1.5-GHz CMOS Voltage-Controlled Oscillator Based On Thickness-Field-Excited Piezoelectric AlN Contour-Mode MEMS Resonators

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Abstract – This paper reports on the first demonstration of a 1.5 GHz CMOS oscillator based on thickness-field-excited (TFE) piezoelectric AlN MEMS contour-mode resonators (CMRs). The measured phase noise is −85 dBc/Hz at 10 kHz offset frequency and −151 dBc/Hz at 1 MHz. This is the highest frequency MEMS oscillator ever reported using a laterally vibrating mechanical resonator. The high frequency operation has been enabled by optimizing the geometrical design and micro-fabrication process of TFE AlN CMRs, so that a low effective motional resistance around 50 Ω is achieved together with a high unloaded quality factor \( Q_u \) approaching 2500 and simultaneously high \( k_t^2 \) up to 1.96\%t. A tunable-supply oscillator design is proposed for fine frequency tuning (or trimming) over a narrow bandwidth. The circuit design enables a novel GHz voltage-controlled oscillator (VCO) without the use of any low-\( Q \) tunable component. The 1.5 GHz VCO exhibits a 1500 ppm tuning range by a DC voltage change of 2.5 V. This technique can be utilized for fine frequency trimming and temperature compensation applications.

I. INTRODUCTION

For timing and frequency control applications, no other electronic components have stood the test of time better than quartz crystal oscillators. However, MicroElectroMechanical Systems (MEMS) technology [1–4] has emerged as a very promising and competitive alternative due to its small form factor, high operating frequency up to GHz, and especially its compatibility with Integrated Circuit (IC) technology. This offers the potential for an on-chip integrated multi-frequency and reconfigurable frequency reference solution for next-generation wireless communications and ultra-compact digital computing applications without the need for bulky quartz crystal resonators. Large scale MEMS-IC co-integration will not only lead to reduction in fabrication cost, routing parasitics and power consumption, but also permit the development of new RF transceiver architectures and electromechanical based computing.

Extensive work has been conducted to develop high-purity oscillators based on MEMS resonators with either electrostatic or piezoelectric transduction [2–4]. However, the synthesis of high frequency (>1 GHz) MEMS oscillators based on laterally vibrating mechanical resonators (which are required to enable banks of on-chip clocks with reconfigurable frequency) is still a challenge, especially for electrostatic Si MEMS resonators, whose motional resistance is prohibitively large for GHz operation. It is only recently that MEMS oscillators around 1 GHz were first demonstrated using a 1.05 GHz lateral-field-excited (LFE) piezoelectric Aluminum Nitride (AlN) MEMS contour-mode resonator (CMR) [5] and a 1.006 GHz AlN-on-Si MEMS resonator [6]. For the lateral field excitation of AlN CMRs, the electromagnetic coupling, \( k_t^2 \), is sensitive to the AlN film thickness, \( T_{AlN} \), and therefore it is not suitable for wide band applications where high \( k_t^2 \) is needed for a very wide frequency range from tens of MHz to a few GHz [5]. For AlN-on-Si MEMS resonators, the \( k_t^2 \) is even lower because the applied electric field is only exciting a small portion of the resonator, namely the AlN thin film part, but not the main resonator body made out of Si [3]. Furthermore, the two-port configuration and large transducer capacitance at each port complicate the oscillator design and constitute a fundamental problem in achieving high closed-loop gain at low power consumption for operation frequencies larger than 1 GHz.

Fig. 1. Micrographs and circuit schematics of the 1.5-GHz thickness-field-excited piezoelectric AlN contour-mode resonator that was wire-bonded to a CMOS integrated circuit chip to form the 1.5-GHz MEMS oscillator.

