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I-T CONVERTING ELEMENT OF QUANTUM TEMPERATURE STANDARD

Bobalo Yuriy, Mykyychuk Mykola, Stadnyk Bohdan, Yatsyshyn Svyatoslav

National University "Lviv Polytechnic"

ABSTRACT

Possibility of researching the most contemporary measure of temperature on the basis of fundamental physical constants with involvement of the Standard of Electrical Resistance on the basis of Inverse of Conductance Quantum as well as the Standard of Voltage based on the Josephson junctions array is considered. Its realization depends mainly on the operation of unique electronic device, the work of which forms the basis of the transformation of pulses of electrical voltage into the calibrated jumps of temperature. On the one hand it should be super miniature and pass currents of magnitude of order 1 nA, and on the other hand it should perform the functions of active temperature-sensitive element.

Index Terms - Quantum temperature standard, quantum unit of temperature, *I-T* converting element.

1. INTRODUCTION

At the end of the 20th century all major SI units, except the temperature, were expressed through fundamental physical constants. A need for Quantum standard of temperature has been demonstrated by the issues of 13th TEMPMEKO International Symposium [1]. Contemporary technologies persistently require the most exact and precise standards as we invariably lose accuracy characteristics by several orders while uploading them to the end user.

At this moment "Temperature" remains the last value among 7 main units of SI that is not regulated with help of the mentioned constants. It is caused partly by the existing preconception that temperature is the only value which cannot be quantized; partly by the absence of proper metrological instruments and mainly by the lack of development the theory and practice of appropriate "intrinsic" temperature standards based on physical laws rather than on stability of material artifacts: for instance, carbon nanotubes (further CNTs) as the such ones in Raman method of thermometry.

2. TEMPERATURE AND ITS DEFINITION

In USA, UK, Germany and other countries through several years the endeavors of elaborating the unit of temperature scale in the form of a quantum energetic unit (minimal by size a discrete value of energy or heat energy that can be defined, established and fixed by the experimenter) have been carried out at the high methodological level. The recommended by [2] new format of unit with new definition is the next. The kelvin, K, is the unit of thermodynamic temperature; its magnitude is set by fixing the numerical value of the Boltzmann constant to be equal to exactly 1.380 65 … $\cdot 10^{-23}$ when it is expressed in the unit $s^{-2}m^2kgK^{-1}$, which is equal to $J\cdot K^{-1}$. The effect of proposed definition is that the kelvin is equal to the change of thermodynamic temperature that results in a change of thermal energy $k_B T$ by 1.380 65 … $\cdot 10^{-}$

^{23} J/K. Then using k_B rather than T_{TPW} to define kelvin better reflects modern practice in determining thermodynamic temperature directly by primary methods, particularly at very high and low temperatures.

The unit of thermodynamic temperature, the kelvin, will be redefined in 2018 by fixing the value of the Boltzmann constant, k_B. The present CODATA recommended value of k_B is determined predominantly by acoustic gas-thermometry results. To provide a value of k_B based on different physical principles, purely electronic measurements were performed by using a Johnson noise thermometer to compare the thermal noise power of a 200 Ω sensing resistor immersed in a triple-point-of-water cell to the noise power of a quantum-accurate pseudo-random noise waveform of nominally equal noise power. Measurements integrated over a bandwidth of 550 kHz and total integration time of 33 days gave a measured value of k_B=1.3806514(48)·10^{-23} J/K, for which the relative standard uncertainty is 3.5·10^{-6} and the relative offset from the CODATA 2010 value is +1.9·10^{-6} [3]. Efforts have led to some success. To provide a value of k_B based on different physical principles, purely electronic measurements have been performed by using a Johnson noise thermometer, by Quantum Voltage Noise Source method [3, Table 1 (Summary uncertainty budget for a determination of Boltzmann constant)]. Recently, "as part of these efforts, researchers from NPL's Temperature & Humidity Group have performed the most accurate determination yet of the Boltzmann constant and built extremely accurate thermometer that measures temperature [4].

Nevertheless, change of the temperature measuring instruments with the energy ones raise severe difficulties in the area of ultralow energies gauging [5-6]. Moreover, the direct measurement of T is proposed to be replaced on the basis of the equation: $T = E/k_B$. Applying energetic method, as the basic one, for measurement of temperature, it can bring in an additional error/uncertainty, since the process of temperature measurement becomes an indirect. Such kind of determination is always less accurate since single error δT of direct measurement is replaced by the sum of two errors: $\delta E + \delta k_B$ in indirect method.

