Ovenized High Frequency Oscillators Based on Aluminum Nitride Contour-Mode MEMS Resonators

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Abstract

This paper reports on the design, simulation, fabrication and characterization of the first micro-ovenized Aluminum Nitride (AlN) Lateral Field Excited - Floating (LFE-F) Contour-Mode Micro-Electro-Mechanical-System (MEMS) resonators (CMR) operating between 250 MHz and 1.11 GHz. The ovenized devices exhibited high quality factors (Q up to 1,550 @ 1.1 GHz) and k_t^2 (up to 0.6% @ 1.1 GHz). A heater power consumption lower than 5 mW for a 100 °C temperature increase and a thermal time constant in the hundreds of µs range were recorded for these devices. As a proof of concept, an ovenized 590 MHz oscillator with good phase noise performance was also demonstrated.

Introduction

Microelectromechanical system (MEMS) resonators have emerged as a promising alternative to bulky and unintegrable quartz-crystal and SAW resonators. Due to their small-form factor, high frequency of operation, and capability to be co-integrated with CMOS circuits, MEMS resonators represent the best candidate for the implementation of compact and multi-frequency banks of high-quality-factor mechanical elements that can be used for the fabrication of next-generation reconfigurable local oscillators for RF transceivers (1,2). Among different resonator technologies, the AlN contour-mode MEMS devices have the ability to span multiple frequencies on the same wafer and have been used to synthesize low phase noise reconfigurable oscillators (3,4). Nonetheless, modern telecommunication systems require oscillators that are stable over a wide range of parameters and especially versus temperature (5). In high precision commercial oscillators either temperature compensated crystals (TCXO) (6,7), or oven stabilized devices (OCXO) (8) are used. Uncompensated AlN-MEMS-based oscillators suffer instead from large temperature dependence and their frequency exhibits a linear dependence on temperature of about -28 ppm/K (9). It has been shown that at the MEMS scale (10,11) low power heaters can be co-integrated with low frequency resonators and few mW (instead of Ws used in OCXO) can be used to thermally stabilize the resonator. A 623 MHz thermally tunable AlN resonator that uses a separate portion of the device for heating has been presented in (12).

In this work, we co-integrate the heater directly into the body of the resonator itself by modifying the traditional layout of the floating plate of LFE CMR (3) with a serpentine-shaped heater (Figs. 1-2). Thanks to this innovative design, it has been possible to obtain ovenized resonators with higher performances, *i.e.* high quality factors (Q up to 1,550 @ 1.1 GHz) and k_t^2 (up to 0.6% @ 1.1 GHz) than any prior implementation. Such high performances are in fact required to demonstrate self-sustained oscillators.

As proof of concept, an ovenized 590 MHz oscillator with good phase noise performance (-84 dBc/Hz @ 1 kHz offset and a floor of -152 dBc/Hz) has been demonstrated. A heater power consumption lower than 5 mW for a 100 °C temperature increase (from room temperature) and a thermal time constant of approximately 400 µs were recorded for these devices. This demonstration of low power ovenization of high frequency AlN-based MEMS oscillators constitutes a step forward in the deployment of high precision frequency references.

