NOVEL TOUCH-FREE DRIVE, SENSE, AND TUNING MECHANISM FOR ALL-DIELECTRIC MICRO-SHELL GYROSCOPE

Raviv Perahia, Hung D. Nguyen, Lian X. Huang, Tracy J. Boden, Jonathan J. Lake, Deborah J. Kirby, Richard J. Joyce, Logan D. Sorenson, David T. Chang
HRL Laboratories, USA

ABSTRACT

This paper demonstrates, for the first time, touch-free electrical sensing and frequency tuning of an all-dielectric micro-shell gyroscope without electrically-conductive coatings. Current vibratory gyroscope technologies rely on an electrically-conductive structure or conductive coatings [1-6]. These conductive materials and coatings often compromise the quality factor (Q), thermal stability, and symmetry necessary to achieve navigation grade performance. The novel mechanism presented herein is based on the manipulation of electric fringe fields and their gradients. Several highly-doped Si electrode structures placed adjacent to the micro-shell can drive, sense, and frequency-tune the micro-shell as experimentally demonstrated in this paper. Micro-shell $n = 2$ wineglass vibration modes with $Q > 10^4$ and frequency splits $\Delta f < 50\text{Hz}$ are experimentally demonstrated using the touch-free gradient field transduction mechanism. Tuning of up to 4 Hz is demonstrated for a modest bias of 20V.

INTRODUCTION

The perceived benefit of a micro-scale navigation grade gyroscope is evident by the explosion in interest from commercial, academic, and government entities [7]. To date, MEMS scale vibratory gyroscopes have shown great promise but have yet to achieve navigation grade performance. The difficulty comes from a complex set of tradeoffs and requirements. This paper addresses a tradeoff between optimal structures, materials, and designs in the context of ultra-small devices ($< 10\text{ mm}^3$) that are fabricated only through processes currently available at MEMS foundries.

The use of a high Q , thermally-stable, structurally-isotropic dielectric material often conflicts with the need for electrically-conductive materials or coatings in traditional electrostatic drive/sense mechanisms [1-6]. A technique for transducing a vibrating dielectric micro-shell without placing dissipative conductive coatings directly on the structure will lead to higher performance by maintaining the high native mechanical Q of the dielectric structure [8]. Several experimental groups have recently shown that electric gradient forces can be used to efficiently drive nano-mechanical cantilevers [9-10], control optomechanical cavities [11], and sense acceleration [12]. In previous work, we demonstrated the ability to effectively drive a dielectric-only micro-shell gyroscope structure using electric gradient forces for the first time [13]. This paper reports experimental demonstration of the full drive, sense, and tuning functionality. It is now possible to design a gyroscope that is fundamentally limited by anchor and material loss of SiO_2 , which opens up the ability to reach frequency quality factor product greater than 10^9 as experimentally demonstrated for this material [8, 14]. In contrast to our previous work, the transduction mechanism is now fabricated from highly-doped silicon-on-insulator (SOI) wafers in a configuration that is readily amenable to full 3D integration.

The cylindrical shell geometry presented in this paper is beneficial both from manufacturing and performance perspectives. The hemispherical and similar curved shell geometry of structures reported in the literature often use non-standard and complex fabrication processes and materials including glass blowing, specialty glasses for wet etching, specialty epoxies, and

topographically-challenging deposition of electrodes pre- and post-hemispherical shell formation [1-6]. In contrast, the cylindrical micro-shell structure proposed here is wafer-scale manufacturable using standard bulk and surface micro-machining processes. The vertical nature of the shell will allow for future 3D wafer-scale integration of the high aspect ratio Si electrodes.

From a performance perspective, a cylindrical shell geometry has the advantage of lowest frequency for a given maximum shell diameter compared with curved/hemispherical shell structures. This is due to the lower effective modal stiffness and larger effective modal mass of cylindrical shells when operated in their wineglass modes. For a gyroscope, this translates into increased sensitivity. While blown glass curved-shell geometries have achieved very high Q s approaching 3×10^5 [4], this has only been achieved using shell diameters greater than 5 mm and minimum cross-sectional shell thicknesses greater than $13\text{ }\mu\text{m}$ due to the challenge of creating small and thin shells with these non-traditional MEMS processes. In contrast, due to its thin oxide sidewalls, the cylindrical shell developed here can be scaled to smaller total device volume while maintaining a low native wineglass resonance frequency for optimal gyroscope sensitivity.

