Y. Lin, R. Liu, W. Li, M. Akgul, C. Nguyen, "A Micromechanical Resonant Charge Pump," in *17th International Conference on Solid-State Sensors & Actuators (Transducers'13). Digest of Technical Papers,* Barcelona, Spain, June 16-20, 2013, pp. 1727-1730. ***(best paper award winner)***

A MICROMECHANICAL RESONANT CHARGE PUMP

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ABSTRACT

A circuit of micromechanical resonant switches (a.k.a., resoswitches) has been demonstrated that mimics the topology of a conventional single stage Dickson charge pump (*cf.* Figure 1) to boost 1V from a DC power supply to 2V while avoiding the diode voltage drop and breakdown voltage limitations of CMOS-based conventional charge pumps. The keys to successful charge pumping are 1) the long cycle lifetime of resonant micromechanical switches, which at 173 trillion cycles (so far), is orders of magnitude higher than non-resonant ones; 2) the use of gated-sinusoid excitation to allow a charging period independent of resoswitch resonance frequency; and 3) the use of resonance operation to lower the needed drive and dc-bias voltages to below the supply voltage. This mechanical charge pump now obviates the need for custom high voltage CMOS for applications where large voltages are needed, e.g., MEMS-based timing references, thereby allowing the use of virtually any CMOS process.

KEYWORDS

Dickson charge pump, resonant mechanical switch, resoswitch, bias voltage, motional resistance.

INTRODUCTION

With very few exceptions, capacitively transduced MEMS devices simply perform better when high voltages are available. Whether the device is a simple resonator, a gyroscope, an accelerometer, a movable mirror, or a motor, the higher the available voltage, the larger the output signal, as measured by a current, a voltage, or a displacement. In a perfect world, the preferred voltage used for MEMS devices would probably be in the 100-200V range.

Unfortunately, other technologies—e.g., the batteries, the transistors with which the MEMS are often enjoined—cannot supply or do not often play well with such large voltages. Nevertheless, some MEMS products on the market require large voltages, such as digital micromirror displays (DMD) [1] and the high Q capacitively transduced resonators [2] used in some timing oscillators. Many of these products rely on charge pumps to supply such voltages, most often realized via the transistor technology that accompanies them. So far, CMOS based charge pumps perform well when generating voltages on the order of 10-15V, but for higher voltages (>15V) transistor body effect [3] substantially degrades pumping efficiency, and dielectric and p-n junction breakdown ultimately limits the maximum attainable voltage. Voltages exceeding 30V call for custom (expensive) CMOS technologies, such as SOI [4] or triple/deep n-well versions [5]. Indeed, it would be nice if voltage levels required or desired by the MEMS devices could be decoupled from other technologies.

In response, this work demonstrates a MEMS-based charge pump, *cf.* Figure 1, that employs micromechanical resonant switches (a.k.a., resoswitches) in a Dickson configuration to generate 2V from a 1V power supply. Here, the use of mechanical switches eliminates diode or threshold voltage drops and raises the breakdown voltage limit to over 100V. This MEMS-based circuit also accepts a much wider range of input DC voltages, from values much smaller than a typical transistor threshold, to values much larger than a transistor's breakdown voltage. In most cases, the charge pump can simply be fabricated alongside other MEMS devices. Before elaborating, it is instructive to first establish how high of a voltage is desired by considering an example application.

