A Resonance Dynamical Approach to Faster, More Reliable Micromechanical Switches

Yang Lin, Wei-Chang Li, Zeying Ren, and Clark T.-C. Nguyen
Department of Electrical Engineering and Computer Science
University of California at Berkeley
Berkeley, CA 94720 USA

Abstract—The resonance and nonlinear dynamical properties of micromechanical structures have been harnessed to demonstrate an impacting micromechanical switch with substantially higher switching speed, better reliability (even under hot switching), and lower actuation voltage, all by substantial factors, over conventional RF MEMS switches. The particular resoswitch implementation demonstrated in this work comprises a wine-glass mode disk resonator, driven hard via a 2.5V amplitude ac voltage at its 61-MHz resonance frequency so that it impacts electrodes along an orthogonal switch axis, thereby closing a switch connecting a signal through switch axis electrodes. The 61-MHz operating frequency corresponds to a switching period of 16ns with an effective rise time of ~4ns, which is more than 50 times faster than the μs-range switching speeds of the fastest conventional (non-resonant) RF MEMS switches. Furthermore, with the signal on during switching, a capacitive version of the switch has hot switched for more than 16.5 trillion cycles without failure, which is substantially more than the 100 billion cycles normally posted by conventional RF MEMS switches. The reliability of the present resoswitch benefits from the high stiffness of its actuating disk resonator, which provides a large restoring force with which to overcome sticking forces; and from the energy stored via resonance vibration that provides a momentum that further increases the effective restoring force. Resonance operation in turn allows the actuation voltage amplitude to be a mere 2.5V, despite the large spring restoring force. Such mechanically resonant switches (dubbed “resoswitches”) used in place of the switching transistors in switched-mode power converters and power amplifiers stand to greatly enhance efficiencies by allowing the use of much higher power supply voltages than allowable by transistors.

Index Terms—microelectromechanical devices, microresonator, nonlinear resonance dynamics, RF MEMS, switch, power amplifier, power converter.

I. INTRODUCTION

RF MEMS switches operating at RF to millimeter-wave frequencies substantially outperform p-i-n diode and field-effect transistor (FET) counterparts in insertion loss, isolation, and switch figure of merit (FOM) [1][2]. Unfortunately, their much slower switching speeds (e.g., 1-15 μs versus the 0.16-1ns [3] of FET’s) and cycle lifetimes on the order of 100 billion cycles (for the good ones) relegates them mainly to antenna switching, reconfigurable aperture, and instrumentation applications, and precludes them from much higher volume applications, such as switched-mode power amplifiers and power converters.

Indeed, the benefits afforded to switched-mode power applications that would ensue if the transistors they presently employ were replaced by switches with FOM’s on the order of those exhibited by RF MEMS switches would be enormous. For example, switched-mode power amplifiers that ideally should be able to achieve 100% drain efficiency presently cannot attain such values in practical implementations, in part because the transistors they use for switching exhibit large input capacitors (for small “on” resistances) and are often limited in the supply voltages they can support. On the other hand, MEMS switches, being made of metal, have very small “on” resistances and would be able to support higher supply voltages. However, if they are to be used in switched-mode power applications, their actuation voltages would need to be lowered substantially (from >50V down to the single-digit volt range), their speeds would need to be much higher (e.g., ns switching times), and their reliability enhanced substantially, since typical power amplifier and converter applications would require cycle counts in the quadrillions.

Pursuant to achieving a switch suitable for power amplifier and converter applications, this work demonstrates a micromechanical switch, dubbed the “resoswitch” [4], that harnesses the resonance and nonlinear dynamical properties of its mechanical structure to greatly increase switching speed and cycle count (even under hot switching), and lower the needed actuation voltage, all by substantial factors over existing RF MEMS switches. The device comprises a wine-glass mode disk resonator driven hard via a 2.5V amplitude ac voltage at its 61-MHz resonance frequency so that it impacts electrodes along an orthogonal switch axis, thereby closing a switch connecting a 10V source to the switch electrode. The 61-MHz operating frequency corresponds to a switching period of 16ns with an effective rise time of ~4ns, which is more than 200 times faster than the μs-range switching speeds of the fastest RF MEMS switches. Furthermore, since the voltage source is on during switching, the switch essentially hot switched with a demonstrated lifetime exceeding 16.5 trillion cycles without failure, but with some observable degradation.

