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ZHARKOV, I. P.[1] (https://orcid.org/0000-0003-1626-5655),
SAFRONOV, V. V.[1] (https://orcid.org/0000 0002 2982 962),
KHODUNOV, V. O.[1] (https://orcid.org/0000-0001-7619-8437),
KONOVAL, V. M.[1] (https://orcid.org/0000-0002-5240-1207),
PALAMARHUK, I. P.[1] (https://orcid.org/0000-0003-4513-9850),
SELIVANOV, O. V.[1] (https://orcid.org/0000-0001-9579-885X),
SOLONETSKY, A. G.[1] https://orcid.org/0000-0001-8837-4776),
ALEYNIKOV, A. B.[2] (https://orcid.org/0000-0001-8234-1746),
and VIRKO, S. V.[2] (https://orcid.org/0000-0001-8868-6729)
[1] Institute of Physics, the NAS of Ukraine,
46, Nauky Ave., Kyiv, 03028, Ukraine,
+380 44 525 1220, fizyka@iop.kiev.ua
[2] V.E. Lashkarev Institute of Physics of Semiconductrs, the NAS of Ukraine,
41, Nauky Ave., Kyiv, 03028, Ukraine
+380 44 525 4020, info@isp.kiev.ua

CREATING EQUIPMENT FOR LOW-TEMPERATURE STUDY OF CURRENT-VOLTAGE CHARACTERISTICS AND GALVANOMAGNETIC PROPERTIES OF SEMICONDUCTOR MATERIALS AND STRUCTURES IN THE FIELD OF AN EXTERNAL MAGNET

Introduction. *The study of volt-ampere characteristics (VAC) and galvanomagnetic properties of semiconductor materials and structures based on them under the action of microwave radiation and magnetic fields in a wide range of temperatures is an urgent task for the development of the element base of spintronics and supersensitive sensors.*

Problem Statement. *Currently, there has been no precision complex of thermoregulated cryogenic equipment for low-temperature studies of VAC and galvanomagnetic properties of semiconductor materials and structures based on them in the field of the external magnet, which fully meets the needs of studying the parameters of superconducting materials.*

Purpose. *The purpose of this research is to design and to manufacture a single computerized complex of thermoregulated cryogenic equipment.*

Materials and methods. *Based on the existing domestic experience of creating cryosystems for magnetophysical studies and accessories to them, the development and manufacture of a set of thermally regulated cryo-*

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genic equipment for studying the volt-ampere characteristics and galvanomagnetic properties of semiconductor materials and structures based on cryostat with a specialized manipulator.

Results. *As a result of the research, we have created a complex of precision cryogenic equipment as a part of a cryosystem thermoregulated within 1,5–300 K, based on a helium continuous flow cryostat with a narrow shank. The system consists of an external magnet built into the interpolar space, a specialized manipulator having a built-in gauge for measuring the liquid helium level in the cryostat shaft, a temperature controller, modules for measuring the volt-ampere characteristics and galvanomagnetic properties of semiconductor materials, and software.*

Conclusions. *The designed equipment has as good characteristics as the best western analogs and exceeds them in terms of cryoagent consumption and costs of its maintenance and service.*

Keywords: volt-ampere characteristics, galvanomagnetic properties, semiconductor materials and structures, thermoregulated helium cryosystem.

The study of volt-ampere characteristics (VAC) and galvanomagnetic properties of semiconductor materials and structures based on them, under the action of microwave radiation and magnetic fields, in a wide range of temperature is an urgent task for developing the element base of spintronics and supersensitive sensors. At this stage, semiconductor integral cryoelectronics or semiconductor microelectronics, as well as the study of fluctuation properties and transport mechanisms in quantum-dimensional structures play an important role in scholarly research. Research made with the help of the proposed equipment allows developing new free-vibration oscillators based on AlGaAs / GaAs heterostructures and AlGaN/GaN heterostructures with a phase noise level below commercial oscillators and technologies for obtaining Si single crystals with a high purity and structural perfectness in the conditions of electron beam zone melting of single crystals. The structural transformations of oxygen complexes during heat treatment of CZ-Si and FZ-Si single crystals implanted with carbon and oxygen ions may also be studied.

The leading manufacturers of cryogenic equipment embedded in external magnets are: *Oxford Instruments Ltd.* (UK), *Cryo Industries of America Inc.* (USA), *JANIS Research Company, Inc.* (USA), *Cryomagnetics Corp.* (USA), and *RTI* (Russia). Most of these manufacturers prefer continuous flow gas cryostats, where the heat exchange gas is forced to flow through the working chamber of the cryostat, and the desired temperature of the sample is created by an electric heater wound on the external part of the working chamber or on the heat exchanger.

The advantage of such cryostats is that they have a simple and are relatively cheap. Their significant disadvantages are high cost of the cryogen and a low stability of temperature at a given level. Such cryostats may operate on both helium and nitrogen as a working cryogen. For the operation of such a cryostat, it shall have a source of cryogen (Dewar vessel), flexible overflow S-traps of the bellows type, a pump for pumping cryogen, rotameter, etc. Some manufacturers of cryoproducts build cryostats on the so-called “Swenson’s method” assuming that the cryostat has a built-in tank with liquid helium, from which liquid helium enters the heat exchanger, where it evaporates and having been heated to the required temperature is fed into the working chamber with a test sample. The temperature is regulated by a valve and a heater mounted on the outer surface of the heat exchanger.

In the first type of cryostats, temperature below 4.2 K is obtained by pumping helium vapors and their throttling (the lowest temperature 2.2 K); in the second type, it is reached by pumping cryoagent vapors (up to 1.3 K) from a helium tank or shaft.

The second principle of operation generally enables studying rather large objects, because it is practically possible to build a cryostat for a specific size of the object under study.