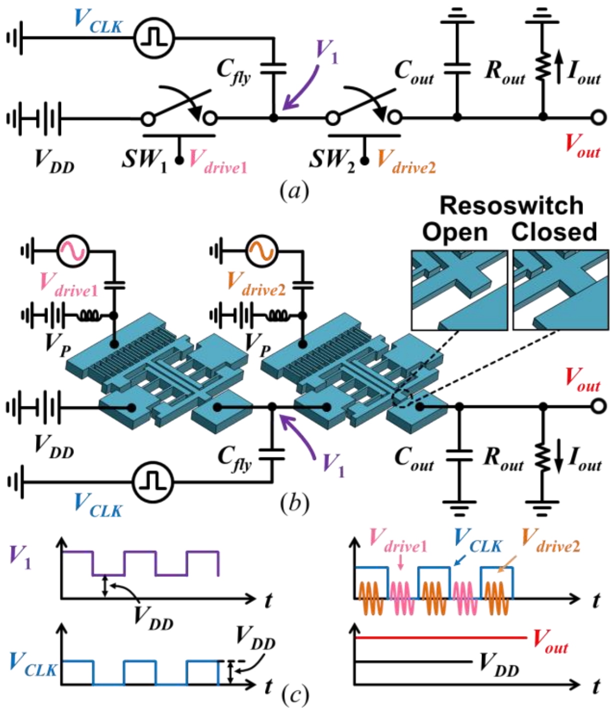

Figure 1: Circuit topology of (a) a single stage Dickson charge pump; and (b) the single stage micromechanical charge pump employing two resoswitches driven by gated sinusoids. (c) illustrates the (ideal) waveforms at different nodes within the circuit.

HIGH VOLTAGE NEEDS

One good example of a MEMS device that benefits greatly from high voltage is the capacitively transduced vibrating RF resonator used in timing oscillators already on the market [2], and targeted for use in next generation wireless communication architectures, such as software-defined cognitive radio [6]. Such devices are attractive for these applications largely due to their unprecedentedly high Q, which now posts over 40,000 at 3GHz [7]. Unfortunately, however, this Q is accompanied by an abysmal coupling coefficient, for which (C_x/C_o) is only

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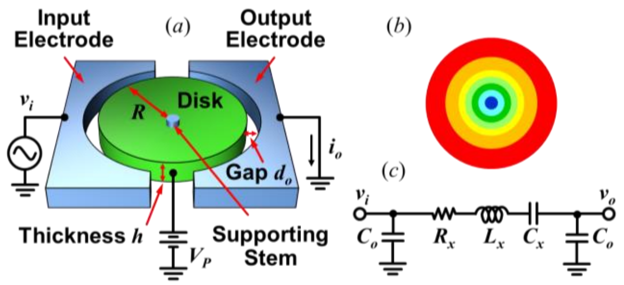

Figure 2: (a) Schematic of a radial mode disk resonator, (b) FEM mode shape and (c) its equivalent circuit.

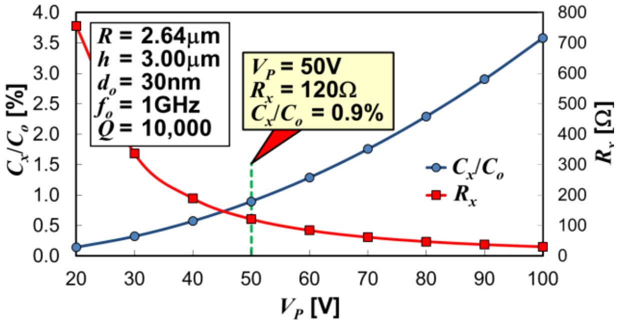

Figure 3: Plot of R_x and (C_x/C_o) versus V_P for a 1-GHz radial-contour mode disk resonator.

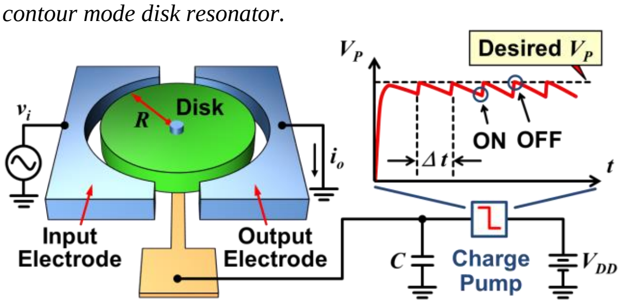

Figure 4: Charge-biased disk resonator employing an intermittent charge pumping scheme.

0.000068% with V_P=8V, which translates to a motional resistance R_x = 81kΩ many times larger than the 50Ω normally expected by conventional RF circuits.

