Investigation of Sensitive Element for Pressure Sensor Based on Bipolar Piezotransistor

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Abstract

The paper summarizes results of investigation of high-sensitivity MEMS pressure sensor based on a circuit containing both active and passive stress-sensitive elements: a differential amplifier utilizing two n-p-n piezotransistors and for p-type piezoresistors. A comparative analysis of a sensor utilizing this circuit with a pressure sensor based on traditional piezoresistive Wheatstone bridge and built on the same mechanical part is provided. MEMS pressure sensor with the differential amplifier (PSDA) has sensitivity of S = 0.66 mV/kPa/V, which exceeded the sensitivity of the element with piezoresistive Wheatstone bridge (PSWB) by 2.2 times. The sensitivity increase allows for the following sensor improvements: die size reduction, increase of diaphragm mechanical strength while keeping high pressure sensitivity, and simplifying requirements to external processing of the pressure sensor output signal. There are two main challenges related to the use of PSDA-based pressure sensors: strong dependence of output signal on temperature and higher than in PSWB noise reducing the dynamic range of the device to 10^3. The article describes methods of addressing these problems. The temperature dependence of sensor output signal can be minimized with help of an offset thermal compensation circuit and by eliminating metallization at the thin part of the diaphragm. The noise can be minimized by reducing the thickness of the active base region of the transistor. Circuit analysis with software NI Multisim shows that sensitivity of PSDA-based pressure sensor can be increased 2.3 times by circuit optimization.

Keywords: sensitive element, pressure, on-chip differential amplifier, piezotransistor, piezoresistor, temperature characteristics, noise

Introduction

Development of the resistive sensitive elements (dies) of the pressure sensors (PS) in the form of microelectromechanical system (MEMS) are aimed at improvement of the operating characteristics, where sensitivity is most significant parameter [1-4]. Increase of sensitivity can contribute indirectly to solving of the following tasks:

- Conservation or minimization of the die's dimensions;
- Increase of strength for MEMS.

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Let us explain each problem separately. The first task: development of PS dies (especially for the small ranges ($P < 1$ kPa)) is requires increase area of mechanical part (membrane) and die (which is limited by the overall dimensions of case), decrease of pressure of destruction and it has not a positive factor for the microelectronics, which aspires to minimization of the elements. The second task: at certain dimensions of a die and geometry of the stress concentrators (rigid islands (RI)) functioning in the lower pressure ranges is reached by reduction of membrane thickness, which is side effect of sharply pressure decrease of membrane destruction. Developments with strength of membrane due to additional design elements in the form of stopper is achieved [5]. Such additional elements can increase the temperature coefficient of the zero signal (TCZ) of PS. For decrease influence of the stoppers on TCZ used additional etched areas in die, which removing parasitic mechanical stresses from bridge circuit. Such methods in totality complicate realization of the technological process. The cardinally new MEMS is solution to the above described problems. The essence of MEMS consists in sensitive element has not only passive components p-type resistors (the elements applied since 1960s). New sensor have additional active elements in the form of vertical bipolar n-p-n transistors (the given choice is not the only one. In future it will be possible to develop relatively bipolar p-n-p transistors [6-15]).