3. INVESTIGATION IN CREATING THE QUANTUM UNIT OF TEMPERATURE

Temperature is the statistically defined quantity, determined by the inner energy of a body of sufficient size for purpose of applying the thermodynamic consideration to this body. It seems to be one of the fittest terms among the considerable number of temperature definitions which try to identify temperature in nanothermometry. A thermodynamical notion of temperature is related to heat exchange between two systems. The necessity to characterize a state of thermodynamic systems by some specific quantity becomes obvious. So, a notion "Thermodynamic temperature" has been introduced for this purpose. The objective measurement of temperature is possible due to the transitivity of a thermodynamic equilibrium. Therefore there is a possibility to compare the object temperatures among themselves per se contact. Temperature as a physical quantity that characterizes the internal energy of bodies is not being measured directly nowadays. All usable measuring instruments transform temperature in some other physical value that could be measured.

Nowadays try to link the term "Temperature" to basic constants of microphysics, on the one hand, and to threshold sizes of nanoparticles where this notion is still applicable, on the other hand. The special significance is bestowed to the definition of the minimum particle size to which the notion "local temperature" could be adopted, i. e. the temperature at which a part of thermodynamic system remains in a canonical state, and the energetic distribution of electrons corresponds to the exponentially falling one-parametric function [7]. We also have moved down the similar path [8] and successfully studied the dependence of temperature measurement trueness on the ratio of linear sizes of sensor and the measured objects while their reducing to the nanodimensions. Anything better was not achieved yet.

3.1 Macro properties and nano properties, expressed by fundamental physical constants

A Boltzmann constant consideration related only to the energy of electrons scattering in process of collision with atoms may be incomplete and therefore not quite correct. Ignoring the process of acquiring energy by electrons to which may be involved in any fundamental physical constant except Planck constant, the obtained model would be not quite perfect. Two conjugated sides of process combine a balanced approach to the problem of temperature arising due to the heat manifestation (in case of transmission of electric current through the substance) of the conduction electrons interacting with atoms. Therefore, availability the Planck constant in the relation of Quantum Temperature Unit becomes relevant.

At the same time, there is another, equally effective way to study the macro properties of materials through their micro- and nano- properties. It is clearly indicated on the example of quantum Hall Effect research [9]. Here, a passing result have turned out in establishing the link between the macro property, expressed in value of 25812.807 557 ± 0.0040 Ω with the nanoscaled characteristics of the substance, which as have been proved are the charge of electron and the Planck constant. Similarly, the studies [10] have envisaged the relation of one of the major electrical unit (voltage) with the same fundamental physical constants.

While studying their phenomenology we prove the possibility of existence of Quantum of Temperature as the manifestation of substance's nano properties due to the electron-phonon interaction. Moreover, considering the phenomenology of the mentioned effects in conjunction with similar phenomenon of thermoelectricity, which nano properties in the form of complex of thermoelectric effects are manifested as macro quantity - integral thermopower, we can can achieve a logical conclusion regarding the metrology. It concerns the experimental fixation of microscopic temperature changes with minimal methodological errors. On the one hand, we get minimal, barely noticeable changes (the temperature jumps ~ 10^{-11} K) due to electron-phonon dissipation; on the other hand by passing, for example, 10^8 electrons per 1 sec., we obtain caused by an integral effect (thermo-EMF) the value, sufficient for measurement (~10^{-3} K).

Let's consider below the possibility of researching contemporary measure of temperature on the basis of fundamental constants of matter with involvement of the standard of electrical resistance on the basis of inverse of conductance quantum [9] as well as the standard of voltage based on the Josephson junctions [11] that can produce voltage pulses with time-integrated areas perfectly quantized in integer values of $h/2e$. The synthesized voltage is intrinsically accurate because it is exactly determined from the known sequence of pulses, the clock frequency, and fundamental physical constants.