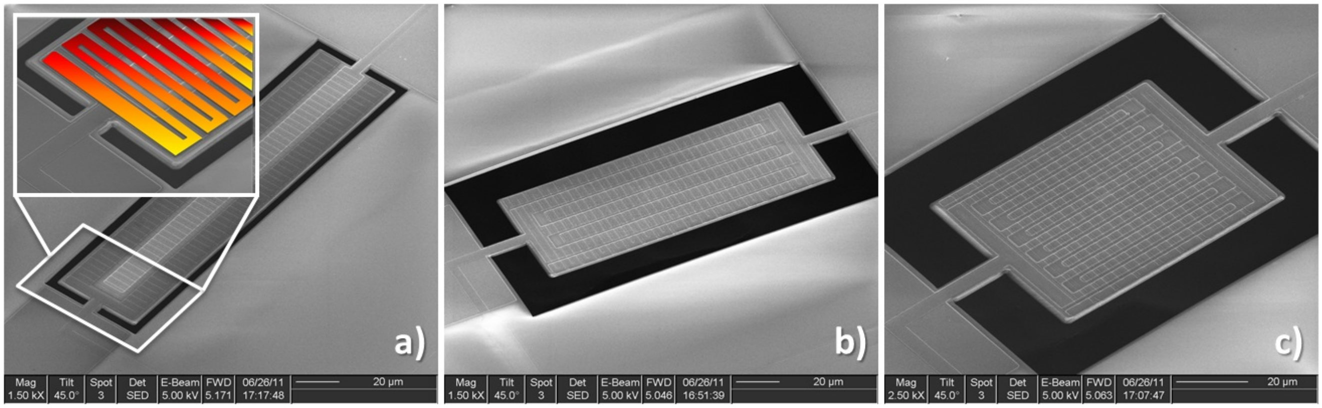

Figure 1: SEM pictures of fabricated micro-ovenized AlN contour mode resonators: 250 MHz (a), 590 MHz (b), 1.1 GHz (c).

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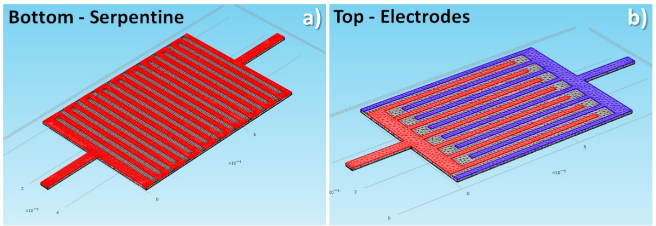

Figure 2: 3D model of the 1.1 GHz resonator: (a) bottom layer, highlighting the integrated serpentine; (b) top layer, highlighting the resonator electrodes.

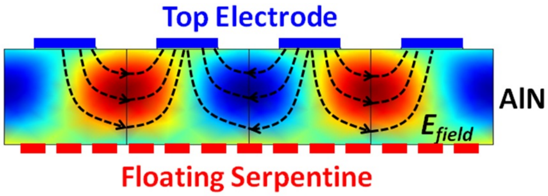

Figure 3: The LFE-F involves depositing the AlN film (forming the body of the resonator) on the top of a floating electrode (here the heater serpentine), which acts to confine the electric field across the thickness of the device. For this cross-sectional view the longest side of the serpentine runs parallel to the top electrode (differently from Figs. 1-2).

Device Design and Fabrication

The resonators of this work are formed by a 1 µm thick Aluminum Nitride film sandwiched between two metal layers. The bottom metal layer constitutes the serpentine (the heater), which is made of 50 nm thick and 2 µm wide series-connected lines of Platinum (Pt) separated by a 2 µm gap (Fig. 2). The serpentine itself acts as the floating bottom electrode in the LFE-F excitation technique. The presence of this bottom metal layer serves the dual purpose of enhancing the electromechanical coupling in the resonator and heating the body of the device when a current is flown through it (Fig. 3). A detailed description of the working principle of the LFE-F excitation method is available in (13). The top metal layer (100 nm thick Aluminum) constitutes the multi-fingered top electrode, whose pitch is used to set the frequency of vibration of the device and effectively excite the contour-extensional mode of vibration in the piezoelectric resonator. In order to prove the efficacy of the concept, this ovenization technique was successfully verified in devices operating at 250 MHz, 590 MHz, and 1.1 GHz.

The AlN LFE contour-mode resonators were fabricated in a four-mask post-CMOS-compatible microfabrication process (Fig. 4). The Pt serpentine/floating electrode was first patterned by lift-off on top of a high resistivity silicon wafer. The 1 µm thick AlN film was sputtered deposited using a Tegal AMS 2004 SMT (Tegal Corp., Petaluma, CA) and its quality was optimized to achieve rocking curve values as good as 1.2°. Vias to the serpentine pads were opened in the thin AlN film by wet etching in phosphoric acid (H_3PO_4). Optical lithography and lift-off were performed for the definition of the top Aluminum (Al) electrodes.

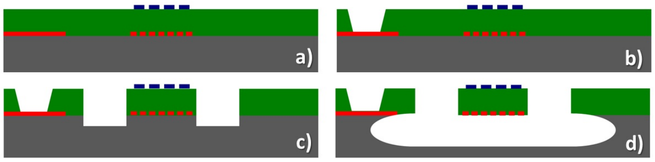

Figure 4: Four mask fabrication process: (a) sputter deposition of Pt (50 nm) serpentine, AlN layer and Al top electrodes; (b) via opening to the serpentine pads in H_3PO_4; (c) dry etching of AlN in Cl_2-based chemistry; (d) XeF_2 dry release of the AlN resonator.

