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# EFFECT OF ELECTRODE CONFIGURATION ON THE FREQUENCY AND QUALITY FACTOR REPEATABILITY OF RF MICROMECHANICAL DISK RESONATORS

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**Abstract:** A statistical evaluation of the standard deviations of the resonance frequencies and quality factors of polysilicon surface-micromachined micromechanical disk resonators with fully-surrounding and split electrode configurations has been conducted by fabricating and measuring a large quantity (>400) of devices. Through this analysis, respective single-wafer resonance frequency standard deviations as low as 642 ppm for fully-surrounding electrode devices; and 984 ppm for two-port split electrode devices; have been measured. Respective average quality factor standard deviations for fully surrounding electrode devices of 5.6% in vacuum; and 3.9% in air; have also been obtained. The standard deviations for both frequency and *Q* of each resonator type are well within values needed to achieve the ~3% percent bandwidth requirements for filters presently used in the RF front-ends of wireless communication devices without trimming.

**Keywords:** Manufacturing, standard deviation, resonance frequency, quality factor.

## 1. INTRODUCTION

With *Q*'s over 150,000 at VHF [1] and over 15,000 into the GHz range [2], plus demonstrated aging and drift stabilities suitable for low-end timing products that are now entering consumer electronics markets [3], vibrating micromechanical resonator technology has garnered considerable momentum and now targets higher-end markets, such as communication-grade filters and oscillators for wireless handsets. Applications like these, however, tend to rely more heavily on the sheer performance of the resonators they use. Since resonator performance is a statistical quantity, the success of a higher-end product often depends more on the degree to which the manufacturing process can consistently achieve a specific frequency and maintain a *Q* above a certain threshold.

Pursuant to better understanding the breadth of applications accessible to *untrimmed* vibrating micromechanical resonator technology, this work compiles a sufficient volume of data to determine the statistical repeatability with which VHF micromechanical contour-mode disk resonators can be manufactured via the self-aligned stem sacrificial-sidewall gap surface-micromachining process of [4]. Through this analysis, respective single-wafer resonance frequency standard deviations as low as 642 ppm for fully surrounding electrode devices; and 984 ppm for two-port split electrode devices; have been measured. This data is much more substantial than that of [5], which included only fully-surrounding electrode data, and which did not include quality factor or air versus vacuum data. Respective average quality factor standard deviations for fully surrounding electrode devices of 5.6% in vacuum; and 3.9% in air; have also been obtained. The standard deviations for both frequency and *Q* of each resonator type are well within values needed to achieve the ~3% percent bandwidth requirements for filters presently used in the RF front-ends of wireless communication devices without trimming.

## 2. TESTED DEVICES

Again, the polysilicon radial contour mode devices used for this work were based on the design and fabrication process of [4]. Figure 1 presents SEM's of the one- and two-port devices tested here. As shown, each device comprises a polysilicon disk suspended at its very center by a self-aligned stem support and surrounded by at least one electrode that overlaps its sidewall with a gap spacing less than 100 nm. An ac excitation signal applied to an electrode can then drive the device

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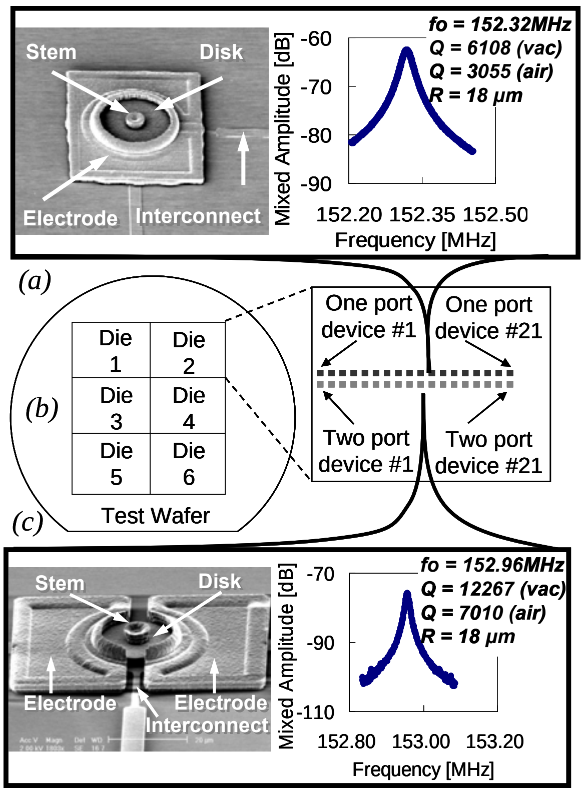


*Fig. 1: SEM's and measured frequency characteristics of fabricated disk resonators with a) a fully surrounding one-port electrode; and c) a split two-port electrode. b) Test die and device location.*

into a resonance vibration mode shape where the disk expands and contracts radially about its circumference, in a "breathing-like" motion. The one-port resonators feature a fully-surrounding electrode, as depicted in the SEM of Fig.1 (a), whereas the two-ports split the electrode to generate two electrode halves, as depicted in the SEM of Fig.1 (c). Typically measured frequency characteristics are also shown in Fig. 1 next to respective SEM pictures.

