Switch-matrix-based Monolithic CMOS Platform Featuring a Large Array of Carbon Nanotube Sensor Elements and a 96-channel Readout Circuitry

Author(s):
Dudina, Alexandra; Seichepine, Florent; Chen, Yihui; Stettler, Alexander; Hierlemann, Andreas; Frey, Urs

Publication date:
2016

Permanent link:
https://doi.org/https://doi.org/10.3929/ethz-b-000127910

Originally published in:
Procedia Engineering 168, https://doi.org/10.1016/j.proeng.2016.11.305

Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 168 (2016) 916 – 919

Procedia Engineering

www.elsevier.com/locate/procedia

30th Eurosensors Conference, EUROSENSORS 2016

Switch-matrix-based Monolithic CMOS Platform Featuring a Large Array of Carbon Nanotube Sensor Elements and a 96-channel Readout Circuitry

Alexandra Dudina[a, b] *, Florent Seichepine[b], Yihui Chen[a], Alexander Stettler[a], Andreas Hierlemann[a], Urs Frey[a, b] †

[a]*ETH Zurich, Department of Biosystems Science and Engineering, Basel, Switzerland*
[b]*RIKEN QBiC, Kobe, Japan*

Abstract

We present a monolithic CMOS biosensor system comprised of a switch-matrix-based array of carbon nanotube field-effect transistors (CNT-FETs) and an associated readout circuitry. The switch-matrix allows for flexible selection and simultaneous routing of 96 sensor elements to the readout channels. The resistances of the CNT-FETs were measured by applying a constant voltage and measuring the resulting current. Variation of the first-stage-amplifier gain and bandwidth allows for measuring resistances in the range between 50 kΩ and 20 MΩ at a bandwidth of up to 20 kHz. A parallel integration of the CNT-FETs has been achieved by using a floating electrode dielectrophoresis (DEP) manipulation technique.

Peer-review under responsibility of the organizing committee of the 30th Eurosensors Conference

Keywords: CNT-FETs, dielectrophoresis, switch matrix, CMOS readout

1. Introduction

Rapid measurements using CNT-FETs as sensing elements can provide new insights into biomolecular functions,

* Corresponding author. Tel.: +41 61 387 33 14;
E-mail address: alexandra.dudina@bsse.ethz.ch

Peer-review under responsibility of the organizing committee of the 30th Eurosensors Conference
doi:10.1016/j.proeng.2016.11.305

dynamic processes and transient states that are invisible to conventional measurements [2]. The CNT-FET sensing mechanism is similar to that of ion-sensitive FETs, namely the effect of the chemical environment on the open gate of the CNT-FET [3]. One important issue in the design of nanoscale sensor arrays is the low-noise readout circuit, which should be located in close proximity to the sensor in order to reduce parasitic capacitances of the connecting wires. A potential problem of nanoscale devices is the variation in sensor properties. For that reason it is beneficial to have large sensor arrays that allow for obtaining data from many sensors with statistical significance.

Nomenclature

CNT-FET	Carbon Nanotube Field-Effect Transistor
DEP	Dielectrophoresis
SPI	Serial Peripheral Interface
DAQ	Data Acquisition

2. System design

A schematic view of the implemented system is shown in Fig. 1. It includes a sensing array of 9,216 CNT-FETs within an area of 2.2x1.4 mm^2 and a density of 2,993 CNT-FETs/mm^2. A matrix of switches, controlled by SRAM cells, is located underneath the array and allows for selecting and routing of CNT-FET sensors in a row or block (8x12 sensor elements) mode.