In addition, in such cryostats, temperature regulation and stabilization are more precise, because the heat exchange gas is heated and supplied to the working chamber in a laminar flow. The cryostats of this type are developed in small quantities by such firms as *Oxford Instruments*, *JANIS*, and *RTI*. However, each company manufactures certain types of cryostats. In the world market of equipment for optical research, optical microscopy, electrophysical measurements, etc., there have been almost no appliances for low-temperature studies of volt-ampere characteristics and galvanomagnetic properties of semiconductor materials and structures based on them with the superposition of the imposition on the studied objects of such factors as electric, magnetic field, high frequencies, mechanical loads, etc. in the field of external magnet.

In Ukraine, the developers of similar products are Galkin Donetsk Institute of Physics and Technology of the NAS of Ukraine and the Verkin Institute of Low-Temperature Physics and Technology of the NAS of Ukraine.

However, the cryostats from these manufacturers do not have such additional options as changing the orientation of the sample relative to the magnetic field vector with simultaneous application of electric fields and the optical factor to the sample.

Thus, today, there has been no precision complex of thermoregulated cryogenic equipment for low-temperature studies of volt-ampere characteristics and galvanomagnetic properties of semiconductor materials and structures based on them in the field of external magnet, which fully meets the needs of studying the parameters of superconducting materials.

Therefore, the task of creating precision thermoregulated cryogenic equipment for the study of current-voltage characteristics (VAC) and galvanomagnetic properties of semiconductor materials and structures based on them is very relevant.

The purpose of this research is to design and to manufacture thermoregulated cryogenic equipment for low-temperature studies of volt-ampere characteristics and galvanomagnetic properties of semiconductor materials in the field of the external magnet.

Since today there has been no thermoregulated cryogenic equipment for studying the VAC of semiconductor materials, which fully satisfies the needs of studying the parameters of superconducting materials and structures based on them, the creation of such one is an urgent task.

The purpose of the research is to create a single computerized complex of thermoregulated cryogenic equipment, which includes a thermoregulated cryostat built into the interpolar space of the external magnet with a built-in field from 0 to 2 T, an automated temperature controller, a manipulator with the option of automatic rotation of a sample with respect to the magnetic field vector and simultaneous application of an electric field to the test sample, with the combined control of operating conditions of all listed components from the central computer.

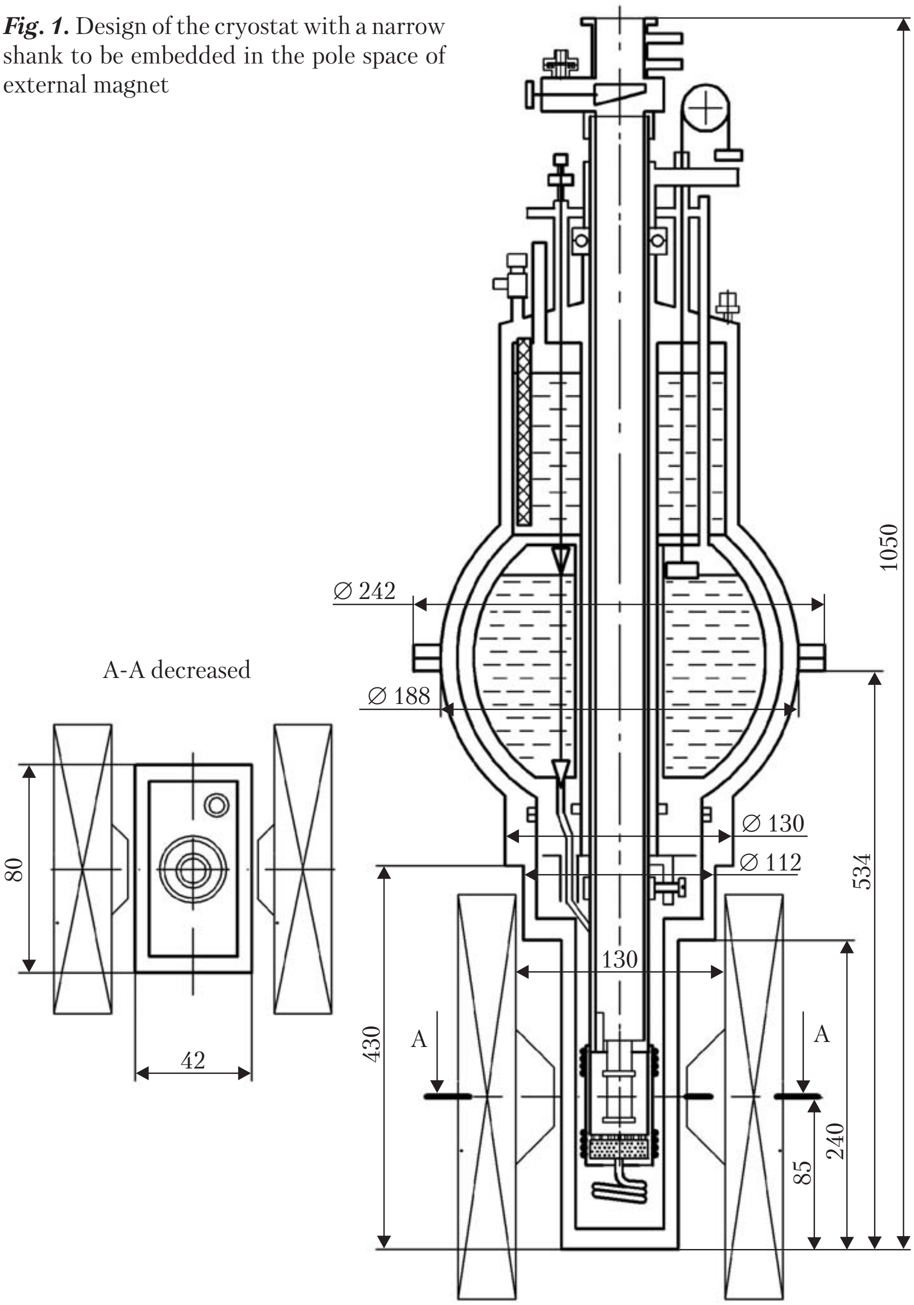
The Institute of Physics of the NAS of Ukraine has accumulated some experience in creating cryosystems for magneto-physical studies [1–5] and accessories to them [6–9]. Given the gained experience, a set of thermally regulated cryogenic equipment has been developed and manufactured for studies of volt-ampere characteristics and galvanomagnetic properties of semiconductor materials and structures based on them, with the use of a cryostat having a specialized manipulator (see their configuration below) and a temperature controller.

