C. T.-C. Nguyen, “Integrated micromechanical radio front-ends (invited plenary),” *Proceedings of Tech. Program*, 2008 IEEE Int. Symp. On VLSI Technology, Systems, and Applications (VLSI-TSA’08), Hsinchu, Taiwan, April 21-23, 2008, pp. 3-4.

Integrated Micromechanical Radio Front-Ends

Clark T.-C. Nguyen
Dept. of Electrical Engineering & Computer Sciences
University of California at Berkeley
574 Cory Hall, Berkeley, California 94705, U.S.A.

***Abstract*—An overview of MEMS technologies capable of realizing the RF front-end frequency gating function needed by true software-defined cognitive radios is presented. Among the technologies described are vibrating disk micromechanical resonators that exhibit record on-chip frequency-*Q* products; medium-scale integrated micromechanical circuits that implement on/off switchable filter banks; and a process technology that integrates nickel MEMS together with foundry CMOS transistors in a fully monolithic single-chip process.**

INTRODUCTION

Recent advances in vibrating RF MEMS technology that yield on-chip resonators with *Q*’s over 10,000 at GHz frequencies and excellent thermal and aging stability, 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 [1]. Indeed, early start-ups have already sprouted to take advantage of this technology for timekeeper applications, and the timing of this technology seems well placed for wireless markets, whose requirement for multi-mode reconfigurability fuels a need for on-chip high-*Q* resonators to prevent the cost of the front-end passives in a typical handset from obviating that of the IC’s [1].

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, mechanical power converters, mechanical power amplifiers, frequency domain computers, and frequency translators. This paper focuses on the MEMS technologies most suitable to micromechanically realizing the frequency gating RF front-end needed by true software-defined radios.

SOFTWARE-DEFINED RADIO

The increasing desire for reconfigurable radios capable of adapting to any communication standard at any location across the world has spurred great interest in the concept of a software defined radio [2], in which the frequencies and modulation schemes of any existing communication standard can be produced in real-time by simply calling up an appropriate software sub-routine. Arguably, the ultimate rendition of such a radio would realize all radio functions, including the RF front-end, digitally, using a programmable microprocessor. To achieve this, the analog-to-digital converter (ADC) that normally resides near the baseband circuits of a conventional receiver would need be placed as close to the antenna as possible, so that as much signal processing as possible could be done digitally.

Ideally, the A/D converter would immediately follow the antenna and would have an input bandwidth covering the full spectrum of received signals, e.g., 3 GHz. Practically, however, a low noise frequency gating function must precede the ADC to remove blockers that can be many orders stronger than the desired signal at the receive antenna. Removing such blockers relaxes the ADC’s dynamic range and power requirements, which otherwise would be too excessive for portable (and even stationary) applications. For reasonable power consumption, all interferers, even those close to the desired signal, would need to be removed.

To eliminate all interferers and pass only the desired signal, a programmable frequency gating device or circuit is needed that can pass and reject tiny (e.g., 0.03% bandwidth) RF frequency channels at will along the entire 3 GHz input frequency span. The need for such a small percent bandwidth makes this especially difficult to implement, since a filter with a 0.03% bandwidth would need to be comprised of resonators with *Q*’s >10,000 to avoid excessive insertion loss. To further complicate things, it is often the case that the higher the *Q* of a resonator, the less tunable it is. In fact, there are no existing on-chip resonator technologies capable of achieving *Q*’s >10,000 while also being continuously tunable over a 3 GHz span.

Fortunately, MEMS technology offers an alternative method for achieving the desired programmable frequency gate. In particular, being a wafer-level manufacturing technology similar to that for integrated transistor circuits, MEMS encourages designers to use mechanical devices the same way transistors are used: in massive numbers. So instead of restricting the implementation of a programmable frequency gate to a single tunable filter, MEMS technology allows realization of the same programmable frequency gate via a bank of on/off switchable micromechanical filters, as depicted in Fig. 1, where each filter is realized using an interconnected network of micromechanical disk resonators, to described next.