Thus, we consider the investigation of the electrical resistance value that is based on Klitzing constant, and of the voltage standard on the Josephson Effect for exact frequency-to-voltage conversion, combined with the clock. As the mentioned resistance we propose to study one of widespread field-effect transistor (FET) constructions, namely the CNTFET with built-in CNT [12] which has to be superconductive. Source and drain have to be manufactured from dissimilar metals that form the thermoelectric pair through the CNT. The latter, being in superconductive state, is characterized by the resistance 25812.807 557 ± 0.0040 Ω, due to transient resistance of contacts. While studying the dissipation of electric power ($I^2R = U^2 / R$) on such an electric resistance in temperature measurement area

$$E = U^2 \Delta t / R_{\mathrm{Kl}} = I^2 R_{\mathrm{Kl}} \Delta t = N \frac{3}{2} k_{\mathrm{B}} T, \tag{1}$$

It was shown opportunity to estimate the change of thermodynamic temperature *T*. Substituting this equation by $I = \frac{\Delta Q}{\Delta t} = \frac{Ne}{\Delta t}$ (*Δt* is the time period), we simplified the equation to

$$\frac{(Ne)^2 h}{(\Delta t)^2 e^2} \Delta t = N \frac{3}{2} k_{\mathrm{B}} T, \tag{2}$$

when the electrical current is formed per unit time by *N* conduction electrons that transfer the energy $\frac{3}{2} k_B T$ to the atoms. From here the temperature jump *ΔT* when passing current *I* through superconductive CNT (cooling is considered to be negligible), is defined as

$$\Delta T = \frac{2hI}{3k_{\mathrm{B}} e} = \frac{2hN}{3k_{\mathrm{B}} \Delta t}, K \,, \tag{3}$$

Otherwise, temperature increment caused by single-electron relaxation on phonon of superconductive CNT's junction with source/drain and due to unit time application, is reduced and defined only by fundamental constants of matter (*h* and k_{B}); it is equal to $2h \cdot 1s / 3k_{\mathrm{B}} = 3.2 \cdot 10^{-11}$ K. Providing power supply from Johnston junctions array, it appears an possibility to pass a particular number of electrons through standard of electrical resistance (or rather through the carbon nanotube of FET). Normalizing the resulting characteristic to unit time, we have derived the formula for the Quantum of Thermodynamic Temperature (macro property), expressed, as should be expected, in fundamental physical constants conjugated with nano properties of substance. Reduced to single electron-phonon dissipation per unit time, value is identified as Reduced Quantum Unit of Temperature (further RQUT)

$$\Delta T\Big|_{\substack{\Delta t \to 1s \\ N \to 1}} = \frac{2h}{3k_{\mathrm{B}}} \left[\frac{K}{s} \right] \cdot 1[s], \tag{4}$$

Hence, the figures in the work [13] regarding interrelation and inter-definition of basic SI units and the principles of study of the mentioned units through the fundamental constants of matter are modified corresponding the obtained results (see Fig.1 and Fig.2).

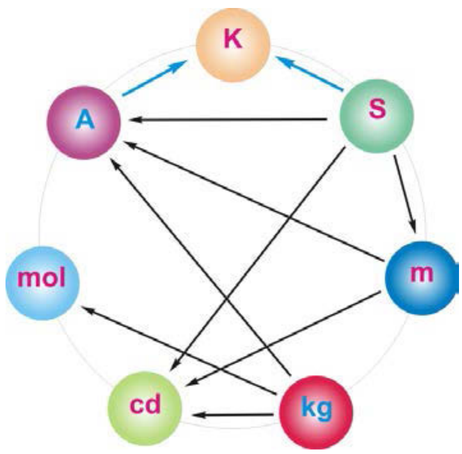
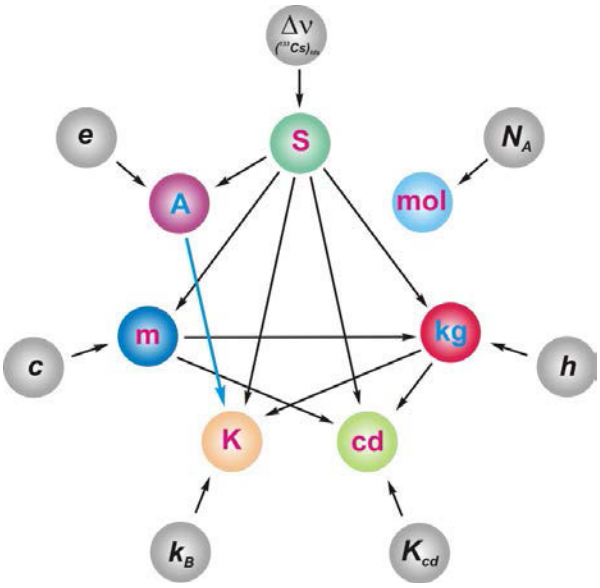


Fig.1. Interrelation and inter-definition of basic SI units: blue arrows show the revealed relationship of the studied unit *T* with unit *I,A* (by unit *V* and unit *R*) and with unit *t, s*

In such a way the **Reduced Quantum Unit of Temperature** independent of kind of matter, is recommended for creation of Temperature standard. It would be the standard based on the couple of quantum effects (von Klitzing Effect and Josephson Effect) and, having been measured against the SI system of units, has a certain value with uncertainty determined by sum of two uncertainties: of Planck constant and of Boltzmann constant [14] which together make its total relative uncertainty value $59.2\cdot10^{-8}$. The last value also includes the relative standard uncertainty of atomic unit of time that is 5 orders of magnitude smaller ($5.9\cdot10^{-12}$ [14]).