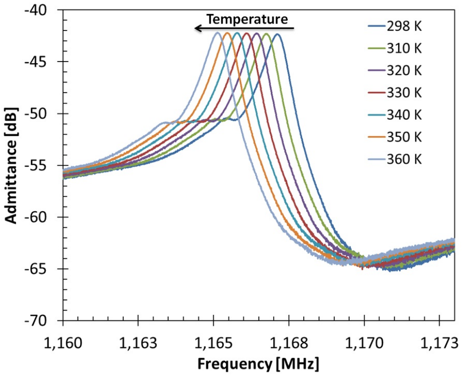

Figure 5: $Y_{11}(f)$ (admittance in dB) measured in a Lakeshore probe station at different temperatures for the 1.1 GHz resonator.

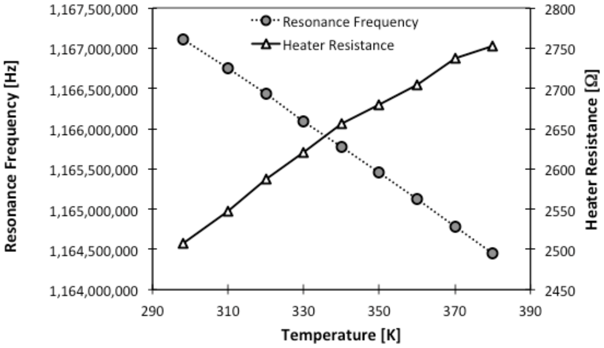

Figure 6: Calibration curve for resonance frequency and heater resistance vs. temperature of the 1.1 GHz resonator.

The in-plane dimensions of the resonators were defined by dry etching (Trion Inductively-Coupled Plasma Phantom III) of the AlN film in Cl_2-based chemistry using photoresist as a mask. The device was released from the silicon substrate by isotropic dry etching in XeF_2. The scanning electron micrographs of some of the fabricated devices are shown in Fig. 1.

Experimental Characterization of The Ovenized Oscillators

The behavior of the heaters was characterized by first using the resonator itself as a thermometer and monitoring its frequency shifts when subjected to external temperature variations induced in a controlled Lakeshore probe station (Fig. 5). The temperature dependence of the serpentine resistance was simultaneously measured with an Agilent B1500 Semiconductor Parameter Analyzer (Fig. 6). A representative 1.1 GHz resonator is reported here, but all devices exhibited similar temperature dependence. A temperature coefficient of frequency (TCF) of -28 ppm/K and

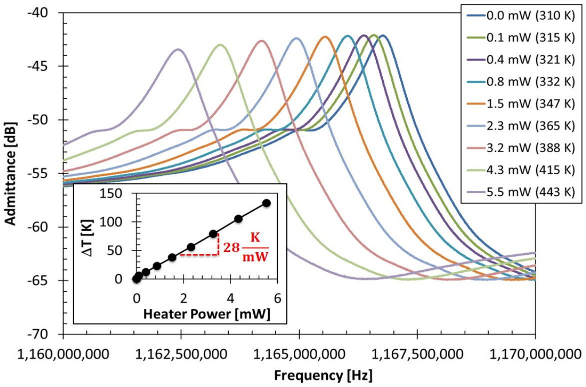

Figure 7: $Y_{11}(f)$ measured at different supplied heater powers (*i.e.* temperatures) for the 1.1 GHz resonator. Minimal change in the device Q and k_t^2 ensures that the resonator will operate in an oscillator even when heated at the max temperature of 443 K.

a temperature coefficient of the heater resistance (TCR) of 3 Ω/K were extracted. The effectiveness of the integrated micro-oven was then tested in air at 310 K by applying different power levels to the heater, and recording the resonator admittance (Fig. 7). According to the calibration curve shown in Fig. 6, it was possible to extract the temperature increase vs. the power supplied to the heater and obtain a temperature rise factor of 28 K/mW. This translates to the ability of operating a resonator at around 100 °C with just few mWs.