Figure 1: (a) Schematic of drive & sense electrodes in close proximity to a cylindrical shell gyroscope structure. (b) Close up of the electrodes showing alternating potentials and electric field. (c) Fabricated highly-doped Si electrode chip.

DEVICE

The touch-free drive, sense, and tuning mechanism for an all-dielectric micro-shell gyroscope is shown in Fig. 1(a). The gyroscope comprises a cylindrical micro-shell structure and integrated drive and sense electrodes. The electrodes are positioned in close proximity to the micro-shell in order to transduce and detect wineglass vibration modes. Both micro-shell and electrode array include unique design features to mitigate known challenges that limit performance of current vibratory MEMS gyroscopes: film stress, structural asymmetry, anchor loss, and loss

contributions from the electrostatic drive/sense mechanism.

A 1.3 mm diameter, 350 μm tall, 2 μm thick, fabricated cylindrical vibratory micro-shell is shown in Fig. 2 on the left hand side. Compared to a shell with curved sidewalls, vertical sidewalls have fewer design constraints and allow for simpler fabrication using standard wafer-scale MEMS processes, resulting in a structure more compatible with the electrode array. The high aspect ratio of the sidewalls enables lower operating frequencies and increased capacitive area which maximizes drive amplitudes and sensitivity compared to those of curved wineglass structures of comparable diameter and height. Using finite element simulation the angular gain factor of cylindrical micro-shell is calculated to be $A_g = 0.26$, comparable to a hemispherical shell with the same diameter and thickness ($A_g = 0.3$) [15-16].

The cylindrical micro-shell is tethered to the anchor by a set of spokes. The spokes are engineered to reduce anchor loss and fabrication stress by isolating the vibrating shell from the substrate. Both the silica spokes and micro-shell are formed monolithically to avoid interfacial defects. The exclusive composition from SiO_2 eliminates anisotropy associated with crystalline materials (i.e. Si) as well as damping and thermal expansion mismatch. Coupled with the touch-free drive and sense mechanisms, the all-dielectric micro-shell gyroscope forgoes the complex manufacturing associated with the deposition of conductive electrodes on dielectric micro-shells (diamond, SiO_2 , etc.).

High-aspect-ratio vertical electrodes are fabricated from the heavily doped 100 μm -thick silicon device layer of an SOI wafer. A close-in SEM micrograph of the electrode array is shown in the inset of Fig. 2. Vertical electrodes with 4 μm spacing are achieved using high aspect Si etching (20:1) producing high electrode density along the micro-shell periphery. Fabricating the electrodes from highly doped SOI allows for the electrodes to conform to the periphery of the micro-shell. Furthermore, this electrode geometry presents a clear path towards 3D wafer-scale integration with the micro-shell.

Figure 2: SEM micrograph of fabricated silica micro-shell ($D_s = 1.3$ mm, height $H_s = 350$ μm , thickness $T_s = 2$ μm) with adjacent highly doped silicon electrodes. The micro-shell is suspended from the underlying silicon handle wafer by a 10 μm silica anchor post.

EXPERIMENT AND RESULTS

The electrode dies, comprising of two sets of electrodes spatially-separated by 45 degrees, are mounted on printed circuit boards (PCBs) as shown in Fig. 3(a). The electrode tips overhang the PCB allowing for close proximity placement relative to the micro-shell. The PCBs provide an interface from die level wire bondable bus bars to coaxial lines that facilitate both biasing and current sensing depending on the transduction mode. Within each electrode set, individual electrodes are wire-bonded to the two bus bars in an alternating fashion, forming inter-digitated electrodes

with alternating potentials. The PCBs are brought into proximity and aligned to the micro-shell in a vacuum chamber ($P = 3 \times 10^{-5}$ Torr) as shown schematically in Fig. 3(b). The top of the electrodes are aligned with the top of the micro-shell. Voltage applied between adjacent electrodes generates fringe fields that interact with the dielectric shell forming the basis for the transduction scheme. In this demonstration, two sets of electrodes are used to drive (E2) and sense (E3) an $n = 2$ wineglass mode. A Laser Doppler Vibrometer (LDV) focused on the side-wall of the micro-shell provides a reference signal of the vibrational motion for verification of the electrical read out. The focused LDV beam can be seen as a red spot at the periphery of the micro-shell shown in Fig. 3(c).

