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A MICROMECHANICAL PRESSURE SENSOR WITH RECONFIGURABLE ASIC

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Abstract. In this paper, a MEMS pressure sensor with reconfigurable ASIC and measurement range of 10 kPa to 100 MPa was designed, based on the system model design approach. The competitive advantages of the method include rapid prototyping and controlling parameters of micromechanical pressure sensor at all design stages; thus, reducing the device development and manufacturing costs. The set of unified piezoresistive sensing elements with different full scale pressure and sensitivity was implemented on a pre-doped silicon on insulator (SOI) wafer. The optimal parameters of sensing elements and integrated circuit were obtained using complex optimization criterion by system level simulation and refined by finite element method. The reconfiguration requirements were obtained by simulation of technological process variations. The reconfigurable ASIC is implemented using 0.18 μm SOI technology. The ASIC provides integrated solution with on-chip programmable offset trimming, temperature sensing, clock generation and digital signal processing. The system level and schematic simulations were performed during ASIC development. The digital signal processing verification was performed by FPGA prototyping. The experimental studies were carried out for sensor prototypes with 100 kPa and 1 MPa full scale range. The developed pressure sensor based on micro-assembly achieves the 0.06% main full-scale error.

Keywords: MEMS, ASIC, SOI, pressure sensor, system model, reconfiguration

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МЭМС ДАТЧИК ДАВЛЕНИЯ С РЕКОНФИГУРИРУЕМОЙ ИНТЕГРАЛЬНОЙ СХЕМОЙ

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Аннотация. В данной работе с помощью методики синтеза, основанной на методе системного моделирования, был разработан МЭМС-датчик давления с реконфигурируемой интегральной схемой и верхними пределами измерений от 10 кПа до 100 МПа. Преимущества данной методики заключаются в возможностях быстрого прототипирования и контроля параметров на всех этапах разработки, что снижает себестоимость разработки и изготовления устройства. На предварительно легированной примесью p-типа КНИ-пластине был изготовлен набор тензорезистивных чувствительных элементов с разной чувствительностью к давлению. Оптимальные параметры чувствительных элементов были получены по комплексному критерию оптимизации с помощью моделирования на системном уровне и уточнены с помощью метода конечных элементов. Требования к реконфигурации интегральной схемы были получены путем моделирования технологических отклонений. Реконфигурируемая интегральная схема была выполнена по технологии КНИ с проектной нормой 180 нм. Интегральная схема представляет собой единое схемотехническое решение, позволяющее проводить подстройку рабочей точки датчика, измерение температуры, генерирование тактового сигнала для цифровой части схемы и цифровую обработку полезного сигнала. Синтез интегральной схемы проводился с помощью системного и схемотехнического моделирования. Верификация алгоритмов цифровой обработки сигналов проводилась с помощью прототипирования на ПЛИС. Для образцов с верхними пределами измерений 100 кПа и 1 МПа были проведены экспериментальные исследования, показавшие, что разработанный датчик давления на основе микросборки позволяет достичь основной ошибки не более 0,06%.

Ключевые слова: МЭМС, ИС, КНИ, датчик давления, системная модель, реконфигурируемость

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Introduction

According to analytical company Yole Development, MEMS pressure sensors occupy more than a third of the current MEMS market and will amount to 2.2 billion US dollars by 2026 [1]. The micromechanical pressure sensors (MMPS) are mainly used in the automotive, aircraft, shipbuilding, medicine, energy, and mining industries. To increase the overall technological capacity of local manufacturing, it is critical to replace the existing pressure sensors in industrial control and management systems in order to improve their efficiency. The competitive advantages of MMPS are low production costs due to serial production technology, small size, low energy consumption, and high measurement accuracy. A standard MEMS pressure sensor consists of a sensing element (SE) and an electronic processing circuit, i.e. an application-specific integrated circuit (ASIC) [2]. The main characteristics of MEMS pressure sensors are full scale (FS) measurement range, measurement accuracy of the FS range, operating temperatures range, bandwidth and power consumption. In general, the SE is based on a pressure difference-sensitive diaphragm. Due to a simple manufacturing, the majority of research of the MMPS consider the pressure sensors, based on the piezoresistive principle, using one or several Wheatstone bridges made of pressure-sensitive resistors located on the SE. As a basis for the fabrication of MEMS structures, a P-doped silicon wafer is used.

