Investigation of sensitive element for pressure sensor based on bipolar piezotransistor

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Research Article

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Abstract

The article translated from Russian to English on pp. 691-693 (please, look down). 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.

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.

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]).

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.

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.

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.

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.

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).

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

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.

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).

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.

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).

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.

Declarations

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Competing interests: The authors declare no competing interests.

References

1. **Gusev E.P., Garfunkel E., Dideikin A.** Advanced materials and technologies for micro/nano-devices, sensors and actuatos. History of early research on MEMS in Russia (U.S.S.R) / NATO Science for Peace and Security Series B: Physics and Biophysics. 2010. Pp. 3-30. DOI: 10.1007/978-90-481-3807-4

2. **Belov N.S., Lihua L., Kim V., Dinh V.** Low pressure sensors and flow sensors // Patent USA. US2015192487 A1. 2016.

3**. Li L., Belov N.S., Klitzke M., Park J.-S.** High performance piezoresestive low pressure sensors // Article for IEEE Sensors 2016 conference. 2016. Pp. 1-4. DOI: 10.1109/ICSENS.2016.7808875

4. **Ignateva E.V., Mikhajlov Ju.A., Timoshenkov S.P.** About the design of a membrane with a rigid center of crystals of silicon strain gauges at a pressure of 0.025 to 25 MPa // Nano- i mikrosistemnaya Tekhnika. 2010. No. 2. Pp. 24-31.

5. **Suhanov V.S., Danilova N.L., Pankov V.V.** Microelectronic pressure sensor with sensitive element protected against overload // Patent RF. RU2564376 C1. Pp. 1-14.

6. **Zhao X., Wen D., Li G.** Fabrication and Characteristics of an nc-Si/c-Si Heterojunction MOSFETs Pressure Sensor // MDPI «Sensors». 2012. No. 12. Pp. 6369-6379.

7. **Poljakova A.L.** On the sensitivity of p-n transitions to small deformations // Moscow. Akusticheskij zhurnal. 1967. №2. Pp. 256-261.

8. **Poljakova A.L.** Physical principles of operation of semiconductor sensors of mechanical quantities // Moscow. Akusticheskij zhurnal. 1972.

№1. Pp. 1-22.

9. **Vaganov V.I.** Integral strain gauges // Moscow. Jenergoatomizdat. 1983. Pp. 104-106.

10. **Poljakova A.L.** Deformation of semiconductors and semiconductor devices // Moscow. Jenergija. 1979. Pp. 124-128.

11. **Ageev O.A., Mamikonova V.M., Petrov V.V., Kotov V.N., Negodenko O.N.** Microelectronic converters of non-electrical quantities / Taganrog. Izd-vo TRTU. 2000. Pp. 54-65.

12. **Dan Mihai Stefanescu.** Handbook of Force Transducers / Springer. 2011. Pp. 49-68.

13. **Dragunov V.P., Ilenkov A.I.** Integral strain-sensitive element // Patent USSR. SU1610243 A1, 1990. Pg. 1-2.

14. **Ash. G.** Sensors of measuring systems / Moscow. Mir. 1992. Pp. 433-440.

15. **Middelhoek S., Date J.W. Noorlag.** Modern electronic measuring systems. Silicon microtransducer: a new generation of measuring elements / Delft university press. 1978. Pp. 16-17.

16. **Babichev G.G., Kozlovskij S.I., Romanov V.A., Sharan N.N.** Silicon two-emitter differential tensotransistor with an accelerating electric field in the base // Zhurnal tehnicheskoj fiziki. 1999. T. 69. No. 10. Pp. 63-68.

17. **Neizvestnyj I.G., Gridchin V.A.** The use of strained silicon in MOS and CMOS structures // Russian Microelectronics. 2009. No. 2. Pp. 71-86. DOI: 10.1134/S1063739709020012

18. **Kanda Y.** A Graphical Representation of the Piezoresistance Coefficients in Silicon-Shear Coefficient in Plane // IEEE Transactions on electron devices. 1982. Vol. ED-29, No. 1. Pp. 64-70.

19. **Vaganov V.I.** Electronic measuring technology. Moscow. Atomizdat. 1978. Pp. 124-130.

20. **Vaganov V.I.** Microelectronic pressure transducer // Patent USSR. SU1328700 A1. 07.08.1987. Pp. 1-2.

21. **Stepanenko I.P.** Fundamentals of the theory of transistors and transistor circuits / Moscow. Jenergija. 1977. Pp. 207-212.

22. **Titce U., Shenk K.** Semiconductor Circuitry / Moscow. MDK Press. T. 1. 2008. Pp. 74.

