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Frequency Tolerance of RF Micromechanical Disk Resonators in Polysilicon and Nanocrystalline Diamond Structural Materials

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Abstract

A statistical evaluation of the absolute and matching tolerances of the resonance frequencies of surface-micromachined micromechanical 1-port disk resonators is conducted by fabricating and measuring a large quantity (>100) of devices in both polysilicon and nanocrystalline diamond structural materials. Through this analysis, respective average resonance frequency absolute and matching tolerances of 450 ppm and 343 ppm for polysilicon, and 756 ppm and 392 ppm for diamond, have been demonstrated on a measured set of 6 dies on 4-inch wafers fabricated using university facilities. The measured matching tolerance is sufficient to allow implementation of RF pre-select or image-reject filters for wireless communications with a confidence interval better than 99.7% over tested dies without the need for frequency trimming.

Introduction

With recent demonstrations of record frequency-Q products (exceeding those of quartz crystals) in both nanocrystalline diamond and polysilicon structural materials [1][2], vibrating micromechanical resonators are emerging as viable candidates for on-chip versions of the high-Q resonators used in wireless communication systems for both frequency generation and filtering. However, there has long been concern that micromechanical resonators might be more susceptible than their macroscopic counterparts to frequency deviations caused by finite planar fabrication tolerances, especially considering their many orders of magnitude smaller dimensions. This work compiles sufficient statistical data on disk resonator frequency tolerance to dispel much of this concern, at least for the case where such resonators are applied to high volume front-end filters for wireless communications, where typical filter percent bandwidths are greater than 3%.

Device Structure, Operation and Placement

Fig. 1 summarizes the test wafer used for this work. As shown, 6 dies situated near the center of the wafer were used, with each die housing (among other devices) twenty-two 18µm-radius self-aligned disk resonators [3] arranged along a horizontal axis passing through its center. Fig. 1 also provides optical micrographs showing the relative location for 3 adjacent resonators in a row used for matching tolerance evaluation, and showing the zoom-in view of a fabricated 18µm-radius disk resonator and its bond pads.

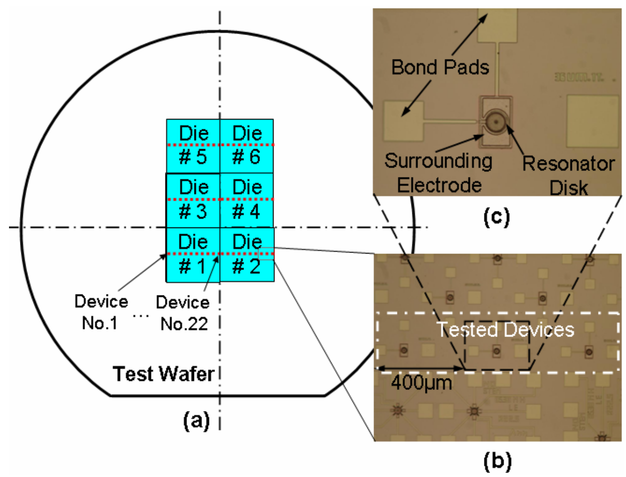

Fig. 1: Top-view schematic and photos illustrating the location of measured devices with respect to the test die and test wafer. (a) Positions of the 6 tested dies at the center of the test wafer; (b) typical relative location for 3 adjacent resonators in a row used for matching tolerance evaluation; (c) zoom-in view of the fabricated 18µm-radius 1-port disk resonator repeated 22 times on each die.

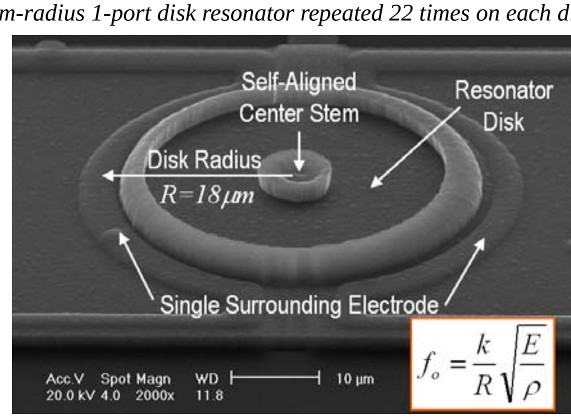

Fig. 2: SEM of a fabricated 1-port 18µm-radius disk resonator with completely surrounding electrode.

