MEMS AT BOSCH – INVENTED FOR LIFE

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ABSTRACT

MEMS is an enabling technology for many new sensors which made their way into automotive, consumer, Internet-of-things and Industry4.0 applications. Their success story is based on miniaturization, high accuracy, reliability, low manufacturing costs and scalability to high production volumes yielding significant economy of scales effects. Today chip- and device-level technology has matured. MEMS innovation happens mainly on the system and product level which represents a move up in the value chain. Technology innovation can be found in new domains away from classical silicon MEMS sensors, like microfluidic solutions for diagnostics at the point of care.

INTRODUCTION

Microsystems or MEMS have revolutionized automotive safety, comfort and engine control systems. Today 100-150 micro sensors can be found in a modern car. High accuracy, reliability, scalability of production technologies to high volumes and low manufacturing costs have enabled many new sensor applications. Examples for “invented for life” are the life-saving airbag and anti-skidding systems, as well as engine control and exhaust treatment systems.

The automotive field was the door-opener to the success of the new micro sensors, providing sufficient market size and economies-of-scales, combined with appreciation of high quality, reliability and product performance.

Today the consumer MEMS field is adding extremely high volumes on top of the automotive MEMS sensor business, with the Internet-of-Things (IoT) firing expectations towards even higher volumes. Experts are predicting a “trillion sensors future”. In the area of Industry4.0, sensors are the key elements to monitor production machinery and workflows, combined with powerful and extremely demanding new software algorithms to extract relevant information from complex sensor data e.g. on wear of machinery and ageing of media, for the prediction of maintenance and service requirements.

There is an increasing demand for complex multi sensor systems integrated with embedded software algorithms and data fusion of individual sensor signals to provide added-value information. Innovation has changed from the aspects of design and simulation, microstructuring, assembly, packaging and interconnection technologies for the individual (multi-) sensor elements into new system architectures, device system concepts and full product solutions for multi-domain use cases, thus moving up in the value chain.

Mechanical sensors have reached a high-level of maturity, and innovation on the chip-level and sensor devices side has been slowing down continuously.

Beyond moving up in the value chain towards system-level integration and system solutions, MEMS technology itself has evolved into new technology domains, like into microfluidics, to name a prominent example. Business opportunities are coming up with the intelligent manipulation and processing of liquid micro plugs through complex fluidic networks inside new microsystems for diagnostics and therapy management at the point-of-care. So-called Lab-on-Chip solutions are one of the innovation pathways in MEMS which are being followed towards industrialization nowadays in several locations. In some cases, we can find a fusion between microfluidic devices fabricated in plastics, and classical MEMS devices made from silicon wherever enhanced functionalities on a micro scale are of importance. As a trend, future MEMS are expanding their scope into new technology and application domains far away from their historic roots.

MARKET SEGMENTS AND VOLUMES

The following chart shows market segments and volumes for MEMS sensors and their respective CAGR’s (cumulative annual growth rates). The automotive market where MEMS originally started from is still an important sub-segment with significant growth. As can be seen, the Consumer segment has taken over both in volumes and in CAGR. Data processing, Industry and Medical Electronics are still smaller in volumes, but taking up pace.

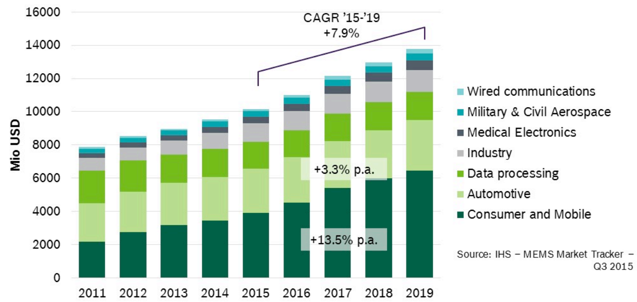

Fig. 1: MEMS market segments, volumes and CAGR’s from 2011-2019 (source: IHS MEMS Market Tracker)

MEMS TECHNOLOGIES OVERVIEW

There are two major technologies in silicon MEMS which are often combined to realize the target devices and packages: Bulk and surface micromachining.

