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Features of circuit-topological design and layout simulation of the operational amplifier on CMOS structures for biomedical applications

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The paper presents the results of circuit topological design and layout simulation of the operational amplifier based on complementary (CMOS) structures using the standard industrial planar CMOS technology on KDB-40 silicon wafers with n-type conductivity wells. The operational amplifier was developed for the implementation of an integral converter signals (ICS) of photoplethysmography, the feature of which is the amplitude regulation and filtering of the constant component in the amplified signal from the diode photosensitive element in the wave range of 400 ÷ 1040 nm. The developed ICS is suitable for creating real devices in an integrated implementation, as an element of sensor microsystems-on-a-crystal or smart sensors.

Keywords: sensor microsystem, integrated signal converter, photosensitive element, circuit design, operational amplifier, CMOS-structures.

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Introduction

Non-invasive methods of monitoring the state of human health are becoming more and more widespread, and with the use of both portable and stationary devices that work on the basis of photoplethysmography [1,2]. The physical principles of photometry for biomedical applications are given in [1]. Methods of determining the ratio of oxygenated and non-oxygenated fractions of hemoglobin in human blood are presented in [3]. Attempts at the practical use of these methods for non-invasive monitoring of hemoglobin and glucose levels in human blood are shown in works [4, 5]. A prototype of a portable biomedical device based on the analysis of optical absorption of light with frequency separation using interference filters is presented. But the required accuracy of determining the glucose level was not obtained, due to practically the same absorption coefficients of water and glucose at the selected frequency. Ways of increasing the accuracy of non-invasive monitoring of the glucose level by computational methods using spectral analysis are considered in works [6, 7], where with the help of methods of coordinated filtering of the absorption spectra of various blood components, it was possible to significantly increase the accuracy of the measurement. The problems of choosing frequencies, radiation sources and receivers for the development of sensor microsystems-on-a-crystal for monitoring such important parameters as the level of glucose in human blood, blood oxygen saturation, heart rate, etc., which can be obtained by non-invasive methods, were considered by the authors in the work [8], where a structural scheme is proposed and a hardware and software prototype is implemented for continuous monitoring of both heart rate and indicators of saturation level, glucose and other blood parameters by photoplethysmography. Prospects of implementation of such systems using hybrid technology in the form of a microsystem on a crystal is considered in [9]. The problems of photoplethysmography signal processing were previously considered by the authors and a functional-electric scheme of IPS from photosensitive elements based on amplifiers was proposed, which can be used to build an element base of hybrid sensor microsystems for biomedical and other applications. It is also worth noting the absence of domestic devices of the mentioned type in an integrated design, therefore the layout development of the operational amplifier on CMOS structures for biomedical applications is quite relevant.

I. Basic electrical circuit of an integrated signal converter from photosensitive elements based on an operational amplifier

The amplitude of the signal received from the photodetector is quite small, less than 2% of the constant component, moreover, the value of the constant component is not known in advance, and the signal itself is very noisy. To eliminate the constant component, a differential scheme on the operational amplifier (Fig. 1) is proposed, with the possibility of dynamically changing the level of compensation. This approach makes it possible to compensate for the constant component of any value, and to pre-amplify the useful signal to extend it to the entire dynamic range of the ADC.

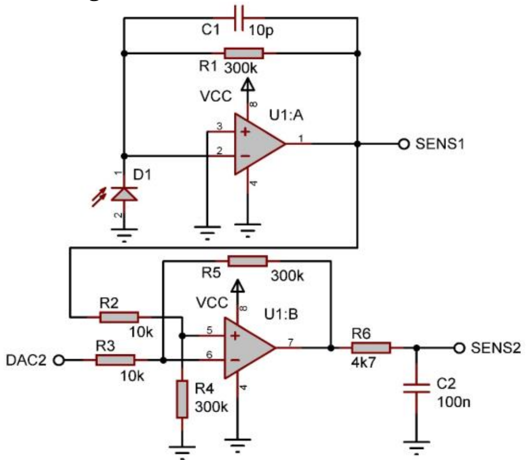


Fig. 1. Basic electrical circuit of the signal converter for photoplethysmography.

Since the determination of various blood parameters requires light sources in a fairly wide range of wavelengths from 450 to 1040 nm, accordingly, the photoreceptor must have high sensitivity in a wide range. With a hybrid or integrated design, it is possible to implement several photodetectors with their own signal processing circuits, which significantly reduces the requirements for the receiver's bandwidth and makes it possible to place the photodetector exactly opposite the corresponding LED source. At the same time, to reduce interference and temperature drifts, it is worth placing the hardware signal processing scheme on one crystal.

