970 MHZ OVENIZED OSCILLATOR BASED ON AN ALN MEMS RESONATOR WITH MONOLITICALLY INTEGRATED SUSPENDED NANO HOT PLATE

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ABSTRACT

This paper presents the design and experimental verification of the highest frequency (970 MHz) ovenized MEMS oscillator ever reported. Such high frequency of operation along with excellent phase noise (PN) performance (-83 dBc/Hz at 1kHz offset and -150 dBc/Hz floor) and efficient ovenization (temperature rise factor of 18.3 K/mW) are enabled by the introduction of a novel technology platform in which a fully anchored Aluminum Nitride (AlN) Lateral Field Excited–Floating (LFE-F) Contour Mode MEMS resonator (CMR) and a monolithically integrated nanoscale heating element are perfectly overlapped and separated by a sub-micron air gap.

INTRODUCTION

Among different MEMS resonator technologies [1], the AlN contour-mode resonator (CMR) [2] has emerged as one of the most promising solutions in enabling the fabrication of multiple frequencies (10 MHz – 10 GHz) and high performance resonators on the same silicon chip [3-4] and has been exploited to synthesize miniaturized reconfigurable CMOS oscillators characterized by low phase noise and low jitter values [5].

Nevertheless, conventional AlN based MEMS oscillators suffer from large temperature dependence and their frequency exhibits a linear dependence on temperature of about -28 ppm/K [6]. Such large temperature coefficient of frequency (TCF) is not suitable for modern telecommunication systems, which require oscillators that are stable over a wide range of parameters and especially versus temperature.

In order to overcome this intrinsic issue associated with AlN MEMS resonators different techniques have been proposed. Temperature compensation of AlN MEMS resonators has been demonstrated by adding a compensating layer of SiO_2 on the material stack forming the body of the resonator [6-8]. Furthermore, low power heaters have been co-integrated with the resonant devices and few mW (instead of the 100s of mWs used in crystal based ovenized oscillators) have been used to ovenize them [9-11]. Low frequency ovenized oscillators based on both electrostatic [9] and piezoelectric [10, 11] MEMS resonators have been previously demonstrated, but none of the previously proposed design solutions and micro-ovenization techniques allowed the implementation of ovenized frequency sources operating in the GHz range. GHz range ovenized AlN CMRs have been recently demonstrated by our group by modifying the conventional layout (continuous plate) of the floating bottom electrode of LFE-F CMRs with a serpentine shaped heater [11]. Although such design solution enabled fast and efficient ovenizaiton of the MEMS resonator it caused a degradation of the device figure of merit ($FOM=k_t^2 \cdot Q$, product of the electromechanical coupling coefficient, k_t^2, and quality factor, Q) compared to the non-ovenized case, which prevented connecting the GHz frequency ovenized MEMS devices to self-sustaining oscillator circuits. Such deterioration of the device *FOM* is due to the employment of a patterned floating bottom electrode instead of a continuous floating metal plate. In fact the employment of a continuous metal plate as floating bottom electrode enables better confinement of the excitation electric field across the thickness of the piezoelectric layer and also permits to attain an overall better quality of the as-deposited piezoelectric film. This translates to achieving a higher $k_t^2 \cdot Q$.

In this work a stepping stone towards the development of a high frequency, miniaturized, low phase noise and temperature stable frequency source is set by placing the heating element outside the body of the resonator (but suspended over it) (Fig.1). This novel design allowed maintaining the electromechanical properties of the device unchanged (same $k_t^2 \cdot Q$ compared to the non-ovenized case). At the same time, efficient ovenization of the MEMS resonator is achieved by scaling the dimensions of the heating element (*i.e.* implementing a nano-hot-plate) and minimizing the air gap between the resonator and the heater.