MICROMECHANICAL FREQUENCY GATE

Fig. 2 presents the SEM and measured frequency characteristic for a 1.51-GHz radial-contour mode disk resonator that achieves an impressive on-chip room temperature *Q* of 11,555 in vacuum, and 10,100 in air [3]. This device consists of a 20μm-diameter, 3μm-thick polydiamond disk suspended by a polysilicon stem self-aligned to be exactly at its center, all enclosed by doped polysilicon elec-

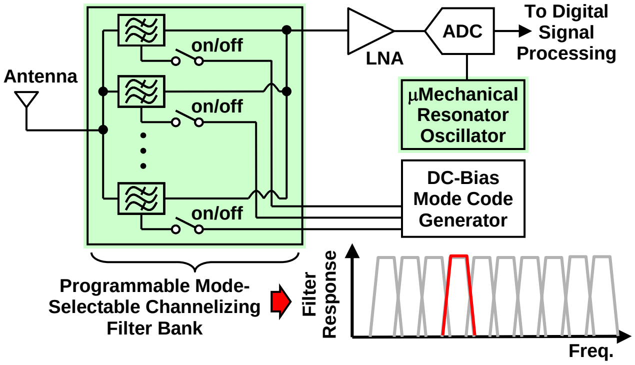

Fig. 1: System block diagram for a software defined radio front-end utilizing a micromechanical RF channel-select filter network to realize a frequency gating function. When one (or more) filters are turned “on”, with all others “off”, the filter bank realizes a frequency gate. When all filters are turned “on”, the bank realizes a real-time spectrum analyzer that could be used to assess the entire received spectrum and determine what frequencies might be permissible to operate a cognitive radio.

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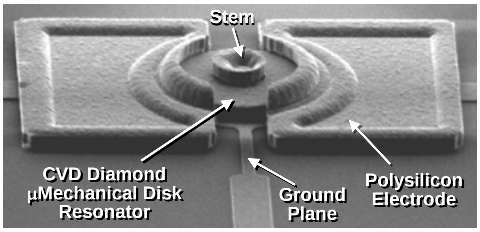

Fig. 2: SEM of a 1.51-GHz μmechanical radial mode disk resonator.

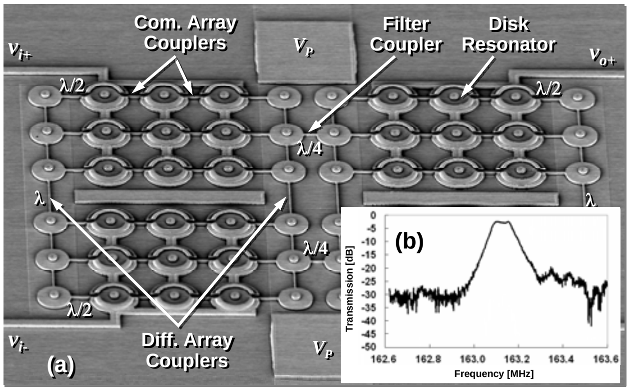

Fig. 3: (a) Mechanical circuit realizing a mode-switchable filter bank that performs the frequency gating function of Fig. 1. (b) Measured passband frequency characteristic for the lowest frequency mode.

trodes spaced less than 80 nm from the disk perimeter. It can be excited into resonance via a combination of dc and ac voltages that can be chosen to turn the device "on" or "off" [1]. When vibrating in its radial contour mode, the disk expands and contracts around its perimeter, in a motion reminiscent of breathing, and in what effectively amounts to a high stiffness, high energy, extensional mode. Since the center of the disk corresponds to a node location for the radial contour vibration mode shape, anchor losses through the supporting stem are greatly suppressed, allowing this design to retain a very high *Q* even at this UHF frequency. A version of this device at 498 MHz achieves a *Q* of 55,300 in vacuum, which corresponds to a frequency-*Q* product of 2.75×10^{13}—the highest for any on-chip UHF resonator at room temperature [3].

With frequency-*Q* products this high, radial-mode disk resonators are quite suitable for realization of the small percent bandwidth mechanical filters needed by the frequency gate of Fig. 1. Pursuant to this, Fig. 3(a) presents a mechanical circuit fabricated via the process of [4] that realizes a switchable bank of side-by-side mechanical filter passbands, each selectable by dc-bias voltages applied to the resonators that form them. As shown, this mechanical circuit is comprised of several identical resonator elements coupled by mechanical links of various designed lengths attached at very specific locations on the resonators. Briefly, the center frequency of each switchable passband is determined primarily by the (identical) frequencies of the constituent resonators vibrating in the mode corresponding to the selected passband; while the bandwidths of the passbands and the spacings between them are determined largely by ratios of the stiffnesses of the various coupling beams to those of the resonators they couple at the attachment locations. Fig. 3(b) presents a measurement of the lowest frequency switched-mode passband, which has a 0.06% bandwidth with a 2.43dB insertion loss.