Fig,2. Principles of the SI units study through the fundamental constants of matter: elimination of interrelation between unit *m* and unit *T* as well as the emergence (blue arrow) of interrelation between unit *I, A* and unit *T, K*

3.2. Metrological conception of quantum unit of temperature and possibility of its implementation

The derived RQUT is equal to $3.199\,493\,42\cdot10^{-11}$ K with relative standard uncertainty $59.2\cdot10^{-8}$ at single electron-phonon dissipation per unit time. Note that the components of this uncertainty are determined as the combined values of the set of following appropriate methods.

For instance, to study the Planck constant are applied the method of Watt balance, installations of studies: of X-rays crystal density, Magnetic resonance, Faraday constant, Josephson constant. CODATA 2010 recommended value of mean Planck constant relative uncertainty is only $u_h = 4.4\times10^{-8}$. Methods of the Boltzmann constant are the next. Constant k_B has been determined from a measurement of the sound speed in helium gas in a quasi-spherical resonator (volume 0.5 l) maintained at a temperature close to the triple point of water (273.16 K). The acoustic velocity *c* is deduced from measured acoustic resonance frequencies and the dimensions of the quasi-sphere, the latter being obtained via simultaneous microwave resonance [15]. An optical (laser) method for the measurement of the Boltzmann constant which reaches an uncertainty of 2×10^{-4} after a cumulative time of 61 hours is very promising [16], and other methods are considered by NIST in k_B determination. So, the obtained value of the Boltzmann constant is determined as as the average of several methods. Each of them is inherent in its particular systematic constituent of error/uncertainty. Therefore, obtaining the mean value is not the simple issue. Note that application the single, although the best method can contribute a component of systematic error (or unsatisfactory trueness in the uncertainty approach).

Definition of 1 A as $6.2415093 \cdot 10^{18}$ e passing through a conductor's section per 1 s reveals that if electron pump would count 10^8 e/s or the precise ammeter would measure the electric current value $6.24 \cdot 10^{-10}$ A, we receive the temperature jump: $3.2 \cdot 10^{-11}\text{K} \cdot 10^8 = 3.2 \cdot 10^{-3}$ K. At sensitivity ~43 μV/K of T-type thermocouple the measured value is ~0.14 μV. The predefined relative uncertainty $59.2 \cdot 10^{-8}$ enables to assert that this value is determined with uncertainty $\sim 1.9 \cdot 10^{-9}$ K.

This evidences the major advantage of the advanced temperature standard on the basis of fundamental physical constants. From priori known precise value of temperature jump or temperature quantum we can come to the extremely helpful temperature standard that relates to the primary thermometric means.

4. RESEARCH OF TEMPERATURE STANDARD ON BASIS OF QUANTUM UNIT OF TEMPERATURE

Realization of temperature standard on the basis of fundamental physical constants takes place on contacts of superconductive CNT, graphene, or another substance with quantum Hall resistance Effect and may occur at the room temperatures [17]. For such purpose are involved the standard of electrical resistance on the basis of inverse of conductance quantum as well as the standard of voltage based on the Josephson junctions array that can produce voltage pulses with time-integrated areas perfectly quantized in integer values of $h/2e$ (Fig.3). Synthesized voltage is intrinsically accurate, because it is exactly determined from the known sequence of pulses, the clock frequency f, and fundamental physical constants h and e.