To explore how high voltage can solve this problem, expressions for the R_x and (C_x/C_o) for the classic radial-contour mode capacitive-gap transduced disk resonator [8] summarized in Figure 2(a) can be written as

$$R_x = \frac{\sqrt{k_r m_r}\, d_o^4}{Q\varepsilon^2 A^2 V_P^2}\ ,\ \frac{C_x}{C_o} = \frac{\varepsilon A V_P^2}{k_r d_o^3} \qquad (1)$$

where A and d_o are the overlap area and gap between the electrode and disk, respectively; k_r and m_r are the dynamic stiffness and mass of the disk, respectively; and V_P is the dc-bias voltage applied to the resonator. Figure 3 uses (1) to plot R_x and (C_x/C_o) versus V_P for a 1-GHz disk with a reasonable electrode-to-resonator gap spacing of 30nm, showing how V_P's above 50V allow (C_x/C_o) >1% and R_x's <200Ω, which are on par with values attainable by similarly-sized piezoelectric resonators. If achievable, use of V_P =100V would actually exceed the capabilities of contour-mode d_{31}-transduced AlN piezoelectric devices.

Note that dc-biasing essentially amounts to charging the electrode-to-resonator overlap capacitance. Thus, if a charge pump were employed to provide the charge, it need be turned on only for very short periods, between which the disk can hold its charge (against very small parasitic leakage currents) for time periods on the order of 15mins

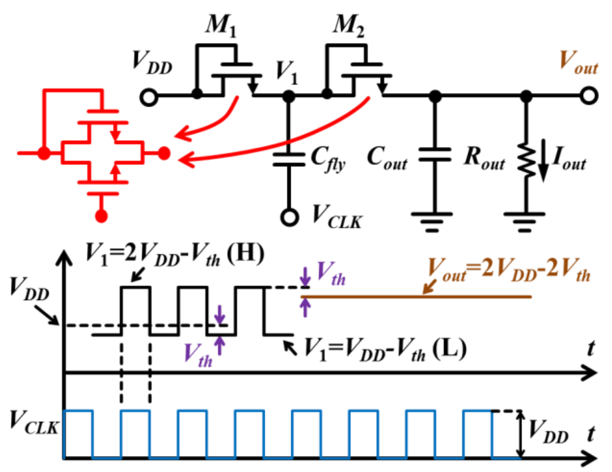

Figure 5: Circuit topology of a conventional single stage CMOS Dickson charge pump and waveforms at each node.

[9]. If a capacitor is placed in parallel with the resonator's bias port, as in Figure 4, the refresh time interval can be quite long, e.g., 65 hours for a 0.18μF capacitor [9].

THE DICKSON CHARGE PUMP

For comparison with the MEMS version, it is instructive to first consider a conventional Dickson charge pump. Figure 5 presents the schematic and waveforms for a classic single-stage CMOS Dickson charge pump, where input DC voltage V_{DD} is fed to two diode-connected MOS transistors in series with the intermediate node V_1 connected to the top plate of a capacitor C_{fly}, with bottom plate driven by a clock signal V_{CLK} toggling between V_{DD} and GND, periodically. When V_{CLK} is at GND, M_1 turns on, and V_{DD} charges C_{fly} until V_1=V_{DD}-V_{th}, where V_{th} is the threshold voltage of M_1 & M_2. Next, when V_{CLK} toggles to V_{DD}, V_1 becomes 2V_{DD}-V_{th} instantaneously, at which point M_1 is off and M_2 turns on to transfer charge stored on C_{fly} to the output node, resulting in an output voltage V_{out}=2V_{DD}-2V_{th}. When N similar stages are cascaded, the output voltage reaches $(N+1)(V_{DD}-V_{th})$. To eliminate the diode drop term, the MOS diodes in Figure 5 can be replaced with pass-gate transistors, such as shown in red, after which the attainable voltage would be $(N+1)V_{DD}$. Ideally any voltage can be generated given enough stages. Unfortunately, in a CMOS charge pump the actual output voltage level is normally limited by the dielectric and p-n junction breakdown voltages of the transistors, e.g. 10-15V in a 0.18μm technology [10]. Custom CMOS technologies, e.g., SOI [4] and triple/deep n-well [5], exist to circumvent this limit, but at the price of higher cost and integration complexity.