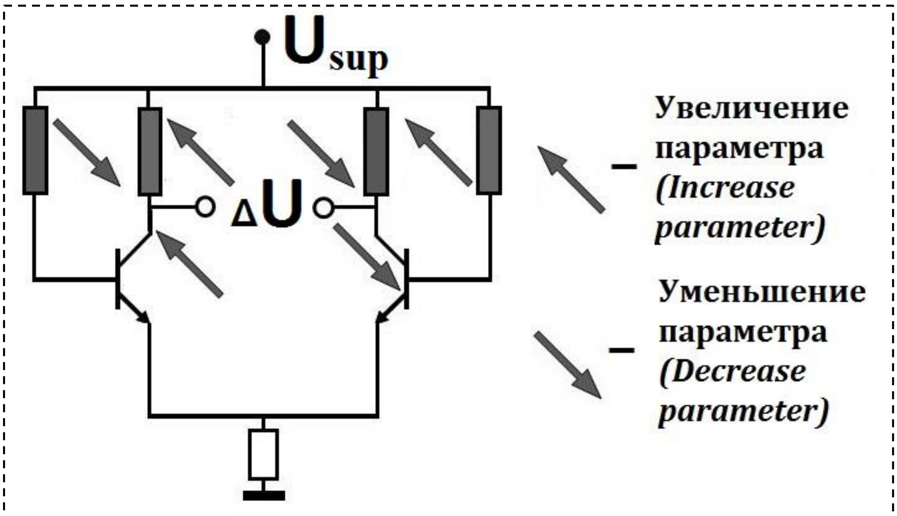

Fig. 1. Die with electrical circuits of differential amplifier

Instead of widespread element with piezoresistive Wheatstone bridge (PSWB) employing four piezoresistors (PR) we have pressure sensor with the differential amplifier (PSDA) (fig.1) is proposed, which uses four PR and two bipolar piezotransistors (BPT). In case of equal mechanical parts of the dies the circuit PSDA has an advantage in sensitivity compared with the standard PSWB.

Development of PSDA

Development of die's PSDA circuit was based on the research of piezoresistive effect for individual BPT. By the results of a review [16-20] and analysis of experimental sample in the form of individual BPT (circuit with common emitter) located separately on thin part of elastic element of die's PSWB (fig.2). Foundation of theory for BPT based on two effects:

1. Anisotropy of mobility of minority carriers in the base;
2. Piezoresistive effect of base's resistive.

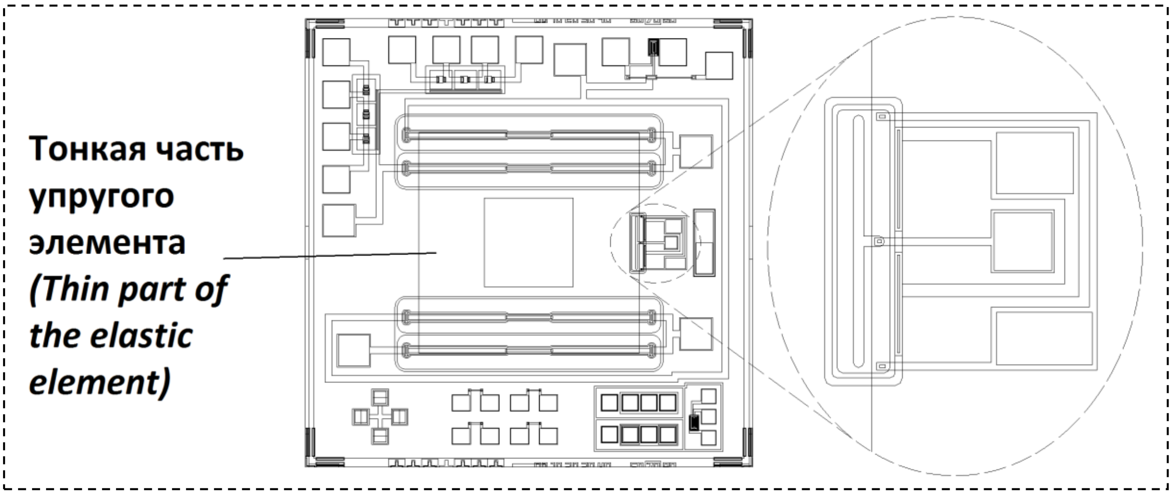

Fig. 2. Die with electrical circuits of Wheatstone bridge and with separately formed BTT

For die's PSDA was constructed model based on theoretical calculation of variation electric parameters and analysis of mechanical stresses (fig.3) in ANSYS system. A comparison of the results modeling and experimental data (table 1) shows a satisfactory convergence for variation amplification coefficient and resistance. In table 1: $\delta\beta_{1,2}$ – relative variation of transistor amplification coefficient, $\delta R_{C1,2}$ – relative variation of transistor collector's resistance, $\delta R_{B1,2}$ – relative variation of transistor base's resistance.

