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1.51-GHz Nanocrystalline Diamond Micromechanical Disk Resonator With Material-Mismatched Isolating Support

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Abstract

The first CVD nanocrystalline diamond micromechanical disk resonator with material-mismatched stem has been demonstrated at a record frequency of 1.51 GHz with an impressive Q of 11,555, which is more than 7X higher than demonstrated in a previous 1.14-GHz polysilicon disk resonator [1], and which achieves a frequency-Q product of 1.74×10^{13} that now exceeds the 1×10^{13} of some of the best quartz crystals. In addition, a 1.27-GHz version with a Q in the excess of 12,000 exhibits a measured motional resistance of only 100 kΩ with a dc-bias voltage of 20V, which is more than 34X lower than measured on a pure polysilicon counterpart at 1.14 GHz. At 498 MHz, Q's up to 55,300 in vacuum and 35,550 in air have been demonstrated, both of which set frequency-Q product records at 2.75×10^{13} (vacuum) and 1.77×10^{13} (air).

1. Introduction

Having recently been demonstrated at frequencies above 1 GHz with measured Q's above 1,500 for radial disk designs [1] and 3,700 for extensional wine-glass designs [2], vibrating micromechanical ("μmechanical") resonators have now attained frequency and Q magnitudes suitable for use in the RF preselect and image-reject filters needed by wireless receiver front ends. Such filters, when realized on a MEMS scale, might eventually make possible multi-band cellular handsets capable of servicing a multitude of worldwide communication standards without an increase in handset size [3]. While already impressive, such an achievement could be greatly amplified if Q's >10,000 were achievable at the same GHz frequencies and in the same tiny sizes. Performance like this might then enable low-loss front-end filters with selectivities suitable for RF *channel-selection*, i.e., capable of removing all interferers, both in- and out-of-band, allowing a substantial reduction in the dynamic range requirements of subsequent electronics [3]. Such filters might even enable ultra-low power receivers that dispense with conventional down-conversion electronics and instead utilize direct sub-sampling A/D converters.

Pursuant to enabling such RF channel-select filters, this paper describes a method for raising the Q's of radial-contour mode disk resonators to values exceeding 10,000 at frequencies greater than 1 GHz. The basic technique employs different materials for the disk (diamond) and its anchoring stem (polysilicon) to affect an acoustic impedance mismatch between the two that suppresses energy transfer from the disk to the stem, thereby suppressing anchor losses and allowing substantially higher Q. Using this technique, a CVD nanocrystalline diamond micromechanical disk resonator with material-mismatched stem has been demonstrated at a record frequency of 1.51 GHz with an impressive Q of 11,555, which is more than 7X higher than demonstrated in a previous 1.14-GHz polysilicon disk resonator [1]. At 498 MHz, Q's up to 55,300 in vacuum and 35,550 in air have been demonstrated, both of which set frequency-Q product records at 2.75×10^{13} (vacuum) and 1.77×10^{13} (air). This paper details the key design strategies that allow such dramatic improvements.

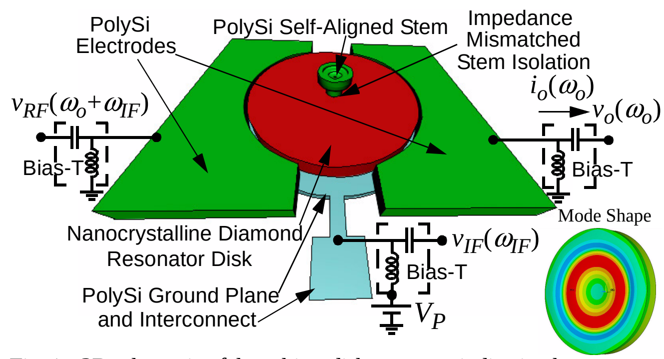

Fig. 1: 3D schematic of the subject disk resonator indicating key components and their materials in a typical mixing measurement scheme with its 2nd radial contour mode shape shown at bottom-right corner.

