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

Chengjie Zuo, Jan Van der Spiegel, and Gianluca Piazza

Department of Electrical and Systems Engineering
University of Pennsylvania
Philadelphia, PA 19104, USA
{czuo, jan, piazza}@seas.upenn.edu

***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%. 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 electromechanical 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.

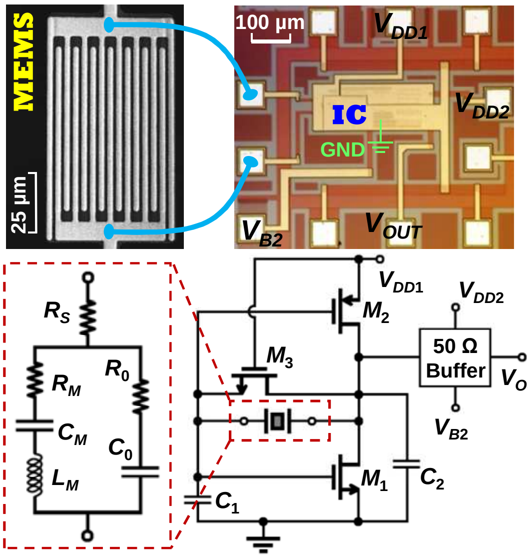

Fig. 1. Micrographs and circuit schematics of the 1.5-GHz thickness-field-excited piezoelectric AlN contour-mode resonator that was wire-bonded to a CMOS integrated circuit chip to form the 1.5-GHz MEMS oscillator.

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

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simple and low power oscillators can be devised. After careful optimization of the resonator geometry deisgn 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 50 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 $Q{\cdot}k_t^2$ 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 $Q{\cdot}k_t^2$ 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 ($nW \times L$ 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 AlN RF MEMS switches [11] (also post-CMOS compatible). 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.

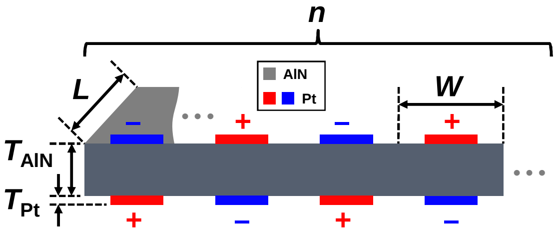

Fig. 2. Cross-sectional schematic of a thickness-field-excited (TFE) piezoelectric AlN contour-mode resonator (CMR). The third dimension is introduced to represent the length of the resonator, *L*.

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_M) and the parasitic electrical resistance (R_S) 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_M ~ 20 Ω) comparable to the parasitic electrical resistance (R_S ~ 20 Ω) in TFE AlN CMRs. This indicates that the measured Q_s at series resonance is significantly loaded by R_S. 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_t^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

f_s [GHz]	Q_s	k_t^2	R_M [Ω]	R_S [Ω]	Q_u
0.501	1200	1.54%	20	18	2400
0.795	1450	1.25%	40	19	2050
1.164	1050	1.41%	22	20	2500
1.528	850	1.96%	22	22	1450

f_s: series resonant frequency; Q_s: quality factor at series resonance;
k_t^2: electromechanical coupling coefficient; R_M: motional resistance;
R_S: parasitic series resistance in the MBVD model;
Q_u: unloaded quality factor of the mechanical resonance

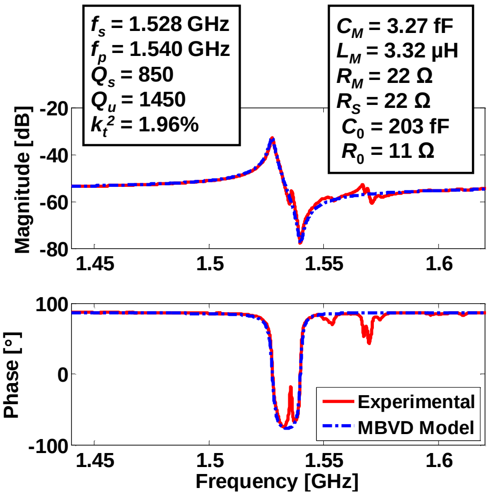

Fig. 3. Measured admittance and its MBVD model fitting for the 1.5-GHz TFE piezoelectric AlN contour-mode MEMS resonator.

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:

$$g_m \approx |\mu_n| C_{ox} \frac{W_1}{L_1}\left[\alpha V_{DD1} - |V_{Tn}|\right] + |\mu_p| C_{ox} \frac{W_2}{L_2}\left[(1-\alpha) V_{DD1} - |V_{Tp}|\right], \qquad (1)$$

where μ_n is the electron mobility; μ_p is the hole mobility; C_{ox} 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_1/L_1 and W_2/L_2 are the effective channel width-to-length ratios for the two transistors; α is the ratio between the DC bias voltage at the drain of M_1 (M_2) and V_{DD1} and it is a parameter depending on the layout design (namely W_1/L_1 and W_2/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.