Table 1. Relative change of parameters for strain elements of the TDC crystal at a pressure P = 100 kPa from the side of the membrane

Данные / Параметр *Data / Paramet*		*ANSYS*	Практика *Practice*
Сжатие *Compression*	$\delta\beta_1$	+5,5 %	+7,9 %
	$\delta R_{К1}$ δR_{C1}	+5,9 %	+8,7 %
	$\delta R_{Б2}$ δR_{B2}		
Растяжение *Extension*	$\delta\beta_2$	-4,4 %	-5,2 %
	$\delta R_{К2}$ δR_{C2}	-4,2 %	-4,5 %
	$\delta R_{Б1}$ δR_{B1}		

Technological parameters and nominal for piezoresistive circuit as result of modeling were selected, which are presented in table 2, where R_B – resistance of transistor base, R_C – resistance of transistor collector, β – amplification coefficient of transistor at I_{BE} = 14 μA, R_{ext} – external resistance insensitive to pressure, I_{BE} – transistor base current, A_{die} –area of die's PSDA, W_{memb} – thickness of the membrane, A_{RI}– area of RI, P – power emitted on electric circuit of die's PSDA, $U_{res\ CB}$ – breakdown voltage of reverse branch transistor's volt-ampere characteristics.

Table 2. Die's electrical and mechanical parameters

Параметр *Parameter*	Значение *Value*	Размерность *Dimension*
$U_{пит}$ U_{sup}	2,0	В *V*
$R_Б$ R_B	5,40	кОм *kOhm*
$R_К$ R_C	0,48	кОм *kOhm*
β	108	
$R_{ВНЕШ}$ R_{ext}	100	кОм *kOhm*
$I_{БЭ}$ I_{BE}	14	мкА *μA*
$U_{проб\ КБ}$ $U_{res\ CB}$	70	В *V*
$A_{кр}$ A_{die}	4,0 x 4,0	мм *mm*
$W_{мемб}$ W_{memb}	28	мкм *μ m*
$S_{мемб}$ S_{memb}	2,0 x 2,0	мм *mm*
Количество ЖЦ *Numbers of RI*	1	
$A_{кр}$ A_{die}	1,2 x 1,2	мм *mm*
P	2,3	мВт *mW*

Series of die's PSDA topologies were developed. From the set of topologies was choose optimal version (presented in fig.4). One of the initial versions die used Darlington transistor connection as active part circuit of piezoresistive elements. The given connections lead to essential noise component of output signal, at which measurement of the sensitivity is actually not possible.

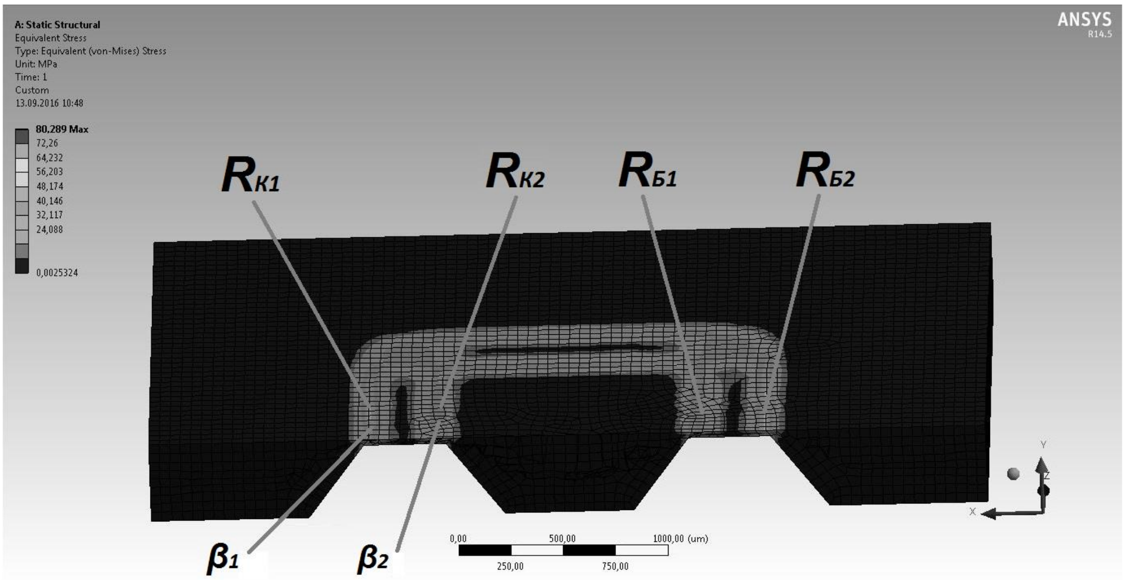

Fig. 3. Mechanical stresses of silicon membrane and the arrangement of strain elements on die

Results and discussion

The positive effect about increase of the sensitivity reached in practice. Parameters of equal mechanical parts for two integral sensitive elements (table 1) have output sensitivity of PSDA die (fig.4) equal to S = 0.66 mV/kPa/V, which 2.2 times exceeded values of PSWB die (fig.2).

