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ARTICLE

Introduction to Thermo-Photo-Electronics

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ABSTRACT

Building the foundations of Thermo-Photo-Electronics became possible only after the correction of thermodynamic errors in the traditional theory of semiconductor Electronics and Photo-Electronics. It is these errors that determined the output of the asymptotics of the operating parameters of semiconductor electronic devices, in particular, both the saturation of the limiting clock frequency of processors, and the saturation of the efficiency of both thermoelectric and photoelectric converters. But in semiconductors, although these thermodynamic errors manifested themselves not only in the instrumental, but also in the technological aspect, they could not prohibit semiconductor Electronics itself, unlike Electronics based on other materials. It's just that a number of qualitative mistakes were made in the theory of semiconductor devices and photo devices. In this work, it is shown that the energy band diagram of semiconductor contacts itself was constructed with a significant omission—without taking into account the temperature force on the contact. At the same time, because of the incorrect calculation of currents according to the outdated formulas of Richardson-Langmuir-Deshman, there were also PROHIBITIONS. So the practitioners compensated for the errors of the theory with "empirical corrections". So electronics engineers often made devices not according to a strict theory (which simply did not exist until now), but on a hunch and according to empirical local laws. And only the correction of the historical mistakes made it possible to expand the phenomenology of the description of processes in a Solid Body, on the basis of which it is possible to make calculations of highly efficient elements of Photo-Thermo-Electronics.

Keywords: Phenomenology; Potential barriers; P-n-junction; Prigogine local entropy production; Richardson-Langmuir models; Local thermo-EMF

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1. Introduction

Ilya Prigogine's discovery of the production of local entropy was not taken into account by Electronics, although it directly relates to micro- and nano-scales. And this phenomenological error in the theory of semiconductor devices is decisive. But it was aggravated by the fact that ALL solid-state physics was "stuck" on the use of flat electron orbitals, which Pauling introduced for "two-dimensional" graphite and for which he received the Nobel Prize. But Pauling himself, as an honest scientist, having discovered his mistake, tried to correct it by introducing "curved" orbitals for graphite itself [1]. Now, after restoring the Planck-Einstein quantization, it is shown how to get the correct orbitals instead of the mystical Schrödinger wave functions [2-4]. And this is the next stage of the rigorous expansion of the phenomenology of Electronics on the basis of the obtained foundations to the phenomenology of Photo-Thermo-Electronics and to the construction of a rigorous theory of semiconductor devices.

The dimensional thermoelectric effect in silicon carbide crystals, which I initially discovered back in the 1980s in the study of contact effects [5-7], has already shown insufficient completeness of thermoelectric phenomenology to describe thermo-EMF [8-10] and output resistance in microstructures with potential barriers (**Figure 1**), which, in fact, prompted me to start a long-term cycle of research on Local (NANO) Effects (formerly called midi-effects).

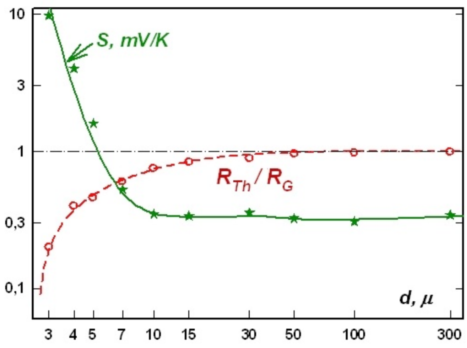

Figure 1. Dependences of thermo-EMF (originally it was assumed that this is the diffuse Seebeck coefficient) and the ratio of the output thermoelectric resistance to the galvanic resistance of a SiC semiconductor crystal depending on its thickness (size along the heat flow).

But a rigorous theoretical extension of the purely diffuse (as analysis showed) theory of thermoelectricity was made me later [11-14], when the existence of Local thermoelectric power was confirmed for a whole class of wide-gap semiconductors [15] and it became clear that not only phenomenology of thermoelectricity, but also the entire phenomenology of the *p-n* junction [16].

And then, neither the laboratory of thermoelectricity of the Ioffe Institute of the USSR Academy of Sciences, nor the International Thermoelectric Society dared to deviate from traditional thermoelectric concepts and, with the need to correctly take into account the concentration force. Take it into account in the same way as it has long been done in the theory of *p-n* junction. And the management of the Global Thermoelectric company, which arranged a radio conference with me at the beginning of this century, summarized both our discussion and the general position of the thermoelectric community by saying: "We are now the world's largest manufacturer of thermoelectric generators based on well-established traditional thermoelectric technology. And where will we be if we switch to the Intel technology you propose for thermoelectricity".

But even at the beginning of the century, even if then at a qualitative level, I already felt that there is a "reverse side of the coin", that phenomenology, and, as a result, calculations of the characteristics of the p-n junction are also not complete without taking into account the temperature force traditionally used in thermoelectricity. I understood and showed at a qualitative level to the management of Intel that Moore's law does not take into account that it was precise because of the lack of taking into account the temperature force that they reached the saturation of the processor clock frequency with increasing miniaturization of individual elements (an increase in the number of elements in a chip).

But Intel also followed a purely empirical path according to its own, mastered technology - first they blind the processor, and then examine what they did. He took so long to respond that I wrote to them: "Dear Sirs, I am not sure that I will live to see the next millennium. So please decide on my project." And INTEL answered: "Thank you for your patience and humor" and was also afraid to move away from its traditional processor manufacturing technology, and tried to solve the problem incorrectly, but to get around it due to multi-core. But this method of increasing the number of elements, even then it was obvious, would not allow going beyond the logarithmic dependence of the speed of processors on the number of elements in them.

My project "NANO-thermopowers" won the Samsung competition, but our Noble Zhores Alferov took the money from it for his heterostructures, which, as it has now become clear, he did WRONG. So, only local, my co-authors, professors Toru Miyakawa, Wang Nang Wang and Satoru Yamoguchi, helped me in conducting research on Local Effects. And now those early qualitative results of mine have received rigorous experimental and theoretical confirmation and have shown the need to expand not only thermoelectricity, but all Electronics to Thermo-Photo-Electronics.

2. Electronics stagnation analysis

2.1 Reasons for the stagnation of thermoelectricity

Thermoelectric instruments and devices have been actively used since the middle of the last century. But already at the end of the last century, both by the demand for them and by the achievements of their marginal efficiency, it became clear that after reaching a certain level, no further progress was observed. On the contrary, refrigerators began to return from thermoelectric to traditional, mechanical ones, and thermogenerators began to be used only if there is a source of waste heat. And thermoelectricity itself as a science actually degenerated into Materials Science [17].

