Summary of Master's Thesis in Electronic Engineering
Politecnico di Torino

Investigation of CMOS Front-End Architectures for C_{60} Single-Molecule Sensor

Student: Gabriele Bonavoglia
Supervisors: Prof. Mariagrazia Graziano, Prof. Gianluca Piccinini, M.Eng. Fabrizio Mo

Introduction and research context

Starting from the twentieth century, climate change and air pollution have progressively become one of the most dangerous threats to human health on Earth, requiring air quality monitoring in outside environments. At the same time, chemical and industrial processes could produce dangerous toxic gases in case of failure of the production chain, leading to the necessity of air quality monitoring in close environments for workers health safeguarding. Recently, molecular sensors have gained popularity thanks to their potential low cost and massive production and miniaturization. An example is the gold-C_{60}-gold molecular quantum dot-based gas sensor (Au-C_{60}), addressed in this work. Furthermore, in 2022, it has been demonstrated the possibility of integrating on a single chip both molecular sensors and CMOS front-end, thanks to fabrication process compatibility.

Project Goals

In this context, the purpose of this thesis work was twofold: (i) investigation of literature proposed CMOS front-end architectures and selection of which of them are promising to be used with electrical (or amperometric) single-molecule sensors, with particular regard to the Au-C_{60} one; (ii) the characterization and the design of one of them. In particular, a CMOS analog front-end based on current-to-frequency conversion was selected, adapted for the Au-C_{60} sensor and designed in Cadence Virtuoso.

Results

A brief description of molecular devices has been provided in order to introduce the molecular sensor based on fullerene, in particular C_{60}. Then, the functioning of the C_{60}-sensor has been explained and its mathematical model has been presented. Considering the likely high noise in Au-C_{60} operating, and its expected current modulation features, the literature study was focused on circuits able to detect small and short current variations, of the order of few or even of a fraction of micro-ampere. A widespread solution is to convert the electrical current into other quantities, easier to be detected. A current-to-frequency converter was selected and adopted for the Au-C_{60} case.

The implemented circuit allows the biasing of the molecular sensor and it acts as an interfacing circuit between the sensor itself and a measuring instrument, characterized by a high accuracy capability (for example, a micro-controller). Moreover, by means of a signature in frequency, the analog front-end provides an indication of the gas to which the sensor is exposed. The implementation of this circuit was performed by means of the Cadence Virtuoso software, starting from the Verilog model of the sensor under analysis.

According to the specifications about the biasing of the sensor, some requirements have been extracted for the design of an interfacing circuit, like the bias voltage values for which the selectivity of the sensor with respect to some gas target is maximized.

These requirements have been used as references for the implementation of the analog front-end that has been carried out by characterizing the two main blocks of the circuit: a readout circuit and a current-to-frequency converter.

The first one has the aim of biasing the circuit and decoupling the input side from the output side, a readout circuit has been designed. The sensor has been biased in amperometric mode, i.e. with constant voltage across its electrodes, then the current that flows through it is constant, too. Then, the current driven by the sensor, which is modulated because of the change in the detected gas, is mirrored at the output of the sub-circuit.

Successively, a current-to-frequency converter has been designed. The current at the output of the readout circuit enters the converter at the input. At the output, there is a spike pattern signal whose time period is acquired by a functional block that emulates a measuring instrument. In particular, it measures the frequency of the output signal, which should be linearly proportional to the current in input to the converter and, then, to the one in the sensor.

These blocks have been simulated separately in order to validate their respective functioning. Firstly, particular attention has been put on the sizing of the MOSFETs present in the circuit. The geometrical dimensions of these transistors have been optimized to respect the electrical requirements of the C_{60}-sensor, in terms of the current through the sensor and the biasing voltage. Moreover, in order to be compliant with the nanometric sizes of the sensing device, they have been minimized as much as possible, but still avoiding design problems related to short channel effects while guaranteeing sufficient current and voltage driving capabilities. Secondly, other design parameters (like power supply voltage, exposure time etc.) have been trimmed to emulate the presence of the gas target and to provide a conversion from current to frequency as accurate as possible.
At the end, the two sub-circuit have been connected to each other and the whole system has been simulated. In Figure 1, the architecture of the analog front-end is depicted.

