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Development of a device for picoampere currents measuring

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Abstract. One of the actual topics in microelectronics is the problem of measuring small currents. We have considered possible solutions to this problem, one of which is a current measurement method based on the use of an amplifier with differential inputs. The advantage of this scheme is that the high-precision measuring resistance is divided between two identical elements that are physically installed in the same orientation and at the same distance from the source of magnetic interference. Interference induced on two resistors in this case creates the same signals, which are suppressed at the output of the amplifier. To solve this problem, we have developed a stand for testing a device for measuring picoampere currents. The stand consists of a measuring unit, a digital-to-analog converter module and special software. The measuring unit consists of a differential amplifier stage, followed by a signal amplification circuit on an operational amplifier, the digital-to-analog converter module is implemented on the basis of an external input-output module L-CARD E20-10, and the L-Graph program was used for signal processing. As a result of the experiments, the ranges of measured values were confirmed.

Keywords: picoampere currents, current measurement, ADC

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Разработка устройства для измерения пикоамперных токов

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Аннотация. Одной из актуальных тем в микроэлектронике является проблема измерения малых токов. В данной работе показана схема прибора для измерения пикоамперных токов. Предложен принцип измерения токов, основанный на схеме усилителя с дифференциальными входами. В результате экспериментов были подтверждены диапазоны измеряемых величин.

Ключевые слова: пикоамперные токи, измерение тока, АЦП

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Introduction

The problem of measuring currents remains relevant in various fields of science [1–8]. This is especially important when conducting physical experiments, for example, measuring the human magnetic field or examining samples during a long cycle, for example, polymerase chain reaction (PCR) [9–16]. The currents required in these cases must be measured with an accuracy of tens of picoamperes [11, 12, 17–19].

To measure currents in the world, magnetoelectric type devices are often used. This type of device does not allow measuring currents less than a few microamperes with an error of less than ten percent. There is a separate class of instruments - galvanometers. These devices are complex, capricious and require special conditions for use, such as protection from shaking, stable temperature and humidity.

Another way to solve the problem of measuring currents is to use microcircuits based on the Hall effect [20]. The principle of operation is based on the occurrence of an electric voltage on a magnetically sensitive element under the influence of a forming magnetic field resulting from the passage of an electric current through a nearby conductor. The main advantage of this measurement method is the absence of a resistive shunt, which results in no undesirable thermal energy release during the measurement. Although the use of this method is applicable for measuring ultra-low currents, it requires special conditions, for example, low temperatures close to absolute zero, as well as highly sensitive measuring equipment, which leads to difficulties in operating devices based on this principle.

Another measurement method can be products based on the use of current transformers. The principle of operation is based on the properties of the transformation of alternating electric current. The resulting alternating magnetic flux is captured by a magnetic circuit perpendicular to the direction of the primary current. This flux is created by the alternating current of the primary coil and induces an EMF in the secondary winding. After connecting the load, an electric current begins to flow through the secondary circuit. Thus, by selecting the required ratio of windings in the primary and secondary windings, you can immediately select the appropriate gain. The advantages of these devices are high accuracy and repeatability of the measured parameters, ease of use. However, the main disadvantage is the inapplicability of this approach in applications where it is necessary to measure direct currents.

The most common alternative solution is to use a resistive current sensor [21–23]. The principle is based on the dependence of voltage on the current passing through the measuring resistor. The advantage of this method of current measurement is the ease of use in both DC and AC circuits. The disadvantages include low noise immunity. To solve the above problem, various circuit solutions can be used.

The measurement methods discussed above have proven themselves in industry and household appliances and can be applied to solve the problem of analyzing small currents, but these solutions will lead to complex technical and technological solutions. Thus, the purpose of this work is to create a circuit solution that makes it possible to measure picoampere currents with high accuracy. We have proposed a method for measuring currents based on the use of an integrated current amplifier - an operational amplifier based on differential stages. The advantage of this circuit is that the high-resistance measuring resistance is shared between two identical elements that are physically mounted in the same orientation and at the same distance from the source of magnetic interference. Interference induced on two resistors, in this case, create the same signals, which are suppressed at the output of the amplifier [4]. This amplifier is capable of handling DC voltage amplification at sub-millivolt levels. The uniqueness of the chosen solution lies in the fact that we use standard techniques, but performed with high quality and simply. This is a special system with which we solve the problem of nanopore sequencing.