Synthesis technique based on the system model

The MMPS design starts with analyzing its main characteristics and components. The major design difficulties of the modern integrated circuits are the extreme complexity of the projects, infeasibility of getting intermediate results of prototyping, and the high manufacturing and designing costs. Integrated circuits for micromechanical sensors include additional criteria related to the provision of accurate operation with SE that are based on different physical principles.

Unlike the traditional technological processes in microelectronics, where technological and statistical process variations ranges are defined, standardized and described in a process design kit (PDK), in micromechanics the existing variety of designs and technologies determines the challenges of taking into account the different technological and statistical process variations when synthesizing the SE.

In microelectronics, the design methodology referred to as “top-down” design is applied to solve the issues described above.

However, when designing the micromechanical sensors, the following problems arise due to the heterogeneous character of the main components:

- lack of the design phase of upper-level model;
- lack of early co-simulating of components;
- lack of early prototyping.

To define the accurate interaction between heterogeneous components, it is feasible to carry out design using system level simulation. The MEMS system model considers functional, structural, and behavioral aspects of a microelectromechanical system, which includes heterogeneous physical subsystems and allows their fast and efficient simulation, preferably in a single simulation environment [3]. To solve the task of synthesizing the MMPS with reconfigurable [4, 5] ASIC, this research considers the sensor system model synthesis method with stepwise optimization of the sensor components based on the complex criterion. Such criterion was developed by applying the SWaP-C [6, 7] criterion to a MMPS and extending it to consider heterogeneous design and technological constraints and process variation of the component parameters.

Architecture

This research focuses on the architecture based on the direct conversion circuit. To design the MMPS, optimal SE structures with different sensitivity of pressure conversion and a reconfigurable ASIC can be used. Fig. 1 shows the MMPS system architecture.

The system consists of SE with the optimal characteristics for the required upper pressure measurement limit (UPML) and the reconfigurable ASIC. The SE is chosen during the sensor microassembly, depending on sensor requirements. The reconfigurable ASIC consists of analog front-end and digital parts. The analog front-end is controlled by digital part and can be reprogrammed. The optimal configuration can be stored and initialized from external non-volatile memory (FLASH).

The SE consists of a piezoresistive Wheatstone bridge formed in P-doped device layer of a SE silicon diaphragm. The ASIC consists of a low-noise programmed analog readout interface based on the instrumentation amplifier with chopping technique, a digital-to-analog converter (DAC) for adjusting the offset after the first gain stage, a switch capacitor low pass filter, a multi-stage noise shaping (MASH)-$\Sigma\Delta$ analog-to-digital converter (ADC), a temperature measurement channel with the option of working with external or internal sensor, a digital filtration and processing, and SPI-interface. The supply voltage of ASIC and the SE piezoresistive bridge is 1.8 V.