II. BASIC RESOSWITCH OPERATION AND ADVANTAGES

The advantages provided by a switch that harnesses resonance dynamics are perhaps best conveyed via comparison with conventional RF MEMS switch counterparts that do not. For this purpose, Fig. 1 presents the top view and cross-section of a typical conventional RF MEMS switch, in this case one demonstrated by Goldsmith [1]. As shown, this switch consists of a metal membrane (or beam) suspended above a switch contact electrode that can be electrostatically pulled down onto the contact electrode by applying a sufficient actuation voltage $V_{\text{switch}}$ to an underlying “gate” electrode. For the case of a sus-
would be the same displacement of the beam (i.e., to close the switch), thereby reducing its off-state isolation (and its reliability; while the latter increases the capacitance of the beam can overcome stiction forces, thereby sacrificing its drawbacks: the former reduces the restoring force with which the beam, by making it thicker or by shrinking its length dimension; or reduce the beam-to-drive electrode overlap capacitance, by increasing the beam-to-drive electrode gap spacing or by reducing its overlap area.

Raising stiffness is quite beneficial, since it effectively raises the speed of the switch by increasing its resonance frequency. It also improves the reliability of the switch by increasing the actuation force available to overcome adhesion forces that might otherwise cause the beam to stick to the electrode. For example, if the thickness of the beam of Fig. 1 were increased to 5 μm, and its length reduced to 150 μm, then the effective beam stiffness at its midpoint would become 4,150 N/m, raising its frequency range (i.e., its resonance frequency) from 180 kHz to 1.06 MHz, which corresponds to a switching speed of [(4)(1.06)(10^6)]^-1 = 236 ns, where switching speed here is approximated as one-fourth the switching period. The available resonance force is also increased by this design change from 0.11 mN to 8.3 mN, as illustrated by the following calculation:

\[
F_{\text{restore}} = kd = \begin{cases}
0.11 \text{ mN} & \text{if } k = 57 \text{ N/m} \\
8.3 \text{ mN} & \text{if } k = 4,150 \text{ N/m}
\end{cases}
\] (1)

where \(F_{\text{restore}}\) is the restoring force, \(k\) is the stiffness of the beam, and \(d (=2 \mu\text{m})\) is the distance between the beam and the contact electrode. Finally, despite the increase in stiffness, the needed resonance actuation voltage amplitude remains quite small, at a calculated 94 mV.

Beyond increasing stiffness, the other option for backing off on actuation voltage, i.e., decreasing the beam-to-electrode overlap capacitance, is also quite beneficial, since it reduces the off-state capacitance of the switch, thereby raising its FOM. Thus, the use of resonance operation improves switch performance in both the mechanical and electrical domains.

As will be seen, the nonlinear dynamical behavior of the resoswitch offers even greater advantages for specific switched-mode applications, such as bandwidth and duty cycle control, which are important for power amplifiers and power converter applications, respectively.

### III. Wine-Glass Disk Resoswitch

Although the resoswitch example so far discussed does present clear advantages over its non-resonant counterpart, its use of a clamped-clamped beam structure confines it to resonance frequencies lower than about 100 MHz, since anchor losses plague this design at higher frequencies [13]. To attain the GHz frequencies demanded by switched-mode power amplifier applications, disk [14] or ring [15] resonator geometries are much more appropriate.

With this in mind, Fig. 2 presents schematics describing the structure and operation of one simple rendition of a resoswitch that comprises a capacitively-transduced wine-glass disk micromechanical resonator [16] (c.f., Fig. 3) made in a conductive material (preferably, a metal) and surrounded by four electrodes, two of which are situated along an indicated...
Fig. 2: Schematics showing (a) the physical structure of the micromechanical resoswitch, identifying its ports and equating it to a functional equivalent circuit; (b) its “on”; and (c) its “off” states.

