EPITAXIALLY-GROWN THICK POLYSILICON FOR BAW DISK RESONATOR GYROSCOPES WITH VERY LOW DISSIPATION

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ABSTRACT

This paper reports, for the first time, on characterization of gyroscopic modes in solid epi-poly disk resonators, showing Qs exceeding 1M at ~3MHz with a maximum $f.Q$ of 4.2ex10^{12}, and on fabrication challenges associated with implementation of solid disk BAW gyroscopes on thick (45µm) epitaxially-grown polysilicon. Our work reveals that the isotropic nature of epi-poly not only enables degenerate n=2 wine-glass modes, but more importantly produces balanced n=3 modes with extremely low anchor loss, both of which are not seen in <100> single crystalline silicon (SCS). Unlike <111> SCS, degenerate modes in epi-poly substrates are insensitive to crystallographic plane misalignments, offering a greater potential for mass production. The n=3 modes of epi-poly disks provide better substrate decoupling compared to their n=2 counterparts, leading to higher robustness against vibration and stress variation for gyro applications. A reduced-temperature HARPSS process is developed to fabricate an epi-poly n=3 solid-disk BAW gyro having nano-gap electrodes with Q of 350k at 3MHz and linear scale factor in mode-matched operation.

WHY EPI-POLY?

Silicon disks, both as center and side supported resonators, are commonly fabricated in the <100> SCS substrate, owing to its compatibility with foundry processing and large commercial availability. However, for the n=3 mode, center-supported <100> SCS disk resonators undergo shear motion at the center of the disk due to non-uniform deformation of antinodes caused by material anisotropy. This causes the n=3 mode to suffer from large dissipation through the support, as shown in figure 1. Hence, center-supported disk resonators must contain decoupling structures to improve Q_{ANCHOR} [1,2]. But the inclusion of such structures also introduces additional thermo-elastic damping, thereby limiting Q to values much lower than the intrinsic Akhiezer limit [2]. Ideally, <111> SCS disks are in-plane isotropic for the n=3 elliptical modes. However, their out-of-plane components are different, causing a large inherent frequency mode split. Therefore, it is desirable to explore the potential of an isotropic substrate such as polysilicon as an alternative material for MEMS BAW gyroscope applications. While it is possible to deposit doped polysilicon using LPCVD process, achievable film thickness is limited by the film stress to less than 10 microns, and devices made from thin films are susceptible to out-of-plane spurious modes. The use of a thick epitaxially grown layer negates these disadvantages and enables in-plane BAW modes that are immune to influences from out-of-plane spurious modes while providing larger capacitive area for efficient transduction.

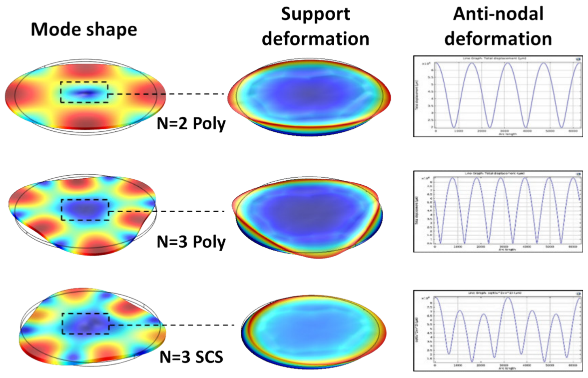

Figure 1: Comparison between polysilicon and <100> SCS gyroscopic modes in terms of deformation of the center post as a result of anti-nodal deformation. The SCS disk has a shear deformation at the center due to material anisotropy, which increases anchor loss in center-supported resonators.

ANCHOR LOSS SIMULATIONS

To verify the advantages of the isotropic epi-polysilicon substrate, anchor loss for center supported disks are compared for <100>, <111> silicon and epi-polysilicon using finite-element simulations. A 45um thick, 2mm disk was simulated in COMSOL, for different anchor diameters for n=2 and n=3 on polysilicon and n=3 on <100> SCS. The n=2 mode for <100> SCS was not taken into consideration, since the mode is not degenerate due to anisotropy of SCS, and cannot be used for mode-matched gyroscopic applications.

