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Large scale integration of silicon nanomechanical resonators above industrial cmos wafers

Willy Ludurczak[1*], Guillaume Gourlat[1*], Marc Gely[1], Gérard Billiot[1], Julien Philippe[1], Patrick Villard[1], Gilles Sicard[1], Thomas Ernst[1] and Sébastien Hentz [1]

[*] These co-authors equally contributed to this work
[1] Commissariat à l'énergie atomique et aux énergies alternatives
Univ. Grenoble Alpes, F-38000 Grenoble, France
CEA, LETI, MINATEC Campus, F-38054 Grenoble, France
Phone: +33-4-3878-2021 E-mail: guillaume.gourlat@cea.fr

Abstract

Real-world applications in the field of chemical, physical or biological sensing require the dense integration of a large number of individually addressed nanomechanical devices for large analyte capture area. One way to achieve this is to place both routing and readout under the sensing mechanical layer with NEMS/CMOS co-integration. We report here the demonstration of resonant Nano Electro Mechanical Systems (NEMS) patterned in monocrystalline silicon above industrial CMOS Back-End-of-Line (BEOL) wafers. Electrical access from the probing pads to the NEMS is performed via the BEOL metal levels of the CMOS wafer. Frequency response, quality factor and frequency stability are measured and compared to those obtained with the same NEMS design without electrical contact through BEOL on the same wafer. This comparison shows no performance degradation. This result was made possible thanks to a 3D sequential integration concept, where 8'' Silicon-On-Insulator (SOI) wafers are bonded onto CMOS substrates. This allows photolithographic precision alignment between NEMS and BEOL interconnects. We demonstrate here how a small array of monocrystalline silicon based NEMS can be addressed with this proposed NEMS/CMOS process. Outstanding integration density and a large number of devices are now made possible. This generic feature opens up new possibilities for silicon based sensing applications.

1. Introduction

NEMS devices have established record limits of detection, in particular in mass [1] and gas [2] sensing. One step towards real-world systems has been performed with the use of VLSI silicon individual devices specifically designed for multi-gas analysis systems and real-time NEMS-based Mass Spectrometry [2-3]. The extreme sensitivity comes at the cost of an extremely reduced analyte capture area therefore limiting the molecule capture probability. Large scale integration of a large number of devices is then highly desirable for the aforementioned applications [3-4]. Individual addressing (for single particle detection) of such a great number of densely packed devices is a critical technological challenge. NEMS/CMOS co-integration is one of the rare solutions to this end, but previously demonstrated methods [5] cannot satisfy the combined constraints of using monocrystalline silicon NEMS and high density.

2. Description of the system and technological process

We present here the demonstration of a 3D sequential co-integration of silicon NEMS above industrial CMOS wafers with the so-called CEA/LETI process "CoolCube™". These wafers do not include CMOS readout circuits but embed interconnect metal levels which we use to demonstrate the new integration process and electrical functionality. The mechanical device designed here is a monocrystalline silicon doubly-clamped beam which is 160nm thick, 300nm wide and 10µm