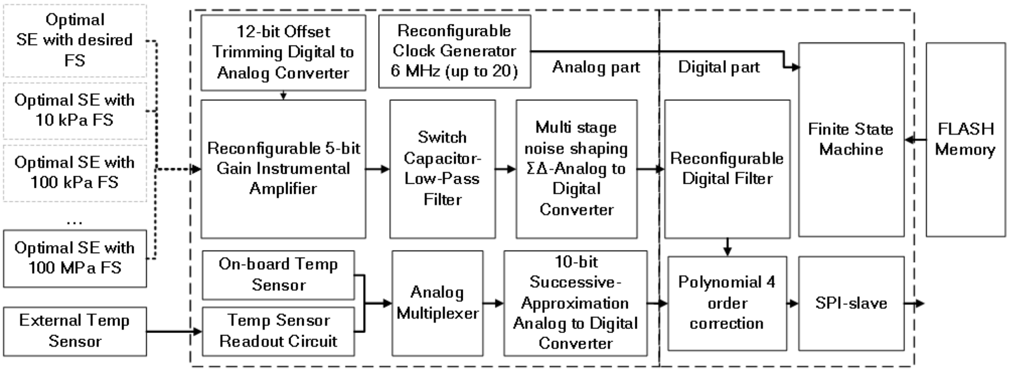

Fig. 1. MEMS pressure sensor system architecture

System model

It is possible to solve the task of the MMPS optimal synthesis with minimal design and manufacturing costs by using system level approach. To synthesize the system model, the analysis of the detection physical principles was carried out. The main formulae describing the physical behavior of a sensing element are as follows [8]:

$$V_{out} = V_A - V_B = \left(\frac{R_4}{R_3 + R_4} - \frac{R}{R_1 + R_2} \right) V_S; \tag{1}$$

$$\frac{\Delta R}{R} \approx \frac{\Delta \rho}{\rho}; \tag{2}$$

$$\left(\Delta\rho/\rho\right)_l = \pi_l \sigma_l + \pi_t \sigma_t; \tag{3}$$

$$\left(\Delta\rho/\rho\right)_t = \pi_l \sigma_t + \pi_t \sigma_l; \tag{4}$$

$$\pi_l \approx -\pi_t \approx \frac{\pi_{44}}{2}; \tag{5}$$

$$\sigma_x = f\left(P,\ a,\ b,\ th,\ x,\ y\right), \tag{6}$$

where V_{out} is the output voltage; V_A and V_B are Wheatstone bridge nodes voltages; $R_1 - R_4$ are the bridge piezoresistances; V_S is the bridge supply voltage; ρ is the resistivity; Δρ is the resistivity change; π_l and π_t are the longitudal and transverse gauge coefficients/factors; π_{44} is the piezoresistivity coefficient; σ is the directional mechanical stress as a function of load pressure (P), membrane width (a, b), thickness (th) and resistors coordinates (x, y).

Based on the provided description, the system model of a SE was defined. To define the optimal parameters for the SE variety in the range from 10 kPa to 100 MPa, a simulation with various geometrical parameters was carried out. As particular optimization criteria, the nonlinearity of the pressure conversion into the output voltage (no more than 0.05–0.5%), the FS normalized pressure sensitivity (no less than 10 mV/V for the full measurement range), the maximum membrane deflection (no more than 20% from the membrane thickness) and the structure integrity (the maximal mechanical stress of no more than 10% from the ultimate tensile strength) were chosen. As a result of the simulation, the optimal set of SE structures with the unified geometrical parameters was identified, and the technical requirements for the ASIC model were defined. As the initial constraints were the maximum and minimum thickness and width of the membrane, which ranged from 30 to 450 um and from 200 to 2000 um.

The MMPS system model was modified by adding an ASIC model. The system model of the integrated circuit consists of the analog and digital parts.

The analog front-end of the integrated circuit includes the following main processing units:

- input readout interface circuit;
- analog low pass filter;
- ADC.

The input readout interface circuit and the analog low pass filter can be represented as a set of blocks with the corresponding transfer functions, the blocks simulating their nonlinear and noise parameters, and the initial SE offset correction blocks. The dynamic parameters – SFDR and SNR – were selected as the main parameters of the processing scheme, while SNR parameter was simulated, taking into account both white and flicker noise (1/f). The earlier reported [9] MASH-ΣΔ-ADC was used as ADC model. The MASH 2-2 architecture provides characteristics of higher order modulators and preserving stability. The determination of the optimal requirements to the analog electronic blocks was carried out by solving the optimization task. The simulating results show that to obtain 0.05% main FS error, it is necessary to have an analog front-end with SFDR parameters of more than 61 dB and SNR of more than 70.4 dB [10]. As a result of the simulation, the technical requirements for the digital signal processing (DSP) were defined.