Bulk micromachining comprises of anisotropic etching of crystalline silicon using KOH-solution, “BOSCH-DRIE” and Wafer-bonding. The bulk silicon wafer material itself is used to create structures from in a subtractive microstructuring process.

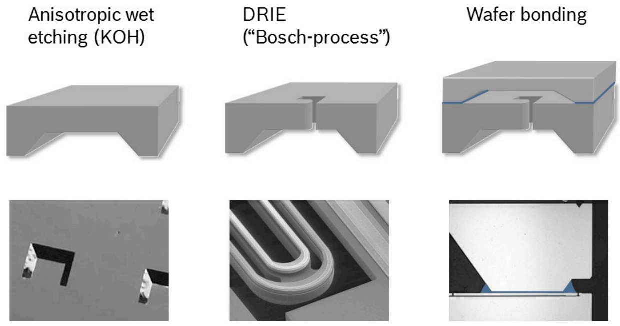

Fig. 2: Technologies for bulk micromachining of silicon

In contrast to this, surface micromachining consists of a sequence of layer deposition and microstructuring steps on top of a silicon wafer. Thick epitaxially deposited polysilicon is mainly used in inertial sensors products from BOSCH. For sacrificial release to yield the free-standing and movable structures, hydrofluoric acid vapor is applied as a semi-dry etching process, to eliminate the need for post-release drying and in-process stiction.

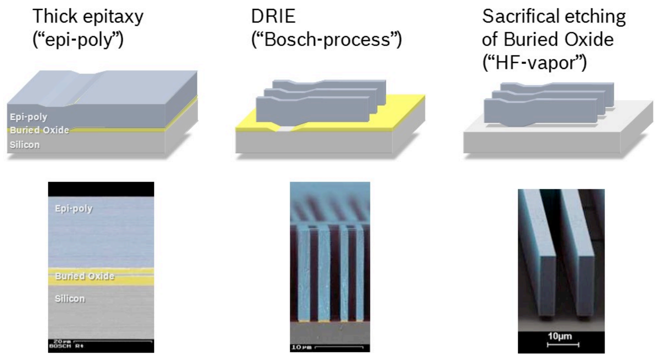

Fig. 3: Technologies for surface micromachining of thick epitaxially deposited Polysilicon

Advanced Porous Silicon Micromachining is a specialty surface-micromachining process technology which was developed at BOSCH. Single crystal silicon is epitaxially deposited on top of porous silicon yielding a monocrystalline seed for the epitaxy. During epitaxial layer formation, porous silicon collapses and reflows, providing a vacuum cavity below the monocrystalline silicon membrane grown on top.

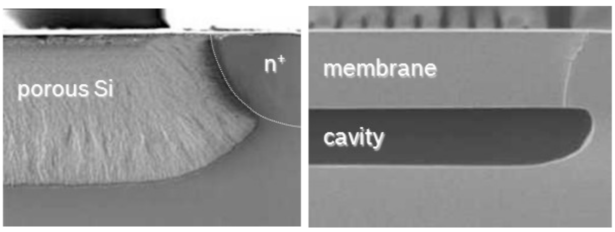

Fig. 4: Advanced Porous Silicon Micromachining Process (APSM) for the epitaxial deposition of a single crystalline silicon membrane on top of a porous silicon cavity.

SENSOR DEVICES

Pressure and Infrared Sensors

BOSCH APSM technology is used for the manufacture of surface-micromachined pressure sensors, as well as Infrared sensor arrays for heat cameras. Both sensors are based on suspended single-crystalline silicon membranes with diffused piezoresistive elements, or integrated temperature sensitive diodes, respectively.