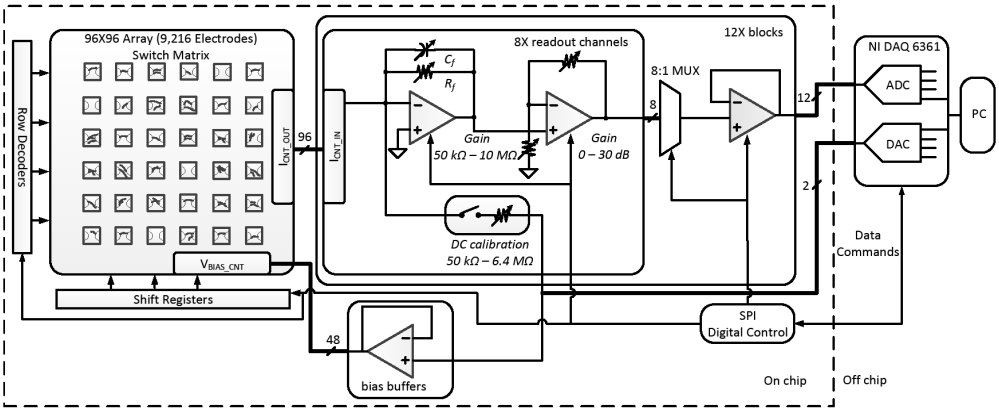

Fig.1 Bock diagram of the designed system.

Each configurable readout channel is composed of two stages. The first stage is a transimpedance amplifier (TIA), which converts the change in the current through the CNT-FETs sensors to an output voltage change. The programmable feedback gain (from 50 kΩ to 10 MΩ) of the TIA allows for input current measurements between 5 pA and 10 µA at a bandwidth of up to 20 kHz and a resolution of 12 bits. Each channel has a dedicated digital block, which allows for the independent gain selection for each channel. The second stage is a variable-gain amplifier. It provides additional gain (from 0 to 30 dB at 6 dB steps) and limits the bandwidth to prevent aliasing. The output of every channel is multiplexed to the output buffers, and, finally, the data are digitized by an external ADC (National Instruments data acquisition card 6361). The low-noise bias buffers provide bias voltages to the CNT-FET sensors. The operational amplifiers for the bias buffers, the 1st and 2nd stage of readout channels were implemented using a two-stage, folded-cascode architecture with a rail-to-rail input stage and a class-A output stage. This provides low-noise characteristics and good driving capabilities of the circuit. An SPI interface, clocked at 20 MHz, is implemented to provide configuration settings for the array and the readout channels.

3. Fabrication

The CMOS chip has been fabricated in 0.18-µm-CMOS technology and the overall chip real estate is 6.4x3.0 mm^2. The chips has been post-processed to feature pairs of platinum microelectrodes on the sensing area. Fig. 2 shows a micrograph of the fabricated chip.

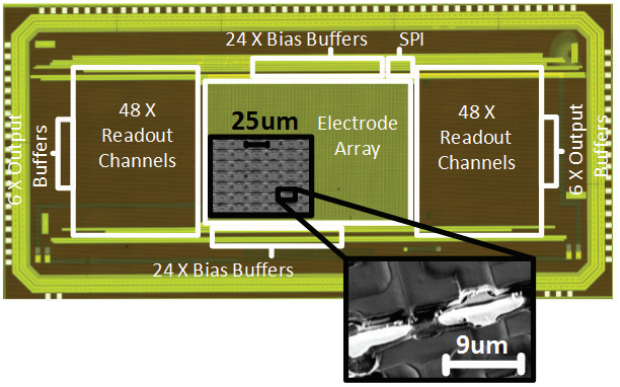

Fig.2 Chip micrograph and inset showing two electrodes with integrated CNTs.

The CNT-FET sensors were integrated by using a floating electrode DEP manipulation technique [1].

4. Results

The chip was glued onto a printed circuit board (PCB) and epoxy was used to seal the bonding wires. The acquisition board controlled by a LabView interface was designed to provide all reference voltages, to configure the chip and to read out the data. Firstly, the electrical characterization of the chip was carried out. Fig.3 shows the results of the gain and noise measurements. The largest measured feedback gain is equal to 171 dBΩ, for which the achieved noise performance of the readout channel is 1 pA_{rms} for a bandwidth of 1 kHz.