The configuration of the cryostat is schematically shown in Fig. 1. The structural and functional diagram of the equipment based on a cryosystem with a cryostat type A.218, a temperature controller K.43, and a manipulator with a programmable rotation of the sample and a level gauge of liquid cryogent in the cryostat shaft is given in Fig. 2.

Inside the collapsible housing, there is a helium tank surrounded by a copper screen cooled by liquid nitrogen poured into the nitrogen tank.

The helium and nitrogen tanks are suspended from the lid on thin-walled tubes made of a material with low thermal conductivity. The helium tank suspension tubes are used respectively: for

Fig. 1. Design of the cryostat with a narrow shank to be embedded in the pole space of external magnet



pouring liquid helium, placing a level gauge, and installing a needle valve for liquid helium supply, which is controlled by the handle.

In the upper part, the suspension tubes of the helium tank are interconnected by a collector for the discharge of evaporating helium into the main through a fitting.

The nitrogen tank suspension tubes are used for pouring in and evaporating nitrogen.

The vacuum cavity of the cryostat is pumped out by a forevacuum pump through a vacuum valve. A high vacuum is created by a cryopump.

In the center of the cryostat housing, there is a shaft (loading pipe) that ends at the bottom with

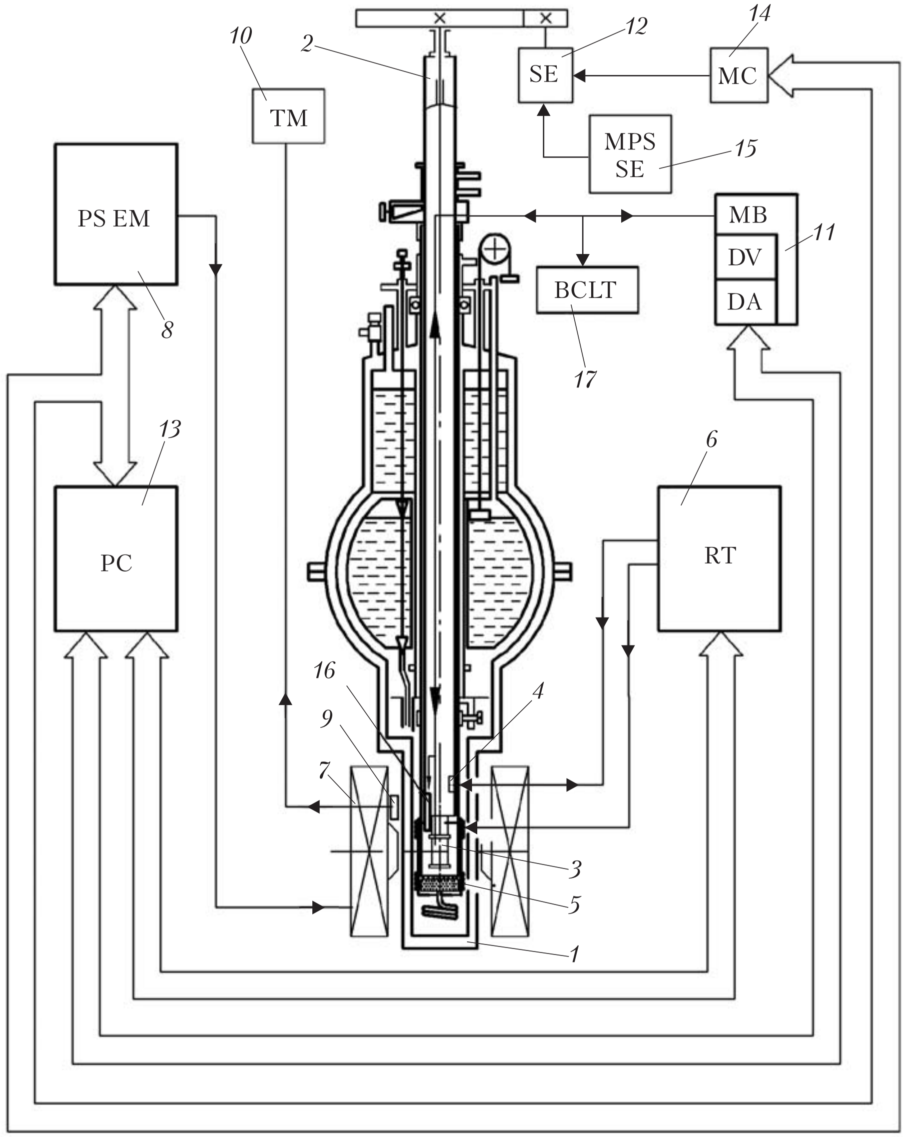


Fig. 2. Structural and functional diagram of the device based on cryostat A.218, temperature controller K.43, and manipulator with programmable rotation of test sample: *1* — cryostat; *2* — manipulator; *3* — sample; *4* — temperature sensor; *5* — electric heater; *6* —temperature controller (TC); *7* — external magnet (EM); *8* — external magnet power supply (EMPS); *9* — Hall's sensor; *10* — teslameter (TM); *11* — measurement module (MM) consisting of a digital voltmeter (DV) and a digital ammeter (DA); *12* — stepper motor (SM); *13* — PC; *14* — process controller (MC); *15* — power supply of stepper motor (PSSM); *16* — capacitive sensor (CS); *17* — capacitive level gauge module (CLGM)

the thermostat, on the outer surface of which an electric heater (R = 100 Ohm ± 20%, U_{max} = = 40 V) is wound up. Its terminals are soldered to the connector. A heat exchanger connected to helium supply tube *25* is soldered to the bottom of the thermostat chamber.