But historically, it was thermoelectricity that allowed Onsager, based on the Curie theorem, to formulate his Principle of Symmetry of Kinetic Coefficients [8]. But there was no feedback. The primitive theory of Thermoelectricity has been built up to now with the violation of the Onsager Principle, admitted by an amateur physicist, watchmaker Peltier. Moreover, she "passed" by Oleg Losev's discovery of a p-n junction, and past the discovery of "anomalous thermo-EMFs" in it, and past Ilya Prigozhin's discovery of local entropy production. So it is not surprising that in the period when all the bureaucratic science degenerated into the knowledge industry, thermoelectricity, as science, simply ceased to claim scientific Fundamentality, and turned into a factory laboratory serving production with obsolete technologies compared to electronics. That is why, in fact, there is no scientific thermoelectric journal, but only factory reports in the proceedings of the international thermoelectric conference, in which my work was published only for decoration [18]. That is why thermoelectricity was not even presented in international multidisciplinary scientific journals either, until the International Journal of Frontier Studies asked me to send my biography. To which I replied that I am no longer a young man and I can tell a lot about myself. But let me tell you the tragic History of Thermoelectricity. And in response, I received an offer to publish this story of mine "Anomalous thermo-EMF is Local thermo-EMF" [19]. And they published, free of charge, like all 70 of my scientific articles in the Open Access in recent years. So even the development of the fundamental aspects of thermoelectricity—contact phenomena, which I was instructed to study 40 years ago by the last Coryphaeus of Thermoelectricity, Lazar Solomonovich Stilbans, and which resulted in this eighth scientific book of mine, was not supported in any way by thermoelectric organizations after the death of Stilbans. And although the technology of some thermoelectric firms like Dexter has already been brought to the nano-level, traditional thermoelectric concepts are still dominant for them. And the main interest in Local thermo-EMF is shown by electronics, which is reflected in the very title of my new book "Thermo-Photo-Electronics".

2.2 Reasons for the stagnation of the Physics of Contact Phenomena

Physics jumped from the macroscopic description of nature to the microscopic one, skipping a whole class of NANO-phenomena [20]. And the point is not only that a very roughly constructed Quantum Theory [2,3] was used in the description of microscopic phenomena, but that at the same time, both in electronics and in optics, the model of the Ideal Infinitely Thin Interface between two media was transferred. Thus, in fact, not the contact of two media was described, but the consequences of its existence in conjugate media. Initially, the length of contact was taken into account in Optics. Both the very emergence of modern Electrophysics of Contact Phenomena, and the certainty in the very formulation of contact experiments arose only when it was understood that it had already been created, intuitively, the technology of forming an extended (of a certain size) contact with well-repeatable properties - this is a *p-n* junction [9-16].

The historical consideration of electronics without taking into account heat flows has imposed a number of restrictions on the design of devices and devices based on it. In addition, these restrictions led to a number of "theoretical" prohibitions on the existence and possibility of registration, which was revealed in the study of the Local thermo-EMF described in previous works. However, an important clarification needs to be made. Lack of understanding of the physics of Local thermodynamic effects not only imposed a ban on the Local Effects themselves, but also led to a attribution (even in WIKIPEDIA) of a primitive device to a photo-thermoelectric converter, while it contains a simple photo-conversion of the thermal radiation flux.

Similarly, under the sign "Thermo-transistor", changes in the properties of a conventional transistor from an average temperature were used, i.e. actually Local effects did not even try to use.

The main, phenomenological reason for the stagnation of the Theory of Contact Phenomena, in particular, the Theory of *p-n* junction and barrier phenomena, is, of course, that the Temperature Force has been completely thrown out of consideration. So, even in adjacent sections of the same fundamental book, thermoelectric and contact effects were considered as unrelated phenomena [5,21,22]. And this led to the fact that in thermoelectricity, Peltier heat, in violation of the Onsager Principle, continued to be attributed to the contact characteristic, and the contacts were actually considered to be infinitely thin. But precision measurements of the temperature distribution near the contact gave on the "infinitely thin" interface the inequality of asymptotics (**Figure 2**).

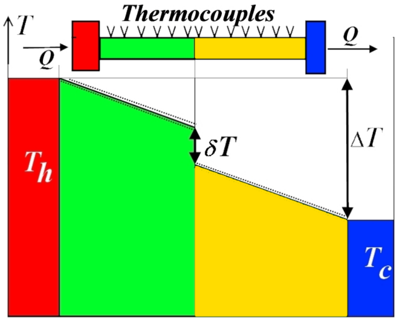

Figure 2. Asymptotic discontinuity of the temperature distribution at the interface between materials with different Fermi electron energies.

The experimentally observed temperature jump at the boundary of dissimilar media naturally follows from the production of the local Prigogine entropy at the potential barrier when current flows through it: From the absorption of energy on one side of the barrier and its release after the electron passes through the barrier. In this case, the application of thermal conductivity to the barrier is not formally applicable—the energy recovery by phonons occurs only partially (no more than half) and with a relative delay determined by the ratio of the electron transit time over the barrier to the phonon transit time through the barrier. So, the "anomalous" size dependences of thermopower and resistance shown in **Figure 1** are not anomalous, but simply not taken into account by the Theory of Contact Phenomena.

In addition, in Electronics, the Langmuir and Richardson models [23,24] are still used to calculate currents through potential barriers. These models, developed at the dawn of the last century, both on a spatial scale corresponding to the millimeter gap between the electrodes the scale of currents corresponding to the current of electrons from graphite heated to 3000 degrees do not correspond in any way to the currents used in electronic devices. In addition, the formulas obtained within these models are very non-rigorous—the Richardson and Deshman formulas are only the first linear approximation for two special cases, giving the saturation current and a linear approximation in the region of reduced voltages less than the average thermal energy [25]. So even in serious monographs on thermionic emission these formulas are used only for decoration. And half a thousand pages are devoted to describing local patterns that have nothing to do with these formulas [26].

