Publishable summary

The three-year FP7 project MSP - Multi Sensor Platform for Smart Building Management started on 1st September 2013. Materials Center Leoben (MCL), an Austrian COMET K2 Competence Centre, coordinates this € 18 million project that is designed to strengthen the leadership of European industries in the highly competitive area of smart sensing systems in wireless mobile and building applications.

The MSP consortium comprises large and small companies, universities and public research centres from 6 European countries. The 17 partners include: Materials Center Leoben, ams AG and EV Group (EVG) from Austria; ams Germany (previous Applied Sensors) GmbH, Fraunhofer Gesellschaft, Siemens AG and the University of Freiburg from Germany; Boschman Technologies B.V. and Holst Centre from the Netherlands; the University of Oxford, the University of Cambridge, the University of Warwick, Cambridge CMOS Sensors and Samsung R&D Institute UK from the United Kingdom; the University of Louvain and VITO from Belgium; and Universitá degli studi di Brescia from Italy.

The MSP project is focused on the development of sophisticated devices and sensors as elements of a “tool-box” that are required for the realization of innovative smart multi-sensor systems capable for indoor and outdoor environmental monitoring:

- Gas sensors for detection of potentially harmful or toxic gases
- Sensors for particulate matter and ultrafine particles
- Development of IR sensors for presence and fire detection
- Development of highly efficient photovoltaic and piezoelectric devices for energy harvesting
- Development of light sensor and UV-A/B sensors
- Development of humidity and temperature sensors.

Major objective is the development of a powerful technology and manufacturing chain enabling flexible “plug-and play” 3D-integration of devices and sensors on CMOS electronic platform chips. The MSP concept is based on rigorous employment of Through-Silicon-Via (TSV) technology and relies wherever possible on CMOS technology being the sound foundation for cost efficient mass fabrication. The multi-sensor system will include devices providing wireless communication between MSP nodes and from MSP nodes to users. By integrating different types of devices and components from the “tool-box” the following MSP demonstrator systems will be realized:

- MSP Device for Smart Building Management
- MSP Device for Wearable Wristwatch Application
- MSP Device for Outdoor Environmental Monitoring.

After having elaborated the first “big picture” in project period 1, the MSP team has successfully elaborated the full manufacturing chain for system integration for fabrication of 3D-integrated multi-sensor systems in period 2. The sensor devices, which will be finally integrated on the CMOS-Platform chip Gen2 PC2 have been fixed now as second “big picture” in the project period 2. A total of 12 sensor chips will be finally integrated on Gen2 PC2: 8 µhp gas sensor chips comprising a maximum of up to 53 gas sensors, a UV-A/B sensor, an infrared (IR) thermopile (TP) sensor array, a temperature sensor, and a V-light sensor.

Sensor types	Kind of 3D stacking
3 gas sensor µhp array chips (MCL/AMS)	TSV, Overmolded
4 gas sensor µhp chips (APPS)	Wirebonded
1 gas sensor µhp (IMEC)	Wirebonded,
1 UV-A/B sensor (FHG-IISB)	Wirebonded,
1 IR sensor array chip (CCS)	TSV, Overmolded
1 temperature sensor (AMS)	Flip Chip, Overmolded
1 V-light (AMS)	TSV, Overmolded

Work in WP2 “Overall Concept Development” was primarily focused on elaborating the process flow for packaging of 3D-integrated MSP-demonstrator devices including TSV-based devices as well as devices requiring wire bonding. A concept for the full manufacturing chain has been developed. Assessment of reliability has been started on device level where the µhp chip developed by AMS and MCL was a critical issue. Due to investigations by FIB-cuts and TEM-analysis the failure mechanism has been clearly identified enabling a robust redesign of the µhp chips which form the platform for next generation gas sensors (see WP5).

Lot of progress has been achieved in WP3 “Development of Components and Devices” by developing optimized Gen1.5 and Gen2 devices. Gas sensors ranging from commercially available products and demonstrator systems to highly sophisticated devices based on graphene and nanowires (NWs) have been developed. Emphasis has been put on CO_2 sensing, which is of essential importance for SBM applications. Extensive characterization and test measurements have been performed in WP4 “Characterization and Test of Components and Devices” both in the test labs of the individual sensor developers as well as in the specialized test labs of SIEMENS and VITO. Most important highlights are:

- Development of portable data logger including an MOx sensor (Fig.1a)
- ZnO-NW-gas sensor array integrated on CMOS-fabricated µhp-chips (Fig.1b)
- High response of CuO-NWs/$BaTiO_3$-NPs hybrid sensor to CO_2 - almost independent of the humidity level (Fig.2a)
- High response of $Ce_xZr_yO_2$ oxide based Kelvin Probe gas sensor to CO_2 at different levels of humidity (Fig.2b)
- Graphene-based gas sensor fabricated on a µhp chip by PDMS transfer process with high sensitivity to formaldehyde (Fig.3a)
- Optimization of P(VDF-TrFE-CTFE) based piezo energy harvester with enough output power for driving 44 LEDs forming the MSP-letters (Fig.3b).

