Design and Implementation of Dynamic FPAA Based Interface Circuit for Thin Film Lead-Free Piezoelectric Sensors

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DOI: 10.5185/amlett.2020.101565

In this paper, we propose interface electronic circuit for thin film piezoelectric sensing structures. An interface electronic prototype based on dynamically programmed Field Programmable Analog Array (FPAA) is configured to implement Root-Mean-Square (RMS) to DC (RMS-to-DC) conversion process, based on direct method. The studied piezoelectric sensors are prepared by conventional microfabrication technology, involving new lead-free piezoelectric polymer-oxide composite, consisting of gallium doped zinc oxide and polyvinylidene fluoride. The devices show sensitivity to low frequency, weak mechanical loads and exhibit excellent stability at multiple vibrational cycles. It was found that a mass load of 80 g causes DC voltage of 111.8 mV with instability of less than 10 mV, which is sufficient for detection purposes.

Introduction

Recently was found that zinc oxide doped by gallium and forming zinc-gallium oxide, which was used in optical devices, possesses piezoelectric effect [**4**]. Since then, the researchers' efforts were focused on the enhancement of its piezoelectric response, because it was found that conventional sputtering technology can be successfully applied, making the material potentially favourable for the advanced sensors. One of the approaches is to prepare compositions between the newly synthesized material and low-cost organic material with similar behaviour, but better typical characteristics (e.g. piezoelectric module, energy dissipation and loss factors, etc.). By the authors' knowledge such approach has been never applied for $ZnO:Ga_2O_3$ in terms of piezoelectric sensors application.

Piezoelectric sensing structures are very promising to work with compact, portable devices, especially mass loaded ones (microfluidic detectors, mass balances, cyclic tension gauges) where the mechanical stimulus is relatively weak and the equivalent mass load is less than 1 kg. Some applications are also biomedical microsensors for heart rate monitoring [**1**], touch screen detectors [**2**], etc. A very important issue in the optimization of the piezoelectric sensors is the stable piezoelectric response that could be converted into stable DC voltage with easy measurable value, which follows linearly the mass load causing the piezoelectric charge. This problem has occurred recently due to the application of lead-free materials, which exhibit less piezoelectric yield in comparison with the traditional lead-zirconium titanate (PZT) [**3**].

In the last ten years, the analysis of the literature resources shows a variety of interface circuits for different piezoelectric sensors [**5-8**]. Of particular interest are the analog processing circuits in [**5**] and [**8**] that convert signals from thin film sensors with a peak-to-peak voltage (differences between the highest and lowest peaks) from 50mV to 300mV. The interface circuit is based on the inverting charge sensitive amplifier, which is combined with low-pass filter. Those types of interface circuits are intended for small AC signals with amplitude up to several hundreds of millivolts. The studied $ZnO:Ga_2O_3$/ polyvinylidene fluoride (PVDF) composite piezoelectric sensors produce an AC voltage with amplitude from 100mV to 300mV.

In this study, the ability of the purely studied $ZnO:Ga_2O_3$/PVDF composite lead-free piezoelectric transducer to work as a sensor, detecting cyclic mass load with frequency up to 50 Hz in the g/cm^2 range is demonstrated. This is possible due to specially designed for this purpose interface circuit based on a Field Programmable Analog Array (FPAA) [**9**], realizing on which Root-Mean-Square (RMS) to DC (RMS-to-DC) conversion process is implemented. In comparison with the FPGA or DSP based implementations for the proposed solution FPAA can be dynamically programmed during the work process [**10**,**11**]. By the authors' knowledge, presently there is no study regarding the strategy for processing signals from similar sensor elements during their low-frequency light loading.

The structure of the electronic system for rms-to-dc conversion is determined by the parameters of the input signals, such as amplitude, frequency range, and noise level. This means that the implementation of the converter has to allow changing of the internal topology, the voltage gain according to the variation of in the amplitude of the signal, and it should be able to change the cut-off frequency of the filters according to the noise levels.

Possible applications of the system could be also flow sensing, tactile sensors, mass balances, etc.