Materials and Methods

To solve this problem, we have developed a stand for testing the device for measuring picoampere currents. The test bench consists of a measuring unit, a digital-to-analogue converter module and special software.

The measuring unit is based on the use of an operational amplifier with MOSFETs in the input circuits. The advantage of this circuit is that due to the use of MOSFETs, the input currents of the op-amp do not exceed 500 fA, which allows leveling the contribution of the op-amp in relation to the high-resistance measurement of resistance. This amplifier can handle DC amplification with levels in the tens of picoamps.

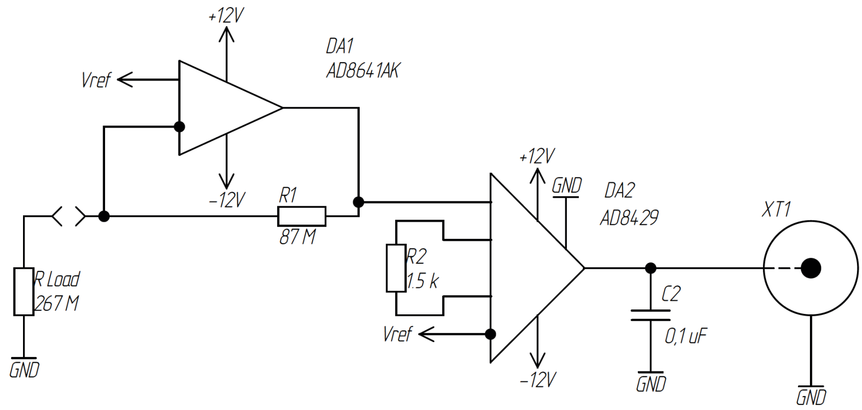

Fig.1. Circuit of the measuring equipment

The digital-to-analogue converter module is implemented on the basis of an external input-output module L-CARD E20-10. E20-10 is a high-speed ADC module with a USB interface for connecting to a PC. The E20-10 has 4 channels of 14bit/10MHz ADC with multiplexing function, 16 channels of digital input and output compatible with TTL logic, and 2 channels of DAC. The FPGA-based architecture with one ADC, switch and input buffer amplifiers in serially polled channels completely eliminates switching noise, third-order active low-pass filters in each channel improve the signal-to-noise ratio. Of the advantages of this ADC, among others, one can note the galvanic isolation of each channel, which provides high noise immunity.

To register, visualize, and process the analog signal, we used special software LGraph 2 (program) adapted to work with an external ADC L-CARD E20-10. A DT-9930 LCR meter was used for control measurement of the load resistor and current shunt. To control the measurement of the reference voltage and output signal frequency oscilloscope Tektronix MSO 2024B. For measuring test currents using a sample load resistor of 267 MΩ.

Changes in the current passing through the load resistor were changed by changing the reference voltage applied to the load resistor. The reference voltage was set using an external L-CARD E20-10 input/output module with a set voltage range of ±5V with a resolution of 12 bits. The parameters were measured in the range of ±3V with a sampling frequency of 50KHz. The measurement duration was 1 second. For each current measurement, 300 measurements were taken for subsequent averaging and calculation of statistical significance. Currents were measured from 0.1 nA to 0.4 nA in 0.025 nA steps.

Results and Discussion

Based on the data obtained, a histogram of the distribution of the measured values was constructed (Fig. 2). Using the Kolmogorov-Smirnov test for the compliance of the sample with normal distributions, it was confirmed that the results obtained belong to the normal distribution and standard statistical methods of comparison can be applied to them. The correspondence of the obtained data to the normal distribution is also shown in Figure 2.