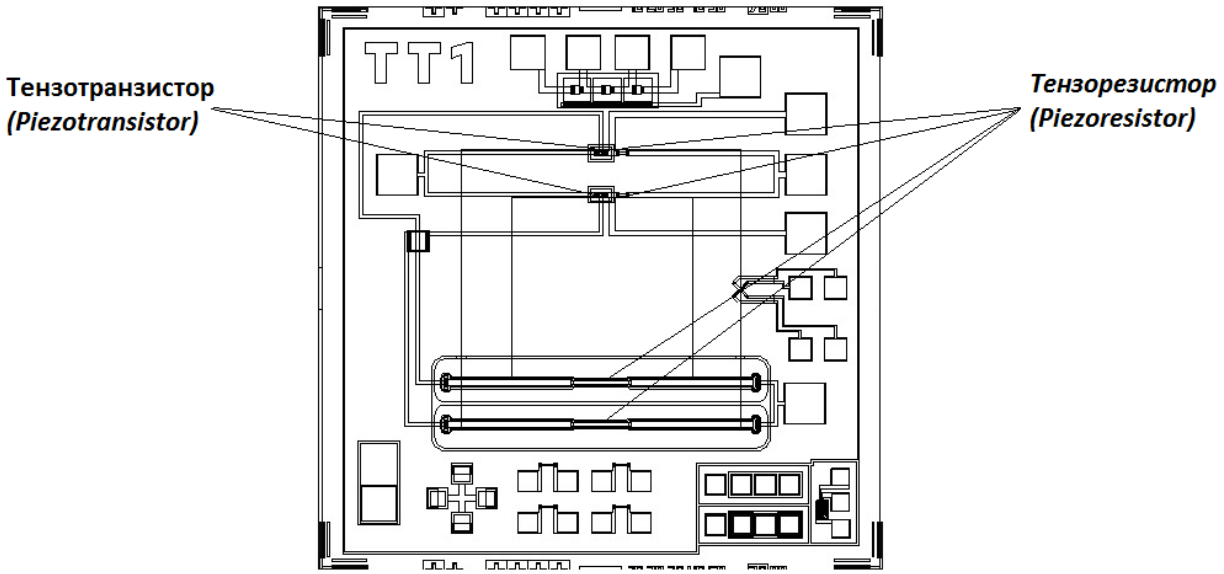

Fig. 4. Topology of die PSDA

Investigation of functioning mode of the PSDA die was analyzed for output sensitivity of S circuit and amplification coefficient β for BPT.