As detailed in [4], the radial contour-mode resonance frequency of this disk depends primarily on its radius, and is only peripherally dependent upon its thickness. There is also a strong dependence on stem placement, where a mere 1 μm of stem offset from the disk center has been measured to cause a 3MHz change in resonance frequency [4]. Stem placement also greatly influences the *Q* of a stem-supported disk resonator. Thus, the present statistical analysis might also be interpreted as an evaluation of how well the process of [4] actually self-aligns the stem.

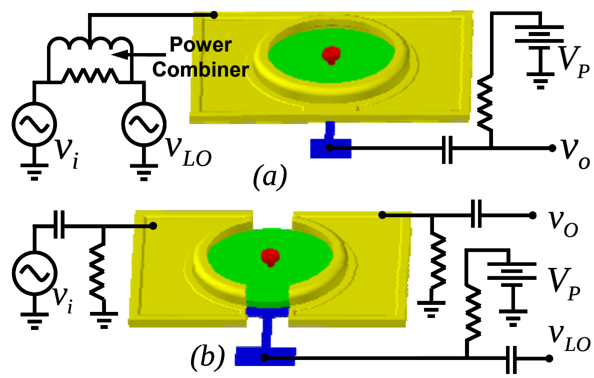


*Fig. 2: Mixing measurement set-up for a) fully-surrounding electrode one port devices; and b) split electrode two-port devices.*

The data presented here were extracted across 12 dies from 2 wafers, 6 dies each, fabricated in two identical but independent runs using university facilities. The wafers from the two runs will be denoted wafer 1 and wafer 2 in the text that follows. Fig.1 (b) illustrates the location of the test devices used for this work. As shown, the 6 dies chosen on each wafer are located near the center, and each die contains 21 self-aligned 36μm-diameter polysilicon disk resonators, in both one-port and two-port configurations.

## 3. EXPERIMENTAL RESULTS

The fabricated disk resonators were tested under vacuum and air environments using the mixing measurement method described in [6] and depicted in Fig. 2 for the cases of (a) one-port and (b) two-port devices. For both cases, a dc-bias $V_P$ of 8V, local oscillator amplitude and frequencies of 3V and 15MHz, respectively, and an unmatched RF input power of -5 dBm, were used. Tables 1 and 2 summarize the measured averages and standard deviations (including pooled).

Fig. 3 presents a histogram giving the resonance frequency distribution for fully-surrounding electrode one-port devices across all dies on wafer 2, showing a standard deviation of 642 ppm. The standard deviation across wafer 2 was considerably smaller than the 1133 ppm on wafer 1, indicating a variance in the processing conditions at the University of Michigan microfabrication facility from run to run. The resonance frequency averages of wafers 1 and 2 are seen to differ by 260 ppm. Although a larger data set is needed to make any useful conclusions, the deviation seen so far

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*Table 1: Resonance Frequency Statistical Summary*

| **Resonant Frequency** | **36 μm Diameter Polysilicon Disk Resonators** | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ***Wafer I*** | | | | | | ***Wafer II*** | | | | | |
| ***One Port*** | *Die 1* | *Die 2* | *Die 3* | *Die 4* | *Die 5* | *Die 6* | *Die 7* | *Die 8* | *Die 9* | *Die 10* | *Die 11* | *Die 12* |
| *Average [MHz]* | 153 | 153 | 153 | 153 | 152 | 152 | 152 | 153 | 152 | 152 | 153 | 153 |
| *Standard Deviation [ppm]* | 407 | 254 | 428 | 530 | 438 | 674 | 690 | 515 | 666 | 345 | 268 | 586 |
| *3 Adj. Pooled Std Dev [ppm]* | 306 | 199 | 404 | 547 | 415 | 586 | 677 | 511 | 599 | 313 | 259 | 636 |
| *Overall Std. [ppm]* | 1133 | | | | | | 642 | | | | | |
| *3 Adj. Pooled Std Dev [ppm]* | 450 | | | | | | 534 | | | | | |
| ***Two Ports*** | *Die 1* | *Die 2* | *Die 3* | *Die 4* | *Die 5* | *Die 6* | *Die 7* | *Die 8* | *Die 9* | *Die 10* | *Die 11* | *Die 12* |
| *Average [MHz]* | 153 | 152 | 152 | 152 | 152 | 152 | 152 | 152 | 152 | 152 | 153 | 152 |
| *Standard Deviation [ppm]* | 365 | 660 | 378 | 751 | 991 | 1061 | 819 | 1702 | 607 | 365 | 660 | 378 |
| *3 Adj. Pooled std [ppm]* | 219 | 316 | 310 | 447 | 429 | 821 | 321 | 1214 | 264 | 631 | 826 | 670 |
| *Overall Std. [ppm]* | 1214 | | | | | | 984 | | | | | |
| *3 Adj. Pooled Std Dev [ppm]* | 584 | | | | | | 695 | | | | | |