In this paper, significant progress has been made to further enhance the overall performance of one-port high-frequency (>1 GHz) thickness-field-excited (TFE) AlN CMRs so that...
simple and low power oscillators can be devised. After careful
optimization of the resonator geometry design and the micro-
fabrication process, TFE AlN CMRs have been demonstrated
from 500 MHz up to 1.5 GHz with high unloaded quality
factor (\(Q_u\)) up to 2500 and high \(k_t^2\) up to 1.96%, which result
in low effective motional resistance (i.e., resistive loss at
series resonance) around 30 Ω for the entire frequency range.
Using the 1.5-GHz TFE AlN CMR with high \(k_t^2\) (1.96%) and
low effective motional resistance (44 Ω), a 1.5-GHz CMOS
voltage-controlled oscillator (VCO) has been implemented
with low phase noise of ~85 dBc/Hz at 10 kHz frequency
offset and ~151 dBc/Hz at 1 MHz offset. This is the highest
frequency MEMS oscillator ever demonstrated using laterally
vibrating mechanical resonators. The MEMS resonator die is
wire-bonded to the IC chip, which is fabricated in the ON
Semiconductor 0.5-μm CMOS process, as shown in Fig. 1.

II. HIGH FREQUENCY TFE AlN CMRS

Two different excitation schemes have been adopted for
the development of high frequency piezoelectric AlN MEMS
contour-mode resonators (CMRs) namely, thickness field
excitation (TFE) [7] and lateral field excitation (LFE) without
any bottom electrode [8]. Based on TFE scheme, AlN CMR
multi-frequency oscillators were demonstrated from 176 to
482 MHz using a single Pierce circuit design [4]. Due to the
difficulties in patterning smaller electrodes (few μm wide and
> 50 μm long) lithographically and depositing high-quality
piezoelectric AlN thin film on uneven surfaces, deteriorations
of the resonator quality factor and oscillator phase noise were
observed for higher frequency operation of the TFE scheme
[4]. Therefore the LFE scheme without any bottom electrode
was introduced to maximize the \(Q_u k_t^2\) of AlN CMRs. By
depositing AlN directly on low-roughness Silicon wafers and
selecting the piezoelectric film thickness to be approximately
0.45 times the desired wavelength of operation, both the
sputtered AlN thin film quality (therefore resonator \(Q\) and the
electromechanical coupling (\(k_t^2\)) were enhanced to a large
extent for GHz CMRs. As demonstrated in [5], simultaneous
high \(Q\) (up to 2200) and \(k_t^2\) (up to 1.2%) were achieved for
LFE AlN CMRs from 843 MHz to 1.64 GHz.

To further pursue wide band operation (10 MHz – a few
GHz) on a single chip and enhance the overall performance of
GHz MEMS oscillators, the \(Q k_t^4\) product (figure of merit) of
AlN CMRs needs to be optimized so as to reduce the effective
motional resistance (primary part of resistive loss in those
MEMS oscillators) [4]. Although it is not easy to predict the
quality factor \(Q\) of a mechanical resonator, the \(k_t^2\) of TFE AlN
CMRs is theoretically more than twice that of LFE AlN CMRs
without a bottom electrode [9]. Therefore, in this work, special
attention has been taken to optimize the resonator geometry
and micro-fabrication process in order to enhance the overall
performance of high frequency TFE AlN CMRs. Compared
with our previous TFE resonator design [4], the thickness of
patterned bottom Pt electrodes (\(T_{Pt}\) in Fig. 2) is reduced from
200 nm to 100 nm to make the wafer surface smoother for
AlN sputtering deposition, while the thickness of the AlN thin
film (\(T_{AlN}\) in Fig. 2) is reduced from 2 μm to 1.2 μm so as to
obtain a higher transducer capacitance (which means lower
device impedance and lower motional resistance) within the
same resonator area (\(W \times L\) in Fig. 2). In terms of the micro-
fabrication process, the TFE resonators were fabricated on the
same chip with dual-layer-stacked (DLS) AlN resonators and
filters [10] in a single process, which is fully compatible with
the previously demonstrated process for making piezoelectric
In addition, a new method for direct dry etching of AlN at low
temperature (12 °C) with photoresist as a mask, instead of the
conventional SiO\(_2\) hard mask, was adopted to improve the
etched profile of the resonator [10]. In this way, the etching
step for the definition of the AlN resonator body has been
greatly simplified and the surface cleanliness of the wafer has
been improved to a large extent.