Figure 3: (a) Photograph of PCB-mounted electrode chip. (b) Schematic of micro-shell and PCB-mounted electrodes. (c) Top view of test configuration with two electrode dies (each composed of two electrode sets). The micro-shell ($D_s = 927$ μm , height $H_s = 350$ μm , thickness $T_s = 2$ μm) sits atop a silica anchor ($D_a = 100$ μm , $H_a = 10$ μm , spoke width $W = 67$ μm). Optical beam of the reference LDV, visible in red, is positioned between the electrodes.

Mode spectroscopy is carried out on the micro-shell by applying an electrical pulse (15 V, 10 μs width) across the E2 electrodes and measuring the time response of the motion using the LDV. The Fourier transform (FT) spectrum of the resultant motional response is presented in Fig. 4(a) (dotted red line). Subsequently, the same excitation and measurement scheme is applied to the E3 electrodes (blue line). The electrode dies are aligned at equal but opposite positions from the micro-shell such that the LDV spectra of the vibration generated by electrodes E2 and E3 are approximately the same in amplitude. Several prominent modes are readily apparent in the spectra. Using finite element (FE) simulations, the mode at $f = 12.74$ kHz is identified as the $n = 2$ wineglass mode of interest. The simulated wineglass mode pattern, shown in Fig. 4(b), indicates that motion is predominantly confined to the top rim the cylindrical micro-shell, a feature that may aid in the reduction of anchor loss. The observed lower frequency vibration modes are expected to be rocking modes from the FE analysis. The FE result of the simple rocking motion is shown in Fig. 4(c). To determine the quality factor of the $n = 2$ wineglass mode, a biased sine wave excitation applied across the E2 electrodes ($V_{p-p} = 2$ V, $V_{\text{offset}} = 1$ V) is swept in frequency and

the resultant vibration amplitude measured using the LDV. A Lorentzian peak exhibiting a quality factor $Q > 10^4$ is shown in the inset of Fig. 4(a).

Figure 4: (a) Fourier-transformed impulse response measured by laser vibrometer (LDV). Inset – swept-sine measurement of $n = 2$ wineglass mode. (b) Finite-element simulation of $n = 2$ wineglass mode in a cylindrical micro-shell geometry. (c) Finite-element simulation of lower order rocking mode of cylindrical micro-shell geometry.

After both E2 and E3 electrode sets were aligned to the micro-shell and proven capable of driving it to the same vibration amplitude, a full drive and sense measurement was performed. Once again, a swept-sine source is applied to drive electrode E2 ($V_{p-p} = 2$ V, $V_{offset} = 1$ V). One pole of the sense electrode E3 is biased ($V_{dc} = 20$ V) while the second pole is connected to a trans-impedance amplifier with a gain of nearly 50 M Ω . Matching frequency sweeps (Fig. 5) that capture the two nearly degenerate $n = 2$ wineglass modes were measured with both the LDV (blue line) and the sense electrodes (dotted red line). Frequency mode splitting of $\Delta f \sim 50$ Hz is observed, with the high-frequency mode showing significantly more sensitivity to the E2 drive, indicating favorable vibration pattern alignment with the drive and sense electrodes. The low-frequency mode is nearly un-observable in the electrical response due to spatial orthogonality of the wineglass modes. Interaction between the parasitic feed-through and the motional response results in the characteristic anti-resonance in proximity to the resonance as observed in the electrical response.

Figure 5: Swept-sine sense electrode measurement driven on E2 and sensed on E3 ($g_{TIA} = 5 \times 10^7$ Ω) and corresponding LDV measurement.

To confirm that the sense signal is indeed a measure of the vibration and coming from the sense electrode, the DC bias applied to the sense electrode, E3, was varied from 0 to 20 V while keeping the drive amplitude constant. The LDV measured peaks (Fig. 6(a)) tune towards lower frequency with increasing voltage. The sense electrode peaks (Fig. 6(b)) perfectly follow the LDV peaks to lower frequency but with increased amplitude.

Figure 6: Swept sine measurement of mode amplitude ($f=12.74$ kHz) with (a) LDV and (b) E3 sense electrode. Modes exhibit red detuning as a function of increased bias voltage on the sense electrode (E3).

