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High-C_x/C_o Hollow Disk Resonators

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***Abstract*—Mass and stiffness reduction via hollowing out a capacitive-gap transduced radial mode disk resonator while maintaining resonance frequency and transduction area has enabled a measured electromechanical coupling strength (C_x/C_o) of 0.56% at 123 MHz without electrode-to-resonator gap scaling. This is a more than 5× improvement in C_x/C_o compared with a conventional radial contour-mode disk at the same frequency. C_x/C_o increases like this stand to improve the passbands of channel-select filters targeted for low power wireless transceivers, as well as lower the power of MEMS-based oscillators.**

Keywords—MEMS, resonator, polysilicon, electromechanical coupling, quality factor

I. INTRODUCTION

Capacitive-gap transduced micromechanical resonators routinely post Q's several times higher than piezoelectric counterparts, making them the preferred platform for HF and low-VHF (e.g., 60-MHz) timing oscillators [1], as well as very narrow-band (e.g., channel-select) low-loss filters [2]. However, the small electromechanical coupling C_x/C_o of such resonators at higher frequency prevents sub-μW GSM reference oscillators [3] and complicates realization of wider bandwidth filters. To the latter point, Fig. 1 illustrates how raising C_x/C_o from 0.11% to 0.56% nicely corrects the passband distortion in a 123-MHz, 600-kHz bandwidth micromechanical filter.

Recent fabrication technology that enables 13-nm gaps in radial-mode disk resonators to now make available C_x/C_o's of 1.62% at 60 MHz stand poised to solve the low-C_x/C_o problem, where the projected C_x/C_o at 123 MHz with 13-nm gaps and 5.5V bias is 1.05% [4]. Still, a method for raising C_x/C_o without such small gaps might be preferable, especially where device yield is paramount, e.g., for a high volume product.

II. HIGH C_X/C_O HOLLOW DISK RESONATORS

This work aims to retain 40-nm gaps towards higher C_x/C_o by strategically reducing the stiffness of the resonator, which in turn raises C_x/C_o via

$$\frac{C_x}{C_o} = \frac{V_P^2}{k_m}\frac{\varepsilon_o A_o}{d_o^3} = \frac{V_P^2}{\omega_o^2 m_m}\frac{\varepsilon_o A_o}{d_o^3} \qquad (1)$$

where C_x, C_o, ω_o, k_m, and m_m are the motional capacitance, overlap capacitance, radian resonance frequency, dynamic mechanical stiffness, and dynamic mass, respectively, of the resonant structure; V_P is the applied dc-bias voltage; ε_o is the free space permittivity; and A_o and d_o are the electrode-to-resonator overlap and gap, respectively. Eq. (1) shows that for a given frequency a reduction in stiffness k_m generally implies a simultaneous reduction in mass m_m. To attain higher C_x/C_o, just remove mass.

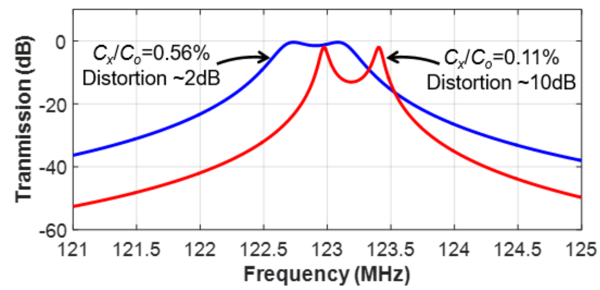

Fig. 1: Measured frequency response curves for a 123-MHz hollow disk resonator as a function of dc bias voltage.