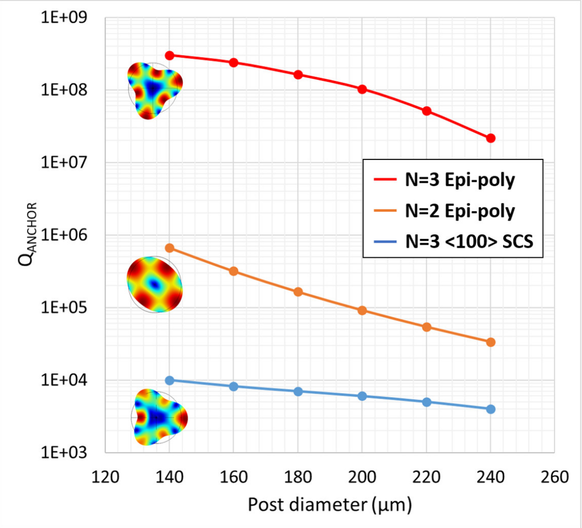

Figure 2: Comparison between Q_{ANCHOR} for center supported fully-solid disk resonators in polysilicon, <111> and <100> SCS, showing >10^4 lower anchor dissipation in polysilicon than <100> SCS.

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MEMS 2018, Belfast, Northern Ireland, UK, 21-25 January 2018

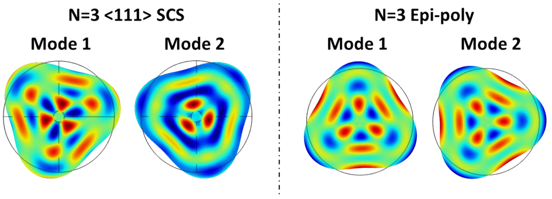

Figure 3: Comparison between out-of-plane displacements for <111> SCS and polysilicon. Even though <111> SCS is radially isotropic, the different OOP displacements result in a different Q_{ANCHOR} for each of the modes and large frequency split.

The simulation was done using a perfectly matched layer (PML) [3]. The results are shown in figure 2. The Q_{ANCHOR} for n=3 poly is found to be over 4 orders of magnitude larger than the n=3 in <100> SCS for the same size stem. It also shows a dissipation of over 2 orders of magnitude lower than n=2 modes in poly, which makes n=3 elliptical mode in polysilicon ideal for substrate-decoupled high-Q solid disk BAW gyroscopes. This clearly highlights the main advantage of isotropic polysilicon over <100> SCS for both n=2 and n=3 mode shapes. <111> SCS are seen to be in-plane isotropic for the n=3 mode, however out-of-plane displacement components add a large frequency split between the modes (~4kHz) even without considering crystallographic misalignments (figure 3). The <111> SCS n=2 elliptical mode is also degenerate, however small OOP crystallographic misalignments of +/-0.5° can increase the mode splits by ~7kHz. Hence, <111> SCS is not the most suitable substrate for implementation of gyroscopic BAW resonators. Furthermore, it is possible to attain high quality factors for epi-polysilicon using large support diameters, which are more suited for gyroscopic applications to allow better out of plane insensitivity, as compared to SCS. In this work, we have used a large support diameter of 200µm for a 2mm diameter disk.

REDUCED-TEMPERATURE HARPSS

To experimentally verify the high Qs, epitaxially grown polysilicon-on insulator (pSOI) wafers are purchased commercially. An as-grown layer of epi-poly >50µm was polished down to 45µm to create a smooth surface with low roughness. The pSOI device layer parameters are given in table 1. Solid disk resonators are fabricated in epi-poly using a two-mask process with backside release holes. The elimination of release holes in the disk offers very low TED, combined with the low support loss of the isotropic material, allows the disk resonators to reach Akhiezer limit. Large 2um gaps are etched by DRIE for capacitive transduction in the resonators to ensure fabrication simplicity.

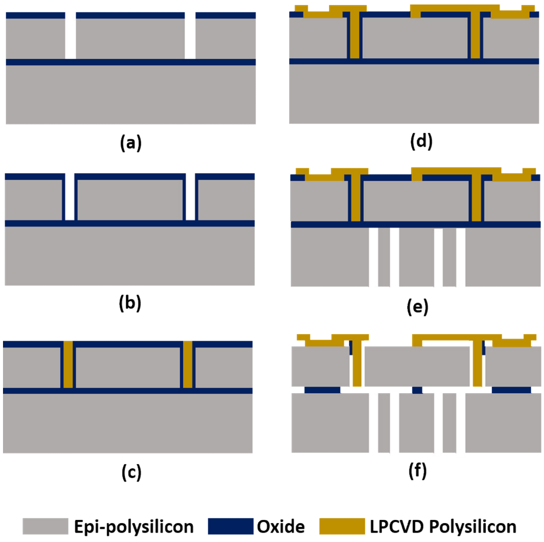

Figure 4: Low temperature HARPSS process flow.