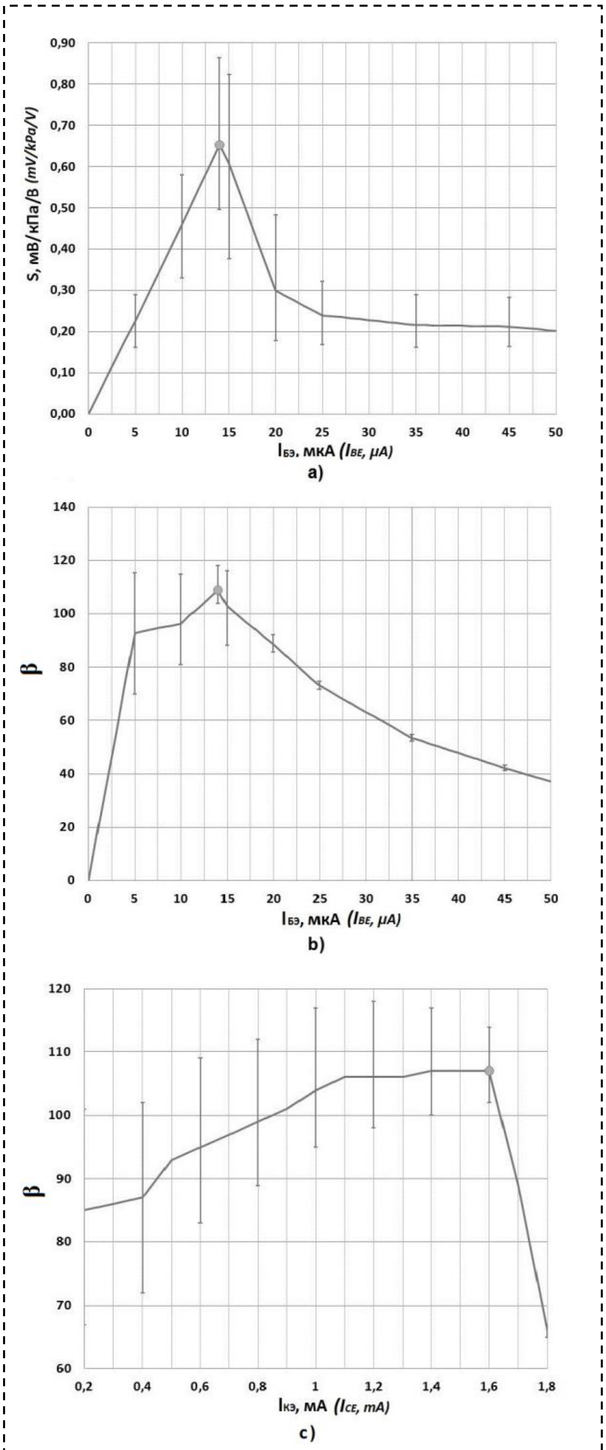

Fig. 5. Dependencies: a) sensitivity S by current of basic's circuit I_{BE}, b) gain β by current of basic's circuit I_{BE}, c) gain β by current of collector's circuit I_{CE}

Diagrams of dependences sensitivity on base's current (fig.5, *a)* and amplification coefficient on base's and collector's current (fig.5, b, c) presented maximum function in «the point of inflection», which exchanged BPT from active mode to saturation mode, was reached. The maximum function at I_{BE} = 14 µA (U_{CE} = 2 V) is reached. Research of dependence sensitivity and amplification coefficient on voltage U_{CE} ($U_{CE} = U_{sup}$ for the circuit (fig.6)) demonstrated maximum function, which belonged to a rather big range.

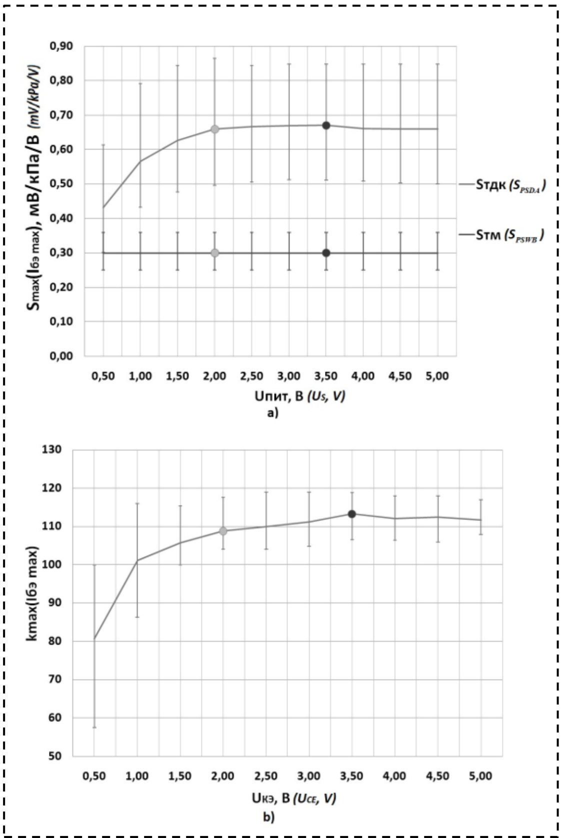

Fig. 6. Dependencies: a) sensitivity S by voltage of base's circuit U_{CE}, b) gain β by voltage of base's circuit U_{CE}

Let us compare two working points of the circuit: at the moment of achievement of extremum by the function with supply voltage U_{sup} = 3.5 V and at the moment of beginning of "the shelf" maximum sensitivity at U_{sup} = 2.0 V. Lower supply voltage has insignificant decrease of sensitivity (< 1 %), but noise's component of output signal is minimized (> 40 %) and unbalance of circuit (> 50 %). Dependence of output signal PSDA die is a linear in working range of measurements 0 … 60 kPa (fig.7).