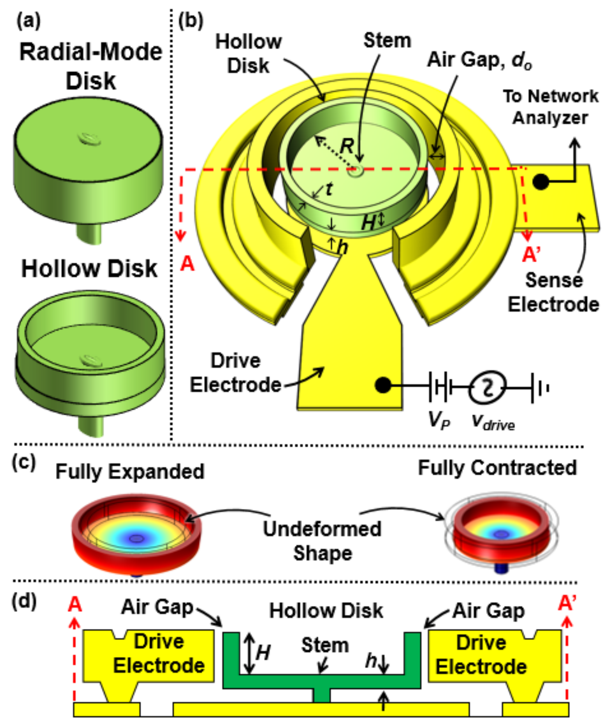

Fig. 2: Comparison of (a) a solid radial-mode disk resonator with (b) the hollow disk device described herein in a typical operating circuit. (c) Hollow disk mode shape in fully expanded and contracted shapes. (d) Cross-sectional view.

This work reduces mass by simply hollowing out a disk resonator, then operating it in a largely radial mode. Fig.2(a) compares a conventional radial mode disk resonator [5] with the hollow disk one demonstrated herein. The main difference between the two is the lack of material in the inner bulk of the latter device, essentially achieved by depositing less structural material. Here, the same sequence of surface-micromachining depositions as used in a conventional disk process [5], but with different thicknesses and etch ordering, achieves the desired hollow disk cross-section in Fig. 2(c). Fig. 3 presents portions of the process and SEM's of a finished polysilicon device, with zoom-in's on the edge ring, gap, and overlapping I/O electrodes.

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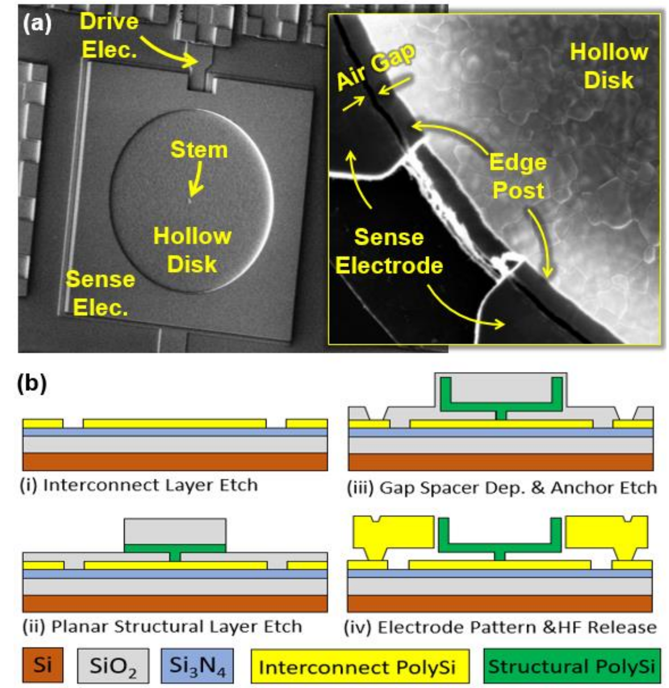

Fig. 3: (a) SEM of a fabricated polysilicon hollow disk resonator. (b) Fabrication process flow.

