INTEGRATED MICROSYSTEMS

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Abstract: *Integrated Microsystems are essential enablers of a smart environment. Two important trends are increasing miniaturization and wireless and autonomous operation. The prominent ingredients of such wireless autonomous transducers are ultra-low power sensor readout architectures consuming microwatts of power, and powerMEMS or energy scavenging technology (generating microwatts of power). Miniaturised 'cubes' in the cm3 range have become possible by antenna integration and 3D SiP integration and packaging methods Truly unobtrusive integrated sensor systems require further downsizing to the mm3 range. This is envisaged by advanced 3D- packaging , and thin film integration of RF and MEMS components. For RF systems and RF-MEMS applications, IMEC's work is a generic extension of its current advanced packaging and interconnect technology RF platform For physical, kinematic as well as optical MEMS applications, a fully CMOS compatible generic above-IC polySiGe MEMS technology is presented. Examples of technology platforms will be given, including reliability of some demonstrated microsystems. Such extremely miniaturized systems will lend themselves to integration into flexible and even stretchable embodiments. This talk will summarize IMEC's efforts positioned within worldwide developments*

Integrirani mikrosistemi

Kjučne besede: mikrosistemi, 3D pakiranje, MEMS, tehnologija SiP

Izvleček: Integrirani mikrosistemi so ključni členi pametnega okolja. Kažeta se dva pomembna trenda pri razvoju mikrosistemov : minaturizacija ter brezžično, oz. avtonomno delovanje. Pomembne sestavine takih avtonomnih brezžičnih pretvornikov so senzorska čitalna elektronika z majhno porabo reda velikosti nekaj mikrowatov in močnostne strukture MEMS, ki lahko proizvajajo energijo v razredu moči nekaj mikrowatov. Izvedbe mikrosistemov z volumnom blizu cm3 so že realnost s pomočjo integracije anten in silicijevih čipov v ustrezno tridimenzionalno ohišje. Cilj zmanjševanja volumna proti mm3 je dosegljiv s tehnologijo tridimenzionalnega pakiranja in izvedbe struktur RF in MEMS s tankoplastno tehnologijo. To področje je pravzaprav nadaljevanje IMECovih raziskav tehnologij povezovanja in pakiranja. V prispevku predstavimo CMOS združljivo tehnologijo s polySiGe materialom za izdelavo MEMS struktur nad končanim inegriranim vezjem. Predstavimo različne primere tehnoloških platform in zanesljivost izdelanih mikrosistemov. Taki izredno majhni sistemi so primerni za integracijo na upogljive in celo raztegljive podlage. V prispevku predstavimo tudi IMECova prizadevanja in njihovo umestitev v svetovne razmere in razvoj.

1. Introduction

It is expected that by the year 2010, technology will enable people to carry their personal body area network (BAN) /1/ that provides medical, sports or entertainment functions for the user. This network comprises a series of miniature sensor/actuator nodes each of which has its own energy supply, consisting of storage and energy scavenging devices (see Fig. 1) /2/. Each node has enough intelligence to carry out its task and is able to communicate with other sensor nodes or with a central node worn on the body. The central node communicates with the outside world using a standard telecommunication network infrastructure. This network can deliver services to the person using the BAN.

One of the main challenges is power. Power consumption of all building blocks of the wireless sensor node has to be drastically reduced to be compatible with energy densities achieved using energy scavenging. An upper limit of the scavenged power (e.g. using thermo-electric generation) is

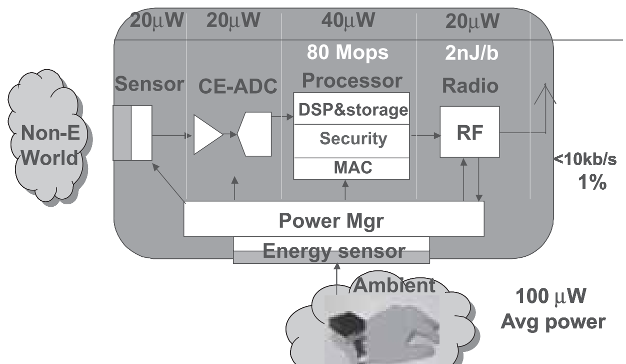

Fig. 1: Building blocks of the smart sensor environment: autonomously powered miniature wireless sensor module. The key ingredients and their tentative power budget are indicated: sensing, analog front-ends, local signal processing, bi-directional ultra-low-power radio, energy generation and management.

