Y. Lin, R. Liu, W.-C. Li, and C. T.-C. Nguyen, "Polycide contact interface to suppress squegging in micromechanical resoswitches," *Tech. Digest*, 2014 IEEE Int. Micro Electro Mechanical Systems Conference, San Francisco, California, Jan. 26-30, 2014, pp. 1273-1276.

POLYCIDE CONTACT INTERFACE TO SUPPRESS SQUEGGING IN MICROMECHANICAL RESOSWITCHES

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ABSTRACT

The use of a Pt-silicide-based contact interface has greatly reduced impact-induced energy loss in comb-driven resonant micromechanical switches (a.k.a., resoswitches) to the point where squegging phenomena (whereby impacts do not occur on every cycle) are eliminated, so no longer constrain the clock frequency of recently demonstrated mechanical charge pumps [1]. This opens the application range of such charge pumps to power converters capable of delivering currents much higher than the low current-draw MEMS dc-biasing applications targeted by [1]. The key to eliminating squegging in the present work is contact engineering, where softer contact materials, including Au, Ag, and Ni, steal too much energy on each impact; but harder contact materials, like Pt-silicide, allow more elastic impact while still maintaining low contact resistance due to the large impulsive force generated by impact—a distinct advantage of the resoswitch over conventional non-resonant counterparts.

INTRODUCTION

If high bias voltages on the order of 50-200V were available on-chip, the corresponding increase in the electromechanical coupling strengths of many capacitively transduced MEMS devices, from gyroscopes, to microphones, to timing oscillators, would bring about substantial performance and cost benefits. Indeed, the size of a mechanical element can often be made substantially smaller when capacitive coupling becomes stronger, since less overlap is required to achieve a given coupling strength. To date, voltages exceeding the supply voltages are generally provided by semiconductor-based charge pumps that use unconventional, expensive transistors designed to support higher voltages. Even so, such devices are still limited by pn-junction and dielectric breakdown limits, so constrain the voltages ultimately achievable by charge pumps using them.

To remedy this, the MEMS-based Dickson charge pump demonstrated in [1] use micromechanical resoswitches [2] to remove the diode voltage drop and junction breakdown issues that plague conventional transistor versions, allowing them to transfer charge with any input voltage level and achieve much higher voltages, perhaps eventually as high as 200V. The resoswitch device is simple enough that its fabrication steps are often already present in the fabrication process flows of many existing MEMS applications, so high voltage and its benefits might come almost for free.

But there were imperfections. In particular, the work of [1] used gated-sinusoid excitation signals to synchronize the movement of charge through the pump topology and to

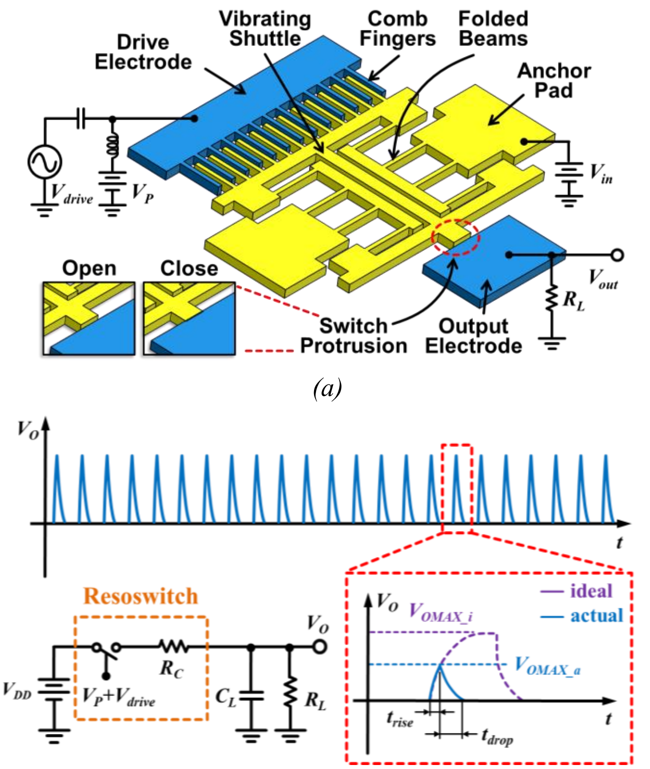


Fig. 1: (a) Detailed schematic of a comb-driven resoswitch with flat contact point on the opposite side of the drive fingers. (b) Simplified equivalent circuit and expected output waveform with zoom in on the shape of each spike.

overcome difficulty with squegging—a phenomenon where an oscillation amplitude is not constant, but rather grows and shrinks with a certain period [3], as shown (later) in Fig. 6.

