Towards on-chip resonators in wireless-communications devices

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A systematic review of technologies currently under investigation identifies nanocrystalline diamond as the most promising material for miniaturization of transceivers.

Vibrating mechanical-signal processors are now widely used in radio-frequency (RF) stages of present-day wireless transceivers. These resonators, which include quartz crystals, surface- acoustic-wave resonators, and thin-film bulk acoustic resonators, typically have a quality factor, $Q$ (a measure of the ability of the pulse to resist energy loss), in the range 500–10,000. For comparison, a tuning fork has $Q \approx 1000$, while atomic clocks can achieve $Q$ values as high as $10^{11}$. Because of the comparatively high quality factors, the resultant devices excel in percent bandwidth, insertion loss, stopband rejection, and dynamic range, and exhibit excellent close-to-carrier phase noise that is, in general, inversely proportional to $Q^2$. However, as off-chip components, these devices must interface with transistor electronics at the board level, hindering the ultimate miniaturization of transceivers and highlighting a need for on-chip replacements. Moreover, the increasing demand for cognitive radio, in which the device has sufficient computational capacity to change operational parameters in anticipation of the user’s needs, has stimulated interest in technologies capable of reducing the size and power consumption of wireless modules.

We (and others) recently demonstrated vibrating RF microelectromechanical-system (MEMS) resonators at frequencies up to 6.2GHz with $Q$-values $>4000$. They are now well positioned for inclusion into a number of future wireless-communications subsystems, from cellular handsets to low-power networked sensors. However, their acceptance has been hindered by several remaining issues, including higher impedances than normally exhibited by macroscopic counterparts, limited linearity and power-handling ability, and insufficient frequency repeatability and stability.

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Figure 1. Pure electrical equivalent-circuit model (A), schematic (B), scanning-electron-microscope photo (C), and simulated mode shape (D) of a mechanically coupled composite resonator on silicon (Si)-on-insulator (SOI) substrates equipped with nanogap capacitive transducers filled with high-$k$ dielectrics. $k$: Dielectric constant. $v_i$: Input alternating voltage. $i_x$: Output motional current. $C$: Capacitance. $L$: Inductance. $R_x$: Motional resistance. $\varepsilon$: Permittivity. $h$: Substrate-layer height. $d$: Capacitive transducer gap. ALD: Atomic-layer deposition.

We conducted a systematic investigation of MEMS resonators fabricated with poly- and single-crystalline silicon, and
chemical-vapor-deposited (CVD) nanocrystalline diamond (characterized by the highest acoustic velocity among all thin-film depositable materials). Given that resonance frequency is generally proportional to the acoustic velocity, while energy dissipation and $Q$ are a function of the material properties, we evaluated several device-oriented and system-level performance-enhancing technologies. We considered both capacitively and piezoelectrically transduced resonators and placed particular emphasis on employing transducers with improved electromechanical coupling as the major device-level approach to reduce motional impedance. The advent of mechanically coupled arraying as a system-oriented approach enables the composite resonators to obtain greatly enhanced performance.

As shown in the simulated mode shape and electrical equivalent-circuit model of a resonator array (see Figure 1), the benefits of a composite resonator are multifold. A composite resonator with all constituents operating in phase provides lower motional resistance, enhanced linearity, increased power-handling ability, and better frequency stability as a result of device parallelization. Superior electromechanical coefficients can be obtained by further shrinkage of capacitive transducer gaps and subsequent filling of those gaps with dielectrics of higher permittivities, resulting in even greater reduction of the motional resistance. Ultrathin layers (10nm) of high-$k$ ($k$: Dielectric constant) dielectric materials (e.g., titanium dioxide, hafnium dioxide, etc.) are deposited in these gaps with ultrahigh conformability and uniformity using atomic-layer-deposition (ALD) technology. This allows mass production of on-chip resonator arrays with nanogap capacitive transducers. Using these techniques, a wide variety of high-$Q$ micromechanical resonators and resonator arrays on silicon-on-insulator substrates operating at ultrahigh frequencies are currently under development.

The list of micromachinable materials used to implement these devices so far includes silicon (both single- and polycrystalline), aluminum nitride, zinc oxide, silicon germanium, silicon carbide, as well as CVD nanocrystalline diamond, the material with the highest frequency-$Q$ product. The fact that the diamond’s acoustic velocity is twice that of polysilicon is instrumental to achieving such an impressive frequency-$Q$ product. The low deposition temperature (below 400°C) of the ultrananocrystalline diamond is amenable to fully planar, single-chip, post-CMOS integration with transistor circuits. We have demonstrated a nanocrystalline-diamond micromechanical-disk resonator operating in its second radial-contour mode at 1.51GHz with $Q$ values of 11,555 in vacuum and 10,100 in air (see Figure 2), achieving an impressive frequency-$Q$ product of $1.74 \times 10^{13}$ that now exceeds the $1 \times 10^{13}$ of some of the best quartz crystals. Our focus can now be shifted to our ultimate goal of developing on-chip narrow-band...
micromechanical filters with unprecedented frequency selectivity and low insertion loss. By finetuning the nonlinear characteristics of the capacitively transduced resonators, we can now explore novel on-chip mechanical signal processors for frequency manipulation (such as mixers and multipliers).

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References