Fortunately, more ideal switches provided by MEMS technology enable a more efficient version of the Dickson charge pump. Figure 1(a) presents the basic approach using ideal switches. Here, switches SW_1 and SW_2 replace the diodes (or MOS switches) of Figure 5. To transfer charge along only one direction, SW_1 and SW_2 must switch on in alternate phases, meaning their turn-on voltages V_{drive1} and V_{drive2} must be on in opposite clock phases. If this is the case, then charge transferred from V_{DD} to V_1 during the clock down cycle gets boosted to V_{DD}+V_{CLK} during the clock up cycle, at which point SW_1 is off and SW_2 turns on to transfer the charge (and voltage) to the awaiting output

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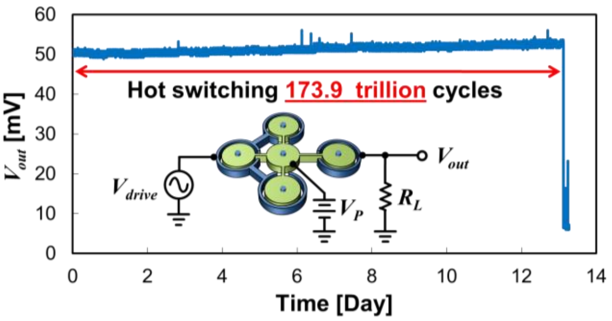

Figure 6: Cycle lifetime data for a displacement amplifying polysilicon disk resoswitch.

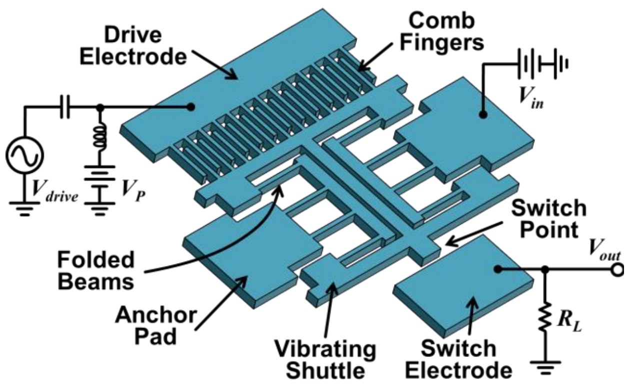

Figure 7: Schematic of a comb-driven resoswitch.

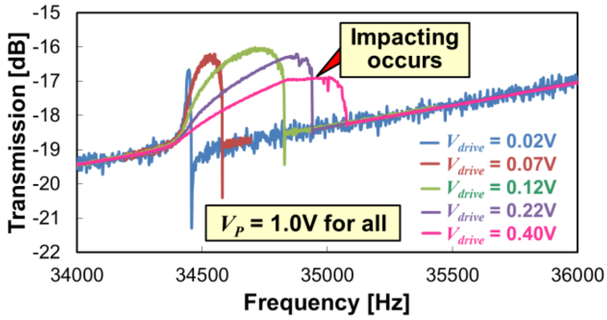

Figure 8: Frequency responses of the comb-driven resoswitch measured in vacuum for varying resonance input ac voltage amplitudes, showing impacting when the response flattens.

capacitor. Since there are no voltage drops and the breakdown voltage can be higher than 100V, the output voltage equal to $(N+1)V_{DD}$ can be quite high, indeed.

Unfortunately, there are a few caveats. Specifically, conventional MEMS switches require very large actuation voltages, usually >50V; and they are notorious for their poor reliability, as measured by limited cycle counts before failure. To solve these problems, this work employs resonant micromechanical switches, a.k.a., resoswitches.