3. Correction & extension of electronics

Let's start the corrections with the elementary formulas for the CVC, which were obtained by Langmuir-Richardson-Deshman for Thermal Emission, i.e. not at all for semiconductor electronics, but, and they continue to be used in it:

$$J_L = \frac{\sqrt{2}}{9\pi}\sqrt{\frac{e}{m}}\cdot\frac{1}{d^2}\cdot U^{3/2},\ J_R = (1-r)AT_h^{1/2}\exp\left(-\frac{\varphi_h}{kT_h}\right) \quad (1)$$

where in the Langmuir formula, *d*—the barrier thickness, a *U*—the potential difference across it and where *A*—the Richardson constant, and φ_h —the work function and *T*—temperature (of the cathode, in thermal emission), respectively, a is the average value of the electron reflection coefficient at the boundary, which is small and, at In the analysis, we will further assume that the first parenthesis is equal to 1.

The Langmuir formula was obtained under the assumption of an initial zero velocity of all electrons above the barrier and its increment due to the electric field. And the Richardson formula—when taking into account (in the Brillouin zone) only those electrons whose velocity vector is directed towards the interface In this case, in fact, the Richardson model took into account only the difference between the electron densities at the emitter and collector above the maximum of the potential barrier (i.e., part of the concentration force) that occurs when the field is applied, multiplied by the average thermal electron velocity.

Taking into account the polarity of the electron dispersion law for a displaced barrier (**Figure 3**) allows a rigorous calculation of the ballistic current over potential barriers, the thickness of which is less than the mean free path of an electron, for electrons in the entire Brillouin zone. In this case, a strict expression for the current over the barrier can be written as a standard expression for the Richardson current with a correction factor:

$$J_R^*\left(eU^*\right) = J_R\left(eU^*\right)\cdot \mathrm{K}^{3D}\left(eU^*\right) \quad (2)$$

where the correction factor is given by expression (3) and essentially depends on the dimensionless stress reduced to thermal energy: $eU^* = \frac{eU}{kT}$.

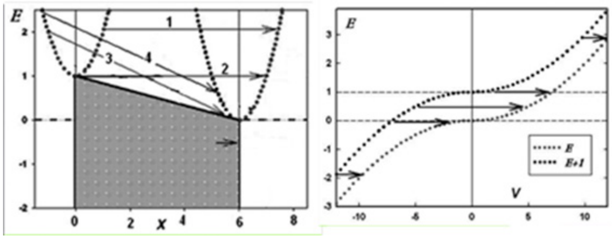

Figure 3. The spatial transition of electrons taking into account the polarity of kinetic energy (on the left—the standard dispersion law, on the right—taking into account the polarity of the current).

Taking into account additional corrections, the expression for the total current (2) turns out to be more complex than given in the work [27], but it can also be divided into factors with the coefficient of current coupling with the reduced voltage (3).

$$\mathrm{K}^{3D}\left(eU^*\right) = \frac{1}{2\left(-1+\mathrm{e}^{eU^*}\right)}\mathrm{e}^{-\frac{eU^*}{2}}\left(1+\mathrm{e}^{eU^*}\right)\sqrt{\pi}\cdot$$
$$\left(\begin{array}{l} 2\mathrm{e}^{\frac{eU^*}{2}}\mathit{HypergeometricU}\left[-\frac{1}{2},0,eU^*\right]- \\ \mathrm{e}^{\frac{eU^*}{2}}\mathit{MeijerG}\left[\left\{\{\},\left\{\frac{3}{2}\right\}\right\},\left\{\{0,1\},\{\}\right\},eU^*\right]+ \\ \sqrt{\pi}\left(\mathit{BesselI}\left[0,\frac{eU^*}{2}\right]+\mathit{BesselI}\left[1,\frac{eU^*}{2}\right]\right)eU^* \end{array}\right) \quad (3)$$

The resulting total ballistic current (2), even without taking into account the temperature force (if the temperatures of the emitter and collector are equal), shows that the Richardson formula describes, purely qualitatively, only that part of it that determines its output to the saturation current at reduced voltages of the order of the average thermal energy (**Figure 4a**). The linear decay, borrowed in all ABC books on the Physics of Semiconductor Devices from the Richardson formula, with a decrease in the reduced voltage below the average thermal energy of electrons, as can be seen from **Figure 4**, is not observed almost to zero. This giant correction at very low voltages (**Figure 4b**) is the fundamental difference between the ballistic current and Ohm's diffuse law, which removes the Langmuir-Richardson prohibition on their measurability of currents at low voltages. A significant, not only quantitative, but also qualitative correction for the ballistic current in terms of saturation current and at voltages is greater than the average thermal energy.

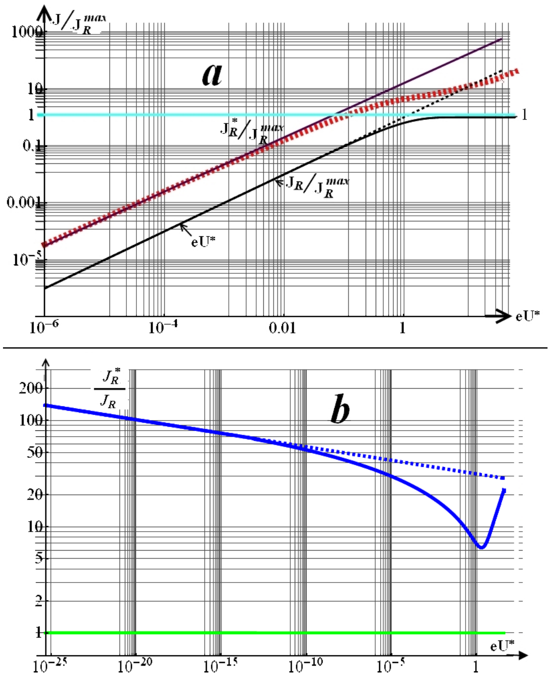

Figure 4. Dependence of the Richardson current and the total ballistic current (Richardson) on the reduced voltage: a—currents in relation to the Richardson saturation current, b—ballistic correction factor to the Richardson current.

Of course, there are limitingly measurable currents, but they are by no means limited to reduced voltages of the order of the average thermal energy of electrons, which characterizes only Ohm's diffuse law. The minimum measurable currents are determined by the signal-to-noise ratio, which depends on the registration time: $kT = U \cdot J \cdot \Delta t_{\text{measurement}}$, and in the limit—by the Heisenberg Uncertainty Principle. But, in fact, the neglect in the p-n junction of currents less than those corresponding to this voltage, which is a rough model limited the linear section of the current-voltage characteristic (theoretically, they were measured experimentally for a long time) and became one of the components of the PROHIBITION of the existence of Local thermo-EMF.

A significant, not only quantitative, but also qualitative correction of the ballistic current was obtained for the saturation current, for current and at voltages greater than the average thermal energy. As can be seen from **Figure 4b**, at reduced voltages greater than the thermal energy of electrons, an avalanche-like increase in current occurs—pre-breakdown.

