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Charge-Biased Vibrating Micromechanical Resonators

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***Abstract*—MEMS-based capacitively-transduced micromechanical disk resonators have been demonstrated that dispense with conventional high voltage source direct dc-biasing and instead use stored charge on their resonant structures to achieve equivalent performance. In particular, a 103-MHz micromechanical contour-mode disk resonator has been demonstrated with the same *Q* (~25,000) and series motional resistance when charge-biased as when biased via a dc voltage source directly connected to its resonant structure. For a stand-alone charge-biased resonator, leaky discharging of the resonant structure in vacuum attenuates the output signal by 3dB after 900s. If a 0.18μF capacitor is charged and attached to the floating resonant structure, the resonator can operate for more than 8.5 days before its signal is attenuated by 3dB, which clearly illustrates the long-term efficacy of this charge-biasing approach. Frequency shifts caused by discharge-induced bias shifts are less than 2.5 ppm per hour with charged 0.18μF capacitor, making plausible a "charge-and-refresh" operating mode with one-hour (or longer) refresh intervals.**

***Keywords*—micromechanical, resonator, filter, high-*Q*, charge-bias, dc-bias, discharge time, charge leakage.**

I. Introduction

With on-chip *Q*'s in the thousands at frequencies from 10-2000 MHz [1]-[4], thermal stabilities on par with quartz [5], and impressive aging characteristics [6], vibrating RF MEMS resonators have become very attractive as frequency generation and filtering devices for future wireless applications. Among the transduction approaches used so far for these micromechanical devices, capacitive transduction offers many benefits, including: (1) a non-intrusive coupling to the resonator that allows much higher *Q*'s than achievable via other transducer methods; (2) greater geometric flexibility; (3) input/output port flexibility, allowing balanced differential or skewed excitation and detection; (4) mode switching from an *LCR* tank, to an open circuit, to a mixer-filter; and (5) a simple, non-exotic fabrication technology largely compatible with transistor integrated circuits. Capacitive transduction, however, does have drawbacks, including: (1) the need for relatively large (e.g., >3V) dc-bias voltages to attain matchable impedances; and (2) susceptibility to noise on the dc-bias lines or in the power supply (e.g., due to digital switching) that cause resonator frequency instability via its electrical stiffness [5].

Pursuant to alleviating the above issues, this work demonstrates capacitively transduced micromechanical disk resonators that dispense with conventional high voltage source direct dc-biasing and instead use stored charge on their resonant structures to achieve equivalent performance. In particular, a 103-MHz micromechanical contour-mode disk resonator has been demonstrated with the same *Q* (~25,000) and series motional resistance when charge-biased, as when biased via a dc voltage source directly connected to its resonant structure. In removing the need for a dc voltage source, charge-biasing affords several important advantages, including: (1) better immunity against power supply variations, which should facilitate integration into mixed-signal analog-digital communication circuits; (2) an ability to supply an effective bias voltage higher than the system power supply without the need for power hungry charge pumping; and (3) with either very slow leakage rates or alternative methods for charging, removal of the interconnects that would normally be needed to supply the dc-bias voltage to the resonant structure. These advantages stand to greatly simplify the use of micromechanical resonator technology in portable systems.

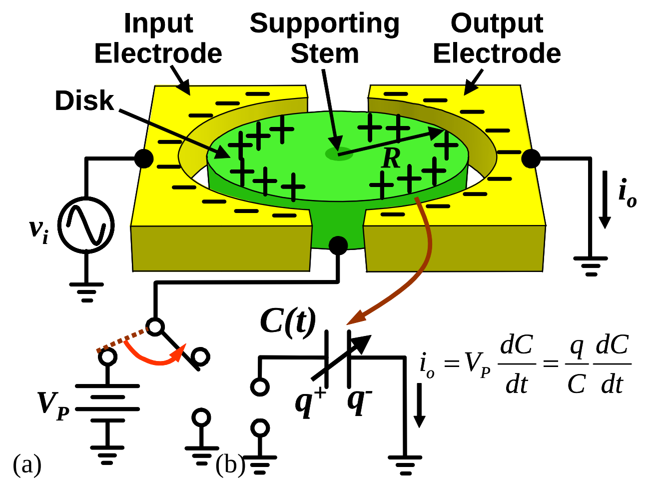

Fig. 1: (a) Perspective-view schematic of a contour-mode disk resonator with a switch to allow either direct dc-biased or charge-biased configurations. (b) Equivalent model for output current generated by the dc-biased time-varying capacitance present during disk vibration.