The shaft position is fixed by three screws.

At the top of the shaft there is a sliding gate that blocks the cross section of the shaft when samples are sluiced.

Gaseous helium from the thermostat chamber is discharged through the shaft and the fitting.

To prevent the destruction of the cryostat when the pressure increases in the vacuum space of the helium tank and the shaft, safety valves are installed, the rupture membranes of which are calibrated to an operating pressure of $5–7 \times 10^4$ Pa.

The cryocomplex consists of the following components:

a) the circuit of controlling and stabilizing temperature, which contains cryostat *1*, manipulator *2* with test sample *3*, temperature sensor *4*, electric heater *5*, temperature controller (TC) *6*, and personal computer (PC) *13* (see Fig. 2);

b) the circuit for regulating and stabilizing magnetic field strength, which contains cryostat *1* built into the pole space of external magnet *7*, power source of the external magnet *8*, manipulator *2* with Hall sensor *9*, tesla-meter (TM) *10*, measuring module *11* with a digital voltmeter and ammeter, and PC *13*.

c) the module automatically controlling the angle of rotation of the sample, which consists of manipulator *2* rotating the rod together with the holder and sample *3* around the vertical axis with the help of stepper motor (SM) *12* connected to control PC *13* via process controller (MC) *14* via electrical and information network and power supply unit of the stepper motor (PSSM) *15*.

d) the system for electrophysical measurements, which comprises measuring module (MM) *11* connected to sample *3* on manipulator *2* via the electrical network and to PC *13* via the information network.

e) the capacitive level gauge of liquid helium in the cryostat shaft consisting of capacitive sensor (CS) *16* and capacitive level gauge module (CLGM) *17*.

g) if necessary to conduct optical studies, it is possible to create a potential optical channel in the manipulator, which consists of tube *28* where a light guide 30 may be installed to bring the optical effect factor from the outer part of the manipulator to the sample in its lower part.

g) if necessary to conduct studies with ultrahigh frequency, there is an option for creating the channel for supply of ultrahigh frequency (UHF) electromagnetic radiation to the sample in the manipulator, which consists of tube *40* where UHF cable *41* arrives from socket *42* on a switch box 17 in the upper part of the manipulator to switchboard *35* in the lower part, see Fig. 3, and Fig. 3, *d*).

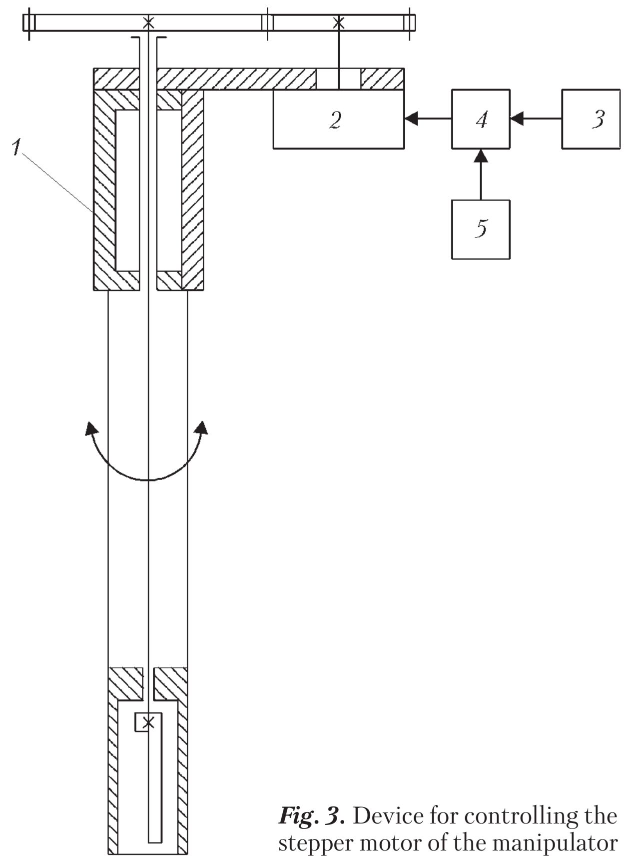


Fig. 3. Device for controlling the stepper motor of the manipulator

The manipulator is shown in drawings: the functional diagram of the device for controlling the stepper motor of the insert (Fig. 3); the vertical section of the insert (Fig. 3, *a*); the side view of the insert (Fig. 3, *b*); the A-view of the insert (Fig. 3, *c*); the B – B section of the insert (Fig. 3, *d*).

The functional diagram of the device (see Fig. 3) consists of: insert *1* with stepper motor *2*, computer *3* that controls the stepper motor according to a given program through process controller *4*, and power source *5*.

