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INNOVATIVE DEVELOPMENT OF COORDINATE-SENSITIVE DETECTOR OF FOCUSED ION BEAMS FOR SPECTROSCOPY

Introduction. *The urgent task for modern analytical apparatus designed for quantitative analysis of multi-elemental composition of substances is to create multichannel coordinate-sensitive detectors (CSD) of charged particles for spectroscopy, which operate in real time.*

Problem Statement. *The Institute of Microdevices (IMD) of the NAS of Ukraine has developed a large-scale integration circuit (LSI circuit) for CSD based on which using microchannel plates (MCP), experimental samples of CSD devices have been designed and manufactured. The studies carried out at the Institute of Applied Physics (IAP) of the NAS of Ukraine have shown high characteristics of the device, in particular, its high sensitivity. The feasibility of further research has been confirmed.*

Purpose. *To create a new generation of multichannel CSD devices with expanded field of analysis and improved technical characteristics.*

Materials and Methods. *The developed CSD device uses the F4772-01 MCP of Hamamatsu, Japan. The LSI circuit is manufactured using the CMOS technology with design standards of 1 μm, n-type pockets, 384 electrode sensors, and 218603 transistors on a 9.8 x 8.9 mm crystal. The microcircuit is made in a discrete wafer form, on flexible carriers of aluminum-polyimide type (modification 2).*

Results. *The development of a new generation 5-crystal CSD device has enabled expanding the field of simultaneous analysis of the spatial distribution of ion beams of arbitrary composition and, accordingly, the range of elements analyzed simultaneously, as well as increasing the speed of analyzing and reading data 5 and 2.5 times, respectively.*

Conclusions. *The use of the circuitry solution protected by the Patent of Ukraine №117788 has significantly reduced the dependence of detector sensitivity on the differences in the design parameters of the driver amplifier transistors, which has made it possible to create a new generation 5-crystal CSD device and to expand the range of elements analyzed simultaneously. Using the advanced CMOS technology for the manufacture of LSI circuit crystals, optimization of circuit design and topological solutions have enabled obtaining high technical characteristics of the CSD device.*

Keywords: coordinate-sensitive detector, mass spectrometry, and large-scale integration circuit CMOS technology.

An urgent task in the field of modern analytical equipment for quantitative analysis of multi-elemental substances is to create multichannel coordinate-sensitive detectors (CSD) of charged particles for spectroscopy, which operate in real time [1]. The photographic recording method and the sequential measurement method for each channel using Faraday's cylinders are slow and time consuming and do not enable real-time analysis. Multichannel CSD devices that can simultaneously obtain information on the entire elemental composition by analyzing the spectrum in real time, with high accuracy, without special sample preparation, allow the researchers to quickly control the analysis by adjusting the mass spectrometer using specific isotopes of impurity elements. As a result, the accuracy and sensitivity of the analysis increases, while the time of analysis and the consumption of material studied significantly reduce, which is especially important when creating nanomaterials or obtaining superfine materials. It is also important that the analysis of the elemental composition of materials in real time makes it possible to quickly and efficiently control the material creation processes.

A large-scale integrated circuit (LSI circuit) UB5709IK01-2.11 for microelectronic coordinate-sensitive detector of devices for elemental analysis of substances has been developed at the Institute of Microdevices of the NAS of Ukraine [2, 3]. Later, on the basis of this LSI circuit and microchannel plates (MCP), experimental samples of CSD devices have been designed and manufactured using one-centimeter MCPs [4]. MS3103 mass spectrometer has been adapted at the Institute of Applied Physics of the NAS of Ukraine to enable working with experimental samples of the developed CSD devices [4, 5]. Fig. 1 shows a detector mounted in the chamber of the mass spectrometer in the focal plane of the magnetic analyzer.

The study of the operation of a CSD prototype as part of the laser mass spectrometer at the Institute of Physics of the NAS of Ukraine has shown a high performance of the device, in particular, its high sensitivity as antimony isotopes ^{21}Sb and ^{123}Sb [4] in atomic concentrations of 0.0008% and 0.0006%, respectively, have been detected.

In 2017—2018, research project D*evelopment of a Multichannel Sensor Device Based on a Specialized Large-Scale Integration Circuit (LSI circuit) for Mass Spectrometry* was implemented at the Research Institute of Microdevices of the Research and Technological Complex Institute of Single Crystals of the NAS of Ukraine.

The purpose of this research is to create new-generation multichannel CSD devices with an

