ACOUSTIC WHISPERING GALLERY MODE RESONATOR WITH $Q > 109,000$ AT 515MHZ

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ABSTRACT

A capacitive-gap transduced micromechanical resonator design based on an acoustic whispering gallery mode (WGM) constructed in micro-crystalline diamond has achieved a $Q > 109,000$ at 515MHz, posting an $f$/$Q$ product of $>5.6\times 10^{13}$. The key to this performance is anchor-loss nulling by the WGM, as evidenced by comparison of $Q$ values between radial-contour modes and WGM ones on the same disk device, where a 2-3× enhancement of $Q$ is observed. $Q$'s exceeding 100,000 should enable unprecedented RF front-end frequency selectivity and low phase noise oscillators for future communications.

INTRODUCTION

On-chip, resonators with CAD-definable resonance frequencies and $Q$'s over 30,000 in the upper UHF range (i.e., GHz), if achievable, have the potential to revolutionize compact wireless transceiver design by enabling on-chip RF channel-select filters, as well as integrated oscillators with extremely low phase noise. While efforts over the past few years have yielded great advances, e.g., $Q=14,600$ at 1.2GHz in [1], still no device with the CAD-definable frequency needed to create single-chip banks of multiple filters has exhibited $Q$'s $>30,000$ at GHz.

The ongoing quest for higher $f$/$Q$ product demands reductions in both anchor loss and fundamental material loss. Among available materials, theoretical calculations [2] identify diamond as an exceptional material, due to its very high acoustic velocity (~12,000m/s) and its low predicted fundamental phonon scattering rate. To address anchor loss, recent work [3] investigating the use of diamond material for radial-contour mode disk resonators, established the efficacy of using a different support stem material (e.g., polysilicon) to engineer an acoustic mismatch that reduces energy transfer to the stem, in turn reducing loss to the substrate. With demonstrated enhancements in $f$/$Q$ product of up to 6.5× for diamond disks with polysilicon stems versus identical all-polysilicon counterparts, significant $Q$ gains are clearly possible via reduction of anchor loss.

With an intent to further reduce anchor loss, this work explores the use of the same high-$Q$ diamond disks with mismatched polysilicon center stems, but this time designs the electrodes (c.f. Fig. 1) to couple to volume-conserving high-order whispering gallery modes (WGM) that reduce motion at a disk’s center, thereby further reducing anchor loss towards unprecedented $Q$’s as high as 109,200 at 515MHz.

THE WHISPERING GALLERY MODE

The name “whispering gallery mode” was first coined by Lord Rayleigh in the early 1900’s while describing acoustic resonances in St. Paul’s Cathedral [4]. The original term as applied to building-sized phenomena eventually became the term of choice to describe similar phenomena in micro-optical devices [5], and more recently, in high-order optically excited acoustic microspheres [6]. Low-order acoustic WGM’s were in fact first used at the micro-scale in the device of [7], which was dubbed the “wine-glass disk”, but was functionally a 2nd order WGM. Higher order WGM’s, however, have not yet been explored in an electrically excited micro-acoustic device suitable for RF filter and oscillator applications.

In a whispering gallery mode, acoustic waves bounce around the circumference of the disk, but do not penetrate close to the center stem. At resonance, as shown in the inset of Fig. 1 (and later in Fig. 2), a standing wave is produced at the edge of the disk with nearby antinodes moving 180° out of phase, providing a mode-shape that conserves overall volume and thereby induces less motion at the center of the disk than other modes. To illustrate, Fig. 2 presents Coventorware FEM mode-shape simulations confirming that whispering gallery modes with multiple lobe maxima along the circumference of a disk produce much smaller motions at the center of the stem-supported disk (as indicated by the blue color) compared to contour modes, and so should allow higher $Q$.