Design of FPAA based converter

To obtain RMC value of the magnitude of an AC signal generated from the piezoelectric sensor, a precision RMS-to-DC conversion circuit based on the direct (or explicit) conversion method was chosen to design. In comparison to the indirect (or implicit) method, a feature of the explicit conversion method is the ability to achieve a wider bandwidth and less error (±0.1% of full scale) in the operating range of the input signals [**12**]. Moreover, it can be converted signals with smaller amplitude using this method. The practical limitation restricts this method to input signals, which have maximum dynamic range with ratio up to 10:1.

The RMS value of an AC input voltage was determined by the following formula [**12**]

$$V_{RMS} = \sqrt{\frac{1}{T}\int_{0}^{T} v_{in}{}^{2}(t)dt}\ , \tag{1}$$

where the time interval T is the period of the signal.

The squaring operation can be implemented by using an analog multiplier, the two inputs to which are short-circuited. In this way, the input signal was applied at both input terminals simultaneously. The integrating is substantially extracting the constant component of the obtained result, which is realizable with a low-pass filter. For a complex periodic signal or non-sinusoidal vibrations

$$v_{in} = V_{m1}\sin\omega_0 t + V_{m2}\sin 2\omega_0 t + V_{m3}\sin 3\omega_0 t + \dots \tag{2}$$

where V_{m1}, V_{m2}, V_{m3} etc. are the amplitudes of the sinusoids and $\omega_0 = 2\pi / T$ is the fundamental frequency. The amplitudes of the harmonics (after the second one) progressively decreased and the infinite series can be truncated. This series described a signal with an approximately sine-wave form.

Substituting the expression for v_{in} into Eq. 1 resulted in

$$V_{RMS} = \sqrt{\frac{1}{T}\int_{0}^{T}(V_{m1}\sin\omega_0 t + V_{m2}\sin 2\omega_0 t + V_{m3}\sin 3\omega_0 t + \dots)^2\,dt}\ . \tag{3}$$

Thus, the following relationship between the effective value of a complex periodic signal and the effective values of the constituent harmonics $V_{RMS,i}$ was found:

$$V_{RMS} = \sqrt{\sum_{i=1}^{n} V_{RMS,i}^{2}}\ . \tag{4}$$

A simplified circuit diagram, by which the direct method is implemented for determining the effective value of an input signal regardless of its waveform, is shown in **Fig. 1(a)**. The input signal was applied simultaneously at the two input terminals of an analog multiplier, thereby performing the squaring operation. The resulting voltage $v_{sq} = Kv_{in}^2$ was applied to a low-pass filter (LPF) where the components with higher frequencies are removed. Finally, the obtained DC voltage V_C was applied to a square root extraction circuit.

Under the construction of the electronic circuit for RMS-to-DC converter the variations of the parameters of the input signal, such as amplitude, frequency, and level of noise voltages and currents are critical for the proper operation. This means that the implemented circuit has to be able to change the transmission coefficient at variations in the amplitude of the input signal and also provide the ability for tuning the pole frequency of the LFP at various noise levels. These requirements can be relatively easily achieved by applying the explicit conversion method, using a dynamically programmable FPAA system.

FPAA programming

The RMS-to-DC converter function according to the block diagram in **Fig. 1(a)** can be programmed in FPAA AN231E04 from ANADIGM. In comparison with the other FPAA systems, the AN231E04 is characterized by the highest degree of integration, providing the greatest functionality and obtaining the widest bandwidth in the range of variation of the input and output signals from 0 to 3.3V. Such a device can be programmed by using the ANADIGM DESIGNER 2 software system. A circuit diagram of the FPAA based RMS-to-DC converter according to the direct conversion method is shown in **Fig. 1(b)**.