This work explores contact engineering to overcome squegging and ultimately uses a Pt-silicide-based contact interface to greatly reduce impact-induced energy loss in resoswitches to the point where squegging phenomena are eliminated, so no longer constrain the clock frequency of recently demonstrated mechanical charge pumps. This opens the application range of such charge pumps to power converters capable of delivering currents much higher than the low current-draw MEMS dc-biasing applications previously targeted by [1].

RESOSWITCH SQUEGGING

To explain squegging in the subject resoswitch, some description of device structure and operation is in order.

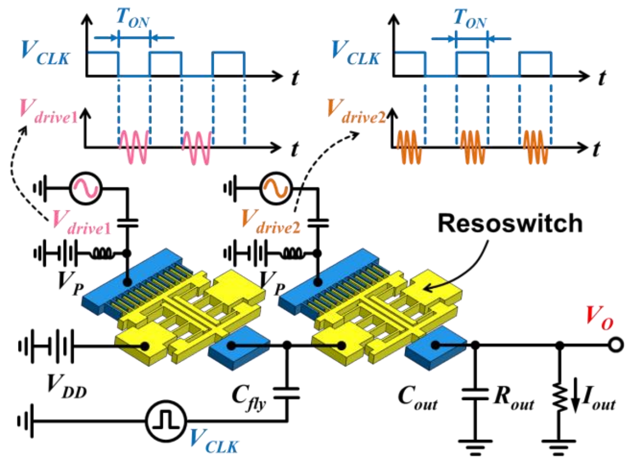


Fig. 2: Schematic of a single-stage MEMS Dickson's charge pump and gated-sinusoid waveforms needed to affect synchronized pumping.

Comb-Driven Resoswitch Structure and Operation

Fig. 1(a) presents the perspective-view schematic of one resoswitch variant, with others shown later in Fig. 8. Like the device of [1], these devices feature folded-beam suspensions and comb-finger transducers that can drive their conductive shuttle protrusions to impact with a switch (or output) electrode. They differ, however, in the placement and type of impact points, which now include flat or sharp points placed either on the opposite or same side as the fingers. Same side placement allows the fingers to apply additional impact force over and above the momentum-based force when fingers and contact point are on opposite sides.

The operation of any of these devices is simple and shown for the device of Fig. 1(a): Drive the capacitive combs with a combined (dc-bias + resonance ac) voltage hard enough to affect impacting, in turn closing a mechanical switch that then periodically transfers charge from the supply V_{in} to the awaiting load (R_L or C_L) at the output. Fig. 1(b) presents the equivalent circuit for the hookup of Fig. 1(a), where R_C is a combination of interconnect resistance and switch contact resistance (but dominated by the latter). The expected normal output waveform from this comb-driven resoswitch is also shown to be a series of spikes shaped by the *RC* circuit formed between R_C, R_L and C_L. The governing expression from which the contact resistance R_C can be extracted takes the form

$$\frac{V_{DD}\cdot R_L}{R_C+R_L}\cdot\left(1-exp\left(-\frac{t_{rise}}{(R_C||R_L)C_L}\right)\right)=V_{OMAX\_a} \qquad (1)$$

where t_{rise} is the charging time of the spike, i.e., the switch contact time; and V_{OMAX_a} is the measured spike amplitude.

Charge Pump Operation

In the actual charge pump application, shown in Fig. 2, the waveforms required to actuate the devices are actually gated sinusoids rather than pure ones. This is a consequence of finite tolerances achievable via planar microfabrication that produce resoswitches with slightly different resonance frequencies. Because of this, the devices cannot be actuated simply by a single signal at one frequency phase shifted to service different pumping phases. Rather, each device requires a different frequency to affect resonant switching. To synchronize impact-based charge transfer events, gated sinusoids tailored to the resonance frequency of each individual device are needed, as illustrated in Fig. 2. Here, impacting charge transfer occurs only during periods when the gate is "on". The amount of charge transferred is a function of the total time of impact, i.e., during which the shuttle and electrode are in contact, which for the low frequency design of the present discussion, is generally only a small fraction of the resonance period, as shown in Fig. 1(b). Indeed, one of the factors that sets the needed "gate-on" period in a charge pump is this impact residence time.