23. **Shahnov V.A., Andreev K.A., Tinjakov Ju.N., Vlasov A.I., Tokarev S.V., Civinskaja T.A., Cygankov V.Ju.** Semiconductor pressure transducer // Patent RF. RU2537517 C1. 10.01.2015. Pp. 1-6.

24. **Bogdan M. Wilamowski, David Irwin J.** Fundamentals of Industrial electronics / Taylor and Francis Group, LLC. 2010. Pp. 221-232.

Tables

Due to technical limitations, the tables are only available as a download in the supplementary files.

Figures

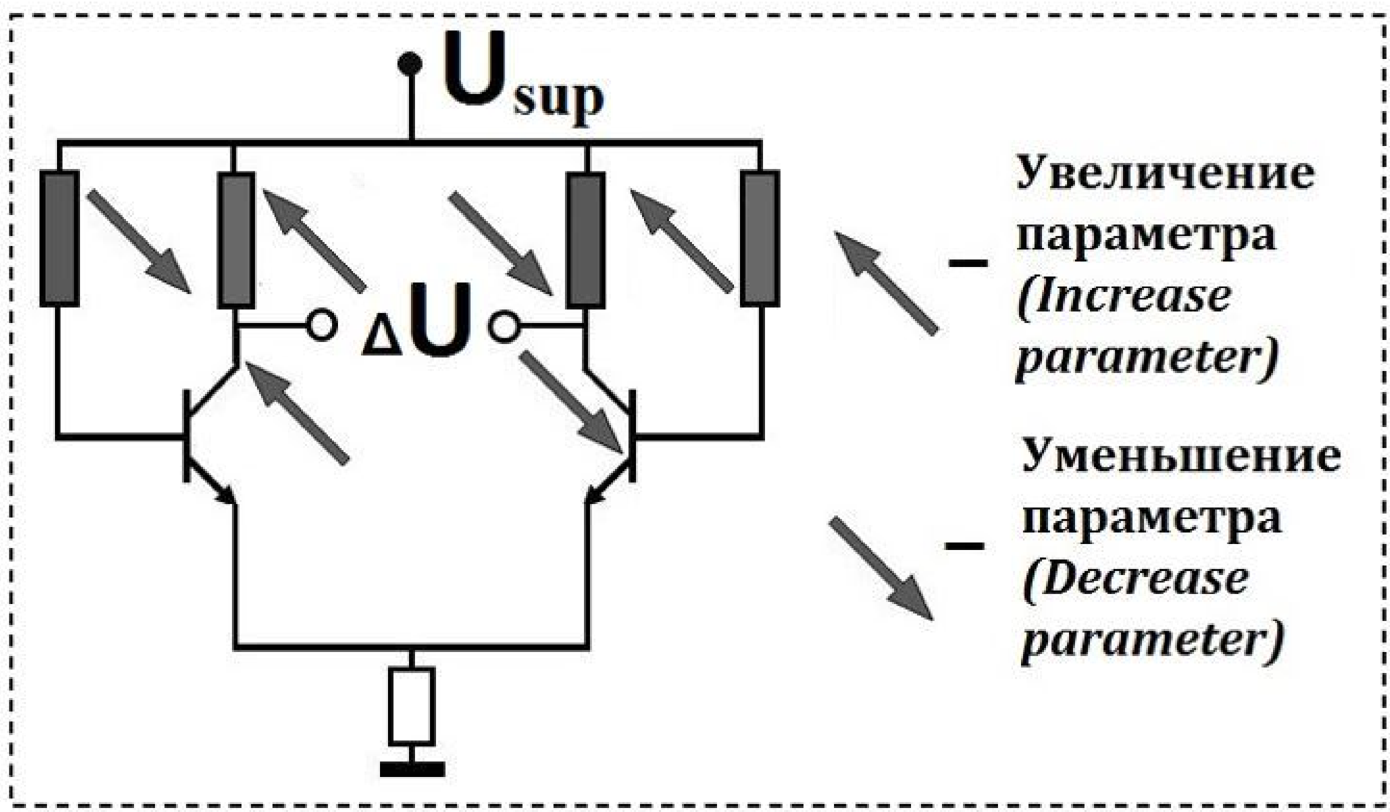

Figure 1

Die with electrical circuits of differential amplifier