II. Operation of Charge-Biased Resonators

Fig. 1(a) presents the perspective-view schematic of a contour-mode disk resonator in a typical two-port bias (with a switch for either dc- or charge-biasing), excitation, and measurement configuration. The micromechanical disk design used in this work to compare charge- and direct dc-biased performance comprises a 26μm-diameter doped-polysilicon disk suspended 650nm from the substrate by a stem at its center,

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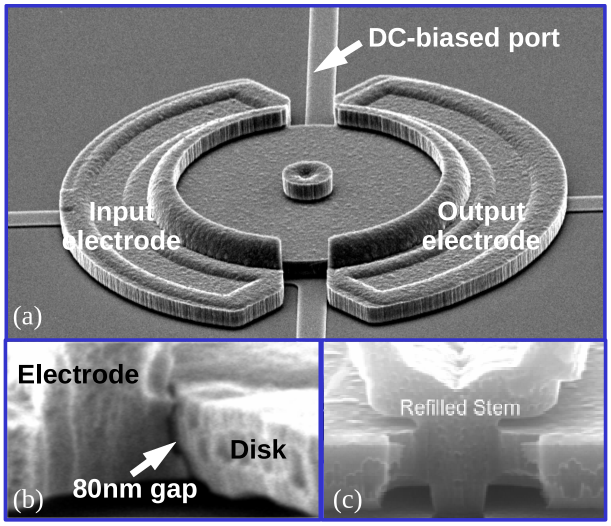

Fig. 2: (a) Wide-view (b) gap-zoomed and (c) refilled-stem-zoomed scanning electron micrographs (SEM's) of a fabricated 103-MHz micromechanical disk resonator.

with two doped-polysilicon electrodes spaced 80nm from the disk edges, each covering about half of the disk's circumference. Several such disk resonators were fabricated via a three-polysilicon self-aligned-and-filled stem process used previously to achieve GHz frequency resonators [2]. Fig. 2 presents an SEM of a fabricated 103-MHz disk and zoom-in shots on its 80nm electrode-to-resonator gap spacing and its central support, clearly showing the refilled stem anchor.

Under conventional operation, a direct dc-bias voltage V_P (left switched circuit in Fig. 1(a)) is applied to the suspended structure through an electrode connected to its conductive stem, and an excitation ac signal v_i is applied to its input electrode. These two voltages combine to generate an electrostatic force at the frequency of v_i that drives the disk into a resonance mode shape where it expands and contracts radially around its perimeter (as shown in the ANSYS simulation of Fig. 3), generating a time-varying electrode-to-resonator capacitance as depicted in Fig. 1(b). An output current then ensues, governed by the expression in Fig. 1(b), that traces out a

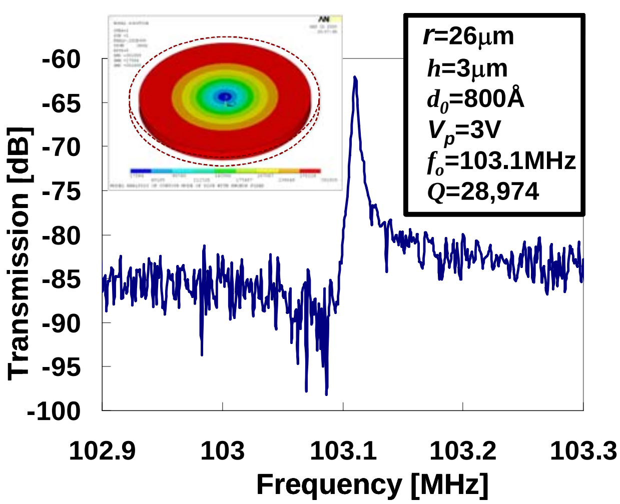

Fig. 3: ANSYS simulated mode shape and measured frequency response for a fabricated 103-MHz micromechanical contour-mode disk resonator under dc-biased operation.