The standard minimal DSP requirements for micromechanical sensors include the calibration coefficients to compensate the sensor offset and the gain error that are generally realized by means of the temperature-dependent polynomial [11]. Besides temperature compensation, the main requirement for the MMPS is the option to control sampling frequency and the bandwidth that is defined by the output digital filters. In practice, to filter ΣΔ-sequences, the recursive and non-recursive cascaded integrator–comb (CIC) filters are applied. The main advantage of the given filter type is the lack of multiplications in its structure. Non-recursive form used [12] in case of low decimation coefficient (up to 32 times), low bit wordlength of the input sequence (1–2 bits) and high operating frequencies (>1 MHz), that is not suitable for this research. For this reason, the structure with applied cascade recursive CIC with a reconfigurable halfband filter and a reconfigurable FIR compensator was selected. As a result of the system simulation, the optimal parameters, such as the filters orders, the number of coefficients and their bit wordlength, were defined. As a result of verifying at the system level, the required value of the main FS error was confirmed.

Application

A sensing element

The Concern CSRI Elektropribor, JSC, was chosen as the semiconductor fabrication for MEMS manufacturing. This semiconductor fabrication plant has limitations on silicon ion-doping operations. The manufacture of the SE without this operation is described in [13]. The SE is manufactured on a pre-doped p-type silicon-on-insulator (SOI) wafer with (100) plane orientation. In this research a standard SOI wafer with conductivity of 0.015 Ohm*cm, that equals the carrier’s concentration of ~$5*10^{18}$ 1/cm^3, is used. Structurally, the SE consists of three layers: a structural layer, a dielectric layer and a bulk. The structural layer thickness of 500 nm was selected as an initial having the minimal surface roughness because of the Smart Cut technology [14]. The structural layer consists of four piezoresistors connected in a Wheatstone bridge configuration with a crystallographic direction [1 1 0] to provide the maximal sensitivity to the mechanical stresses. The piezoresistors and their interconnection are made in a structural layer by means of photolithography and further deep reactive-ion etching (DRIE) from the upper side to the dielectric layer. The dielectric layer consists of 1 μm of SiO_2 that electrically insulated the structural layer from the bulk. The bulk thickness is 450 μm. The piezoresistive bridge is placed on the membrane formation.

The structure's synthesis of MMPS SE was carried out by application of the finite element methods. This research employed the COMSOL Multiphysics package to solve the simulation tasks as this software's competitive advantage is micromechanical system simulation option [15, 16]. Integrated COMSOL library materials were used, in particular, the model of silicon with p-type doping and anisotropic elasticity [17], and the model of silicon oxide. The orientation of silicon crystallographic direction was set as [1 1 0] in accordance with the system model. The search of the structure geometric parameters was carried out by taking into the account the limitations identified at the system simulation phase. The model calculation was carried out in a combined multiphysics by applying the *Piezoresistivty*, *Domain Currents* module that includes *Solid Mechanics* module and *Electric Currents* module.

According to the optimization results of the main and additional geometric parameters, the following set of the final structures with their output parameters was obtained (Table 1). The optimal synthesis procedure is not the main topic of this article and will be discussed in future articles.

Table 1

Main parameters of SE

UPML	10 kPa	100 kPa	1 MPa	10 MPa	100 MPa
Half membrane width, μm	1800	800	1800	800	300
Membrane thickness, μm	30	30	250	250	250
Sensitivity, normalized to the full range (*S*), mV/V	–13.2	–22.8	–16.9	–28.3	27.1 (Pressure act on the clamp)
Nonlinearity to the full range NL_{FS}, %	0.35	0.08	0.1	0.06	0.5

The sensitivity test to the technological process variation ranges and additional geometric parameters for MMPS SE in the UPML range from 10 kPa to 10 MPa was carried out. According to the calculation results, the maximal sensitivity to process variation happens in the values of membrane thickness and piezoresistors thickness. Thus, the greatest impact occurs on the structures with a small membrane thickness as the variation range of the membrane etching width can reach in this case up to 20%.

Integrated circuit

Integrated circuit design for MMPS was performed using the PDK of 180 nm SOI technology carried out by the local silicon chips manufacturer JSC "Mikron" with a unipolar voltage of 1.8 V.

