Microelectronic Engineering 132 (2015) 58–73

Contents lists available at ScienceDirect

Microelectronic Engineering

journal homepage: www.elsevier.com/locate/mee

Review Article

CMOS–MEMS resonators: From devices to applications

A. Uranga [a], J. Verd [b], N. Barniol [a,*]

[a] Department of Electronics Engineering, Universitat Autònoma de Barcelona, 08193 Bellaterra, Spain
[b] Department of Physics, Universitat de les Illes Balears, Palma, Illes Balears 07122, Spain

ARTICLE INFO

Article history:
Received 28 May 2014
Received in revised form 15 August 2014
Accepted 21 August 2014
Available online 29 September 2014

Keywords:
MEMS
CMOS–MEMS
Resonators
Oscillators
RF-MEMS

ABSTRACT

This review summarizes the reported MEMS resonators integrated monolithically in CMOS technology and their main applications as oscillator circuits in timing applications and in sensory systems. An overview of the CMOS–MEMS resonators acting as filters for signal processing is also included. Special emphasis will be given to the different technological fabrication approaches and their performance, providing specific figures of merit for their comparison as stand-alone resonator as well as oscillator and filter. This review contributes to establish the state-of-the art on CMOS–MEMS resonators.

1. Introduction

Monolithically integration of MEMS resonators in CMOS technology is one of the main streams to decrease power and cost for RF communication systems providing a single-chip solution with enhanced performance for the demanding area of portable devices. The off chip quartz crystals resonators used as elements in clocks or frequency references do not allow an optimal size miniaturization and at the same time cannot be integrated with CMOS. In comparison, MEMS based oscillators are being considered as a clear alternative for implementing stable reference clocks with large scale integration capability, reduced production cost and additionally reduced power consumption [1,2]. Considering the development of multiband wireless systems, along with the high social demand for portable and wearable devices, the market for this kind of MEMS devices is expected to increase with a similar evolution that evidenced in MEMS inertial sensors. In this way a clear demand for MEMS resonators for frequency references [1] and added RF signal processing (filters and mixers, [3]) is envisioned. In last years some companies have started to sell programmable frequency references based on MEMS resonators [4–7]. Most of the proposed systems consist on MEMS devices connected to a specific CMOS circuitry following an hybrid approach, by a mere wire bonding or embedded with other dies constituting a system in package. Only SiLabs company is selling a MEMS resonator deposited over the CMOS pre-processed chip, providing the first-commercial available monolithical MEMS-based oscillator [7].

In addition to the necessity of MEMS resonators for the RF communication systems, other required functionalities related to the sensing applications field, can benefit from the monolithical integration of the MEMS resonator in the CMOS technology. Small device dimensions and an enhancement of the signal to noise ratio reverts in very high final resolution as has been reported for gravimetric MEMS sensors integrated in CMOS in several applications: mass sensing [8,20,21], chemical sensors [48–52], and-temperature sensors [53–55]. These Sensor Systems on Chip (SSoC), provide at the same time, a more robust fabrication process, high yield with a more easily portable solution.

This review summarizes the reported MEMS resonators integrated monolithically in CMOS technology (see Fig. 1) and their main applications in RF communication systems as well as in sensory systems. Special emphasis will be given to the different technological approaches reported from various research groups and their main properties, trying to provide specific figures of merit in order to compare their performance. We restrict this review to resonator devices excluding all the MEMS systems applied to other applications (as for example inertial sensors). For a deeper discussion and review on the integration of MEMS devices into CMOS technology including a wider perspective the reader can refer to [9–11]. A MEMS resonator is a mechanical vibrating element exhibiting a well-defined frequency spectrum with a high amplitude response at its modal resonance frequency [2,3]. Most of the MEMS resonators reported in this article will be driven to its resonance vibrational mode using an electrostatic excitation, while the

---

* Corresponding author.
E-mail address: nuria.barniol@uab.cat (N. Barniol).

http://dx.doi.org/10.1016/j.mee.2014.08.015
0167-9317/© 2014 Elsevier B.V. All rights reserved.

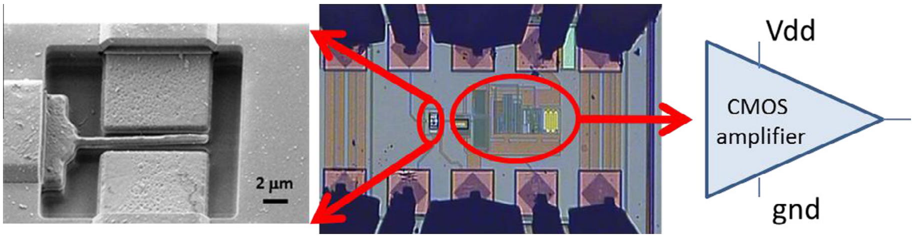

Fig. 1. Example of a CMOS–MEMS resonator Left: SEM image of a cantilever MEMS resonator using top metal layer from of 0.35 µm AMS (Austria Microsystems) CMOS technology, Middle: Optical image of the overall system (MEMS resonator and CMOS amplifier circuit), showing the electrical pads and test probes. In this case the system has been used as a gravimetric mass sensor obtaining a mass resolution of 24 ag in air [8].