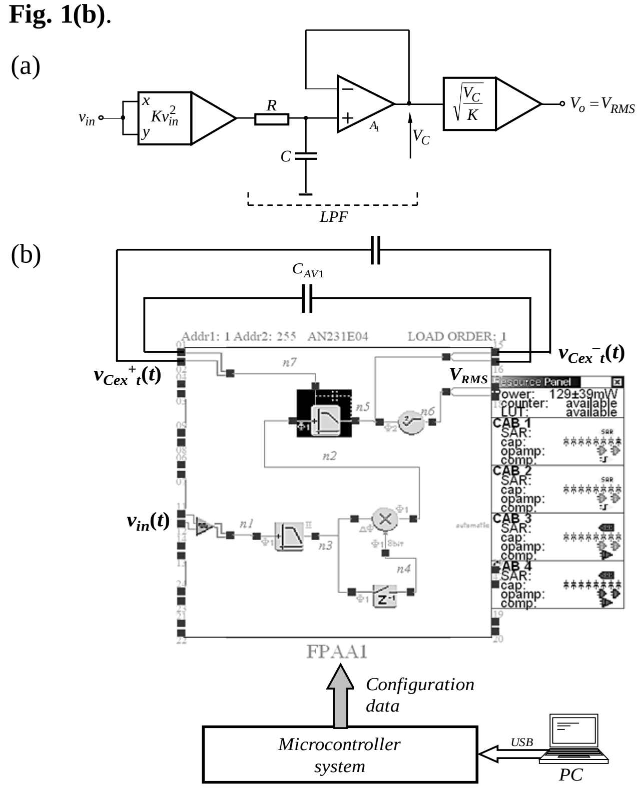
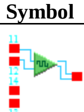
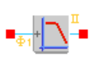
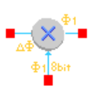
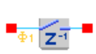
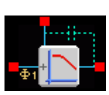
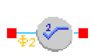


Fig. 1. RMS-to-DC converter using direct method: a) Schematic block diagram; b) Circuit diagram implemented in FPAA AN231E04. External view of the FPAA configuration in ANADIGM DESIGNER 2 program.

As can be seen from **Fig. 1(b)**, an analog multiplier, a LPF, and a square root extraction circuit are required for the implementation of Eq. (1). Such function blocks can be relatively easily obtained by using the standard Configurable Analog Blocks (CABs) available in the selected FPAA. Moreover, the parameters of the CABs can be easily organized by using the user interface of the program.

Table 1 summarizes the complete information of the CABs available in the AN231E04 system. The analog multiplier *Multiplier1* was used to square the input voltage, with a scale factor of K equal to $1V^{-1}$. Furthermore, there is no additional amplification of the input AC voltage, as well as amplification of the contained noise components.

Table 1. Configurable Analog Blocks for the RMS-to-DC converter according to the block diagram in Fig. 1.

Name	Symbol	Options	Parameters
IOCell3		I/O Mode: Low Offset Chopper	Gain 0 dB (1V/V)
FilterBiquad1		Filter Type: Low Pass Polarity: Non-inverting	Corner Frequency: 500Hz Gain: 1.00 Quality Factor: 0.707
IOCell6		I/O Mode: Output Output Type: Bypass	none
Multiplier1		Sample and hold: off	Multiplication factor: 1,00
Hold 1 (2)		Input sampling phase: phase1	none
FilterLow FreqBilinear2		Independent variable: External Cap Value Polarity: non-inverting	External cap value [nF]: 33nF Gain: 1,00 Corner frequency [Hz]: 0,753
SquareRoot1			none

There are two clock frequencies when selecting clock frequencies to control switched capacitors, as recommended by the manufacturer the ratio has to be 16:1. Connecting a Sample-and-Hold CAB (*Hold 1 (2)*) to one input terminal of the multiplier provides synchronous sampling. *FilterLow FreqBilinear1* CAB was used to determine the average value of the input voltage. The cutoff (corner) frequency was obtained through external capacitors C_{AV1} and C_{AV2} between specially provided filter terminals. The filter capacitors C_{AV1} and C_{AV2}, connected between nodes *n3* and *n6*, are selected with capacitances equal to 33*nF* determined by the cutoff frequency of the end LPF [**2**]:

$$f_p = \frac{f_S}{\pi}\frac{C_{out}}{(2C_{\text{int}} + C_{out} + 2C_{ext})} \quad \text{or} \tag{5}$$

$$C_{ext} \geq \frac{f_S}{2\pi f_p}C_{out} - C_{\text{int}} - C_{out}/2\,, \tag{6}$$

where f_p is the cutoff frequency of the LPF and has a value equal to 1Hz, fs is the master cutoff frequency of the chosen CAM, $C_{\text{int}} \approx 7.9\,pF$ и $C_{out} \approx 0.63\,pF$ (for the chosen FPAA system).

