Nanonets2Sense Project

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Nanonets2Sense develops a new technological approach for the 3D CMOS integration of label-free sensors for medical applications.

This technology is based on nanonets, another name for random networks of nanowires. Indeed, nanonets feature all the advantages of thin crystalline nanowires in terms of electrical properties, while being suited to the fabrication of devices by standard, low-cost, microelectronic technologies.

Two model molecules will be used to evaluate the potential of this technology for applications like breath analysis for diabetes monitoring, and circulating tumour DNA detection for cancer monitoring. While the potential applications are clinical, the research carried out in the project is technology focused. The project coordinator FMNT is already making and studying nanonets. Now the researchers must determine whether the nanonets can be integrated onto CMOS circuits in a way that meets stringent compactness, efficiency, and cost demands.

www.nanonets2sense.eu

Consortium

A strong consortium, with partners of perfectly complementary expertise, has been built. It includes two academic partners (FMNT in France and KTH in Sweden), a foundry and large company in the field of sensors (ams AG in Austria), an SME working on gas sensing (ams Sensors UK Limited), and the European Sinano Institute.

ams Sensors UK Ltd

Private limited Company

- Micro hot plates for gas sensing
- Demonstrator for acetone in breath

Grenoble INP/FMNT

Academic Lab

- Project coordination
- Nanonets fabrication
- Bio-functionalization of nanonets
- Device characterization and modelling

SINANO Institute

European Nanoelectronics Association

- Management
- Dissemination

KTH Royal Institute of Technology

Academic Institute

- CMOS compatible process development
- Circuit design
- Demonstrator for biosensing

ams AG

Large Foundry

- Wafers fabrication with dedicated CMOS readout
- Exploitation of results

Prepared by Pascale Caulier (SINANO Institute), Communication Manager.

Nanonets2Sense Newsletter

N°2 - AUGUST 2018

Highlights of Nanonets2Sense results at ESSCIRC-ESSDERC 2018 Workshop

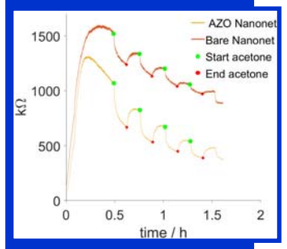
CONTENT:

The trend towards point-of-care monitoring is growing rapidly, as a complement to high precision techniques available in central laboratories. The aim is to provide patients with the ability to have the level of specific biomolecules checked by a doctor or by a nurse, or even by themselves depending of the degree of technicity required for device use and measurement interpretation. One example is the detection of circulating micro ribonucleic acid (m-RNA) strands that are release by cancerous tumours during treatment. Point-of-care monitoring of such molecules could allow a more reactive follow-up of tumour evolution, more personalized treatments, the use of smaller doses, and hopefully lead to a better care for the patients. Another example of application is the monitoring of chronic diseases with easy and non-invasive follow-up of the evolution of some key biomarkers. The technology required for such use should be robust and cheap.