From [8], the transcendental equations governing the whispering gallery mode frequency, $f_0$, are given by:

$$\frac{\psi'(\xi)}{\psi(\xi)} - n - q = (n \cdot q - q)^2$$

$$\psi(x) = \frac{xJ_{n-1}(x)}{J_n(x)}; \quad q = \frac{\xi^2}{(2n^2 - 2)};$$

$$\xi = 2\pi f_0 R \sqrt{\frac{\rho(2\sigma + 2)}{E}}; \quad E = \frac{2}{\sqrt{1 - \sigma}}$$

where $R$ is disk radius, $\rho$ material density, $\sigma$ Poisson’s ratio, $E$ Young’s modulus, $n$ mode number, and the $J$’s denote Bessel functions of the first kind. Many such whispering gallery modes with different numbers of lobes...
TABLE 1: CALCULATED PARAMETERS FOR A DIAMOND DISK WGM DEVICE

<table>
<thead>
<tr>
<th>Mode (n)</th>
<th>Frequency (MHz)</th>
<th>( R_x ) (kΩ) (100nm gap)</th>
<th>( R_x ) (kΩ) (20nm gap)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>259</td>
<td>620</td>
<td>1.0</td>
</tr>
<tr>
<td>3</td>
<td>397</td>
<td>760</td>
<td>1.2</td>
</tr>
<tr>
<td>4</td>
<td>516</td>
<td>820</td>
<td>1.3</td>
</tr>
<tr>
<td>5</td>
<td>627</td>
<td>830</td>
<td>1.3</td>
</tr>
<tr>
<td>6</td>
<td>735</td>
<td>830</td>
<td>1.3</td>
</tr>
<tr>
<td>7</td>
<td>840</td>
<td>830</td>
<td>1.3</td>
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<tr>
<td>8</td>
<td>945</td>
<td>830</td>
<td>1.3</td>
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<td>9</td>
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<td>830</td>
<td>1.3</td>
</tr>
<tr>
<td>10</td>
<td>1151</td>
<td>830</td>
<td>1.3</td>
</tr>
</tbody>
</table>

Figs. 1 and 2: FEM analysis of motional amplitude comparing the fundamental contour mode with the 3rd and 10th WGMs. As WGM number is increased, motion at the stem-supported center of the disk can be seen to decrease, reducing anchor loss.

With the exception of the fractional increase in capacitance, the effective resonator stiffness must be excited and detected in the opposite phase. This is certainly realizable, but requires a more challenging fabrication process, so is not done in this initial work. With only half the maximum possible combined electrode-to-resonator overlap area, the electrodes of this work generate anR half the available drive force and sense only half the output current, so exhibit 4× larger motional resistance than if it had more complete electrodes.

Alongside frequency, Table 1 also provides predicted values of motional impedance, given by [10]:

\[ R_x = \frac{\sqrt{k_r m_r}}{Q \eta^2}; \quad \eta = V_p \frac{\partial C}{\partial r} \]  

where \( k_r \) is effective resonator stiffness, \( m_r \) is effective resonator mass, \( V_p \) is applied bias voltage, and \( \frac{\partial C}{\partial r} \) is the overall change in electrode-disk capacitance per unit of radial motion of the resonator integrated over the mode-shape across the electrode. From Table 1, the motional resistance predicted by (4) is nearly independent of mode number for a given disk with constant radius.

If the radius of the disk is allowed to change, however, the motional resistance at a given frequency can be tailored to any desired value, so long as the disk size is not constrained. Specifically, since the \( \frac{\partial C}{\partial r} \) term in (1) is directly proportional to the number of motional lobes overlapped by electrodes, while \( \sqrt{k_r m_r} \) increases only linearly with increasing lobe number, an increase in the number of lobes reduces the overall motional resistance. So for a given frequency, an increase in disk circumference (as realized by a corresponding increase in radius) serves to reduce motional resistance in a manner comparable to that achieved by arraying of resonators [11], but in this case in a single device. Fig. 3 plots motional impedance versus disk radius and mode number for a 500MHz design with 20nm electrode-to-resonator gaps [12][13], showing resistance reductions with increasing mode number or radius.
The design of a WGM resonator, then, reduces to first determining the wavelength of the surface wave at the desired frequency; then, scaling the disk radius to achieve a circumference equal to an integer multiple of this wavelength that attains the desired value of motional resistance.