COMB-DRIVEN RESOSWITCHES

Micromechanical resoswitches, first described in [11], use resonance operation to greatly improve switch performance. In particular, when at resonance, displacements amplify by Q, so actuation voltages are small even though the stiffness of the device can be quite large. The large stiffness in turn allows very fast operation (due to the high resonance frequency) and very reliable operation, since large stiffness equates to large restoring forces against any sticking phenomenon. To illustrate, Figure 6 presents cycle lifetime data obtained for a displacement amplifier version of a polysilicon disk resoswitch [12] (shown in the inset),

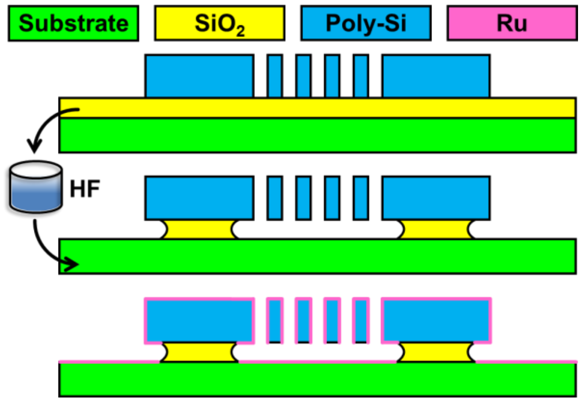

Figure 9: Cross-sections summarizing the one-mask process flow used to fabricate comb-driven resoswitches.

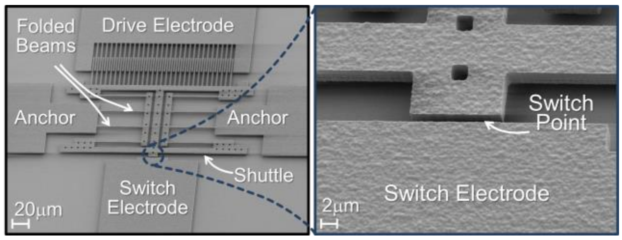

Figure 10: SEM photos of a fabricated ALD-Ru-coated polysilicon comb-driven resoswitch.

which posts 173 trillion hot-switched cycles. The device actually did not fail; rather, its frequency shifted away from that of the drive signal, preventing further impacting.

The resoswitch of [11] and [12] are overkill for the present dc-biasing target application, at least from a frequency perspective. In particular, since a capacitively transduced MEMS device draws practically no current, a very low frequency charge pump is all that is needed. Thus, this work utilizes the much simpler comb-driven resoswitch depicted in Figure 7. Here, a folded-beam supported shuttle is capacitively driven into resonance by an AC/DC voltage combination applied to comb fingers on one side. The ensuing resonance vibration then induces impacting at the switch point on the other side, which of course periodically opens and closes the mechanical switch. During hot switching, the input DC voltage applied onto the shuttle, is transferred to the output electrode periodically. When operated under vacuum, the voltage amplitude required to actuate this device can be quite small. To illustrate, Figure 8 presents measured curves of displacement amplitude versus frequency and drive voltage for a dc-bias of 1V. Here, impacting occurs when the drive voltage amplitude is only 0.4V, which is well under the 1V supply voltage, all enabled by resonance Q amplification.

One advantage of the present comb-driven resoswitch versus previous disk versions is its amenability to fabrication via most traditional MEMS processes, which makes it compatible with a wide array of MEMS products. This work actually fabricates comb-driven resoswitches via the very simple one-mask process summarized in Figure 9. Here, 3μm of poly-Si structural layer is first deposited and patterned over a 2μm SiO_2 sacrificial layer. Then the structure is time-released in HF solution, followed by a (not-so-conformal) ALD deposition of 2-5nm Ru. The Ru coating reduces switch contact resistance, which is needed for comb-driven resoswitches since their contact forces are much smaller than those of previous disks. Figure 10 pre-