100uW but in practice, the average power scavenged will be even lower. The successful realization of this vision will therefore require innovative solutions to remove the power obstacles and bring down the power consumption of each component down below the levels indicated in Fig. 1.

Second, the overall size should be compatible with the required formfactor and take the shape of a small cube or of a smart bandaid. This requires new integration and packaging technologies. Figure 2 shows a schematic system integration roadmap and the need for wafer-level integration technologies to achieve overall volumes around 10mm^3.

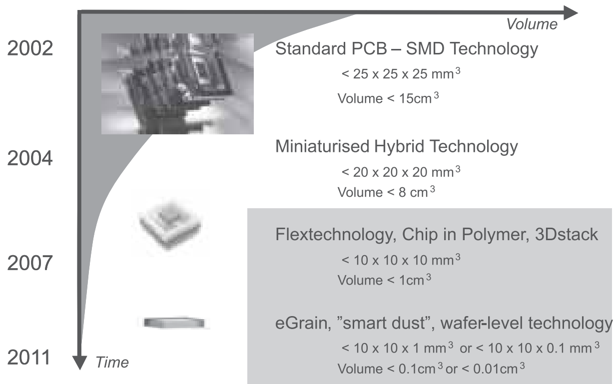

Fig. 2: System integration roadmap for the coming decade: the development of 3D System-in-a-Package technology, chip-on-flex technology, followed by full wafer-level 3D System-on-Chip integration. The latter will bring 2 orders of magnitude reduction in volume and enable smart unobtrusive autonomous sensor systems.

2. Wireless sensor systems-in-a-package (SiP)

One form factor suitable for many applications is a small cube sensor node. To this end, we have developed a generic and modular wireless sensor node in a cubic centimetre. Compared to standard PCB technology this leads to a volume reduction of a factor of 3…4 (Fig. 3),. In this so-called *three-dimensional system-in-a-package* approach (3D-SiP) /3/, the different functional components are designed on separate boards and afterwards stacked on top of each other through a dual row of fine pitch solder balls. This system has the following advantages: (i) modules can be tested separately, (ii) functional layers can be added or exchanged depending on the application, (iii) each layer can be developed in the most appropriate technology.

A

B

C

Fig. 3: (A) Wireless sensor module as miniaturized but conventionally-connectorized module or (B, C) as integrated 1cm^3 volume 3D stack. The dedicated folded dipole integrated antenna is located on top of the stack.

A key element was the development of a 14x14mm^2 electrically small antenna at 2.4GHz. Two 1.6mm standard FR4-layers were selected as base material for the 3D module and antenna as the use of a standard board-material reduces the module cost while allowing reasonable antenna properties at 2.4GHz. The antenna design required special attention as it directly influences the power consumption and range of the radio link. The design optimally uses the limited module volume to optimize the antenna bandwidth and efficiency. The antenna is therefore placed at the perimeter of the module by double-folding it around the RF transceiver. Shielding layers are inserted below the antenna to protect the low-power microcontroller at the bottom of the module from the radiated output power generated by the antenna. The antenna design takes the influence of the packaged transceiver and shielding layers and the effect of antenna placement on the human body into account.