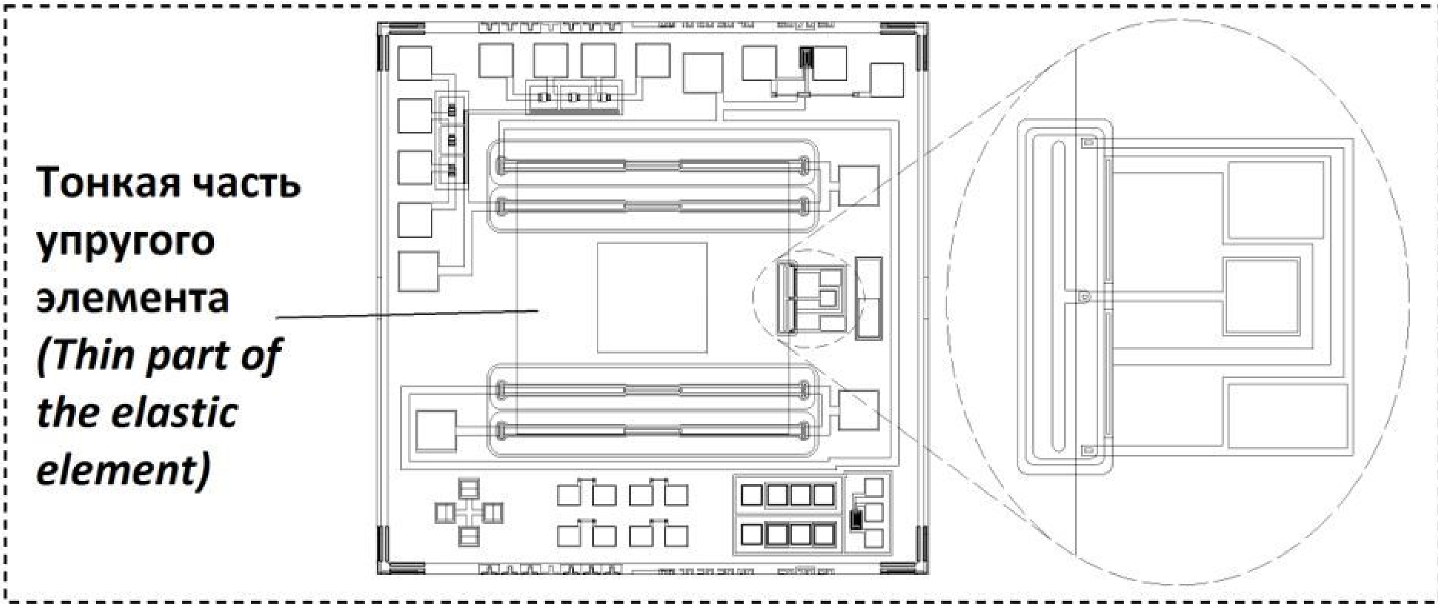

Figure 2

Die with electrical circuits of Wheatstone bridge and with separately formed BTT

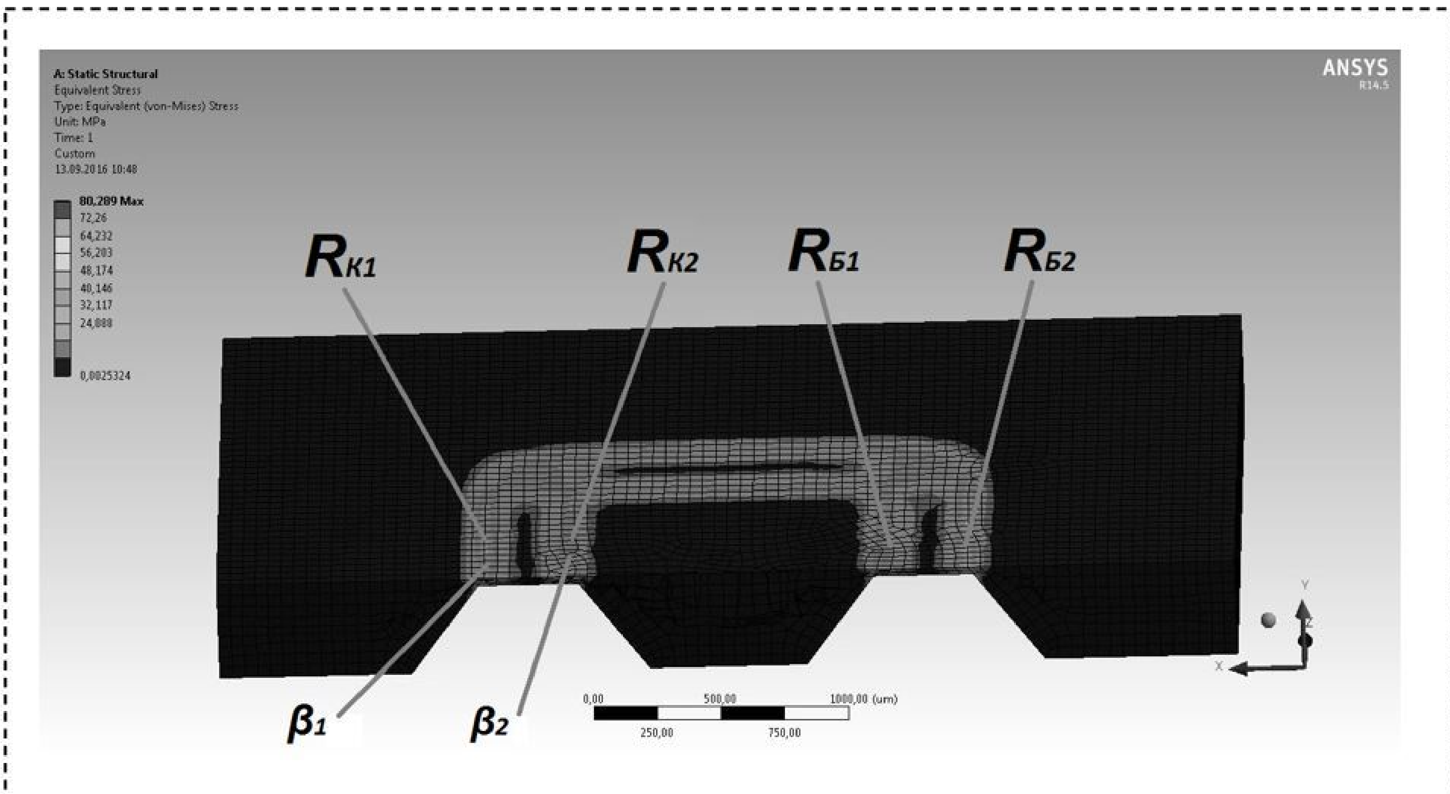

Figure 3

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

