Microelectromechanical (MEM) switch and Inverter for Digital IC applications

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Abstract—**Microelectromechanical (MEM) switch and MEM switch-based inverter was proposed and fabricated using a CMOS-compatible poly-Si surface micromachining process. The key concept is developed that the MEM switch-based inverter with the same implementation as CMOS inverter has a high noise immunity and low power dissipation because the MEM switch can clearly eliminate the leakage current when the device is off. The fabricated MEM switch showed ideal on/off characteristics with a sub-threshold swing of 4 mV/decade, an essentially zero off current, and a very high on/off current ratio over 10^5 and also the MEM switch-based inverter showed an ideal voltage transfer characteristics.**

I. INTRODUCTION

According to Moore's Law, the number of transistors on an integrated circuit for minimum component cost doubles every 24 months, and it has been the guiding principle for the semiconductor industry over the past four decades. The steady scaling of dimensions of complementary metal-oxide-semiconductor (CMOS) devices has been a significant stimulus in the digital revolution. However, this aggressive scaling beyond sub-100nm in conventional CMOS devices to increase both the density and the speed is rapidly approaching physical limitations such as short-channel effects, gate oxide tunneling and power dissipation [1, 2] These fundamental limitations have led to pessimistic predictions of the "End of Moore's law" for the semiconductor industry. On the other hand, the rapid scaling of CMOS devices is accelerating the introduction of new technologies that will overcome physical limits and have robustness under harsh environments for various applications. These new technologies are expected to keep Moore's law alive.

Recently, mechanical-type logic devices using micro-electro-mechanical system (MEMS) and nano-electro-mechanical system (NEMS) technology have been reported as alternative devices to meet the aforementioned requirements [3~9]. Logic devices based on MEM [3~7] and NEM [8, 9] switches are a potential substitute for CMOS and CMOS-based logic devices because of their high switching speed, low actuation voltage, low power consumption, and insensitivity to temperature variation and radiation error. However, it is difficult to assemble MEM/NEM switch-based logic devices into arrays owing to the complexity of their structures and fabrication process. We believe that this kind of mechanical-type switching and logic devices is worth pursuing due to its excellent switching characteristics.

In this paper, microelectromechanical (MEM) switch and MEM switch-based inverter have been studied as a preliminary step to fabricate MEM switch-based logic devices for digital IC applications and fabricated, and their fundamental characteristics were investigated.

II. DEVICE STRUCTURE AND FABRICATION

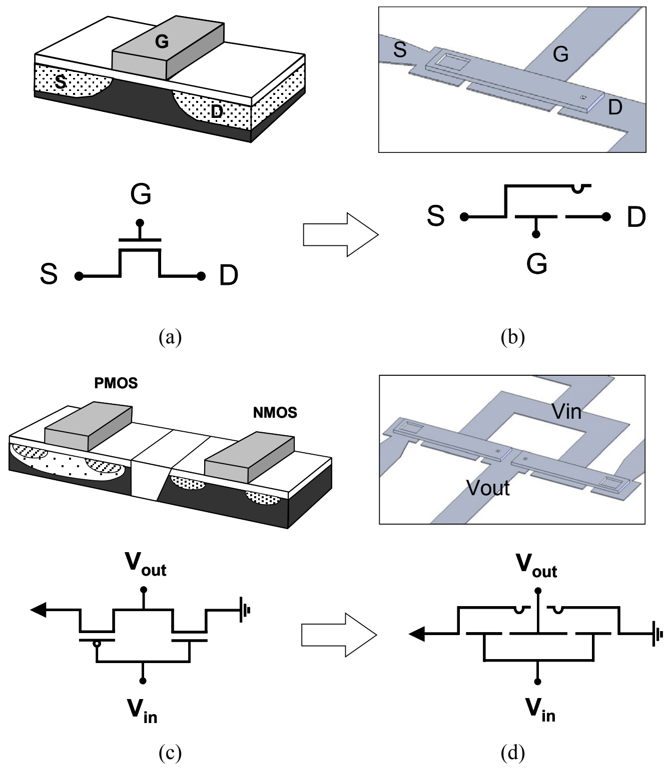
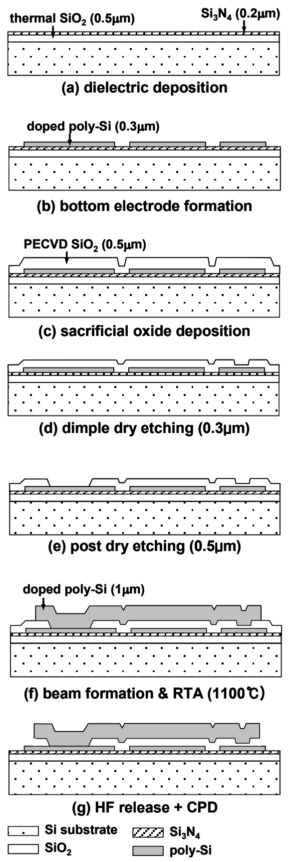
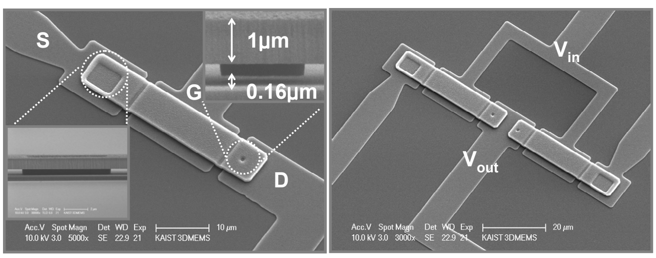