II. Basic electric circuit and layout of the operational amplifier for the integrated converter of photoplethysmography signals

The developed basic electric circuit of the operational amplifier (OP) in an integrated design, as part of the IPS circuit, is shown in fig. 2.

The power supply voltage of the operational amplifier is +5V. On the basis of the developed electrical circuit, the OP layout was designed in MicroWind CAD. The general view of the OP layout is shown in fig. 3.

When developing the layout, a scalable design approach was used using the lambda parameter (λ), which ensures in-variance with respect to manufacturing technologies. For most OP transistors, both n-channel and p-channel, the same length $L = 2 \cdot \lambda = 2$ μm is adopted, and the width of the channels W is scaled depending on the results of circuit modeling and the purpose in the scheme. The results of channel width scaling from $W = n \cdot \lambda$, where n=1..5, for n-channel MOS transistors are shown in Fig. 4, and for p-channel MOS transistors – in fig. 5.

As can be seen from the simulation results in fig. 4-5 I/V curves scales linearly with a factor of n. Most OP transistors are implemented using a comb layout, so they occupy a smaller area on the crystal and have smaller parasitic parameters. Contact windows to polysilicon

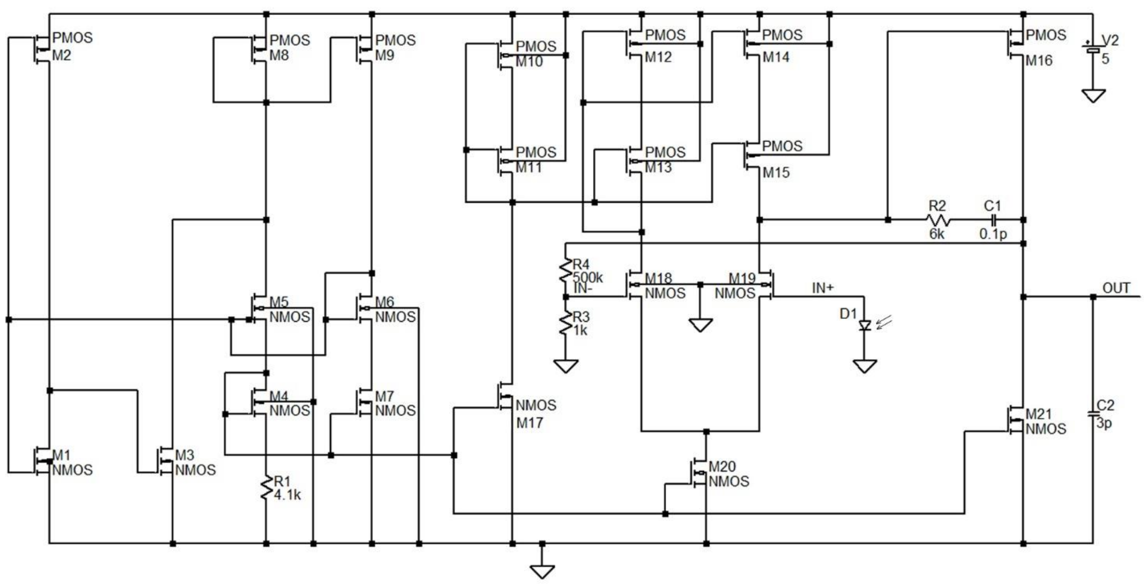


Fig. 2. Part of the basic electrical circuit of the IPS (one operational amplifier).