Fig. 2 presents the SEM of a fabricated disk resonator, comprised of a disk suspended by a stem at its center, and enclosed by a fully surrounding capacitive transducer electrode capable of generating a fully symmetric electrostatic force in the radial direction that can drive the disk into its radial-contour vibration mode shape [3]. Once vibrating, the motion creates a time-varying capacitance between the disk and electrode that then sources an output current proportional

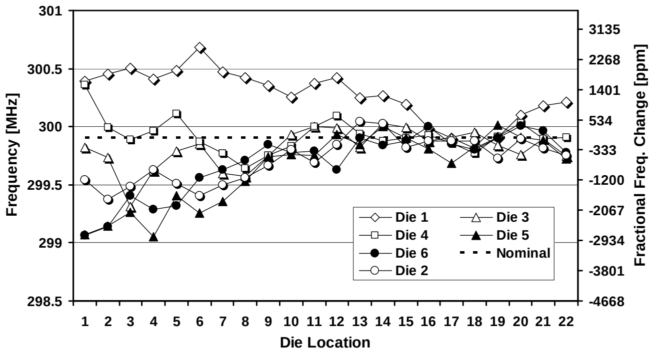

Fig. 3: Plot of frequency versus die location for CVD diamond disks on each of the six measured dies. (One curve per die.)

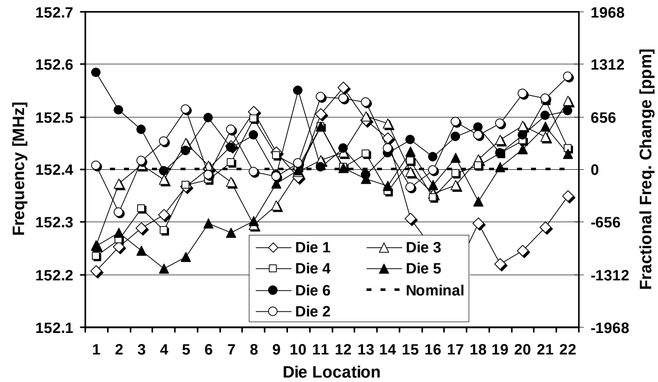

Fig. 4: Plot of frequency versus die location for polysilicon disks on each of the six measured dies. (One curve per die.)

to the square of an applied dc-bias voltage. This fully balanced drive configuration contributed to an impressive 100% yield for tested devices. It also seemed to improve the device pull-in voltage to greater than 50V (consistently), which is more than 2X better than that of the device with single-sided electrode excitation [3], giving further testament to a previous hypothesis [3] that tilting might indeed be a likely mechanism for dc-bias-instigated pull-in of the disk to its electrode. For testing in this work, a rather healthy dc-bias voltage of 20V was used to maintain the strength of the resonance signal.

From the equation in Fig. 2, the resonance frequency of the disk resonator is inversely proportional to its radius and proportional to the acoustic velocity of its structural material, defined as the square root of the Young's modulus E over density ρ ratio. As such, an 18μm-radius polysilicon disk operates in the fundamental mode with a nominal (i.e., designed) resonance frequency of 152.4MHz, whereas the identical device in nanocrystalline diamond (with ~2X the acoustic velocity of polysilicon) resonates at 299.9MHz.

Experimental Results

Figs. 3 and 4 plot measured resonance frequency versus disk location on each of the six CVD diamond and polysilicon dies, where each resonator was tested under identical conditions (i.e., identical DC bias, AC input amplitude, and vacuum pressure). Table 1 summarizes the statistics obtained from this data. Among the parameters tabulated are the average absolute frequency tolerance, given by

$$Avg.\ Absolute\ Tol. = \sum_{i=1}^{N} \left| f_i - f_o \right| / N \qquad (1)$$

where N is the number of the devices investigated, f_i is measured resonance frequency of the ith device, f_o *is the nominal resonance frequency;* and the average matching tolerance, given by

$$Avg.\ Matching\ Tol. = \sum_{i=2}^{N} \left[2\left| f_i - f_{i-1} \right| / \left(f_i + f_{i-1} \right) \right] / (N-1) \qquad (2)$$

where f_i and f_{i-1} are the measured resonance frequencies of two adjacent devices.