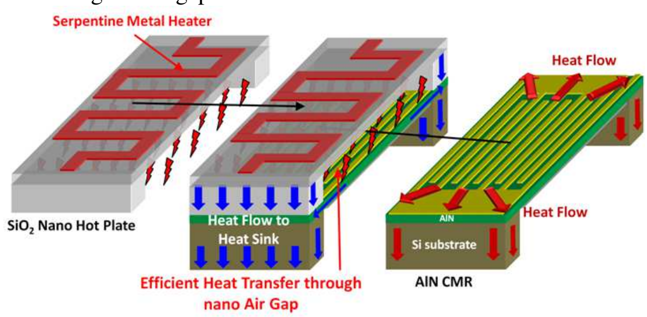

Figure 1*: Schematic representation of the innovative technology platform in which an AlN CMR and a monolithically integrated nano-hot-plate are perfectly overlapped and separated by a sub-micron air gap. Efficient ovenization is achieved by scaling the dimensions of the heating element (i.e. implementing a nano-hot-plate) and minimizing the air gap between the resonator and the heater.*

DESIGN

The AlN CMR of this work (Fig. 1) was designed to operate at a frequency of ~ 1 GHz. Therefore, the period, W, of the metal electrode patterned on the AlN plate was set to 4 μm while the other geometrical dimensions, thickness, *T*, length, *L*, and number of electrode fingers, *n*, were opportunely scaled in order to maintain a low value of the device equivalent electrical impedance [2,4] (T=500 nm, L=80 μm, n=11). Lateral field excitation with floating bottom electrode (LFE-F) [5] was employed to excite a higher order contour-extensional mode of vibration in the AlN structure. In addition, the suspended AlN resonant body was fully anchored to the silicon substrate instead of partially anchored through narrow tethers. Such configuration improves power handling and overall robustness of the MEMS resonator. At the same time, since a large number of fingers-electrode (n=11) are used to excite a higher mode of vibration in the AlN plate, the acoustic energy remains confined in the body of the AlN resonator (high Q) [8]. The simultaneous achievement of high quality factor, Q, and high power handling is crucial for the implementation of a low phase noise frequency source [8].

In order to properly design the dimensions of the suspended heater and its distance from the resonant device (Fig. 1) a simple one dimensional model was considered which includes heat transfer through conduction, convection and radiation. In this model the metal serpentine is the heat source. For a given power level, P_{in}, supplied to the serpentine, the temperature of the hot plate, T_H, can be found by solving the following equation:

$$P_{in} = \left(\frac{T_H - T_0}{R_{Pt}}\right) + \left(\frac{T_H - T_0}{R_{Ox1}}\right) + \left(\frac{T_H - T_0}{R_{Ox2} + R_{Air} + R_{AlN}}\right) + $$
$$+ \sigma\varepsilon A(T_H^4 - T_0^4) + h_{Air}A(T_H - T_0) \quad (1)$$

Where T_0 is the ambient temperature, R_{Pt} is the thermal resistance between the heat source (serpentine) and the heat sink (silicon substrate) thorough the platinum routing, R_{Ox1} is the thermal resistance between the heat source and the heat sink thorough the length of the SiO_2 suspended plate, R_{Ox2} is the thermal resistance between the heat source and the air gap thorough the thickness of the SiO_2 suspended plate, R_{Air} is the thermal resistance between the the SiO_2 suspended plate and the AlN CMR thorough the thickness of the air gap, R_{AlN} is the thermal resistance between the AlN CMR and the heat sink (silicon substrate) thorough the length of the AlN suspended structure, σ is the Stefan–Boltzmann constant, ε is the emissivity of the SiO_2 plate (~0.9), A is the area of the serpentine heater and h_{Air} is the convective heat transfer coefficient of air (typically between 10 and 100 W/(m^2 K)).

Knowing the hot plate temperature, T_H, it is possible to calculate the AlN resonator temperature, T_{CMR}, as function of the input power, P_{in}, by considering the thermal circuit in figure 2.