Ultimately, the other factor governing the "gate-on" time is squegging. As mentioned, squegging refers to a phenomenon where an oscillation amplitude is not constant, but rather grows and shrinks with a period [3] governed by the degree to which losses vary with time. For the resoswitch device, the loss in the system rises abruptly from its free vibration value once impacting occurs, during which each impact steals an amount of energy from the system governed by the elasticity of the impact. Squegging occurs when the energy stolen on impact is large enough to reduce the amplitude of motion so that no impact occurs on the next cycle(s). Rather, energy must build up towards another impact, after which energy is lost again, and the cycle continues with a period essentially governed by impact loss.

Of course, a squegged waveform, generates fewer impacts per "gate-on" period T_{on}, thereby requiring a longer T_{on} for a given amount of charge transfer and a smaller pumping frequency. This in turn means less pumping ability, so smaller current (or power) delivery to a load, i.e., squegging compromises the ultimate power delivery of a power converter. Thus, the power delivery capability of a MEMS-based charge pump (or other power converter type) cannot be maximized unless squegging is eliminated.

Squegging Model

The energy loss per impact can be modeled by the restitution law governing the relationship between velocity before and after impact: [3]

$$dx/dt\,|_{after\ impact} = -r\cdot dx/dt\,|_{before\ impact} \qquad (2)$$

where x is displacement, and r<1 is the coefficient of restitution, governed largely by the contact material interface. Loss of velocity after impact, of course, means loss of kinetic energy, and the more energy lost per impact, the longer it takes to recover, and the larger the number of non-impact cycles during squegging. From (2), squegging is minimized via use of materials with higher hardness, i.e., less plastic deformation when impacting, for which r is closer to 1. In this regard, polysilicon is preferred over most metals. Polysilicon alone, however, is too resistive; but a polycide that combines polysilicon and a metal makes good sense.

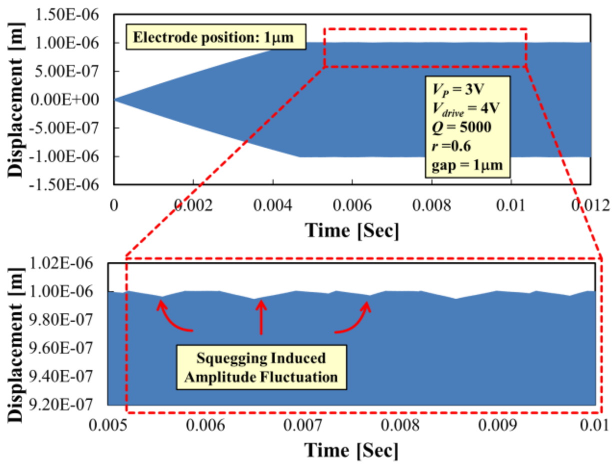


Fig. 3: Theoretically simulated resoswitch shuttle displacement by solving (2) and equation of motion numerically in MATLAB.

The squegging behavior of the resoswitch can be captured theoretically by solving a group of ODE's consisting of (2) and the equation of motion. Fig. 3 shows the simulated shuttle displacement with the parameters summarized in the inset table, where a fluctuation of displacement amplitude is clearly observed.

Simulation also reveals that besides choosing harder structural materials, careful mechanical design can also suppress squegging. For instance, reducing switch gap constrains the system to smaller displacements, so smaller energy deficits to recover after lossy impact, hence, less squegging. In addition, locations of electrodes relative to the contacts can affect squegging. As mentioned, placement of comb electrodes on the same side as the contact allows the electrode-generated force to drive the shuttle into the contact point, so adds to the impulsive impact force, making for more efficient energy recovery. In contrast, having drive electrodes and contacts on the opposite sides relies on less efficiently generated moment forces when contacting, so displays much more simulated squegging.

FABRICATION PROCESSES

Pursuant to gauging the influence of contact interface design on squegging, comb-transduced resoswitches were realized in various materials with various contact interfaces. These include electroplated nickel devices coated with Ruthenium to serve as soft contact resoswitches; and polycide devices to serve as hard contact ones. All devices utilized simple one-mask surface-micromachining fabrication process flows, such as used in [1], where oxide mesas that remain after a timed release etch serve as anchors for suspended structures. Ni/Ru device fabrication is rather straightforward, comprising a molded Ni electroplating above an oxide spacer, followed by subsequent release and coating with 10-20nm of Ru via sputtering, which was found to be sufficiently conformal to coat the sidewalls of the structures. Fig. 4 presents SEMs of a Ni/Ru device.