The insert (see Fig. 3, *a*) contains a mechanism for rotating substrate *6* with sample *7* around its

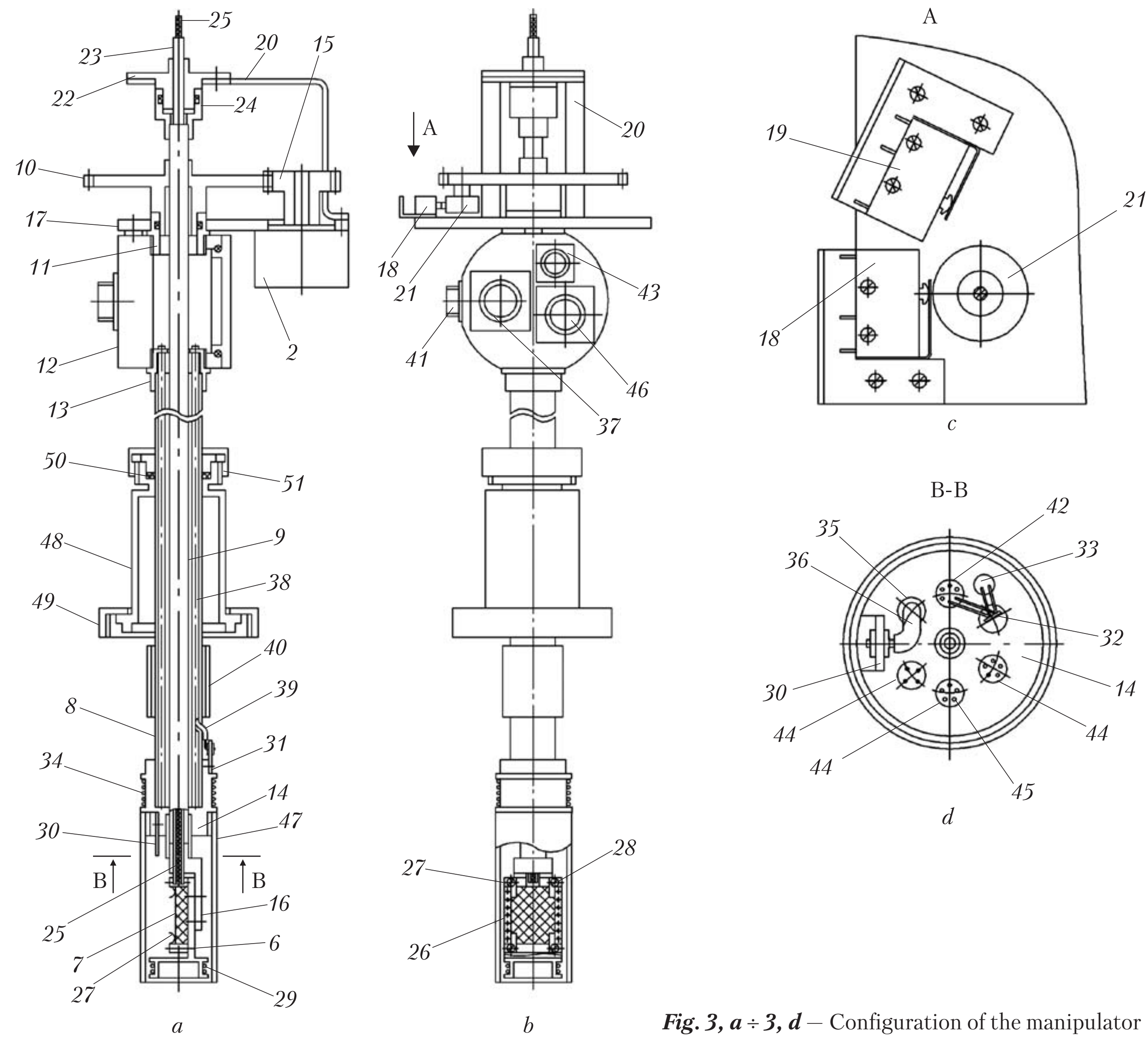


Fig. 3, a ÷ 3, d — Configuration of the manipulator

vertical axis. The mechanism consists of central tube *8*, inside which there is fixed tube *9* that is rigidly fixed on gear wheel *10* and rotates with it in sleeve *11*. The sleeve is rigidly fixed at the top on switch box *12* connected to the upper part of the central tube through sleeve *13*. In the lower part, tube *9* is fixed so that it may rotate, in housing *14*. From above, tube *9* through tooth gear *10* and gear *15* is kinematically connected to stepper motor *2*, and from the bottom, it is rigidly connected through holder *16* to substrate *6* with sample *7*. Thus, stepper motor *2* rotates substrate *6* with sample *7* around the vertical axis of the insert.

On the upper part of box *12*, there is fixed platform *17* (see Fig. 3, *a, b*) that is equipped with the following: stepper motor 2 with gear *15*; tooth gear *10*; microswitch *18* that determines the initial position of the rotation mechanism of substrate *6* with sample *7*; microswitch *19* (see Fig. 3, *c*) that determines the final position of the rotation mechanism; and bracket *20*. At the bottom of tooth gear *10*, there is fixed sleeve *21* that actuates microswitches *18* and *19,* while rotating the tooth gear. On bracket *20*, above, there is mounted sleeve *22*, into which tube *23* is soldered. Around sleeve *22*, together with tube *23,* there rotates sleeve *24* with tube 9 soldered in it. Immovable tube *23* ends at the bottom above the upper end of sample *7* and is used to install light guide *25*. On substrate *6*, near sample *7*, there is switchboard *26* and spring-loaded clamps *27* and *28* for fixing sample *7* on substrate *6*. In the lower part of the substrate, there is wound electric heater *29*. On housing *14*, there are fixed switching boards *30*, *31*, and *32*, temperature sensor *33* (see Fig. 3, *d*), and wound electric heater *34*. In addition, in the housing, the tubes for conducting the cables and conductors going from switching boards through housing *14*, tube *8* is fixed to sockets on switching box *12* (Fig. 3, *a* and *b*). Tube *35* (see Fig. 3, *d*) is used to conduct UHF cable *36* from switchboard *30* to connector *37* on box *12* (see Fig. 3, *b*). Tube *38* (see Fig. 3, *a*) is used to conduct HF cable *39* from sensor *40* of the capacitive indicator of the helium level through switching board *31* to connector *41* on box *12* (see Fig. 3, *b*). Tube 42 (see Fig. 3, *d*) is used to conduct the conductors from temperature sensor *33* through switching board *32*, as well as from electric heaters *29* and *34* to connector *43* on box *12*. Tubes 44 (see Fig. 3, *d*) are used to lead conductors *45* from sample *7* through switchboard *26* to connector *46* on box. In the lower part of housing *14*, there is fixed copper screen *47* to reduce the temperature gradient along the sample. The insert has extension *48* for fixing it to the upper connection pipe of the cryostat by means of cap nut *49*. In the upper part, the extension has gland seal *50* for moving central tube 8 up or down and rotating around the vertical axis with subsequently fixing the tube by means of cap nut *51*.

