

Towards LSI Vibrating Micromechanical Signal Processors

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Recent advances in vibrating RF MEMS technology have now positioned vibrating micromechanical devices as strong candidates for inclusion into a number of future wireless communication sub-systems, from cellular handsets, to PDA's, to low-power networked sensors, to ultra-sensitive radar and jam-resistant communicators designed for hostile environments. Among the most groundbreaking of these advances are (1) demonstrations of resonance frequencies in the gigahertz range [1] (c.f., Figure 1), which now cover the RF range needed in wireless handsets; (2) removal of the need for vacuum to attain Q 's greater than 10,000 at gigahertz frequencies [1], which should significantly lower cost; (3) achievement of Q 's greater than 150,000 at VHF frequencies [2] (c.f., Figure 2), which should allow communications-grade oscillators with exceptional stability; (4) demonstrations of resonance frequency temperature stabilities better than 18 ppm over 27-107°C [3] (c.f., Figure 3), putting them on par with the performance of most quartz crystals; (5) demonstrations of impedances approaching 50Ω allowing them to match to macroscopic antennas; and (6) demonstrations of medium-scale integrated (MSI) micromechanical circuits and functions, including low insertion loss bandpass filters (c.f. Figure 4), mixers, and even amplifiers. With many of the above attributes superior to those attainable by macroscopic counterparts, the technical argument for the use of vibrating RF MEMS as high- Q replacement components in wireless sub-systems is already quite strong.

But the benefits of vibrating RF MEMS technology go far beyond mere component replacement. In fact, the extent of the performance and economic benefits afforded by vibrating RF MEMS devices grows exponentially as researchers begin to perceive them more as building blocks than as stand-alone devices. In particular, when integrated into micromechanical circuits, in which vibrating mechanical links are connected into larger, more general networks, previously unachievable signal processing functions become possible, such as reconfigurable RF channel-selecting filter banks, ultra-stable reconfigurable oscillators, frequency domain computers, and frequency translators. When further integrated together with other micro-scale devices (e.g., transistors, micro-ovens, micro-coolers, atomic cells), system-level benefits for portable applications abound, particularly those for which architectural changes allow a designer to trade high Q for lower power consumption and greater robustness, with potentially revolutionary impact.

Indeed, circuit complexity and frequency range should only increase as MEMS technologies evolve into NEMS (or "nanoelectromechanical system") technologies, with feature sizes that support frequencies exceeding 10 GHz. In fact, with knowledge of the micromechanical circuit concepts described above, one might now ponder whether or not the nanowires targeted for transistor functions might instead be better employed more naturally as vibrating resonators capable of doing mechanical signal processing when mechanically linked into circuit networks, such as that of Figure 5. Such nanomechanical networks would not only be completely passive, consuming substantially less power, but would also dispense with the need for the electrical contacts that presently inhibit large scale integration of nanowire transistors. This paper suggests the NEMS technologies and attributes most suitable to enabling such an integrated nanomechanical circuit technology.

- [1] J. Wang, *et al.*, "1.51-GHz polydiamond micromechanical disk resonator with impedance-mismatched isolating support," *Proceedings*, IEEE MEMS Conf., Maastricht, The Netherlands, Jan. 25-29, 2004, pp. 641-644.
- [2] Y.-W. Lin, *et al.*, "Low phase noise array-composite micromechanical wine-glass disk oscillator," *Tech. Digest*, IEEE Int. Electron Devices Mtg., Washington, DC, Dec. 5-7, 2005, pp. 287-290.
- [3] W. -T. Hsu, *et al.*, "Stiffness-compensated temperature-insensitive micromechanical resonators," *Tech. Digest*, IEEE MEMS Conf., Las Vegas, Nevada, Jan. 20-24, 2002, pp. 731-734.