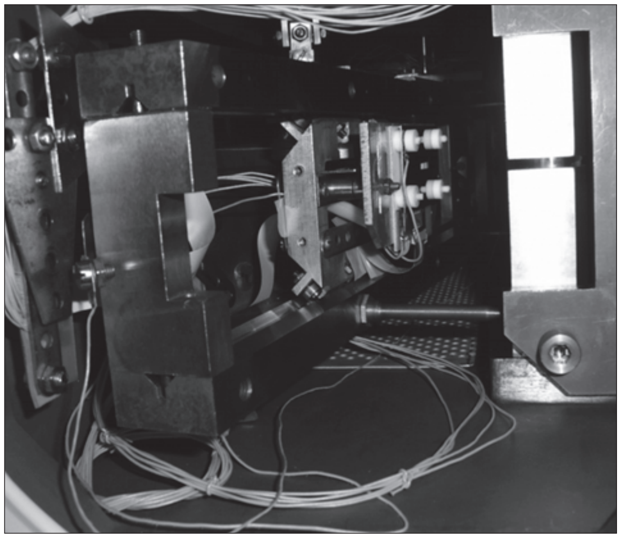

Fig. 1. CSD in the mass spectrometer chamber

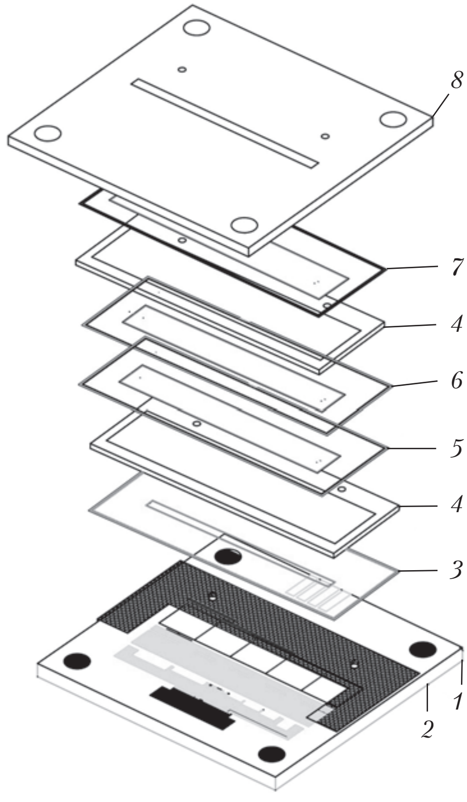

Fig. 2. CSD device structure: *1* — base; *2* — holder of the chevron node; *3* — MCP contact electrode; *4* — frame holder of MCPs; *5*—*7* — contact electrodes for MCPs of various configurations; *8* — screen

expanded field of analysis and improved technical characteristics.

The goal has been achieved due to designing a 5-crystal CSD device, using the modern CMOS technology for the production of LSI circuit crystals with minimum design rule of 1 micron, as well as due to optimizing the circuit and topological solutions.

The main functional units of the CSD instrument are as follows (Fig. 2):

- input aperture slit that selects the area for analysis in the focal plane;
- ion-electron converter as multiplier of secondary electrons (ion-electron avalanche), which consists of two microchannel plates in a chevron assembly;
- five specialized LSI circuits containing 1920 counting channels;
- multilayer ceramic base on which the device units and interface sockets are mounted;
- slots and plugs-and-sockets for connection of the device controller and sources of voltage of the LSI circuits and high voltage of MCPs;
- metal nonmagnetic shield for protection against the ingress of ions on the device's elements, except the focal plane;
- test outputs for testing performance without ion beams.

Table 1

Technical Parameters of CSD Device

Parameter	Value
Area of the focal plane where ions are simultaneously detected, mm	50.0
Number of simultaneously operating channels for receiving and processing information	1920
Maximum frequency of information reception, MHz	At least, 15
Maximum heart beat of information readout, MHz	At least, 10
LSI circuits voltage, V	+5
CSD power consumption at a nominal voltage of+5V, W	At most, 0.25
MCP voltage, V	–2000
CSD dimensions, mm	66 × 63 × 5

The CSD device provides simultaneous detection of isotopes of elements in a wide range of masses of the test substance and concentrations, from 10–7 to 100%.

The protocol of information exchange between the CSD device and the periphery is serial.

The main parameters of the CSD device are given in Table 1.

DEVICE OPERATION THEORY

A coordinate-sensitive detector is a device for simultaneous detection of a range of charged particles that are separated in space. It is located in the focal plane of the spectrometer, its dimensions of which are determined by the number of detectors and the step of the periodic structure of the CSD, and it is made on a semiconductor crystal.

Fig. 3 shows the functional flowchart of LIC, and Fig. 4 features the time diagram of the LIC operation in the CSD device.

The detector's sensor electrode *EL* (Fig. 3) is a strip of aluminum on the surface of the LSI circuits crystal connected to the input of the driver amplifier *DIF*. The number of such strips is determined by the number of detector channels on the crystal. The driver amplifier *DIF* is a device that is sensitive to the charge of electron flux entering the surface of the aluminum strip. To record an ion located in the focal plane of the mass spectrometer as a single event (one ion — one counting impulse of the counter), it is necessary, firstly, to put an ion-avalanche of electrons converter in front of the detector, and secondly, an avalanche of electrons shall change the potential of a specific sensor electrode *EL* against which the ion is located to a voltage lower than the *DIF* driver amplifier response threshold. Only in this case, it will switch, generate a single counting impulse for a specific counter and through the feedback will reset its input to its initial state. This process shall be rapid enough, until the next ion arrives at the detector, to avoid a miss of ions by the detector.

ION-ELECTRON CONVERTER ON MCPS

Typically, MCP [6] is a glass plate with a honeycomb structure having a large number (500–1000) of regularly arranged and sintered hexagonal micro-channels, each consisting of 5,000–10,000 regularly arranged and sintered miniature tubular channels with a diameter of 2—12 μm and a density of (0.5—5) × 10^6/cm^2. In terms of structure, the MCP's active elements are microchannel fill and a monolithic frame.

The main material is lead silicate glass (LSG). There are strict requirements for the smoothness and cleanliness of the end faces and channels. The parallel electrical connection of all channels is realized by thermal evaporation of a contact metal coating (usually nichrome, chromium or *Inconel* alloy) in vacuum on both sides of the MCP as electrodes. The thickness of the contact coating is approximately 0.2—0.4 The coating is extended to a certain depth at the inlet and outlet of the channels that are usually inclined at a certain angle (4–13°) with respect to the normal to the ends. The whole structure shall be mechanically strong, have as perfect geometric structure of the channels as possible and the minimum number of structural defects.

The total resistance between the electrodes is about 10^8—10^9 Ohms and is determined by the chemical composition of the LSG, as well as by the resistance of the resistive emission layer (REL) on the surface of the channel walls. The REL is formed by hydrogen thermal reduction method, at the stage of production of MCP.