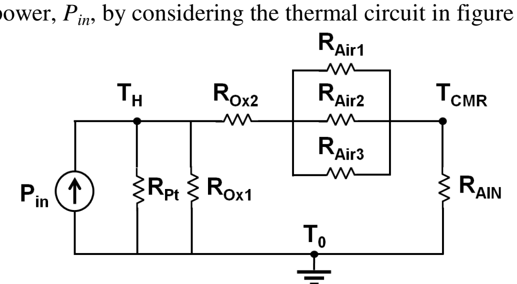

***Figure 2**: Equivalent thermal circuit describing the heat transfer from the nano hot plate to the AlN MEMS resonator.*

In the thermal circuit in figure 2 the thermal resistance associated with the air gap between the hot plate and the AlN CMR is expressed as the parallel combination of conduction (R_{Air1}), convection (R_{Air2}) and radiation (R_{Air3}) thermal resistances. Given the geometrical dimensions of the hot plate and the low values of input power level (10s mW) the convection and radiation thermal resistance values are in the order of 10^6-10^7 K/W. Therefore, R_{Air2} and R_{Air3} can be considered as open circuits for the calculation of T_{CMR} (the contribution of convection and radiation mechanisms to the heat transfer is not significant compared to the conduction through such small air gap).

In order to achieve efficient heat transfer between the hot plate and the AlN CMR ($T_H \approx T_{CMR}$) it is necessary that (R_{Ox2}+R_{Air1})< R_{AlN}. For a given geometry of the AlN CMR ($R_{AlN} \approx 5{\cdot}10^4$ *K/W* for the device of this work) this can be achieved by reducing the values of R_{Ox2} and R_{Air1}, which translates in the following design considerations:

a. Scaling of the hot plate thickness (*i.e.* implementing a nano-hot plate) to reduce R_{Ox2}.

b. Employment of a low thermal conductivity material (*i.e.* SiO_2) for the implementation of the nano hot plate (lower R_{Ox2}).

c. Scaling of the air gap between the nano hot plate and the AlN CMR to reduce R_{Air1}.

The implementation of a SiO_2 nano hot plate also ensures that a very high value of thermal resistance exists between the heat source and the heat sink (large R_{Ox1}). Therefore, even a small amount of power applied to the serpentine generates a significant temperature increase of the SiO_2 nano plate. The generated heat is then efficiently transferred to the MEMS resonator placed right underneath by conduction through the nanoscale air gap.

According to the aforementioned design considerations the integrated nano hot plate of this work was composed of a platinum (Pt 100 nm thick) serpentine shaped heater deposited on top of a 600 nm thick SiO_2 nano plate. Figure 3 shows the calculaed AlN CMR temperature rise versus the input power level applied to the heater for different values of air gap. Smaller air gaps guarantee significantly larger values of temperature rise factor of the ovenized MEMS resnator. Therefore, the air gap between the nano hot plate and the AlN CMR was set to 250 nm.

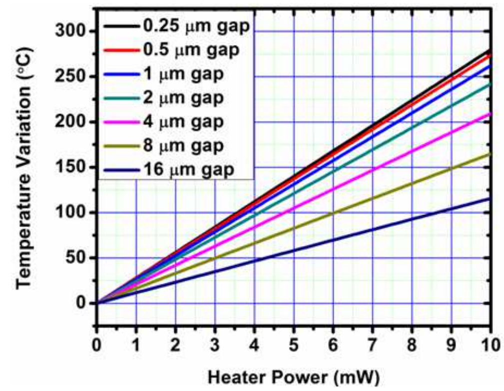

***Figure 3**: Calculated AlN CMR temperature rise for different levels of input power and different values of air gap. The calculation uses the nominal geometrical dimension of the structure and generic material parameters available in literature. The result of the analysis indicates that higher values of temperature rise factor can be achieved by scaling the air gap between the heating element and the MEMS resonator.*