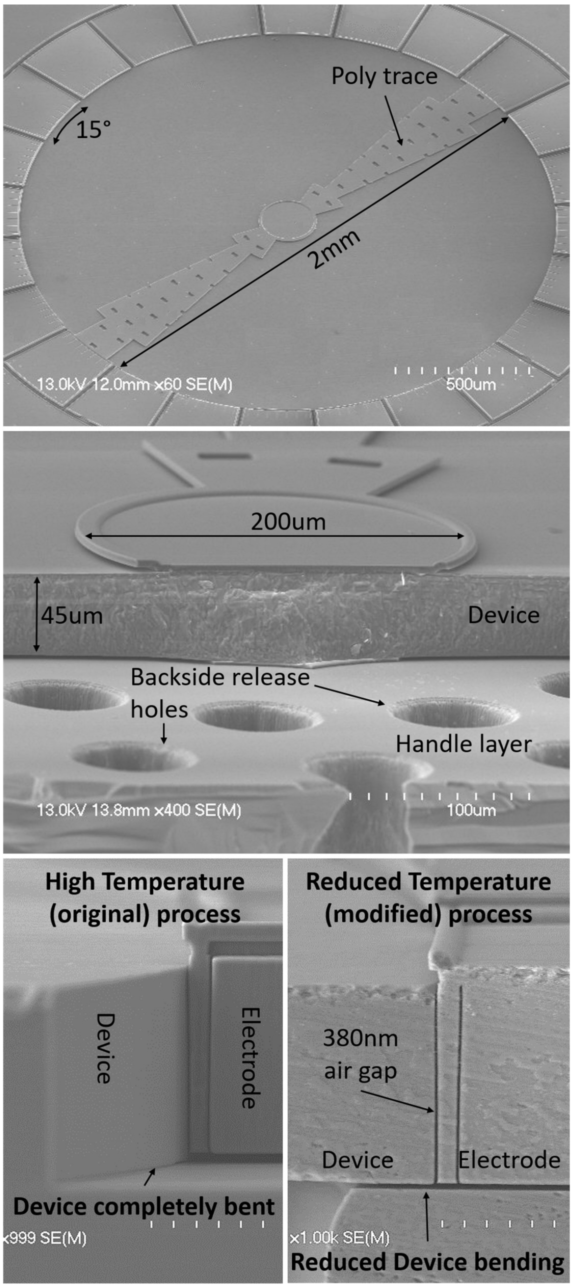

Figure 5: SEM images of the polysilicon gyroscope (top), a cross section of the 200µm post (middle) and the improvement in device bending by reduced temperature processing (bottom).

However, for gyroscopic applications, smaller gap sizes are required to provide full mode-matching coverage over fabrication variations. For this, the HARPSS process,

Table 1: Epitaxial pSOI device layer specifications

Parameter	Specification
Thickness (µm)	45
Resistivity (Ω-cm)	0.01-0.1 [P/B]
Roughness (µm)	<0.05
Stress (MPa)	+/- 30
Surface finish	Polished

which has been used previously to enable sub-micron gaps for MEMS BAW devices [4-6], is modified and adapted for the polysilicon. Conventional HARPSS processes involve oxidation and annealing at high temperatures of 1100°C. Despite containing lower residual stress than LPCVD films, epitaxially grown polysilicon is not suited for high temperature processing. For this purpose, a reduced-temperature HARPSS process must be developed to fabricate the disk resonators, so that large stress is avoided in thick epi-poly films during high temperature processing [7].

