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OSCILLATOR FAR-FROM-CARRIER PHASE NOISE REDUCTION VIA NANO-SCALE GAP TUNING OF MICROMECHANICAL RESONATORS

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ABSTRACT

Substantial improvements in the far-from-carrier phase noise of oscillators referenced to stand-alone (as opposed to arrayed) capacitively transduced micromechanical disk resonators have been attained via the use of atomic layer deposition (ALD) to tune the electrode-to-resonator capacitive gaps. Specifically, ALD of about 30nm of hafnia (HfO_2) onto the surface of a released 60-MHz micromechanical disk resonator to reduce its effective resonator-to electrode gap size from 92nm to 32nm provides an increase in power handling leading to more than 15-20dB reduction in the far-from-carrier phase noise of an oscillator referenced to this resonator. This ALD-enabled nano-scale gap tuning provides a simple and effective method to satisfy increasing demands for higher short-term stability in frequency references for electronic applications.

KEYWORDS

MEMS resonator, oscillator phase noise, atomic layer deposition, capacitive transducer

INTRODUCTION

With measured on-chip *Q*’s exceeding 150,000 at VHF and 15,000 at UHF, surface-micromachined capacitively transduced micromechanical disk resonators have already combined with properly-designed sustaining circuits to achieve phase noise marks commensurate with the reference oscillator specifications required by the GSM cellular phone standard [1]. Specifically, GSM demands phase noise < -130dBc/Hz at 1 kHz offset from a 13-MHz carrier, and <-150dBc/Hz at far-from-carrier offsets. In satisfying these specs, the sheer *Q* of a capacitively transduced micromechanical resonator easily makes the close-to-carrier number. The far-from-carrier number, on the other hand, is much less dependent on *Q* and rather relies more on the power handling capability of the resonator, which for capacitive transduction is smaller than that of quartz crystals.

To overcome the power handling deficiencies of capacitively transduced disks, [2] mechanically coupled many disks into an array composite resonator that behaved like a single high-*Q* resonator, but with a power handling capability larger than that of a single resonator by a factor equal to the number of resonators used in the array. The solution of [2] comprises a mechanical circuit approach to raising power handling, so requires no changes in technology to achieve the needed performance. Arguably, such a circuit approach is perhaps the most elegant solution to the far-from-carrier phase noise issue for commercial wireless needs. However, another method to raise the current handling ability of a capacitively transduced micromechanical resonator is to reduce its electrode-to-resonator gap spacing, which essentially provides it with a more efficient electromechanical transducer.

Pursuant to investigating the efficacy of this approach, this work explores the use of ALD gap-filling methods [3] to reduce gaps towards a 15-20dB improvement in the far-from-carrier phase noise of an oscillator referenced to a micromechanical disk resonator. Although impressive, this figure comes at the expense of the close-to-carrier phase noise, which ends up suffering from 1) a lower *Q* caused by ALD; and 2) noise aliased by the larger nonlinearity arising from smaller electrode-to-resonator gap spacing. Before delving in, some review of phase noise theory is in order.

OSCILLATOR PHASE NOISE

Figure 1 presents a schematic of the circuit used in this work to sustain the oscillation of a micromechanical disk resonator. Briefly, in order to start up oscillations, the loop gain must be larger than 1 and its phase shift must be 0°. One way to insure this is to use a transresistance sustaining amplifier with current-to-voltage gain larger than the motional resistance of the resonator. Once oscillation begins, the amplitude of oscillation grows until some form of nonlinearity limits the amplitude, after which steady-state oscillation ensues. Unlike quartz crystal oscillators, where the oscillation amplitude is generally limited by amplifier nonlinearity, MEMS resonator-based oscillators limit via either a nonlinearity in the resonator itself, or by a limiter circuit placed in the feedback loop.