Fig. 1 Schematic diagram and equivalent circuit symbol of the (a) MOSFET (b) MEM switch (c) CMOS inverter (d) MEM switch-based inverter.

The MEM switch-based inverter is simply composed of two MEM switches and its configuration looks very similar to that of conventional CMOS inverter, as shown in Fig. 1. However, it is expected that the MEM switch-based inverter has a larger noise margin and lower power consumption than the CMOS inverter because it uses the MEM switch instead of metal-oxide-semiconductor field-effect transistor (MOSFET), which inevitably suffers from sub-threshold leakage current at the off state. The key concept of the proposed inverter is that the MEM switch can clearly eliminate the leakage current when the device is off to the mechanical disconnection between the source and the drain. Also, only the voltage difference between the source and the gate makes the actuation of the MEM switch.



(a)

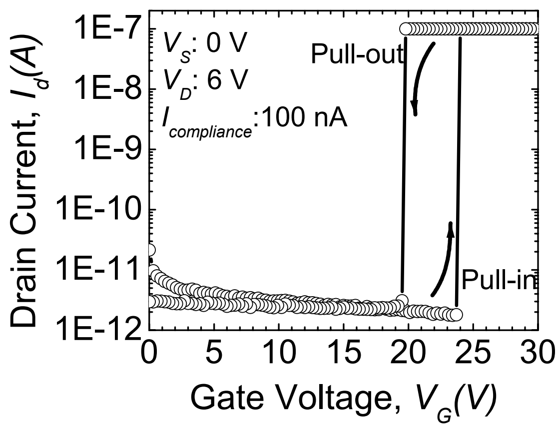


(b)

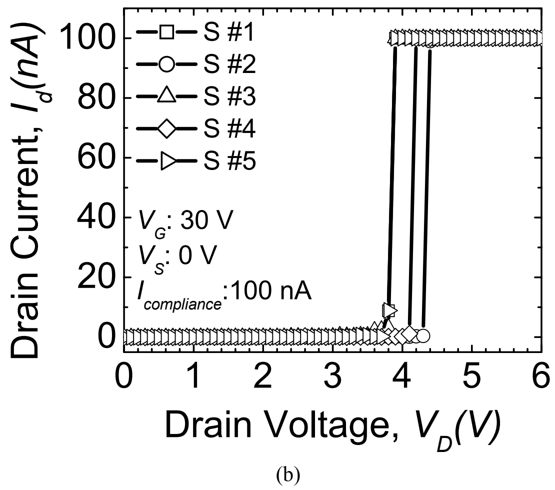
Fig. 2 (a) Simplified fabrication process and (b) SEM side-view of the fabricated MEM switch and MEM switch-based inverter. The MEM switch size is 30 μm long by 8 μm wide with a thickness of 1 μm.