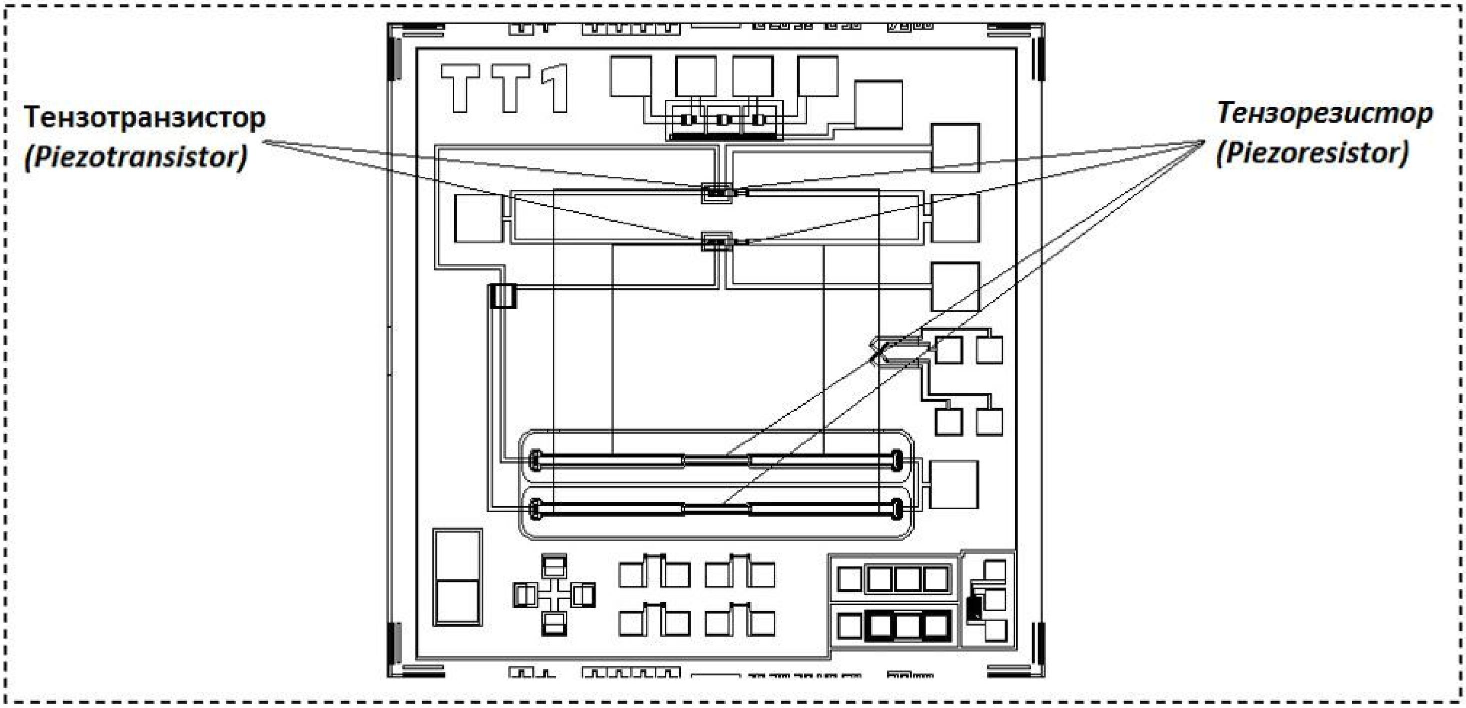

Figure 4

Topology of die PSDA

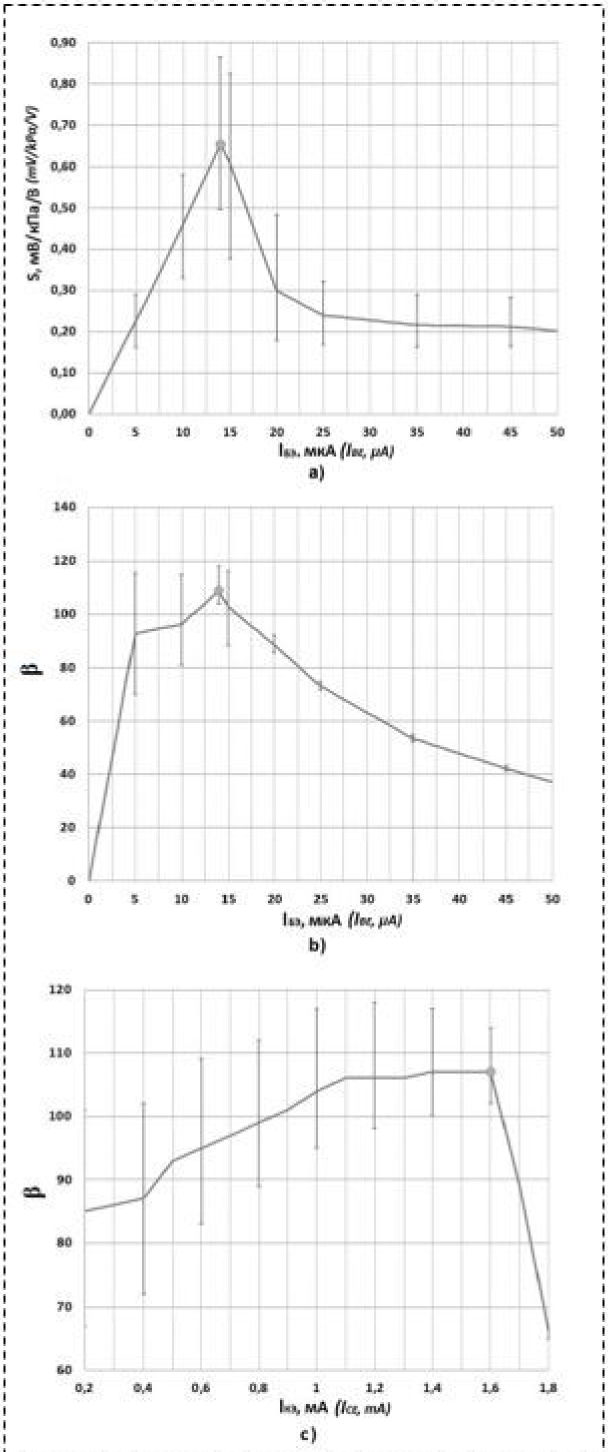

Figure 5

Dependencies: a) sensitivity S by current of basic's circuit IBE, b) gain β by current of basic's cir-cuit IBE, c) gain β by current of collector's circuit ICE