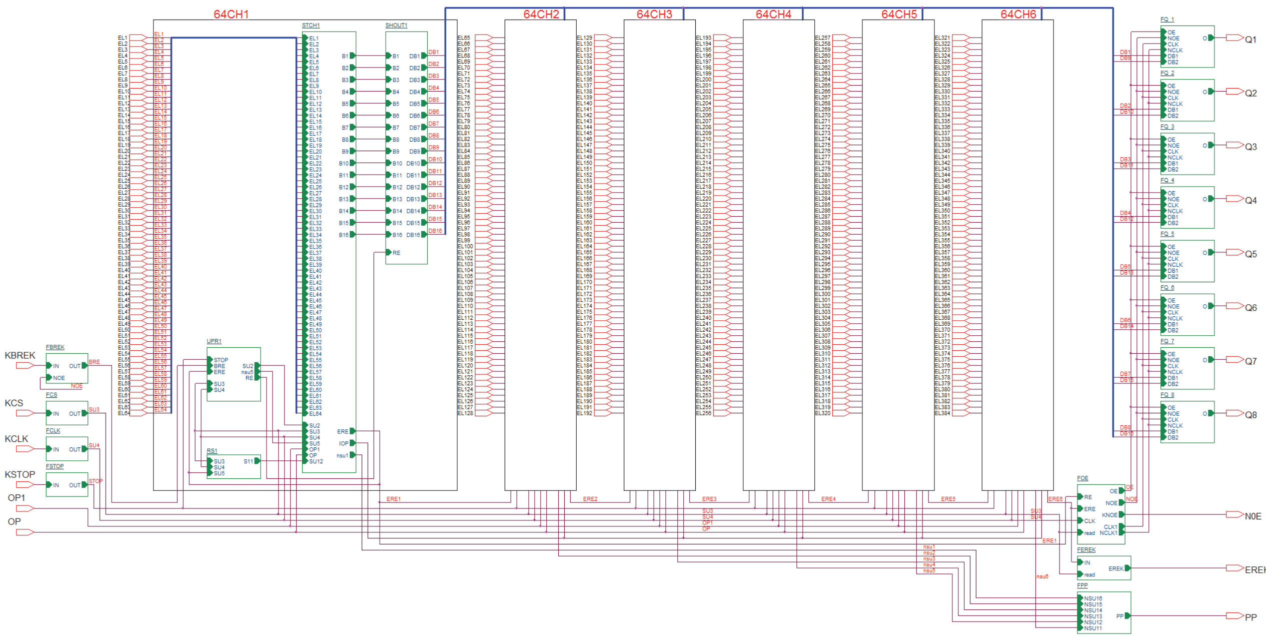

Fig. 3. Functional scheme of LSI circuit: *KBREK* — input of *BREK* readout start signal*; KCS* — input of *CS* crystal selection signal*; KCLK* — input of *CLK* clock signal; *KSTOP* — input of *STOP* counter stop signal; *OP1* — input of reference voltage source *OP1; OP* — input of reference voltage source *OP; Q1* — output of information *Q1/Q9; Q2* — output of information *Q2/Q10; Q3* — output of information *Q3/Q11; Q4* — output of information *Q4/Q12; Q5* — output of information *Q5/Q13; Q6* — output of information *Q6/Q14; Q7* — output of information *Q7/Q15; Q8* — output of information *Q8/Q16; NOE* — output of *OE* information release signal*; EREK* — output of *EREK* readout end signal*; PP* — output of *PP* counter overflow signal*; EL1...EL384* — sensor electrodes; *64CH1...64CH6* — units of 64 channels for processing, accumulation, and release of information; *FOE* — *OE* output signal conditioner; *FEREK* — *EREK* output signal conditioner; *FPP* — *PP* output signal conditioner; *FQ1...FQ8* — *Q* output information signal conditioners; *UPR* — circuit for control of reception, processing, and accumulation of information; *RS* — additional single-bit register

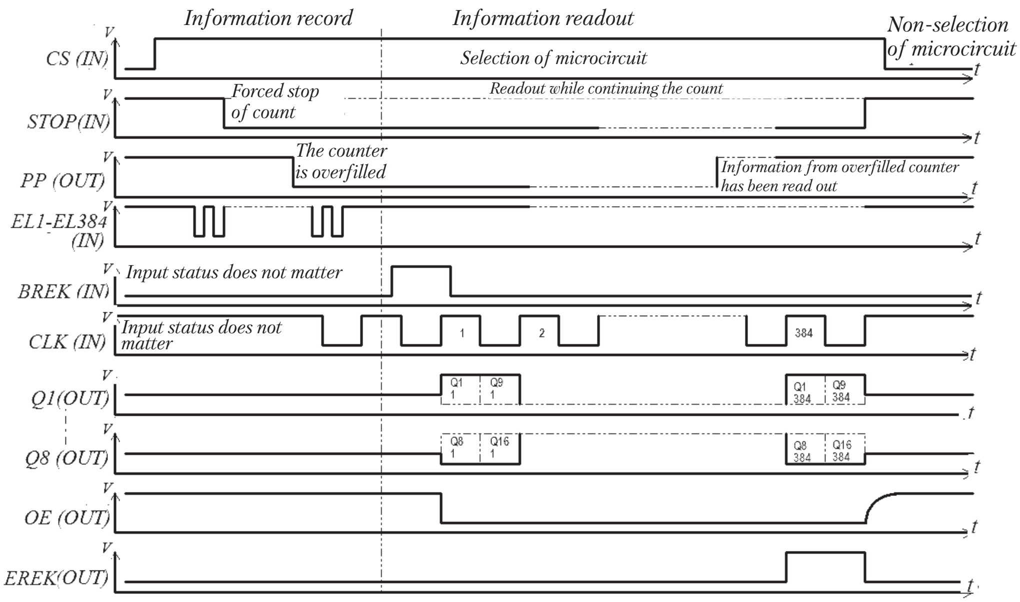

Fig. 4. Time flowchart of LSI circuit operation

Modern microchannel plates used individually or in assembly enable to reach an electronic multiplication factor of 10^4–10^7 together with high time (<100 ps) and spatial resolutions limited only by dimensions of the channel and step of the cellular structure.