Fig. 2 (a) illustrates the simplified fabrication process utilizing CMOS-compatible poly-Si surface micromachining technology. Here, thermally grown silicon dioxide film with a thickness of 0.5 μm and silicon nitride film with a thickness of 0.2 μm deposited by plasma-enhanced chemical vapor deposition (PECVD) were formed respectively in order to make the insulating layer. Silicon dioxide film with a thickness of 0.5 μm was deposited by PECVD as a sacrificial layer and a doped poly-Si film with a thickness of 1um deposited by low pressure chemical vapor deposition (LPCVD) is used as a structure layer. The inductively coupled plasma (ICP) etching was employed to make the dimple and the post, respectively. After a rapid thermal annealing (RTA) process for relaxing the residual stress gradient of the doped poly-Si film, HF release and critical point drying (CPD) process are finally conducted so as to release the sacrificial oxide and also prevent the stiction between the dimple and the drain.

III. RESULT AND DISCUSSION



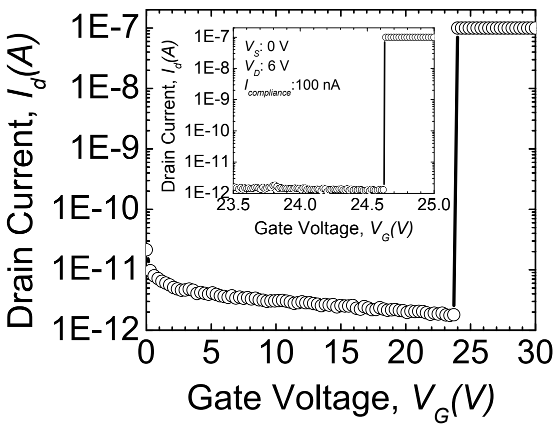
(a)



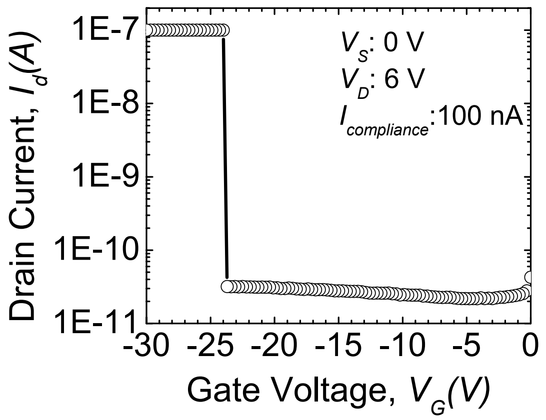
(b)

Fig. 3 (a) V_G versus I_D characteristics for the fabricated MEM switch (b) V_D versus I_D curve to determine a certain minimum V_D

As shown in an inset of Fig. 3(a), the MEM switch has a hysteresis curve with a pull-in and pull-out characteristic which is common in MEM switches. The pull-in voltage (V_{PI}) is about 24 V and pull-out voltage is about 20 V. The electrical current abruptly flows between the source and the drain because the MEM switch actuate electrostatically if the gate voltage larger than the pull-in voltage is applied. In these measurements, since a native silicon dioxide always exists on the surface of the poly-Si film, we applied a drain voltage higher than a certain minimum value (about 5 V in this case) to overcome the contact resistance due to the thick native silicon dioxide between the dimple and the drain as shown in Fig. 3(b). Also, a current compliance of 100 nA was used to prevent in-use stiction in an air ambient.



(a)



(b)

Fig. 4 V_G versus I_D characteristics for the MEM switch with (a) the positive V_{PI}=24 V (b) the negative V_{PI}=-24 V. Inset show V_G versus $logI_D$ plot for the sub-threshold swing.