Fig. 3: (a) Perspective-view schematic of a micromechanical wine-glass-mode disk resonator in a typical two-port bias and excitation configuration (where A,A’ are electrically connected, as are B,B’). (b) ANSYS simulated wine-glass-mode shape. (c) ANSYS simulated wine-glass-mode shape delineated by the dotted curve in Fig. 2(a). As the resonance amplitude rises, the disk eventually impacts the switch electrode. Again, the use of such a large spring restoring force is made possible by resonance operation, under which the displacement of the actuator is $Q$ times larger than off-resonance, allowing a mere 1-3V amplitude drive voltage to generate impacting switch axis amplitudes in spite of the large stiffness of the disk structure.

The cycle count of the resoswitch would need to be much larger (3 quadrillion) than so far achieved by conventional non-resonant RF MEMS switches (1 trillion). In this regard, the reliability of the present resoswitch benefits from two major advantages: 1) the stiffness of its actuating disk resonator is on the order of $1.15 \times 10^6$ N/m (for a 61-MHz wine-glass disk), which is several orders larger than that of a conventional RF MEMS switch, so provides a substantially larger restoring force with which to overcome sticking forces; and 2) the energy stored via resonance vibration of the device provides a momentum that further increases the effective restoring force and that reduces in some cases the force with which the disk edge impacts the switch electrode. Again, the use of such a large spring restoring force is made possible by resonance operation, under which the displacement of the actuator is $Q$ times larger than off-resonance, allowing a mere 1-3V amplitude drive voltage to generate impacting switch axis amplitudes in spite of the large stiffness of the disk structure.

Fig. 4 presents a finite element simulated (using ANSYS) topographical plot showing the sliding distribution seen at the disk edge-to-switch axis electrode interface upon impact. From multiple such simulations, plots of gap spacing versus time can be generated, two of which are shown in Fig. 5(a) for cases where 1.25V and 2.5V input signal voltages are applied. Here, the larger 2.5V input clearly generates the larger disk vibration amplitude, and as shown, the longer resulting impact interval. Fig. 5(b) shows the voltage waveforms generated by switch contacting, clearly showing that the duty cycle of the output waveform is controlled by how hard the resoswitch is driven. In particular, when the resoswitch is driven softly, so that it only barely touches the switch axis electrodes, the duty cycle is very small. When driven very hard, the duty cycle rises closer to its 50% maximum. Fig. 5(c) plots duty cycle versus input voltage (using FEA-simulated points) to more clearly illustrate the relationship between input amplitude and output duty cycle. Such control of duty cycle is very useful for switched-mode power converters, for which the conversion...
ratio is often set by duty cycle.

Not only is the duty cycle adjustable, but so is the bandwidth of the resoswitch. In particular, as shown in Fig. 6, the bandwidth over which impacting occurs can also be controlled by the amplitude of the ac input voltage. In effect, the larger the input voltage amplitude, the lower the frequency of first limiting on the frequency characteristic of the device, and the higher the frequency of last limiting. This bandwidth-widening is a nonlinear dynamical effect that provides simultaneous high-Q and wide bandwidth—something not generally available in purely linear systems, where high Q often means small bandwidth. In particular, nonlinear resonance dynamics provides on the one hand high Q along the input axis, which lowers the required input ac voltage; while also providing on the other hand a wide effective bandwidth along the switch (or output) axis. The availability of simultaneous high-Q and wide bandwidth obviously benefits transmit power amplifier applications in communications, since it permits wide frequency modulations on the transmitted signal while simultaneously lowering the input capacitance needed to operate the device with a given input signal amplitude.