Highlight of WP5 “Development of CMOS Platform Chip” was the fabrication of Gen1 PC1 (Fig.4a) and of a specific Evaluation-Kit (Fig.4b). The high flexibility of PC1 was demonstrated by successfully operating all available sensor devices. In addition an optimized µhp chip with TSVs, comprising an array of 8 µhps for a total of 16 gas sensors has been designed.

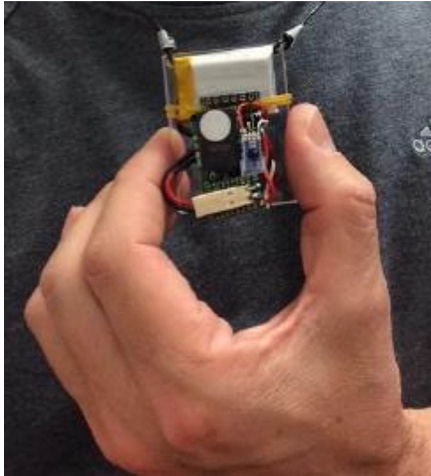

Fig.1a: Neck wearable data logger including an MOx sensor.

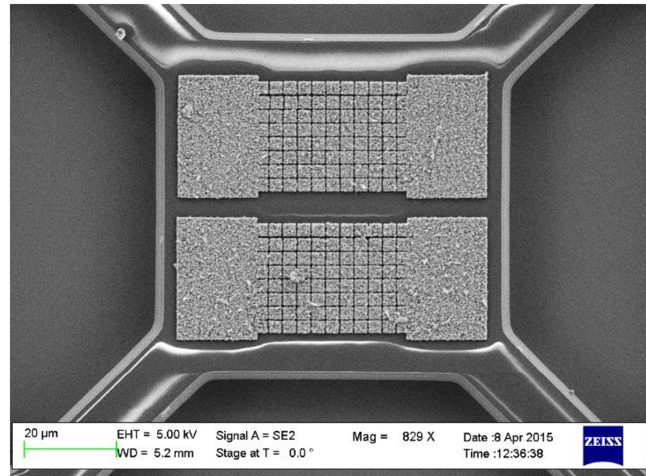

Fig.1b: ZnO-NW-array implemented on CMOS-fabricated µhp-chip.

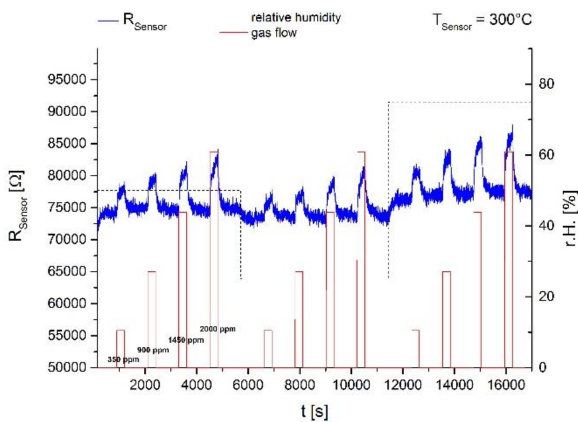

Fig.2a: Response of CuO-NWs/$BaTiO_3$-NPs hybrid sensor to CO_2 at different levels of humidity.

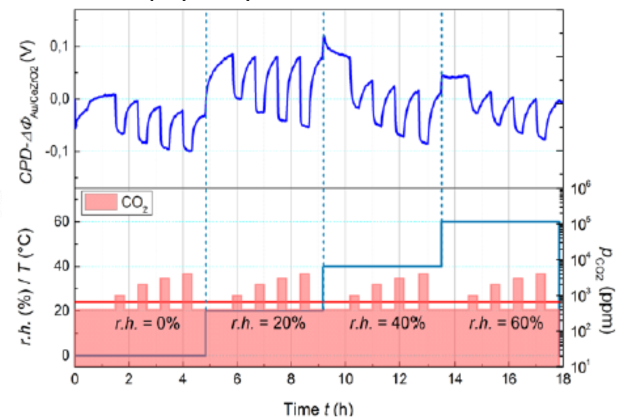

Fig.2b: Response of $Ce_xZr_yO_2$ oxide based Kelvin Probe gas sensor to CO_2 at different levels of humidity.