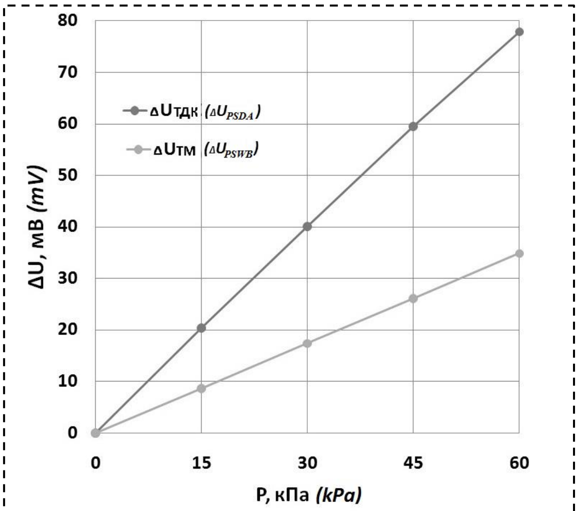

Fig. 7. Linear dependence of output signal by pressure

Investigation of PSDA die has negative moments of development. Characteristics had two recoverable problems: the temperature characteristic and the noise component of output signal. TCZ reached the value of 0.65 %/^{0}C and the temperature hysteresis of zero signal (THZ) was equal to 1 %. High value of TCZ is a result of a high temperature dependence of the transistor TCβ = 0.6…0.9 %/^{0}C, which has a linear character in the range of temperatures of T = 30…+80 ^{0}C [21, 22]. We want to reduce the effect by creation of the circuit of temperature-compensation of the zero signal, which functioning by the principle described in [23] with mirror reflexion of circuit on a unstressed area of die. Reason of high value of THZ is arrangement of metalized paths on the thin part of elastic element. The difference of temperature coefficients' linear expansion for silicon and metal was reason no return of the zero signal. Metal on membrane can be avoided due shift of the transistor areas to unstressed area of die. The second recoverable drawback of PSDA die is a high noise component of output signal. We want to reduce the noise by change of the technological norms for transistor designing, i.e. necessary to reduce the thickness of the base BPT [24]. When thickness of the active base in the present samples has value $W_{act\ base}$= 0.8 micrometers and voltage U_{CE} = 2 V is dynamic range lowered down to 3 orders (ΔU_{noise} = ± 150 µV). In case of selection of working point's BPT with lower voltage U_{CE} = 0.5 V (fig.8) was decreased more than 6.5 times of noise component, less considerable decrease of output sensitivity by 35% (S = 0.43 mV/kPa/V) and sharply decrease of average unbalance of output signal from 26 mV to 3 mV.