Honest experimenters carry out precision measurements and trust their results, rather than theoretical prohibitions, which are canonized, but sometimes reflect only some local patterns. But in Science, this happens, unfortunately, often—the Ideas of its true Creators are not fully understood, but are picked up by opportunists (market players)—developers. So these Ideas are actively promoted by developers, but with distortions and errors. So it was, for example, with many operating devices created by Geniuses: Leonardo da Vinci, Nikola Tesla and Lev Theremin, who could not reproduce later. And now, when the fundamental sections of Physics have reached the modern level, it has become clear that an entire industry has been formed—Electronics, the instrumental and technological problems of which are related to the fact that the theory of the p-n transition is built in violation of the laws of non-equilibrium thermodynamics and that this is largely determined by the distortion of Ideas, which the founders of electronics, Losev and Tauc, came to purely intuitively (the Nobel laureates for the transistor themselves called the creator of Losev's resistance transformer his father).

So, it was with the p-n junction, first created in silicon carbide and described in the 30s of the last century by Oleg Losev. Losev himself immediately intuitively realized that this was a current device. And he was able to use it almost immediately: He created on it an LED, a photodiode, and a resistance transformer, which the Nobel laureates called in short (in English) a transistor and even a transistor receiver. But the physics of the p-n junction and the description of the operation of the listed devices based on the p-n junction were built by analogy with a radio tube, which, in principle, is a field device. Thus, when solving various problems for semiconductor devices in the p-n junction, the cause-current and the effect-voltage were rearranged. And the prominent physicist Abram Fedorovich Ioffe did not fully understand Losev then, who was half a century ahead of modern electronics. But academician Ioffe, not like the current "luminaries" of science, achieved the assignment of a candidate of physics and mathematics to him. And only after almost 100 years, the return to Losev's current circuit made it possible to significantly improve the characteristics of semiconductor devices.

Tauc is another, Czech Corypheus, ahead of his time. He was the first, immediately after the liberation of Prague by the Soviet troops, to establish the production of point transistors in Prague (formerly of the Bell Company). And he immediately discovered thermoelectric effects in the p-n junction and honestly described them. But then (and even now) thermoelectricity itself was stuck at the macroscopic, purely diffuse level of describing the phenomenon and classified Tauc's results as anomalies.

The description of the generation of photo-EMF in the *p-n* junction was also carried out for a field device. Photo-EMF, in principle, was correctly associated with a potential barrier and an electric field in it, as a force, but balancing only the concentration force. In this rough approximation, the p-n junction diagram shows the complete alignment of the Fermi levels of the electron and hole regions (**Figure 5**) with the formation of a region with full compensation of electrons and holes (i-region).

The thermodynamic discovery by Ilya Prigogine of the production of local entropy helped to restore the correct description of the physics of the p-n junction. It made it possible to understand that in the p-n junction, described for the reasons noted above, within the framework of a truncated concentration-electric phenomenology, it is necessary to use an extended phenomenology supplemented by a heat flux [11-16].

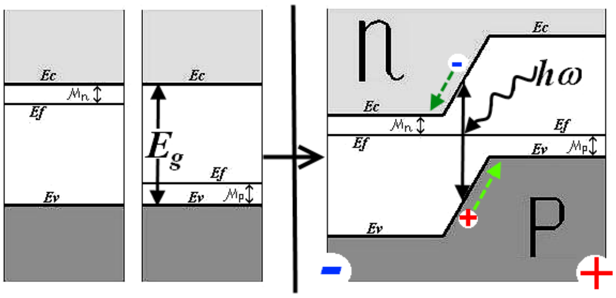

Figure 5. The traditional scheme for the transformation of energy bands of semiconductors with different types of conductivity upon their contact and the opening of the p-n junction formed in this case when the i-region is irradiated with light.

From the balance of thermodynamic flows ***J***, the equality of the concentration force FN and the electric force ***FE*** in the p-n junction naturally follows. But we will not dwell on this refinement of the description of the photoelectric effect for the time being. The analysis of thermoelectric and thermionic effects showed that from the general phenomenology, strictly corresponding to the Curie theorem and the principle of symmetry of the Casimir-Onsager kinetic coefficients, in the description of the *p-n* transition and, thereby, the photoelectric effect, the temperature force ***FT*** is excluded from consideration of thermodynamic flows ***J*** (**Table 1**).

Table 1. Three private phenomenologies, traditionally using only two thermodynamic forces in three different branches of Physics.

E-T phenomenology $J_E = \sigma E + \sigma(S\Delta T)$ $J_T = \Pi J_E + K\Delta T$	Thermoelectricity $J_E = L_{EE}F_E + L_{EN}F_N$ $J_T = L_{ET}F_E + L_{TT}F_T$
E-N phenomenology p-n junction	Volt-Amp Characteristic (VAC) $J_E = L_{EE}F_E + L_{EN}F_N$ $J_N = L_{EN}F_E + L_{NN}F_N$
T-N phenomenology Vacuum gap	Thermal emission $J_T = L_{TT}F_T + L_{NT}F_E$ $J_N = L_{TN}F_E + L_{NN}F_N$

Table 1 shows the Phenomenologies underlying the incomplete description of a number of effects as Fragments of the General Phenomenology (for thermoelectricity, the system of equations, in addition to

the canonical form, is also written using traditional coefficients: electrical conductivity σ, thermal conductivity **K**, Seebeck **S** and Peltier **Π**).

At the same time, the standard band structure of the junction itself is modified, taking into account the temperature force, and the energy diagram of the equilibrium p-n junction is modified, which, without taking into account the temperature force, gave, as shown in **Figure 5**, the potential barrier value approximately equal to the band gap of the semiconductor. Taking into account the temperature force, in the absence of heat flux, the value of the potential barrier turns out to be equal to half the band gap (**Figures 6a-6b**). And when it turns on the heat flow, the value of the potential barrier will increase until a tunnel breakdown occurs (**Figure 6c**).