For each value of the tested current value, 300 measurements were carried out, after which these values were averaged and compared with each other. The graph for comparing the results is shown in Fig. 3. The step of changing the set current value was 0.025 nA, and the calculated RMS values do not exceed 0.0035 nA, which allows us to assert a significant difference in the experimentally obtained data.

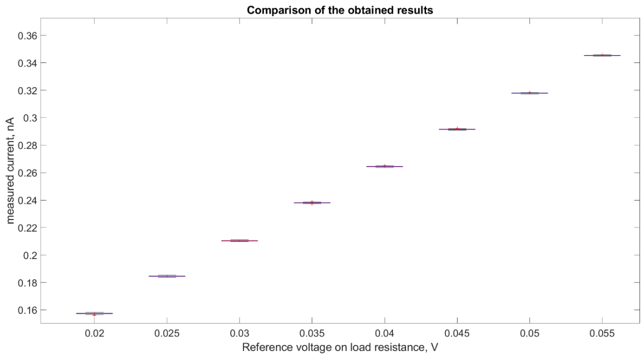

Fig.2. Comparison of the obtained results

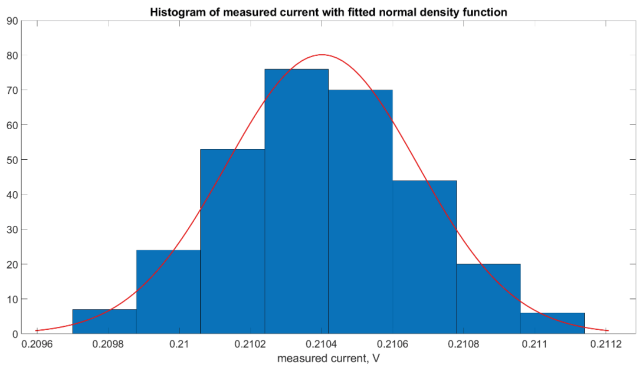

Fig.3. Histogram of current distribution

Conclusion

As a result of the obtained data, we were convinced that the proposed circuit solution corresponds to the specified characteristics. The measuring stand allows measuring picoampere currents with an accuracy of ±10pA, and the results obtained correlate with the theoretical parameters of the circuit. A significant disadvantage of the measuring unit is the large leakage currents associated with the relatively low, compared with the analyzed samples, the resistance of the insulating material. In the manufacture of the measuring unit, a printed circuit board based on the FR4 insulating material was used, which does not allow achieving high electrical resistance. This parameter can be improved by using a separator based on polytetrafluoroethylene (PTFE).

REFERENCES

1. **Dyumin V., Smirnov K., Myazin N.,** Charge-coupled Device with Integrated Electron Multiplication for Low Light Level Imaging, Proceedings of the 2019 IEEE International Conference on Electrical Engineering and Photonics, EExPolytech. 8906868 (2019) 308–310.

2. **Grevtseva A. S., Smirnov K. J., Rud V. Yu.,** Development of methods for results reliability raise during the diagnosis of a person's condition by pulse oximeter, Journal of Physics: Conference Series. 1135 (1) (2018) 012056.

3. **Makeev S. S., Grevtzeva A. S., Glinushkin A. P., Matorin D. N.,** Possibilities of using spectral analysis in method of nuclear magnetic spectroscopy for condensed media investigation, Journal of Physics: Conference Series. 1695 (1) (2020) 012112.

4. **Davydov V. V.,** Determination of the Composition and Concentrations of the Components of Mixtures of Hydrocarbon Media in the Course of its Express Analysis, Measurement Techniques. 62 (2) (2020) 1090–1098.

5. **Davydov V. V., Grebenikova N. M., Smirnov K. Y.,** An Optical Method of Monitoring the State of Flowing Media with Low Transparency That Contain Large Inclusions, Measurement Techniques. 62 (6) (2019) 519–526.

6. **Kuzmin M. S., Rogov S. A.,** On the use of a multi-raster input of one-dimensional signals in two-dimensional optical correlators, Computer Optics. 43 (3) (2019) 391–396.