FABRICATION PROCESS

The AlN MEMS resonator with monolithically integrated nano hot plate was fabricated in a six-mask post-CMOS-compatible microfabrication process (Fig. 4). The platinum (Pt) bottom floating electrode (100 nm thick) of the LFE-F device was first patterned by optical lithography, sputtered deposited and lifted off on top of a high resistivity silicon wafer. The 500 nm thick AlN film was sputtered deposited using a Tegal AMS 2004 SMT (OEM Group, Petaluma, CA) and its quality was optimized to achieve rocking curve values as good as 1.8°. Optical lithography, sputter deposition and lift-off were performed for the definition of the top aluminum (Al) multi-fingered electrode (100 nm thick). The in-plane dimensions of the AlN resonator were defined by dry etching (Inductively Coupled Plasma, ICP) of the AlN film in Cl_2-based chemistry using photoresist as a mask. A 250 nm thick polysilicon layer was deposited by RF sputtering and patterned by optical lithography and dry etching (Reactive Ion Etching, RIE) in F-based chemistry in order to create a sacrificial layer covering the surface of the AlN resonator. The thickness of the polysilicon sacrificial layer determines the gap between the nano hot plate and the AlN CMR. A 600 nm thick SiO_2 layer was deposited by Plasma Enhanced Chemical Vapor Deposition (PECVD) and patterned by optical lithography and dry etching (RIE) in F-based chemistry in order to define the structural layer forming the suspended nano hot plate. Optical lithography, sputter deposition and lift-off were performed for the definition of the Pt serpentine shaped element acting as heat source for the ovenized MEMS resonator. Isotropic dry etching in XeF_2 was finally employed to simultaneously release the MEMS resonator from the silicon substrate and etch the polysilicon sacrificial layer forming the air gap between the nano hot plate and the resonant element. The scanning electron micrographs of the fabricated device are shown in figure 5.

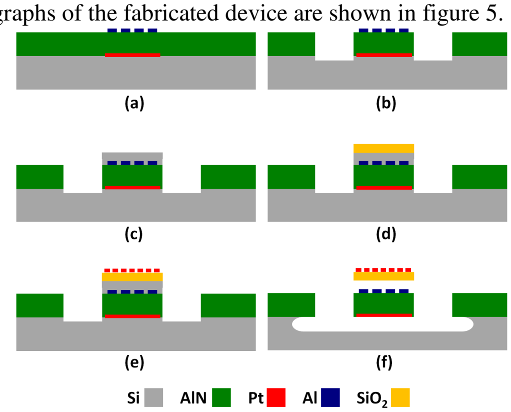

***Figure 4**: 6 mask fabrication process for the making of the AlN resonators with integrated SiO_2 nano hot plate: (a) sputter deposition of Pt (100 nm) bottom electrode, AlN (500 nm) and Al (100nm) top electrodes; (b) dry etching of AlN in Cl_2-based chemistry; (c) deposition and patterning of polysilicon sacrificial (250 nm) layer forming the airgap between the heater and the CMR; (d) deposition and patterning of SiO_2 nano-plate (600 nm); (e) deposition and patterning of Pt serpentine heater (100 nm); (f) XeF_2 dry release of the AlN resonator and the air gap between AlN CMR and the nano-hot-plate.*

EXPERIMENTAL RESULTS

The electrical response of the fabricated ovenized AlN MEMS resonator was characterized in a Semiprobe RF probe station and the admittance curve measured by an Agilent N5230A network analyzer after performing a short–open–load calibration on a reference substrate. The measured electrical response of the device was fitted to the Butterworth–van Dyke (BVD) equivalent electrical circuit [5] and showed high values of quality factor, Q=1805 and electromechanical coupling coefficient, k_t^2 =0.9% (Fig. 6). Such high value of the device figure of merit (FOM=$k_t^2 \cdot Q$ >15), is higher than what measured for conventional AlN CMR fabricated in the same batch and comparable to what is typically achieved with conventional non-ovenized AlN CMRs (employing a 500 nm thick AlN film). This value represents the best *FOM* ever reported for ovenized MEMS resonators operating in the GHz range. The achievement of a high value of device *FOM* is of crucial importance for the direct connection of the ovenized MEMS resonator to a compact and low-power oscillator circuit. In fact, the primary power loss in an oscillator circuit is due to the motional resistance, R_m, of the resonator [5], the value of which is inversely proportional to the device *FOM* [4, 5]. Given the opportunely designed device geometrical dimensions (device capacitance, C_0=220 fF) and the achieved high value of *FOM* a motional resistance, R_m, of only 56 Ω is obtained for the fabricated 968 MHz ovenized MEMS resonator ($R_m \propto 1/(C_0 \cdot k_t^2 \cdot Q)$).