2. The Diamond Frequency Advantage

Figure 1 presents the perspective-view schematic of the subject disk resonator in a typical mixing measurement scheme [4], indicating key parts and the materials used for them. As shown, this device consists of a polydiamond disk, suspended 800nm above the substrate by a centrally located, self-aligned polysilicon stem, and surrounded by two polysilicon electrodes spaced less than 100nm from its perimeter that can be used to electrostatically drive it into a resonance mode shape where it expands and contracts radially around its perimeter. This device is identical in structure to that in [1], except that the structural material used for its disk is now nanocrystalline diamond, not polysilicon. As such, its operation and quantitative modeling are also identical, and the reader is referred to [1] for these details.

Among the currently available set of thin-film-depositable materials, diamond potentially offers the largest acoustic velocity, with ideal polycrystalline values (under an assumption of no grain boundaries) on the order of 18,076 m/s [5]. This is to be compared with the 8,024 m/s of single crystal silicon [6] and 11,500 m/s of silicon carbide [7], which are 2.25X and 1.57X smaller, respectively. Given that resonance frequency is generally proportional to acoustic velocity, diamond provides the largest boost towards even higher micromechanical resonator frequencies. This is certainly the case for the disk resonator of this work, for which the resonance frequency is given approximately by $f_o = (\alpha/r)\sqrt{E/\rho}$ [8], where r is the disk radius; E

Table 1: Frequency vs. diameter for different materials

Diameter	16 μm		20 μm		24 μm	
Mode	1st	2nd	1st	2nd	1st	2nd
Si	318.2	868.9	254.5	695.1	212.1	579.3
SiC	449.1	1238.2	359.3	990.6	299.1	825.5
Diamond	698.8	1939.1	559.0	1551.3	465.8	1292.8

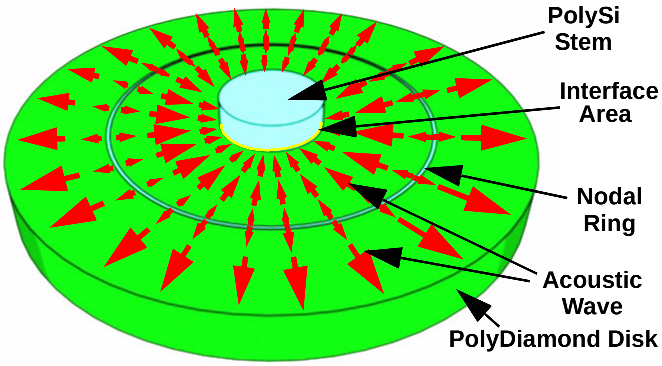

Fig. 2: Schematic of a polydiamond disk resonator with polysilicon stem illustrating acoustic wave propagation in its 2nd radial contour mode.

and ρ are the Young's modulus and density, respectively, of its structural material; ($\sqrt{E/\rho}$) is the acoustic velocity; and α is a parameter dependent upon the Poisson's ratio of the structural material and the desired mode shape. (α=0.3093 when a polydiamond disk vibrates in a fundamental radial-contour mode. α=0.8584 in the second mode).

Table 1 utilizes the more accurate frequency equations of [1] to tabulate the frequencies attainable by 2μm-thick disk resonators with various diameters and using different high frequency materials. With frequencies 2.20X and 1.57X higher than silicon and silicon carbide, diamond is clearly the most attractive of the three from a frequency perspective.

3. Material-Mismatched Support

As shown in Fig. 1, the device of this work differs from previous polysilicon disk resonators [1] not only in its use of polydiamond for its disk, which allows it to achieve more than twice the frequency of an identically-sized polysilicon disk, but also in its use of dissimilar materials for its stem (polysilicon) and disk (polydiamond). In particular, the differing acoustic velocities of these dissimilar materials create an impedance mismatch at the disk-stem interface that attenuates energy transfer from the vibrating disk to the stem, thus, allowing the disk to retain its vibrational energy and exhibit record *Q*'s in excess of 12,000 (to be shown later in Section 5). In contrast, previous disks that used identical stem and disk materials had a perfect impedance match between the two, which allowed maximum power transfer from the disk to the stem, thereby allowing significant loss from the disk, through the stem, to the substrate, resulting in substantially lower *Q* values (less than 1,600 at 1.14 GHz [1]). The degree to which disk-to-stem anchor losses are suppressed via this technique can be quantified by considering the transmission across the disk-stem interface of bulk acoustic waves generated during resonance vibration (depicted in Fig. 2).