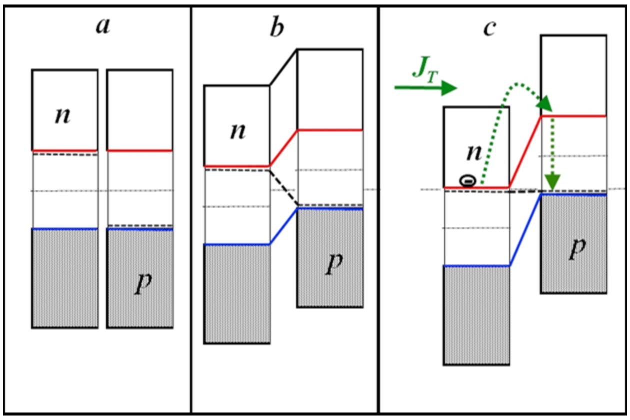

Figure 6. Energy diagrams of two semiconductors of different types of conductivity: a—before bringing them into contact, b—equilibrium state after their contact at equal temperatures, c—equilibrium state with heat flow through the p-n junction.

As shown in **Figures 6a and 6b**, between the semiconductors brought into contact in an equilibrium state, due to the balance of electric and concentration forces, the difference in electric potentials at the contact (the red line is the bottom of the conduction band, the blue line is the top of the valence band) is equal in magnitude and opposite in sign to the difference at the boundary of the concentration potential (dashed black line). Thus, given in **Figure 5**, in accordance with the complete system of equations for thermodynamic forces and flows, it already allows eliminating the theoretical equal 2 in the description of the transition without a temperature gradient, which was associated with an empirical coefficient due to the imperfection of materials. The potential difference across the transition plates is equal in this case to half the band gap. And the equality of concentration potentials corresponds to the Local Thermo-EMF and occurs, of course, only with a heat flow through the transition (**Figure 6c**).

In this case, the current-voltage characteristic (CVC) of the p-n junction, of course, depends on the temperature difference on its plates, which is determined by the heat flux through the p-n junction. If, in accordance with Losev's theory, we take into account the primacy of the current in the p-n junction, then the contribution of the temperature force gives a shift in the CVC, described by the formula:

$$\Delta J_{Th/Ph} = k_{Th//Ph} \cdot O_{Th/Ph} \tag{4}$$

where $O_{Th/Ph}$ the energy flow through the p-n junction, and $k_{Th//Ph}$ the current coupling coefficient in the *p-n* junction from the heat or light flux (for light—the quantum yield at a given wavelength of light).

There is a current-voltage characteristic shift, similar to the photo-effect shift, but of the opposite sign EMF (**Figure 7**).

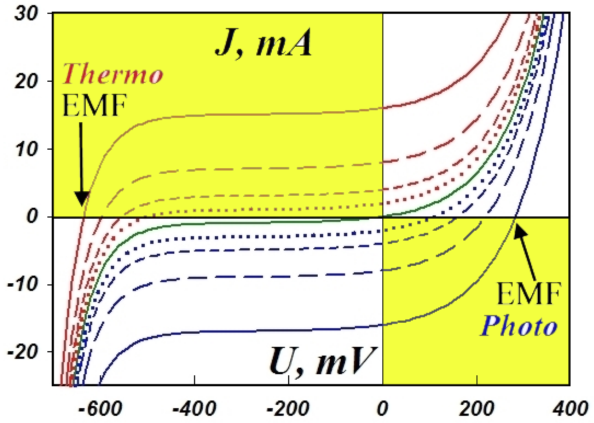

Figure 7. Calculated shifts in the current-voltage characteristic of an ideal p-n junction by equivalent (in terms of power) flows: thermal (red curves) light (blue curves), with an increase in flows by 2 times. Generation quadrants are marked in yellow.

The experiments confirmed the qualitative picture of the displacement of the CVC by a constant, stabilized heat flux (**Figure 8**).

But as dynamic experiments have shown, when a stabilized but modulated heat flux is applied, the shift of the transition by a constant stabilized current leads to a change in the frequency response with its passage, in accordance with "Experimental and Theoretical Expansion of the Phenomenology of Thermoelectricity" [12], through the Gaussian thermoelectric resonance, which is determined by the phase reversal of the thermal signal (**Figures 9a, 9b, 9c**).

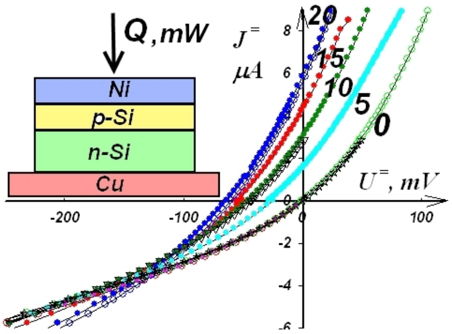

Figure 8. Experimental current-voltage characteristics of a p-n junction with stabilized different heat fluxes through it.

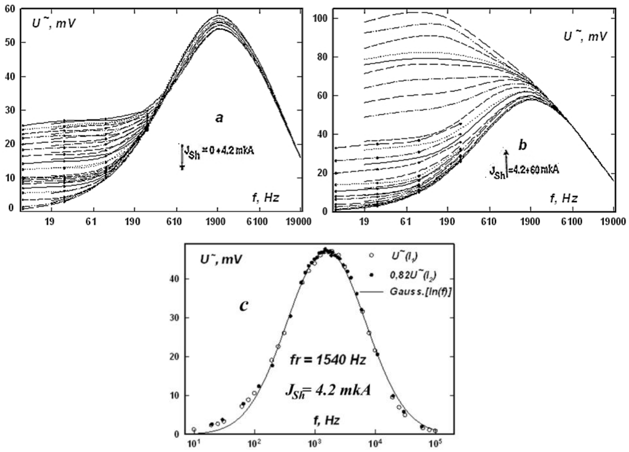

Figure 9. Dependence of the frequency response of the p-n junction on its DC bias [28]: a—decrease in the low-frequency branch with an increase in the bias current to a critical value of 4.2 μA, b—increase in the low-frequency branch with an increase in the bias current above the critical value, c—Thermo-Photo-Electric resonance at a critical value of the bias current, described normally by the Gauss dependence from the logarithm of the frequency.

So the differences in the I-V characteristics in **Figures 7 and 8**, in principle, not only do not violate the overall picture, but they detail it as the presence of two antiphase signals determined by technological and design factors.

As shown in **Figures 7 and 8**, when a heat flow flows through the p-n junction, an area of positive currents arises in its I-V characteristic in the upper left quadrant at negative voltages at the p-n junction, which, in full accordance with the concepts of generators (the simplest is an electric battery), is the area of generation of electrical energy due to the flow of heat flowing through the transition (**Figure 10**).