The insert works as follows.

Sample *7* is fixed on substrate *6* by means of clamps *27* and *28* (see Fig. 3, *a*, *b*). Stepper motor *2* through gear *15* and tooth gear *10* rotates tube *9* together with holder *16* and substrate *6* with sample *7*. The angle of rotation of sample *7* around the vertical axis of the insert depends on the number of steps of motor *2,* which is set by computer *3* via the process controller (Fig. 3) and on the gear ratio of gear *15* and tooth gear *10* ($i = 2/9$). Given that the stepper motor rotates the shaft by an angle of 0.9° per one step, and the gear ratio between gear *15* and tooth gear *10* is $i = 2/9$, it is possible to set the angle of rotation of substrate *6* with sample *7* per one motor step: $0.9° \times 2/9 = 0.2°$.

The angle of rotation X of sample *7* can be set and fixed through the number of steps *N* of the motor controlled by the computer:

$$N = X/0.2.$$

For example, rotating the sample for an angle $X = 180°$ requires *N* motor steps:

$$N = 180°/0.2° = 900.$$

The maximum rotation angle depends on the angular position of microswitch *19* and is 320°.

Since the operation and principle of operation of such components of the complex as temperature controller, power supply of SCS, etc. have been described in detail in [1–9], we skip this information and focus on describing in detail the capacitive level gauge of liquid cryogen in the cryostat shaft designed by us, since maintaining the level of cryogen at a certain level in the cryostat shaft, especially while pumping cryoagent vapors, is of great importance for keeping a stable temperature of the test sample.

There are two types of liquid cryogen level measurement systems: the discrete and the continuous ones. The discrete level gauges are built on the basis temperature sensor resistors. The measuring current flowing through the resistors heats those that are in cryoagent vapor, while the resistors that are in the cryogenic fluid are not heated. The difference between the resistances of the resistors in the cryoagent vapor and in the liquid cryoagent is a measure for determining the level of cryoagent in the vessel.

The continuous level gauges are represented by superconducting level gauges widely manufactured by companies [10–14]:

As a rule, in such a level gauge, SC wire made of niobium-titanium alloy NbTi is used as a vertical probe. This alloy is characterized by the fact that as its temperature decreases from ambient to critical (T_{cr} = 9.5 K), its resistance drops by about 10–15%. At $T < T_{cr}$, the resistance falls sharply to zero, as the alloy becomes a superconductor. This specific feature of superconductors is used in various superconducting level gauges of liquid helium. All of them are based on the fact that the part of the level gauge probe immersed in liquid helium has zero resistance, and the higher part has a critical point resistance under the assumption that the presence of liquid helium in the vessel guarantees a temperature that does not exceed the critical one along the entire probe height. The normal phase in the part of the probe beyond the liquid helium is initiated by some heating of the probe by a special heater connected according to a certain scheme. The heater current is selected experimentally.

In addition, a significant disadvantage is the inability to use these level gauges to measure the level of other liquid cryoagents such as nitrogen, hydrogen, oxygen, etc.

That is why the same companies offer liquid nitrogen level systems of discrete and continuous type. The discrete level gauges are built on the basis temperature sensor resistors. The measuring current flowing through the resistors heats those that are in cryoagent vapor, while the resistors that are in the cryogenic fluid are not heated. The difference between the resistances of the resistors in the cryoagent vapor and in the liquid cryoagent is a measure for determining the level of cryoagent in the vessel. The resistors are scanned with a certain frequency automatically or manually. The disadvantage of such level gauges is the limited possibility of their use in cryostats when pumping cryoagent vapors from the working shaft of the cryostat due to the heat inflow that they “bring” additionally to the cryostat in the operating mode thereby disturbing the heat balance in the cryostat. The continuous level gauges are built on the basis of a capacitive type level sensor. The level gauge has a probe immersed in a tank with liquid nitrogen and a control unit. The probe is made in the form of two coaxial thin-walled stainless steel tubes. The gap between the tubes is 0.7 mm. The tubes are isolated from each other: the probe is a cylindrical capacitor.

The principle of operation of the level gauge is based on linear change in the capacity of the probe when the gap between the coaxial tubes of the probe is filled with liquid nitrogen. The dielectric constant of liquid nitrogen is higher than that of gaseous nitrogen, so the capacity of the probe increases as it is immersed in liquid nitrogen. The electronic module located at the top of the probe converts the change in capacitance into a change in the amplitude of the electrical signal that comes to the control unit. In the control unit, the high-frequency analog signal is amplified and converted to digital one, and the initial value of the probe capacitance is compensated.

Nitrogen level gauge of continuous type LEVMETNL4-02 manufactured by *RTI* and *Cryomagnetic systems* (Chernogolovka of the Moscow Oblast, the Russian Federation) [15] indicates the level of liquid nitrogen in tanks with accuracy of 2%. A significant disadvantage of this solution is the inability to measure the level of liquid helium without reconfiguring the level gauge.