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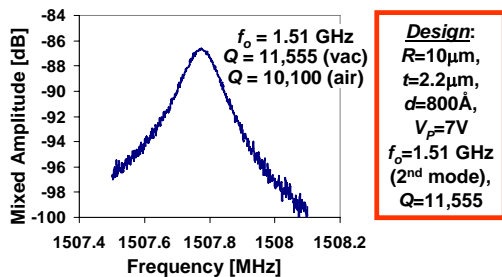
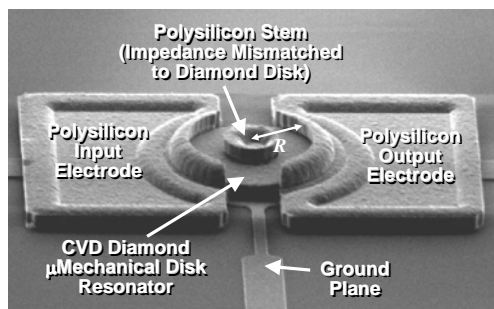


Figure 1: SEM of a polydiamond radial-contour mode micromechanical disk resonator (with isolating polysilicon stem) and measured frequency characteristic, showing Q 's $>10,000$ in both air and vacuum.

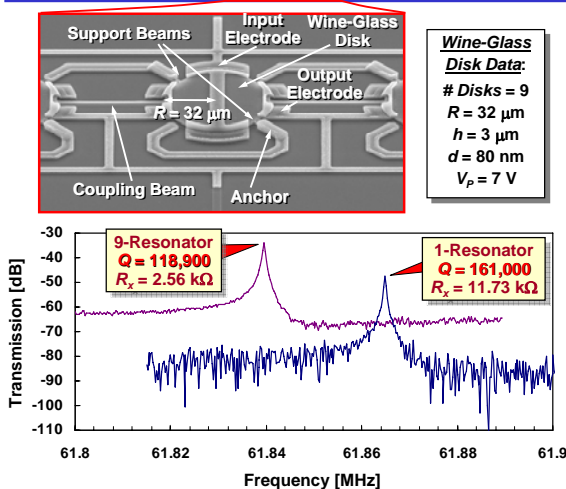
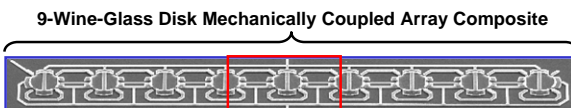


Figure 2: SEM of a mechanically coupled array of 9 wine-glass disk resonators (with a zoom-in on one of the resonators) and measured frequency characteristic showing Q 's $>100,000$ for arrays and single resonators alike.

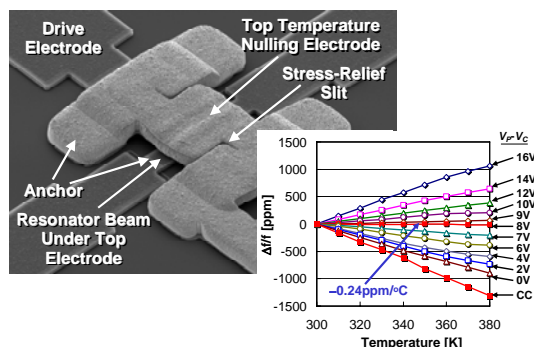


Figure 3: SEM and schematic of an electrical stiffness-compensated temperature-independent micromechanical resonator, which uses a temperature-dependent top electrode gap spacing to reduce the overall resonance frequency change to less than 18 ppm over 27-107°C.

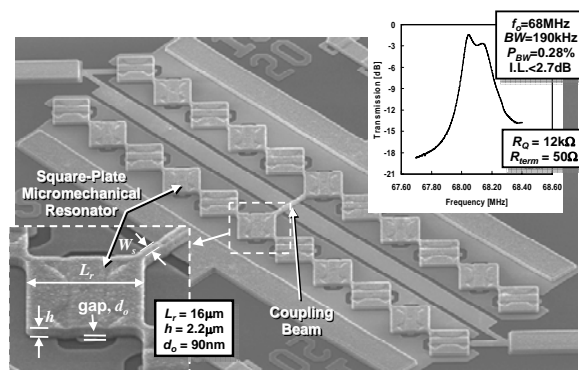


Figure 4: SEM of a 68-MHz micromechanical filter comprised of two composite 11-square resonator arrays coupled by a flexural mode beam, exhibiting an impressive insertion loss of less than 2.7dB for a 0.28% bandwidth.

Figure 5: (Right) A general mechanical circuit composed of vibrating nanomechanical links that process signals in the mechanical domain. This circuit harnesses high Q and low mechanical loss to allow cascading of mechanical links in sufficient numbers to effect signal processing functions as general as those realized by transistor IC's.