DEVICE FABRICATION

The fabrication process used for the devices presented here closely follows that of [3] and is summarized in the cross-sections of Fig. 4. The 2μm-thick microcrystalline diamond film is formed on the sacrificial oxide by first seeding the wafer with diamond nanoparticles to provide nucleation sites, then depositing diamond material via a hot-filament chemical-vapor deposition tool, made by sp3, at 730°C in a 25torr atmosphere with flows of 30sccm CH₄, 3000sccm H₂, and for doping, a mixture of 2% trimethylboron in H₂ flowing at 1sccm.

EXPERIMENTAL RESULTS

Using the fabrication process of the preceding section, 17μm diameter diamond disk devices with 100nm capacitive gaps were constructed using electrodes designed to couple to the fourth mode. Fig. 5 presents the SEM of one such device. Despite its segmented geometry, the electrode of Fig. 1 is capable of exciting not only the 4th WGM, but also the radial contour mode. This then allows direct comparison of $Q$’s for these modes.

Devices were tested using a Lakeshore model FWPX probe station to provide a 10μTorr environment while allowing electrical access to devices via probes. To overcome smaller-than-expected output currents caused by the lack of ideal electrodes described earlier, and to maximize the accuracy of extracted $Q$-values, measurements employed the mixing technique of [14] to separate desired motional currents from competing parasitics.

Fig. 6 presents the measured responses in vacuum for a 17μm-radius disk operating in (a) its radial-contour mode at 309MHz with a $Q \sim 17,300$; and (b) in the 4th WGM, at a higher frequency of 511MHz with a higher $Q \sim 47,900$—an overall $fQ$ increase of 4.6×. This data, measured on the same device, confirms the expectation that anchor losses indeed dominate among loss mechanisms at high frequency, allowing the WGM device with its smaller stem motion to attain significantly higher $Q$.

From the measured curves, the motional resistances of the devices were extracted using the methods of [14] and were found to be 770kΩ and 560kΩ for the contour and whispering gallery modes, respectively. These agree, within the uncertainty of the measurement, with theoretical calculations using (4) on this electrode shape.
together with measured $Q$ values and a 100nm electrode-to-resonator gap spacing.

One remaining question is whether or not the stem isolation provided by the WGM device is enough to eliminate anchor losses to the point of revealing the maximum $Q$ value permitted by structural material losses. To shed some light on this, Fig. 7 presents the measured frequency characteristic for another of the same WGM disk devices, this one exhibiting the best performance among ~60 measured devices, with a startlingly high $Q = 109,000$ at 515MHz. This is the highest $Q$ measured to date at ~500MHz for any on-chip room temperature resonator, yielding an $f \cdot Q$ product of $5.6 \times 10^{13}$, which is the highest so far demonstrated in diamond structural material. Does this represent the limit of the hot filament CVD diamond material used here? It’s anyone’s guess, but theory does predict that even higher $Q$’s should be possible.

**CONCLUSIONS**

By designing electrodes to couple to a specific WGM in an HF CVD diamond disk, the WGM has been shown to greatly enhance $fQ$ product by suppressing anchor losses, in particular posting a record-setting $Q$ of 109,200 at 515MHz, the highest $Q$ reported to date in this frequency range for a room-temperature acoustic device. The corresponding $fQ$ of $5.6 \times 10^{13}$ is comparable to previous best reported values for FBAR resonators [15], but with the marked advantage of having a CAD-definable frequency dependent mainly on lateral dimensions. The improved anchor isolation and very high $Q$’s at UHF should enable unprecedented RF front-end frequency selectivity and low phase noise in oscillators for future portable communications. Additionally, the reduced motion at the center of the WGM disk suggests the possibility of larger anchors or the use of simpler non-self-aligned processes, greatly reducing cost and difficulty of fabricating such devices in a production setting.

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**REFERENCES**