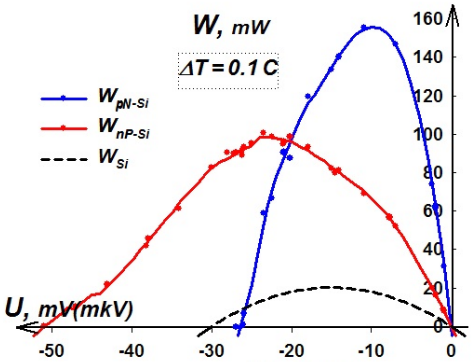

Figure 10. Experimental thermo-generator characteristics of p-n junctions and optimally doped silicon (for silicon, the optimal EMF—μV is three orders of magnitude lower than that of p-n junctions—mV).

This was experimentally confirmed on the developed detectors based on Local Thermo-EMF in silicon junctions, the volt-watt sensitivity of which was obtained three orders of magnitude higher than that of detectors based on the traditional macroscopic Seebeck effect.

At the same time, the extended phenomenology shows that there can be complex, three-phase effects in the *p-n* junction, which makes it possible to optimize, in particular, the combination of local thermoelectric effects with photoelectric effects in it.

Previously, the generator characteristic of the transition was constructed without taking full account of the specifics of the equilibrium state, taking into account the local production of Prigogine's entropy. In this case, zero current through the junction corresponds to a zero temperature drop. But in fact, the p-n junction is Maxwell's demon—a "gear" wheel separating hot and cold current carriers, in principle, allowed at the micro level by the production of Prigogine's Local Entropy. And the mechanism of its operation is obvious from **Figure 5**: When semiconductors come into contact, its asymmetry (polarity) occurs. At the same time, to start the electron transfer process, an energy equal to half the band gap is sufficient, while after their transfer and annihilation with holes, their reverse transfer requires an energy equal to the full band gap. So, a local temperature drop occurs on the plates of the p-n junction, which determines the local thermodynamic equilibrium. In this case (**Figure 10**), the experiment shows that the CVC has a shape fundamentally similar to that shown in **Figure 8**.

The sign of the Local thermo-EMF arising in the p-n junction does not depend on the polarity of the heat flux, as in the case of voltages determined by the diffuse Seebeck coefficient (which are 3 orders of magnitude less), but is completely determined, in accordance with the displacement of the CVC (**Figure 7**) by the heat flux modulus of polarity p-n transition, i.e. diffusion of the main carriers of its hot lining (**Figure 11**).

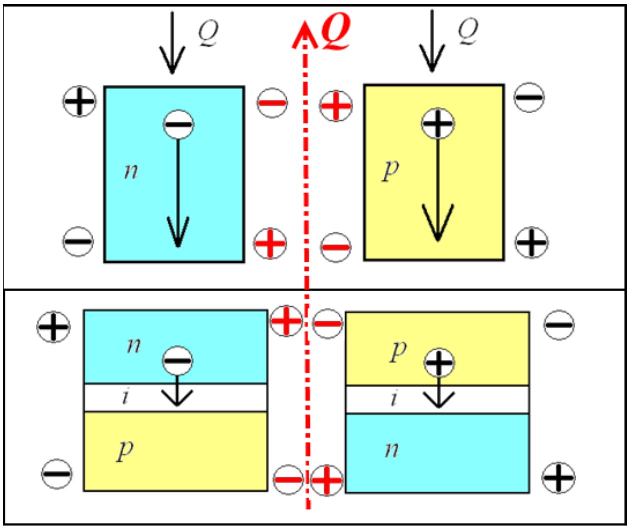

Figure 11. Dependence of the polarity of the EMF on the direction of the polarity of the heat flux for conventional diffuse thermoelectrics (top) and the dependence of the polarity of the Local EMF only on the polarity in the p-n junction (bottom).

On a structure of series-connected *p-n* junctions with a thickness of 3 µm, grown on a 300-micron device silicon substrate, a similar independence of the generated temperature drop from the current polarity is observed at short recording times. And at long measurement times, only a certain asymmetry is observed, which is associated with the shunting effect of a thick substrate (**Figure 12**).

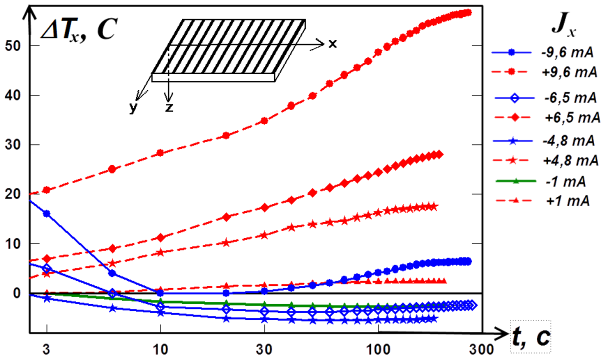

Figure 12. Separation of an analogue of Peltier heat by a structure of series-connected p-n junctions grown on a silicon substrate [28-31].

As can be seen from **Figure 12**, the fast temperature response, determined only by the polarity of a three-micron structure of series-connected *p-n* junctions, has a slow temperature effect, determined by a thick silicon substrate.

It is also characteristic that the thermal shunting of the structure of p-n junctions completely linearizes the CVC, which directly indicates that the heat released by the structure is determined by the Local thermo-EMF.

The use of extended concentration-electrical-thermal phenomenology made it possible both to confirm the current (primacy of the current) of the Losev *p-n* junction, and to transfer the "anomalous" thermoelectric power discovered by Tauc in the p-n junction to the category of normal-local, and to describe new experimental results of studies of contact thermoelectric power. In addition, the extended phenomenology made it possible to understand that macroscopic thermoelectricity is artificially limited only by diffuse thermoelectric materials and showed that for diffuse thermoelectrics, the efficiency of thermoelectric conversion achieved in practice is already close to the theoretical limit.

In addition, extended phenomenology has shown that the efficiency of thermoelectric conversion based on local thermoelectric power does not have a diffuse limit and can be dramatically increased by several times compared to that achieved using the Seebeck effect in traditional diffuse materials (**Figure 10**).

This was experimentally confirmed on the developed detectors based on Local Thermo-EMF in silicon junctions, the volt-watt sensitivity of which was obtained three orders of magnitude higher than that of detectors based on the traditional macroscopic Seebeck effect.

At the same time, the extended phenomenology shows that there can be complex, three-phase effects in the p-n junction, which makes it possible to optimize, in particular, the combination of local thermoelectric effects with photoelectric effects in it.

4. Reversible effects

Since what differs from the generally accepted one often "does not fit in the head" and is perceived as erroneous or mystical, an ELEMENTARY explanation is required for the material shown in **Figure 11** and **Figure 12**.