The folded-cascode operational transconductance amplifiers (OTA) were used as core amplifiers for switched capacitor integrators in ΣΔ-modulators. This OTA was selected as it can provide high direct current (DC) gain (~80 dB), wide input signal range and does not require the frequency compensation. The integrator gain is set by capacitors ratio in accordance with the system model of ΣΔ-modulator. The nominal value of 1 pF was used as the optimum one in terms of the ratio of kTC noise and the crystal area.

The schematic design of low pass filter was chosen based on the first order non-inverting switching capacitance low pass filter [18] using the folded-cascode amplifier (120 dB DC gain) with a class AB output stage as rail-to-rail output provides the minimization of nonlinear distortions.

Fig. 3 illustrates the schematic of the instrumental amplifier [19, 20]. The architecture of the instrumental amplifier assumes a zero offset correction of the SE by 12-bit fully matched resistive array DAC, combined with chopping technique of useful signal from SE and offset correction signal. For the minimization of nonlinear distortions, the single-ended version of the low pass filter core operational amplifier was used. To ensure operation in the optimal amplitude range, taking into account different

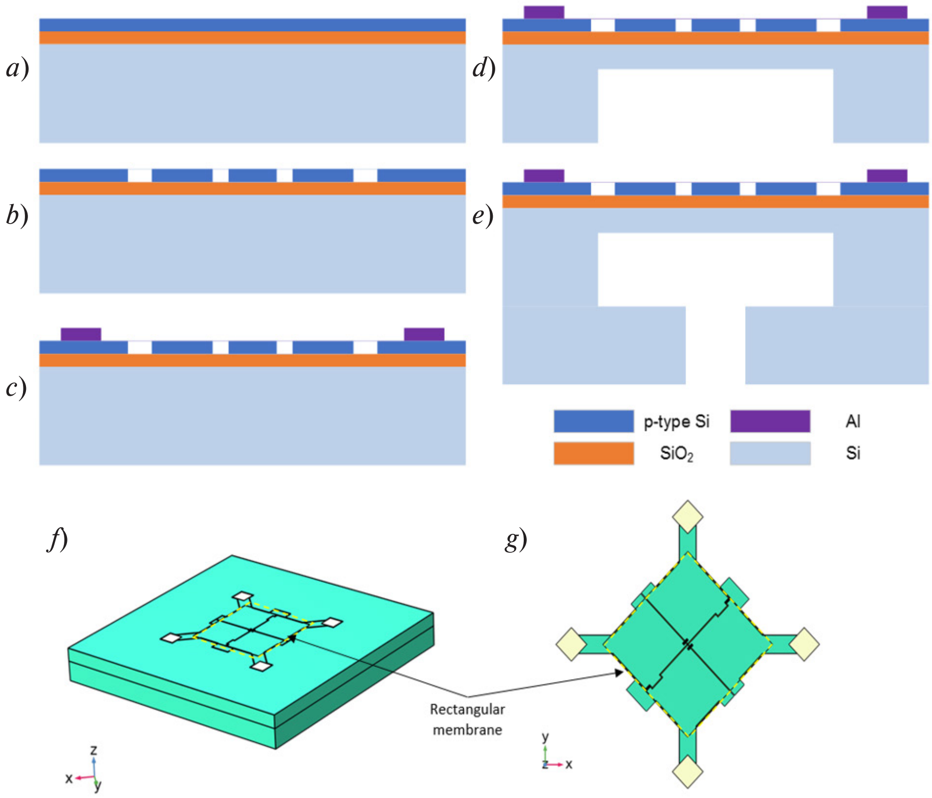

Fig. 2. SE manufacturing: *a*) SOI wafer, *b*) top DRIE for resistors and interconnections, *c*) Al deposition, *d*) bot DRIE for membrane cavity, *e*) connection to SE substrate, *f*) 3D-model of SE, *g*) Wheatstone bridge structure

SE sensitivities and technological process variations, a 5-bit reconfigurable gain from 1 to 32 times was implemented via resistive matched array.