*Table 2: Quality Factor Statistical Summary*

| **Quality Factor** | **36 μm Diameter Polysilicon Disk Resonators With Single Surrounding Electrode** | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ***Wafer I*** | | | | | | ***Wafer II*** | | | | | |
| ***Vacuum*** | *Die 1* | *Die 2* | *Die 3* | *Die 4* | *Die 5* | *Die 6* | *Die 7* | *Die 8* | *Die 9* | *Die 10* | *Die 11* | *Die 12* |
| *Average* | 6387 | 6262 | 6317 | 6471 | 6279 | 6406 | 6418 | 6478 | 6427 | 6364 | 6363 | 6417 |
| *Standard Deviation* | 428 | 372 | 395 | 352 | 290 | 495 | 399 | 318 | 260 | 386 | 314 | 459 |
| *3 Adj. Pooled Std Dev* | 495 | 317 | 320 | 302 | 228 | 414 | 292 | 313 | 234 | 368 | 306 | 396 |
| *Overall Std Dev* | 393 (i.e. 6.14%) | | | | | | 357 (i.e. 5.58%) | | | | | |
| *3 Adj. Pooled Std Dev* | 361 (i.e. 5.64%) | | | | | | 320 (i.e. 5.00%) | | | | | |
| ***Air*** | *Die 1* | *Die 2* | *Die 3* | *Die 4* | *Die 5* | *Die 6* | *Die 7* | *Die 8* | *Die 9* | *Die 10* | *Die 11* | *Die 12* |
| *Average* | 4091 | 4018 | 4031 | 4149 | 4019 | 4122 | 4071 | 4052 | 4082 | 4123 | 4091 | 4018 |
| *Standard Deviation* | 132 | 139 | 231 | 164 | 185 | 177 | 143 | 161 | 157 | 151 | 132 | 139 |
| *3 Adj. Pooled Std Dev* | 135 | 150 | 220 | 121 | 158 | 155 | 121 | 175 | 165 | 171 | 153 | 138 |
| *Overall Std Dev* | 179 (i.e. 4.48%) | | | | | | 156 (i.e. 3.90%) | | | | | |
| *Overall 3 Adj. Pooled Std* | 161 (i.e. 4.03%) | | | | | | 151 (i.e. 3.78%) | | | | | |

from these two wafers is good enough to achieve 3%-bandwidth pre-select RF filters for communication front-ends without the need for trimming.

Since micromechanical filters [7] generally consist of coupled resonators in close proximity, the standard deviation obtained from the pooled variance amongst all sets of three adjacent resonators is perhaps more useful than the simple device-to-device standard deviation [5]. The three-adjacent pooled standard deviation over wafer 1 is 450 ppm; over wafer 2 is 534 ppm; and over both wafers is 462 ppm. Again, these are all is actually good enough to reliably attain 3%-bandwidth filters without trimming.

Fig. 4 presents a histogram for the split electrode two-port devices of wafer 2. Here, a much wider spread in frequencies than for wafer 2's fully-surrounding electrode devices is seen, with a standard deviation of 984 ppm. It is possible that this larger standard deviation derives from the asymmetrical nature of a two-port drive and sense configuration versus the more balanced drive of a fully-surrounding electrode. In particular, the more balanced excitation afforded by the fully-surrounding electrode may help to reduce anchor-derived frequency shifts, leading to a tighter distribution. On the other hand, a two-port drive excites the disk on one side, and thus, pushes on the anchor from that direction, giving the anchor more influence on the frequency of the device. More study is required to verify this hypothesis, but if true, then anchor design now becomes crucial for frequency repeatability, as well as $Q$ (for which it has always been important).