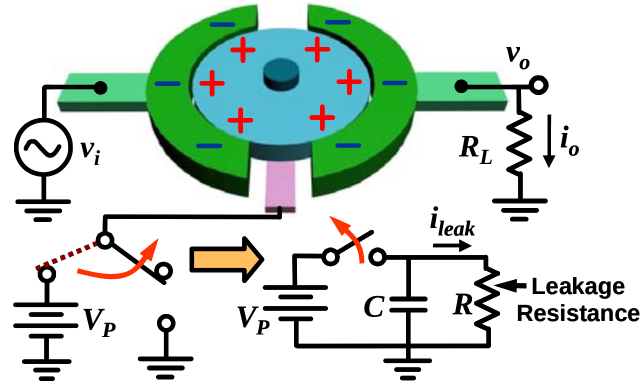

Fig. 4: Leaky discharging model for a charge-biased disk resonator.

very high Q bandpass biquad transfer function as the input frequency is swept. Fig. 3 presents a two-port-measured frequency characteristic using direct dc-biasing for a fabricated disk resonator vibrating in vacuum with a center frequency of 103.1MHz, and Q greater than 25,000.

To implement charge-biasing, the lead from the resonant structure to the dc-bias voltage source is abruptly broken, creating an open circuit, and leaving charge on the resonator structure as depicted in Fig. 1(a) to maintain its bias state. Since the bias voltage is retained via the charge stored in the capacitance between the suspended structure and its surrounding electrodes and ground planes, this resonator operates nearly identically to the direct dc-biased one described above. (The operation is identical if the total capacitance holding the charge is much larger than the motional capacitance between the resonator and its input electrode.) Since the resonator is electrically well isolated from its surroundings, its charge leaks out very slowly, allowing the resonator to remain operational for long periods.

The leaky discharging performance of a charge-biased micromechanical resonator can be simulated using the simple discharging RC model shown in Fig. 4, which predicts the time constant $\tau = RC$ governing the rate at which charge on the resonator structure (or aiding capacitor) is drained. Here, R models the resistance of the effectively open-circuited resonant structure, which should be very large, but not necessarily infinite due to substrate and atmospheric (e.g., humidity) leakage; while C models the electrode-to-resonator overlap capacitance plus any additional capacitance from the bias port to ground.

III. Experimental Results

Of main interest, here, is the degree to which a charge-biased micromechanical resonator or circuit can mimic the performance of a direct dc voltage source-biased one. To insure consistent comparative data, the procedure for testing involved first measuring the frequency response of a pc-board-mounted resonator biased by a direct dc voltage source, then breaking the lead supplying the dc-bias voltage, at which point the resonator becomes charge-biased. Among the important parameters to measure are the resonance peak amplitude, the resonance frequency, and the Q, all as a function of time. Note that changes in resonance frequency and Q are

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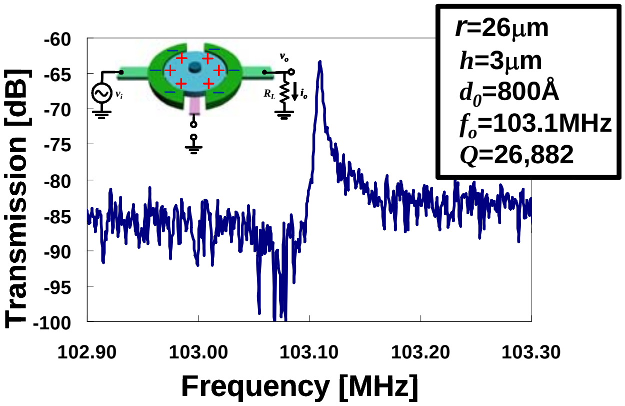

Fig. 5: A measured spectrum of a micromechanical contour-mode disk resonator under charge-biased operation, demonstrating similar performance with that of conventional dc-biased versions.

expected as stored charge is drained, since the associated bias voltage decrease causes a decrease in electrical stiffness [1], and in turn, an increase in total stiffness.

Fig. 5 presents the measured frequency characteristic for a fabricated 103-MHz micromechanical contour-mode disk resonator immediately after the dc-bias voltage source lead is broken, showing practically identical values for resonance frequency, Q (~25,000), and peak height (i.e., motional resistance) compared with those obtained under direct dc-biasing from Fig. 3. As expected, the performance of this resonator under charge-biased operation immediately after lifting the dc voltage source lead is every bit as good as that of any direct dc-biased counterpart. And this without the need for charge pumping circuitry (which can be turned off at this point, or at least given a very slow refresh rate for cases of leakage), and with the advantages of immunity from temperature-induced dc power supply voltage perturbations, or noise that would otherwise be collected by the dc-bias lines.

While the performance is good immediately after lifting the direct dc-bias, how long before leakage currents discharge the effective charge-bias to the point of noticeable performance degradation? To answer this question, Fig. 6 presents measured plots of resonant peak height versus time after the dc voltage source lead is broken for two cases: one where a stand-alone unassisted disk resonator is used; and another, where a 0.18μF capacitor is attached from the dc-bias pad to ground before removal of the dc voltage source.