As shown in Table 1, for devices built in nanocrystalline diamond with nominal frequencies of 299.9MHz, the average absolute tolerance of resonance frequency from one die to the next varies over a considerable range, from 331 ppm to 1274 ppm. On the other hand, a much more consistent and smaller average absolute tolerance of resonance frequency in the range of 450 ppm is observed for identical devices in polysilicon with a nominal frequency of 152.4MHz. Fig. 5

Table 1: Measured Disk Resonator Statistics

	18μm-Radius 1-Port Diamond Disk Resonators (Nominal Frequency = 299.9 MHz)						18μm-Radius 1-Port Polysilicon Disk Resonators (Nominal Frequency = 152.4 MHz)					
	Die#1	**Die#2**	**Die#3**	**Die#4**	**Die#5**	**Die#6**	**Die#1**	**Die#2**	**Die#3**	**Die#4**	**Die#5**	**Die#6**
Average Freq. [MHz]	300.27	299.72	299.81	299.92	299.63	299.69	152.35	152.46	152.41	152.40	152.36	152.46
Std. Deviation [ppm]	743	642	568	490	1043	923	710	457	436	476	533	333
3 Adjacent Res. Pooled Std. Deviation, σ [ppm]	332	320	451	366	388	359	375	345	285	270	256	298
Max. Abs. Freq. Tolerance [ppm]	2618	1747	1954	1547	2828	2784	1266	1155	945	1083	1240	1207
Die Averaged Abs. Freq. Tolerance [ppm]	1274	699	455	331	978	799	662	466	337	351	465	417
Die Averaged Matching Tolerance [ppm]	333	357	454	384	443	382	388	370	305	342	303	350
Overall (6 Die) Averaged 3 Adj. Res. Pooled σ [ppm]	360						300					
Overall (6 Die) Averaged Abs. Freq. Tol. [ppm]	756						450					
Overall (6 die) Averaged Matching Tol. [ppm]	392						343					

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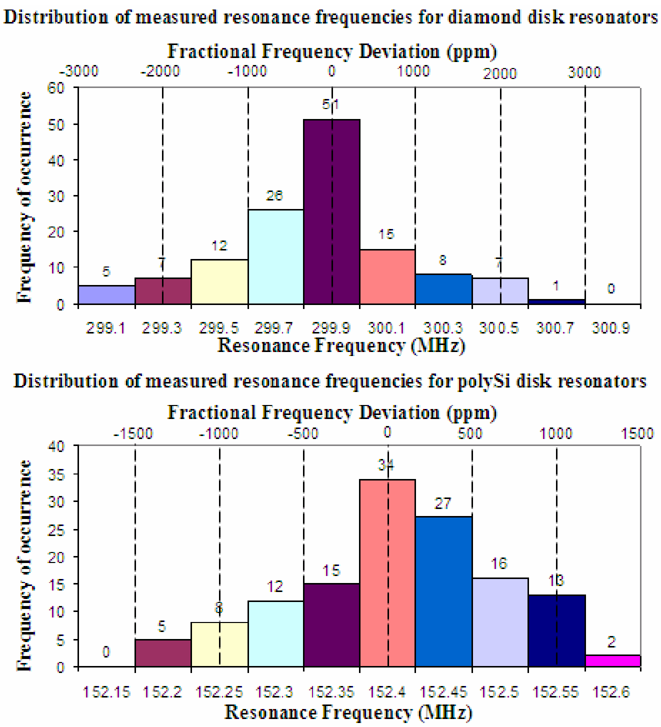

Fig. 5: Distribution for measured resonance frequencies for disk resonator devices in (a) nanocrystalline diamond and (b) polysilicon structural materials.

presents the distribution of measured frequencies for both nanocrystalline diamond and polysilicon disk resonators. A normality test [4] suggests that the measured resonance frequencies for both types of devices are normally distributed (i.e., p-value > 0.05).