Finally, *SquareRoot1* CAB extracts the effective value of the ac input voltage.

By routing of the electrical connections between the configurable modules represented in the above paragraphs, within ANADIGM DESIGNER 2 program the complete electrical circuit of the converter was constructed.

Development of input and output stage

Since the supply voltage was equal to 3.3V, the possible range of variation of the input and output voltages was [0, 3] V. Very often, a lower value, such as 2.8V, is selected to avoid the saturation mode of operation. When the input symmetric source has a "floating point" and small amplitude, the input port, as shown in **Fig. 2**, can be configured to use an internal input chopper-stabilized amplifier. This allows small input differential signals to be accurately amplified so that they will be less affected by larger input offsets in the switched capacitor core of the FPAA. A reconstruction filter *FilterBiquad1* was connected to the output port of the amplifier to remove the higher frequency components introduced into the signal by the clocked switched capacitor CAMs constructed within the FPAA. The filter corner frequency was set based on the signal frequency and the sample clock rate.

Since the chopper amplifiers do not provide on their input terminals + 1.5V or +2V, it was necessary to add two resistors connected between the differential inputs and the VMR output, as shown in **Fig. 2**. The resistances have to be significantly larger than the internal resistance of the signal source, which had a relatively high value for this type of signal.

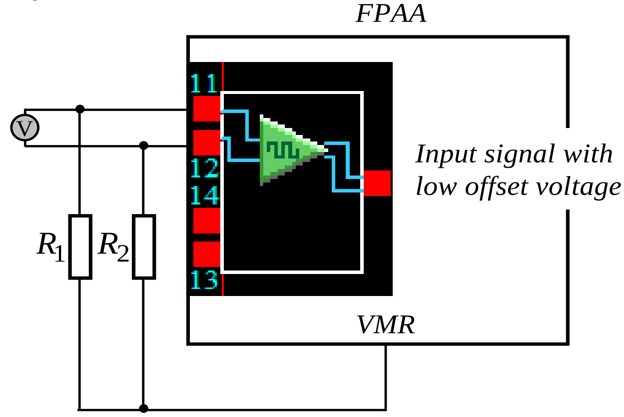


Fig. 2. Circuit for a symmetrical analog signal to a differential input of FPAA using internal chopper amplifier.

To obtain the output voltage from FPAA it can be used a circuit diagram of a difference amplifier in Fig. 4. The difference amplifier circuit uses an op-amp MPC6024 (from Microchip), which is a precision amplifier (with a maximum value of an input offset voltage equal to $\pm 500\mu V$) and can provide rail-to-rail input/output voltage. The maximum output positive voltage that occurs without limitation has value approximately equal to $V_{DD}^{+} - 20mV$. The power supply voltages of the op-amps can be set to values that are within the range from 2.5V to 5.5V, which is in the possible voltage ranges of FPAA systems.

To avoid damage of the op-amps, rectifier diodes D_1 and D_2 are also connected between the input terminals and the positive supply voltage. The D_1 and D_2 protect the input terminals when the input voltages become larger than the voltage drop of a forward-biased *pn* junction. Moreover, the resistors also limit the possible increase of the input currents.For the circuit in **Fig. 3** the voltage gain was approximately equal to unity, taking into account the tolerances of the used resistors. Since the output voltages are referred to 1.5V removing this DC level was determined mainly by the mismatch in the resistance ratios.

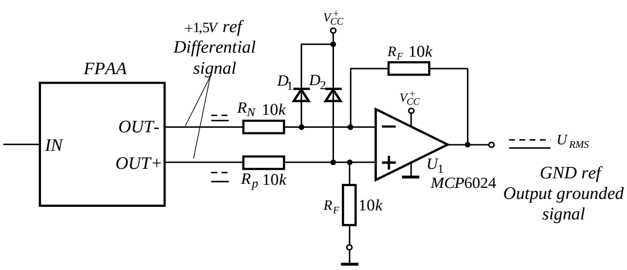


Fig. 3. An electrical circuit of a differential amplifier for obtaining output DC voltage from FPAA.