The electrical performance of the fabricated MEM switch is shown in Fig. 4. The positive pull-in voltage to turn on the MEM switch by using electrostatic actuation is about 24 V, which is similar to a threshold voltage of n-MOSFET to turn on. The negative pull-in voltage (about -24 V), like the threshold voltage of p-MOSFET, corresponds with the absolute value of the positive pull-in voltage because only the voltage difference between the source and the gate makes the actuation of the switch. Consequently, only one MEM switch simultaneously offers the symmetrical positive and negative pull-in voltage. The fabricated MEM switch has ideal on/off characteristics, namely an essentially zero off current, a near zero sub-threshold swing (SS<4 mV/decade), and a very high on/off current ratio exceeding 10^5 as shown in the inset of Fig. 4(a). These electrical characteristics of MEM switch play an important role in high noise immunity of the MEM switch-based inverter.

Fig. 5 plots the measured resonant frequency of the MEM switch using a laser doppler vibrometer (LDV). The first mode resonant frequency is measured to be about 300 kHz corresponding to a switching time of 3 μs.

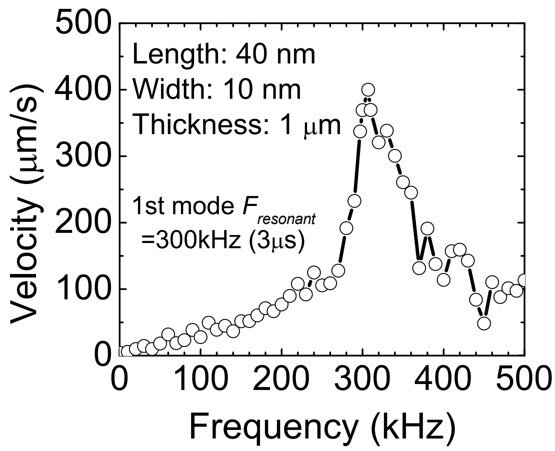


Fig. 5 Measured resonant frequency of the MEM switch.

Fig. 6 plots the voltage transfer curve (VTC) of the MEM switch-based inverter, which shows the ideal voltage transfer characteristics because the MEM switch don't almost have leakage current at the off state. Then, MEM switch-based inverter have larger noise margin than CMOS inverter.

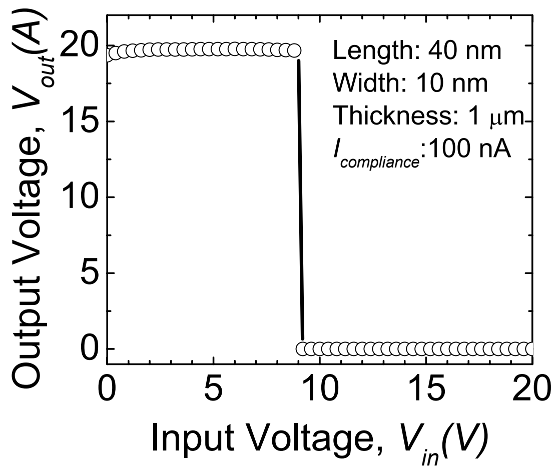


Fig. 6 VTC curve of the fabricated MEM inverter.

IV. CONCLUSION

The newly-proposed MEM switch-based inverter was developed wherein n-MOSFET and p-MOSFET of CMOS inverter is replaced by a MEM switch that shows no leakage current due to an excellent on/off performance with a sub-threshold swing of 4 mV/decade, an essentially zero off current, and a very high on/off current ratio over 10^5. Fortunately, most MEM switches with electrostatic actuation can be scaled down with a factor of α, thereby yielding a decrease in the pull-in voltage and an increase in the resonant frequency by α. For example, if a fabricated MEM switch is scaled by 100 times, being nano-size, it will have a pull-in voltage below 1 V and a switching time below 1 ns. As such, it can show scalability comparable with a MOSFET with respect to the power and the speed. Also, it can be expected that we will be able to make logic circuits on any substrate, even on a polymer substrate because the MEM switch-based inverter is only mechanically operated. This letter shows the feasibility of the MEM switch and MEM switch-based inverter as a potential substitute comparable with CMOS-based logic device.

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