These design and process improvements led to TFE CMRs
operating from 500 MHz up to 1.5 GHz with high unloaded
quality factor (\(Q_u\)) up to 2500 and high \(k_t^2\) up to 1.96%,
resulting in a low effective motional resistance (which means
resistive loss at series resonance) around 50 Ω for the entire
frequency range. The experimental results are listed in Table I.
The electrical response of TFE CMRs can be described by an
equivalent circuit model called the modified Butterworth–Van
Dyke (MBVD) model [4]. As an example, the experimental
admittance and the corresponding MBVD model fitting for the
1.5 GHz resonator are plotted in Fig. 3. Unlike the high
frequency LFE AlN CMRs [5], whose series resistive loss is
dominated by the mechanical motional resistance, the resistive
loss at series resonance for TFE AlN CMRs demonstrated
herein consists of two parts: the motional resistance of the
mechanical resonance (\(R_0\)) and the parasitic electrical
resistance (\(R_3\)) from the Pt thin film electrodes and top-to-
bottom electrode vias. For LFE AlN CMRs, no via process is
needed and the Pt electrodes are twice the thickness, therefore
causing less parasitic resistive loss. On the other hand, the
TFE AlN CMRs also have much larger \(k_t^2\), as experimentally
demonstrated to be from 1.25% to 1.96%, instead of the
0.39% – 1.2% exhibited by LFE AlN CMRs. All these
differences result in a mechanical motional resistance (\(R_0 \sim
20\ Ω\) comparable to the parasitic electrical resistance (\(R_3 \sim
20\ Ω\) in TFE AlN CMRs. This indicates that the measured \(Q_u\)
at series resonance is significantly loaded by \(R_0\). The unloaded
\(Q_u\) of the real mechanical resonance is therefore calculated
and given in Table I. As we can see, high \(Q_u\) up to 2500 has been
demonstrated with simultaneously high $k_r^2$ up to 1.96%. This proves that there is no intrinsic deficiency from a material perspective in using the TFE scheme for exciting AlN CMRs. Nonetheless, further optimizations of the electrode resistance and the via fabrication process can be performed to minimize the $Q$ loading and ultimately improve the device performance.

TABLE I. EXPERIMENTAL RESULTS OF TFE AlN RESONATORS

<table>
<thead>
<tr>
<th>$f_s$ [GHz]</th>
<th>$Q_s$</th>
<th>$k_r^2$</th>
<th>$R_m$ [Ω]</th>
<th>$R_p$ [Ω]</th>
<th>$Q_m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.501</td>
<td>1200</td>
<td>1.54%</td>
<td>20</td>
<td>18</td>
<td>2400</td>
</tr>
<tr>
<td>0.795</td>
<td>1450</td>
<td>1.25%</td>
<td>40</td>
<td>19</td>
<td>2050</td>
</tr>
<tr>
<td>1.164</td>
<td>1050</td>
<td>1.41%</td>
<td>22</td>
<td>20</td>
<td>2500</td>
</tr>
<tr>
<td>1.528</td>
<td>850</td>
<td>1.96%</td>
<td>22</td>
<td>22</td>
<td>1450</td>
</tr>
</tbody>
</table>

$f_s$: series resonant frequency; $Q_s$: quality factor at series resonance; $k_r^2$: electromechanical coupling coefficient; $R_m$: motional resistance; $R_p$: parasitic series resistance in the MBVD model; $Q_m$: unloaded quality factor of the mechanical resonance