The process flow is shown in figure 4. A 3µm layer of PECVD oxide is first deposited on the epi-poly wafer at 250°C, on both the front and back side of the wafer to nullify the stress of the film. Trenches are then etched on the wafer with a 45um substrate which define the resonator shape using the first mask (figure 4a). A 300nm LPCVD oxide defining the capacitive gap is then deposited on the sidewalls at 725°C using TEOS, which is used as a substitute for high temperature oxidation (4b). The trenches are then filled with LPCVD polysilicon which is conformally deposited on their sidewalls at 588°C. This polysilicon must be in-situ P/B doped, since diffusion and drive-in processes for polysilicon are generally at higher temperatures of 1050°C. The high temperature drive-in annealing generally reduces polysilicon stress. However, in this case, the polysilicon must be etched back to the surface of the oxide after every deposition to prevent the accumulation of too much LPCVD poly on the surface of the wafer, which may cause cracking due to stress (4c).

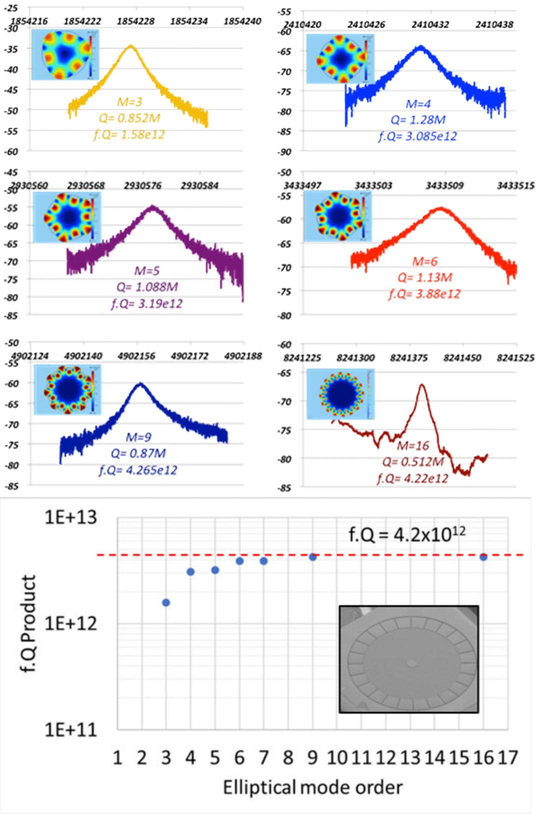

Figure 6: High Qs are measured for modes n=3-6,9,16 on a solid polysilicon resonator despite wire bonding to the center of the device (SEM in inset), thus proving low support loss of substrate. f.Q product was measured at 4.2e12.

The top oxide is patterned on the surface over the electrodes and the top poly is then deposited with the same conditions as the vertical poly (4d). Top poly is annealed at 850°C in N_2 after every deposition which reduces some stress from the top poly film. After this, the poly is etched from the unwanted trenches, defining the entire HARPSS electrode. A short oxidation is done at 850°C to oxidize any possible debris from the trenches. Finally, the backside holes are patterned at the back of the wafer and etched through to the BOX layer from the back side (4e) and the devices are cleaned and released in 49% HF (4f). As seen from figure 5, high temperature causes the released epi-poly disk to bend vigorously and short to the handle layer. This is avoided by reduced temperature processing at <850°C.

EXPERIMENTAL RESULTS

The first batch of epi-poly disk resonators were fabricated using large DRIE capacitive gaps. Figure 6 shows measured high *Q*s exceeding 1M in center-supported polysilicon disk resonators without any decoupling structures. The polarization voltage was applied to these disks by wire bonding directly to the center of the disk, which is only enabled by the large support size at the center. The high *Q* verifies the claim for low support dissipation in epitaxially grown polysilicon disk resonators with the n=4 mode showing the highest quality factor of 1.28M. The higher order modes are found to be intrinsically limited to a measured *f.Q* of 4.2×10^{12}, which is getting close to the Akhieser *f.Q* limit of silicon (2.3×10^{13}) [8]. The difference in these two

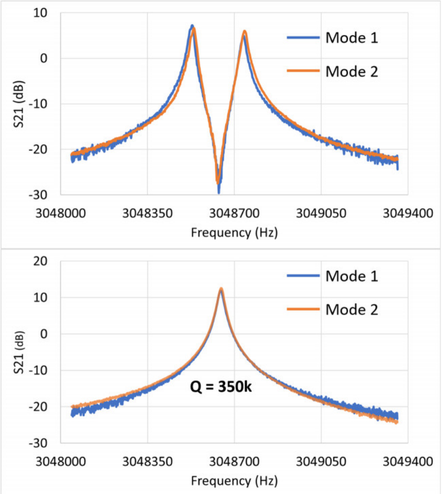

Figure 7: Initial mode split of 250Hz in a 3MHz n=3 solid epi-poly BAW gyro (top) is mode matched using small voltages Vp = 21V, Vq = 13.1V, Vt = 1.5V (bottom).

values can come from the Gruneisen's parameter between poly and SCS [9] or additional intrinsic loss in epi-poly.

