Towards A Generic Technology For Integrating MEMS With CMOS

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The development of future micro-electromechanical systems (MEMS) demands a generic process flow that enables the realization of a wide variety of cheap, high-performance MEMS devices. IMEC sees a SiGe-based technology for integrating MEMS on top of CMOS as the most promising approach. In this article, a generic technology is presented for the processing of different types of MEMS devices (resonators, accelerometers, etc.) on top of standard CMOS wafers. The technology, which enables the creation of future highly miniature systems, is part of IMEC’s CMORE platform. CMORE offers R&D programmes which accelerate the development and commercialisation of emerging semiconductor-based process technologies.

Trends in MEMS development

MEMS development today is driven by three important goals: increased performance, further miniaturization and price reduction. These goals can be achieved by the monolithic integration of MEMS structures (sensor/actuator) together with driving, control and signal processing electronics on the same die. In recent years, many alternative routes towards monolithic integration have been explored, such as the so-called MEMS-first approach (in which MEMS structures are fabricated before the CMOS is processed), the interleaved process (in which MEMS and CMOS process steps are interleaved) and the transfer and join technology (in which MEMS structures that have been fabricated on a separate wafer are transferred to the CMOS wafer). Each of these concepts has its own pros and cons – some of them have already been applied in commercial products.

An alternative and most promising approach is the so-called MEMS-last or post-CMOS approach. This concept consists in fabricating MEMS structures on top of the CMOS wafer after completion of the CMOS processing. Consequently, MEMS processing can only be done at temperatures below 450°C, which is a major drawback.

In general however, the ability to process and interconnect MEMS devices above (any) underlying circuitry offers significant simplification. An important advantage of this approach is an efficient use of the Si area. Moreover, there is no need for compromise between MEMS and CMOS performance as in some of the other monolithic approaches.

Post-CMOS poly-SiGe MEMS integration: a generic approach

Since the mid nineties, IMEC has explored poly-Si1-xGex as a structural material for the realization of micromachined Si1-xGex devices integrated with CMOS circuitry in a MEMS-last approach. SiGe was selected as a structural material because of its very interesting mechanical, electrical, optical and thermal properties. SiGe has a high Young’s modulus, high yield strength, no creep, no plastic deformation at typical operation temperatures and is insensitive to fatigue failure. Moreover, it can be doped for optimization of the electrical and thermal properties as needed for some thermoelectrical applications. Si and Ge are completely soluble and have the same crystal structure. Hence, the relative composition of these two elements can vary in a very wide percentage range, resulting in an additional degree of freedom.

Figure 1 – Optical microscope picture of a free-standing SiGe gyroscope processed above CMOS
Poly-SiGe can be deposited on the CMOS wafer using plasma enhanced chemical vapor deposition (PECVD) for later surface micromachining. This PECVD process results in high-quality poly-SiGe material deposited at temperatures that are compatible with CMOS circuitry. Another reason for selecting SiGe is that it does not pose any contamination problems for the CMOS process environment. IMEC is convinced that this poly-SiGe-based technology will become a generic technology which enables the creation of a whole range of highly integrated miniature systems with improved performance over current options. A number of successful applications, such as micro-bolometers, thermopile arrays for energy harvesting, accelerometers etc, could already demonstrate the versatility of this approach, which not only aims at meeting performance specifications, but also at fulfilling price and reliability requirements.

**Demonstrator: poly-SiGe gyroscope**

IMEC, together with its partners in the European IST project SiGeM, has developed a poly-SiGe-based integrated gyroscope targeted for low-noise, high-resolution applications. The gyroscope is contained in a single chip that adds a poly-SiGe layer on top of a standard Si layer. The poly-SiGe layer is the structural layer of the MEMS device that uses Coriolis forces to sense the rate of turn, while the underlying Si includes CMOS circuitry to amplify the signal and convert it to a digital one.

The gyroscope was processed on top of a commercial high-voltage (20V) 0.35µm double-poly CMOS process. The poly-SiGe structural layer, which is at least 10µm thick for increased sensitivity, is deposited by using an advanced multilayer technology resulting in high-quality films (i.e. low resistivity, low tensile stress, low strain gradient, high quality factor) at low temperature (below 450°C). The release is done using wet chemical processing and CO₂ super-critical drying to eliminate stiction. Hence, the free-moving gyroscope has been obtained above a fully functioning CMOS by using only three extra mask steps. Measurements have shown that a resolution of 0.07°/s can be reached within a minimum 50Hz bandwidth, showing the excellent accuracy of the gyroscope. Accurate gyroscopes will be essential, among other things, for the development of future vehicle systems.