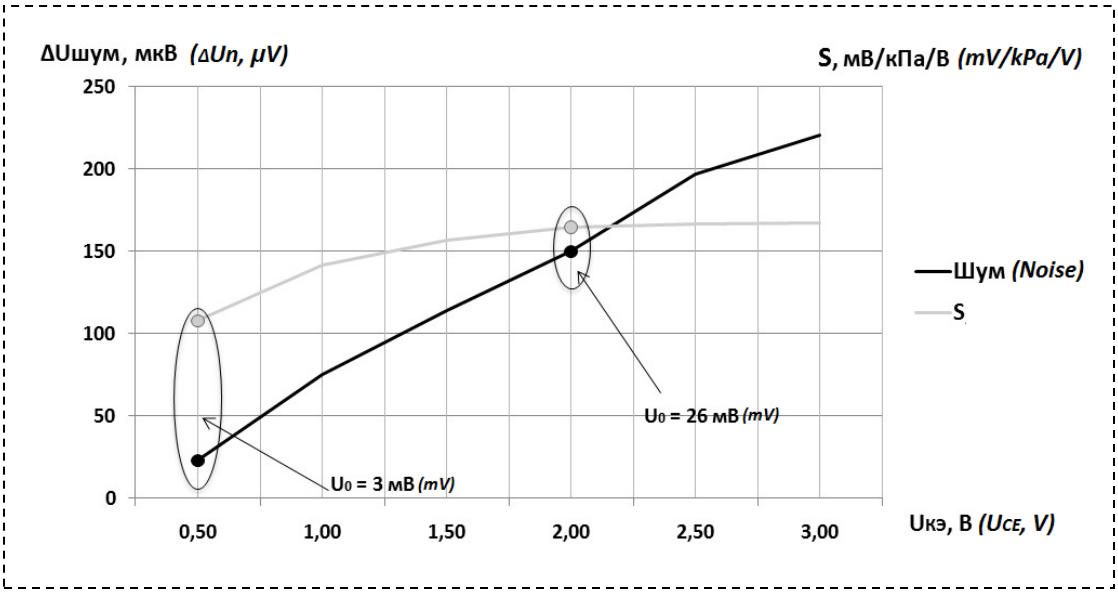

Fig 8. Dependences of noise's component from output signal and the sensitivity by voltage U_{CE}

PSDA die can be modernized for increase output sensitivity owing to variation of nominal's elements. Modeling was done with a simulator of electric circuits (SPICE) in NI Multisim software. Used values of relative change nominal's elements are presented in table 1. Reproduction of sensitive element received in practice with account of basic technological parameters of BPT (the potential of field of the base – emitter junction U_{BE} = 0.68 mV, the reverse current of collector junction I_B = 1 nA). Values of sensitivity S of modeled system coincided exactly with results of experiment S = 0.66 mV/kPa/V (fig.9, a). Variation of nominal elements (R_C = 2.2 kOhm, β = 50) and supply voltage (U_{sup} = 5 V) will allow us to raise potentially sensitivity 2.3 times relatively S = 1.51 mV/kPa/V (fig.9, b).

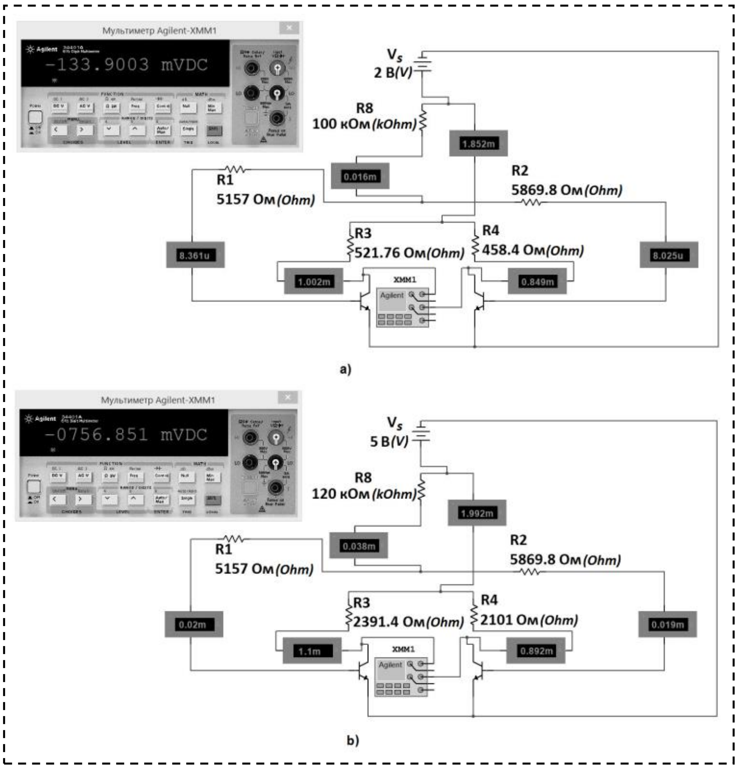

Fig. 9. Modeling of circuit for: a) samples obtained in practice, b) samples with changed values of elements

Conclusion

Use of BPT as the elements of the circuit for pressure sensitive element raises output sensitivity. The drawbacks of PSDA are temperature characteristics and noise component of output signal are recoverable. As an additional factor increasing the thermostability (and also the sensitivity) of circuit is creation of PSDA die, which in differential amplifier uses resistors of base divider and resistor of emitter circuit for realization of negative feedback. The subsequent improvement of all above described methods for modernization of PSDA die will allow us to receive the sensitive elements, which surpassing by the quality of certain parameters the analogues on resistive Wheatstone bridge.

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