As shown in *Figure 1*, this work takes the latter ap-

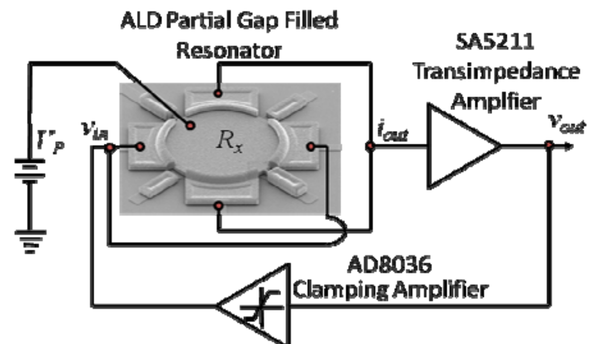

Figure 1: Schematic of the oscillator circuit used in this work, which comprises a micromechanical disk resonator, a transimpedance amplifier, and a clamping amplifier.

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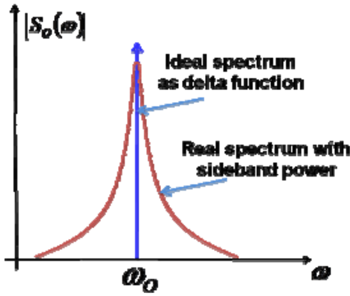

Figure 2: Schematic comparing the ideal delta function output signal of a noiseless oscillator with the actual output of a real oscillator possessing sideband noise components.

proach. In particular, the circuit utilizes an SA5211 transimpedance amplifier with a transresistance gain of 14kΩ, together with an AD8036 clamping amplifier that clamps the voltage applied to the micromechanical disk resonator to a specifiable value, thereby limiting the oscillation amplitude of the overall oscillator.

Given that the main function of an oscillator is to provide a very distinct and stable frequency, the output of a perfectly ideal oscillator should in principal be a delta function in frequency domain, where all energy is at one and only one frequency. However, in practice, noise from the electronics or the resonator element superposes itself onto the output sinusoid, generating power at frequencies adjacent to the output frequency as shown in *Figure 2*. This adjacent power is considered undesired noise. In general, this noise comprises both amplitude and phase components. However, when the oscillation amplitude is limited at a constant level during steady state operation, e.g.,, by the limiter in circuit of *Figure 1*, only phase noise remains.

Leeson's model describes the oscillator phase noise as the single-side band noise-to-carrier power ratio at an offset frequency Δf from the oscillator's carrier frequency f_o via the expression [6]

$$L\{\Delta f\} = 10\log\left(\frac{k_b TF}{P}\left(\frac{1}{4Q^2}\left(\frac{f}{\Delta f}\right)^2 + 1\right)\right) \quad (1)$$

where k_b is the Boltzmann constant; T is the absolute temperature in Kelvin; F is the noise factor of the sustaining amplifier; Q is the loaded quality factor of the resonator; and the oscillator carrier power P is given by

$$P \approx v_{in}^{\;2} / R_x \quad (2)$$

where v_{in} is the voltage applied to the resonator input and R_X is the resonator motional resistance. R_x is given approximately by [7]

$$R_x = \frac{m_r \omega_o}{(\varepsilon_o A_o)^2 V_P} \cdot \frac{d^4}{Q} \quad (3)$$

where A and d are the electrode-to-resonator overlap area and gap spacing, respectively; m_r is the equivalent dynamic mass of the disk; ω_o is the radian resonance frequency of the disk; V_P is the dc-bias voltage; ε_o is the permittivity of air; A is the electrode-to-resonator overlap area; and d is the electrode-to-resonator gap spacing. Assuming that the first term in the product in (1) remains constant, and given that the clamping amplifier sets v_{in} constant, (2) can be rewritten

$$P \propto Q / d^4 \quad (4)$$

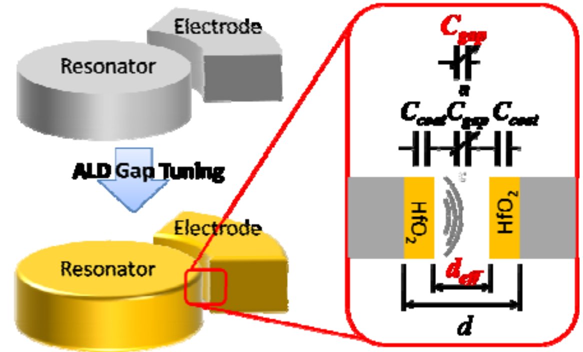

Figure 3: After high-k dielectric film coating, the capacitance between the resonator and the electrode becomes approximately equivalent to that between the two coated surfaces (C_{gap}), effecting a reduction in gap size from d to d_{eff}.