The basic element of the MCP is a tubular channel with diameter d, length l, and caliber $a = l/d$. The peculiarity of the MCP microchannel structure is that the multiplication factor is a function of neither the length of the channel nor its diameter. Only the ratio l/d is important.

While manufacturing MCPs, a 0.2–0.3 μm thick resistive emission layer is formed on the surface of the channel. In the first approximation, it consists, of the two layers: the upper (the emissive) one is very thin (about 100 Å) and provides the secondary electronic emission. It is almost dielectric and is based on SiO_2. The bottom layer is thicker, resistive, has electrical conductivity, and contains the concentrated reduced lead.

The channel is supplied with voltage U, and current $I_p = U/R$ passes through the REL The current causes a voltage drop, and a homogeneous electric field with a linearly increasing potential $\phi(x) = (U/l) \cdot x$ arises in the channel. Its intensity $E = U/l$ is directed along the axis of the channel. An electron entering the channel, near the entrance, makes the first collision with the surface. In this case, on average, more than one secondary electron is knocked out. Having entered the electric field, the secondary electron under the action of axial force F increases the axial component of its velocity Vx and while moving along the channel, accumulates energy. Under the influence of the horizontal component of the initial velocity V_0y that field does not act on, it shifts horisontally as well. In the general case, the trajectory of motion of the secondary electron is a parabola shaped by the initial conditions (the energy and the angle of electron exit) and by the field strength in the channel. As a result, the secondary electrons again collide with the wall and generate secondary electrons. This process is repeated many times along the channel, with an electron avalanche moving rapidly and in a time of 10^{-9} s reaching the outlet of the channel.

Assuming that the electrons fly perpendicular to the channel walls, the multiplication factor G of the MCP channel having length L and inner diameter d is calculated by the formulaю:

$$G = \left(\frac{A \cdot V}{2\alpha \cdot V_0^{1/2}}\right)^{\frac{4V_0\alpha^2}{V}},$$

where V is voltage on the MCP; $\alpha = \frac{L}{d}$; $A = \frac{\delta}{V_c^{1/2}}$; V_0 is initial energy of the secondary electron, ~ 1—2 eV; δ is secondary emission coefficient; Vc is energy of the electron before collision with the wall.

The analysis has shown that the multiplication factor G depends on the voltage (field strength in the channel), the caliber of the channel, the REL secondary emission properties, and on some other factors.

Using two MCPs in a chevron assembly eliminates ion feedback and ensures a sufficient electron multiplication for direct ion count.

The developed CSD device uses MCP F4772-01 manufactured by *Hamamatsu*, Japan. This MCP, the structure of which is shown in Fig. 5 and the technical characteristics are given in Table 2, has dimensions that are optimal for its placement over the charge-sensitive part of the LSI circuit crystal. A sufficiently small diameter of the channel (less than the width of one charge-sensitive LSI circuit electrode) ensures a high resolution of the device.

The ion-electron converter consists of two such plates mounted towards each other in the directional channels (the chevron assembly); the gap between them is 100 + 5 μm. The chevron assembly forms a separate functional and structural unit.

Table 2

Technical Specification of MCP F4772-01

Parameter	Value
External dimensions A–A′, mm	61.9 × 13.9
Working area C–C′, mm	61 × 13
Thickness, mm	0.48
Diameter of the channel, μm	12
Step of cells, μm	15
Angle of inclination of channels	8°
Working surface coefficient, %	60
Electrode material	*Inconel*

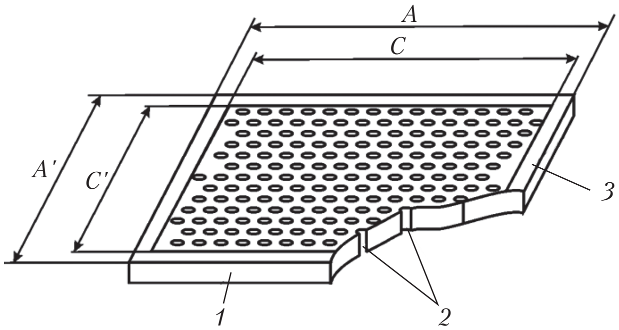

Fig. 5. Structure of MCP F4772-01 (*Hamamatsu*): *1* — glass-like structure; *2* — channels; *3* — electrode area; *A*, *C* — external dimensions; *A′*, *C′* — work area

The microchannel plates being fragile and rather expensive, several measures have been taken to protect them against possible mechanical stresses, critical for the MCP, which may arise while mounting and operating it as part of the device within the temperature range from 0 to 150 °C.

For this purpose, each MCP in the detector is built in a special frame of vacuum ceramics VK-96 with an opening for the dimensions of the MCP plus 100 μm, 0.48 mm thick with a tolerance of minus 10 μm. The MCP frames are made similarly to the elements of the case. The electrical contact in the MCP is provided by two layers of metallized polyimide, 50 μs thick, of which flexible electrodes for supplying a high voltage to the MCP are made. The lower intermediate electrode mounted with its metallized side downwards provides the supply of potential to the upper surface of the lower MCP, and the upper intermediate electrode placed with its metallized side upwards provides the potential to the lower surface of the upper MCP [7].

The ends of the electrodes are connected to the metallized paths on the ceramic base of the case using the ultrasonic welding method. Due to polyimide, this design ensures a "soft" fit of the MCP when pressed.

The ceramic case elements are made of VK-96 ceramics by laser cutting with subsequent grinding to ensure the required dimensional accuracy.

All operations related to the assembly of the device elements are performed using a MBS-9-

type microscope for optical positioning of parts. The case elements are connected by gluing the ceramics with SIEL 159-322A compound followed by drying at 150 °C for 3 hours. Usually, the thickness of the compound in such operations is 10 μm and its high fluidity provides its uniform spread on the surface of the glued parts.