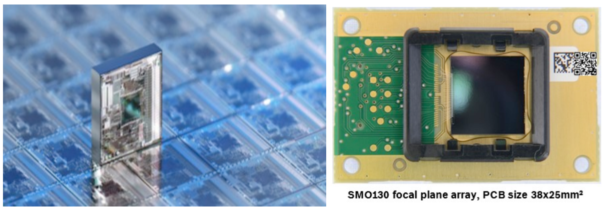

Fig. 5: Pressure Sensor (left) and Infrared Camera Module (right), both based on APSM technology

Inertial Sensors

The most important MEMS products of today are inertial sensors for the measurement of acceleration (accelerometers) and yaw rate (gyroscopes). They are often combined as multisensors in one package.

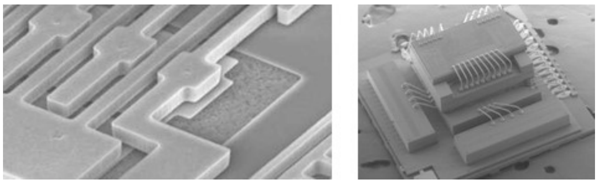

Fig. 6: Comb structure detail of acceleration sensor (left), and inertial multisensor (right) consisting of a 3-axis acceleration sensor and 3-axis gyroscope, together with signal conversion ASIC as a system-in-package.

Limited and ever shrinking space in today’s smartphones is continuously pushing towards sensor product miniaturization: on-going miniaturization is achieved by chip-scale design shrinks, chip-stacking and interconnection as well as smart packaging technologies for the so-called “Systems-in-Package”. As an example for the miniaturization trend, two generations of inertial multisensor products from BOSCH are shown below.

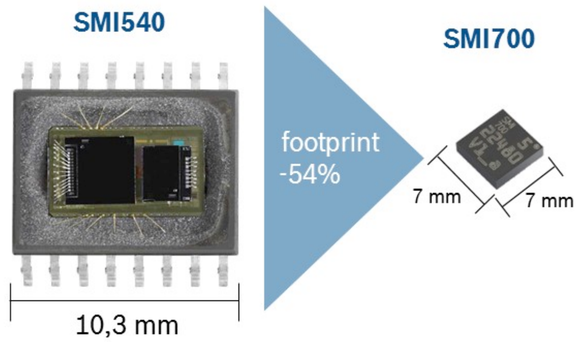

Fig. 7: Product generation sequence for an inertial multisensor product showing significant miniaturization

Combi sensors

Through the integration of magnetic sensors (Hall and/or Fluxgate) with inertial sensors in a "system-in-package", compass functionalities can be added to the sensor system. This is useful for fully autonomous inertial-based navigation, e.g. when no satellite contact is available. A barometric pressure sensor enables detection of the respective floor-levels in buildings. Combination with a chemical sensor for the detection of volatile organic compounds yields additional Air Quality control functionality.

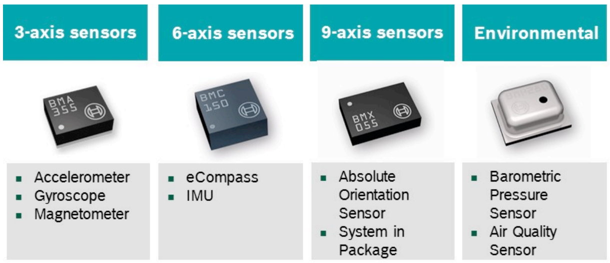

Fig. 8: Different combi sensor products from BOSCH. 9-axis sensor product consists of 2 inertial sensors and a magnetic sensor with three sensing-axis each (3rd left). Another combi-sensor product contains a barometric pressure sensor and a chemical sensor for Air Quality (right).

