Article Identifier
DOI: 10.22032/dbt.58678
URN: urn:nbn:de:gbv:ilm1-2023isc-026:8

60th ILMENAU SCIENTIFIC COLLOQUIUM
Technische Universität Ilmenau, 4 – 8 September 2023
URN: urn:nbn:de:gbv:ilm1-2023isc:1

DEVELOPMENT OF QUANTUM TEMPERATURE STANDARD AND VERIFICATION OF THERMOELECTRICITY LAWS

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1. INTRODUCTION

Issues in nowadays Thermoelectricity is developing in 2 main areas:
• Thermoelectric phenomena and means for energy production. The main thing here is high parameters: thermoelectric quality factor ZT and similar coefficients;
• Thermoelectric phenomena and means for measuring temperature (thermoelectric thermometry). Here the main item seems to be the high stability of thermoelectric characteristics, or rather their temperature dependence. There exist reasons to update scientific and technological approaches to the considered thermoelectricity.
These two areas are based on thermoelectricity laws which were revealed about 2 centuries ago and not verified yet, although the accuracy of measuring the temperature necessary for specifying thermoelectric constants and laws, in general, has significantly increased over the past few centuries.

2. PURPOSE OF WORK

The goal of the current paper is the study the possibilities of implementing the researched Quantum temperature standard as an intrinsic standard for verification of the major thermoelectric laws since previous studies could operate with less exact measuring means.

3. TEMPERATURE MEASUREMENT AS A BASIS FOR THERMOELECTRIC RESEARCH

To characterize the substances of thermoelectric materials science concerning their properties, regardless of their type, it is necessary to determine exactly the temperature. In thermoelectric thermometry, the temperature determines by the conversion function. In thermoelectric energetics, the temperature significantly affects the figure of merit ZT. Independently of the application, the accuracy of temperature measurement becomes essential.
Currently, the world is stimulating the overall process of transition to a radically higher level of metrology by transferring the reference base to a quantum basis. Almost all standards of physical quantities, except temperature, have been replaced. The need for a reproducible Quantum standard of temperature was demonstrated by [1]. Activities were related to the cardinal problem of thermometry: CODATA has clarified the redefinition of the concept of "Temperature".
Change of temperature measuring instruments with the energy ones raises difficulties in development and implementation [2]. It can be noticed additionally that the direct measurement of T is replaced by the energetic method which brings in an additional uncertainty since the process of temperature measurement becomes indirect.
Our previous research that was reported in TEMPMEKO Symposium, 2016, has tried to link the term “Temperature” with basic constants of microphysics, namely with fundamental physical constants (h and k_B) per their ratio [3].

3.1. Quantum of temperature.

We have proved earlier the existence of a quantum of temperature and also revealed the possibility of its use in the Quantum Temperature Standard [4]. The latter is realized based on the current Quantum standards of electrical resistance based on the inversely proportional value of the Conductivity Quantum and the voltage standard on the array of Josephson junctions. While conducting current I through the CNT on such contacts it arises a temperature jump ΔT (where k_B is the Boltzmann constant; h is the Planck constant; e is an electron charge; N is the number of electrons passing within Δt):

$$\Delta T = \frac{2hI}{3k_B e} = \frac{2hN}{3k_B \Delta t}, \tag{1}$$

$$\Delta T|_{\substack{\Delta t \to 1s. \\ N \to 1}} = \frac{2h}{3k_B}\left[\frac{K}{s.}\right] \cdot 1[s.] = 3.199\,493\,42 \cdot 10^{-11}\ \mathrm{K}.$$

3.2. Interrelationships of the main SI units and their definition through fundamental physical constants.

According to the results of the conducted research, it was established that the relationships of the basic SI units with each other (Fig. 1) and the principles of determining these units through the fundamental physical steels (Fig. 2) presented in [5] are changing, and this is reflected by the corresponding arrows.

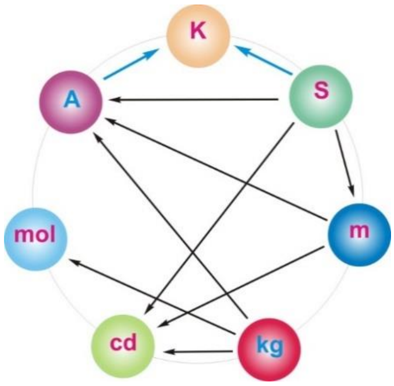

Fig. 1. Definition of basic SI units: blue arrows show the revealed relationship of unit **T** with unit **I**, *A* (by **I** and **R**)

We have expressed it in terms of the ratio of fundamental physical constants h/k_B; it is equal to $3.199\,493\,42 \cdot 10^{-11}$ K with a relative standard uncertainty of $59.2 \cdot 10^{-8}$. This is the main advantage of the temperature standard created based on fundamental physical constants. Based on the predetermined value of the temperature jump with known relative and absolute uncertainties, it is possible to propose a methodology for creating an extremely useful temperature standard, which belongs to the primary thermometric tools and is qualified by analogy with the known Quantum standards of other SI quantities, as an "internal standard" (Fig. 3).

