Summary Description of Project Context and Objectives

The FP7 project MSP - Multi Sensor Platform for Smart Building Management started on 1st September 2013 and ended 30th April 2017. Materials Center Leoben (MCL), an Austrian COMET K2 Competence Centre, coordinated this € 18.5 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; Applied Sensors GmbH (now: ams Sensor Solutions Germany 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 (now: ams Sensors UK Limited), 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 was focused on the development of a variety of sophisticated sensors and devices 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 was 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 employed Through-Silicon-Via (TSV) technology and relied wherever possible on CMOS technology being the sound foundation for cost efficient mass fabrication. The multi-sensor system includes devices providing wireless communication between MSP nodes and from MSP nodes to users. The initial goal of the MSP project was to integrate different types of devices and components from the “tool-box” to three different MSP demonstrator systems:

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

The following “big pictures” are the most essential results achieved within the 3 periods of the MSP-project:

- Within period 1 (1/9/2013 – 31/8/2014) the MSP team has elaborated the first “big picture” – the overall concept to finalize with overmolded 3D-integrated MSP demonstrator devices,
- Within period 2 (1/9/2014 – 31/8/2015) the second “big picture” – elaboration of the full manufacturing chain for system integration and selection of sensor devices being finally integrated on the CMOS-Platform chip to 3D-integrated multi-sensor systems - has been elaborated,

- Within period 3 (1/9/2015 – 30/4/2017) In WP7 the MSP team has decided to head for the ultimate goal and to realize a MSP demonstrator for wearable wristband application. The third “big picture” – realization of overmolded fully 3D-integrated multi-sensor system device - has been elaborated and realized.

Elaboration and realization of the highly challenging full manufacturing chain for 3D system integration – a complex manufacturing chain that was never realized before! – was key for success. Instead of setting up 3 different MSP demonstrators, the MSP consortium decided to head for a unique *3-in-1* multi-functional MSP demonstrator for wearable applications combining all the features of the planned demonstrators except particle sensing. This is by far the most challenging demonstrator system with respect to required minimum footprint, minimum power consumption, and maximum number of sensor device.

The final MSP-demonstrator system was designed, sophisticated sensor devices were fabricated, 3D-integrated on the platform chip, and finally mounted on a specific PCB including the wireless communication. The wearable wristband device with integrated MSP-demonstrator being the ultimate output of the MSP-project is shown in Fig.1. The MSP multi sensor system comprising a total of 57 sensor devices is a unique device worldwide – such a complex system has never been realized before.

Fig.1: Final MSP demonstrator device fabricated to fit into a wearable wristband device, which has been specifically designed for the MSP project by IMEC.

Lot of progress was achieved in all work packages. Major topic in WP3 “Development of Components and Devices” was to further optimize Gen2 devices. Gas sensors ranging from commercially available products and demonstrator systems to highly sophisticated devices based on nanowires (NWs), nanoparticles, and graphene were developed. Specific emphasis was on CO_2 sensing, which is of essential importance for smart building and smart home 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.

The development and fabrication of the Gen2 platform chip PC2 based on TSV technology as carrier for the 3D-integrated sensor devices was successfully achieved in WP5 “Development of CMOS Platform Chip”. A miniature wireless communication module for the MSP demonstrator device based on the 40nm radio chip, that achieves reduced supply voltage (20%), power consumption (25%), and chip area (35%) including an ultra-low-power microcontroller SoC, a test chip named SleepRunner, was developed in WP6 “Data Processing and Wireless Communication”.

A unique highly complex full manufacturing process flow for 3D-stacking of the sensor devices on the PC2 including overmolding of the 3D-integrated system was realized in WP7 “Fabrication of 3D-integrated Demonstrator Systems”. Fig.2a shows the final MSP demonstrator device representing a unique integrated system worldwide. A wearable wristband device as housing and a proper PCB as carrier of the MSP demonstrator were designed and fabricated for the MSP demonstrator devices. Fig.2b shows the MSP demonstrator device on the PCB designed to fit into the housing of the wearable wristband device. The MSP demonstrator has a footprint of only 3 x 5 cm^2 and a total power consumption under real life conditions of < 50 mW!

Fig.2a: Overmolded 3D-integrated MSP demonstrator device including a total of 57 sensor devices.