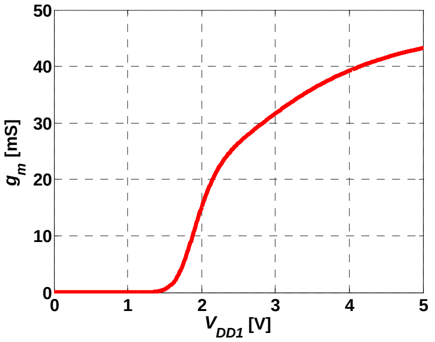

Fig. 4. Simulated g_m as a function of V_{DD1} for the oscillator design.

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.

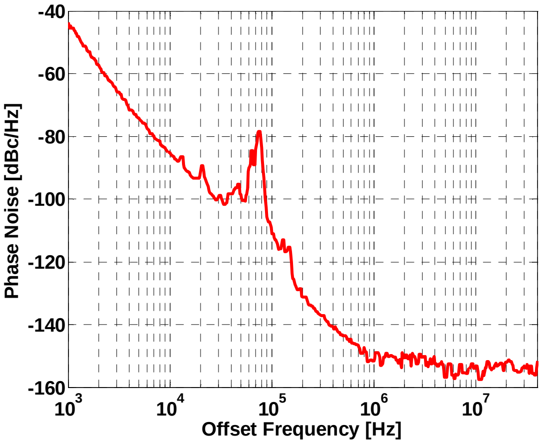

Fig. 5. Measured phase noise of the 1.5-GHz MEMS oscillator.

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

V_{DD1} [V]	2.5	2.8	3.0	3.4	3.8	4.2	4.6	5.0
Phase Noise @ 10 kHz [dBc/Hz]	-85	-92	-93	-94	-95	-96	-96	-96
Phase Noise Floor [dBc/Hz]	-155	-158	-159	-158	-158	-157	-157	-156

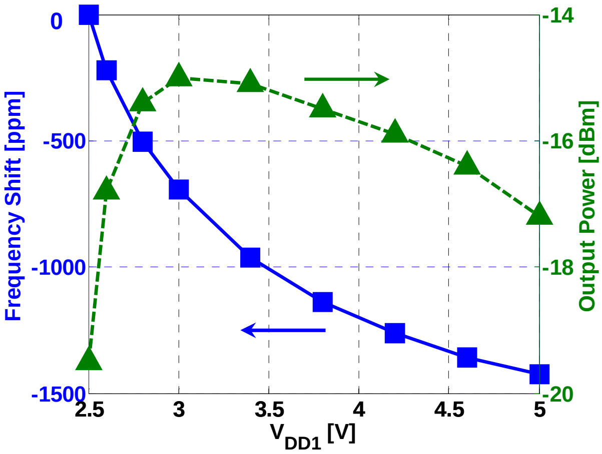

Fig. 6. Measured frequency shift and output power of the 1.5-GHz MEMS oscillator when V_{DD1} is varied between 2.5 and 5 V.

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.

V. CONCLUSION

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_t^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 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.

REFERENCES

[1] C. T.-C. Nguyen, *TUFFC*, vol. 54, no. 2, pp. 251-270, 2007.

[2] W.-T. Hsu, *IMS 2006*, San Francisco, CA, USA, 2006.

[3] R. Abdolvand, *et al.*, *TUFFC*, vol. 55, pp. 2596-2606, 2008.

[4] C. Zuo, *et al.*, *IFCS 2008*, Honolulu, Hawaii, USA, 2008.

[5] C. Zuo, *et al.*, *TUFFC*, vol. 57, no. 1, pp. 82-87, 2010.

[6] H. M. Lavasani, *et al.*, *ISSCC 2010*, San Francisco, CA, 2010.

[7] P. J. Stephanou, *et al.*, *IUS 2006*, Vancouver, Canada, 2006.

[8] M. Rinaldi, *et al.*, *MEMS 2009*, Sorrento, Italy, 2009.

[9] J. H. Kuypers, *et al.*, *IFCS 2008*, Honolulu, Hawaii, 2008.

[10] C. Zuo, *et al.*, *MEMS 2010*, pp. 719-722, Hong Kong, 2010.

[11] R. Mahameed, *et al.*, *JMM*, vol. 18, 105011, 2008.

[12] E. A. Vittoz, *et al.*, *JSSC*, vol. 23, no. 3, pp. 774-783, 1988.