In the case of the stand-alone charged biased resonator, leaky discharging of the resonant structure in vacuum attenuates the output signal by 3dB after 900s, as shown in Fig. 6(a). In addition, after 900s, the resonance frequency has changed by 41 ppm, and the Q has changed from 27,400 to 27,000, or 1.46%, as shown in Fig. 6(b). These are all acceptable deviations for most communication applications, meaning that a charge refresh time of 900s (or actually, even longer) would be permissible in an actual system. Based on the RC model of Fig. 4, and on a calculated total capacitance from the bias pad to ground of 113 fF, a time constant τ of 2444s and resistance R of 2.2×10^{16} Ω are extracted from the data of Fig. 6(a). The large value of R clearly indicates good isolation between the resonant structure and its surroundings.

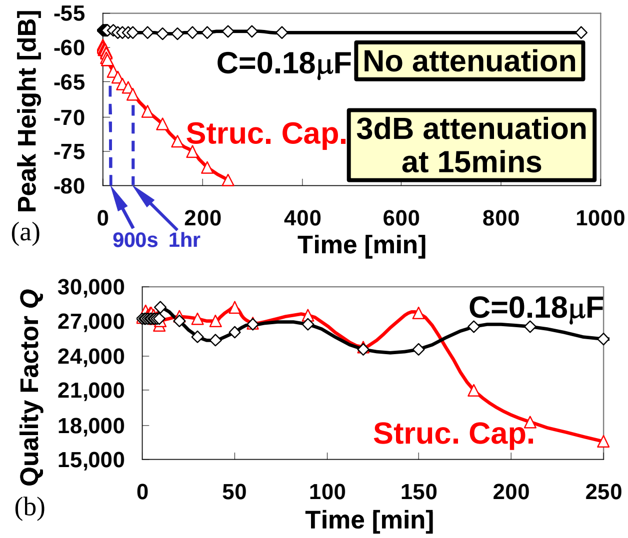

Fig. 6: Discharging response of a charged-biased micromechanical disk resonator. (a) Signal attenuation due to charge leakage. (b) Q versus discharging time.

If a longer refresh time is desired, this can be attained by merely connecting a relatively large capacitor in shunt with the dc-bias pad before removing the dc-bias voltage source, where the much larger charge held by the capacitor can keep the dc-bias in an acceptable range much longer than the resonator itself. For the case where a 0.18μF capacitor is charged and attached to its floating resonant structure, the disk resonator of this work can operate normally for more than 20 hours without any signal attenuation (shown in Fig. 6(a)) and still maintain similar Q's (shown in Fig. 6(b)). Longer term measurements reveal that it can operate for 8.5 days before its signal is attenuated by 3dB, which clearly illustrates the long-term efficacy of this charge-biasing approach. Frequency shifts caused by discharge-induced bias shifts are less than 2.5 ppm per hour with the 0.18μF capacitor, making plausible a DRAM-like "charge-and-refresh" operating mode with one-hour (or longer) refresh intervals. To turn off the device, an erase operation can be applied by merely connecting the structure to ground, which drains charge from the suspended structure, effectively zeroing its dc-bias and placing it in an "off" state (i.e., with no resonance response).

To gauge the efficacy of charge-biased operation under different operational environments, with some concern that moisture or other vapor mechanisms might steal charge from a

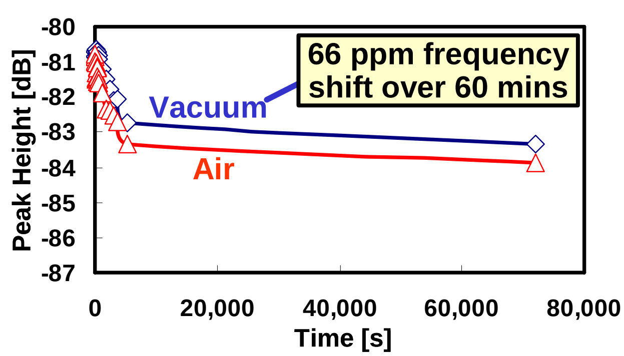

Fig. 7: Signal attenuation versus time for a charge-biased micromechanical disk resonator measured in vacuum and in air.

