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3D Heterogeneous Integration for Nanosensor Systems – the EU-Project e-BRAINS

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Abstract

A few examples of innovative nanosensors for gas detection and biofludic applications have been successfully implemented and heterogeneous integrated within the European e-BRAINS project showing efficient miniaturization and extremely low detection limits (5 ppm).

1. Introduction

3D integration is recognized as a key technology for heterogeneous products, demanding for smart system integration rather than extreme high interconnect densities. According to surveys on revenue forecast by Yole Developpement such "More than Moore" products, as heterogeneous MEMS/IC systems, may even be the main driving markets for 3D-TSV integration. Many R&D activities worldwide are focusing on heterogeneous integration for novel functionalities [1]. Corresponding 3D integration technologies are still in evaluation at several companies and research institutions, such as the European "e-BRAINS" consortium, with a dedicated focus on reliability issues of such sophisticated heterogeneous products [2].

There are significant advances for integrated MEMS systems using 3D integration technologies. By 2020, Yole Developpement predicted: "it is likely that MEMS fabs will have developed internal standard process blocks but it will be fab-specific standard tools." [3]. There have been many publications describing the combination of CMOS with MEMS. CMOS MEMS is likely to be restricted to very specific applications where MEMS arrays will need very close electronic processing. For all other case, it will depend on MEMS product cycle time, flexibility, cost, integration, market demand and power consumption. However, with the development of TSV technology, for a few applications "…users are willing to pay the higher cost to get the better performance and smaller size from the shorter connections. Yole projects demand for MEMS with 3D-TSV will reach several hundred thousand wafers a year by 2015." [3]. With the maturity of 3D technologies, more 3D integrated CMOS-MEMS products will be developed with low cost.

Moreover, as shown in Fig. 1, heterogeneous integration technologies have being developed for functional diversification systems (More than Moore) [4], i.e., integration of CMOS with other devices, such as analog/RF, solid-state lighting, HV power, passives, sensors/actuators, biochips and biomedical devices. This heterogeneous integration started with system-in-packaging technology, and is expected to evolutionally move to 3D heterogeneous integration with TSVs and wafer bonding.

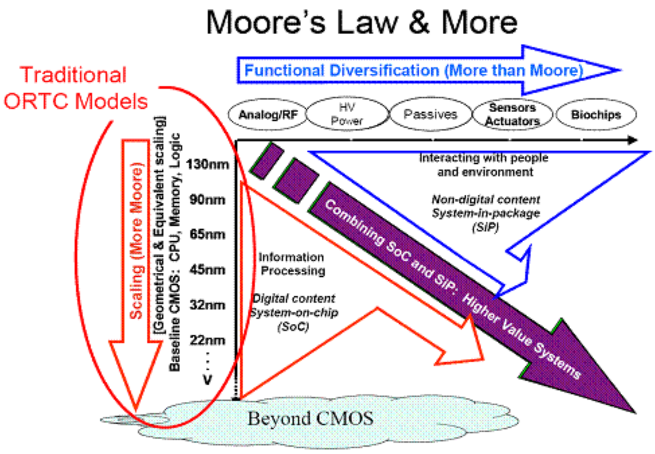

Fig. 1 Beyond Moore´s law [4].

On the other hand, in recent years, the application area of biosensors has experienced substantial growth with the global biosensor market estimated to exceed $14.42 billion by 2016. The emerging trend for point-of-care instrumentation is driving the development of miniaturized systems capable of reliable and rapid quantification of a wide range of biomolecules. Detecting low concentrations of glutamate, glucose, DNA molecules or toxic gases such as CH_4, CO_x, NO_2, SO_x are of great interest for the society and the coming market. Innovative nanosensors fabricated within e-BRAINS project have been designed to address these applications and their functionality and heterogeneous integration have been successfully demonstrated.

At follows four of the most relevant e-BRAINS nanosensors are presented; 3D vertically stacked silicon nanowires (SiNWs) FET and smart biosensor grain for biofluidic applications, and CNT and NW-based gas sensor.

2. Integrated nanosensors for biofluidic applications

Determination of specific DNA sequences in biological samples can lead to detection and identification of infectious, inherited diseases, genetic disorders or cancers. An early detection is only possible by measuring ultra-low concentrations which has been the motivation of e-BRAINS to design novel sensors based on 3D SiNWs FET structures with significantly enhanced sensitivity or fully integrated as the “smart biosensor grain”.

3D vertically stacked SiNWs FET

The sensor with unique sensitivity and excellent gate coupling (SS=75 mV/dec) has been successfully fabricated to be integrated within a liquid biosensor heterogeneous environment using a differential ISFET/REFET pair circuit. The large intrusive external reference electrode is avoided and efficient miniaturization is achieved. Streptavidin has been sensed [5] and two DNA-biomolecule immobilization methods have been tested as functionalization to determine the highest oligonucleotide binding affinity.