Si nanowire-based biosensors integration with CMOS, P.-E. Hellström

Silicon nanowires can be used for charge based, label free detection of charged molecules such as DNA or RNA. Integration of Si nanowires with CMOS electronics would enable a low cost, compact biosensor with potential in point-of-care applications. Uniform single crystalline silicon nanowires is commonly defined in the Si device layer of an SOI wafer using optical lithography with self-aligned double patterning or e-beam lithography. Integration with CMOS requires process adaption of a SOI based CMOS process in order to define Si nanowires and allowing access to the Si nanowires from the top surface of the die. However, conventional bulk CMOS technology without process changes could be used in connection with low temperature post-processing of Si nanowires after fabrication of the CMOS circuits. In the Nanonets2Sense project, Si nanowires is grown on Si substrates and a random network of Si nanowires, so called Si nanonets, is transferred onto wafers with pre-processed CMOS circuits. Several integration challenges, imposed by the constrains from nanonet processing and fabricated CMOS wafers, has been addressed. Si nanonet processing requires etching in hydrofluoric acid and annealing at 400 °C to cross-link Si nanowires in the nanonet. Electrical contacts between Si nanonets and CMOS top level metal has to withstand nanonet processing and achieve adequately low and reliable contact resistance. Furthermore a back-gate with a dielectric, resistant to hydrofluoric acid and thin enough to enable threshold voltages within the 1.8 V supply voltage in ams 0.18 µm CMOS technology is mandatory for successful integration. Ni was evaluated as contact material to Si nanonet since NiSi can form at temperatures below 400 °C . Ni was confirmed to withstand buffered hydrofluoric acid etching and RTA anneals at 400°C. However, poor adhesion of Ni after Si nanonet transfer was found and resolved by introduction of a TiW liner. To contact W vias on the top of the CMOS wafer TiN was employed and a resistance of 3 Ω/contact was measured. The TiN layer also formed the back gate electrode. ALD 10 nm SiO_2/15 nm HfO_2 stack was used as gate dielectric, on top of the TiN back gate electrode, and excellent resistance to buffered hydrofluoric acid etching was found. Processes for patterning of HfO_2 and Ni was established using SiO_2 hard masks and Ar ion milling. The post-processing scheme was confirmed on wafers with top metal level fabricated at ams. Electrical measurements confirm leakage current <100 pA between back-gate and source/drain areas. Finally Si nanonet transfer was successfully performed on the wafers and Si nanonet pFET electrical characteristics has been measured.

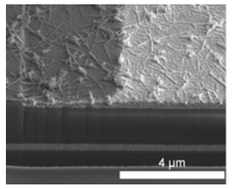
Chemiresistors for breath analysis C. Zuliani and J. Luque



Breath acetone is an important biomarker which has been linked to glucose-related metabolic disorders such as diabetes.

CMOS-based chemiresistors have received considerable attention as miniaturized and low-cost gas sensors and in this regard hold the potential to transform the field of diagnostics. However, specificity and response/ recovery time are still two major unresolved hurdles which need to be overcome for deploying this technology in the breath-analysis field. In this regard, the ZnO nanonets (NN) may afford a solution in terms of sensing material suitable for detecting low concentrations of gases and for decreasing the response/recovery time thanks to their large surface to volume ratio.

Nanonets were deposited on back-etched CMOS-wafers which have an embedded microheaters in order to control the operational temperature of the chemiresistors. A FIB-cross section of the devices after the NN deposition is shown below



Following this step, wafers were diced, packaged and tested towards acetone. In particular, two types of materials were assessed: bare and aluminum doped-ZnO (AZO) passivated ZnO nanonets. The passivation was carried out with the aim of stabilizing the electrical performances of the nanonets. The passivated devices were more conductive than the bare ones because of the AZO film. Both NN types responded to exposures of 1.5ppm acetone when microheater operated at 400 °C. Significantly, the sensors coated with the AZO-passivated nanonets showed more stable responses upon multiple exposures of acetone as shown on the left. Other passivation layers for the ZnO NN have been developed and are currently under testing

Low-power readout for threshold voltage S. Rodriguez

The development of nanonets-based FET sensors that can be integrated on the top of commercial CMOS processes opens a myriad of opportunities. Threshold voltage variations due to the presence of a particular molecule can be efficiently detected with almost no power consumption when the nanonet FET sensors are operated in weak inversion (subthreshold). This is an important characteristic, for instance, for handheld, battery-operated point-of-care devices.

We have exploited this characteristic and designed a readout solution for nanonet FETs which is based on a single analog mixed-signal ASIC. This integrated circuit includes 32 nanonet-FETs which are distributed in 4 groups around the chip (figure). Each nano net FET sensor can be individually selected and its threshold voltage can be extracted by forcing different drain-source DC currents while measuring gate-source voltages. Complete DC curves for a single device can be extracted in around 20 ms, therefore, allowing very fast measurements.