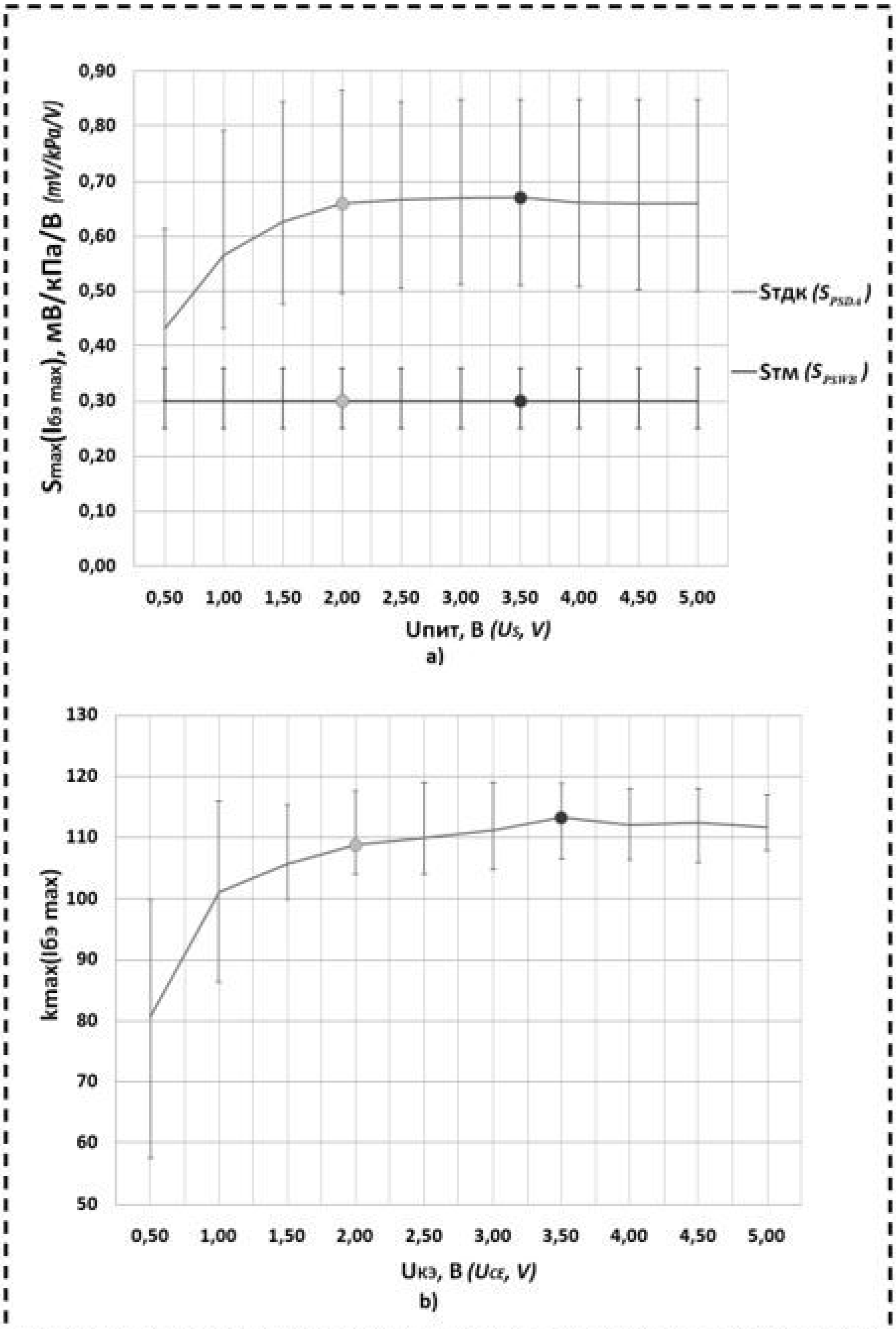

Figure 6

Dependencies: a) sensitivity S by voltage of base’s circuit UCE, b) gain β by voltage of base’s cir-cuit UCE