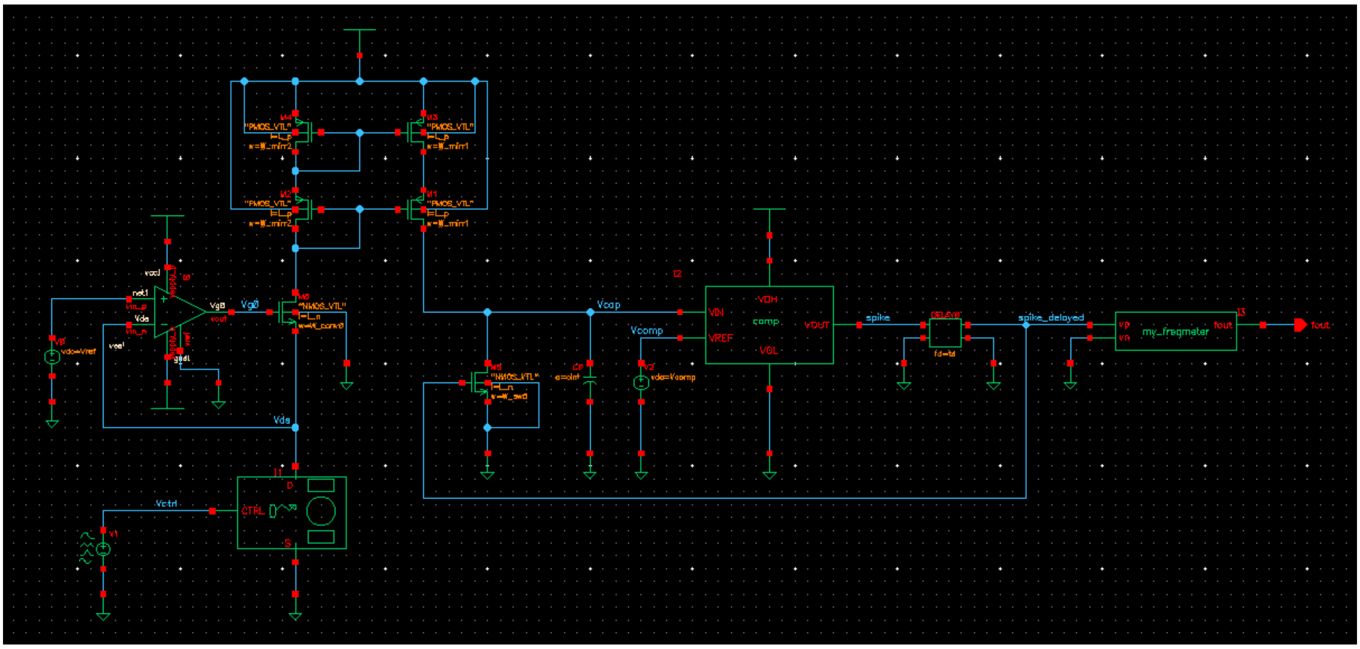


Figure 1: Analog front-end for C_{60} gas-sensor (implementation in Cadence Virtuoso).

The simulations have been performed in the time domain to emulate the succession of different gas targets that are detected by the sensor. In addition, this approach allows to observe the modulation of the current flowing to the sensor itself and of the frequency measured at the output of the front-end. An example of simulation is shown in Figure 2.
The alternate presence of two gas targets is "encoded" by two values of a control voltage V_{CTRL}. This is a fictitious voltage input of the Verilog model of the Au-C_{60}, used to select the sensor current response relative to a specific gas. According to the two values of V_{CTRL}, the sensor drives a current I_{DS} which has constant values in the two phases, since the input reference voltage has been imposed constant as well. As a consequence, the output frequency f_{out} follows the behaviour of the I_{DS} time evolution and the values it assumes are proportional to the current flowing through the sensor.
In post-processing phase, the values of I_{DS} and f_{out} for all the examined cases have been extracted and stored. For the recognition of the gas target - for example, nitric oxide (NO) - with respect to common atmospheric gases (like argon, carbon oxide etc.), there have been calculated differential values of the quantity of interest. In this way, a simpler comparison between many cases of exposure can be ensured.
In the final part, to evaluate the overall performance of the implemented analog front-end, all the data have been collected and used to calculate the sensitivity of the circuit with respect to the current of the sensor (I_{DS}) and to the voltage across it (V_{DS}), as shown in Figure 3.