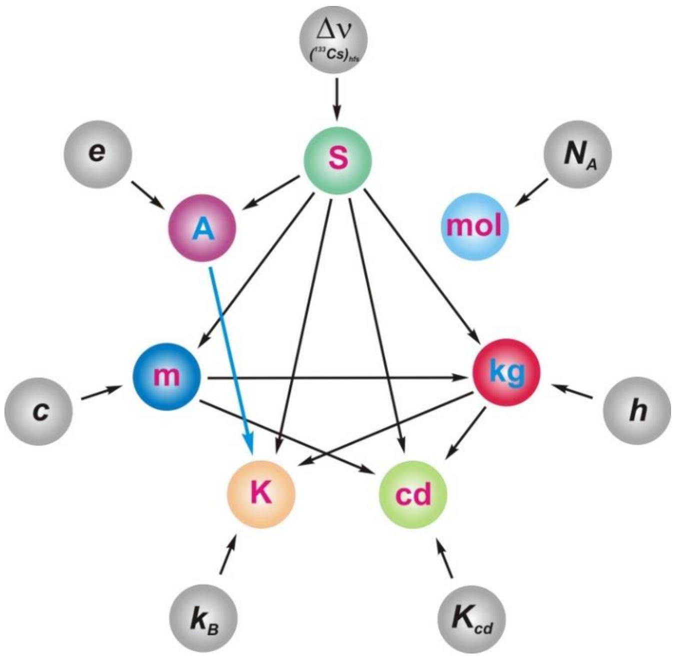

Fig. 2. The principles of studying the SI units through fundamental physical constants: the appearance (blue arrow) of the relationship between the units **I**, A and **T**, K

Creating a quantum temperature standard based on fundamental physical constants becomes possible as a result of development of the unique electronic nanodevices, such as:

- "Intrinsic" **Standard of Electrical Resistance** (based on the inversion of Conductivity Quantum or the Quantum of Electrical Resistance - von-Klitzing constant $R=h/e^2$ = 25812.807 557 ± 0,0040 Ohm).
- "Intrinsic" **Standard of Electrical Voltage** based on the Josephson junctions' array, by which voltage is linked with frequency and with the aforesaid fundamental physical constants.
- "Intrinsic" **Standard of Time (Frequency).**

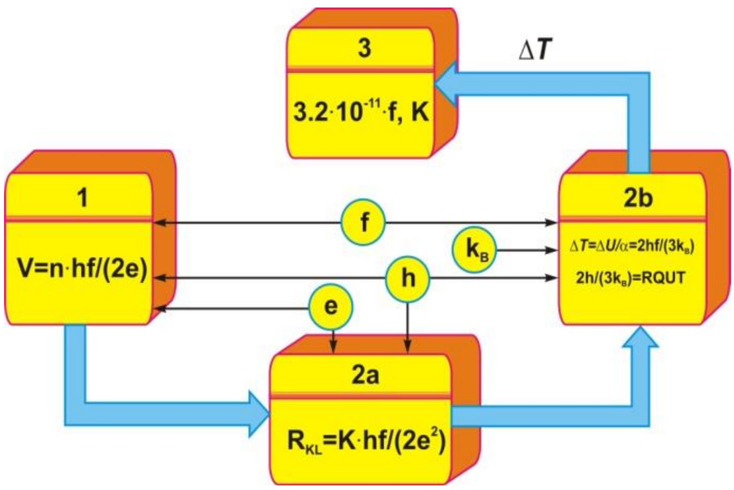

Fig.3. Design of Quantum temperature standard which consists of 1 is Quantum voltage standard; 2 is Quantum standard of electrical resistance and its elements - 2a is CNTFET, 2b is temperature unit transfer block; 3 is the Secondary temperature standard

The investigated Quantum temperature standard is recommended for use as an "intrinsic standard", which does not require continuously repeated measurements (to check its accuracy) concerning the current unit of temperature. The possibility of the introduction of standard quantum temperature requires paying significant attention to the I (current) - T (temperature) converting element as a unique electronic device that is subject to significant stress during operation. Considering its nanosized dimensions, since this element is made based on CNTFET by transforming it into a nanosized thermocouple (source and drain) with a superconducting CNT gate as the thermocouple junction, we foresee particularly stringent requirements for this element. The solution to this problem can be accomplished with the help of elastic stress engineering, which has previously been successfully applied to scale the manufacturing processes of multigate complementary FETs. The technology of the I - T converting element of the quantum temperature standard is complicated and provided by the Cu coating (or another similar metallization) of the free ends of the nanotube. The negative influence of defects in the production of I - T elements, in particular electrodes of the thermoelectric nanosensor, on the quality of subsequent operations can be significant. As a result, the metrological characteristics of the nanosensor (drift of thermo-EMF, the impact of deformation, number of operation cycles, etc.) become enough unpredictable [6].

