CMOS Embedded NEMS Resonator with Acoustic Confinement

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The integration of CMOS electronic circuits and electromechanical resonators has been pursued for a long time to improve the overall performance of electromechanical oscillators. However, the post processing on the CMOS substrates that is necessary to attain this integration increases the production cost. This project presents a method of embedding a nano electromechanical resonator within a CMOS substrate with simulated resonator quality factor of more than 3000 at a frequency of 3.3 GHz.

The integration of additional electromechanical components on a CMOS chip has been subject to extensive research as it would allow for footprint and cost reduction. One of the main challenges in integrating MEMS resonators is the definition and release of the structure. The goal of this project is to embed a bulk acoustic resonator in the CMOS BEOL (interconnecting metal) layers that avoids the release step while still maintaining a high quality factor and electromechanical coupling of the device.

The release step is circumvented by placing the resonator in an acoustic bandgap created using a phononic crystal (PnC) structure that is made of the BEOL metals and dielectrics, as shown in Figure 1. The bulk acoustic resonator is a rectangular copper slab placed in the M5 layer which is designed to operate at its first fundamental mode of resonance. The resonator is actuated and sensed with neighboring electrodes placed on either side of the resonator and separated by 100 nm dielectric gaps.

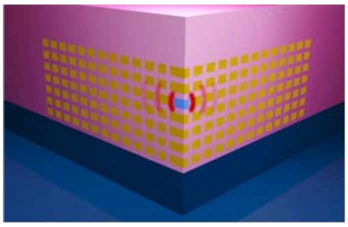

Figure 1: Schematic of one quarter model of the 3D acoustic cage with the mechanical resonator.

This particular implementation was designed using parameters of the TSMC 65 nm node technology with 7+2 metals. Phononic crystals are periodic structures designed such that the ensemble (metamaterial) shows a collective acoustic behavior that is different from either of the individual materials. Acoustic bandgaps were created due to the difference in densities and elastic properties (acoustic impedances) of the materials, namely Cu as a metal and low-κ porous oxide (SiOC) as the inter-metal dielectric [1]. The PnC is formed by repeating a unit cell consisting of a metal region surrounded by a dielectric (Figure 2). The band structure was computed by simulating the unit cell using finite element method and applying appropriate boundary conditions to emulate an infinitely repeating structure. The optimal effective acoustic length of each layer forming the reflector pair was matched to $\lambda/4$ of the required wavelength, in order to be confined for maximum efficiency. However, since heights of the metal and dielectric layers are fixed within a given node, it is not possible to match the $\lambda/4$ condition. Instead, the effective path length of the reflector pair to $\lambda/2$ was matched. Taking n as the ratio of the longitudinal speed of sound in the inter metal dielectric (IMD) to that in the metal, the relation between heights and wavelength is given by $h_{Cu} + \frac{h_{\kappa}}{n} = \frac{\lambda}{2}$.

A bandgap between 2.5 GHz to 4.3 GHz was simulated using such a simple 2D model as shown in Figure 2. The resonator was designed so that its frequency lies in the center of the bandgap and a high-Q bulk acoustic resonator was achieved.

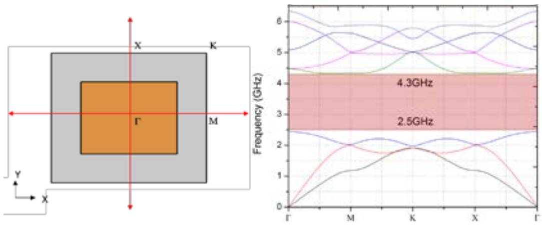

Figure 2: Unit cell and band structure indicating bandgap: frequency vs reduced wave vector path Γ-M-K-X-Γ.

The finite reflectors simulation was performed starting with a 2D model, followed by 3D extension to account for the appearance of new modes. Figure 3 shows the contour plot of displacement to visually demonstrate the effectiveness of the acoustic confinement.

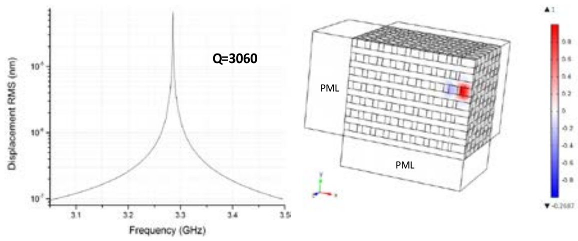

Figure 3: 3D quarter symmetric model.

A 3.3 GHz embedded CMOS NEMS resonator reaching a quality factor slightly above 3000 was designed and simulated. A Figure of Merit (FOM) $Q \cdot f = 10^{13}$ Hz could hence be obtained for an unreleased resonator that would come out of the foundry. Evaluated electromechanical coupling of these devices was 0.015 % thereby achieving a total FOM $Q \cdot k_t^2$ =0.46. Provided those promising results are confirmed by the measurements of test structures, further work will address the design of a complete oscillator. This project was carried out in collaboration with the ANEMS group, EPFL.

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[1] K. W. Lee, *et al.*, "Highly manufacturable Cu/low-k dual damascene process integration for 65 nm technology node," IITC Int. Interconnect Technology Conference (2004) 55.