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THE STANDARD BASE OF RUSSIA FOR MEASURING SMALL DIRECT-CURRENT IN THE 10^{-16}–10^{-9} A RANGE

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The present state of the standard base of Russia for measuring small direct-current in the 10^{-16}–10^{-9} A range is considered, and the metrological characteristics of the state primary and transferable standards are given.

***Key words**: standard, small direct current, nanotechnologies, comparisons.*

Instruments for measuring small direct currents in the 10^{-16}–10^{-9} A range and the physical quantities related to them (a dc voltage in high-resistance circuits of up to 10^{17} Ω, high resistances of up to 10^{18} Ω and charges of up to 10^{-16} C) are called electrometers. Improvements in the components and their input devices and structural principles have led to the design of a new generation of electrometers using microprocessors.

These instruments are employed in various areas of science and technology: in biology – for investigations at the molecular level, for example, the noise characteristics of the membranes of biological cells, in nuclear physics – when investigating the properties of different materials, in space research – to determine the radiation belts of the Earth, and measurements of the degree of a vacuum, in atomic power – to monitor the neutron flux power level and to deliver signals to provide preliminary warning signals, in the area of ionizing radiation – when measuring radiation energy and the parameters of neutron fluxes, and in medicine, to monitor the level of radiation in chemotherapy. They also find wide application when investigating the properties of dielectrics, semiconductors and microcircuits. During the last few years work has been carried out to increase the accuracy of the conversion and measurement of small currents to solve problems in the area of nanotechnology: to produce components for microelectronics, nanoelectronics and quantum computers.

In Russia, a considerable number of different electrometers are employed: the ITL-02, ITN-7, EM-1, V7E-3, V7-29, V7-30, V7E-42, V7-45, and V7-57 electrometer voltmeters in three modifications, U5-8 and U5-9 electrometer amplifiers, IT-12, EK1-6, and NK4-1 standard calibrators of small direct currents, and IIT-9–IIT-13 standard low-current sources. At the present time, the list of electrometer instruments has rapidly lengthened mainly due to developments by foreign companies. In particular, the Keithley Instruments Company has marketed instruments in more than ten different modifications.

In Russia, the provision of instruments for measuring small direct currents in the 10^{-16}–10^{-9} A range has been carried out in accordance with the State Checking Scheme [1], headed by the State Primary Standard of the unit of direct electric current GÉT 4-91 [2, 3]. The State Standard is an automated measuring system. The measurement equation, on which its construction is based, has the form

$$I = CdU/dt,$$

where I is the current strength, C is the capacitance of a standard capacitor, and dU/dt is the change in voltage per unit time.

When transmitting the dimensions of the unit of the standard measures of current, a zero compensation method is used, the basic principle of which is the compensation of charges produced on the plates of a standard capacitor by currents

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TABLE 1. Metrological Characteristics of GÉT 4-91

Range of reproduced current, A	Uneliminated systematic error	Root mean square deviation
10^{-16}–10^{-15}	$25\cdot10^{-3}$–$6\cdot10^{-3}$	$5\cdot10^{-3}$–$2.5\cdot10^{-3}$
10^{-15}–10^{-14}	$6\cdot10^{-3}$–$1.5\cdot10^{-3}$	$2.5\cdot10^{-3}$–$0.2\cdot10^{-3}$
10^{-14}–10^{-13}	$1.5\cdot10^{-3}$–$1\cdot10^{-3}$	$0.2\cdot10^{-3}$
10^{-13}–10^{-11}	$1\cdot10^{-3}$	$0.2\cdot10^{-3}$
10^{-11}–10^{-9}	$1\cdot10^{-3}$–$0.3\cdot10^{-3}$	$0.2\cdot10^{-3}$–$0.02\cdot10^{-3}$

from the primary standard and the measure being checked. The apparatus of the standard guarantees reproduction, storage of the unit of direct current strength and the transfer of its dimensions in the 10^{-16}–10^{-9} A range. Its metrological characteristics are given in Table 1. The measurement and calibration capabilities of the All-Russia Research Institute of Metrology in the area of small direct-current measurements have obtained international recognition and are reflected in the MBMV data bank (the SMS system).

According to [1], current measuring instruments in the 10^{-16}–10^{-5} A range are collectively checked against small direct current standards, but a component-by-component check is also allowed. However, the drawbacks of a component-by-component check are the low productivity and low accuracy together with the high requirements imposed on the qualifications of the checkers and, moreover, the impossibility of determining random errors in the instruments that have been checked [4]. In this connection, preference must be given to a complete check, which is carried out using current measures. Hence, to provide a metrological backup of instruments for measuring small constant currents, methods and means of checking have been developed which enable the dimensions of the unit to be transferred directly from the standard of the working measuring instruments in order to eliminate a component-by-component check from the lower sections of the circuit being checked.

To check and calibrate different types of instruments for measuring small direct currents, standard measures are required both with a single known value of the current at the output, and multivalued output currents. The first standard measures are designed to be built in to the working measuring instruments, in order to ensure periodic calibration of the measuring instrument, including under automatic operating conditions [5]. In particular, instruments for measuring small currents with a logarithmic characteristic [6] cannot generally be calibrated or checked without built-in measures of small direct currents. Measures of small constant currents are also used in the compensation method of checking. They should ensure a change in the reproducibility of the current over the whole range with a discreteness of at least one-third of their error. This enables one, when checking instruments for measuring small currents with a pointer reading, to set the arrow of the instrument on the appropriate numerical reading by changing the current of the measure, and when checking digital measuring instruments one can set the necessary value of the current taking their resolving power into account.