The wave transmission between two different media interfaces is often quantified in terms of the reflection coefficient, defined simply as the ratio of the reflected and incident wave amplitudes. If the waves are normally incident to the boundary, which is the case for the bulk acoustic waves moving toward the stem-disk boundary, then the reflection coefficient *R* can be expressed as [9]

$$R = \frac{(Z_2 - Z_1)}{(Z_2 + Z_1)} \quad (1)$$

where Z_i is the acoustic impedance of material *i*, given by

$$Z = \rho \times \sqrt{\frac{E}{\rho}} \quad (2)$$

In the ideal case, where the reflection coefficient *R* at the disk and stem interface is unity, there is no path for acoustic energy to leave the system through the stem, and the total energy in the system is preserved. In this case, there would be no anchor losses, and the total *Q* of the resonator would be much higher, governed by the inverse *Q*'s of other loss mechanisms (e.g., viscous gas damping, hysteretic movement of dislocations, etc.).

Unfortunately, for the case of previous disk resonators that utilized identical stem and disk materials, a perfect impedance match (*R*=0) exists at the disk-stem interface, and acoustic energy is radiated freely from the disk to stem, then through the substrate, inducing significant energy loss and resulting in the substantially lower *Q* values measured in [1]. On the other hand, for the case of the present work, the differing acoustic velocities of disk (polydiamond: Z_1=6.18×10^7kg/m^2/s) and stem (polysilicon: Z_2=1.85×10^7kg/m^2/s) built in intentionally dissimilar materials create an impedance mismatch at the disk-stem interface that substantially reflects the acoustic wave (*R*=54%) and attenuates acoustic energy radiated from the vibrating disk to the stem. Furthermore, in addition to material property-derived impedance mismatching, the columnar structure of CVD diamond [10] further induces a rough or inefficient boundary at the disk-stem interface, which serves as an additional wave propagation barrier that further reflects the incident waves via anomalous scattering, raising *R* to a value even closer to unity, and further reducing anchor losses.

It should be noted that the described material-mismatched isolating support design technique is largely independent of the vibration mode shape, and thus, should work in general for a wide-variety of resonator designs.

4. Fabrication Process

Figure 3 succinctly summarizes the fabrication process that yields polydiamond disks with self-aligned polysilicon stems. This process differs from a previous self-aligned polysilicon disk resonator surface micromachining process [1] mainly in the diamond deposition and dry etching steps, which essentially replace those for polysilicon in the process of [1]. In this work, the nanocrystalline diamond is formed on the sacrificial oxide layer by first seeding the surface with nanodiamond particles, then coalescing and growing a 2-3μm-thick film by microwave plasma assisted chemical vapor deposition (CVD), with 800 W of microwave power, an 800°C substrate temperature, and 15 torr pressure, while flowing putrefied 900 sccm hydrogen, 3 sccm methane, and 2 sccm 1% diborane, as reactants. Uniform and conformal nucleation densities exceeding 10^{12} cm^{-2} are achieved, which is key to attaining a large Young's modulus [10]. After deposition and patterning of the oxide mask (same as [1]), the nanocrystalline diamond film is then patterned via an O_2/CF_4 RIE, with flows of 40 sccm O_2 and 1 sccm CF_4 at 50mTorr, and with 250W of power. These conditions yield an etch rate around 1.8μm/hr with a 15: 1 selectivity between diamond and oxide, and with fairly vertical sidewalls, as shown in