The chopping frequency was selected as ¼ sampling frequency in accordance with the system model. The residual signal filtration at the modulation frequency is carried out by means of non-inverting switching capacitance low pass filter and a digital CIC filter.

Simulation results show that the developed schematic model of the analog front-end with MMPS SE achieves following characteristics: SFDR ranging from 71 dB to 84 dB for operating voltage range from 300 mV to 450 mV that satisfies the developed system model requirements.

The analog part also includes the reconfigurable ring-oscillator for the clock signal generation and the temperature sensor readout circuit, consisting of 10-bit SAR-ADC, with the option of working with external or internal sensor.

The digital part was synthesized based on the developed system description. This digital part includes the cascade connection of CIC filter of order 3-3-6 with the decimation coefficient for each stage equal to 4 and application of CIC register pruning technique. The digital part also includes polynominal temperature compensation of 4^{th} order. The digital part was prototyped in FPGA and tested by applying a ΣΔ-bitstream input data derived from system model simulation and SPICE simulation. The prototyping stage allows the verification of the digital part algorithms and client software backend.

Results and discussion

Sensing element

MMPS were assembled and manufactured at the production facility of The Concern CSRI Elektropribor, JSC. Each MMPS was optimally configured for maximizing its performance.

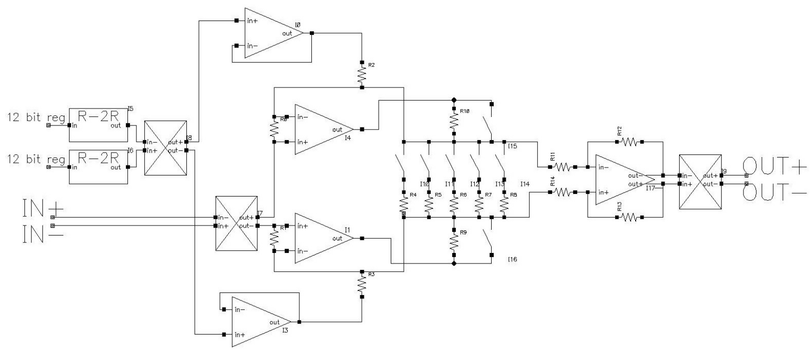

Fig. 3. Schematic of instrumental amplifier

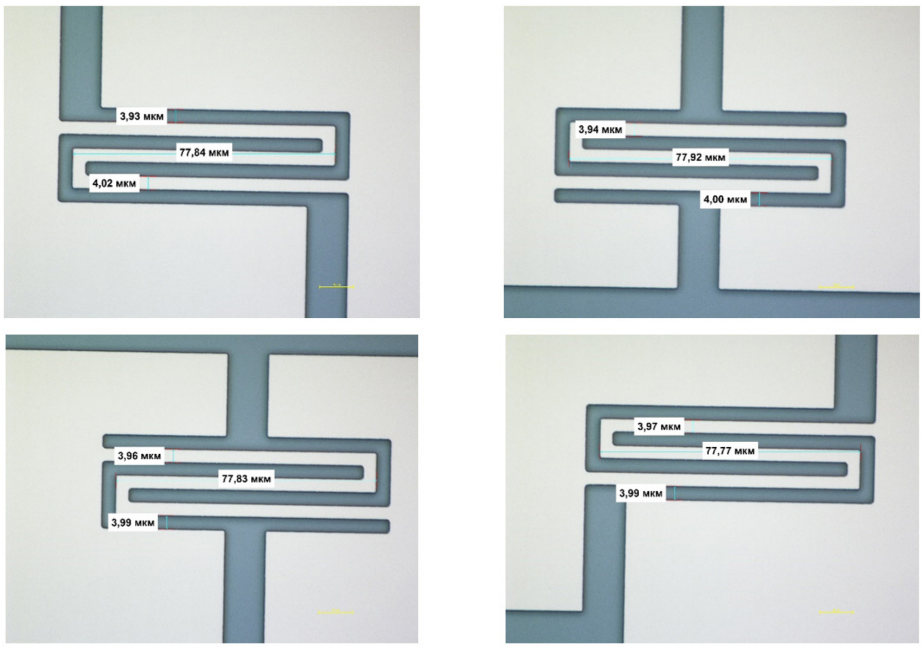

Fig. 4. Optical measurements of geometrical parameters of SE piezoresistors

The measurement of MMPS SE characteristics was carried out during several stages. Testing was done by the group method on the silicon wafer with SE. Five sampled MMPS SE on the wafer were subjected to the non-destructive optical control (Fig. 4) over the main geometrical parameters of piezoresistors. As a result of the optical control, the parameters variations of the piezoresistors did not exceed 2%.

