical models of fixed-fixed MEMS beams calculations on switching time, frequency and pull-down voltages were carried out for various thicknesses of Silicon nitride, polysilicon and tungsten with fixed length (l) and width (w). The results obtained were plotted, as shown in fig. 5 and 6. The operating frequencies were plotted based on a fixed thickness and width, with varying thicknesses to determine a suitable combination for GHz range operation as illustrated in fig. 5(b).

![XOR Gate AND Gate](image)

**Fig. 2:** Cross section of XOR and AND gates.

![Fig. 3](image)

**Fig. 3:** a) Fabricated XOR gate. G1 and G2 are gate electrodes. S and D represent Source/Drain. Gr is the ground electrode used to separate bridges if stuck together b) Fabricated AND gate. S-D will connect only if gate 1a

![Fig. 4](image)

**Fig. 4:** XOR implemented using individual switches require 8 devices each 25 µm$^2$ while our single XOR device requires only 25 µm$^2$ area.

![Fig. 5](image)

**Fig. 5:** a) Switching time vs thickness for fixed length using SiN, PolySi and W used in existing device, $f_0$~MHz range. b) Graph showing potential NEMS dimensions corresponding to GHz range operational frequencies.

It can be seen from fig. 5(a) that for all combinations shown, silicon nitride portrays quicker switching speeds than polysilicon or tungsten. This is mainly due to the large amount of thin film stress built into the layer during deposition. However, it was observed during experimentation that to structurally buttress the silicon nitride throughout the extensive
fabrication process a composite structure of polysilicon and silicon nitride was preferable – the nitride being placed on the inner side of the cross-bridge platform. Although the current device operates at MHz range frequencies, with miniaturization GHz range devices is a possibility as shown by Fig. 5(b).

Other calculations on actuation voltage were also carried out based on a similar model used for the calculations discussed previously. These results are illustrated in Fig. 7. Once again, sub-1V actuation is a possibility with miniaturization. Our results are currently comparable to existing CMOS equivalent circuits.

I. Results

The switching characteristics in ambient conditions are provided in fig 7(a). The results indicate a portion of the switching operation of the device over its entire lifetime (~10⁹ cycles). The switching voltage remains at approximately 1.5-2V throughout indicating stable operation at this voltage. Also, the device has very low leakage power characteristics, less than 1µW, as shown in fig 7(b).

In addition, harsh environment operation (high temperature) was investigated in a specially designed environmental chamber that precisely controlled temperature, pressure and humidity. At high temperatures of 409K the operating voltage was only slightly shifted to lower voltage (fig. 8) indicating temperature stability of the device.

The results of operation in high radiation environment, given in fig. 9, reveal that during exposure to prolonged (120 min.) 90kW ionizing radiation environments, solid state devices, such as MOSFETs, fail due to large increase in charge carriers and thus leakage current. The Iᵩₛ current increases by an order of magnitude after 120mins, thereby; the gate fails to maintain control over the MOSFETs on/off states. However, MEMS switches continue to function with clearly defined on/off states even after prolonged I-R. However, the ionizing radiation introduces lattice defects in these devices which do not contribute to electrical characteristics changes in the way CMOS is affected. Over time, however, the buildup of large defect densities leads to embrittlement and changes in mechanical properties that may affect NEMS/MEMS electrical characteristics.

At 90kW the typical neutron flux was recorded at approximately 3x10¹² neutrons/cm²-s with energy range varying between 0.025eV to 10MeV – most of which are at 1MeV. It is known that alpha particles do not exist in the reactor core apart from inside the fuel element. The gamma radiation flux was higher than 10¹³ gamma/cm²-s with energy ranging from ~keV to 3MeV. Beta radiation was recorded at 10¹⁳ beta/cm²-s with typical energy of 100keV to 1500keV. These I-R experiments were carried out at the TRIGA reactor at the University of Utah.
CONCLUSION

The design and operating principle of single device functional MEMS/NEMS structures (XOR and AND) was presented. Such novel structures greatly decrease device count to design functional MEMS based circuits and increase reliability and yield. A discussion on switching frequency voltage and related calculations were also provided. In addition, operational characterization data showed a ~2V actuation, <1µW leakage power consumption and lifetime of ~10⁹ cycles. Harsh environment operation at elevated temperatures (409K) and high ionizing radiation environment testing also revealed successful and reliable operation of these MEMS devices over CMOS equivalents.

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REFERENCES


Fig. 9  a) MOSFET $I_{ds}$-$V_{ds}$ at 1 W ionizing radiation, 1min. b) its $I_{ds}$-$V_{ds}$ at 90 kW ionizing radiation, 120min. c) I-V of XOR gate between drain/gate2 and source/gate contacts. Blue trace is the initial I-V at 1 W, Green curve is after 60 minutes and the Red curve is after 120 minutes in 90 kW radiation.