***3.3. Implementation of the Quantum Temperature Standard*.**

The special significance was bestowed on the direct definition of the temperature jump caused by passing the current through the CNTFET junction.

In the considered Temperature Standard based on the CNTFET, the source, and drain are made from nickel and copper, which together form a thermocouple through a CNT performing the function of hot quasi-junction of linear dimension ~ 0.02 μm. As a result, we provide the ability to measure the temperature jump on the sensitive element of the Standard by thermoelectric method with minimal methodic error while measuring the current through the CNT. The mode of operation of the device is pulsed. It is powered by a sequence of short (~ 10^{-2} s.) pulses. In the 1st stage, while supplying, a temperature jump is created. In the 2nd stage (the absence of current) a temperature increase is measured with the help of a thermocouple. Specifically, at $I = 10^8$ e/s. $\approx 6.24 \cdot 10^{-10}$ A temperature jump of $3.2 \cdot 10^{-3}$ K is achieved, which is to be measured. For a K-type thermocouple ($\alpha \sim 41$ μV/K) the measured value is 0.14 μV, and for a semiconductor thermocouple, it can be up to 1.4 μV. Pre-established uncertainty ~ $59.2 \cdot 10^{-8}$ permits to suggest that the temperature jump is determined with absolute uncertainty ~ $1.9 \cdot 10^{-9}$ K.

Providing power supply from Johnston junctions' array (Quantum voltage standard), it appears the possibility to pass a certain number of electrons through the quantum Standard of electrical resistance. While passing 10^8 e/s. (62.4 nA), it can be produced by the temperature jump of 3.2 mK measured by thermocouple as the constructive item of the $I – T$ converting element.

It evidences the major advantage of an extremely helpful Temperature Standard based on fundamental physical constants. A priori knowledge of the precise value of temperature jump with the predefined relative uncertainty $59.2 \cdot 10^{-8}$ makes it possible to realize the Temperature Standard. We emphasize that a few electrons dissipate in the converting element, sufficient to guarantee a quasi-thermodynamic approach to the description of the considered phenomenon. Moreover, such an approach is realized for ultramodern FETs, where the linear size of the elements coincides with the similar size of the $I – T$ converting element.

4. DEVELOPMENT OF THERMOELECTRIC RESEARCH AND VERIFICATION OF THERMOELECTRICITY

In 1853, Thomson verified his prediction that is valuable the thermodynamic theory of thermoelectricity by recording Thomson's heat with thermometers. With the Quantum Standard of Temperature, such studies should be repeated, especially since they relate to nanoscale effects as being performed on CNT and therefore update the Thermoelectricity model [7].

By making the source and drain from the same material, we can study the low-temperature effect of phonon drag on thermo-EMF. After all, it occurs according to [8] at the smallest diameters (1.0… 10.0 nm, which corresponds to the diameter of the CNT) of the conductive material in the area of its contact with another bulk.

The dependence of thermo-emf on several impact factors helps to identify the peculiarities of the formation of not only thermo-EMF at the micro and nano levels, and also to clarify the ambiguous statistical and thermodynamic interpretation of temperature in nanotechnology.

Studies of mechanical stresses' impact on thermo-EMF can provide a positive effect on the substance's properties. Since this effect becomes more obvious while diminishing, micro/nanoscale materials and structures can withstand exceptionally high elastic deformations until failure [9].

With the use of Quantum Temperature Standards:

- verify and clarify the laws and provisions of Thermoelectricity and boundaries of their application in micro- and nanoworld (by embedding thermoelectric transducer into current-temperature conversion element of Standard);
- explore the possibility of transfer of the unit temperature dimension of Standard to the Working temperature-measuring means of the level (for instance, thermocouple);
- clarify the nature of thermoelectricity phenomena, including the effect of phonon drag on the Seebeck coefficient and applied aspects of the model of thermoelectric eddy currents;
- check the efficiency of certain postulates of Thermoelectricity, for example, the Peltier effect, etc. on the micro- and nanoscale [10].

6. CONCLUSIONS

Progress in thermoelectric energetics is determined by the advances in materials science and is based, on the one hand, on the achievements of nanotechnology as a source of implementation of significant specific technological trends and, on the other hand, on the achievements of Metrology 4.0 as part of Industry 4.0, which provides the foundation pillars for emerging quantum technologies in the branch of temperature.

It can be accelerated by the introduction of the Quantum temperature standard, not only as a metrological instrument for ensuring the exactness and precision of temperature measurements, and as a tool for studying the spectrum of thermoelectric phenomena by using CNTFET as the kernel construction element, corresponding in the measuring cycle to a nanosized thermocouple.

Evaluating Lord Kelvin's achievements in thermoelectricity, built on classical thermodynamics, while providing the Quantum temperature standard, we gain the ability to detail study the reserves of thermoelectricity and to clarify the validity of the basic laws of thermoelectricity for the nanoworld.

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