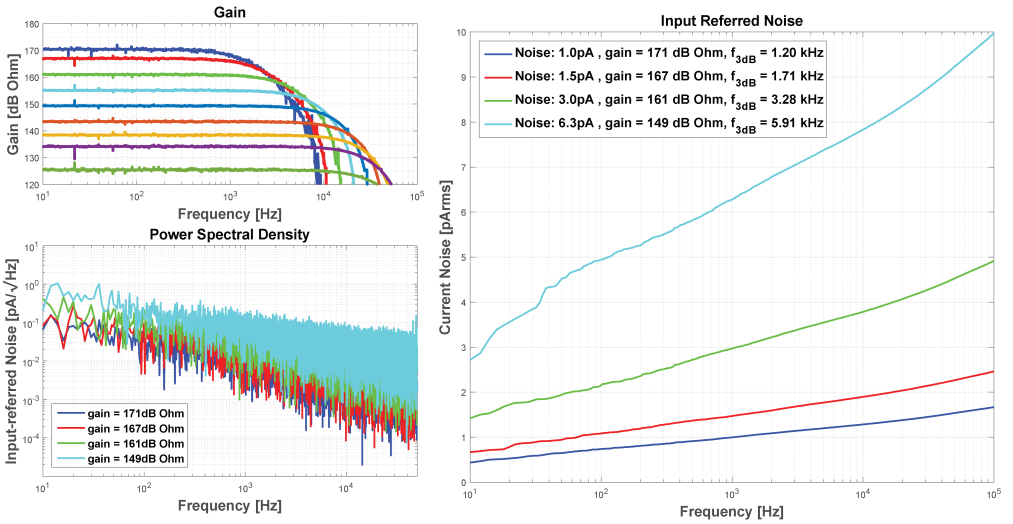

Fig.3 Gain and noise characterization measurement of the readout channels.

In order to verify the proper connection of the CNT-FETs to the electrodes and to the readout channels a dry measurement was performed. Fig.4 shows the current flowing through a sub array of CNT-FETs integrated onto the sensor array (rows 74-81, columns 61-72), as a function of the applied voltage (I-V curve). The characteristics are linear, showing Ohmic behavior of the CNT-FETs. The overall bundle resistance corresponds to the different numbers of parallel-integrated sensors. Unfortunately, not all electrode pairs produced an output, meaning that there is no CNT-FETs connected between the electrodes. This is why only nine curves are plotted out of ninety-six. In future the parameters of the DEP integration process will be optimized in order to achieve high integration yield.

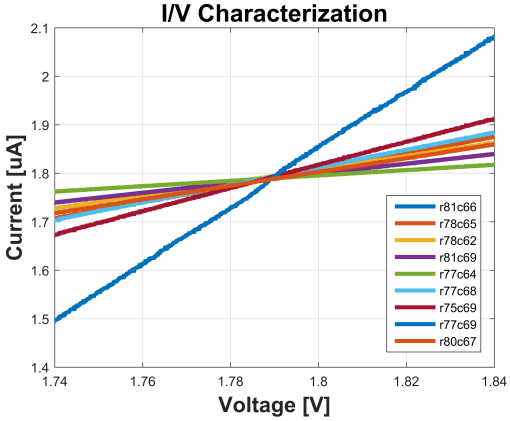

Fig. 4 Measured IV curves for a subset of the array.

5. Conclusion

A monolithic CMOS chip integrating both, interface circuitry and a large array of carbon nanotube sensor elements has been successfully fabricated and tested. The chip can control the voltage across CNT-FETs while measuring the resulting current. Currents in the range of 5 pA to 10 µA can be measured and digitized with a maximum resolution of 12 bits. The CNT-FETs have been successfully structured on the chip after the CMOS fabrication by using a floating electrode DEP manipulation technique. The resistive behavior of the integrated CNT-FETs has been verified in dry air measurements. We plan to use the platform for a multiplexed sensing of biochemical substances at low concentrations in liquid phase.

Acknowledgements

This work was financially supported through RIKENs program for Junior Scientists, Japan Society for Promotion of Science (JSPS) under Grants-in-Aid for Young Scientists or KAKENHI (B) (No. 26790035) and the European Union FP7 ERC Advanced Grant "NeuroCMOS" under contract number AdG 267351.

References

[1] F. Seichepine, et al (2014):"CMOS – integrated high-density arrays of carbon nanotube sensors", 18th International Conference on Miniaturized Systems for Chemistry and Life Sciences, µTAS.

[2] Y. Choi, et al. (2013): "Dissecting single-molecule signal transduction in carbon nanotube circuits with protein engineering". *Nano Letters* **13**, 625-31.

[3] I. Heller, et al. (2008): "Identifying the mechanism of biosensing with carbon nanotube transistors". *Nano Letters* **8**, 591–595.