APPLICATION AREAS

Automotive Applications

The Automotive Applications Area was the early adopter for MEMS. MEMS sensors made a tremendous success story in automotive systems for passenger safety like Overturning protection, Airbag and seat-belt tightening, as well as active accident prevention systems like the Electronic Stability Program (ESP) against skidding. In car engine control systems, pressure and mass-flow sensors measure the amount of air intake to the car engine, and calculate the optimum amount of injected fluid fuel for clean combustion. Autonomous driving will add enhanced sensing requirements to the field. Most of the new sensors will likely be cameras, radar and MEMS devices.

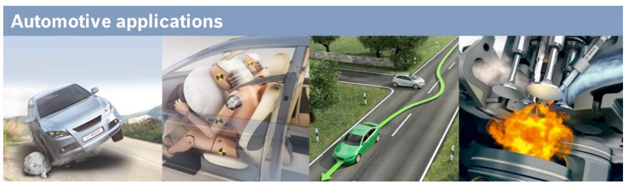

Fig. 9: Automotive safety systems (Overturning protection, Passenger Airbag, Anti-skidding) and clean combustion engine control

Consumer Applications

The consumer MEMS field is dominated by navigation, user interface, imaging and health&fitness applications. Most consumer sensors are found in smartphones today. Extreme miniaturization and ultra-low price are the dominant features in this high-volume market.

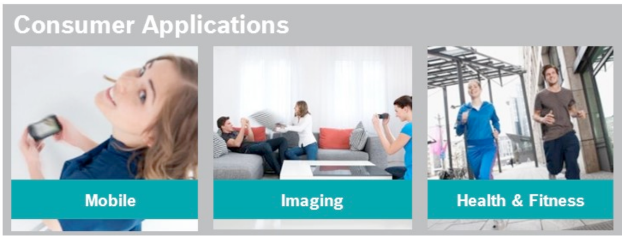

Fig. 10: Consumer MEMS sensors are mostly found in smartphones for mobile navigation, user interface and imaging. Lifestyle products are coming up as well.

Internet of Things

In future, home appliances, smart systems solutions like "Smart Home" and industrial machinery will be connected to the Internet. Sensors are the sensing elements in these solutions, picking up data to transmit to the cloud to make them accessible from anywhere in the world. Apart from the sensors business, services around the data are expected to grow and develop into a huge business for the service providers in future. In industry and logistics, workflows, material flows and flow of goods are continuously monitored and optimized. Machinery up-time can be significantly improved by predictive maintenance and service approaches, with intelligent software algorithms as the key enablers to gain valid predictions from complex sensor data patterns. In this context of "Industry4.0", terms like "machine learning" and "artificial intelligence" have seen a strong renaissance and found their way back into public focus.

Fig. 11: Examples for Internet of Things Applications

The Internet of Things is seen as the 3rd wave of MEMS Market penetration, after the automotive and consumer MEMS markets.

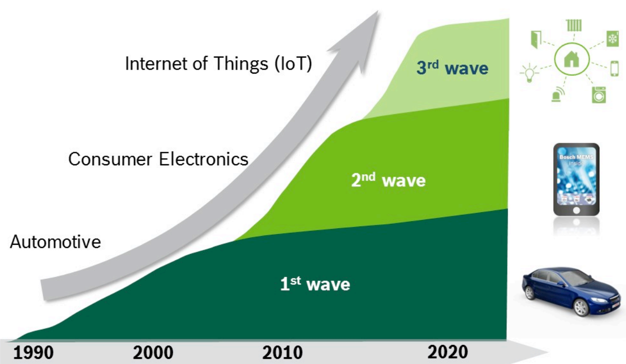

Fig. 12: MEMS market development from Automotive to Consumer Electronics and the Internet of Things.

MICROFLUIDIC SYSTEMS FOR THE AUTOMATION OF MOLECULAR DIAGNOSTIC WORKFLOWS

In the classical MEMS application areas, advances on chip-level technologies have been steadily slowing down. Technical progress can still be seen in some places, e.g. in the form of new packaging approaches and smarter integration solutions for systems-in-package, mostly driven by the need for reaching even higher levels of miniaturization. With increasing maturity of the technology came a shift towards design and simulation capabilities, similar to what was happening in the semiconductor field a long time ago.