Figure 7 shows a typical measured frequency response from a 3MHz n=3 solid epi-poly disk gyro fabricated using the reduced-temperature HARPSS process, showing a *Q* of 350k with an initial mode split of 250Hz (Δf/f ~80ppm). Ideally, the split should be closer to zero due to the isotropic nature of polysilicon. However, since the center support is defined by the backside release holes of the disk, misalignment between the disk center and the release hole pattern combined with the use of the poly trace causes a larger than expected frequency split. The poly trace is used to apply polarization voltage to the center of the disk. The device was fully mode-matched using a 380nm capacitive gap, with a small polarization voltage of 21V, shown in figure 6. A larger-than-usual quadrature cancellation voltage was needed due to the presence of the poly trace, which misaligns the mode shape from the electrode positions. A quasi-solid disk, with front side release holes with *Q* of 200k was measured using a rate-table at different rotation speeds. A large linear scale factor of 4.3 nA/dps was measured and the corresponding time domain rate response is shown in figure 8.

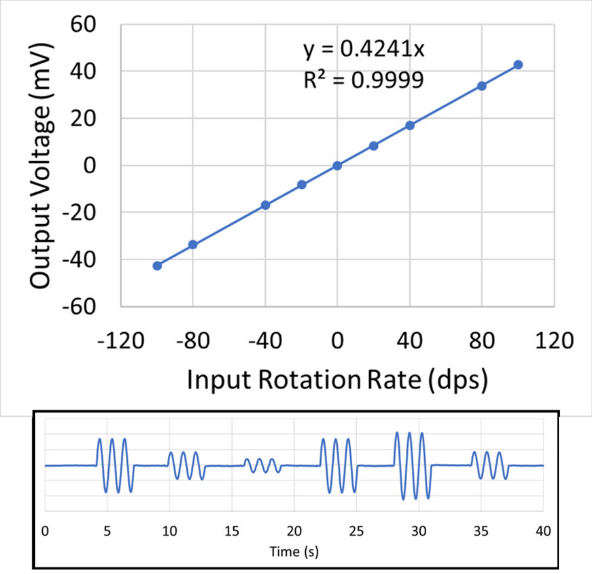

Figure 8: Output response of a quasi-solid poly gyro shows a linear behavior to rotation rate stimuli of up to 100 dps (top) and the rate-response (bottom). The measured scale factor is 4.3 nA/dps.

In contrast to the n=3 mode, the n=2 mode of the same device showed a Q of 51k, thereby verifying the lowest support dissipation for the n=3 mode. However, it is interesting to note that this quality factor for n=2 is still much higher than the simulated value for the n=3 SCS disk shown in figure 2 having the same center support, despite the addition of poly trace and center support misalignment. A better self-aligned mask design which alleviates the errors due to misalignment will enable even the n=2 elliptical mode in polysilicon to show fully mode-matched degenerates. This in turn will have better performance than the n=3 SCS disk for high-Q BAW gyroscopic applications because of higher Q and larger transduction area.

CONCLUSION

We have successfully verified for the first time, high quality factors in thick epitaxially grown polysilicon resonators and a process flow to fabricate the same. As the need for high performance gyroscopes increases in the industry, an isotropic substrate such as epi-polysilicon can be used to fabricate high-Q BAW gyroscopes enabling large *Q*s which are minimally susceptible to fabrication variations. Using a robust fabrication process, higher performance can be achieved with both n=2 and n=3 mode shapes in polysilicon as compared to SCS.

ACKNOWLEDGEMENTS

This work was supported in part by the DARPA Microsystems Technology Office, Single-Chip Timing and Inertial Measurement Unit (TIMU) program through SSC pacific contract #N66001-11-C-4176.

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