![Measurement admittance and MBVD model fitting for the 1.5-GHz TFE piezoelectric AlN contour-mode MEMS resonator.](image1)

III. TUNABLE OSCILLATOR CIRCUIT DESIGN

For the purpose of designing a single oscillator circuit that works for multi-frequency piezoelectric AlN CMRs, a tunable inverter-type amplifier was previously proposed (see Fig. 1). The CMOS inverter-type amplifier consists of transistors $M_1$ and $M_2$, and transistor $M_3$ serves as a large resistor to bias the gate and drain voltages of $M_1$ and $M_2$. The DC bias current of the NMOS transistor $M_1$ is efficiently reused in the PMOS transistor $M_2$ to provide additional AC gain for starting and sustaining the oscillation. Except for having both the NMOS and PMOS transistors contributing to the transconductance ($g_m$), the small-signal AC analysis of the oscillator system and the critical $g_m$ for starting oscillations is the same as presented in [4].

The tunability of the amplifier is achieved by varying the supply voltage $V_{DD1}$ (Fig. 1) such that the DC bias current and therefore $g_m$ can be tailored to different values according to the oscillation gain requirements. The total $g_m$ in the oscillator core with transistors working in the saturation region can be expressed as:

$$g_m = \frac{W}{L} \mu \frac{W}{L} \left[ a V_{DD1} \left[ V_{Tn} - V \right] + \mu_p \frac{W}{L} \left[ 1 - a \right] V_{DD1} \left[ V \right] \right]$$

where $\mu_n$ is the electron mobility; $\mu_p$ is the hole mobility; $C_m$ is the capacitance per unit area of the gate oxide; $V_{Tn}$ and $V_{Tp}$ are the threshold voltages for NMOS and PMOS transistors, respectively; $W/L$ and $W/L_2$ are the effective channel width-to-length ratios for the two transistors; $a$ is the ratio between the DC bias voltage at the drain of $M_1$ ($V_{DD1}$) and $V_{DD1}$ and it is a parameter depending on the layout design (namely $W/L_1$ and $W/L_2$) of the transistors. Since transistors $M_1$ and $M_2$ are self-biased by transistor $M_3$, the proposed tuning mechanism works not only in the saturation region but also the moderate and weak inversion regions, as verified by Cadence Spectre simulations. The total $g_m$ was simulated for $V_{DD1}$ varying from 0 to 5 V. The results show that $g_m$ can be tuned over a broad range (0.6-26.4 mS) for $V_{DD1}$ varying between 1.5 and 2.5 V. Because $V_{Tn} = 0.7$ V and $V_{Tp} = -0.9$ V, it can be concluded that the tuning is most effective with the transistors $M_1$ and $M_2$ working in the weak and moderate inversion regions. On the other hand, the proposed tunable-supply self-biasing topology also circumvents the well-known difficulty in biasing MOS transistors for stable weak-inversion operation, and facilitates low-voltage sub-threshold CMOS design for extremely low power applications.

By tuning $g_m$ for the circuit, not only the effective negative resistance, but also the relative frequency pulling can be set to the desired value for the oscillator [12]. When a bank of multi-frequency switchable MEMS resonators is connected to the circuit, the $g_m$ tunability can be utilized for reconfiguring the system and selecting operation at a specific frequency [5]. After the resonator bank is configured for single frequency operation, the tunable $g_m$ can be used to change the relative frequency pulling, and therefore tune the oscillation frequency over a narrow bandwidth, as experimentally demonstrated in this paper.

![Simulated $g_m$ as a function of $V_{DD1}$ for the oscillator design.](image2)

IV. EXPERIMENTAL RESULTS

The TFE piezoelectric AlN CMRs were fabricated in the Wolf Nanofabrication Facility at Penn and the tunable circuit design was implemented in the ON Semiconductor 0.5-μm
CMOS process. The MEMS and IC dies were connected via wire-bonding (Fig. 1) and mounted on a printed circuit board (PCB). A carefully designed on-chip 50-Ω buffer was used to interface the oscillator core with the measurement instruments.