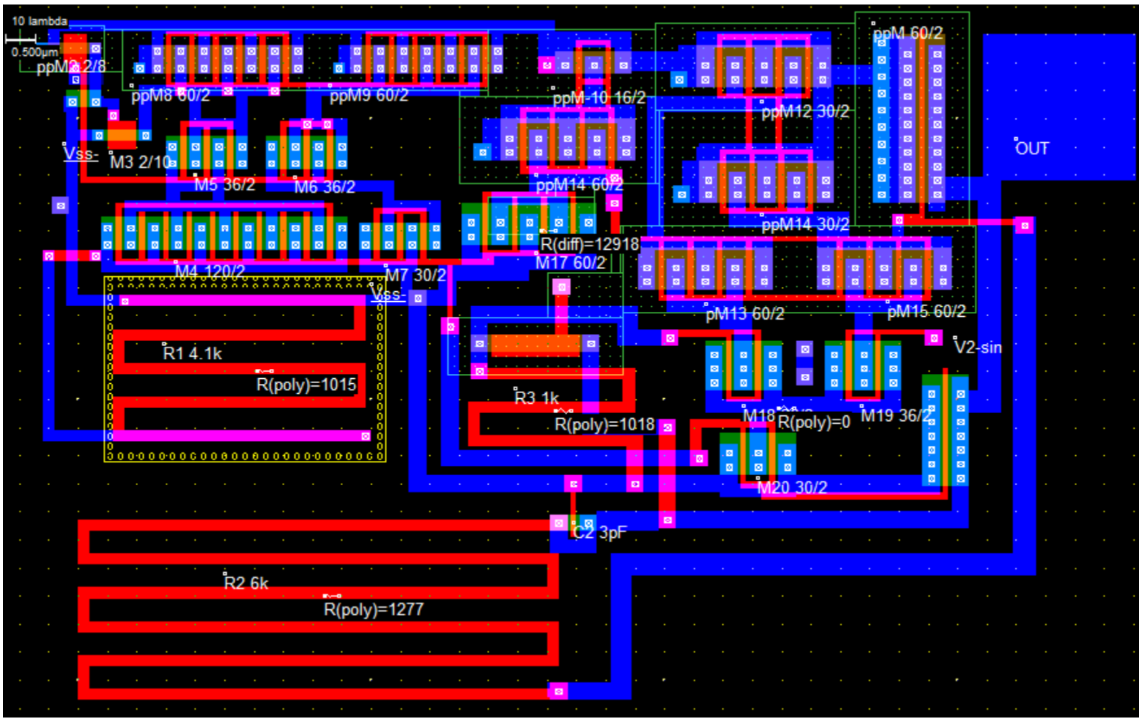
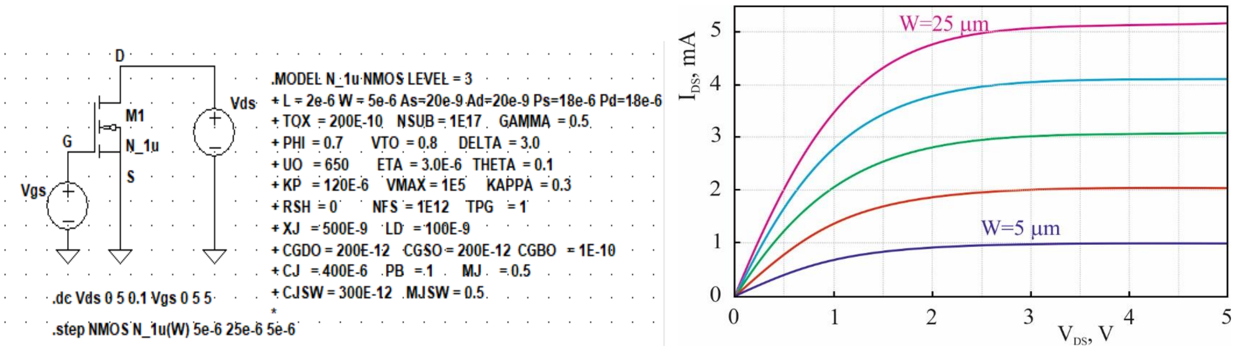
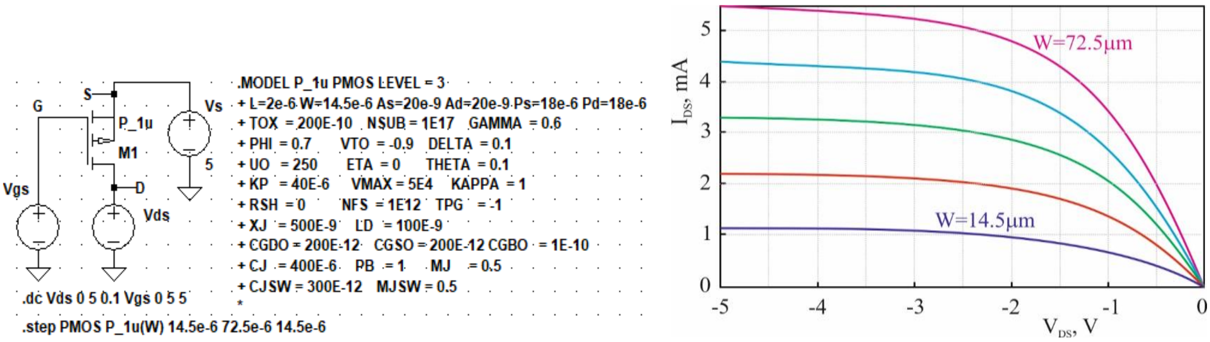