A summary of mode frequency and sense signal amplitude is shown in Fig. 7. The sense amplitude increases nearly linearly with increased bias, thus confirming the sense mechanism is an electrostatic effect. As the bias across electrode set E3 is increased, the strength of the fringe field increases and the total charge stored in a capacitor formed by E3 electrodes and the micro-shell must correspondingly increase. Thus, for the same mechanical motion, a larger current is generated. The micro-shell frequency tunes down and is nearly quadratic with bias voltage. This red detuning phenomena is consistent with spring softening in electrostatically-transduced devices. The maximum tuning range at 20 V bias is 4 Hz. This range would allow frequency mode-matching on a gyroscope structure with frequency splits of < 1 Hz. Even for this prototype structure with frequency splits of 50 Hz, due to the quadratic nature of the tuning, only 70 V would be needed for perfect mode matching. To the authors' knowledge, this is the first demonstration of tuning a high Q resonant gyroscope structure via gradient forces.

Figure 7: Spring softening frequency shift and sense mode amplitude (including parasitic feed through) vs. sense bias.

CONCLUSION

We reported on a technique for driving, sensing, and tuning a dielectric micro-shell gyroscope without the need for conductive structural materials or conductive coatings on dielectric structures. Shell vibratory motion is transduced and measured using a fully non-contact gradient field transduction mechanism. A unique all SiO_2 cylindrical micro-shell has been fabricated and tested in a gyroscope configuration. Wineglass $n = 2$ vibration modes with $Q > 10^4$ and frequency splits $\Delta f < 50$ Hz are experimentally demonstrated. Frequency tuning of up to 4 Hz is demonstrated for a modest bias of 20 V.

All aspects of the gyroscope architecture presented herein, including the cylindrical micro-shell and doped Si electrode arrays, are designed to address key limitations that have hindered current MEMS vibratory gyroscope from achieving navigation grade performance. Efficiently transducing the cylindrical micro-shell without electrically conductive coatings paves a path towards achieving material limited gyroscope performance and therefore navigation-grade performance. While the current testing was carried out using separate dies, the geometry is fully amenable to full wafer-scale 3D integration without the introduction of specialty processes.

Future work will focus on achieving material limited gyroscope performance by improving fabrication, spoke design, reducing mechanical stress, and reducing parasitic capacitance of the electrodes.

ACKNOWLEDGMENTS

The authors would like to acknowledge B. Holden, M. Cline, and F. Stratton for the fabrication effort and R. McElwain for assistance in testing.

REFERENCES

- [1] N. Yazdi, F. Ayazi, K. Najafi, Proc. IEEE, Vol.86, pp.1640-1659, 1998.
- [2] S. A. Zotov, A. A. Trusov, A. M. Shkel, J. MEMS, Vol. 21, No. 3, pp. 509-510, 2012.
- [3] L. D. Sorenson, P. Shao, F. Ayazi, Proc. IEEE MEMS 2013, pp. 169-172, 2013.
- [4] J. Cho, J.-K. Woo, J. Yan, R. L. Peterson, K. Najafi, IEEE Transducers 2013, pp. 1847-1850, 2013.
- [5] A. Heidari, et. al., IEEE Transducers 2013, pp. 2415-2418, 2013.
- [6] X. Luo, C. K. Eun, Y. B. Gianchandani, IEEE MEMS 2014, pp. 64-67, 2014.
- [7] D. K. Shaeffer, IEEE Comm. Magazine, Vol. 5, pp. 100-109, 2013.
- [8] R. Sandberg, K. Mølhave, A. Boisen, W. Svendsen, J. Micromech. Microeng., Vol. 15, pp. 2249-2253, 2005.
- [9] Q. P. Unterreithmeier, E. M. Weig, J. P. Kotthaus, Nature, Vol. 458, pp. 1001-1004, 2009.
- [10] S. Schmid, C. Hierold, A. Boisen, J. Applied Phys., Vol. 107, p. 54510, 2010.
- [11] K. H. Lee, T. G. McRae, G. I. Harris, J. Knittel, W. P. Bowen, PRL, Vol. 104, p. 123604, 2010.
- [12] S. Aoyagi, Y. C. Tai, IEEE Transducers 2003, pp. 1382-1386, 2003.
- [13] R. Perahia et. al., IEEE MEMS 2014, pp. 721-724, 2014.
- [14] W. Zhengzheng et. al, IEEE MEMS 2013, pp. 122-125, 2013.
- [15] D. M. Rozelle, 19th AAS/AIAA Space Flight Mechanics Meeting, pp. 1157-1178, 2009.
- [16] A. Meyer, D. Rozelle, IEEE/ION PLANS 2012, pp. 24-29, 2012.

CONTACT

*R. Perahia, tel: +1-310-317-5612; RPERAHIA@HRL.com