At the present time, working standards of direct current of the 1st class have been introduced into Russian metrological practice, the confidence error of which for $P = 0.95$ is $1.6\cdot10^{-2}$–$1\cdot10^{-6}$:

- the UMPT-5 resistive-capacitive standard equipment (range of current reproduction and measurement 10^{-15}–10^{-5} A), in which the compensation method of measuring the current is employed;
- P320 type resistive current measures (current calibrators) (range of reproduction 10^{-4}–10^{-1} A), as well as the P321 type (range of reproduction 10^{-4}–10 A), and the MP3001 type (range of reproduction 10^{-4}–30 A);
- working standards of the 2nd class, the confidence error of which at P = 0.95 is $10\cdot10^{-2}$–$5\cdot10^{-3}$;
- IT-12 type resistive-capacitive standard current calibrators (reproduction range 10^{-16}–10^{-7} A), the EK1-6 type (reproduction range 10^{-16}–10^{-3}), and the NK4-1 type (reproduction range 10^{-16}–10^{-2} A);
- IIT-12–IIT-9 ionization measures of current (reproduction ranges 10^{-12}–10^{-9} A);
- the P320 type resistive current measures (current calibrators) (reproduction range 10^{-7}–10^{-5} A), the P321 type (reproduction range 10^{-7}–10^{-5} A), the MP3001 type (reproduction range 10^{-7}–10^{-5} A), and the mod261 type manufactured by Keithley, USA (reproduction range 10^{-14}–10^{-6} A).

TABLE 2. Metrological Characteristics of the Transportable Low Direct-Current Standard

Nominal value of the current strength, A	Type A uncertainty, u_A	Type B uncertainty, u_B	Extended uncertainty (P = 95%, k = 2), U
$1.0 \cdot 10^{-15}$	$8.5 \cdot 10^{-3}$	$1.3 \cdot 10^{-2}$	$3.0 \cdot 10^{-2}$
$1.0 \cdot 10^{-14}$	$6.2 \cdot 10^{-4}$	$3.7 \cdot 10^{-3}$	$7.5 \cdot 10^{-3}$
$1.0 \cdot 10^{-13}$	$3.4 \cdot 10^{-4}$	$1.5 \cdot 10^{-3}$	$2.8 \cdot 10^{-3}$
$1.0 \cdot 10^{-12}$	$3.3 \cdot 10^{-4}$	$1.4 \cdot 10^{-3}$	$2.7 \cdot 10^{-3}$
$1.0 \cdot 10^{-11}$	$2.3 \cdot 10^{-4}$	$7.5 \cdot 10^{-4}$	$2.0 \cdot 10^{-3}$
$1.0 \cdot 10^{-10}$	$2.2 \cdot 10^{-4}$	$7.0 \cdot 10^{-4}$	$1.5 \cdot 10^{-3}$
$1.0 \cdot 10^{-9}$	$2.3 \cdot 10^{-5}$	$4.8 \cdot 10^{-4}$	$1.0 \cdot 10^{-3}$

During the last few years, metrological laboratories in the leading countries of the world have shown increasing interest in the reproduction and measurement of extremely low direct currents (less than 10^{-10} A) in view of research on instruments which use the single-electron tunneling effect [7]. The need has therefore arisen for a comparison of the initial standards intended for operation in this measurement range. As is well known, transportable comparison standards are used in practice for this purpose. A transportable standard also enables one to transfer the dimensions of the unit from the State Primary Standard of the unit of direct current strength to working standards and working measuring instruments of higher accuracy to the location where they are used.

To solve this problem, a small-size transportable standard of low direct currents was constructed at the All-Russia Research Institute of Metrology in 2003 [8]. This was based on the same method of measurement used in the GÉT 4-91. However, in this case, to produce a saw-tooth voltage a digital measure of a linearly varying voltage was employed. The operating principle of the measure is based on the conversion of digital signals, generated by a special control system, into a linearly varying voltage, which is applied to the input of a differentiating circuit. A set of differentiating circuits guarantees reproducibility of the currents in the 10^{-15}–10^{-9} A range. The voltage at the output of the digital measure can be increased or reduced linearly in the 0–24 V range automatically, the duration of its reproduction can be set in the 20–2000 sec range, and the slope can be regulated in steps of 1 mV/sec in the 1–100 mV/sec range.

The transportable standard was investigated by the method described in the GÉT standard, but it was also provided with a component-by-component check using a developed method. The metrological characteristics of the standard are shown in Table 2.

The metrological characteristics of effective standards enable measuring instruments to be checked and calibrated. However, the observed trend towards increasing the metrological characteristics of electrometers, manufactured by Russian companies and used in larger and larger numbers in Russia, requires both a modernization of the existing standard, and the design of a standard of low direct currents using an essentially new method. One of the possible ways of constructing such a standard is to use the counting of electrons to extend the range of the current through extremely small currents. Investigations in this area should enable a method for the absolute reproduction of small direct currents down to 10^{-19} A to be proposed in addition to the use of the single-electron tunneling effect.

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