IV. EXPERIMENTAL RESULTS

To demonstrate the resoswitch, doped polysilicon wineglass mode disk resonators based on the design and fabrication process of [16] were employed. Fig. 7(a) presents the SEM of one of the 61-MHz wineglass disk resonators used in this work, with a zoom-in shot in (b) showing the tiny gap between the disk and its switch electrode. For most power amplifier and converter applications, the resoswitch should be constructed of metal, not polysilicon, to reduce its contact and series resistance. The use of doped polysilicon in this work does compromise resoswitch performance, especially with regards to the switch “on” resistance, which is dominated by the 1.1 kΩ parasitic resistance $R_p$ of its polysilicon leads and interconnects. Nevertheless, it still allows demonstration of practically all other important resoswitch performance parameters. It should be noted that, despite its high series resistance, the polysilicon version of the resoswitch is actually still quite applicable for use in low current drain switched-mode on-chip dc-to-dc power converters (i.e., charge pumps), such as needed to supply the large dc-bias voltages often required by vibrating resonators and RF MEMS devices [1][13]-[16].

For simplicity in this early demonstration, the strategy of using different electrode-to-disk spacings along the input and switch axes shown in Fig. 2 was not used in this implementation. Rather, the electrode-to-resonator gap spacings for both axes were 100 nm for direct contact switches, in which the conductive disk and electrode materials actually make electrical contact; and about 97 nm for capacitive switches, in which a thin layer of oxide exists over conductive surfaces that prevents electrical contact, but still allows switching through the large capacitance that results when the disk impacts its switch electrodes. For the direct contact version of the resoswitch, one obvious consequence of the use of identical input and switch axis electrode-to-resonator gap is that the input gets shorted to the disk during operation, which then complicates use of the resoswitch in actual applications. (For example, the Class E power amplifier topology later shown in Fig. 12(b) would not be permissible under these conditions.)

To deal with input shorting, the test set-up used to measure resoswitch performance, depicted in Fig. 8, uses a less practical configuration, but one still valid for evaluation of switch performance. Here, a dc-bias voltage $V_p$ is applied to the disk structure that is effectively applied to the output node when the switch closes (i.e., comes “on”) in the fashion shown in Fig. 2. As shown, this circuit allows both time domain (i.e., oscilloscope) and frequency domain (i.e., network analyzer) observation of the resoswitch output. The output buffer used in this circuit effectively removes the 80pF of coaxial capacitance that would otherwise load the output node of the resoswitch and greatly reduce the signal level due to 3dB bandwidth roll-off. The output buffer, however, is not perfect, as it still loads the output node of the resoswitch with about 4pF. This is large...
enough to round out the corners of the expected output square wave (c.f., Fig. 5(b)) so that it looks more sinusoidal.

Fig. 9 and Fig. 10 present the oscilloscope waveform and swept frequency response spectrum (for various input amplitudes), respectively, of the direct contact resoswitch, verifying switching operation, impact limiting, and also the bandwidth-widening effect previously discussed. Switching clearly occurs when the frequency response grows suddenly and limits with a “flat top”, as shown on Fig. 10. This occurs when the voltage amplitude reaches 2.5V. The measured output signal in Fig. 9 has a peak-to-peak amplitude of about 1V, which is the value expected when considering attenuation via the finite 3dB bandwidth of the measurement circuit of Fig. 8, and when considering the voltage divider formed by the parasitic polysilicon interconnect resistance $R_p$ and the bleed resistor $R_{bleed}$. The signal is not quite a square wave due to bandwidth limitations of the measurement circuit, but the amplitude is correct. To emphasize this point, Fig. 8 also includes a SPICE simulated waveform that includes the effects of 1.1 kΩ of parasitic resistance $R_p$ and 3.5 pF of buffer input capacitance, and that clearly matches the measured waveform.

Fig. 11 presents a measured plot of output power (seen at the switch axis output node) versus frequency. Here, the buffer of Fig. 8 was not used, so load-induced attenuation somewhat compromised the measurement, resulting in a measured output power considerably lower than in Fig. 10. Nevertheless, Fig. 11 does verify the nonlinear resonance dynamical behavior of the resoswitch, since the bandwidth does indeed widen as the input voltage amplitude increases.