A

B

C

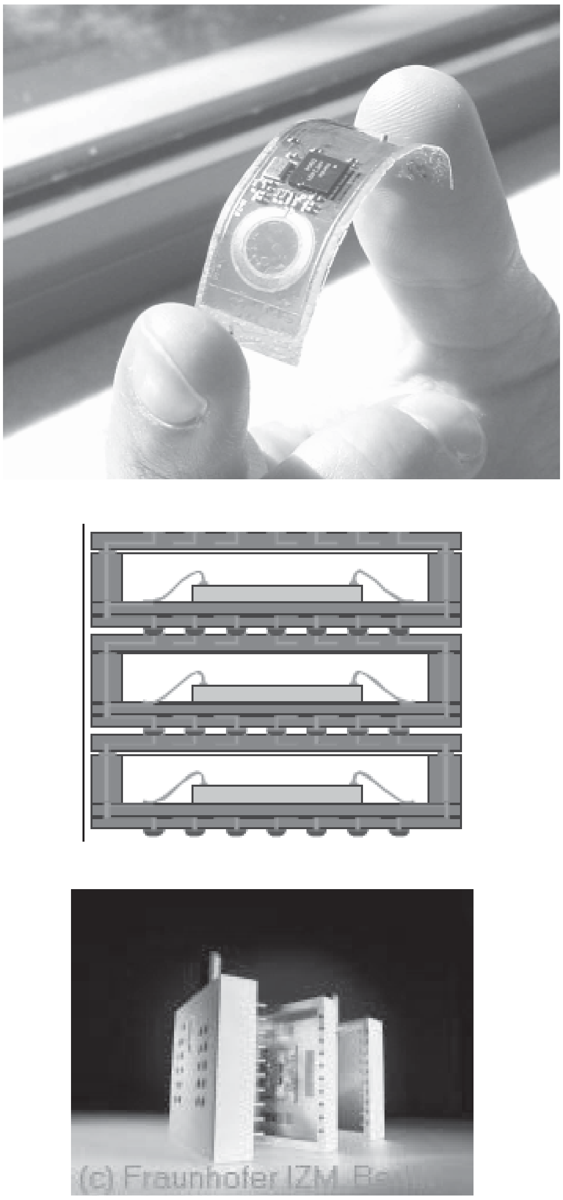

Fig. 4: (A) IMEC Wireless sensor module and as component on flex, featuring a loop antennas; (B and C) Sensor node building blocks of Match-X.

For wearable applications, a thinner embodiment may be desired, and a degree of mechanical flexibility is advantageous. We have integrated the same wireless functionality on a flexible substrate (Fig. 4), a so-called 2D SiP embodiment.

Using commercially available components, a network of the above 3D SiP was demonstrated where the sensors share a single communication medium (a radio-channel in the 2.4GHz band) /4/ The resulting average power consumption for long measurement intervals (minutes) , a single channel sensing of temp. w/io data processing, and in practical operating conditions, i.e. including the occurrence of synchronization errors, was 100µW.

Functional prototypes have also been demonstrated by other groups. The working group Match-X in the German Engineering Association VDMA developed another small but modular device (Fig 4). It consists of different building blocks, measuring 12.5x12.5 mm, each having a different functionality. A re-configurable sensor system has been developed at Philips under the name SAND (Small Autonomous Network Device), like the IMEC system, also around 1 cm^3.

Future research areas concern the physical packaging of the sensors, RF and processor, such that application specific parts can be added. The package should be small enough to fit in different types of applications specific packages for easy deployment.

3. Ultra low power sensor read-out: case study of biopotential measurement

EEG is a monitoring tool used by neurologists to measure the electrical activity of the brain and trace neurological disorders such as epilepsy. In hospitals, it is typically used during several days and involves hospitalization of the patient. A small-size, ultra low-power, and portable biopotential acquisition system capable of measuring the EEG, ECG, and EMG signals will not only improve the patient's quality of life but can also extend the device applications to sports, entertainment, comfort monitoring and etc.

Fig. 5a shows the architecture of an ASIC single readout channel configurable for extracting EEG (electroencephalogram), ECG (electrocardiogram), and EMG (electromyogram) signals. It includes an AC-coupled chopped instrumentation amplifier, a spike filtering stage, a constant gain stage, and a continuous-time variable gain stage, whose gain is defined by the ratio of the capacitors. Such circuit consumes 20µA from 3V. Equivalent input referred noise density of the circuit is 60nV/$\sqrt{Hz}$, and common-mode rejection rate of the channel is higher than 110dB while filtering 50mV DC electrode offset. The gain of the channel can be digitally set to 400, 800, 1600 or 2600. Additionally, the bandwidth of the circuit can be adjusted via the bandwidth select switches for different biopotentials. Figure 5b shows the extracted EEG, ECG, and EMG waves from the single-channel biopotential readout front-end and summarizes the measured results. This circuit has achieved the lowest reported power for the given high performance /5/.

The complete ASIC read-out has 8-readout channels, which are multiplexed at the back-end. Each channel of the ASIC is similar to the single channel biopotential readout front-end ASIC and optimized for EEG acquisition. In addition to single channel front-end, this front-end includes a bias generator circuit. The total current consumption of the circuit is around 100µA from 3V, including bias circuitry.