Experimental

Materials/chemicals details

Zinc oxide doped by gallium target (3 inches) with a purity of 99.998% was purchased from Kurt Lesker for the piezoelectric film. Gold target (2 inches) with purity 99.999% was purchased from Goodfellow for electrode films. Piezoelectric uniaxial polymer polyvinylidene fluoride (PVDF) with a piezoelectric coefficient of 20 pC/N was purchased from Goodfellow for smoothening piezoelectric layer decreasing the total dissipation factor. Silicon wafers with crystallographic orientation <100> purchased from Sil'tronix were used as substrates.

Characterizations/device fabrication/response measurements

The piezoelectric sensors used in this work were not commercial, but laboratory-made. Silicon wafers were cleaned following the standard procedure for removing the native SiO_2 in diluted water solution of hydrofluoric acid, acetone supersonic bath and deionized water rinsing. Zinc-gallium oxide films were synthesized by sputtering of ZnO doped by gallium target with additional oxidation during growth. The vacuum chamber was evacuated to 10^{-6} Torr, the oxygen partial pressure was 10^{-4} Torr and the total sputtering pressure (argon + oxygen) was 10^{-2} Torr. Sputtering power was 25 W/cm^2. Gold electrodes were DC sputtered at plasma current 35 mA. Patterning procedure was lithographic-free and was made by a stencil mask applied for square electrodes formation. The area of the sensors was 4 cm^2. The thickness of the implemented piezoelectric oxide films was 560 nm and the average surface roughness was approximately 18 nm. PVDF solution in methylethylketone (MEK) solvent was prepared for spin-coated layer of 950 nm over the zinc-gallium oxide coating, making the contact surface at the electrode interface zone smoother (an average roughness was 12 nm) without to suppress the piezoelectric effect.

The films' thickness and surface roughness were measured by surface scanning with Alpha-step Tencor. Chemical composition and bonds states of the layers were determined by Fourier Transform Infrared Spectroscopy (FTIR) to identify the presence of the typical piezoelectric groups. It was used Shimadzu spectrophotometer IRPrestige-21 in transmission mode. Device mass loading was conducted with reference vibrational setup with controllable magnitude and frequency of loading, causing the sample to experience cycling tensile and compression stress. The AC piezoelectric response and the produced current were controlled by Agilent 34410A 6 1/2 digital multimeter and additionally observed with digital oscilloscope DQ5202. Converted DC voltage was recorded by Voltcraft VC 820 voltmeter connected with PC.

Results and discussion

Materials characterization

FTIR study reveals bands typical for ZnO:Ga_2O_3, which is proof that the sputtering conditions were properly selected and the resulting films possess the necessary piezoelectric properties as expected (**Fig. 4a**). The deposition process doesn't affect the resulting film's stoichiometry.

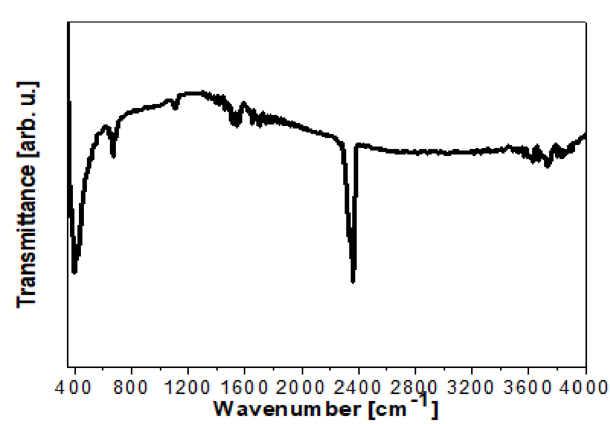


Fig. 4. FTIR spectrum of a thin zinc-gallium oxide film;

The two clear peaks around 2340-2360cm^{-1} are due to CO_2 presence in the air as the FTIR measurements are performed in air. The weak absorption band at 1531cm^{-1} can be due to C=O. All other bands could be attributed to the zinc oxide:gallium oxide presence. Below 1000 cm^{-1}, metal-oxygen vibrations characteristic for this composition occur. The absorption bands in spectral range 615-670 are due to stretching modes of Zn-O, as was reported in [**13**].