The next stage consisted of measuring the resistances of the parts of piezobridges by applying the group method using SUMMIT 1200B-AP probe station, Agilent 34401A digital multimeter and B2201A switch matrix. The measurement results showed that the piezoresistance sections correspond with the finite element model with nominal values ranges from 14 to 17 kOhm, depending on design.

Integrated circuit

The measurements of different integrated circuit (Fig. 5) characteristics were carried out under normal climate conditions. To test the dynamic parameters the Stanford Research Systems DS360 signal generator was used in the mode of differential harmonic signal with the constant value 900 mV.

To acquire data from ASIC by means of SPI interface the National Instruments USB-8452 circuit board was used. Three samples were selected for testing. Fig. 6 shows the dynamic parameters dependence

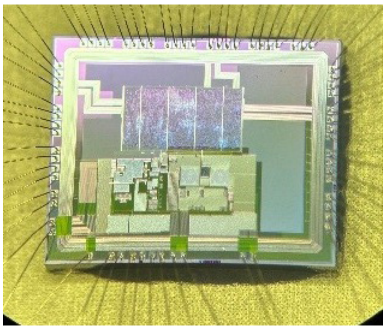

Fig. 5. Developed ASIC packaging microphotograph [21]

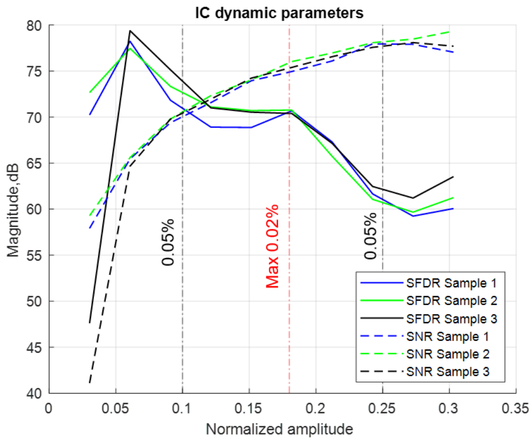

Fig. 6. Dynamic parameters of reconfigurable ASIC

on the normalized amplitude of the input signal in the range from 0.033 to 0.33. The figure illustrates that after the fabrication the SFDR parameter with the optimal amplitude of 360 mV or 1/5 the source voltage is lower than the expected by ~16 dB, when the SFDR parameter reached its peak with the low normalized amplitude of 0.07 with the maximal value of 79 dB. The area of the optimal parameters with nonlinearity is achieved with the normalized amplitudes from 0.05 to 0.1, while the optimal noise parameters are achieved within the normalized amplitudes from 0.1 to 0.3. Based on test results and additional schematic analysis in this research, it is supposed that the reason behind the conversion linearity decrease is the charge leakage effect in switched-capacitor circuits [22]. The integrated circuit provides precise measurement of almost 0.05% accuracy in the optimal range of the output amplitudes [10].

Micromechanical pressure sensor

To carry out testing of three samples, the MMPS were assembled by wire bonding MMPS SE and MMPS integrated circuit from each other onto a special circuit board. Taking into account MMPS SE and MMPS integrated circuit parameters, the optimal settings of MMPS integrated circuit amplification coefficient for each type of MMPS SE were selected based on the criterion of minimizing the possible error. To carry out MMPS testing, the measurement system presented in Fig. 7 was applied. The measurement unit consists of the following:

1) ELMETRO-Paskal-03/04 pressure calibrator with modifications made by 160K (160 kPa) convertor and 1M (1MPa) convertor was used for controlling and setting the pressure.