Plugging (4) into (1), the oscillator far-from-carrier phase noise (when Δf is large) becomes,

$$L(\Delta f) = 10\log\left(\frac{k_b TF}{P}\right) = 10\log\left(\frac{k_b TF}{c \cdot Q / d^4}\right) \quad (5)$$

where "c" is a constant. Using reduction scale factors, the change in far-from-carrier phase noise can be expressed as

$$\Delta L = -10\log(n_Q) + 40\log(n_d) \quad (6)$$

where n_d is the gap reduction scale factor and n_Q is the Q reduction scale factor. From (6), although Q influences the far-from-carrier phase noise, the gap spacing has a much stronger pull, with a fourth power dependence.

ALD PARTIAL-GAP FILLING

One very effective way to reduce the electrode to resonator gap spacing of a lateral micromechanical resonator is the ALD partial-gap filling method first described in [3] and depicted in *Figure 3*. Here, ALD is used to conformally deposit a thin high-k dielectric film on all surfaces of a micromechanical disk resonator, including within the electrode-to-resonator gaps. Upon doing this, the capacitance between the electrode and resonator becomes the series of three capacitors, C_{coat}, C_{gap}, and C_{coat}, where C_{gap} is much smaller than C_{coat}. Since the smallest value dominates when capacitors are in series, the resonator-to-electrode capacitance boils down to the capacitance between the two coated surfaces, or C_{gap}. This effectively reduces the gap spacing to the distance between the surfaces of dielectric coating.

To capitalize on this, micromechanical disk resonators were first fabricated by a small-lateral gap polysilicon sur-

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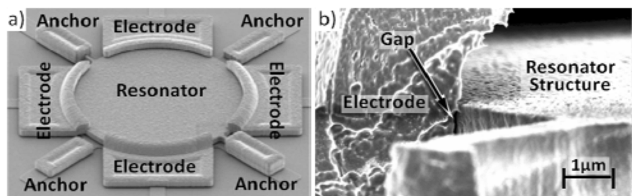

Figure 4: SEM images of (a) a polysilicon wine-glass mode disk resonator before gap tuning; and (b) cross-section after ~30nm conformal atomic layer deposition of HfO_2. The resonator-to-electrode gap was reduced from 92nm to 32nm.

face micromachining process similar to that previously used in [1][3]. Devices were patterned in a 3µm-thick polysilicon layer and a conformal sacrificial sidewall spacer high temperature oxide (HTO) deposition provided 92nm lateral gaps between resonator structure and electrodes. Next, devices were released using hydrofluoric acid wet etching followed by critical point drying. *Figure 4(a)* shows the SEM of the resonator device at this point in the fabrication process. Next, atomic layer deposition was used to coat the surfaces of devices with 30nm of HfO_2 (κ~30), which reduced electrode-to-resonator gap spacings down to ~32nm.. *Figure 4(b)* presents the device cross-section after this partial-gap filling process.

EXPERIMENTAL RESULTS

Resonator Frequency Response Measurement

Frequency response spectra for the fabricated micromechanical disks were measured under 1 µTorr vacuum before and after gap reduction via ALD. *Figure 5* compares the measured characteristics after normalization to their respective center frequencies by making the x-axis fractional frequency offset from resonance. (This normalization was necessary, since the added mass (and stiffness) of the ALD film shifted the resonance frequency from 61.04 MHz without ALD, to 59.82 MHz with it.) The plot clearly shows