This paradigm shift motivated many technology researchers to move away from the classical application fields and look into other areas where MEMS technologies promise benefits, and which offer new opportunities for technical innovation. One of these areas is the field of molecular diagnostics, with its complex biomolecular assays, long process and hands-on times, and significant costs resulting from manual workforce requirements.

Automation of workflows is an urgent unmet need in this field. Apart from the huge and costly bio-robots in centralized laboratories, the idea of smart automation systems applicable at the point of care, in the form of disposable microfluidic Lab-on-Chip cartridges found many proponents. Major benefits are ease of use, process automation with little hands-on time only, low costs, high degree of multiplex and short time-to-result.

Use cases range from the identification of pathogens in infectious diseases, bacterial antibiotics resistances, genetic mutation analysis and tumor diagnostics in oncology. In the latter area, the growing number of drugs for targeted therapies requests for molecular diagnostic tests, to verify that a tumor's driver mutations fit the scope of a targeted therapy. Patient stratification and therapy monitoring are the key towards better and more successful therapies against cancer.

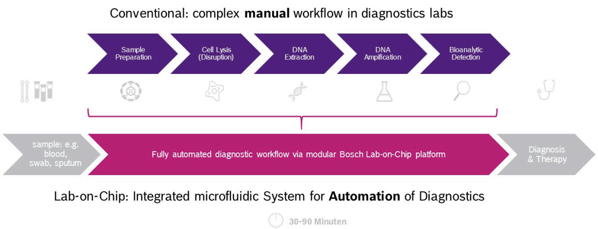

Fig. 13: Typical molecular diagnostic workflow, as a complex manual process (top), and fully automated on a Lab-on-Chip platform (bottom)

A demonstrator Lab-on-Chip platform from BOSCH comprises of a laboratory tool (diagnostic unit) combined with disposable cartridges (Lab-on-Chips). The latter contain all reagents necessary for the complete automated workflow. Reagents are stored on-chip long-term stable at room temperature within sealed reservoirs. The disposable chips are assembled as a stack of polymeric multilayers. Active fluid manipulation is performed by pneumatic actuation of elastic membranes placed between fluidic and pneumatic layers. All unit operations (sample prep, lysis, purification, elution, Polymerase Chain Reaction and array hybridization and readout) can be integrated. Due to their small sizes and high levels of functionality, MEMS chips are the ideal complement to make the microfluidic system a perfect total analysis solution.

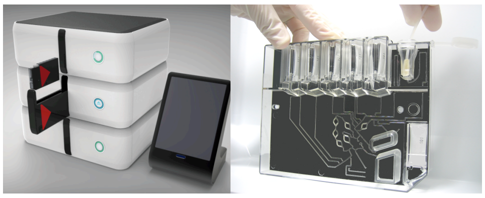

Fig. 14: Diagnostic unit (left) and disposable Lab-on-Chip cartridge (right)

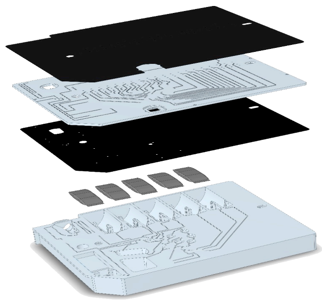

Fig. 15: Polymeric multilayer stack of fluidic and pneumatic elements, including hermetic reagent containers, with elastic membrane in between.

SUMMARY AND CONCLUSIONS

MEMS has evolved over three decades meanwhile, starting from the automotive field, via applications in the consumer electronics area and the Internet-of-Things, and most recently into medical and molecular diagnostic applications. The key performance indicators of small size, high performance, reliability and quality, at a low cost have opened a wide range of use cases and paved the way to success. With an ever growing scope of potential applications on the horizon, even those reaching far away from historic roots, the MEMS story will go on into a successful future.

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