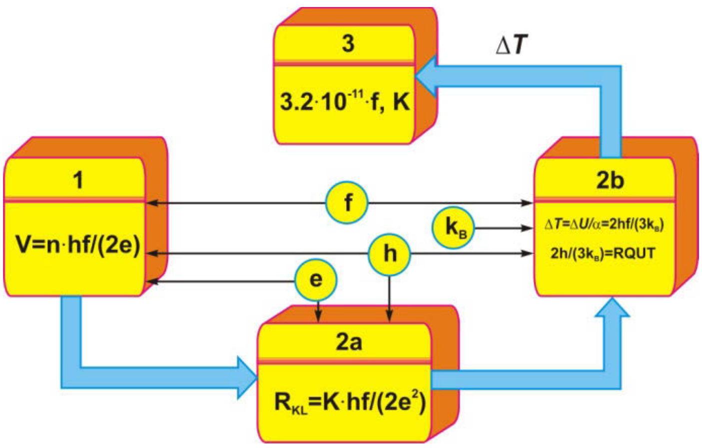


Fig.3. Scheme of Advanced Temperature Standard on Basis of RQUT and transfer of Unit Temperature to the Working Standard: 1 is the Josephson Voltage Standard; 2a is the CNT FET; 2b is the block of adjustment; 3 is the Working Standard

The mentioned, very small quantity as ΔT is quite difficult to be measured. As the standard of electrical resistance can be applied the CNTFET [12] which source and drain have to be manufactured from two dissimilar metals (for example from Ni and Cu), that constitute the built-in thermocouple via superconductive CNT quasi-junction of ~ 0.1 μm length. In such a way we obtain the possibility of measuring the temperature jump with maximal trueness while simultaneously determining the electron quantity that pass via CNT.

The same device serves as generator of known in advance temperature jump at the 1st stage and as Temperature measuring instrument at the 2nd stage. Firstly, the studied appliance is proposed to supply by short (~10^{-2} s.) pulse voltage consequences, effect of which is measured at the 2nd stage (power absence). Measuring temperature with minimal methodical error is easy with help of the built-in thermocouple. Superconductive CNT as the 3rd intermediate body (regarding the major laws of thermoelectricity) forms a quasi-junction of thermocouple. Further transfer of the particular temperature jump may be realized with help of standard procedures, or better with 2nd thermocouple applying with its junction located nearby the mentioned quasi-junction. At deviation of the received signal from the signal of reference thermocouple that may be caused by heat removal, the considered signal has to be powered to the required value.

4.1. *I-T* converting element

I-T converting element is built on the FET, which gate is made from superconducting CNT as it is considered in [12]. Source and drain together make thermocouple via nanotube that at the length ~ 0.1 μm serves as the junction. Technology of *I-T* converting element is complicated and provides coppering (of another similar) process for nanotubes free ends. Impacts of *I-T* element's manufacturing defects on the quality of subsequent operations, which causes the emergence phenomenon, can be significant and essentially different. For their analysis the classical theory of Markov processes turns out to be not quite suitable.

Methods of design, manufacture and operation simulation stages of similar radio electronic elements enable to conduct formalized issue for solving the problem of optimizing parameters behind two original stochastic optimization models. Application of one of them as a target function, and the second - as constraint, opens up the possibility to solve optimization task, particularly in terms of providing the highest possible quality at acceptable costs, depending on the abovementioned purpose of *I-T* converting element and other conditions.

5. CONCLUSIONS

1. Advance in technologies is impossible without temperature gauging that demands the continuous development of experimental techniques, namely in creation of standards. Expanding the set of quantum standards of SI units towards the study of major pillars of temperature standard on the basis of physical fundamental constants becomes possible as a result of emerged opportunities of unique electronic devices, in particular electrical resistance standard (on the basis of inverse of conductance quantum) and voltage standard (on the basis of Josephson junctions array) combined in addition with cesium frequency standard.
2. Researching the foundations of the temperature standard we have derived the value of Quantum Unit of Temperature as the value of temperature jump at single electron-phonon dissipation per unit time via h/k_B; it is equal to $3.199\ 493\ 42 \cdot 10^{-11}$ K with relative standard uncertainty $59.2 \cdot 10^{-8}$.
3. Due to progress in nano dimensional phenomenology that conjugates macro- and nano-properties through self-integration effects in matter, the quantization of temperature unit on the basis of fundamental physical constants and its implementation in temperature standard become possible. The studied quantum standard may be recommended for application as "intrinsic standard that does not need permanently recurring measurements against the realization of the SI unit in order to validate its accuracy.
4. Possibility of implementation of Quantum Temperature Standard by involving the quantum electrical resistance standard and quantum voltage standard needs the consideration the *I-T* converting element as a unique electronic element which has to be significantly workloaded

while operating. To achieve the declared exactness by Quantum Temperature Standard we have to ensure sufficient reliability of *I-T* converting element by means of two stochastic optimization models of its designing and operating.

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CONTACTS

Prof. Dr.-Ing. habil. S. Yatsyshyn slav.yat@gmail.com
Prof. Dr.-Ing. habil. B. Stadnyk stadnyk@polynet.lviv.ua