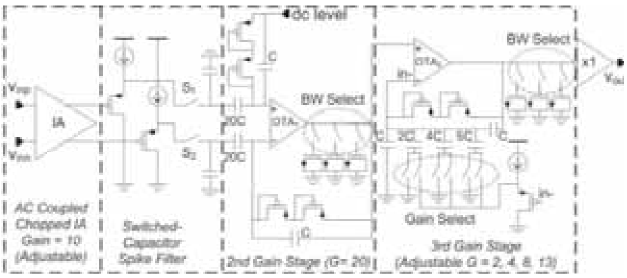

Fig. 5a: Schematic of a single channel biopotential readout

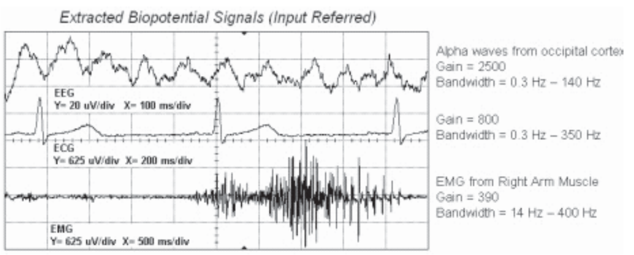

Fig. 5b: Extracted biopotential signals using the single-channel readout front-end.

4 Ultra-low power wireless communication

Ultra-low-power radios are an essential ingredient for body-area network sensors. These radios are providing the last meter connection from a central body-worn pda-like device to the sensor nodes. In short range wireless systems with low data rate, the baseline power dominates the dynamic power. This baseline power is strongly dependent on the chosen architecture. Low power radios such as Bluetooth and Zigbee cannot meet the stringent Wireless BAN power requirements.

The power budget in the sensor node and in the master device are also very different. The sensor has an extremely tight power budget, whereas the master has a slightly more relaxed power budget. In the air interface definition this asymmetry is exploited by shifting as much complexity as possible to the master device.

For these reasons we have chosen to make use of Ultra-Wideband modulation. This allows us to use an ultra-low-power, lowest-complexity transmitter and shift as much as possible the complexity to the receiver in the master. An UWB transmitter has been designed in 90nm CMOS, enabling a reduced power consumption (30pJ per 1GHz pulse) as well as a high frequency range including the 3-5 and 6-10GHz high UWB band. A corresponding receiver was designed in 0.18µm CMOS (Fig. 6). Next to the front-end components responsible for (low-noise) amplification and down-conversion, an analog approach of the base-band design was used.

Selecting accurately starting and stopping instants for the integration enables an excellent correlation with the transmitted pulse (0.94) while keeping a very low complexity thanks to delay-line based generation of multiple clock signals. On top of that, this analog matched filtering reduces the required sampling rate to the pulse repetition frequency (nominally 40MHz) while other systems require GHz sampling with problems of clock generation and ADC power consumption.

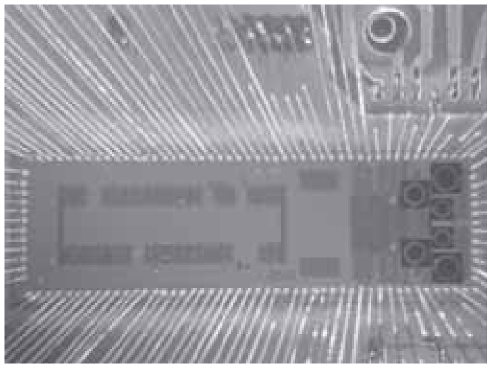

Fig. 6: UWB receiver ASIC. /6/

Fig. 7: Thermoelectric bracelet plus flex on which the radio and the sensor electronic are implemented.

5. Micropower generation

While modern electronic components become smaller and smaller, the scaling down of traditional batteries faces technological restrictions. For this reason a worldwide effort is ongoing to replace batteries with better performing, miniaturized power sources. For devices with relatively high power consumption the advantage is made by using fuel based power systems, as fuel has a much higher energy density than batteries. Examples of these systems are microturbine /7/, micro fuel cells /8/, microcombustor /9/. Low power applications, like, for example, the sensor node of a wireless sensor network, might benefit instead from generators that harvest wasted ambient energy. These so-called *energy scavengers* exploit energy sources like light, temperature or mechanical vibrations. The generated power strongly depends on environment conditions. In the majority of the cases, it is sufficient to fulfil the average power demand of a micro-device, but it can hardly handle the power peaks occurring during operation (e.g. the power needed for wireless data transmission in a sensor node). For this reason a storage device, as a supercapacitor or a rechargeable battery, will still be needed. The dimension of the power storage device will be anyhow smaller than the primary battery necessary to power the system without the contribution of a scavenger; furthermore the system will be capable to operate unattended for a very long time. IMEC is developing thermal scavengers for human body applications /10/ and vibration scavengers for industrial applications /11/. In both cases the target power is in the 10-100 µW range for systems having a footprint of a cm^2. A 100 µW device will generate in a few months the same energy contained in a primary lithium battery of the same dimensions.