There is also a technical solution for measuring the level of liquid cryoagent model LM-510 from *Cryomagnetics* [16], which with the use of two-channel configuration, enables measuring the level of either liquid helium or liquid nitrogen by appropriate switch of channels and interface from

Table 1. **Dielectric Constant of Cryogenic Liquids (at 18 °C and normal pressure) [17]**

Substance	ε
Liquid nitrogen (–198.4 °C)	1.4
Liquid hydrogen (–252.9 °C)	1.2
Liquid helium (–269 °C)	1.05
Liquid oxygen (–192.4 °C)	1.5

IEEE-488.2 to RS-232 or vice versa. The disadvantage of this solution is the need for simultaneous presence of two level sensors for liquid helium and for liquid nitrogen.

The dielectric constant widely differs for different cryogenic liquids. For example, the dielectric constant of nitrogen is almost 1.3 times higher than that of liquid helium, 1.17 times higher than that of hydrogen, and almost equal to that of oxygen (Table 1).

From the above we may conclude that in the case of one configuration of the level meter, the useful signal for the reactive capacitor filled with liquid helium is 1.3 times less than that for the capacitor filled with nitrogen, 1.17 times less for the capacitor with liquid hydrogen and almost equal to that for the one with liquid oxygen. Therefore, it is necessary to create an additional multiplier factor of the weaker signal to equalize the final useful signals from nitrogen, helium, or hydrogen.

A capacitive level gauge is used to measure the level of liquid helium and liquid nitrogen in the working chamber of the cryostat. Its advantages are: no heat dissipation, independence of readings from temperature and magnetic field. The capacitive sensor is a capacitor consisting of four tubes (all four are located in each other). The dielectric constant of helium Σ = 1.048, i.e. in the case of filling the capacitor gap with liquid helium, the capacity may change up to ~ 4.8%. The functional diagram of the level gauge is shown in Fig. 4, the configuration of the capacitor is given in Fig. 5.

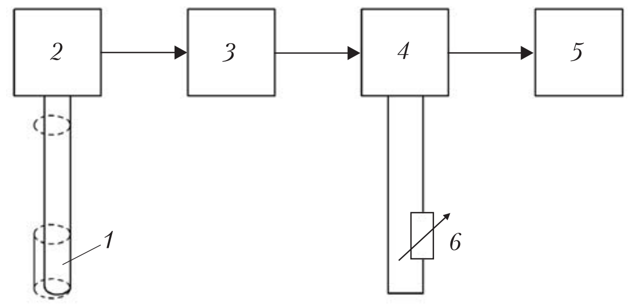


Fig. 4. Functional diagram of the capacitive level gauge of liquid helium: *1* — capacitive sensor; *2* — high frequency generator; *3* — frequency discriminator; *4* — DC amplifier; *5* — arrow indicator; *6* — resistor for setting "0"

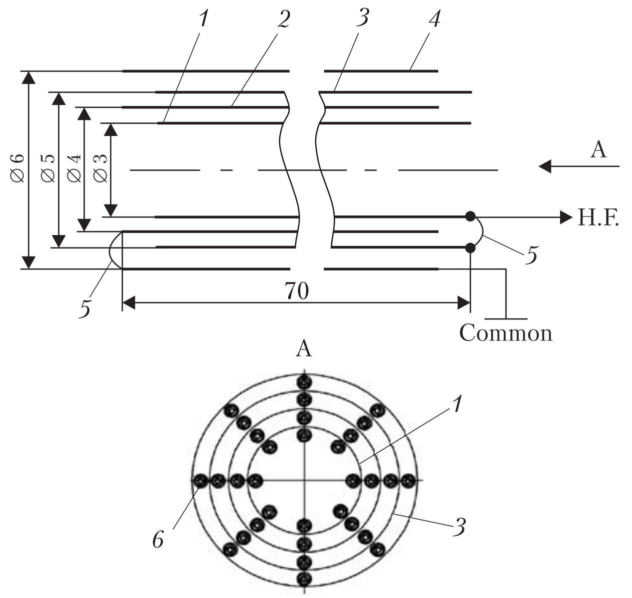


Fig. 5. Capacitive level sensor: *1*, *2*, *3*, and *4* — metal tubes; *5* — wires; *6* — threads

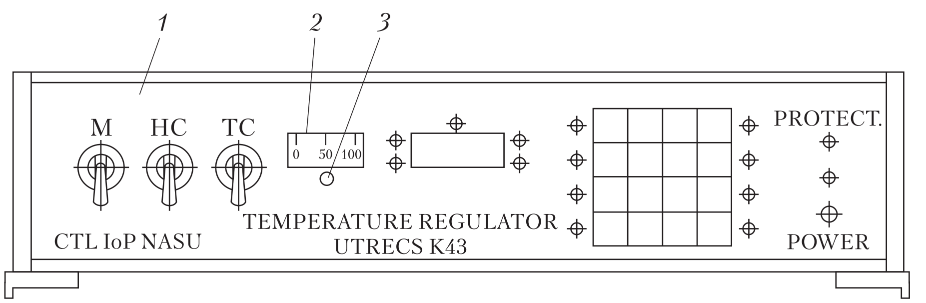


Fig. 6. Switch device of the capacitive indicator built in the temperature controller

Table 2. **The Cryosystem Specifications**

1	Range of temperature regulation, K	1.6 – 300 77; 80 – 300
2	Cryoagents:	liquid helium, liquid nitrogen
3	Liquid helium consumption:	
	in the case of cryostat cooling down, cm³	at most 500
	when keeping temperature 15 K, cm³/h	at most 0.15
	when keeping temperature 20 K, cm³/h	at most 0.08
4	Continuous operation time at 1.6 K without refilling with cryoagents, h	at least 6
5	Volume of tank with liquid nitrogen, cm³	1200
6	Volume of tank with liquid helium, cm³	1700
7	Diameter of cryostat loading channel	19
8	Dimension of cryostat chamber, mm	∅ 19×60
	Dimensions, mm мм, at most:	
	cryostat	∅ 210×807
	manipulator	∅ 60×916
	overflow S-trap H 520	615×360
	Weight:	
	cryostat, kg	6
	manipulator, kg	1.5
	Electric heaters:	
	electric heater mounted on the outer wall of the cryostat thermostat chamber:	
	resistance, Ohm	100
	material: nichrome	∅ 0.12; L = 1000 mm
	supplied voltage, V	0–40
	Electric heater mounted on the manipulator at the location of the sample:	
	resistance, Ohm	20
	material: nichrome	∅ 0.12; L = 200 mm
	supplied voltage, V	0 – 6
1.2.1.4	Working pressure of rupture membranes of safety valves, Pa	$5 \div 7 \times 10^4$
11.	Magnetic system properties:	
	a) Magnetic field strength in the center of the external magnet, T	1.5