Fig. 3. Layout of the CMOS operational amplifier.



a) b)

Fig. 4. Scaling of the channel width of an n-channel MOS transistor: a) electrical circuit and model parameters, b) I/V curves of an n-channel MOS transistor with dimensions $n{\cdot}W$, n=1..5.



a) b)

Fig. 5. Scaling of the channel width of a p-channel MON transistor: a) electrical circuit and model parameters, b) I/V curves of a p-channel MOS transistor with dimensions n W, n=1..5.

layers, n- and p-type diffusion's are made with sets of square-shaped contacts. OP resistors R1, R2 and R3 are made of gate polysilicon with calculated values, respectively, R1=4.1 kΩ, R2=6 kΩ, and R3=1 kΩ, and resistor R4 with a value of 500 kΩ is implemented as a p-channel MOS transistor with zero gate offset. The design value of capacitor C1 is less than 0.1 pF and integral capacitor C2 is 3 pF, and it is designed as a transistor with shorted drain-to-drain regions forming the first cap of the capacitor, the other cap of the capacitor is the gate of the transistor. This design is optimal in terms of area on the crystal and from the point of view of performing layout connections. P-channel MOS transistors have polarized well biases and are topologically combined as a single integral layout polygon. The substrates of all n-channel MOS transistors over the entire OP area are connected to the p-type conductivity substrate and the ground bus.

Typical structures of n- and p-channel MOS transistors of OP are shown in fig. 6. Fig. 6, b on the left also shows the polarization bias of the n-type conductivity pocket. The main parameters of the layers of the transistor structure are shown in table. 1.

Table 1.

Basic parameters of transistor structure layers.

Layer	Thickness, μm
Contact	1.20
Diffn	0.30
Diffp	0.30
N well	0.70
Thin oxide	0.0012
Double oxide	0.0030

The developed layout of n-channel (a) and p-channel (b) MOS transistors with W/L dimensions of 5/2 and 10/2, respectively, are shown in Fig. 7. The well bias is shown on the *p*-channel MOS transistor topology.

For the developed layout, the channel width of the p-channel MOS transistor is almost three times larger, compared to the n-channel MOS transistor, with the same lengths of the transistor channels, which ensures their symmetrical *I/V* curves characteristics, as can be seen from the results of computer simulations (Fig. 8-9).

III. Results of computer simulations of OP elements

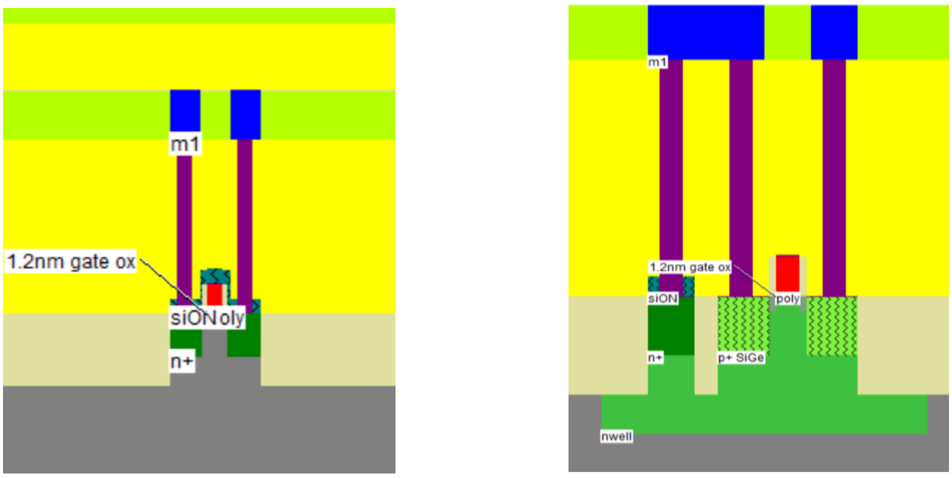
Taking into account the developed layout, a computer simulation of transistor operation was carried out. The results of computer simulation in the LTSpice XVII x64 program of *I/V* curves of p- and n-channel MOS transistors and their connection configuration are shown in fig. 8-9.