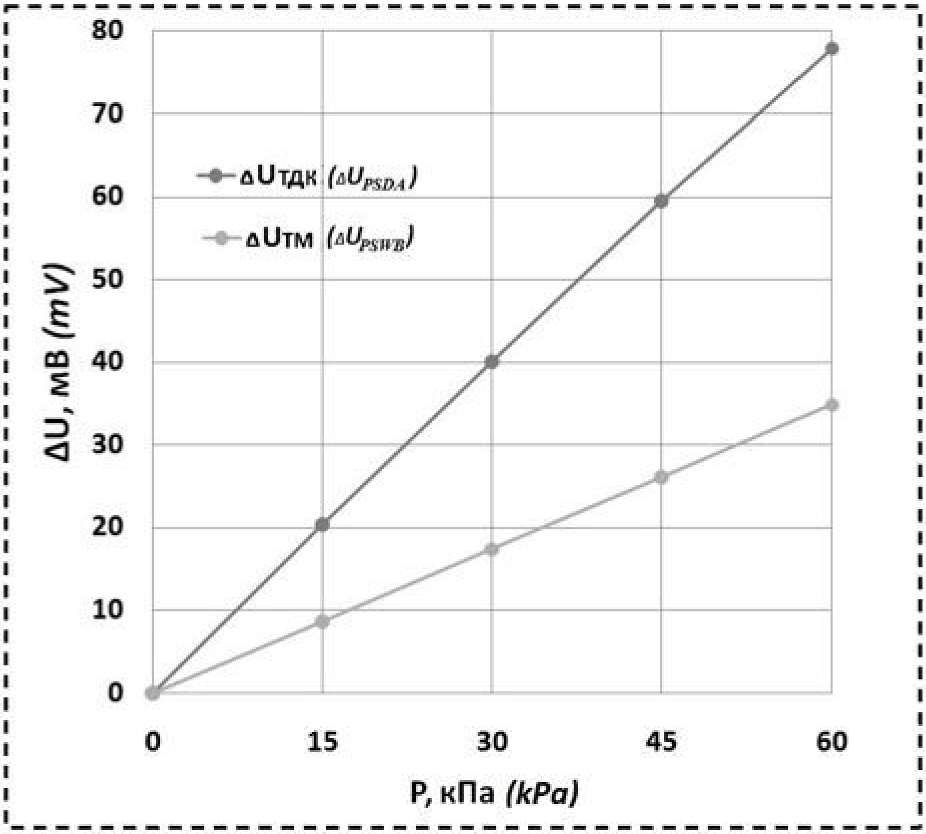

Figure 7

Linear dependence of output signal by pressure

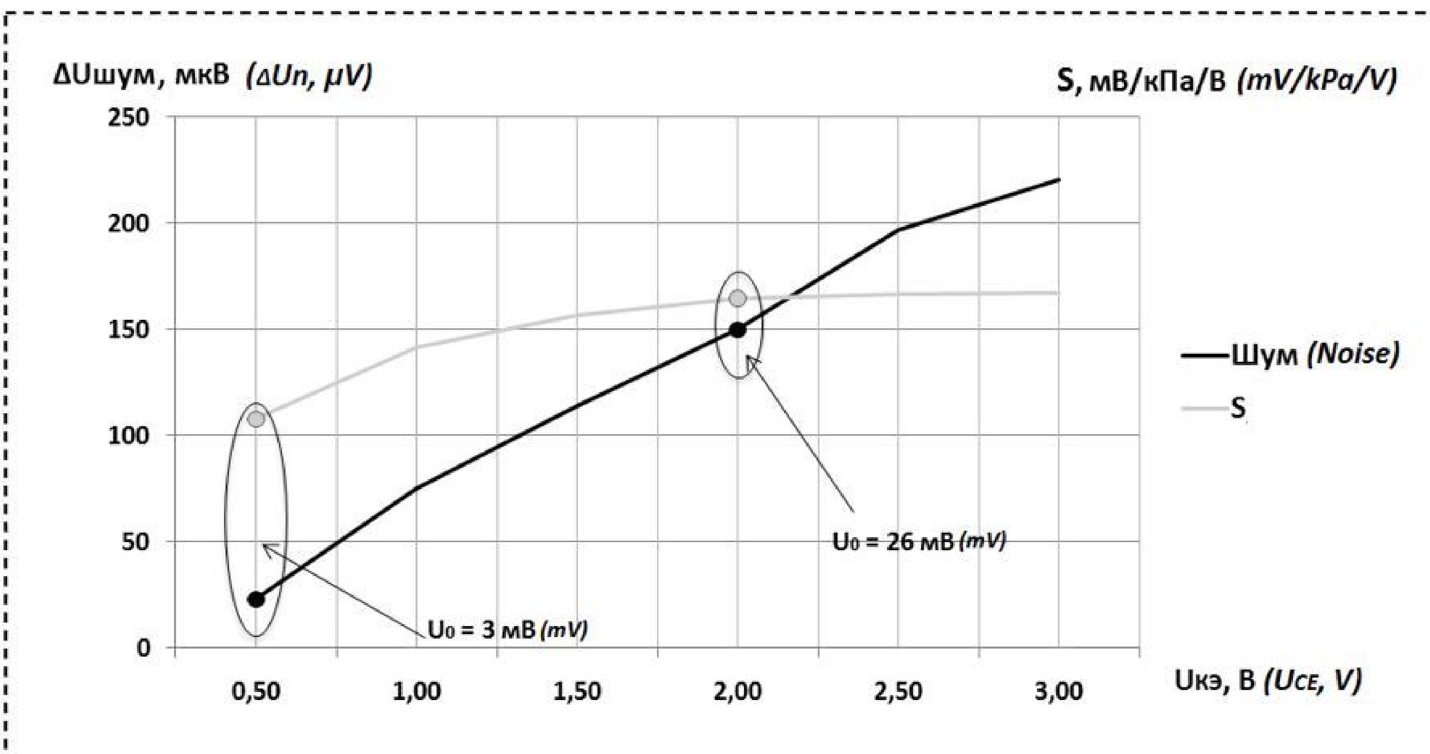

Figure 8

Dependences of noise's component from output signal and the sensitivity by voltage UCE