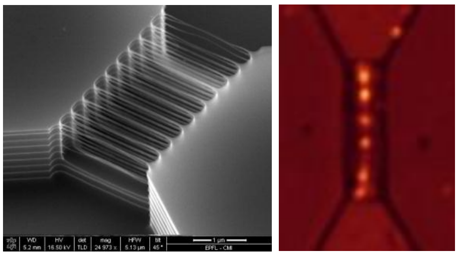

Fig. 2 Left: SEM of 7x20-array SiNW. Right: CLSM of NW-area after immobilization of DNA-biomolecules.

Smart biosensor grain

A fully integrated magnetoresistive (CMOS-TMR) sensor is developed with an RF-chip/antenna for a wireless data transfer between the disposable bio-chip and the analyzer. This allows realizing a system, which exhibits a high degree of miniaturization, speed and simplicity, both in the microfluidic cartridge as well as the accompanying instrument through 3D-heterogeneous integration [6].

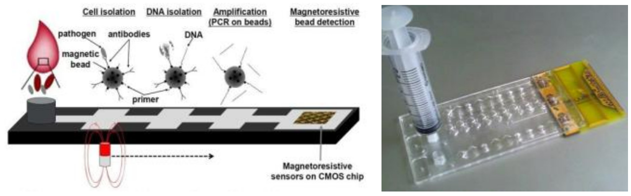

Fig. 3 Up: Schematic drawing of the transport principle based on functionalized magnetic beads and the microfluidic cartridge (produced together with Microfluidic ChipShop GmbH) with PCB including the TMR-CMOS chip.

3. Integrated nanosensors for gas detection

Gas sensing is an upcoming technology that will penetrate various aspects of daily life, provided their performance within the size and prize constraints satisfy the application requirements. High sensitivity gas sensors have been conceived using integration technologies of e-BRAINS to develop ambient, flexible and stable nanosensors with high levels of performances, selective detection and possibilities of integration to other systems. The devices are primarily intended for environmental monitoring purposes and target detection of gases such as CH_4, CO_x, NO_x, SO_x.

CNT-based gas sensor

Carbon nanotube (CNT) based gas sensor has been first experimental demonstrated via a selective and directional catalytic horizontal growth process performing dense CNT arrays in-situ and at the wafer-scale. Proof of concept of this novel, high throughput CNT integration method is given by conductance-based gas sensors which were electrically tested. A CNT array resistivity of $5.3 \cdot 10^{-5}$ Ω.m was extracted and conductance responses to various gases such as NH_3, H_2, NO_2 and relative humidity were measured with detection limit as low as 5 ppm [7].

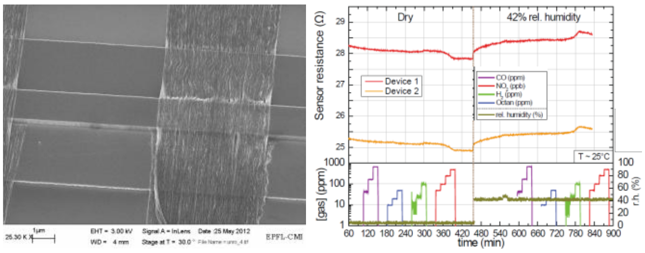

Fig. 4 SEM image and conductance variation of CNT-based gas sensor under different gases and relative humidity (bias at 50 mV).

Optical gas sensing

The small form factor of solid state vertical nano wires gas sensors is combined with the high selectivity of optical gas detection for the first time worldwide. Vertical NWs forming a photonic structure is a key element in reducing the dimension of the optical absorption path which has strong dependence on the detection limit and accuracy. Compact sensors are achieved by integrating the hardware with the temperature and current drivers, signal acquisition and communication module which surpass existing cost/performance/size levels by 2 orders of magnitude [8].

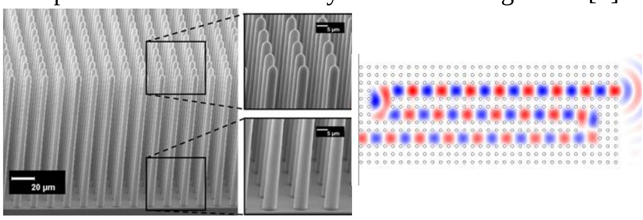

Fig. 5 Left: SEM picture of poly-Si rods on a-Si substrate (aspect ratio of 1:25). Right: Photonic crystal light interaction schematic.

3. Conclusions

3D integrated highly sensitive Si NWs, rods, CNT and magnetoresistive sensors were successfully tested for DNA/ streptavidin biofluidic sensing and optical/ conductance gas detection.

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