Fig. 6 features the built-in temperature controller with an arrow indicator. Tubes *1, 2, 3*, and *4* with different diameters are concentrically located in each other. Tubes pairs *1* & *3* and *2* & *4* are soldered to each other by wires *5*. Threads *6* are wound along the entire length of tubes *1* and *3*. The threads are wound around both the inner and the outer sides of the pipe walls and fixed with glue. The level gauge works as follows. Let the generation frequency be f_0. When the capacitor is filled with liquid cryoagent, its capacity increases while the generation frequency decreases. Varying generation frequency leads to a change in the frequency discriminator output voltage supplied to the DC amplifier. Switch device *2* (Fig. 6) mounted in the K.43 temperature controller has a scale from 0 to 100%. Handle *3* is used for setting zero.

The cryosystem specifications are given in Table 2.

A complex of precision cryogenic equipment has been designed. It is a part of the cryosystem thermoregulated within 1.5–300 K. The system is based on a flow-type helium cryostat with a narrow shank, which is built into the interpolar space of an external magnet with a specialized manipulator having a built-in capacitive gauge for measuring the level of liquid helium, temperature controller, and modules for measuring volt-ampere characteristics and galvanomagnetic properties of semiconductor materials and software.

The designed equipment is as good as the best western analogs in terms of the specifications and is better in terms of cryoagent consumption, stability of the set temperature, and maintenance/service costs.

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І.П. Жарков[1] (https://orcid.org/0000-0003-1626-5655),
В.В. Сафронов[1] (https://orcid.org/0000 0002 2982 9627),
В.О. Ходунов[1] (https://orcid.org/0000-0001-7619-8437),
В.М. Коновал[1] (https://orcid.org/0000-0002-5240-1207),
І.П. Паламарчук[1] (https://orcid.org/0000-0003-4513-9850),
О.В. Селіванов[1] (https://orcid.org/0000-0001-9579-885x),
А.Г. Солонецький[1] (https://orcid.org/0000-0001-8837-4776),
А.Б Алейніков[2] (https://orcid.org/0000-0001-8234-1746),
С.В. Вірко[2] (https://orcid.org/0000-0001-8868-6729)

[1]Інститут фізики НАН України,
просп. Науки, 46, Київ, 03028, Україна,
+380 44 525 1220, fizyka@iop.kiev.ua
[2]Інститут фізики напівпровідників ім. В.Є. Лашкарьова НАН України,
просп. Науки, 41, Київ, 03028, Україна,
+380 44 525 4020, info@isp.kiev.ua

СТВОРЕННЯ АПАРАТУРИ ДЛЯ НИЗЬКОТЕМПЕРАТУРНИХ ДОСЛІДЖЕНЬ ВОЛЬТ-АМПЕРНИХ ХАРАКТЕРИСТИК І ГАЛЬВАНОМАГНІТНИХ ВЛАСТИВОСТЕЙ НАПІВПРОВІДНИКОВИХ МАТЕРІАЛІВ ТА СТРУКТУР НА ЇХНІЙ ОСНОВІ В ПОЛІ ЗОВНІШНЬОГО МАГНІТА

Вступ. Дослідження вольт-амперних характеристик (ВАХ) та гальваномагнітних властивостей напівпровідникових матеріалів та структур на їхній основі під дією НВЧ випромінювання та магнітних полів у широкому діапазоні температур є актуальною задачею для розробки елементної бази спінтроніки та надчутливих сенсорів.

Проблематика. Наразі не існує прецизійного комплексу терморегульованої кріогенної апаратури для низькотемпературних досліджень в полі зовнішнього магніта ВАХ та гальваномагнітних властивостей напівпровідникових матеріалів та структур на їхній основі, яка б повністю могла задовільнити потреби вивчення параметрів надпровідних матеріалів.

Мета. Розробка конструкції та виготовлення єдиного комп'ютеризованого комплексу терморегульованої кріогенної апаратури.

Матеріали й методи. На основі наявного вітчизняного досвіду створення кріосистем для магніто-фізичних досліджень та аксесуарів до них виконано розробку та виготовлення комплексу терморегульованої кріогенної апаратури для досліджень вольт-амперних характеристик та гальваномагнітних властивостей напівпровідникових матеріалів та структур на їхній основі на базі кріостата із спеціалізованим маніпулятором.

Результати. Створено комплекс прецизійної кріогенної апаратури у складі терморегульованої у діапазоні 1,5–300 К кріосистеми на базі гелієвого кріостата рідинно-проточного типу з вузьким хвостовиком, з вбудованого у міжполюсний отвір зовнішнього магніта із спеціалізованим маніпулятором з вбудованим ємнісним вимірювачем рівня рідкого гелію в шахті кріостата, з регулятором температури, з блоками вимірювання вольт-амперних характеристик та гальваномагнітних властивостей напівпровідникових матеріалів та програмним забезпеченням.

Висновки. Характеристики розробленої апаратури не поступаються показникам кращих західних аналогів, а за витратами кріоагента й сервісу перевищують їх.

Ключові слова: вольт-амперні характеристики, гальваномагнітні властивості, напівпровідникові матеріали та структури, терморегульована гелієва кріосистема.