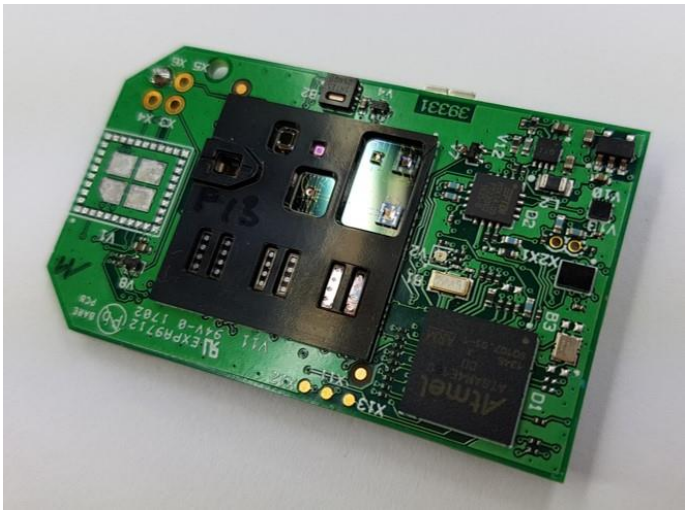

Fig.2b: MSP demonstrator device on PCB designed to fit into the housing of the wearable wristband device.

Lot of effort has been performed in WP8 “Performance Evaluation of Demonstrator Systems” is both on single component level as well as on integrated level in order to push the measurement campaigns in real-life settings.

For WP9 “Exploitation” a comprehensive Exploitation Plan has been elaborated by the Exploitation & Dissemination Team, which by far exceeds the initial objective of the MSP-project. This exploitation plan includes a market study and a detailed list of potentially innovative products ranging from applications in Smart Buildings, Smart Home, Security and Industrial to Environmental Monitoring, Health & Consumer Electronics, and Internet-of Things. A major achievement is the extension of ams’ well-recognized and reliable prototyping service known as Multi Project Wafer service (MPW) into photonic sensors including UV and NIR sensing, temperature sensor, advanced packaging service, molding service (in cooperation with BOS), TSV80 technology, and the MEMS based µhp-device.

In WP10 “Dissemination” the MSP-team has been able to achieve a total number > 70 of contributions to peer reviewed journals. Contributions to high impact journals such as *Nano*

Energy and *Nature Scientific Report*, as well as to *Nanoscale* and *Nanotechnology* have been achieved. A total number of > 130 dissemination actions such as presentations at conferences and workshops, or organization of multi-project workshops have been achieved. The highlights include the successful organization of two nanoFIS "Functional Integrated nanoSystems" conferences in Graz, Austria, in 2014 and 2016, where lot of MSP partners disseminated their outstanding results.

In summary, the MSP demonstrator device is a unique multi-sensor system worldwide, which has never been realized so far and features the following highlights:

- A variety of highly sophisticated gas sensors based on nanomaterials such as SnO_2, CuO, ZnO, and WO_3 nanowires, (bi)metallic nanoparticles, their hybrid combinations, and graphene(oxide), have been developed,
- Realization of highly promising CO_2 sensors based on very specific hybrid nanomaterials,
- An electronic platform chip based on TSV technology has been designed and fabricated as stacking platform for the sensor devices,
- Development and fabrication of 8x microhotplate array for 16 gas sensors on a single chip – this is a worldwide unique gas sensor array,
- Development of GaN-on-Si technology based micro-hotplate and integration of GaN/AlGaN 2-D electron gas sensor for NO_2,
- Realization of hybrid MEMS-FBAR based micro sensor system utilizing high frequency acoustic wave devices for the real time monitoring of airborne fine particulates (< 2.5 µm),
- SiC-based UV-A/B sensors, development of sensors for visible light with near photopic responsivity, and development of thermopile-based infrared sensors,
- Development of microcontroller SoC with record computing efficiency at the full SoC level being a 10× improvement compared to the 2016-2017 research state of the art,
- A complex manufacturing process has been elaborated and realized to enable the fabrication of the 3D-stacked multi-sensor system by TSV-technology and wire-bonding,
- A specific overmolding process has been applied to realize the fully overmolded MSP demonstrator system exhibiting an extremely challenging topography due to different thickness and geometry of the devices. Such a complex system has never been realized so far,
- A new wristband device has been designed and fabricated to end up with a wearable showcase for the MSP demonstrator,
- The MSP demonstrator is a fully 3D-integrated overmolded multi-sensor system comprising a total of 57 sensor – this is a unique sensor system worldwide.

Demonstrating the ultimate state-of-the-art in multi-sensor system integration worldwide, the MSP project paves the way for future integrated sensor systems. The MSP consortium is proud to announce that the MSP project contributes to reinforce European industrial leadership through miniaturization, performance increase and manufacturability of innovative smart systems.