As can be seen from the *I/V* curves characteristics comparison (Fig. 8-9), the selection of channel width of the p-MOS transistor achieves practical symmetry of the characteristics, so at V_{DS}=3 V, I_{DS}^{p}= 0.40 mA, and I_{DS}^{n} = 0.39 mA. The symmetry of the *I/V* curves allows the transistors to work in the amplifier as a complementary pair.

The graphs of power consumption of p-MOS and n-MOS transistors depending on the V_{DS} voltage are shown in Fig. 10.

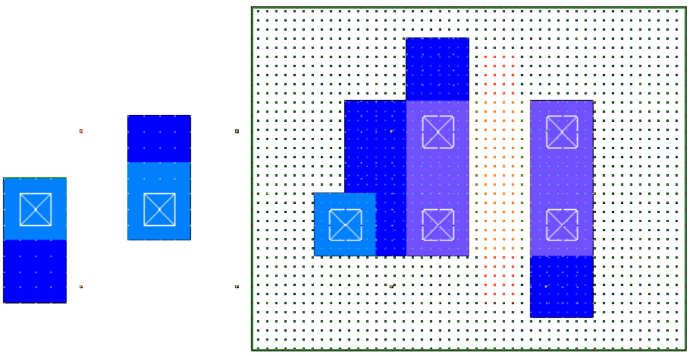
Since the developed device is supposed to be used at temperatures from 10 °C to 50 °C, the variations of the *I/V* curves in this temperature range were simulated, as shown in Fig. 11.

As can be seen from fig. 10, the energy consumption of transistors is insignificant, and from Fig. 11 it can be seen that in the operating temperature range of 10÷50 °C, changes in the characteristics of the transistor are also insignificant. As a result, it made it possible to develop an



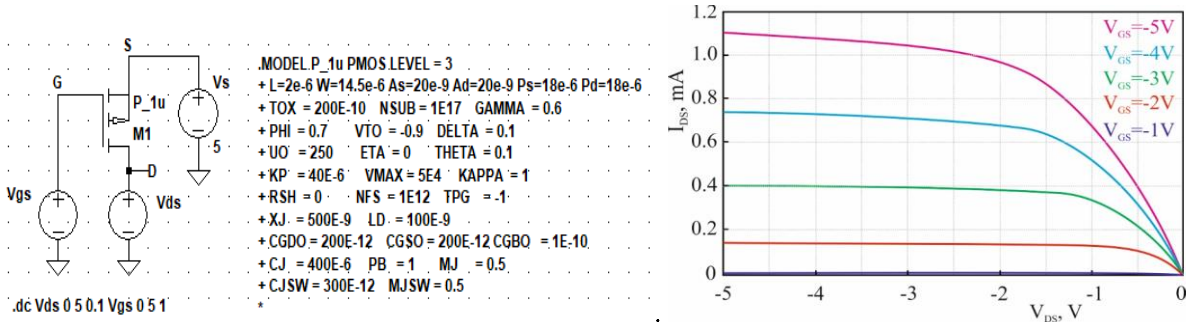
a) b)

Fig. 6. Typical structures of n-channel (a) and p-channel (b) MOS transistors OP.



a) b)

Fig. 7. Topology of n-channel (a) and p-channel (b) MOS transistors.



a) b)

Fig. 8. Electrical circuit and parameters of the model (a), *I/V* curves of p-channel MOS transistor with dimensions *W/L*=14.5/2 (b)