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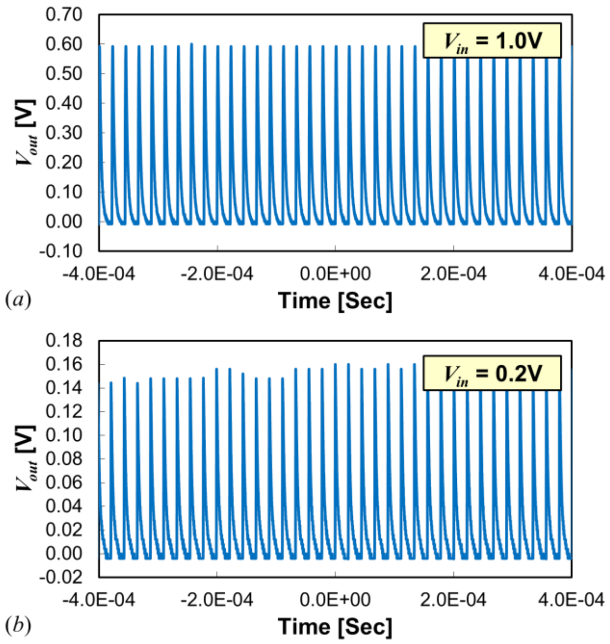

Figure 11: Measured oscilloscope output waveforms for the comb-driven resoswitch when operated in the circuit of Figure 7 with (a) 1.0V and (b) 0.2V of V_{in}, respectively.

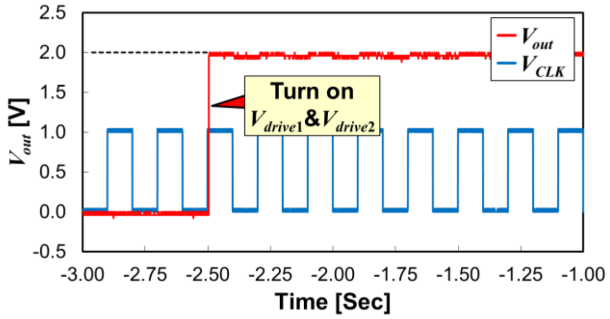

Figure 12: Measured oscilloscope output waveform of the single stage micromechanical charge pump together with the clock signal controlling gated-sinusoids.

sents SEMs of the resoswitch device coated with ALD-Ru.

Figure 11 presents measured output waveforms for the resoswitch of Figure 7, taking 1V and 0.2V as input voltages, respectively, and showing that with no "diode" drop very small voltages can be transferred by these switches.

RESOSWITCH CHARGE PUMP

Using the comb-driven resoswitches described above, a Dickson charge pump was built mimicking the circuit topology of Figure 1(a), but with a few modifications shown in (b) to accommodate the apparent drawback that switching occurs only at the (possibly different) resonance frequency of each resoswitch. This work overcomes this seeming limitation via use of gated-sinusoids, *cf*. Figure 1(c), top right, 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-sinusoid excitation stands to revolutionize the use of resonant switches, since it effectively removes the previously cumbersome restriction to resonance!

Figure 12 finally presents the output voltage waveform of the charge pump circuit of Figure 1(b), where a 1V input has been successfully boosted to 2V at the output. And of course, as more resoswitch-capacitor stages are added, the charge-pumped voltage increases.

CONCLUSIONS

This work demonstrates a micromechanical Dickson charge pump employing comb-driven resonant switches to boost 1V of V_{DD} to 2V. In doing so, this mechanical circuit opens a path towards much higher voltages attained by merely utilizing more charge pumping stages—something easily done right next to a given MEMS device, using virtually the same fabrication process sequence that achieved that MEMS device. By raising voltages directly on the MEMS chip, this mechanical charge pump greatly improves MEMS device performance, while simultaneously lowering cost by obviating any need for (expensive) custom high voltage CMOS processes. But perhaps the most important contribution here is psychological: With this technology, MEMS designers need no longer put limits on permissible voltage levels. It would be wonderful if this new-found freedom inspires new designs and capabilities previously unthinkable.

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