The frames with MCP and intermediate electrodes are sequentially placed in the holder of the chevron unit, a special slot in the case. The input surface of the upper MCP, where the ion beam falls, forms the focal plane of the detector.

GENERAL SPECIFICATION OF THE MICROCIRCUIT

LSI circuit as part of CSD provides simultaneous detection of isotopes in a wide range of masses and concentrations, from 10^{-7} to 100%.

LSI circuit is manufactured by CMON technology with design rules of 1 μm, has n-type pockets and contains 384 sensor electrode and 218603 transistors on a 9.8 × 8.9 mm crystal.

LSI circuit contains 384 channels for receiving and processing information and provides reception of electrons by the sensor electrodes, transformation of electron charge into count pulses, their calculation by 16-bit binary counters, and readout of count results.

The LSI circuit sensitivity at each input is 10^6 electrons/pulse.

The chip is made in a naked version on flexible carriers of aluminum-polyimide type (modification 2). The chip design ensures its mounting on the ceramic board, welding and sealing of the outer pins, mounting of the microchannel plates over the area of the electrode sensors and enables to create a multi-crystal chipboard.

The LSI circuit maintains the electrical parameters, has the required resistance to mechanical and climatic factors, and operates under a pressure of 10^{-5} Pa.

LSI CIRCUIT FUNCTIONAL DIAGRAM AND OPERATING MODES

The functional chart of LSI circuit (Fig. 3) contains 384 channels for receiving and processing information about ion beams distributed in space. Structurally, the channels are divided into six blocks 64CH1... 64CH6 by 64 channels.

Fig. 6 shows a functional diagram of one block of LSI circuit channels. Each channel contains an electrode *EL* that receives electron pulses from the electron multiplier on the MCP, an amplifier *DIF*, a 16-bit counter *SHB*, and a bit of 384-bit serial-parallel shift register *RS*.

The pulse of electrons falling on the sensor electrodes from the microchannel multipliers is fed to the input of the driver amplifier *DIF* (Fig. 6). At the output *OUT* of the driver amplifier there is formed a count pulse fed to the input of the 16-bit *SHB* counter.

While counting, as the number of count units of, at least, one of the counters reaches 65 529, a low level voltage (a sign of overflow of, at least, one of the counters) is formed at the outer output *PP* (Figs. 4, 5). In this case, the input of the overfull *SHB* counter is blocked, while other (not overfull) counters may continue counting. As the readout of the information from the overfull counters at the outer output *PP* is completed, high voltage is renewed. The count can also be stopped by user through supplying a low voltage to the outer output *STOP*. In this case, the inputs of all LSI circuit counters are blocked.

To start reading out information, a high-level *BREK* pulse (Figs. 4, 6) (the start of readout) that shall exceed a low level of, at least, one clock pulse (*CLK*) is sent to the *KBREK* input (Fig. 3). A low signal that determines the start and the end of information flow is displayed at the *OE* output. During the first clock pulse, outputs *Q1*... *Q8* display information accumulated in the counter of the first channel. At the next clock pulses, information from the counters of the following channels are read out. To reduce the number of outputs, information outputs *Q1*... *Q8* are multiplexed. Eight outputs are used to read information from a 16-bit counter. At a high clock speed, information of the low-order digits is given, while at a low speed, higher-order information is output. During the last clock pulse of information

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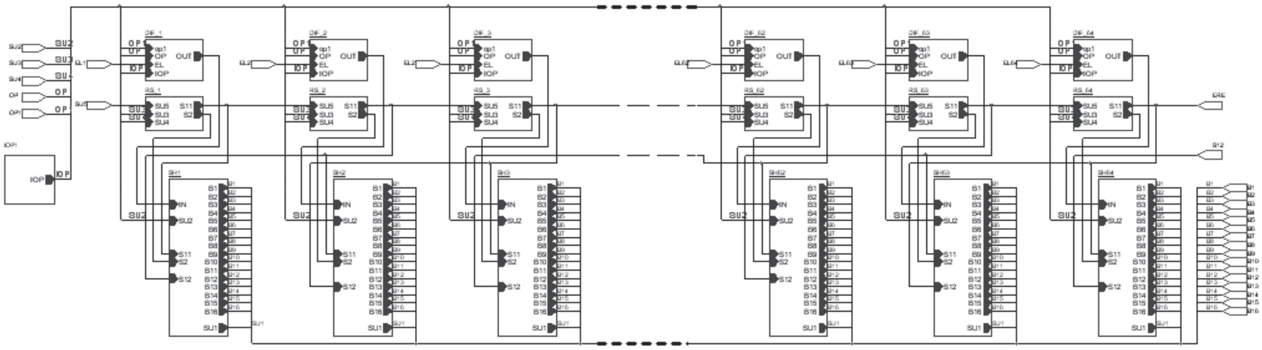

Fig. 6. Functional flowchart of a LSI circuit channel unit

readout at the *EREK* output, there is issued a signal that can be used as a *BREK* signal to start reading the information from the next chip in the multichip CSD devices.

At the beginning of the microcircuit operation, it is necessary to clean the internal register and counters. For cleaning the register, firstly, it is necessary to send a low level *CS* signal to the *KCS* input with a duration of, at least, one clock pulse, and then to realize a readout cycle to set the counters to zero.

In the intervals between the readout cycles and the chip "non-selection" mode, the outputs *Q1... Q8* are in the third state of infinitely high resistance when both output transistors are closed, which enables combining the like outputs of several microcircuits in multi-crystal CSD devices.