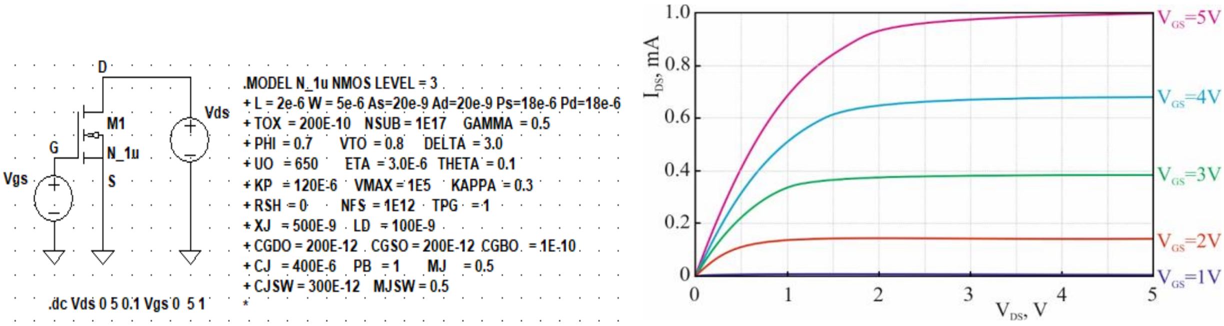


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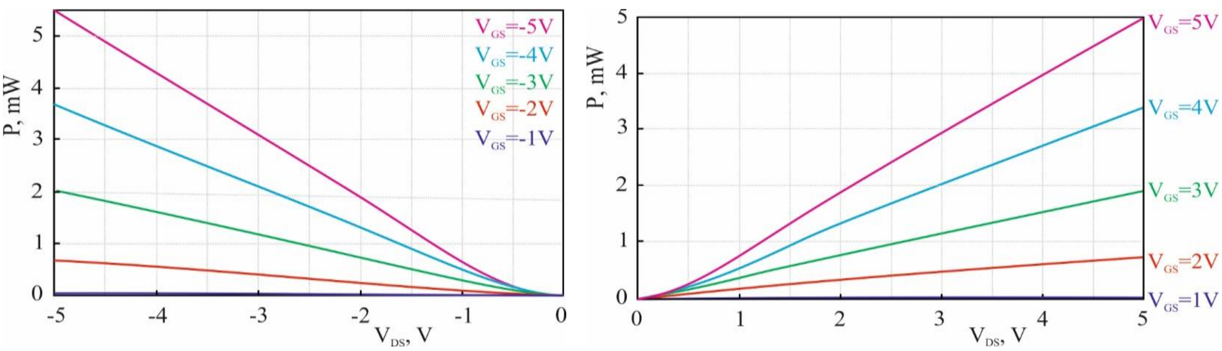
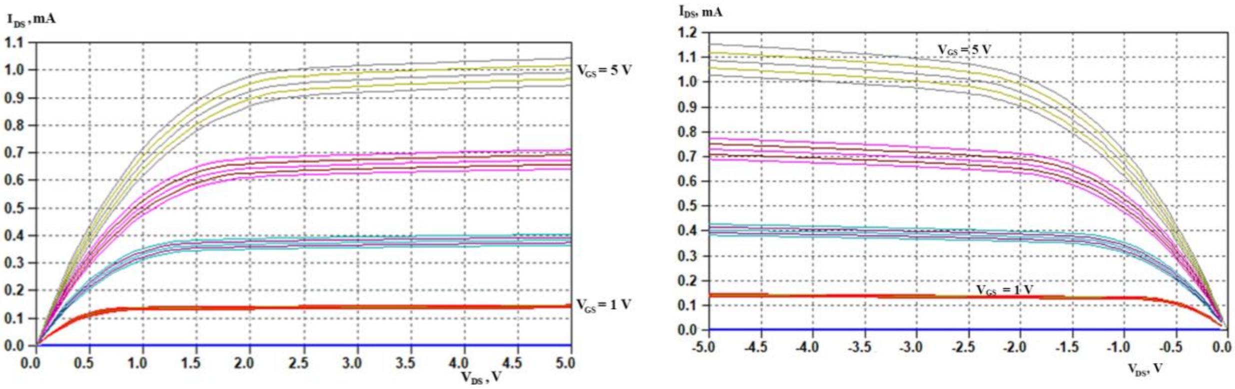
Fig. 9. Electrical circuit and parameters of the model (a), I/V curves of an n-channel MOSFET with dimensions *W/L* = 5/2 (b).



a) b)

Fig. 10. Powers of p-MOS (a) and n-MOS (b) transistors.



a) b)

Fig. 11. Dependence of I/V curves (at V_{GS} voltages from (0 V to 5 V in steps of 1 V) on temperature from 10 °C to 50 °C in steps of 10 °C.

energy-efficient and highly stable operational amplifier for an integrated converter of photoplethysmography signals.

Conclusions

The layout of the operational amplifier based on complementary (CMOS) structures according to the standard industrial planar CMOS technology on KDB-40 silicon wafers and n-type conductivity wells was developed for the construction of an integral signal converter from diode photosensitive sensor elements in the frequency range from 400 to 1040 nm.