2) B5-71/1-pro power source was used to power the hardware kit and the control circuit board.

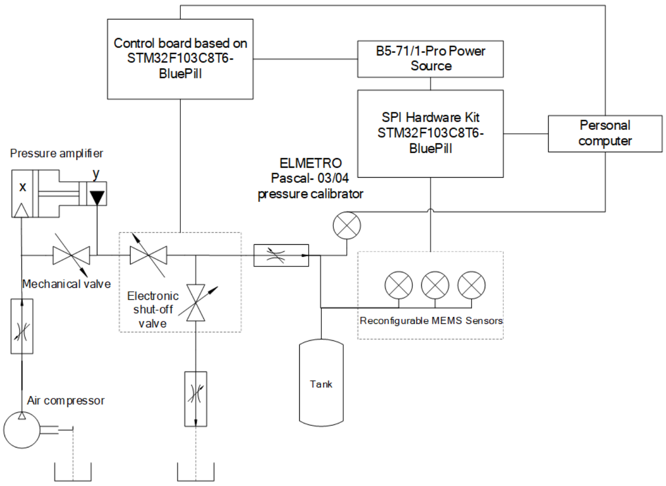

Fig. 7. The structural diagram of the measuring unit

To automate the samples testing, the hardware kit based on STM32F103C8T6-BluePill microcontroller was used for multichannel digital reading from digital SPI interface of the MMPS as well as automated setting the pressure by the relay control in accordance with the reference pressure gauge.

To define the pressure measurement precision under the normal climatic conditions the pressure cycle with 22 load points from 0 to 105% with 5% step from UPML was used. For the experimental studies samples with UPML from the most common and practically applied ranges (100 kPa, 1 MPa) were chosen. The measurement precision of MMPS was calculated using the following equation:

$$\Delta Error = \Delta NL + \Delta Noise, \tag{7}$$

where $\Delta Error$ is the pressure measurement inaccuracy; ΔNL is the measurement inaccuracy caused by the pressure conversion nonlinearity calculated by the least square method; $\Delta Noise$ is the pressure measurement inaccuracy caused by sensor noise.

The measurement results of MMPS characteristics are presented in Table 2.

The overall pressure measurement error for two samples of MMPS with the UPML of 1 MPa makes up no more than 0.09%, which correlates with the theoretical results obtained earlier. Whilst the testing results for sample No. 3 demonstrated a higher nonlinearity caused by the significant hysteresis of the output value. This hysteresis value can be explained by the presence of residual mechanical stress in the structure as well as the influence of adhesive connection of the SE with a stainless-steel frame. The overall pressure measurement error for three samples of MMPS with the UPML of 100 kPa makes up less than 0.075% that corresponds to the theoretical results that were obtained earlier.

Table 2

Measured characteristics

Sample No.	**$\Delta Error$, % from FS**	
FS	100 kPa	1 MPa
1	0.075	0.09
2	0.064	0.09
3	0.06	0.34

Conclusion

This article deals with the development piezoresistive MMPS with reconfigurable integrated circuit. The MMPS was synthesized using system level design method. The competitive advantages of the method consist in rapid prototyping and controlling parameters of MMPS at all stages; thus, reducing the device development and manufacturing costs.

The set of unified piezoresistive SE with different FS pressure and sensitivity was implemented on a pre-doped SOI wafer. The optimal parameters of sensing elements and integrated circuit were obtained using complex optimization criterion by system level simulation and refined by finite element and schematic simulations. The reconfiguration requirements were obtained by simulation of technological variations.

The reconfigurable ASIC is implemented in 0.18 μm SOI technology. The ASIC provides integrated solution with on-chip programmable offset trimming, temperature sensing, clock generation and DSP. The ASIC was developed using system level design method with schematic simulations. The DSP verification was performed by FPGA prototyping. For sensors prototypes with 100 kPa and 1 MPa FS range experimental studies were carried out.

The developed pressure sensor based on micro-assembly achieves the 0.06% main FS error.

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