In this contribution we focus on thermal energy scavengers. Thermal energy scavengers exploit the Seebeck effect to transform the temperature difference between the environment and the human body into electrical energy. As this temperature difference is low the development of such scavengers is not straightforward. This problem is amplified by the fact that the thermal resistances of the body and of the air are much larger than the one of the thermoelectric element, further reducing the useful temperature drop that it experiences. A sizeable power can be obtained only by means of an efficient thermal design. During the last years IMEC has improved performances and decreased dimensions of this type of thermo-electric generators for human body application. Generators are mounted on a bracelet and closely resemble to a wristwatch in terms of weight and dimensions (see Fig. 7). The prototype delivers 150µW when worn on one's wrist. A flexible wireless sensor module especially developed is attached to the strap and powered by the thermoelectric generator, which was sufficient to feed a sensor node which can transmit simple quantities (like heart beat or body temperature) with a sample frequency of 0.5 Hz.

The heart of the bracelet is a custom made, commercial bismuth telluride thermoelectric block, consisting of about 3000 thermocouples. The large cost of this block makes impossible the penetration of this device in a large consumer market. A possibility of cost reduction resides in the use of batch fabricated MEMS thermoelectric generators. Micromachined thermopiles are not new in the scientific literature, and are used, e.g., in miniaturized commercial thermoelectric coolers /12/. Micromachining has the potential advantage of scaling down the lateral size of the thermocouple thus increasing their surface density. Unfortunately, at the same time, the thermocouples height is reduced to a few micrometers only. This drastically decreases the thermal resistance of the generator, the temperature drop on the device becomes very small and the generated power becomes negligible. In order to overcome this difficulty, IMEC has developed a special design of a micromachined thermoelectric generator for application on humans, which combines a large thermal resistance of the device with a large number of thermopiles. The schematic is shown in Figure 2a. Several thousands of thermocouples are mounted on a silicon rim. The function of this rim is to increase the overall thermal resistance between the hot and cold side of the generator. If Bi_2Te_3 is used as thermoelectric material an optimized device fabricated according to this scheme and positioned on the human wrist can generate up to 30 $\mu W/cm^2$. Fig. 8 show a realization of such a device based on SiGe thermocouples. Because of the inferior thermoelectric properties of this material with respect to Bi_2Te_3, an optimized device is expected to generate 4.5 $\mu W/cm^2$.

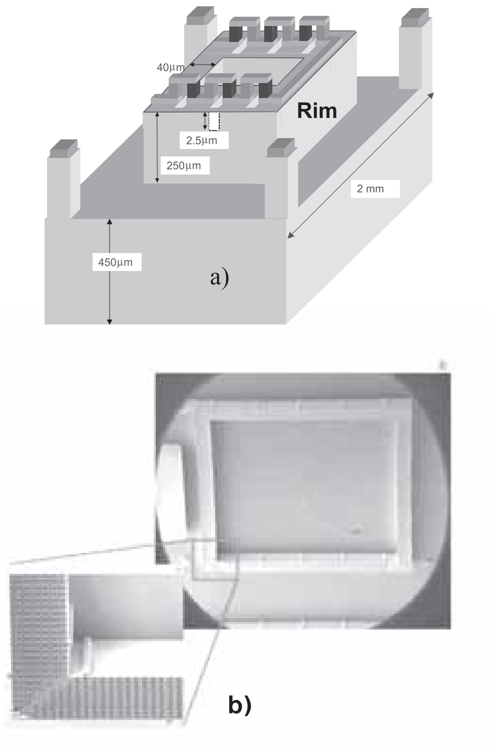

Fig. 8: Schematic (a) and an implementation (b) of MEMS thermopile for use in human body applications

6 Above-IC MEMS

MEMS components provide miniaturized sensing functionality to integrated microsystems.. Ultimate miniaturization requires the MEMS component to be monolithically integrated with electronic circuits, by post-processing MEMS on top of the electronics. However, post-processing restricts the available thermal budget for MEMS processing.