The AlN MEMS device with monolithically integrated nano hot plate was directly wire-bonded to a Pierce oscillator implemented with an ATF-551M4 E-pHEMT GaAs transistor. The use of such high gain amplifier (GaAs technology) allowed exploiting the extended dynamic range of the fully-anchored AlN CMR [8].

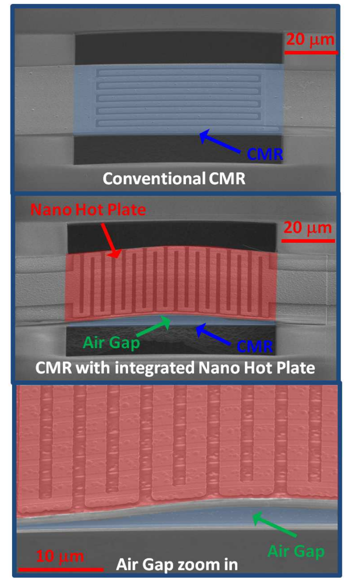

***Figure 5**: SEM of a 968 MHz conventional fully anchored AlN CMR and SEM of the 968 MHz AlN CMR with integrated suspended nano-hot-plate. The air-gap between the resonant device and the nano-hot-plate (designed to be 250 nm) is larger in the center of the device because of residual stress in the SiO2 layer.*

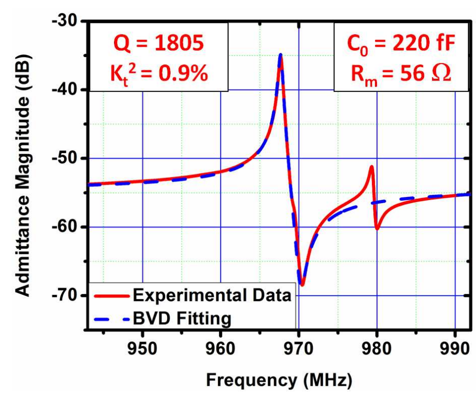

***Figure 6**: Measured admittance and BVD model fitting of the fabricated 968 MHz ovenized AlN MEMS resonator. The monolithic integration of the suspended nano hot plate does not affect the FOM of the device. A value of motional resistance, R_m, of only 56 Ω is obtained for the fabricated 968 MHz ovenized MEMS resonator.*

The ovenized oscillator was calibrated inside a Tenney TPS climatic chamber and showed a temperature coefficient of frequency (TCF) of ~ - 32.5 ppm/K with no current flowing in the nano-hot-plate. To test the performance of the ovenized oscillator, the nano hot plate was then turned on and the device response recorded for different levels of power into the heater. The ovenized oscillator frequency and phase noise were monitored with an Agilent E5052B Signal Source Analyzer. The oscillator frequency shifts due to different power levels applied to the nano hot plate were recorded. Taking into account the measured TCF of the oscillator, it was possible to extract the resonator temperature increase versus the power supplied to the nano hot plate and obtain a temperature rise factor of 18.3 K/mW (Fig. 7). This value of the temperature rise factor is comparable to what previously achieved using heating elements directly integrated into the body of lower frequency AlN resonators [10, 11] and demonstrates the efficiency and effectiveness of the proposed innovative design solution.