A computer simulation of the functioning of the operational amplifier was carried out, the constituent components were determined, and their parametric optimization was carried out. It is shown that three times the channel width of the p-channel MOS transistor compared to the n-channel transistor with the same length of their channels ensures their symmetrical *I/V* curves characteristics.

The developed integrated signal converter is suitable for creating real devices in an integrated design as an element of sensor microsystems-on-a-crystal or smart sensors for biomedical applications.

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[1] B. K. Alexandra, A. N. Semenova, V. A. Zyulin and D. V. Olga, *Determination of Pulse Oximetric Parameters of the Body by Photoplethysmography*, 2022 Conference of Russian Young Researchers in Electrical and Electronic Engineering (ElConRus), 123 (2022), https://doi.org/10.1109/ElConRus54750.2022.9755665.
[2] Elisa Mejia-Mejia, John Allen, Karthik Budidha, Chadi El-Hajj, P.A. Kyriacou, P.H. Charlton, *Photoplethysmography Signal Processing and Synthesis*. Photoplethysmography. 1 (2022); https://doi.org/10.1016/b978-0-12-823374-0.00015-3.
[3] R.G. Khemani, N.R. Patel, R.D. Bart, C.J.L. Newth, *Comparison of the Pulse Oximetric Saturation/Fraction of Inspired Oxygen Ratio and the* PaO_2 *Fraction of Inspired Oxygen Ratio in Children*, Chest. 135 (3), 662 (2009); https://doi.org/10.1378/chest.08-2239.
[4] J. Moraes, M. Rocha, G. Vasconcelos, J. Vasconcelos Filho, V.de Albuquerque, A. Alexandria, *Advances in Photopletysmography Signal Analysis for Biomedical Applications*, Sensors. 18(6) N. 1894 (2018); https://doi.org/10.3390/s18061894.
[5] R.I.R. Javier, A.O. Baloloy, N.B. Linsangan, I.V. Villamor, *Portable Non-Invasive Glucometer using N Infrared Sensor and Raspberry Pi*, 4th International Conference on Electrical, Telecommunication and Computer Engineering. 35 (2020).
[6] J.H. Kwon, S.E. Kim, N.H. Kim, E.C. Lee, J.H. Lee, *Preeminently Robust Neural PPG Denoiser*, Sensors. Vol. 22, 2082 (2022); https://doi.org/10.3390/s22062082.
[7] K.V. Pozhar, M.O. Mikhailov, E.L. Litinskaia, *Near-Infrared Spectroscopy for Noninvasive Measurement of Blood Glucose: Problems, Progress, Tasks*, Biomed Eng., 56, 64 (2022); https://doi.org/10.1007/s10527-022-10168-5.
[8] Б.С. Дзундза, І.Т. Когут, В.І. Голота, Л.В. Туровська, М.В. Дейчаківський, *Принципи побудови гібридних мікросистем для біомедичних застосувань*, Фізика і хімія твердого тіла, 23(4), 776 (2022); https://doi.org/10.15330/pcss.23.4.776-784.
[9] I.T. Kogut, A.A. Druzhinin , V.I. Holota, *3D SOI elements for system-on-chip applications*, Advanced Materials Research, 276, 137 (2011); https://doi.org/10.4028/www.scientific.net/AMR.276.137.

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Особливості схемотопологічного проектування і моделювання топології операційного підсилювача на КМОН-структурах для біомедичних застосувань

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В роботі наведено результати схемотопологічного проектування і ком'ютерного моделювання операційного підсилювача на основі комплементарних (КМОН)-структур за стандартною промисловою планарною КМОН-технологією на кремнієвих пластинах КДБ-40 з кишенями n-типу провідності. Операційний підсилювач розроблявся для реалізації інтегрального перетворювача сигналів (ІПС) фотоплетизмографії, особливістю якого є здатність регулювання та фільтрація амплітуди постійної складової у підсиленому сигналі від діодного фоточутливого елементу в діапазоні довжин хвиль 400 - 1040 нм. Розроблений ІПС застосовується для створення реальних мікроелектронних пристроїв в інтегральному виконанні, як елемент сенсорних мікросистем-на-кристалі або інтелектуальних сенсорів.

Ключові слова: сенсорна мікросистема, інтегральний перетворювач сигналів, фоточутливий елемент, схемотехнічне проектування, операційний підсилювач, КМОН-структури, КМОН топологія.