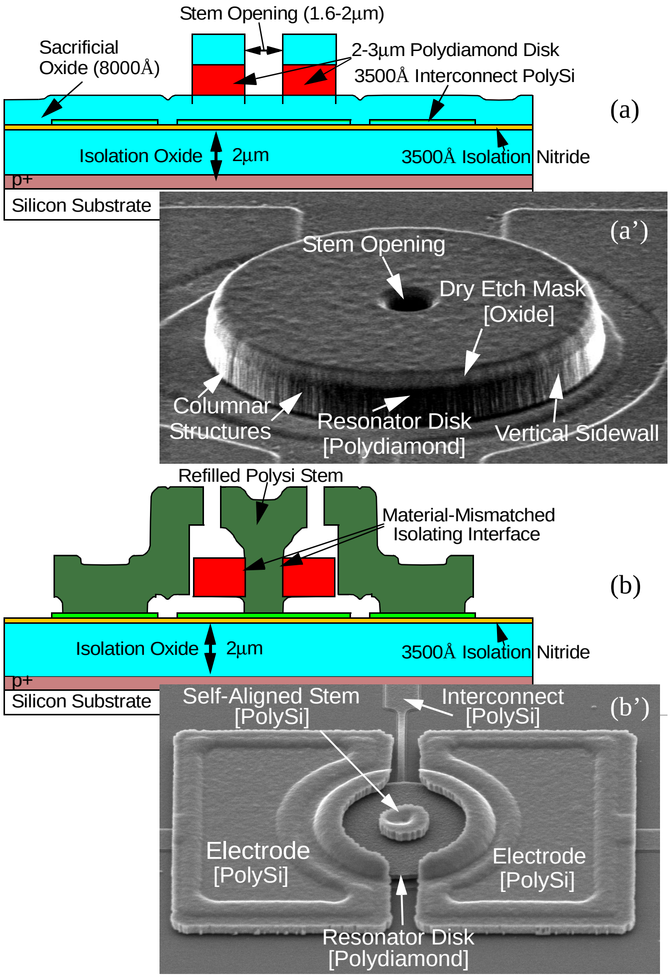

Fig. 3: Fabrication process flow cross-sections and associated SEM's at different stages of the process. (a) After diamond disk definition. (b) After polysilicon stem refilling and electrode definition.

Fig. 3(a)(a'). After polysilicon stem refilling and electrode definition as in [1], structures are then released in 49% concentrated HF to yield the final cross-section and SEM of Fig 3(b)(b').

5. Experimental Results

Using the described process, 3µm-thick radial-contour mode polydiamond disk resonators like the one shown in Fig. 3(b') with center self-aligned polysilicon stems ranging from 1.6µm to 2.0µm in diameter were fabricated with disk diameters ranging from 16 to 24µm, and with electrode-to-resonator gap spacings of 90nm. For comparative purposes pure polysilicon disks were also fabricated with similar dimensions.

To circumvent device-to-instrument impedance mismatches (that cause the low dB levels in the data to be shown), mixing measurement techniques [4] were used. Figure 4 presents frequency characteristics for a 22µm-diameter polydiamond disk resonator with a 1.6µm-diameter stem measured in (a) vacuum and (b) air, showing a frequency of 497.6 MHz with very impressive Q's of 55,300 and 35,550 respectively. The measured frequency of this diamond resonator reflects a new high in polydiamond acoustic velocity at 17,690 m/s (the previous high being 14,252 m/s [11]), and is 2.19X that of an identically dimensioned pure polysilicon disk resonator. Its Q is 7.1X larger in air, and 6.8X larger in vacuum. To our knowledge, the vacuum and air frequency-Q products of 2.75×10^{13} and