The complete structure of Fig. 3(a) comprises a medium-scale integrated (MSI) mechanical circuit that can be equated to an equivalent electrical circuit [4], with a one-to-one correspondence between mechanical and electrical elements. The values of the circuit elements are specified by the lateral dimensions of the associated mechanical elements, so the whole structure is amenable to automatic generation by a computer-aided design (CAD) program. Such a program could also automatically generate the layout required to achieve a specific filter specification, making the realization of a VLSI circuit of such filters as convenient as for VLSI transistor IC's.

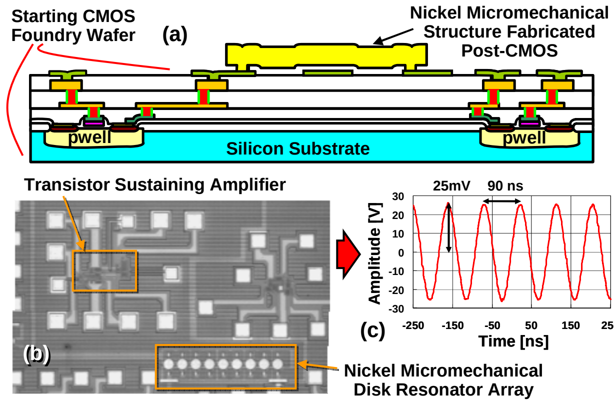

Fig. 4: (a) Cross-section of the nickel MEMS-transistor integration process of [6]. (b) Die photo of a fully monolithic micromechanical resonator oscillator using this process. (c) Oscilloscope waveform of the oscillation.

MEMS-Transistor Integration

Not shown in Fig. 3 are the transistor circuits needed to route the bias voltages that select (i.e., turn "on") the desired passbands. Given the complexity and density of the MEMS-to-transistor interconnections needed, it would be best if the MEMS and transistors were integrated together onto a single chip. Among approaches to doing this, MEMS-last ones are perhaps the most attractive, since they allow the use of virtually any foundry for transistor circuits.

To date, however, MEMS-last integration approaches have had little traction in consumer markets, partly because they require that processing temperatures for the MEMS stay below a certain ceiling that insures minimal degradation in transistor performance. Very few of the popular high-*Q* materials used for MEMS resonators, including the polydiamond and polysilicon materials of Fig. 2 and 3, have deposition temperatures under the needed ceiling, which may soon be around 300°C to accommodate the advanced low-k interconnect dielectrics targeted for future CMOS generations [5]. Recent work, however, has shown to the surprise of many that metal materials can achieve high *Q* at high frequencies as long as the right resonator designs (e.g., disk geometries) are utilized [6]. In particular, wine-glass disk resonators with *Q*'s >50,000 have now been demonstrated in nickel material electroplated at only 50°C. Capitalizing on this discovery, Fig. 4 presents the cross-section, die photo, and oscilloscope output waveform for a fully monolithic single-chip micromechanical resonator oscillator that combines nickel MEMS over foundry CMOS, recently demonstrated with reasonable high-*Q* oscillator performance [6]. With this demonstration, it may not be too long before top-level CMOS metals are used to implement micromechanical circuits, such as that of Fig. 3, allowing the whole system of Fig. 1 to reside on a single tiny silicon-chip.

References.

[1] C. T.-C. Nguyen, "MEMS technology for …,"_*IEEE Trans. Ultrason., Ferroelect., Freq. Contr.*, vol. 54, no. 2, pp. 251-270, Feb. 2007.

[2] M. Dillinger, *et al.*, *Software Defined Radio: Architectures, Systems, and Functions*. New York, NY: Wiley, 2003.

[3] J. Wang, *et al*., "1.51-GHz polydiamond micromechanical disk …," *Proceedings*, 17th IEEE Int. MEMS Conf., Jan. 25-29, 2004, pp. 641-644.

[4] S.-S. Li, *et al*., "An MSI micromechanical differential disk-array filter," *Dig. of Tech. Papers*, Transducers'07, June 11-14, 2007, pp. 307-311.

[5] G. Maier, "The search for low-k and ultra-low-k dielectrics: …," *IEEE Electrical Insulation Magazine*, vol. 20, no. 2, pp. 6-17, Dec. 2004.

[6] W.-L. Huang, *et al*., " Fully monolithic CMOS nickel μmechanical … , " Tech. Digest, 21st IEEE Int. MEMS Conf., Jan. 13-17, 2008, pp. 10-13.