There are three readout options in LSI circuit. In the first case, the readout is realized without interrupting the count. In this case, the count is blocked only in the counter from which the information is read out. Upon completion of readout from the counter (while reading information from the next counter), the counter is set to zero and the count is released. In the second case, the *STOP* command blocks the count in all counters and information is read out sequentially from all counters, followed by their setting to zero after the readout. After the completion of readout, the block is removed and the count is resumed. In the third case, the readout is performed upon appearance of the sign of overflow (a low voltage at the output *PP*) of, at least, one of the counters. The readout process is realized according to the first or the second option.

Due to the specificity of the device (the operating mode can be implemented only as part of the spectrometer), for testing LSI circuit, there is a special test mode simulating the pulse of electrons that, if the device operates as part of the spectrometer, come from microchannel multipliers. For this purpose, special test inputs *TEST1* and *TEST2* have been introduced into the LSI circuit. They are connected through a capacitive coupling to the input sensor electrodes *EL*: *TEST1* to the odd and *TEST2* to the even ones. When supplying negative pulses to these test inputs, on the leading edge of the pulses on the input electrodes there appears a negative charge that simulates a pulse of electrons from microchannel multipliers. The charge amount is determined by the amplitude of the negative pulse and the capacity of the connection between the test electrode and the input of the amplifier. Varying the voltage at the mentioned outputs enables monitoring the crystal performance and evaluating the sensitivity and speed of the driver amplifier.

DRIVER AMPLIFIER OF COUNT PULSES AND PROCESSING OF INFORMATION RECEIVED

The most functionally important node of the LSI circuit, which determines the microelectronic CSD parameters is input driver amplifier. Its diagram is shown in Fig. 7.

The operation of the driver amplifier and its sensitivity in LSI circuit UB5709IK01-2.11 [3, 8] depend on the difference in the slopes of the input transistors of the differential stage, which at the same voltages on their gates is created by design parameters. The sensitivity at the same voltages on their gates is determined by the design parameters of these transistors, which may have various deviations in different channels of the same crystal, and, especially, in different LSI circuits in multi-crystal CSD. There is no possibility to adjust the sensitivity of the circuit to optimize it when doing research on driver amplifier.

Since the designed LSI circuit is designed for use in multi-crystal CSD devices, the reproducibility of the amplifier parameters in different channels and different LSI circuits is particularly important. Therefore, a new circuit design protected by patent of Ukraine is used in the driver amplifier [9].

In the innovative LSI circuit, in the amplifier circuit, the input transistors of the differential stage are structurally identical, and the operation of the circuit is based on the voltage difference on the gates of the input transistors of the differential stage, for which an additional source of reference voltage *OP1* is introduced into the circuit [9, 10]. This addresses, to a significant extent, the problem of reproducibility of the transistor design parameters and enables to adjust the sensitivity of the amplifiers depending on the experimental conditions by varying voltage U_{op1}.

The analog part of the amplifier contains a differential stage with active load in the form of a current mirror on *M3-M7* transistors and inverter on *M8, M9* transistors. The first input of the differential stage (the gate of the transistor *M4*) is connected to the corresponding sensor electrode *EL*, and the second one (the gate of the transistor *M7*) is supplied with a voltage *Uop* from the source of reference voltage *OP*. The first input of the differential stage is also connected to the source of reference voltage *OP1* via the parallel-connected n-channel transistors *M1* and *M2*. In this case, the gate of the transistor *M1* is supplied with voltage from the power source *Vcc*, whereas the gate of the transistor *M2* is connected to the output of the inverter on the transistors *M8, M9*.

In the initial state, the input capacity of the amplifier is charged through the transistor *M1* from the source of reference voltage *OP1*, and voltage U_{op1} is set on the gate of the transistor *M4*. The transistor's slope is low and therefore it does not affect the formation of count pulses, but prevents the possible flow of positive charges to the input of the amplifier. Structurally, the *M4* and *M7* transistors are identical and the voltage U_{op1} is set higher than the voltage U_{op}. Therefore, the current in the transistor *M4* circuit exceeds that in the circuit of the transistor *M7*, and therefore, while the transistor *M6* is "saturated", it operates as current mirror of the transistor *M3*, and its current exceeds the current of the transistor *M7*. Therefore, the voltage at the output of the differential stage increases until the transistor *M6* gets "unsaturated" and the currents of the transistors *M6* and *M7* get equal to each other. In this case, a high voltage close to the voltage *Vcc* is formed on the sink of the *M6* transistor. Therefore, the *M8* p-channel transistor gets closed, and a low voltage is set at the output of the *M8*, *M9* inverter and the output of the *OUT* amplifier.

The electron pulse coming from the output of the MCP to the corresponding sensor electrode discharges the input capacity of the amplifier. The voltage on the gate of the transistor *M4* drops, and its current decreases, while the current of the transistor *M7* increases. If a voltage drop on the gate of the transistor *M4* exceeds the sensitivity threshold of the amplifier, the current of the transistor *M7* exceeds the current in the circuit of the transistors *M4, M3*, and, accordingly, the that of the transistor *M6*. The sink voltage of the *M6, M7* transistors drops until the *M6* transistor gets "saturated", the *M7* transistor gets "unsaturated", and the currents of the *M6* and *M7* transistors get equal to each other. In this case, a low voltage is set in the sink node of the transistors *M6* and *M7*, the *p*-channel transistor *M8* is open, and a high voltage close to the supply voltage *Vcc* is set at the output of the inverter *M8, M9* and at the