Poly-SiGe provides the desired mechanical and electrical properties for MEMS applications at significantly lower temperatures compared to Poly-Si (≥ 800°C). This is made possible using poly-SiGe as the MEMS structural material. The poly-SiGe material is very comparable to the poly-Si used for surface micro-machining, except that it can be processed at much lower temperatures.

The use of poly-SiGe for processing MEMS above CMOS has been described /13/. Within the SiGeM project an integrated gyroscope with dedicated MEMS and ASIC designs targeted for low-noise, high-resolution applications (0.015degree/sec for 50Hz bandwidth) was demonstrated (Fig. 9). The CMOS used is a high voltage (20V) 0.35µm commercial double poly CMOS process with five wiring levels and 500nm Si-oxide/Si-nitride passivation. It was also found that poly-SiGe is, as expected, a very reliable material exhibing no creep (tested 20 days) or fatigue (tested 1.6E10 cycles) over the duration of the tests done, making it an excellent MEMS structural layer.

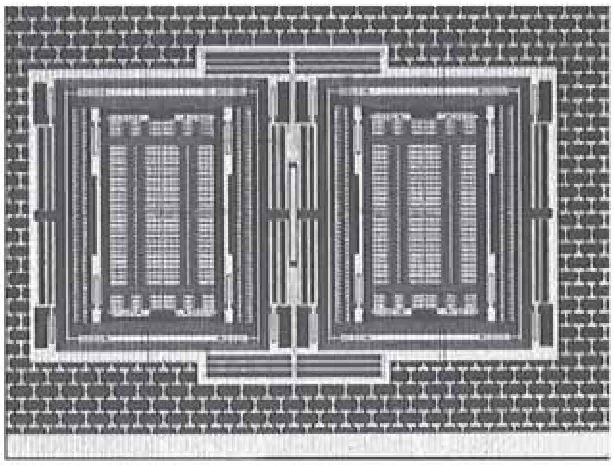

Fig. 9: Optical microscope picture of free standing SiGe gyroscope processed above CMOS.

The use of poly-SiGe is envisioned for many more above-IC applications. Other interesting applications are accelerometers, resonators, micromirrors etc. The poly-SiGe material is also suited for use as a *thin-film* cap - thus reducing the total thickness of the MEMS device – including the cap - to less than 50 um.

7 Roadmap for further integration

While today's 3D-"System-in-Package" integration is limited to relatively low packaging density, it is the most mature technology and already available in high volume production. Further scaling requires altogether different platforms: dies and wafers will be thinned and stacked on one another. This is referred to as 3D- Wafer Level Packaging (WLP) technology. Using fully finished wafers as a starting material, which are further processed by techniques such as wafer thinning, flip chip bumping, and deep anisotropic Si-etching (Fig. 10) 3-D electrical connections can be realized at the wafer level with very high-density.