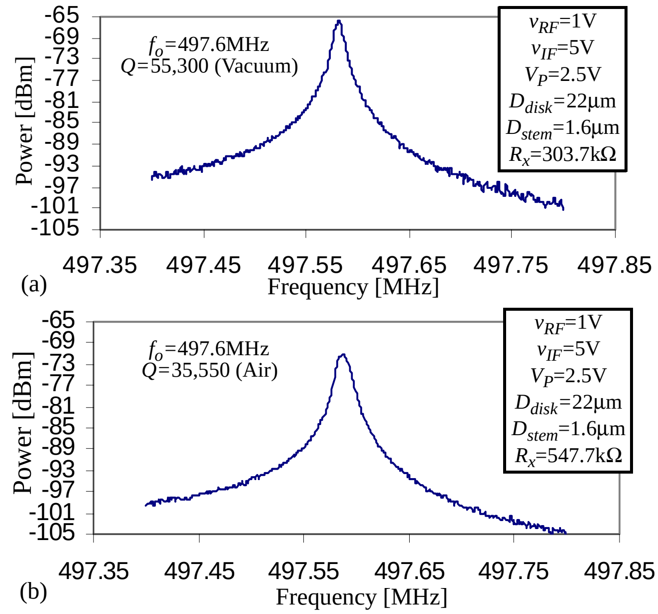

Fig. 4: Measured 1st mode frequency characteristics for a 22µm-diameter diamond disk with 1.6µm-diameter stem in (a) vacuum; and (b) air.

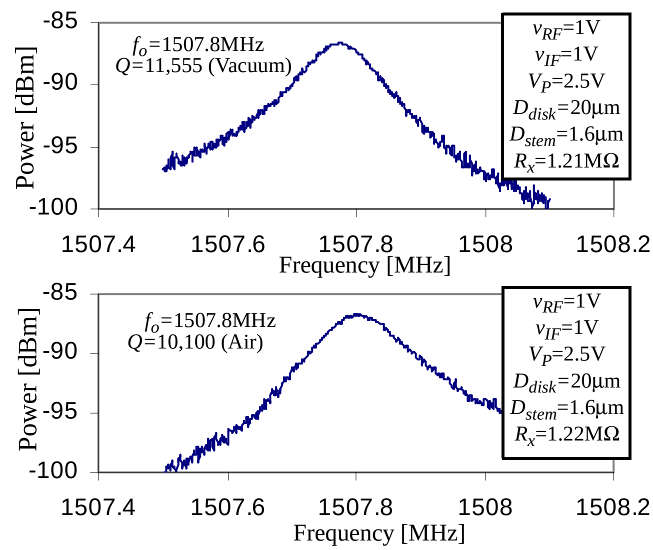

Fig. 5: Measured 2nd mode frequency characteristics for a 20µm-diameter diamond disk with 1.6µm-diameter stem in (a) vacuum; and (b) air.

1.77×10^{13}, respectively, attained by this particular diamond resonator are the highest yet seen for any *on-chip* resonator technology at room temperature, and serve as strong testament to the effectiveness of diamond material and the use of material-mismatched anchoring.

Figure 5 presents measured frequency characteristics for a 20µm-diameter diamond disk with 1.6µm-diameter stem, operating in its second radial-contour mode at 1.51 GHz with Q's of 11,555 in vacuum and 10,100 in air, achieving an impressive frequency-Q product of 1.74×10^{13}. To illustrate the R_x-lowering influence of Q, Fig. 6 presents frequency characteristics for a 24µm-diameter diamond disk resonator with 1.6µm-diameter stem. Due to a very high Q of 12,050 at 1.27 GHz, this resonator exhibits a measured motional resistance of only 100kΩ for a dc-bias voltage of 20V, which is more than 34X lower than that measured on a pure polysilicon counterpart sized to be in the same frequency range.

Finally, Fig. 7 presents measured plots of fractional fre-

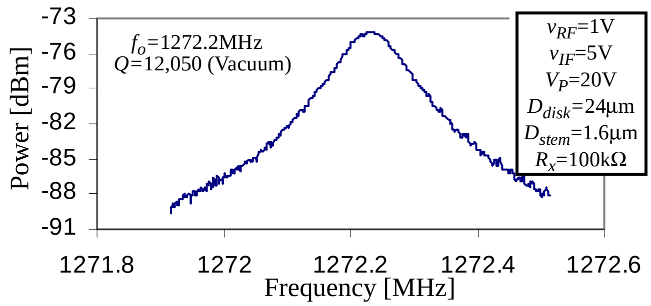

Fig. 6: Measured 2nd mode frequency characteristics for a 24µm-diameter diamond disk with 1.6µm-diameter stem, demonstrating only 100kΩ of series motional resistance.