Usually, systems like this are made of two separate chips. The demonstrated advantages of this integrated approach are: (1) increased sensor performance compared to current two-chip solutions; (2) increased sensor reliability by the omission of connecting wires between separate sensors and electronics chips and (3) reduced size by exploiting a single-chip solution.

In this study, a gyroscope was developed. The technology can also be applied to a whole range of devices that integrate mechanical sensors, such as accelerometers, micro-mirrors, resonators and others with silicon circuits.

**Enabling lower deposition temperatures**

While some CMOS processes are capable of withstanding post-processing temperatures of 450°C, more advanced CMOS processes – with low-k dielectrics for example – demand a more realistic temperature limit of 400°C. Therefore, techniques that allow depositing SiGe at a lower temperature are currently under investigation. These include metal-induced crystallization of SiGe, laser annealing and crystallization and hydrogenated SiGe. The advantages of the latter approach have already been illustrated by the fabrication of micro-mirrors in hydrogenated microcrystalline SiGe (µc-SiGe:H). Such a structural layer can be deposited at lower temperatures (300 – 400°C) than the thick poly-SiGe (450°C) used for gyroscopes. Moreover, the maximum diameter of SiGe grains of 100nm ensures uniform and reproducible mechanical properties of the submicron mirror hinges.

Using µc-SiGe:H, IMEC produced micro-mirrors with sizes between 7.5x7.5µm² and 16x16µm² and sub-micron hinges ranging from 250-400nm. The very flat mirrors showed no hinge creep over 20 days and no fatigue damage after
5x1010 cycles. The devices are a very good alternative for the current 5x1010 Al-based micro-mirrors, which often give rise to reliability problems. Replacing Al by Si could also solve the problem, but integrating the Si mirrors with the CMOS driving circuitry can only be accomplished by wafer-bonding techniques. As in the case of the gyroscope, IMEC’s solution to use SiGe allows above CMOS processing of the MEMS devices. It is a good candidate to meet all flatness, uniformity and reliability specifications for future demanding micro-mirror applications such as video projection, adaptive optics, mask writers etc.

The technology presented in this article has the potential to become a generic technology in which different MEMS devices can be processed together on top of standard CMOS. It uses SiGe as a structural material for the realization of micromachined structures integrated with CMOS circuitry in a post-CMOS approach. SiGe can be deposited at temperatures compatible with CMOS processing and provides the desired mechanical and electrical properties for MEMS applications. The realization of a monolithically integrated high-resolution gyroscope, using poly-SiGe as a structural material, and the development of a highly reliable and extremely stable micro-mirror, using hydrogenated µc-SiGe, elegantly demonstrate the potential of this promisingly versatile concept.

These results largely contribute to the MEMS community’s efforts to develop a generic, scalable technology that allows a monolithic integration of a large variety of MEMS structures.

**Traceability And Validation Aid For Medical Device Manufacturing**

Asymtek, a world leader in automated fluid dispensing, conformal coating, and jetting technologies, and YesTech, who provide automated optical and high-resolution x-ray inspection systems, have developed a process that helps enable medical device manufacturers to meet regulatory requirements for traceability and validation for placement and accuracy when fluid dots are dispensed.

Precision, accuracy and reliability are mandatory in the manufacture of medical devices. During the production process, fluids such as reagents, gels and liquids often need to be placed at specific locations on these devices, which include Lab-on-a-Chip lateral flow test strips, sensors and many others. Asymtek combines its dispensing capabilities with YesTech’s automated optical inspection technology to validate that fluid droplets are accurately dispensed and that they are placed in the correct location. These capabilities enable device manufacturers to meet stringent FDA requirements for traceability and validation.

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**New Precision Cutting Laser Unveiled**

Trumpf, a company focusing on production, laser and medical technology, recently unveiled its new TruFiber 300 single mode fiber laser. Integrated into the TruLaser Cell 3004 workstation, the TruFiber 300 will cut bronze leadframes with a thickness of 0.3 mm. This makes it particularly useful in fine welding applications, for example of fuel cells, membranes, sensors, airbag igniters and battery housings, where welding is typically performed with a welding depth of up to 2 mm. The TruFiber 300 has a laser power of 300 W and is suitable primarily for precision processing, scanner welding and wherever the application requires especially narrow welding seams. Furthermore, the laser achieves a defraction limited beam quality, thereby supplementing the spectrum of pulsed lasers and cw lasers in the power range of less than 1 kW.

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