Fig. 5 presents histograms of measured $Q$ across all dies of all wafers for fully-surrounding electrode devices operated under (a) vacuum and (b) air. Here, a tighter distribution is clearly seen for air-operated devices, which (at the expense of lower $Q$) exhibit a 4.18% standard deviation ver-

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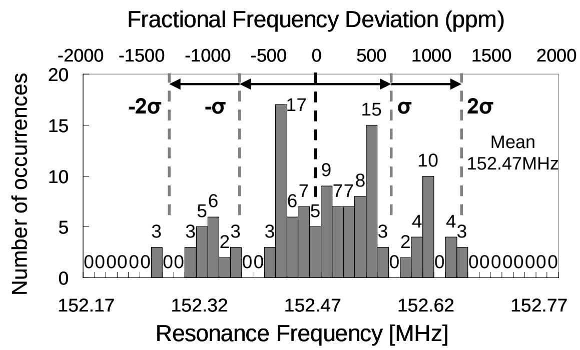



*Fig. 3: Resonance frequency distribution of one port devices on wafer 2.*

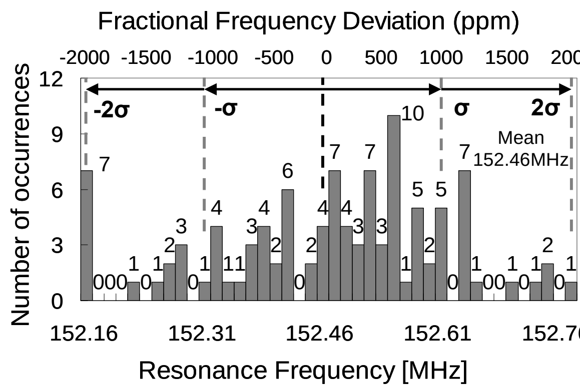
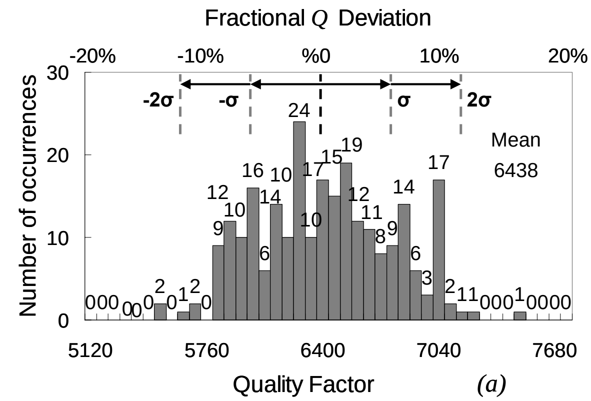



*Fig. 4: Resonance frequency distribution of two-port devices on wafer 2.*

sus the 5.86% seen under vacuum. It appears that viscous gas damping in air provides a more repeatable damping mechanism than the anchor loss mechanisms that dominate in vacuum.

## 4. CONCLUSIONS

A statistical evaluation of standard deviations of the resonance frequencies and *Q*'s of polysilicon surface-micromachined micromechanical disk resonators with fully-surrounding and split electrode configurations has been conducted by fabricating and measuring a large quantity (>400) of devices. Through this analysis, one port devices exhibit better frequency repeatability than two-port, and devices working in air better quality factor repeatability, albeit at the expense of lower *Q*. The standard deviations for both frequency and *Q* of each resonator type are well within values needed to achieve the ~3% percent bandwidth requirements for filters presently used in the RF front-ends of wireless communication devices without trimming.



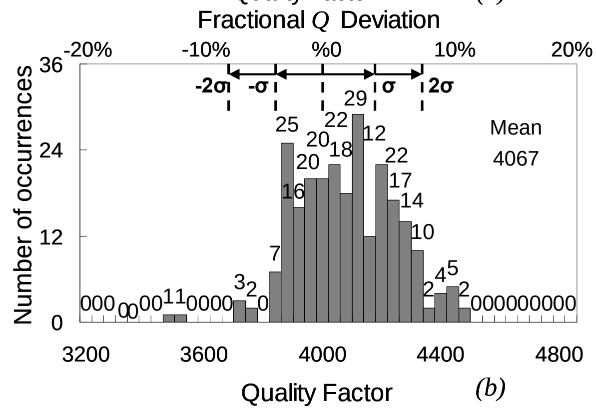




*Fig. 5: Quality factor distributions for the fully surrounding electrode one port device operating a) under vacuum; and b) in air.*

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