To evaluate reliability, the resoswitch was operated continuously with $V_p = 10$V for 75 hours (~3 days or 16.5 trillion cycles) without failure at a frequency of 61 MHz [4], which is a frequency in the flat region of Fig. 10, and thus, a frequency where impacting occurs. Although no failure was observed, degradation was seen, where after about 1.5 days, the output voltage began to decrease significantly. Although 1.5 days corresponds to 7.7 trillion cycles at 61 MHz, which is more than two orders of magnitude higher than the 100 billion cycles typically achieved by (good) RF MEMS switches, there is still cause for concern, here, since typical switched-mode power applications will require quadrillions of cycles. More study into the degradation mechanism is needed, but one possible reason for the observed degradation could be the growth of a thicker oxide or other dielectric on the switch contact interfaces. In the future, resoswitches constructed of metal with engineered contact surfaces will be investigated.

V. CONCLUSIONS

In this work, the resonance and nonlinear dynamical properties of a micromechanical wine-glass disk have been harnessed to demonstrate an impacting micromechanical switch with substantially higher switching speed, better reliability (even under hot switching), and lower actuation voltage, all by substantial factors, over existing RF MEMS switches. Although next generation versions of this resoswitch constructed in metal material [22] should be more widely applicable, the present polysilicon version can still find application to low current drain applications, such as Dickson charge pumps [5], where replacement of diodes with resoswitches should allow a very high output voltage, suitable for dc-biasing of capacitively transduced micromechanical resonators.

Perhaps the best way to gauge the benefits of the described resoswitch is by comparison with other switches. To this end, Table I compares the described micromechanical resoswitch with transistor FET and RF MEMS switch counterparts, showing clear advantages in maximum supply voltage and input capacitance over transistor FET’s, and in actuation voltage and speed over RF MEMS switches. The *’ed items also convey expectations that a metal version of the resoswitch should be able to match the series resistance and $FOM$ of a conventional RF MEMS switch.

Although the device-to-device comparisons are already favorable for the resoswitch, the advantages provided by the
resoswitch are perhaps best elucidated in the context of an application. To this end, Fig. 12 shows the circuit topologies of (a) a conventional Class E power amplifier (PA) using a transis-
tor switch device; and (b) one simplified rendition of the same amplifier utilizing the vibrating micromechanical reso-
nant switch demonstrated in this work. The use of a micromechanical resoswitch in place of the switching transistor in this application stands to enhance performance as follows:

1) It allows the use of much higher voltages (e.g., 10V vs.
the 1-3V limit of conventional CMOS) [11]. This then al-
loresoswitch the resonant device to directly drive the 50Ω
load, and thereby dispense with the lossy matching net-
work needed by the transistor version. Removal of the
matching network and raising the driven impedance from
2Ω to 50Ω can raise the efficiency of a Class E power
amplifier by as much as 23%.

2) The use of the resoswitch further allows the same or
smaller “on” resistance than its FET counterpart, but with
substantially smaller input capacitance, e.g., only 20fF for
the resoswitch versus 20pF for a CMOS PA switch—a
1000× difference that removes much of the input power
that would otherwise be needed to drive the PA. Again,
better efficiency ensues.

Again, the above benefits ensue only when the resoswitch is
implemented in a metal structural material. Work towards this
is in progress.

Acknowledgment: This work was supported by DARPA.

REFERENCES

[1] Z. J. Yao, S. Chen, S. Eshelman, D. Denniston, and C. Goldsmith, “Mi-
cromachined low-loss microwave switches,” IEEE/ASME J. Microelec-
521.
for 10-GHz’s Systems,” Proceedings, IEEE CSIC, Jul. 2004, pp. 97-
100.
nant switch (“Resoswitch”),” Tech. Digest, 2008 Solid-State Sensor, Ac-
tuator, and Microsystems Workshop, Hilton Head, South Carolina, June
cuits using an improved voltage multiplier technique,” IEEE J. Solid-State
switching-mode power converters,” Proc. IEEE, vol. 76, no. 4, pp.343-354,

* Potentially achievable by a metal version.