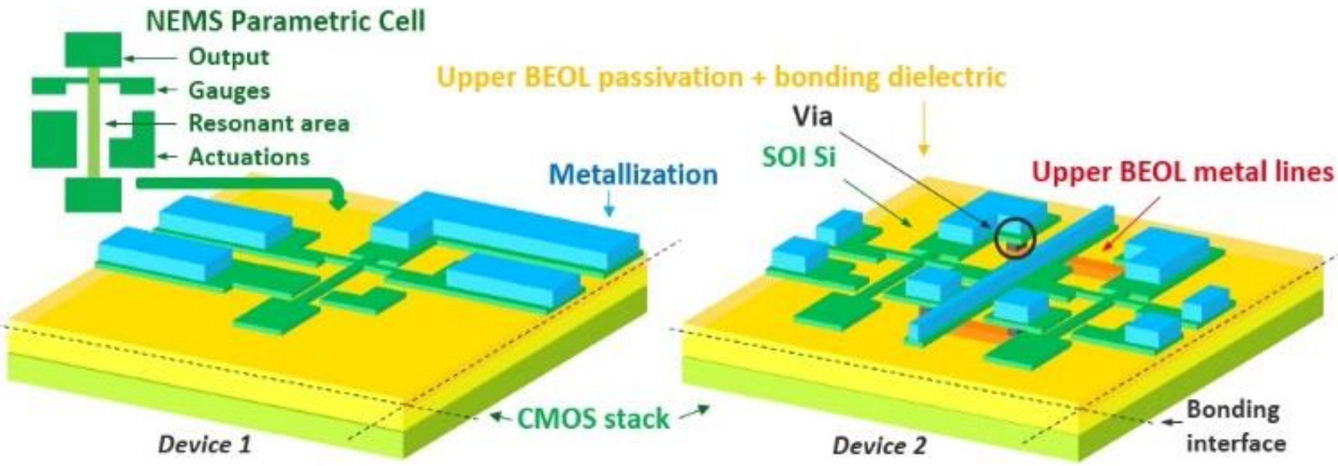

Fig. 1 Schematic principle of NEMS resonators connected to CMOS BEOL

Fig. 2 SEM and optical observations of NEMS structured above CMOS BEOL

long. This resonator is electrostatically actuated gap ~100nm) and the in-plane motion is transduced in the electrical domain thanks to piezoresistive nano-gauges (~80nm wide). The individual addressing is based on individual connections of NEMS outputs and on frequency addressing, enabling the readout of each single NEMS in an array (each resonator is designed to have a slightly different resonance frequency).

3. Experimental results

The principle of the structure is presented Figure 1. 3D sequential integration is realized after 8" wafer bonding of SOI reported upside down on CMOS BEOL. The upper part of the stack is grinded to obtain a full sheet monocrystalline Si as top layer. NEMS are patterned in top Si. Vias are etched through the bonding interface before deposition of a metal layer that realizes the contact between top Si and BEOL. SEM and optical observations are shown Figure 2. Two types of devices are compared in terms of performances. Device 1 is a single NEMS without through-BEOL routing which is considered as a reference. Device 2 is an array of 4 NEMS having common outputs and through-BEOL routing. Both devices exhibit similar performance (Fig. 3 & 4) with quality factor of 7292 and 6452 respectively. Furthermore, they present similar frequency stability (characterized in terms of Allan deviation) around 10^{-7} at 100ms integration time. NEMS density of more than 7400 devices/mm² can be reached with this co-integration scheme without degrading the device performance for chemical or mass sensing applications.

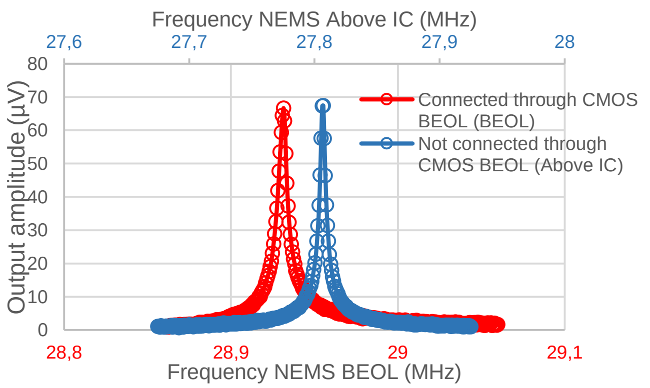

Fig. 3 NEMS electrical response measured on device 1 (Above IC) and device 2 (connected through the CMOS wafer BEOL)

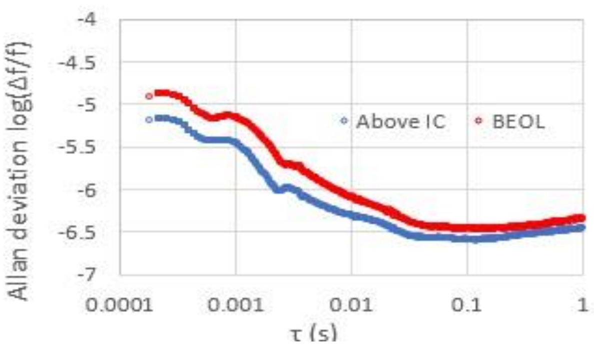

Fig. 4 Allan deviation of device 1 (Above IC) and device 2 (BEOL)

4. Conclusions

This works presents a new 3D sequential NEMS/CMOS co-integration scheme which provides a high interconnection density for monocrystalline Si NEMS devices and an industrial CMOS wafer where the readout circuitry may be designed. We successfully demonstrated similar electrical performance of the NEMS devices, whether or not they are routed through CMOS BEOL. This work opens up new perspectives in terms of high density integration of NEMS which is required for biological, chemical or mass sensing applications. For these applications, the small capture area of nanomechanical resonators is the limiting factor in terms of analyte detection probability. Ultimately, a dedicated electronics will be integrated in bottom CMOS Front-End, capable of individually addressing a large number of identical resonators. The 3D sequential co-integration process will ensure the readout and addressing of NEMS structured in above IC silicon layer through BEOL connections allowing the resonators to be even more densely packed with the removal interconnecting metal line at the Above IC level. Furthermore, this new integration scheme will permit a high density interconnection between the read-out electronics and the NEMS which could potentially be addressed individually without the need of a frequency addressing technique.

Acknowledgements

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