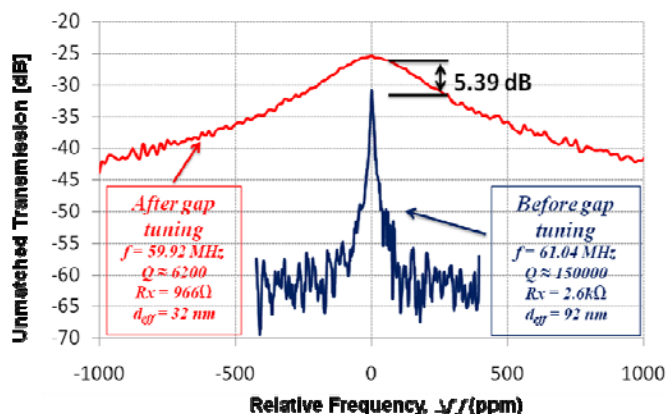

Figure 5: Comparison of frequency response before and after gap tuning. The loss after gap tuning is 5.39dB less than before gap tuning, due to enhanced power handling by reduced gap size, although quality factor was lowered after the ALD. In both cases, the bias voltage was the same (V_P=16V).

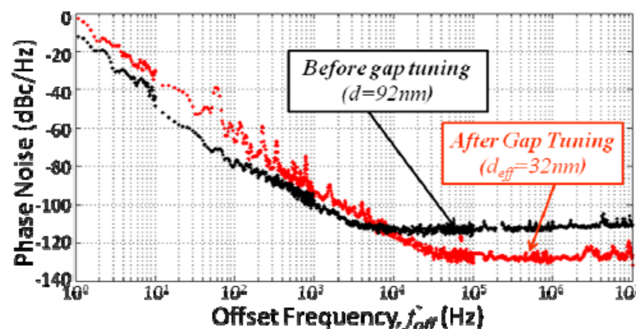

Figure 6: Plot comparing the phase noise of the 60-MHz wine-glass mode disk resonator oscillator before and after ALD gap tuning. As can be seen, the "far-from-carrier" phase noise has been improved by more than 15dB.

a 5.39dB increase in the (unmatched) transmission at resonance for the partial ALD-gap-filled device over the unfilled one, even after a significant reduction in quality factor (from 150,000 to 10,000). This reduction in quality factor was discussed in [3] and is probably caused by added surface losses induced by the deposited HfO_2 film.

Oscillator Phase Noise Measurement

Both ALD partial-gap-filled and non-filled disk resonators were mounted and bond-wired to the circuit of *Figure 1*, then placed into a custom-built vacuum chamber with electrical feedthroughs to allow connection to external power sources and measurement instrumentation. *Figure 7* presents a photo of the "glass bulb" vacuum chamber with the oscillator board within. During testing, a turbomolecular pump provided vacuums down to 1 µTorr, which eliminates gas damping and allows a given resonator to take on its highest Q value.

The application of a dc-bias voltage V_P (c.f., *Figure 1*) to the disk resonator and supply power to the sustaining circuit was all that was needed to induce startup of oscillations. *Figure 8* presents the oscillation waveform produced by the oscillator circuit referenced to a 32µm-radius wine-glass disk without ALD operating in its 61-MHz wine-glass disk mode. Given that the output voltage was clamped at 10mV by the AD8036, it is no surprise that the ALD partial-gap

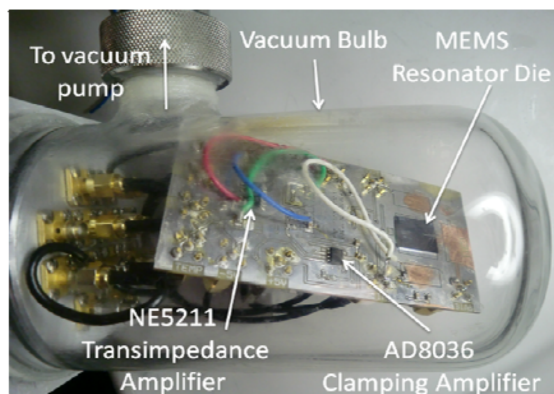

Figure 7: The test setup. Here, the resonator die is mounted on the circuit board and installed in a custom-made chamber for phase noise measurement under high vacuum (~µTorr).