The experimentally obtained results are in agreement with 3D FEM analysis performed in COMSOL Multiphysics, which was also used to predict the heater time constant (Figs. 8-10). Convective and conductive heat transfers were both considered in the model, and a fixed temperature of 298 K was set for the edges of the suspending tethers. The experimental results are best fit by a thermal conductivity of 80 W/mK for the AlN film. This value is 3.5 X lower than that of the bulk material (285 W/mK), but is in line with what was previously reported for sputtered thin films (12).

All the ovenized resonators exhibited high quality factors and electromechanical coupling, k_t^2. The figure of merit ($k_t^2 \cdot Q$) of these resonators was always around 10 and comparable to non-ovenized devices. Thank to this it was possible to direct wire-bond an ovenized 590 MHz AlN CMR to a Pierce-like oscillator (14,15) fabricated in the ON Semiconductor 0.5 µm CMOS process (Fig. 11). An Agilent E5052B signal source analyzer was used to monitor the phase noise (PN) performance of this first ovenized AlN CMR oscillator. The PN of the micro-ovenized oscillator was measured for different power levels applied to the heater, and hence different temperature conditions (Fig. 12), showing values between -84 and -80 dBc/Hz at a 1 kHz offset and PN floor varying between -152 dBc/Hz and -147 dBc/Hz (Fig. 13). It is important to note that the same serpentine heater can be used as an in-situ sensor of the resonator temperature, therefore enabling the implementation of an integrated and regulated micro-oven or a method for studying the resonator temperature evolution at different power levels.

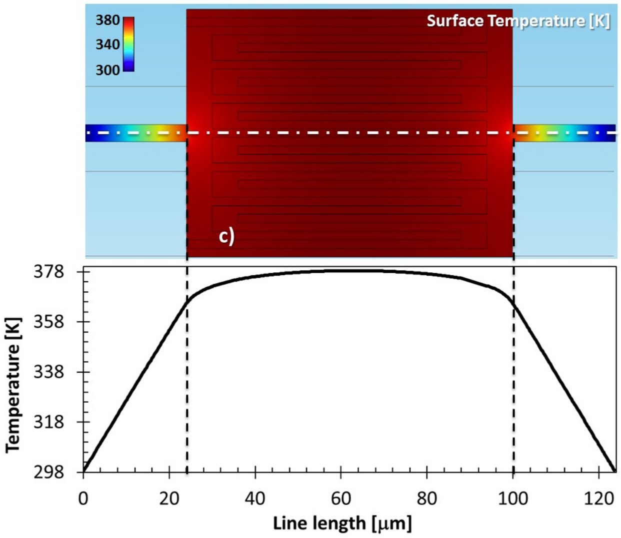

Figure 8: Stationary simulation of the Joule heating of the resonator with 1 mA applied to the serpentine (top) and temperature profile distribution along its central axis (bottom).

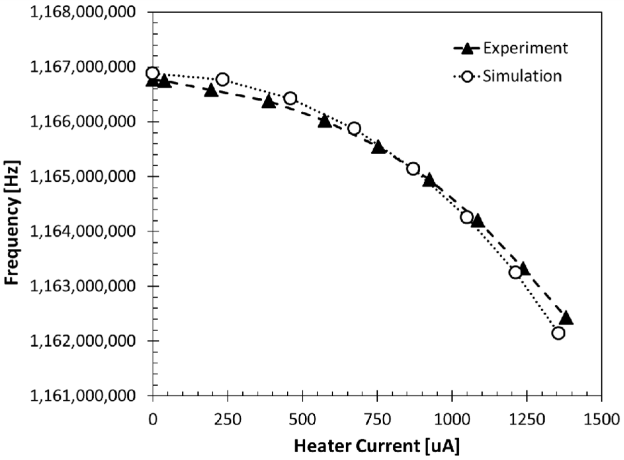

Figure 9: Experimental results and simulation of the frequency shift as a function of the heater current in the 1.1 GHz resonator.

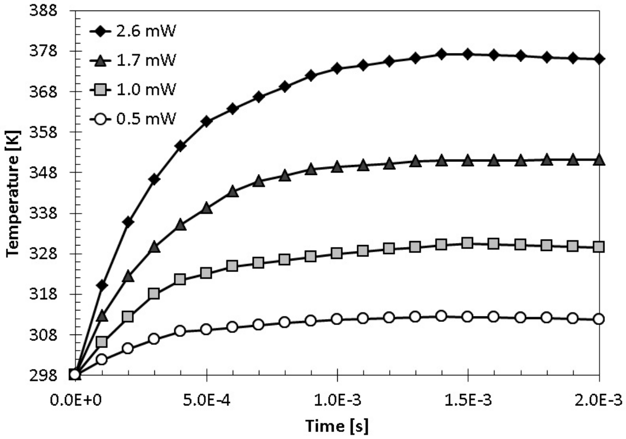

Figure 10: Simulated time response of the temperature increase in the 1.1 GHz resonator. This particular device has a time constant of approximately 400 µsec.