As shown in Fig.2(b), this hollow disk resonator essentially combines a regular (but very thin) bottom disk of radius R with a high-aspect-ratio circular edge ring of width of t that provides more coupling to the electrodes. Mechanically, the bottom disk sets the stiffness, while the edge ring contributes additional mass, lowering the resonance frequency, which takes the form

$$f_o = \left\{ \frac{K_{mat}}{2R} \sqrt{\frac{E}{\rho}} \right\} \frac{1}{\sqrt{1 + \Delta m / m_m}} \qquad (2)$$

where the term in the curly bracket is the resonance frequency of a radial-contour mode disk with a radius R, K_{mat} is a parameter dependent upon material properties (0.654 for polysilicon [6]), E is the Young's modulus, ρ is the Poisson ratio, Δm is the additional mass loading from the edge ring, and m_m is the equivalent disk mass referenced to the edge.

The finite element analysis (FEA) simulated mode shape in Fig.2(c) does resemble the mode shape of a conventional radial-contour mode disk with added mass near its edges, confirming the logic behind (2).

III. Measurement Results

The fabrication process yielding the device of Fig. 3 was largely successful, except for high film electrical resistance caused by issues with phosphorous-doping. This compromised Q's somewhat. Fortunately, these resistance issues did not negate the focus of this work on increasing C_x/C_o.

Fig.4 presents measured frequency response curves for a 123-MHz hollow disk resonator with 37-nm electrode-to-edge ring gaps at various dc-bias voltages V_P. Consistent with (1), C_x/C_o values rise from 0.17% at V_P=5V to 0.56% at V_P=9.5V, the latter of which is 5 times larger than the 0.11% for a conventional

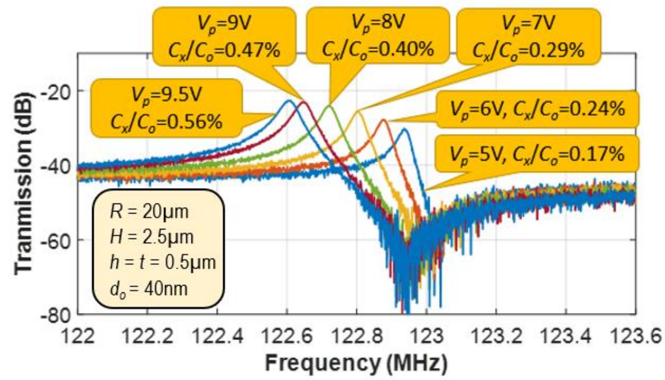

Fig. 4: Measured frequency response curves under 50µTorr vacuum for a 123-MHz hollow disk resonator as a function of dc bias voltage.

TABLE I. Comparison Chart with Other Technologies

Ref.	f_o (MHz)	C_x/C_o (k_t^2) (%)	R_x (Ω)	Q	k_t^2-Q	Area (µm²)
[7]	85	0.86	125	2,100	18	10,000
[8]	149	0.48	460	10,000	48	21,200
[4]	60	1.62	54	29,640	480	3,200
This Work	123	0.56	1,250	2,271	13	1,600

filled radial-contour mode disk with the same gaps. The benefits to filter performance are clear from Fig. 1.

The measured Q of 2,271 is well short of the >10,000 often seen for capacitive-gap transduced polysilicon devices. While higher than expected electrical resistance likely contributes to this, finite-element simulation reveals transverse (vertical) motion of the bottom disk portion of the resonant structure that radiates energy into the stem anchor and subsequently to the substrate, thereby lowering Q. A more symmetric design, with edge rings both above and below the thin disk structure, is one solution to this problem. Work to confirm this is in progress.

Even with loss issues, the k_t^2-Q value of 12.7 for this resonator is decent compared with some of the best piezoelectric alternatives in Table I. The 480 mark of the 13-nm-gap capacitive-gap transduced device of [4] remains a target to match.

IV. Conclusions

The increase in C_x/C_o to 0.56% at 123 MHz is impressive, given that it does not require gap scaling. When combined with gap scaling, some very large C_x/C_o values might soon be possible. Reasonable expectation that the Q of this device will increase to a value appropriate for capacitive-gap transduced resonators, e.g., 20,000, might eventually yield k_t^2-Q values on par with the enormous values posted by 13-nm-gap device of [4].

V. References

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