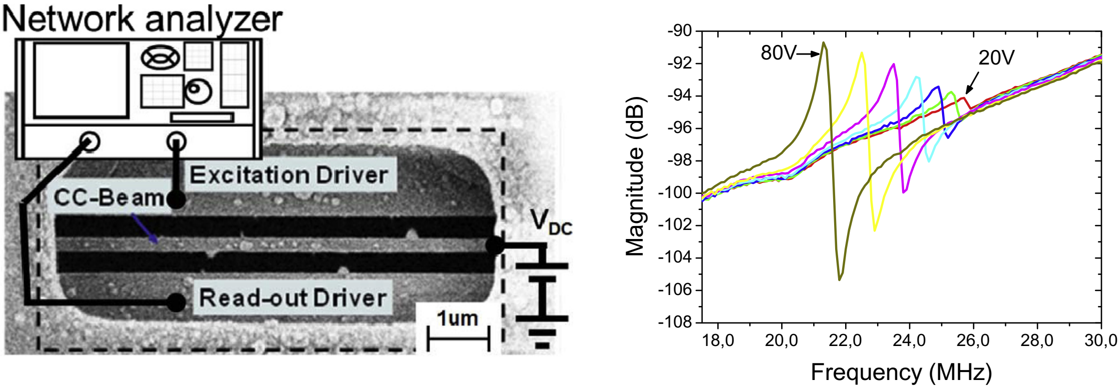

Fig. 2. (a) SEM image of a clamped–clamped metal beam integrated using the metal layer of the 0.18 µm UMC (United Microelectronics Corporation) CMOS technology. The electrical set-up used for the frequency response characterization is shown. (b) Electrical frequency response of the CMOS–MEMS clamped–clamped beam acquired using a network analyzer [22].

transduction of the movement will be made capacitively (see Fig. 2). The electrical characterization set-up uses a network analyzer for the electrical actuation and frequency response characterization, and a voltage source to polarize the MEMS vibrating element. Additional voltage source is needed to bias independently the CMOS circuitry. Schematic overview of this electrical set-up is also depicted in Fig. 2

The article is structured in five sections. After this brief introduction, Section 2 describes the main technological approaches for the integration of MEMS resonators in standard CMOS technologies. In this Section 2 a comparative review of the main reported CMOS–MEMS resonators is also provided. Section 3 is devoted to the oscillators implemented monolithically with MEMS resonators and CMOS circuitry as well as a brief overview on sensing applications. In Section 4 main applications as RF filters are presented. Finally Section 5 will end with some prospective about the future directions of the integration of MEMS in CMOS technologies.

2. Technology approaches and performance

This section is devoted to the MEMS resonators as devices, explaining main technological approaches for their monolithical fabrication in CMOS as well as main performance characteristics as stand-alone resonators. The monolithical integration of MEMS resonators with CMOS integrated circuits entails that the MEMS and the IC are integrated using the same substrate or chip [9–11]. The whole system is realized using a fabrication process optimized for integrated circuits with a few compatible process steps for MEMS definition when necessary. From a technological perspective the main classification used in relation to the CMOS–MEMS integration is based according to the moment in which the mechanical structure is defined: (a) MEMS-first or pre-CMOS, (b) intra-CMOS and (c) MEMS-last or post-CMOS. Adopting the definition provided in [9], we will only refer to CMOS–MEMS as an intra-CMOS process in which the MEMS is defined using one or more layers of the CMOS back-end-of-line (BEOL) materials already available in the standard CMOS technologies (see Fig. 1)

We consider the MEMS-first and MEMS-last approaches, non-standard approaches, in the sense that they require special technological processes not available in a standard CMOS technology. Among them we distinguish between approaches using standard CMOS processes based on bulk silicon [12] and CMOS processes based on silicon-on-insulator CMOS (SOI-CMOS) [13–16]. This second approach based on SOI, provides crystalline silicon for the MEMS resonator enhancing its performance with higher quality factors to the expense of more complexity in the technological process used, thus increasing final device cost. In relation with MEMS-last vibrating devices using bulk silicon CMOS, a low temperature range to deposit the MEMS structural material, decrease the resonant performance of the vibrating element providing elements with intrinsic low quality factors [12]. In this review some MEMS-first approaches and MEMS-last approaches will be considered for completeness as a full system in the oscillators section.

The intra-CMOS or CMOS–MEMS approach exploits all the characteristics of the CMOS foundries having the following benefits: fast turnaround fabrication time, reproducibility, yield, reliable MEMS dimensions definition due to the strict CMOS technology tolerance and good matching with the interfacing circuitry minimizing the parasitic effects and optimizing the signal-to-noise ratio. Other benefits are related with the intrinsical possibility to obtain a zero-level package using some of the BEOL metal layers as pre-covers for a final metal sealing providing in this sense with a full packaged CMOS–MEMS solution. On the other hand some