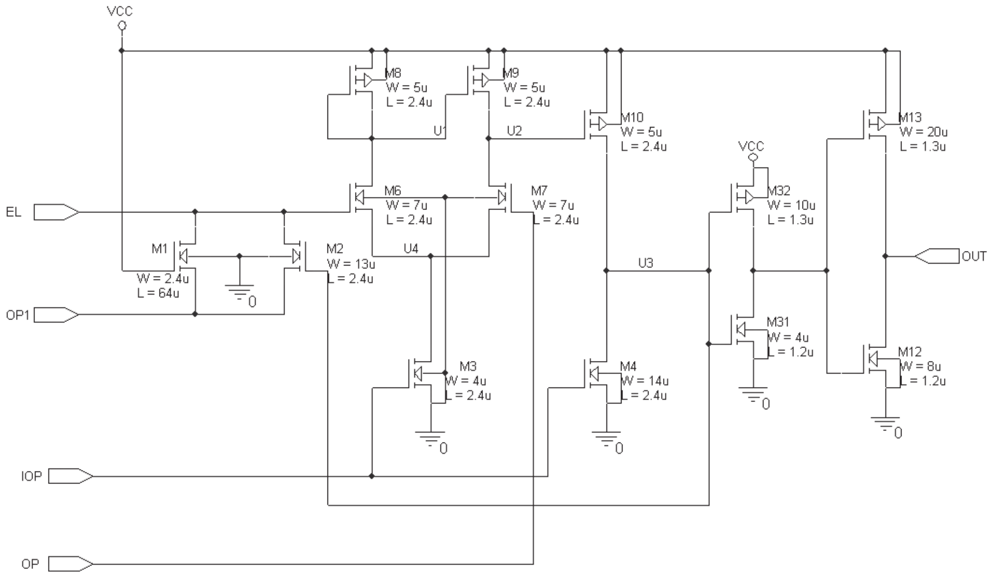

Fig. 7. Circuit diagram of LSI circuit driver amplifier

OUT output of the amplifier thereby completing the formation of the leading edge of the count pulse.

The circuit returns to its original state through feedback via the *M2* transistor. When the potential of the sink node of the transistors *M4* and *M10* exceeds the potential on the gate of the transistor *M6* by a value greater than the threshold voltage of the transistor *M2*, the latter is open and the reverse process begins. The gate node of the transistor *M6* starts charging to the level of the reference voltage U_{o1}, and the circuit returns to its original state, completing the cycle of count pulse formation.

Thus, as the ions fall on the microchannel plate and create electron avalanches that charge the corresponding sensor electrodes *EL*1–*EL*384 at the *OUT* outputs of the corresponding amplifiers *DIF*1–*DIF*384, positive count pulses are formed. The obtained pulses are received at the inputs of the respective counters *SHB*1–*SHB*384. Each channel for receiving and processing information (Fig. 6) contains an amplifier *DIF*, a 16-bit counter *SHB* with an appropriate cleaning and control scheme, and a register bit *RS*.

While designing the amplifier the following problems have been addressed: finding a compromise between the magnitude of currents, sensitivity, and speed of the amplifier, reducing the dimensions (the need to coordinate the size along the *X* axis with the step of the electrodes), ensuring the transmission of count pulses to far-distanced counters, and departing from the critical dimensions of transistors in the analog part of the amplifier.

The ratio between I_{op}, the dimensions of *M3* and *M4* transistors, the dimensions of output transistors *M13* and *M14*, which ensure recharging the loading capacity of up to 2 pF have been optimized, the inverter on the *M10* and *M11* transistors has been used to reduce the capacitive load at the sink nodes of the *M8* and *M09* transistors. Its recharge affects the performance of the amplifier.

The circuit operation and the parameters of the amplifier and the whole LSI circuit have been tested by computer simulation using *Cadence OrCAD* v.16.6 package and models of CMOS transistors BSIM3v3 (Level 7) for calculations with the use of *PSpice* software.

The simulation has been made at a frequency of 20 MHz for recording and 10 MHz for reading. It has confirmed the circuit operation with such speedwork.

The MCSD device with a MCP and the designed LSI circuit shall ensure direct count of ions. The MCP gain multiplier k_{MCP} in chevron assembly of two plates amounts to 10^6. Therefore, it is necessary to ensure the activation of the driver amplifier and the formation of count pulse when feeding charge ΔQ_{input} to the sensor electrode:

$$\Delta Q_{inpu} = q_e \times k_{\mathrm{MCP}} = -1.6 \times 10^{-19} \times 10^6 = \\ = -1.6 \times 10^{-13}\ \mathrm{C},$$

where q_e is electron charge.

The input capacity of the designed amplifier is:

$$C_{input} = 0.9\ \mathrm{pF}.$$

The negative voltage variation at the input of the amplifier corresponds to:·

$$\Delta U_{input} = \Delta Q_{input} \cdot C_{input} = -0.18\ \mathrm{V}.$$

The calculations have showed that at U_{oR} = 2,5 V, the voltage variation at the input of the amplifier ranges from 2.274 V to 2.261 V and causes a voltage drop from 3.089 V to 2.671 V, on the sinks of *M6*, *M7* transistors, and a voltage increase from 0.727 V to 4.180 V, at the output of the inverter on the *M8*, *M9* transistors, and from 0 V to 4.9 V, at the output of the OUT amplifier, that means the calculated sensitivity is higher than the required one by an order of magnitude. Therefore, when operating the MCSD device, its sensitivity is limited only by the level of protection from noise during measurements.

Thus, the amplifier converts the electron pulse coming from the output of the MCP to the sensor electrode into a count pulse. At the same time, it ensures the amplification of input signal and the formation of count pulse.

So, in the course of research, a new generation 5-crystal coordinate-sensitive detector has been created. This has enabled extending the field of simultaneous analysis of the spatial distribution of ion beams of arbitrary composition and, accordingly, the range of elements analyzed simultaneously.

The use of circuit configuration protected by the patent of Ukraine No. 117788 *Microelectronic Coordinate-Sensitive Detector for Spectrometry* in the input amplifier significantly reduces the dependence of the detector sensitivity on differences in the design parameters of the input transistors of the differential stage of the amplifier and makes it possible to optimize the detector sensitivity during analysis.