Reversible Processes, forbidden by the Second Law of Thermodynamics, connected with the transformation of Chaos into Harmony (the impossibility of this transformation in inanimate Nature), we will not consider here [32-35].

"The law of non-decreasing entropy, or the so-called physical meaning of the second law of thermodynamics, was discovered by Rudolf Clausius (1865), and its theoretical justification was given by Ludwig Boltzmann (1870s)."

But we will consider not just Reverse Processes, such as a change in the sign of a mechanical or electrical force with a corresponding change in the sign of movement, as in the same linear Ohm's Law, but we will consider exactly the Reverse Processes, which, in principle, are not prohibited by the Second Law of Thermodynamics, but simply limited in effectiveness. The simplest examples are the conversion of mechanical or electrical energy into heat, which the Heat Engine has long "learned" to convert back into mechanical or electrical energy. And the limit of effectiveness of this Reverse Transformation, as follows from the Second Law of Thermodynamics itself, is determined by the Carnot cycle. One of these Thermal Engines is a thermoelectric generator, the efficiency of which, in principle, is determined by the same Carnot cycle, but in reality it is less than three times, since the diffuse Seebeck effect is used, i.e. friction is used squared. In this regard, Local thermo-EMF, using not diffuse, but ballistic effects, eliminates the friction multiplication, thereby making it possible to approach the Carnot cycle. But thermoelectricity itself also demonstrates the Reverse Process—the flow of electrical energy (into an external circuit) from a thermogenerator can, in principle, be opposed to the flow of heat from a thermoelectric refrigerator.

And in this regard, there is nothing supernatural in the fact that with the help of Local thermo-EMF it is possible to generate electricity both due to the flow of the body, and to generate a heat flow due to electric energy.

In considering Local thermo-emfs, we have already started from the band diagram and from the current-voltage characteristics, similar to those used to describe the photo-effect. And for the photo effect, the reverse effect used in LEDs is also well known. In principle, these both effects are also the implementation of the Heat Engine, simply because of the high light temperature, which acts as a hot temperature in the Carnot formula, it is believed that their Carnot coefficient is close to unity and, at the same time, all energy processes in the p-n junction can be fully described by the change in the electron energy in the transition diagram. In practice, this is far from the case, and in terms of efficiency, photocells only approach the efficiency of an internal combustion engine. And the LEDs heat up so much that they even burn out with improper cooling. And when indirect-gap semiconductors are used as a material for these diodes, the efficiency also decreases further due to the fact that the transition of an electron from one energy level to another is carried out not only due to a quantum of light, but also due to thermal vibrations of phonon atoms.

Nevertheless, their principles of operation in an ideal diode can be described in the "language" of light-electron.

For a photodiode, as shown in **Figure 7**, the light flux shifts the current-voltage characteristics of an ideal diode. At the same time, in the photo-quadrant marked in yellow, the current and voltage are in antiphase and the corresponding power is negative (**Figure 13**).

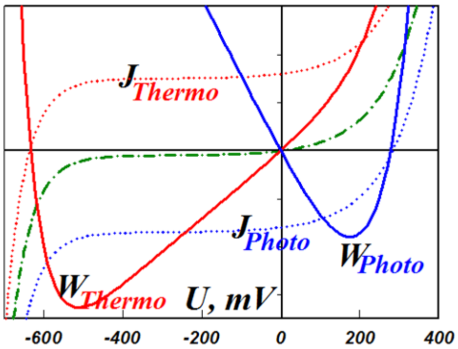

Figure 13. Anti-phase current and voltages give negative (generator) power both with the photo effect (blue color) and with the Local thermal effect.

As shown in **Figure 13**, we obtain a similar negative power peak for the thermal quadrant, where the current and voltage are in antiphase (in experimental **Figure 10**, the corresponding thermal power peaks are shown positive for convenience). It is like a battery delivering positive power to an external circuit, the current and voltage inside it are also in antiphase, which corresponds to the removal of this power from the battery to transfer it to the external circuit.

The light effect, the reverse of the photo effect, has been studied quite well. Therefore, we will begin the analysis of Reverse Effects with him. As was customary in all Electronics, and analyze the light effect as a field effect, determined by the achievement of a certain critical voltage on the p-n junction on the direct branch of the CVC. But if we take into account the linear relationship of different flows (formula 4), then the experimental CVC of the direct branch of the LED corresponds to positive current displacements of the direct branch of its CVC, which corresponds to the expansion of the phenomenology of the description of the p-n junction when taking into account the light flux (**Figure 14**, on the right).

So, taking into account the primacy of the current, it is possible to construct a differential I-V characteristic of an ideal diode, displaced, as in the case of the photo effect, by the opening (of a different polarity) current, determined by the emitted light flux. So for an ideal diode, we will get the power released in the p-n junction near the critical voltage, only in the form of light. For a real diode, for the reasons noted above, only a part of the power will be released in the form of light, and, at high currents, the light will be extinguished. All the electrical power consumed by the diode will be released as heat. Such a current analysis of the light effect makes it possible to clarify the description of the direct photo effect as well. As shown in **Figure 5**, the photo effect, due to the smallness of the photon momentum, is associated precisely with vertical transitions of electrons. But the critical voltage of the light of the diode is reached when the spatial transition of electrons becomes possible (**Figure 3**), which, at the same time, strictly corresponds to the law of conservation of momentum and does not require the participation of phonons in direct-gap semiconductors.

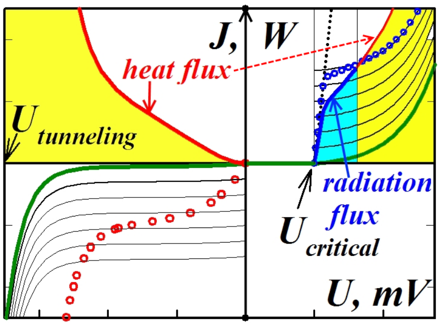

Figure 14. Schematic diagram of the description of the forward and reverse branches of the I-V characteristics (shown by circles, blue for the light effect, red for the Local thermal effect in the p-n junction) by the current bias of the I-V characteristics of an ideal diode.

When the ideal diode is displaced by the current in the shutoff direction, the electrical energy consumed by the diode in the initial section of the I–V characteristic (**Figure 12**) will in fact similarly turn into a heat flux, which, as in the light effect, corresponds to the displacement of the I–V characteristic of the ideal diode, but in terms of the shutoff current (**Figure 14**, left).