For Ga_xO_x system, the absorption lines appear at: 690 cm^{-1} – Ga_2O bending mode, 621 cm^{-1} – Ga-O band, deformation modes of Ga_2O_6 octahedra are at 418 and 472 cm^{-1}, the bending and stretching vibrations of GaO_4 units are in the range 630-767 cm^{-1}. These bands are typical fingerprints in this case, as was previously reported in [**14**].

The average roughness of the coating was measured ~ 12 nm for a total thickness of 1500 nm and a scanned length of 200 µm. Thus, the smoothening effect of the PVDF insertion is expected to improve the electrode contact conditions, playing a role for the stable piezoelectric signal.

Device electrical characterization and sensor response

To investigate the efficiency of the proposed FPAA based RMS-to-DC converter, with additional input and output stages, shown in Fig. 2 and Fig. 3, a prototype using the AN231K04-DVLP3 development system built around the FPAA AN231E04 was synthesized. AN231E04 was biased with a single power supply voltage equal to +3.3V. To test the electronic circuit input sinusoidal signals with a frequency of 20Hz and 50Hz are applied. **Fig. 5(a)** and **Fig. 5(b)** shows the relative error depending on the effective output value at non-distorted sinusoidal input signal with frequency of 20Hz and 50Hz, respectively. As can be seen, the maximum value of the error was below 5%, which guarantee a sufficient degree of accuracy. The value of the error for the crest factor (CF) was approximately with the same value.

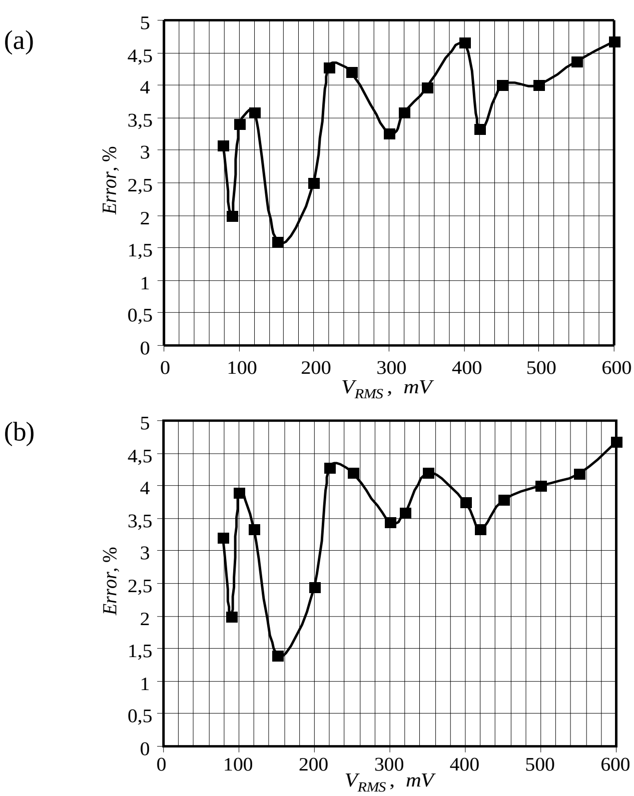


Fig. 5. Relative error depending on the output effective value: (a) at non-distorted sinusoidal input signal with a frequency of 20Hz; (b) at non-distorted sinusoidal input signal with a frequency of 50Hz.

