IN NON-LINEAR CHARACTERIZATION OF ELECTROSTATIC MEMS RESONATORS

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Abstract
Encapsulated micromechanical resonator technology is becoming important as a potential replacement for quartz for several applications. In this work we report the nonlinear characterization, particularly the A-f effect, in these resonators. The A-f effect in quartz has been well studied in the 1970's and 1980's, as it dictates the maximum power (current) that can be handled by the resonator. MEMS resonators tend to have a strong A-f effect compared to quartz, and this is the reason for the traditional low power handling in these devices. In this work we report the mechanisms that cause the nonlinearities in these devices, and find design parameters to improve performance.

Encapsulated Micromechanical Resonators
Encapsulated micromechanical resonators are fabricated in single crystal silicon and encapsulated with epitaxially deposited polysilicon. The structures are defined by deep reactive-ion etching in a silicon-on-insulator wafer, released with a HF vapor etch, and then encapsulated with epitaxial deposition [1] (shown on the right). The resonators are sufficiently robust for standard IC dicing and handling, and show low aging. The resonator designs chosen for these experiments are double-ended tuning forks (DETF), with a resonant frequency of 1.3 MHz, and Q of ~10k.

Nonlinearity in MEMS resonators
Nonlinearities in electrostatic MEMS resonators limit the achievable frequency stability. We found that these resonators tend to have high A-f coefficients compared to quartz crystals. MEMS resonators show two kinds of A-f effects - the mechanical stiffening effect (similar to the one seen in quartz [2]) and the electrical softening effect. The nature of the nonlinearities depends on the DC polarization (bias) voltage \( V \).

Mechanical A-f Effect, \( V_{bias} = 25 \) V
Electrical A-f Effect, \( V_{bias} = 90 \) V
Intermediate A-f Effect, \( V_{bias}=44 \) V

Nonlinearity Mechanisms
Mechanics for mechanical nonlinearities are related to structural/material effects at high amplitudes [3]. These nonlinearities can be represented by a third order term \( k_3 \) in the restoring mechanical force. Electrical nonlinearities are caused by higher order terms in the spring softening force.

Nonlinearity Cancellation
At intermediate bias voltages it is possible to cancel mechanical and electrical nonlinearities [4]. This cancellation enables higher drive currents and operation conditions where phase noise due to amplitude perturbations becomes negligible. However, higher order non-linearities eventually limit the maximum output current. This is confirmed by measuring the output current at critical duffing bifurcation, shown here.

Conclusions
In this work we investigated the mechanisms and impact of nonlinearities on the frequency stability of MEMS resonators. Models for the A-f effect in MEMS resonators were developed and verified. Also, useful cancellation of nonlinearities was observed and is being reported here. In our low frequency DETF test structure, we found that the A-f coefficient is several orders of magnitude larger (poorer) than quartz. However, we conjecture from that the A-f coefficient scales well with frequency.

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