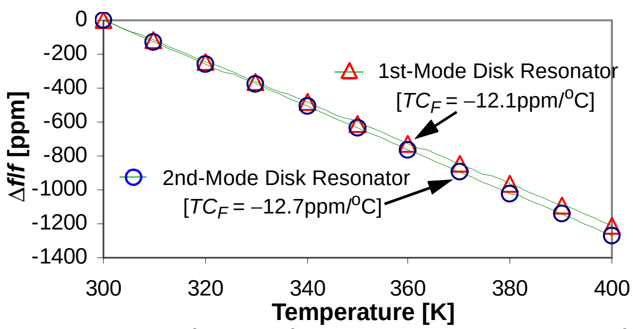

Fig. 7: Measured fractional frequency change vs. temperature for 1st and 2nd mode 22µm-diameter diamond disk resonators.

Table 2: Polysilicon vs. Polydiamond Devices

Mode	Stem Material	Disk Material	Stem Diam. [µm]	Disk Diam. [µm]	Res. Freq. [MHz]	Quality Factor
1st	Silicon	Diamond	1.6	24.0	455.8	24,117
2nd	Silicon	Diamond	1.6	24.0	1272.2	12,050
1st	Silicon	Silicon	1.6	22.0	245.1	8,100
1st	Silicon	Diamond	1.6	22.0	497.58	55,300
2nd	Silicon	Silicon	1.6	22.0	657.45	6,400
2nd	Silicon	Diamond	1.6	22.0	1388.1	10,680
1st	Silicon	Silicon	2.0	22.0	243.8	4,500
1st	Silicon	Diamond	2.0	22.0	495.64	27,500
2nd	Silicon	Silicon	2.0	22.0	655.82	4,900
2nd	Silicon	Diamond	2.0	22.0	1386.9	8,760
1st	Silicon	Diamond	1.6	20.0	545.9	17,458
2nd	Silicon	Diamond	1.6	20.0	1507.8	11,555
1st	Silicon	Diamond	2.0	20.0	547.2	11,448
2nd	Silicon	Diamond	2.0	20.0	1519.7	4,648
1st	Silicon	Diamond	1.7	17.0	639.2	10,531
1st	Silicon	Diamond	2.0	16.0	681.7	10,246

Data: thickness, t=3.0µm; elect.-to-resonator gap, d_o=90nm

quency change versus temperature for a 22µm-diameter disk resonator operating in its fundamental and second modes. The uncompensated temperature coefficients of –12.1ppm/^{o}C and –12.7 ppm/^{o}C for the fundamental and second modes, respectively, are fairly good versus macroscopic counterparts, and are on par with values seen in pure polysilicon counterparts.

Table 2 compares measured data for disks in various materials and geometries, providing the following insights into how individual parameters affect disk resonator performance:

(1) As disk radius decreases, resonance frequency increases proportionally for both fundamental and higher modes.

(2) Diamond disks achieve more than twice the frequency (~2.03X) of identically-sized polysilicon ones.

(3) Regardless of disk and stem material types, thinner stemmed devices exhibit higher measured Q's, which further verifies a stem-dominated loss mechanism.

(4) The use of dissimilar materials for a vibrational resonator and its support structure can raise Q substantially.

Work to verify the generality of anchor material-mismatching for Q-enhancement is presently in progress.

6. Conclusions

Via material-centric design strategies, this work has demonstrated micromechanical resonators with record-setting frequencies past 1.5 GHz and with order of magnitude increases in Q at these frequencies to values >10,000. The key features that allow this degree of improvement are: (1) the use of polydiamond as the disk structural material, which has a 2.19X higher acoustic velocity than polysilicon; (2) a new CVD nanocrystalline diamond recipe that achieves higher Q material and a higher acoustic velocity (17,690m/s) than a previous recipe (14,252m/s) [11]; and (3) the use of different materials for the stem (polysilicon) and disk (polydiamond) to affect an impedance mismatch from the disk to the anchor that suppresses energy transfer between the two, thereby suppressing anchor losses and allowing substantially higher Q. Of these advantages, (3) is perhaps the most ground-breaking, as it should work in general for a wide variety of resonator designs. The performance resulting from these design methods is expected to encourage future work on front-end, on-chip, RF *channel-select* filters that, if possible, might be enablers for low-power direct digital down-conversion in communication handsets.

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