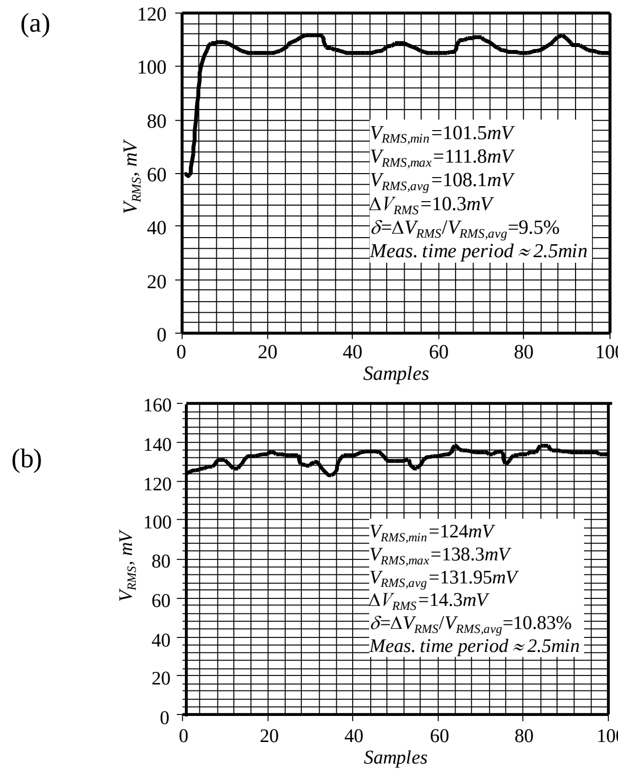


Fig. 6. Output DC voltage: (a) at 80g; (b) at 100g mass loading, where samples are the number of scanned and recorded voltage values, corresponding to vibrational cycles.

Fig. 6(a) and **Fig. 6(b)** show the output DC voltage proportional to the RMS value of the input AC signal, produced by piezoelectric sensors, at two values of the mass loading (80g and 100g). As can be seen, for mass loading 80g and 100g the deviation was equal to 10.3mV and 14.3mV, respectively. Based on those values to relative deviation according to the average values are equal to 9.5% and 10.83%, which guarantee good degree of accuracy taking into account the tolerances of the parameters of the sensors.

Conclusion

The results demonstrate fabrication of transducers with novel lead-free piezoelectric oxide successfully working as a mass loading detector. The devices exhibited stable piezoelectric response at relatively weak mass load and low frequency. They showed sufficient piezoelectric yield, in order to convert the generated AC piezoelectric voltage to useful DC signal with parameters value sufficient and suitable for real application. For those types of sensors used as a mass loading detector new original solution of interface circuit and sensor signal processing based on dynamically programmed FPAA system is proposed. The developed approach to estimate the sensors is based on the classical RMS-to-DC converters used direct method, as the implemented circuit allows dynamically programming of the electrical parameters for the CAMs according to the amplitude, frequency range, and noise level of the input signal. This approach is proposed for first time to estimate such types of sensors.

Future work will be related to precisely determine the response and recovering time, as well as longer-term reliability.

Acknowledgements

The work was supported by the Bulgarian National Science Fund, grant number КП06-Н27/1. The authors are thankful to Dr. Tatyana Ivanova from CL-SENES, BAS for the FTIR measurement.

Conflicts of interest

There are no conflicts to declare.

Supporting information

No supporting informations are available.

Keywords

Analog processing circuits, piezoelectric transducers, Thin film sensors, Lead-free materials, FPAA, RMS to DC converter.

Received: 15 March 2020
Revised: 23 April 2020
Accepted: 04 May 2020

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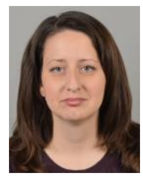
Authors biography

Ivailo Pandiev received the M.S. degree in electronic and microelectronic engineering, and the Ph.D. degree in electronic circuit theory from the TU-Sofia, in 1996 and 2000, respectively. Since 2006, he has been an Associate Professor with the Department of Electronics and the Head the Analog Electronics Laboratory, TU-Sofia. He is the author or co-author of 14 books and 130 papers in international journals and conference proceedings. His current research interests include analog mixed-signal circuit design.



Mariya Aleksandrova received her MSc degree in electronics and the Ph.D. degree in technology of electronic manufacturing from the TU-Sofia, in 2007 and 2010, respectively. Since 2015, she is an Associate Professor with the Department of Microlec-tronics, TU-Sofia. She is an author or co-author of 6 books and more than 80 papers in international journals and conference proceedings. Her current research interests include microelectronic technologies, MEMS, piezoelectric energy harvestig, flexible electronics. films, vacuum deposition.

Graphical abstract

An interface electronic system for thin film piezoelectric sensing structures is presented. The prototype of the system based on dynamically programed Field Programmable Analog Array (FPAA) AN231E04 is configured to implement Root-Mean-Square (RMS) to DC (RMS-to-DC) conversion process, based on direct (or explicit) method. Possible applications of the system could be flow sensing, tactile sensors, mass balances and etc.