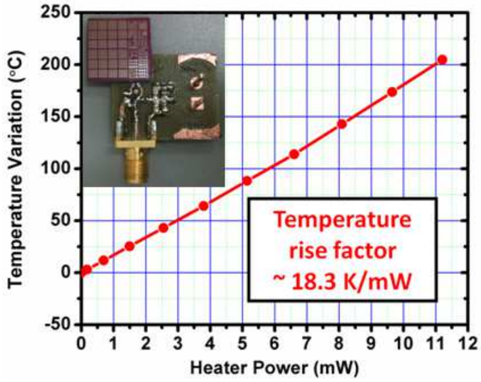

***Figure 7**: Measured temperature variation of the AlN resonator for different power levels supplied to the nano-hot-plate. The inset shows the AlN MEMS die wire-bonded to the oscillator printed circuit board. The high value of temperature rise factor (18.3 k/mW) demonstrates the efficiency and effectiveness of the proposed innovative design solution.*

The phase noise of the ovenized oscillator was also measured for different power levels into the heater, hence different temperature conditions, showing values as good as -83 dBc/Hz at 1kHz offset and -150 dBc/Hz for the floor (Fig. 8). No phase noise degradation was recorded for device temperatures up to ~235 °C (Fig. 9). This means that oscillator temperature variations could be easily compensated over a range of 125 °C with a power consumption < 7 mW and without affecting at all the phase noise performance of the oscillator.

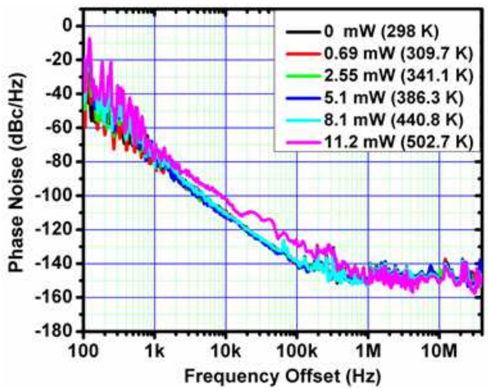

***Figure 8**: Measured phase noise of the ovenized oscillator for different values of power applied to the nano hot plate. Values of -83 dBc/Hz at 1 kHz offset and -150 dBc/Hz floor are recorded.*

CONCLUSION

In this paper, a novel technology platform suitable for the implementation of high frequency and high performance ovenized MEMS frequency sources has been introduced. Taking advantage of the unique performance enabled by the proposed technology the highest frequency (970 MHz) ever reported ovenized MEMS oscillator has been demonstrated. A resonator temperature rise factor of 18.3 K/mW has been measured demonstrating the efficiency and effectiveness of the proposed innovative design solution. The phase noise of the ovenized MEMS oscillator has been measured for different values of power applied to the nano hot plate showing values of -83 dBc/Hz at 1 kHz offset and -150 dBc/Hz floor. In addition, no phase noise degradation has been recorded for device temperatures up to ~235 °C. This means that temperature variations of the presented ovenized MEMS oscillator could be easily compensated over a range of 125 °C with a power consumption < 7 mW and without affecting at all its phase noise performance. This prototype can be considered a stepping stone towards the demonstration of wafer level packaged ovenized AlN MEMS resonators with a heating element integrated inside the walls of the device package.

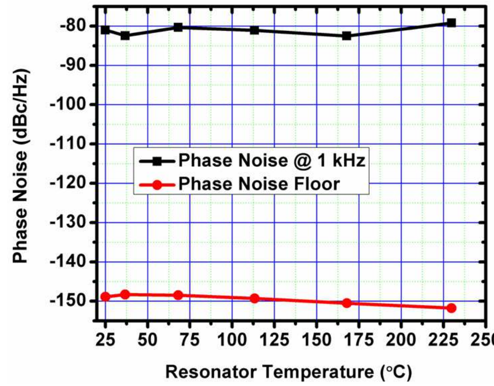

***Figure 9**: Measured phase noise of the ovenized oscillator for different values of the resonator operating temperature (i.e. different power levels applied to the heater). No phase noise degradation was recorded for temperatures up to ~235 °C.*

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