Conclusions

The first ovenized AlN-based laterally vibrating MEMS resonators operating between 250 MHz and 1.1 GHz have been demonstrated. The innovative design is based on transforming the conventional bottom electrode of CMR resonators into a heater and using it for low power ovenization of the resonators with minimal impact on their performance. As a proof of concept a 590 MHz ovenized oscillator was also characterized. This work lays the foundation for the demonstration of high performance and temperature stabilized high frequency sources.

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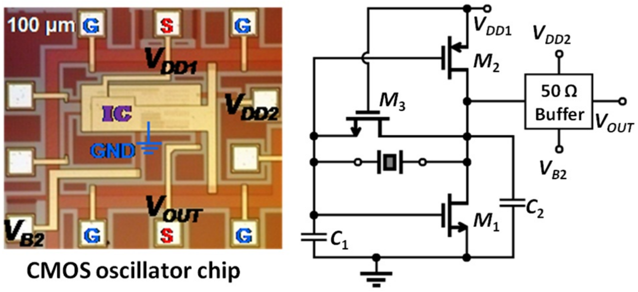

Figure 11: The oscillator circuit topology used for the CMR of this work is described in (14). The circuit consists of a Pierce oscillator implemented by means of a CMOS inverter biased in its active region. Transistors M1 and M2 form the CMOS inverter while transistor M3 acts as a large resistor to provide biasing in the active region of M1 and M2.

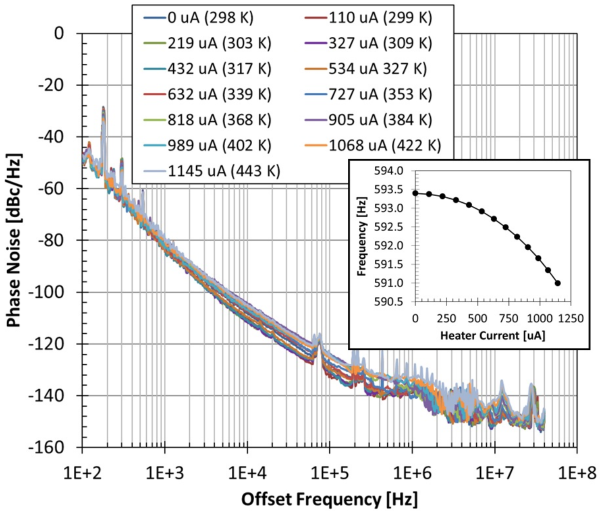

Figure 12: Phase noise measurements for a 590 MHz oscillator performed at different temperature condition induced by the integrated heater. The inset shows the shift of the frequency vs. the heater current. The oscillator PN is almost unchanged proving that it can be operated as an ovenized oscillator.

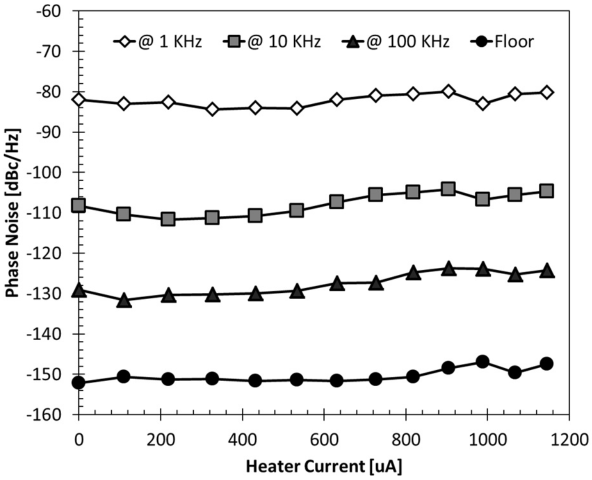

Figure 13: Evolution of phase noise @ 1 KHz, 10 KHz, 100 KHz, and floor phase noise under different heater current conditions (*i.e.* different temperatures).