A MEMS-Based Charge Pump

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Abstract

A micro-scale mechanical charge pump, cf. Fig. 1(a), comprising a circuit of micromechanical resonant switches (a.k.a., resoswitches) has been demonstrated that generates 3V and 9V from 1V and 3V power supplies, respectively, using a 2-stage design; and 6V from 1V supply using a 5-stage design; all while avoiding the diode voltage drop and breakdown voltage limitations of conventional CMOS-based charge pumps. This MEMS-based charge pump additionally accepts a much wider input voltage range than semiconductor technology and obviates the need for custom high voltage CMOS for applications where large voltages are needed, e.g., MEMS-based timing references [1], thereby allowing the use of virtually any CMOS process for a wide variety of MEMS-based products.

Keywords: MEMS, charge pump, resonant mechanical switch, resoswitch, high voltage, resonator, micromechanical

Introduction

The reduction of power supply voltage with each new generation of CMOS technology continues to complicate the design of charge pumps needed for high voltage applications, such as the increasing number of MEMS-based ones, e.g., gyroscopes, timing oscillators, gas sensors, etc., that integrate into systems alongside transistors chips. Indeed, aggressive scaling in CMOS leading to lower dielectric and junction breakdown voltages have forced the use of customized CMOS processes, e.g., with increased gate oxide thicknesses and/or added deep-n-wells [2]. Clearly, advances in transistor technology are going in the opposite direction of the needs of high voltage MEMS applications.

Well, if MEMS benefits from such large voltages, then they should have no problem handling such voltages. So as long as we’re already using MEMS, why not also use them to generate their own needed voltages? This work does just this by exploiting the longevity and low actuation voltage attributes of recent resonant micromechanical switches (a.k.a., “resoswitches”) [3] to replace the diodes or transistor switches in a Dickson charge pump topology, cf. Fig. 1(b) [4], and realize a MEMS-based charge pump, cf. Fig. 1(a), that avoids the turn-on voltage and breakdown limitation of CMOS. With much higher breakdown voltages than transistor counterparts, the demonstrated MEMS charge pump implementation should eventually allow voltages higher than 50V desired for capacitive-gap transduced resonators that presently dominate the commercial MEMS-based timing market [1].

Mechanical Circuit Design and Operation

Fig. 2 describes the resoswitch device used in this work, comprised of a folded-beam-supported movable shuttle driven electrostatically to impacting at the switch point by a combination of AC and DC voltages applied at the drive electrode. The input DC voltage, i.e., the supply voltage, is applied to the shuttle, and during hot switching this voltage is periodically transferred to the output electrode. When operated under vacuum, the resonance voltages required to actuate this device can be quite small, cf. Fig. 3, which presents measured curves of displacement amplitude versus frequency and drive voltage for a de-bias of 1V. Here, impacting occurs when the drive voltage amplitude is only 0.4V, which is well under a 1V supply.

Although this resonant switch provides low actuation voltage and orders of magnitude better reliability than non-resonant ones [5], it does have the apparent drawback that switching occurs only at its resonance frequency. This work overcomes this seeming limitation via use of gated-sinusoids, cf. Fig. 2, bottom left, to effectively turn switches “on” and “off” at the period of the gate signal. In particular, during half-cycles where the resonance sinusoid is on, the switch impacts, moving charge from one side to other at its contact interface; and during the off cycle, the switch does not move, so transfers no charge and is effectively “open”. The use of this gated-sinusoindent excitations stands to revolutionize the use of resonant switches, since it removes the previously cumbersome restriction to resonance!

Experimental Results

Fig. 4 presents the SEM of one resoswitch device constructed in polysilicon with 2-5nm of Ru deposited by ALD covering its switch contact areas to reduce contact resistance. A second fabrication run also yielded functional electroplated nickel devices coated with Ru ALD in a process that maintains temperatures suitable for integration directly over CMOS.

Fig. 5 presents output waveforms of a 2-stage charge pump, showing boosting of 1V and 3V supply voltages by 3×, to 3V and 9V, respectively. Fig. 6 presents the output waveform of a 5-stage MEMS-based charge pump that pumps the 1V supply voltage to 6V. Given N stages, the output voltage level can very simply be calculated using (1):

\[ V_O = V_{DD} \times (N+1) \times V_{DD} \]

(1)

Conclusions

The MEMS-based Dickson charge pump of this work successfully boosts supply voltages by 3× and 6× using 2-stage and 5-stage designs, respectively. By removing the diode drop and junction breakdown issues of conventional transistor implementations, this MEMS-based charge pump can transfer charge with any input voltage level and can actually achieve ultra-high voltages needed by MEMS devices—something that becomes exponentially more difficult as CMOS continues to scale.

References


Fig. 1 Schematic of (a) a N-stage MEMS-based resonant charge pump; and (b) a conventional N-stage Dickson charge pump.

Fig. 2 Schematic of a micromechanical resoswitch—the building block element of the charge pump depicted in Fig. 1—together with illustrations of the gated-sinusoidal drive signals used to actuate it.

Fig. 3 Measured frequency responses of the resoswitch measured in vacuum for varying resonance input ac voltage amplitudes, showing impacting when the resonance flattens at less than 0.4V peak-to-peak amplitude.

Fig. 4 SEM pictures of the resoswitch used in this work with a zoom-in on the switch contact region.

Fig. 5 Output waveforms of a 2-stage MEMS charge pump with (a) 1.0V and (b) 3.0V input voltages, both showing 3× voltage boosts.

Fig. 6 Output waveforms of a 5-stage MEMS charge pump with 1.0V input voltage indicating a 6× voltage boost.