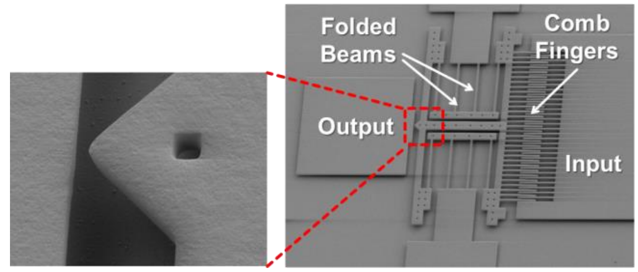


Fig. 4: SEM photos of the comb-driven resoswitch using electroplated Ni as structural material with sputtered Ru covering contact interfaces.

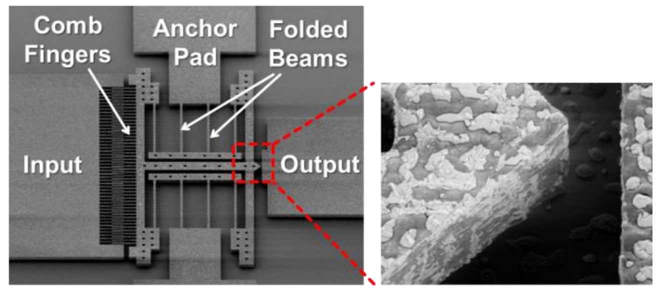
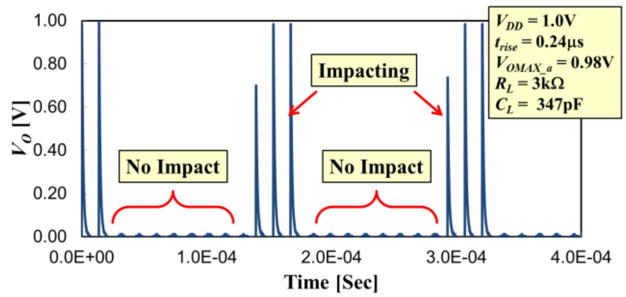


Fig. 5: SEM photos of the poly silicon resoswitch with Pt-silicide covering the entire structure.

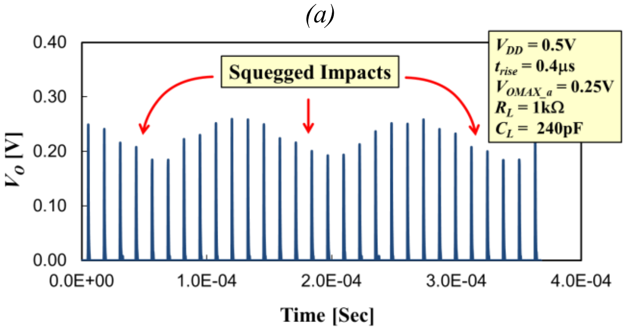
Polycide devices were achieved by first fabricating one-mask polysilicon device, coating them with 25nm of Pt via atomic layer deposition (ALD), then RTA annealing for 3 mins. to form platinum polycide. The polycide forms only over polysilicon, allowing simple removal of unreacted Pt over oxide mesa sidewalls via liquid regia. The end result is a polycided resoswitch that actually sports a lower contact resistance than the Ru-coated polysilicon devices of [1], since the polycide layer actually ends up being thicker than [1]'s 2-5nm Ru coating. Fig. 5 presents SEMs of the polycide device. Here, somewhat non-uniform silicidation [4] over the polysilicon surface does increase the contact resistance over what could have been, but still delivers sufficient conductivity for charge pumping of MEMS devices.

MEASUREMENT RESULTS

Fig. 6(a) and (b) present voltage output waveforms for the fabricated Ni/Ru and PtSi resoswitches, respectively, when driven hard enough to impact across 1000nm switch gaps. Clearly, the softer Ni/Ru contact interface induces considerable squegging, where periods of no contact are clearly visible. On the other hand, the polycide device displays much less squegging and appears to make contact at all times, although some impacts are less forceful than others, so achieve larger contact resistances, hence, slightly lower output voltages. Using (1) with the parameters summarized in Fig. 6, the contact resistances are found to be 49Ω and 870Ω for the Ni/Ru and PtSi devices, respectively. These are larger than desired for high power converters, but are comfortably sufficient for low power, high voltage charge pump applications, like MEMS dc biasing.



(a)



(b)

Fig. 6: Squegged output waveforms of the (a) Ni/Ru and (b) PtSi resoswitches tested using the circuit of Figure 1. Here, both resoswitches had switch axis gaps of 1000nm.