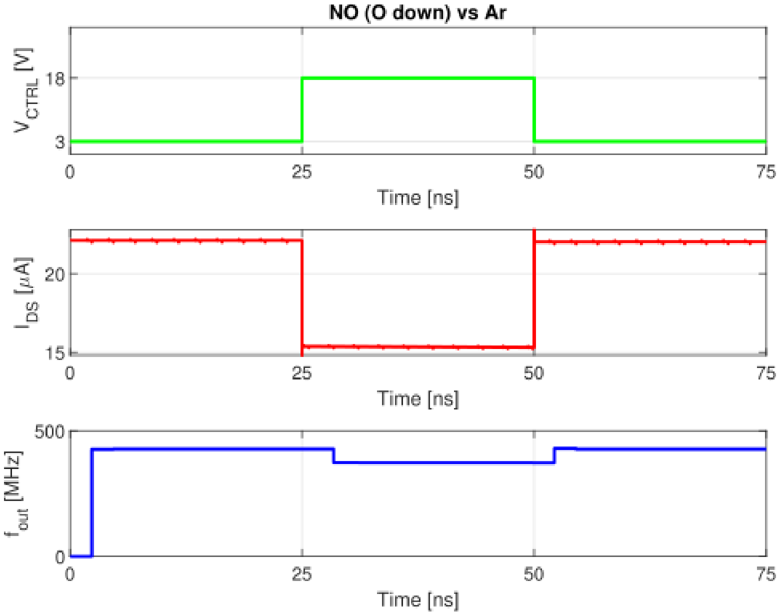
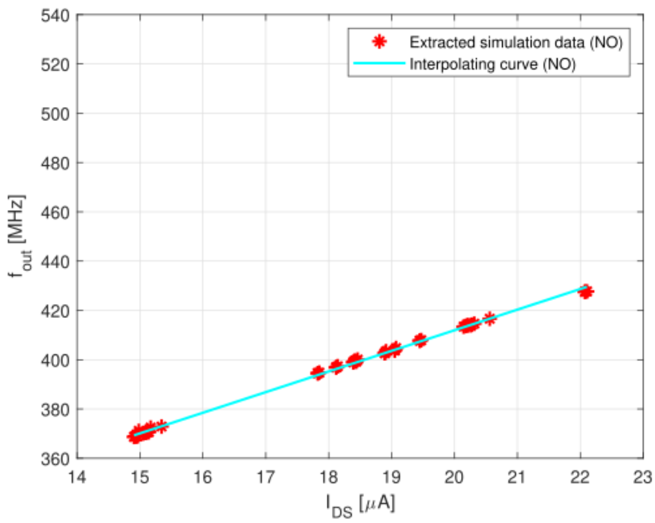
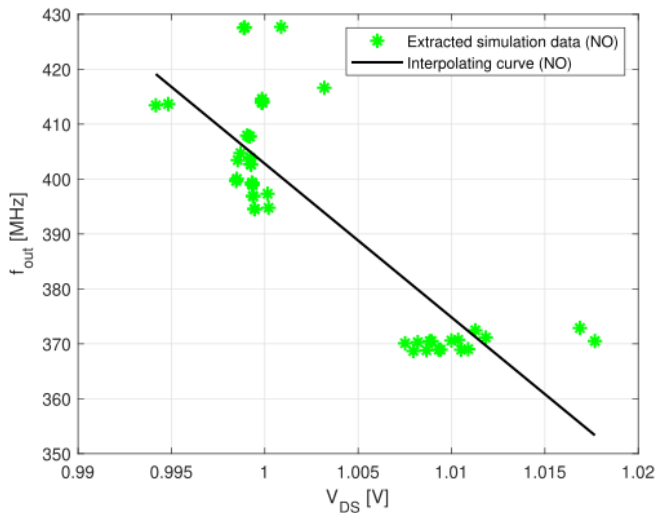


Figure 2: Exposure to Ar and NO ("O down"). Time evolution of control voltage (V_{CTRL}), current (I_{DS}) and output frequency (f_{out}).



(a) Sensitivity to I_{DS}.



(b) Sensitivity to V_{DS}.

Figure 3: Sensitivities of the analog front-end, for NO exposure.

The interpolation of the extracted data highlights the linear relation between the current I_{DS} and the frequency f_{out}, which demonstrates the effectiveness of the conversion. On the other hand, the graph in Figure 3.b shows that for small variations of V_{DS} the output frequency modulates significantly.

Conclusions and Future Works

The simulations of the implemented analog front-end confirm the correctness of the adopted approach. Still, the connection between the device in molecular technology and the CMOS interfacing circuit is not able to ensure fully accurate recognition of gas target molecules. Nevertheless, the proposed CMOS front-end architecture showed good performance and significant reliability for the detection of some specific gas analytes. Thus it is promising for further investigations.

Future works may enhance the accuracy of the biasing of the C_{60}-sensor by further optimizing the design of the proposed circuit and investigating the constraints about the interfacing of devices in different technologies. In addition, they may be concentrated on parasitics effects, layout study, and Au-C_{60} dynamic response to understand if the transient features of the proposed circuit match the requirements or if it should be modified accordingly.