And in both considered cases, in the initial sections of the CVC, the parameters of the p-n junction plates will determine on which plate the release of light or heat will occur more. And with an increase in currents above certain critical ones, heat will be released purely ohmic-isotropically. And this is the boundary between flows and isotropic selection.

Strict, quantitative consideration requires, as shown above (**Figure 6**), taking into account the "Maxwell's demon" in the initial CVC, taking into account that the equilibrium state of the p-n junction corresponds to a small temperature difference between its plates. But this temperature drop is associated with specific details of the p-n junction and will not be considered here. We only note the main thing - a strict phenological description, developed, in principle, for any number of independent forces (***J***) and flows (***F***), as shown by studies on the NANO-scale, requires taking into account not three (as shown in **Table 1**), but four pairs of forces and flows: electrical, concentration, thermal and light.

$$\begin{aligned} J_E &= L_{EE}F_E + L_{ET}F_T + L_{EN}F_N + L_{EPh}F_{Ph} \\ J_N &= L_{NE}F_E + L_{NT}F_T + L_{NN}F_N + L_{NPh}F_{Ph} \\ J_T &= L_{TE}F_E + L_{TT}F_T + L_{TN}F_N + L_{TPh}F_{Ph} \\ J_{Ph} &= L_{PhE}F_E + L_{PhT}F_T + L_{PhN}F_N + L_{PhPh}F_{Ph} \end{aligned} \tag{5}$$

where L is the corresponding 16 kinetic coefficients related to each other, as follows from the "reversibility"—the reversibility of effects (**Figures 13-14**), by the Onsager symmetry principle, which reduces the number of independent kinetic coefficients to 10:

$$\begin{aligned} J_E &= L_{EE}F_E + L_{ET}F_T + L_{EN}F_N + L_{EPh}F_{Ph} \\ J_N &= L_{EN}F_E + L_{NN}F_N + L_{NT}F_T + L_{NPh}F_{Ph} \\ J_T &= L_{ET}F_E + L_{NT}F_N + L_{TT}F_T + L_{TPh}F_{Ph} \\ J_{Ph} &= L_{EPh}F_E + L_{TPh}F_T + L_{NPh}F_N + L_{PhPh}F_{Ph} \end{aligned} \tag{6}$$

By solving this system for any flow (force) and using the boundary conditions, one can obtain the maximum efficiency of electric power and heat flux generation [11-13], or the maximum efficiency of light generation. Moreover, it is possible to achieve the maximum efficiency of the transistor and thereby reduce its own noise level and increase its speed.

Only in this case it must be borne in mind that these are Local Kinetic coefficients that characterize a non-homogeneous material, an artificially created "Maxwell's demon"—an element of a working nano-structure, in particular, the ideal diode described by us.

In semiconductor devices with weak light and photo effects, to find the maximum efficiency, one can limit oneself to three simplified systems of equation (6) and analyze the three-dimensional thermo-voltage-ampere surface (**Figure 15**).

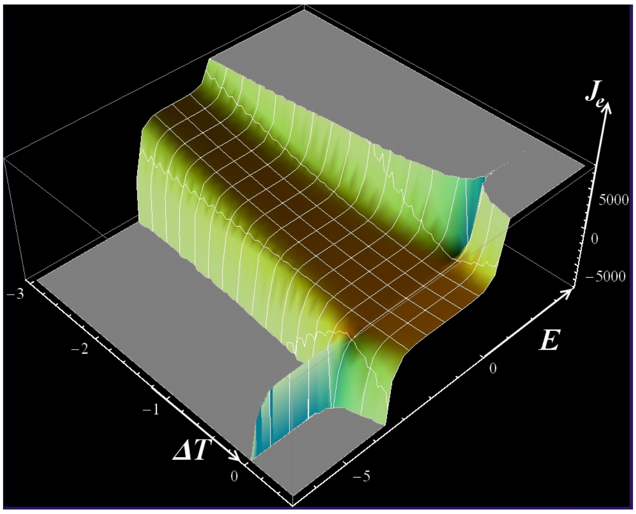

Figure 15. CVC expansion takes into account the temperature force.

In the general case, it is necessary to analyze a 4-dimensional thermo-photo-voltage-ampere surface.

5. Conclusions

The registration of the Effects, which were classified as quantum, as if by itself, implied their measurability. Additionally, this was supported by hastily made Quantum Statistics, which, as it were, fenced off the measurability of Quantum Effects from its limitations by Classical Thermodynamics (how loosely this was done will be shown in the chapter of my future work "Quantum Extension of Classical Representations" [36]). But, even without the macroscopic parameters calculated from the mystical Schrödinger wave functions, simply from the analysis of Newton's Elementary Particle, it is possible to obtain both their measurable diffuse light quanta flux, and the measurable wave of coherent laser light.

Local—missed between macroscopic and microscopic NANO-effects, in this regard, were less fortunate, because they directly adjoined, and in thermoelectricity they were determined by Thermodynamics and its limitations simply forbade their measurability. And these restrictions-prohibitions were lifted by

Ilya Prigogine's own Thermo-Dynamics of flows, which transferred the science itself, previously called Thermodynamics, to the category of Thermo-Statics.

At the same time, the study of Local Effects raised a number of fundamental questions that turned out to be in the "fork": From—this cannot be, to the same—elementary. This also applies to the registration of the Local thermo-EMFs discovered and previously classified as anomalous, but not only—the entire Physics of semiconductors contains a systematic elementary error in Phenomenology itself.

But by and large, not a primitive, but an elementary solution allows you to create devices with fundamentally (drastically) improved characteristics. This was the case before, when new devices were created based on the well-known First Principles, the same was confirmed when creating detectors based on the discovered NANO-effects, the study of which resulted in the previously missed NANO-Physics.

Thus, in order to achieve this fundamental improvement in the characteristics of devices and devices, it was necessary to eliminate this fundamental error and solve a number of fundamental issues, a number of methodological measurement issues, and a number of issues related to the technology of manufacturing efficient semiconductor nanostructures, and a number of design issues.

Within the framework of this study, answers were obtained to a number of fundamental questions.

1) Measurability of Local Effects.

2) The primacy in the effects of the current as the cause of the effect and the secondary nature of the voltage, as a consequence, taking into account external conditions.

3) Electric currents over potential barriers in semiconductors.

4) Thermal force in the p-n junction.

5) Extended Thermo-Photo-phenomenology for describing effects in a Solid State.

Conflict of Interest

There is no conflict of interest.

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