Thus, the following results have been achieved in the development of new-generation CSD:

- a 5-time increase (up to 50.0 mm) in the range of simultaneously detected ions, which enables to reduce 5 times the time of analysis of the entire range of elements;
- ensuring of reproducibility of parameters, especially, sensitivity and performance, in different LSI circuit channels and in different LSI circuits;
- a 5-time increase (up to 1920) in the number of channels of simultaneous reception and processing of information;
- an increase in the number of bits of the counters to 16, which expands 64 times the amount of received and processed information;
- a 5-time increase (up to 15MHz) in the recording speed to prevent any miss of input information;
- an increase in the readout speed up to 10 MHz (2.5 times), which is crucial in view of growing volumes of information to be read out from the counters (the 5-crystal CSD devise has 1920 16-bit counters);
- improved detector sensitivity as a result of the creation of possibility to adjust it for specific experimental conditions.

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ІННОВАЦІЙНА РОЗРОБКА КООРДИНАТНО-ЧУТЛИВОГО ДЕТЕКТОРА СФОКУСОВАНИХ ІОННИХ ПУЧКІВ ДЛЯ СПЕКТРОСКОПІЇ

Вступ. Актуальним завданням для сучасної аналітичної апаратури, призначеної для кількісного аналізу багатоелементних за складом речовин, є створення багатоканальних координатно-чутливих детекторів (КЧД) заряджених частинок для спектроскопії, які працюють в реальному масштабі часу.

Проблематика. В Інституті мікроприладів (ІМП) НАНУ було розроблено велику інтегральну схему (ВІС) для КЧД, на базі якої та з використанням мікроканальних пластин (МКП) було спроектовано й виготовлено експериментальні зразки приладів КЧД. Виконані в Інституті прикладної фізики (ІПФ) НАНУ дослідження показали позитивні характеристики приладу, зокрема його високу чутливість. Було підтверджено доцільність подальшого проведення робіт.

Мета. Створення багатоканальних приладів КЧД нового покоління з розширеним полем аналізу та покращеними технічними характеристиками.

Матеріали й методи. В розробленому приладі КЧД використано МКП F4772-01 фірми *Hamamatsu*, Японія. ВІС виготовлено за КМОН-технологією з проектними нормами 1 мкм, кишенями n-типу, 384 електродами-датчиками і 218603 транзистора на кристалі розміром 9,8 × 8,9 мм. Мікросхему виконано в бескорпусном варіанті на гнучких носіях типу алюміній-поліімід (модифікація 2).

Результати. Створення 5-ти кристального КЧД нового покоління з покращеними технічними характеристиками забезпечило розширення поля одночасного аналізу просторового розподілу іонних пучків довільного складу та, відповідно, діапазон елементів, які аналізуються одночасно, дозволило підвищити швидкодію при аналізі і при зчитуванні інформації в 5 і 2,5 рази відповідно.

Висновки. Використання схемотехнічного рішення, яке захищено патентом України №117788, значно зменшило залежність чутливості детектора від розбіжностей конструктивних параметрів транзисторів підсилювача-формувача, що дало можливість створити 5-ти кристальний прилад КЧД нового покоління і забезпечило розширення діапазону елементів, які одночасно аналізуються Використання для виготовлення кристалів ВІС сучасної КМОН-технології, оптимізація схемотехнічних і топологічних рішень дозволили одержати високі технічні характеристики приладу КЧД.

Ключові слова: координатно-чутливий детектор, мас-спектрометрія, велика інтегральна схема, КМОН-технологія.

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ИННОВАЦИОННАЯ РАЗРАБОТКА КООРДИНАТНО-ЧУВСТВИТЕЛЬНОГО ДЕТЕКТОРА СФОКУСИРОВАННЫХ ИОННЫХ ПУЧКОВ ДЛЯ СПЕКТРОСКОПИИ

Введение. Актуальной задачей для современной аналитической аппаратуры, предназначенной для количественного анализа многоэлементных по составу веществ, является создание многоканальных координатно-чувствительных детекторов (КЧД) заряженных частиц для спектроскопии, работающих в реальном масштабе времени.

Проблематика. В Институте микроприборов (ИМП) НАНУ была разработана большая интегральная схема (БИС) для КЧД, на базе которой и с использованием микроканальных пластин (МКП) были спроектированы и изготовлены экспериментальные образцы приборов КЧД. Выполненные в Институте прикладной физики (ИПФ) НАНУ исследования показали высокие характеристики прибора, в частности его высокую чувствительность. Была подтверждена целесообразность дальнейшего проведения работ.

Цель. Создание многоканальных приборов КЧД нового поколения с расширенным полем анализа и улучшенными техническими характеристиками.

Материалы и методы. В ИМП НАНУ, в соответствии с «Программой научного приборостроения НАН Украины», выполнена научная работа, в результате которой была разработана новая специализированная БИС на основе использования современной технологии комплементарных структур металл-оксид-полупроводник (КМОП), проведена оптимизация схемотехнических и топологических решений, и на ее основе разработан пятикристальный прибор КЧД.

Результаты. Разработка пятикристального прибора КЧД нового поколения обеспечила расширение поля одновременного анализа пространственного распределения ионных пучков произвольного состава и, соответственно, диапазон элементов, которые анализируются одновременно, позволила повысить быстродействие при анализе и при считывании информации в 5 и 2,5 раза соответственно.

Выводы. Использование схемотехнического решения, которое защищено патентом Украины № 117788, значительно уменьшило зависимость чувствительности детектора от расхождения конструктивных параметров транзисторов усилителя-формирователя, что позволило создать пятикристальный прибор КЧД нового поколения и обеспечило расширение диапазона элементов, которые одновременно анализируются. Использование для изготовления кристаллов БИС современной КМОП-технологии, оптимизация схемотехнических и топологических решений позволили получить высокие технические характеристики прибора КЧД.

Ключевые слова: координатно-чувствительный детектор, масс-спектрометрия, большая интегральная схема, КМОП-технология.