Fig. 7 presents the measured output waveform from a resoswitch identical to that of Fig. 1(a), but with a smaller switch gap of only 500nm. Here, the smaller gapped device exhibits much less squegging, in agreement with simulation. Fig. 8 further shows that placement of actuating comb fingers on the same side as output electrode suffers less squegging than configuring them on opposite sides.

CONCLUSIONS

The reduction of squegging demonstrated here not only solves an important issue with resoswitches that previously constrained the operation frequency of charge pumps using them, but also identifies polycides or silicides as compelling contact interfaces. Although the use of a polycide contact yielded a rather high contact resistance for the low frequency switches demonstrated here, higher frequency disk-based resoswitches, such as demonstrated in [2], should exhibit much smaller resistances, since their impact force is much larger. With high frequency, no squegging, and potentially good contact resistance, disk resoswitches using polycide material might just fit the bill for their targeted power amplifier and converter applications.

Acknowledgement: This work was funded by DARPA under the NEMS Program.

REFERENCES

[1] Y. Lin, *et al.,* "A micromechanical resonant charge pump," in *Proc., Transduers 2013*, Barcelona, Spain, Jun. 2013, pp. 1727-1730.

[2] Y. Lin, *et al.,* "The micromechanical resonant switch

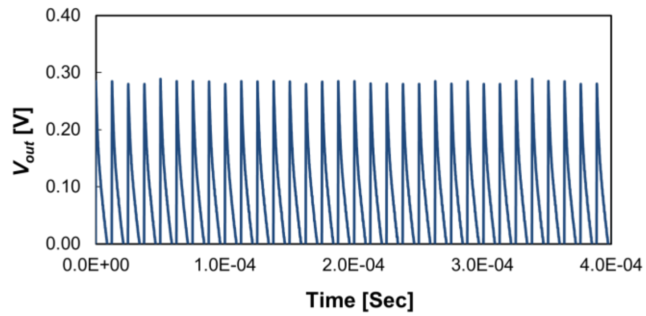
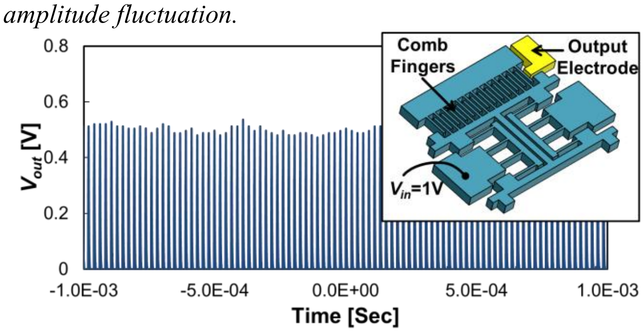
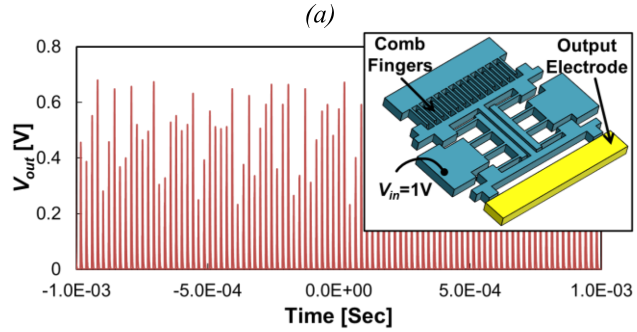


Fig. 7: Output waveform of the PtSi resoswitch with a 500nm lateral switch gap showing much less squegging induced amplitude fluctuation.



(a)



(b)

Fig. 8: Output waveforms of the PtSi resoswitch with output electrode placed on (a) the same side and (b) opposite side of the actuating comb fingers.

(“Resoswitch”)," in *Technical Digest, 2008 Solid-State Sensor, Actuator, and Microsystems Workshop*, Hiltion Head, SC, Jun. 2008, pp. 40-43.

[3] C. Budd and F. Dux, "Chattering and related behaviour in impact oscillators," *Philosophical Transactions of the Royal Society of London. Series A: Physical And Engieering Sciences,* vol. 347, no. 1683, pp. 365-389, May 1994.

[4] P. Shrestha, *et al.,* "Investigation of Volmer-Weber growth during the nucleation phase of ALD platinum thin films and template based platinum nanotubes," *ECS Transactions,* vol. 33, no. 2, pp. 127-134, 2010.

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