The ASIC is designed in 180 nm CMOS AMS process, is powered at 1.8V, and consumes only a few µA during normal operation. The whole ASIC including the nanonet FETs has a total size of 7 mm x 7 mm. The readout CMOS circuits (inset at the bottom) occupy around 1 mm x 0.35 mm and contain an analog front-end including current DAC converters, amplifiers, buffers, analog multiplexers, etc. Furthermore, the ASIC integrates a considerable portion of digital circuits for configuration, self-test, and external control by means of a 2-wire serial communication interface.

The ultra low-power ASIC including nanonet FET sensors can be easily integrated in a small handheld medical system including wireless connectivity, user interface, etc. Accordingly, it opens new clinical opportunities for diagnose and control of various medical conditions.

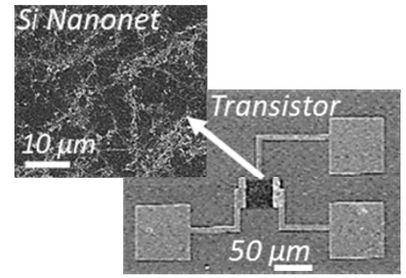
Engineering of Si and ZnO nanonets for the fabrication of functional devices C. Ternon

Thanks to an intense work and a fine understanding of the phenomena, we demonstrate that a good management of nanowire/nanowire junctions and of nanonet surface states make these random nanowire networks (nanonet) strong candidates for various applications.

For the ZnO nanonets, the second year of the project was extremely rich and provided solutions to previous issues concerning material instabilities: one concerning the integrity of the material during the integration processes and the other concerning the electrical properties of ZnO devices when exposed to air. Various approaches have been carried out to improve the properties of ZnO nano nets and, as a result, we have developed a technology that meets the project's objectives. This technology allows the integrity of the material to be maintained throughout its integration into functional devices, whether resistors or transistors. Furthermore, device sensitivity to acetone is preserved and our process is also suitable for the fabrication on top of micro-hotplates which are developed by ams UK Ltd.

For silicon nanonets, the integration process into transistors has been further improved. Notably, the nanonet surface treatment helped reducing charge trapping by minimizing defaults and interface states. It allowed obtaining highly performant and reproducible transistors (Figure). With 30 µm long-channel devices, an On-Off ratio up to 10^5 and good sub-threshold slope around 1V/dec were reached. Such performances are highly comparable with single SiNW device ones which were reported in literature.

Our last results on ZnO and Si nanonets – both material and devices – demonstrate their great interest for electronic applications. From the perspective of the "More-than-Moore" approach, we believe that these major technological breakthroughs can push the boundaries of NW-based devices and open a wide application range.



Characterization and modelling of Nanonet-based FETs in the presence of percolating effects T. Cazimajou - G. Ghibaudo

We investigated the current-voltage transfer characteristics of percolating Silicon P-type Nanonet FETs operated in back-gated transistor mode, for future use as gas or biosensors. It was found that a Lambert-$\mathcal{W}$ function based compact model could be used for parameter extraction of electrical parameters such as apparent low field mobility, threshold voltage and subthreshold slope ideality factor. Their variation with channel length and nanowire density was analysed. It was found consistent with the change of conduction regime from direct source/drain connection by parallel nanowires to percolating channels. The experimental results were interpreted to some extent by the influence of the threshold voltage dispersion of individual nanowires. In order to better understand the experimental results, we developed a numerical program solving the electrical conduction in a randomly distributed gate-voltage controlled resistance network, which emulates the transport in NN-Field-Effect Transistors. Our numerical simulations systematically accounted for the percolation in such nanonets FETs. They enabled the calculation of the current-voltage characteristics with account for NW transport parameters and the probable presence of a contact resistance at the junction between nanowires. Simulation results were consistent with main experimental trends. This model will be further used to analyse NN-FET biosensors operation.