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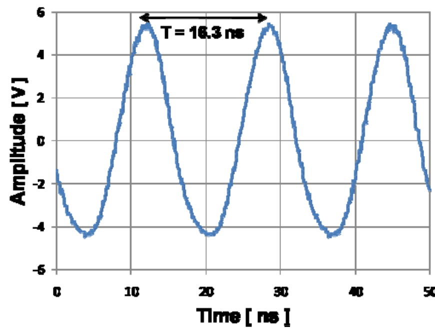

Figure 8: Oscilloscope waveform of the oscillator output.

filled devices gave similar output waveforms.

An Agilent E5500 Phase Noise Measurement System was utilized to accurately measure the phase noise of 1) a 32μm-radius disk without ALD gap-filling, so with an electrode-to-resonator gap spacing of 92nm; and 2) a 32μm -radius disk with an ALD partial-gap-filled electrode-to-resonator gap spacing of 32nm. *Figure 6* plots the respective phase noise curves, each divided down to a common carrier frequency of 13MHz for fair comparison. Here, ALD partial-gap filling is seen to provide an improvement in far-from-carrier phase noise by more than 15dB, and up to 20dB at certain far-from-carrier frequency offsets!

It should be noted that the observed improvement in far-from-carrier phase noise actually does not match the prediction of (6). In particular, if the measured gap spacing and Q reduction factors of ~3 and ~15, respectively, are inserted into (6), the predicted improvement in far-from-carrier phase noise is only 7dB. This is much smaller than the observed 15-20dB. At present, this is difficult to explain, although there are two plausible possibilities:

1) It is possible (but not likely) that the AD8036 clamping circuit increased its clamping voltage value when the ALD partial-gap-filled disk was inserted in to the oscillator loop, which would then raise the power level.
2) The very small gap of the ALD'ed disk incites nonlinearity at much smaller displacement amplitudes, leading to much larger output current amplitudes than predicted by linear theory for any given input voltage, and thus, generating more power than expected.

If either of the above occurred, then the loop power given by (2) would be larger and more capable of achieving the 15-20dB improvement in phase noise.

Regardless of the above, the observed improvement in far-from-carrier phase noise comes at a heavy cost to the close-to-carrier phase noise, which becomes considerably poorer after ALD-coating of the disk resonator. Much of the poorer close-to-carrier phase noise derives directly from the fact that the Q of the ALD'ed disk dropped by a factor of ~15×. Since (1) has a $1/Q^2$ dependence, this factor is equivalent to a 23dB increase in phase noise at close-to-carrier offsets, which then negates the apparent 20dB improvement afforded by the higher power handling ability of the ALD partial-gap-filled disk.

But there's actually more to it than this. In particular, some portions of the ALD partial gap-filled resonator oscillator's close-to-carrier curve are more than 20dB higher than that of the non-ALD case, and this cannot be explained by the observed Q reduction. Closer inspection of the close-to-carrier region on the ALD'ed resonator oscillator curve shows that this curve exhibits a $1/f^3$ dependence, whereas the non-ALD curve has a $1/f^2$ dependence. From [4] and [5] this suggests that the ALD partial-filled gap resonator was driven to amplitudes large compared to its static gap spacing, which is not surprising given the tiny size of the gap. As explained in [4] and[5], operation at such large amplitudes induces nonlinearities than can then alias transistor $1/f$ noise into the oscillator passband, where they are then filtered by the oscillator transfer function to generate $1/f^3$ noise. This would also support mechanism (2) above in explaining the larger far-from-carrier phase noise improvement.

CONCLUSIONS

Although it requires some sacrifice in close-to-carrier phase noise and exhibits some unexpected performance enhancement, the 15-20dB increase in far-from-carrier phase noise obtained via ALD partial-gap filling in this work is nevertheless very impressive. Given that present MEMS-based GSM-phase-noise-compliant oscillators actually beat the GSM close-to-carrier phase noise requirements by a fairly large margin (e.g., by 10dB in [2]), there is actually some room to sacrifice in close-to-carrier phase noise. This, together with a reduction in the number of resonators needed over the array approach of [2] makes the described ALD partial-gap filling approach quite compelling for future high performance MEMS-based oscillators.

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