Given the expression for disk resonance frequency in Fig.2, finite manufacturing tolerances that cause variations in device radius and material properties are the dominant source of frequency deviation for devices across the wafer. (The thickness of the disk ideally only has a second order effect on its resonance frequency.) Using the equation in Fig. 2, the fractional change in nominal resonance frequency due to a change in these parameters can be obtained and expressed as

$$\frac{\Delta f}{f_o} = -\frac{\Delta R}{R} + \frac{\Delta E}{2E} - \frac{\Delta \rho}{2\rho} \tag{3}$$

In addition to structural dimensions, a variation in electrode-to-resonator gap spacing is also a potential source of frequency deviation. In particular, nonlinearity in the electrode-to-resonator capacitance introduces an electrical spring constant k_e that is a function of gap spacing d_o, and that counteracts the mechanical spring constant k_m of the disk, pulling the frequency away from its nominal value. Fortunately, due to the extremely high mechanical stiffness (e.g., 10's of MN/m) exhibited by the disk resonators of this work, the overall frequency pull via gap-dependent electrical stiffness (~1,560 N/m) ends up being negligible, e.g., less than 5 ppm for a 10 nm change in gap spacing.

The larger absolute frequency tolerance for devices in

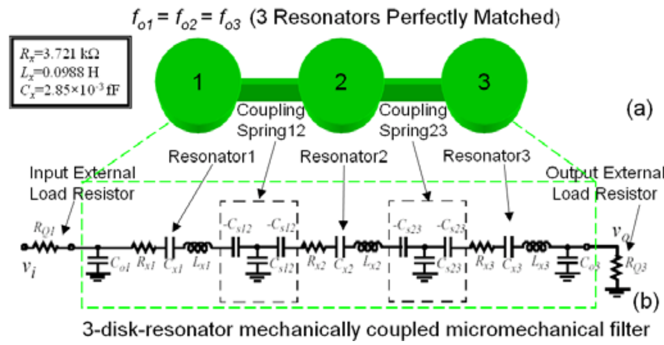

Fig. 6: (a) Schematic of a radial contour mode, mechanically-coupled three-resonator, micromechanical filter (b) Equivalent circuit for the filter. The element values for a 300MHz 3-disk-resonator filter in nanocrystalline diamond is given at the upper-left corner.

CVD nanocrystalline diamond material can be attributed to poor control over film thickness and Young’s modulus for this relatively new technology [5], where a substantial (50%) reduction of the film thickness from the center towards the border of the test wafer and thickness dependence of Young’s modulus [5] impose second order effects on resonance frequency deviation across the wafer.

Impact of Finite Tolerances on Filter Design

Even the worst measured single die absolute frequency tolerance of 2,828 ppm for CVD diamond disks is actually acceptable for front-end RF pre-select filters, meaning that such filters constructed in micromechanical technology would likely not require trimming to fix absolute offsets.

However, for *small percent bandwidth* micromechanical filters (e.g., <1%), the requirement on the matching tolerance between adjacent coupled resonators can be more stringent than for the absolute tolerance [6]. Fortunately, from the previous section, even with the absolute frequency variations of a university process, the matching tolerance still seems to be very good, and should be even better when the absolute tolerance is improved in a production environment. As shown in Table 1, the average matching tolerance for 3 adjacent disks in a row, separated from one another by 400μm, is 392 and 343 ppm for devices in nanocrystalline diamond and polysilicon, respectively. The average fractional standard deviations obtained from the pooled variance amongst all sets of three adjacent resonators in each die are σ=360ppm and σ=300ppm for the diamond and the polysilicon devices, respectively.

To convey the impact of the frequency matching tolerance on overall filter performance, a 3rd order filter (c.f., Fig. 6) consisting of 3 disk resonators mechanically coupled together by 2 quarter-wavelength coupling beams was designed and its frequency response simulated for several different bandwidths using the equivalent circuit in Fig. 6. Here, the values in the equivalent circuit correspond to those for the nanocrystalline diamond disk resonator in order to benefit from their 5X larger Q (of 50,000), which enables smaller filter percent bandwidths with negligible insertion loss penalty.

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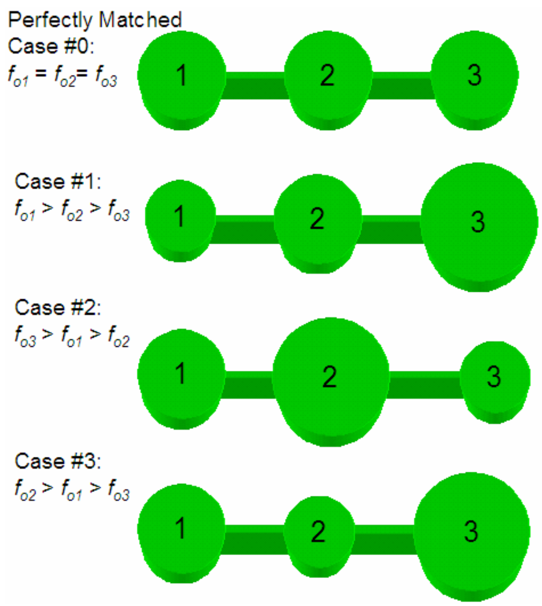

Fig. 7: Schematics for several possible unbalanced (exaggerated) mismatched cases for a 3-resonator mechanically coupled filter. Here, resonators with frequencies different from nominal are represented by smaller or larger radii, where it is understood that frequency is inversely proportional to radius.