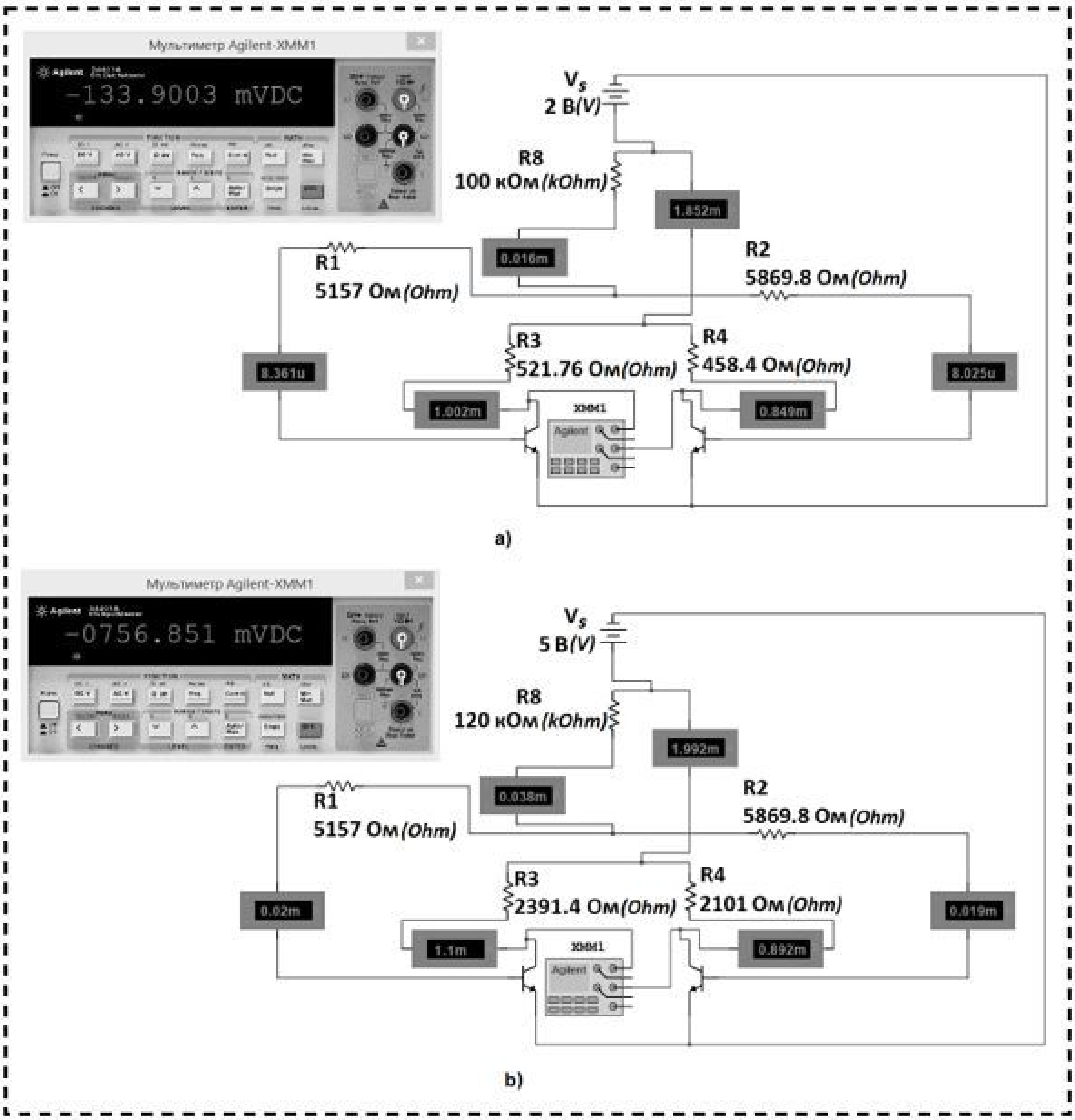

Figure 9

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

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