A

B

C

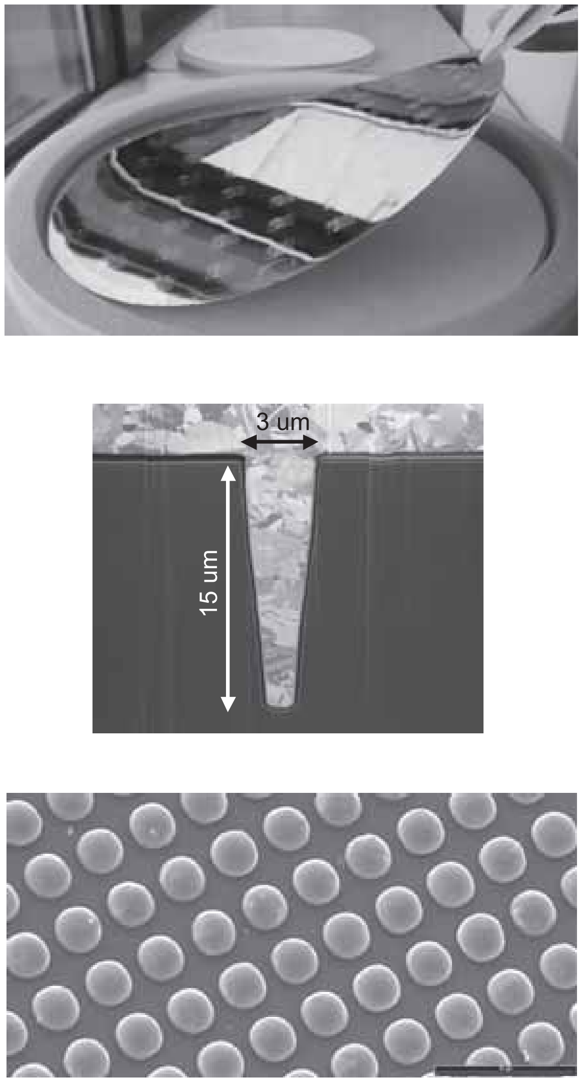

Fig. 10: Ingredients of 3D Integration technology that will enable further microsystem integration: thinned wafers (A), micro-via holes (B) and 7 micron In bumps on 10 micron pitch. (C)

Again two different form factors are developed: die stacking and thin chip embedding. In die stacking technology, through wafer vias are realized using deep reactive ion etching, conformal dielectric deposition, and (partial) filling using electroplated Cu. This via process is carried out before or after wafer thinning to a final thickness of 50 – 100 micron. After dicing, the dies are flip-chip assembled using solder or an intermetallic compound as the electrical interconnect. In the die embedding flow, the wafers are thinned down to 10…20 µm, and subsequently transferred to a host substrate. The electrical interconnection is realized by MCM processing using thick dielectric layers and Cu electroplating. Both methods allow vertical interconnect densities of 10 – 20 per millimeter and 100 …500 per square millimeter.

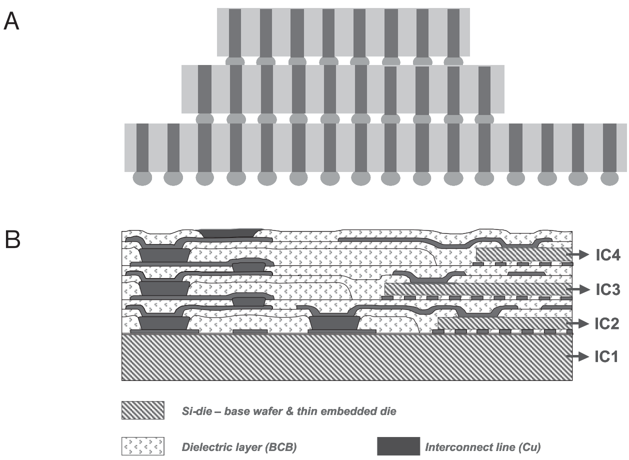

Fig. 11: Different interconnect approaches for 3D-WLP: using through wafer vias and bump interconnects (A), and thin chip embedding (B).

Research in the area of integration is also oriented to stretchable embodiments of wireless sensor nodes as stretcheability and bendability are required in many applications "on-and-around-the-body". Silicone is a suitable carrier material in view of his high stretcheability and biocompatibility, and can be processed by various means including thin film technology. Based on FEM modelling, metal tracks embedded in such a silicone matrix can be designed to stay functional upon more than 50 % stretching. (Fig. 12)

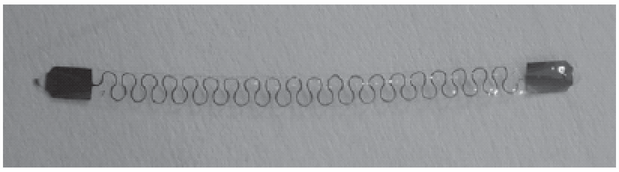

Fig. 12: Stretchable metal conductors integrated in a silicone "wire" /14/.

8. Conclusion

The revolution that has started in sensor networks will bring about truly autonomous, highly miniaturized, multiparameter sensing. This paper gave an overview of autonomous sensor research at IMEC and worldwide. Several working prototypes have been discussed, such as micropower generation devices and a 1cm^3 low-power wireless sensor node. This modular wireless 3D stack is now used as a platform for the integration of future developments (sensors and actuators, energy scavenging devices, ultra-low-power local computing and transceiver) in order to realize fully integrated, autonomous ultra-low-power sensors nodes for body area networks. Cost reductions will broaden commercial applications from fitness and medical to automotive, consumer, building… New integration technologies are key in order to reduce system size beyond today's System-in-Package technology. Future technology directions using poly-SiGe MEMS and 3D –WLP technologies were indicated.

9. Acknowledgments

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