Fig. 7 illustrates schematics for ideal as well as other possible filter configurations with mismatched resonator tanks, assuming the frequencies of two of the mismatched disks deviate from the nominal frequency in opposite directions by an amount Δf, where there is a 95.5% confidence interval if Δf is chosen to correspond to 2σ = 720 ppm, and a 99.7% confidence if 3σ = 1080ppm, and where the diamond σ is used here. Fig. 8 compares the simulated frequency responses using the equivalent circuit of Fig. 6 with $\Delta f = 2\sigma$ for 0.5% and 1.6% bandwidth filters for the ideal case and for the mismatched cases of Fig. 7. As shown, with 2σ mismatching, the 0.5% bandwidth filter response distorts significantly, exhibiting more than 2dB ripple within the filter passband in one mismatched case. On the other hand, the 1.6% bandwidth filter with the same 2σ mismatch exhibits acceptable passband distortions of less than 0.3dB from the designed 0.5dB ripple, indicating that 1.6% bandwidth filters should be manufacturable with 95.5% yield (in a university facility) without the need for trimming. The same procedure with $\Delta f = 3\sigma$ indicates that 3% bandwidth filters can be manufactured with 99.7% yield without the need for trimming. Since the pre-select and image-reject filters in cellular phones typically use percent bandwidths >3%, it seems that even the matching frequency tolerances attainable in (less controlled) CVD diamond material by a university facility are sufficient to realize high-volume RF filters without the need for trimming. (And polysilicon, with a smaller σ, would be even better.)

Again, this work is based on data collected on 6 centrally located dies on a single wafer, and not on numerous whole wafers. Thus, although the results are still valid and compelling, a more exhaustive study is in order, and is underway.

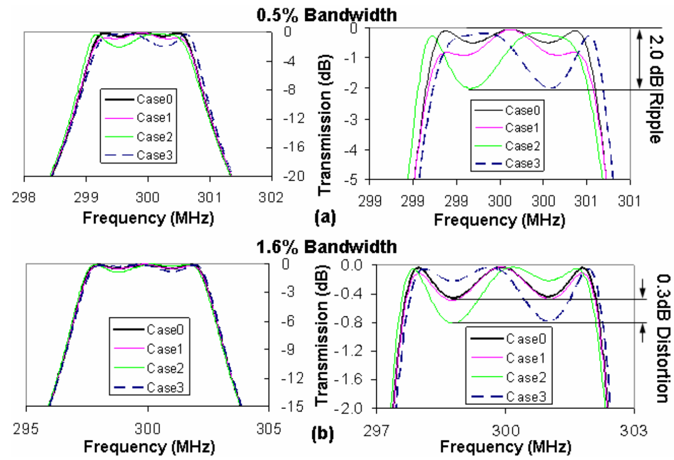

Fig. 8: Simulated frequency response spectra for 3-resonator micromechanical filters under the mismatched (by 2σ) cases of Fig. 7. (a) 0.5% bandwidth (0.5dB ripple) filter design, showing significant passband ripple greater than 2dB. (b)1.6% bandwidth (0.5dB ripple) filter design, showing acceptable distortion less than 0.3dB.

Conclusions

A statistical evaluation of the absolute and matching tolerances of the resonance frequencies of surface-micromachined micromechanical 1-port disk resonators was conducted by fabricating and measuring a large quantity (>100) of devices in both polysilicon and nanocrystalline diamond structural materials. Through this analysis, resonance frequency average absolute and matching tolerances of 450-756 ppm and 343-392 ppm, respectively, have been demonstrated on 4-inch wafers fabricated using university facilities. The measured matching tolerance is good enough to allow implementation of 3% bandwidth micromechanical filters for wireless communications with a 99.7% confidence interval without the need for frequency trimming.

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