7. **Logunov S. E., Vysoczky M. G.,** New method of researches of the magnetic fields force lines structure, Journal of Physics: Conference Series. 1038 (1) (2018) 012093.

8. **Mazing M. S., Zaitceva A. Yu., Kislyakov Yu. Ya., Kondakov N. S., Avdushenko S. A., Davydov V. V.,** Monitoring of Oxygen Supply of Human Tissues Using A Noninvasive Optical System Based on A MultiChannel Integrated Spectrum Analyzer, International Journal of Pharmaceutical Research. 12(2) (2020) 1974–1978.

9. **Reznik V. S., Kruglov V. A.,** Using of «bubble sensors» to control the quality of sequencing by the Illumina / Solexa method, Journal of Physics: Conference Series. 2086 (1) (2021) 012120.

10. **Kruglov V. A., Reznik V. S., Glinushkin A. P.,** Development of a hydraulic system for bridge amplification, Journal of Physics: Conference Series. 1695 (1) (2020) 012067.

11. **Reznik V. S., Kruglov V. A., Petrov A. I., Glinuchkin A. P., Rud V. Y.,** Development of a measuring device for the study of thermal processes during the polymerase chain reaction, Journal of Physics: Conference Series. 1410 (1) (2019) 012078.

12. **Davydov V. V., Kruzhalov S. V., Grebenikova N. M., Smirnov K. J.,** Method for Determining Defects on the Inner Walls of Tubing from the Velocity Distribution of the Flowing Fluid, Measurement Techniques. 61 (4) (2018) 365—372.

13. **Matvienko I. V., Bayramov V. M., Parygina N. A., Kurochkin V. E., Alekseev Y. I.,** Synthesis of Dihydroquinoline-Based Derivatives of Fluorescent Rhodamine Dyes for Nucleic Acid Analysis by a Real-Time Polymerase Chain Reaction, Russian Journal of Bioorganic Chemistry. 46 (3) (2020) 349—359.

14. **Fedorov A. A., Berdnikov A. S., Kurochkin V. E.,** The polymerase chain reaction model analyzed by the homotopy perturbation method, Journal of Mathematical Chemistry. 57 (4) (2019) 971—985.

15. **Davydov V. V., Davydova T. I.,** A nondestructive method for express testing of condensed media in ecological monitoring, Russian Journal of Nondestructive Testing. 53 (7) (2017) 520—529.

16. **Myazin N. S.,** Features of formation of structure of a nuclear magnetic resonance signal in weak magnetic field, Journal of Physics: Conference Series. 1135 (1) (2018) 012061.

17. **Natyrov A. N., Vlasova N. A., Matvienko I. V., Kurochkin V. E., Alexeev J. I.,** Synthesis of Unsymmetrical Polymethine Cyanine Fluorescent Dyes for Nucleic Acid Analysis by Real-Time PCR, Russian Journal of Bioorganic Chemistry. 44(5) (2018) 562—571.

18. **Davydov V. V., Dudkin V. I., Velichko E. N., Karseev A. Y.,** A Remote Nuclear-Resonance Magnetometer for Measuring Intense Nonuniform Fields, Measurement Techniques. 58 (5) (2015) 556—561.

19. **Davydov V. V., Dudkin V. I., Karseev A. Y.,** A two-channel nutation nuclear-magnetic magnetometer for remote control of the magnetic-field induction, Instruments and Experimental Techniques. 58 (6) (2015) 787—793.

20. **Hobbs P.,** Photodiode Monitoring with Op Amps, Components & Technologies, 3 (2009) 48–49.

21. **Salakhov R. F., Miskov D. N.,** Techniques for measuring the current in modern microelectronics, Tests. Quality control and management, 3 (2015) 9–62.

22. **Wenn D.,** Resistive current measurement methods for precise control in electronic circuits, Components and technology, 7 (2011) 156–158.

23. **Sakharov K. Y., Turkin V. A., Mikheev O. V., Sukhov A. V., Ugolev V. L., Denisov M. Y.,** Pulse measuring instruments electromagnetic fields and currents, EMC Technologies, 1 (72) (2020) 63–70.

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