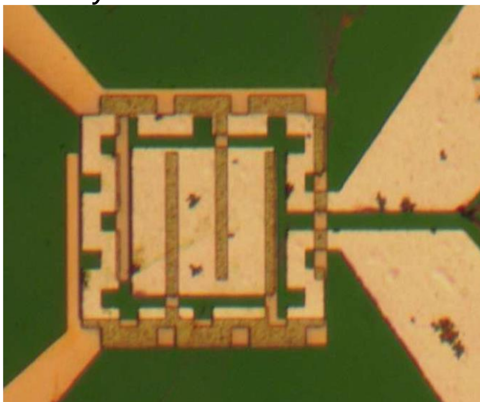

Fig.3a: Graphene-based gas sensor for formaldehyde fabricated on a µhp chip by PDMS transfer process.

Fig.3b: P(VDF-TrFE-CTFE) based piezo energy harvester with enough output power for driving 44 LEDs forming the MSP-letters.

Lot of progress has been achieved in WP6 “Data Processing and Wireless Communication” by successful development of the Artemis 2.0 platform, including the transceiver and microcontroller for MSP demonstrator devices. This platform is based on IMEC’s designed multi-standard PAN2G chip, a combo of BLE and IEEE 802.15.4/Zigbee covering both short-range and long-range wireless applications in the MSP project. Wireless communication

between the Eval-Kit board from FHG-IIS and the IMEC Artemis 2.0 boards has been successfully setup.

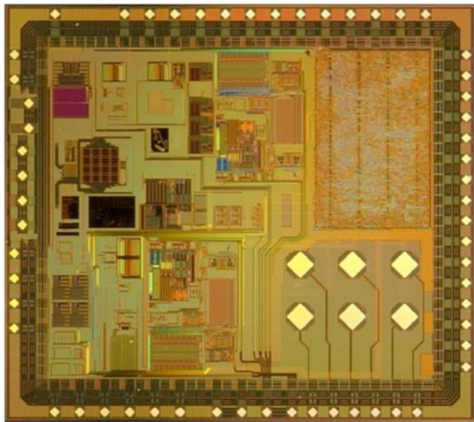

Fig.4a: PC1 platform chip with TSV connections for V-light sensor.

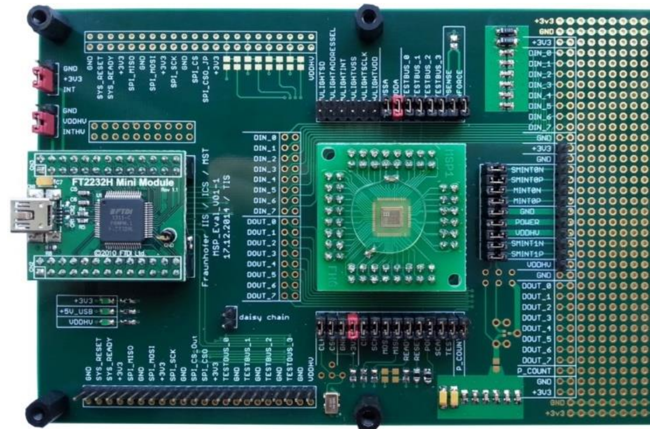

Fig.3b: Eval-kit board for successfully operating all MSP sensor devices.

Highlight in WP7 “Fabrication of 3D-integrated Demonstrator Systems” was the elaboration of the full manufacturing process flow including molding for D2D and D2W system integration. A first full system design based on the Wearable Wrist Band demonstrator from IMEC has been developed.

Although the major focus in WP8 “Performance Evaluation of Demonstrator Systems” is on performance measurements of 3D-integrated components, characterization has been started on single component level in order to push measurement campaigns in “real-life” settings. Field test settings have been elaborated and very interesting results such as NO_2 sensing with IMEC’s GaN-based sensor device in a parking garage have been already obtained.

WP9 “Exploitation” has gained significant momentum and the most relevant exploitation possibilities on end user application level have been identified being as Smart Building (commercial level), Smart Home (consumer level), Consumer Market (smartphones, wearables), and Industrial applications. Extended MPW-service options have been developed and are now being stepwise made available (design rule & process parameter documents, design kit implementation) and offered to interested customers: A press release from AMS has announced the new TSV based V-light sensor and samples & eval kit availability for customers. With proceeding project duration AMS is evolving more and more into a sensor company: AMS has acquired CMOS sensor business from NXP in order to enhance the sensor business.

In WP10 “Dissemination” the MSP-team has been able to increase the number of contributions to journals and conferences from ~ 12 in Year 1 to ~ 35 in Year 2. In addition contributions to high impact journals such as *Nano Energy* and *Nature Scientific Report*, as well as to *Applied Physics Letters* and *Nanotechnology* have been achieved. Major highlight was the successful organization of the first conference nanoFIS “Functional Integrated nanoSystems” in Graz, Austria, 3 – 5th December 2014. A total of 145 scientists, researchers, engineers, technologists, and advanced students – 40% of them female! - from 26 nations from all over the world joined the first nanoFIS 2014 and made the conference a raving success.