The circuit starts oscillation when the supply voltage $V_{DD1}$ reaches 2.5 V and the corresponding DC power consumption of the oscillator is 6.9 mW. The oscillator phase noise is measured to be −85 dBc/Hz at 10 kHz offset frequency and −151 dBc/Hz at 1 MHz, as shown in Fig. 5.

By optimizing the geometrical design and microfabrication process of thickness-field-excited piezoelectric AlN contour-mode MEMS resonators, low effective motional resistance around 50 Ω has been achieved from 500 MHz to 1.5 GHz together with high unloaded quality factors ($Q_u$) up to 2500 and high $k^2$ up to 1.96%. A tunable-supply oscillator design is proposed not only to operate a bank of switchable resonators that span a wide frequency range (from MHz to a few GHz), but also for fine frequency tuning (or trimming) in a narrow bandwidth. By combining the progress on TFE resonators and the tunable-supply circuit design, a novel 1.5-GHz voltage-controlled oscillator (VCO) has been demonstrated without the need for any low-$Q$ tunable component. This is so far the highest frequency MEMS oscillator reported using laterally vibrating mechanical resonators. When operated at 6.9 mW DC power consumption, the oscillator shows a phase noise value of −85 dBc/Hz at 10 kHz offset and −151 dBc/Hz at 1 MHz. A tuning range of 1500 ppm for a DC voltage change of 2.5 V has been shown, which can be used for frequency trimming and temperature compensation applications. In future work, we plan to demonstrate a multi-frequency reconfigurable and temperature compensated oscillator using this technology.

V. CONCLUSION

The frequency tuning feature of the tunable-supply design is experimentally verified in this paper. As shown in Fig. 6, the output frequency of the 1.5-GHz oscillator can be tuned by 1500 ppm by varying $V_{DD1}$ from 2.5 to 5 V. The phase noise at 10 kHz offset frequency reaches a minimum of −96 dBc/Hz when $V_{DD1}$ is larger than 4.2 V and the phase noise floor is minimum (−159 dBc/Hz) when $V_{DD1}$ equals 3.0 V, as shown in Table II. With this novel analog tuning technique, a simple voltage-controlled oscillator (VCO) has been realized without using any low-$Q$ tunable component. The proposed VCO constitutes a promising solution for frequency trimming and possibly temperature compensation of MEMS oscillators. For example, the TFE AlN CMRs generally have a temperature coefficient of −25 ppm/˚C, which means that the demonstrated VCO would be able to compensate for a temperature range of about 60 °C. With further optimization of the circuit design and the resonator, a full-range temperature compensation from −40 to 120 °C can be envisioned.

TABLE II. PHASE NOISE RESULTS OF 1.5-GHZ MEMS VCO

<table>
<thead>
<tr>
<th>$V_{DD}$ [V]</th>
<th>2.5</th>
<th>2.8</th>
<th>3.0</th>
<th>3.4</th>
<th>3.8</th>
<th>4.2</th>
<th>4.6</th>
<th>5.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase Noise @ 10 kHz [dBc/Hz]</td>
<td>-85</td>
<td>-92</td>
<td>-93</td>
<td>-94</td>
<td>-95</td>
<td>-96</td>
<td>-96</td>
<td>-96</td>
</tr>
<tr>
<td>Phase Noise Floor [dBc/Hz]</td>
<td>-155</td>
<td>-158</td>
<td>-159</td>
<td>-158</td>
<td>-157</td>
<td>-157</td>
<td>-156</td>
<td>-156</td>
</tr>
</tbody>
</table>

REFERENCES


Fig. 5. Measured phase noise of the 1.5-GHz MEMS oscillator.

Fig. 6. Measured frequency shift and output power of the 1.5-GHz MEMS oscillator when $V_{DD}$ is varied between 2.5 and 5 V.