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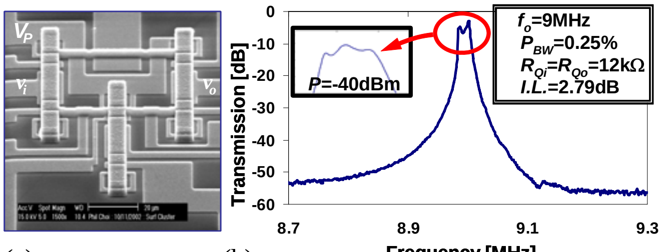

(a) (b)

Fig. 8: (a) An SEM and (b) measured frequency characteristic of a fabricated 9-MHz bridged micromechanical filter.

floating resonator structure at an accelerated rate, Fig. 7 presents measured plots of peak height versus time for charge-biased disks operating in vacuum and in air. Although some difference in the initial rate of discharge is seen up to 1,000 seconds, both rates seem to saturate at longer times. This phenomenon certainly merits more study, but one might initially hypothesize that a protective layer forms on the resonator surface over time that slows diffusion of charge-stealing particles.

IV. Charge-Biased Bridged Filters

To study the degradation versus time behavior of charge-biased micromechanical filter circuits, old (and leaky) dies for the bridged 3-resonator micromechanical filters of [7] were tested under charged-biased operation. The high leakage of the substrates housing these filters versus those for the previous disks likely derives from the use of a poorer nitride passivation film in the former, i.e., a 350nm-thick film versus a 1μm low-stress nitride used in the disk process. This observation emphasizes the importance of a quality surface layer to minimize undue leakage when using charge-biasing. In the meantime, for the measurements at hand, the poorer leakage performance did allow for accelerated observation of the degradation sequence for the filter devices.

Fig. 8 first presents the SEM and measured direct dc-biased frequency characteristic for one of the fabricated 9-MHz bridged micromechanical filters of [7], showing an insertion loss of 2.79 dB for a 0.25% bandwidth centered at 9 MHz with an impressive 51 dB of stopband rejection [7].

Fig. 9 presents measured frequency characteristics versus time for the filter of Fig. 8 under charge-biased operation. As shown, even under accelerated charge leakage conditions, the filter response retains its overall shape and bandwidth as its passband height shrinks with time. However, the frequency of the filter changes very quickly with time, mainly because the change in electrical stiffness [1] brought about via the ensuing shift in effective dc-bias is on par with the relatively small mechanical stiffnesses of its constituent clamped-clamped beam resonators [1]. (The much stiffer disk resonators of the previous section would suffer much smaller frequency shifts.) The frequency shift is on the order of 2,500 ppm shift over 60s, to be compared with the 66 ppm over 60 mins. measured for charge-biased disk resonators (on a less leaky substrate). Although the rate of change for the filter was measured under accelerated charge leakage conditions, so is much worse than would actually be seen, these results still illustrate how electrical stiffness can be troublesome under charge-biased operation, and discourage the use of low stiffness resonators when charge-biasing.

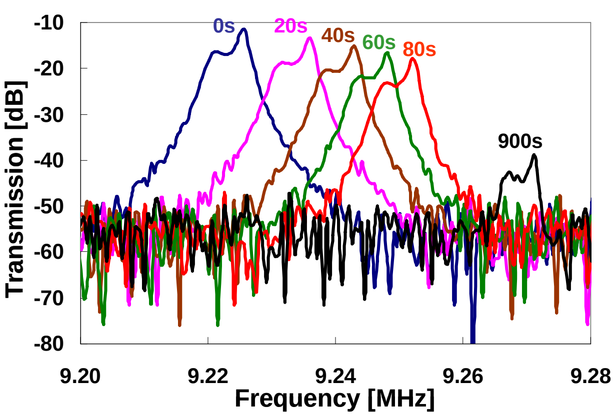

Fig. 9: Measured frequency characteristics versus time for a charge-biased bridged micromechanical filter under accelerated discharging.

V. Conclusions

Micromechanical disk resonators dispensing with conventional high voltage source direct dc-biasing and instead using stored charge on their resonant structures to achieve equivalent performance have been demonstrated. In particular, a 103-MHz micromechanical contour-mode disk resonator has been demonstrated with the same *Q* and series motional resistance when charge-biased, as when biased via a dc voltage source directly connected to its resonant structure. For a stand-alone charge-biased resonator, leaky discharging of the resonant structure in vacuum attenuates the output signal by 3dB after 900s. If a 0.18μF capacitor is charged and attached to the floating resonant structure, the resonator can operate for more than 8.5 days before its signal is attenuated by 3dB, which clearly illustrates the long-term efficacy of this charge-biasing approach.

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