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Cardinal Increase in the Efficiency of Energy Conversion Based on Local Thermoelectric Effects

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Abstract: *The refinement of the phenomenology of thermoelectricity made it possible to determine the theoretical limit of diffuse thermoelectricity, which for many years has limited the effectiveness of thermoelectric devices based on the macroscopic effects of Seebeck and Peltier. The expansion of the phenomenology of thermoelectricity due to the account of the giant concentration force made it possible to explain local thermoelectric effects in semiconductor structures that do not have a diffuse limitation of the efficiency of energy conversion. Based on local thermoelectric effects, the effectiveness of thermoelectric devices can be radically improved. In addition, local thermoelectric effects are needed to optimize the performance of any nano- and microelectronic devices.*

The concept of local entropy production introduced by Ilya Prigozhin made it possible to describe not only its dissipative structures [1], but also to advance in understanding thermoelectric processes in semiconductor artificial structures that are quasi-equilibrium in the operating temperature range [2, 3]. The local thermo-EMF detected and studied at p-n junctions are several orders of magnitude greater than generated due to the Seebeck effect (Fig. 1, 2).

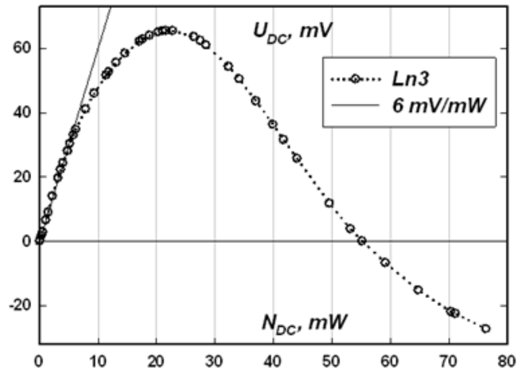

Fig1. *The characteristic volt-watt dependence of the detector on the basis of longitudinal local thermo-EMFs (for a similar detector based on the Seebeck effect, the volt-watt sensitivity is of the order of 1 mV / W, but in the whole range of heat flux shown).*

The thermo-EMF that appears on potential barriers is proportional to the height of the barrier, and not to the small difference between the average electron energy in the flow and their average statistical Fermi energy, which determines the Seebeck small thermoelectric power. Therefore, the giant values of barrier thermo-EMF were quite expected (Fig. 2).

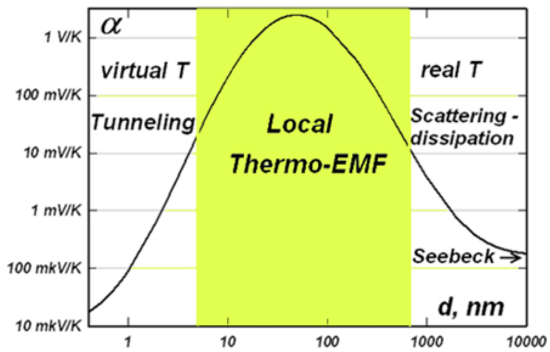

Fig2. *The size dependence of the thermo-EMF*

But previously these giant thermoelectric power observed episodically on contacts dropped out of consideration by thermoelectric phenomenology, which does not take into account the giant concentration force in the p-n junction [4]. At what the barrier thermoelectric models constructed earlier gave very small currents and, thus, giant output impedances of such thermoelectric devices, whereas, while the output resistances found on the mock-up of generators based on local thermo-EMF were several orders of magnitude less than the predicted ones (Fig. 3).

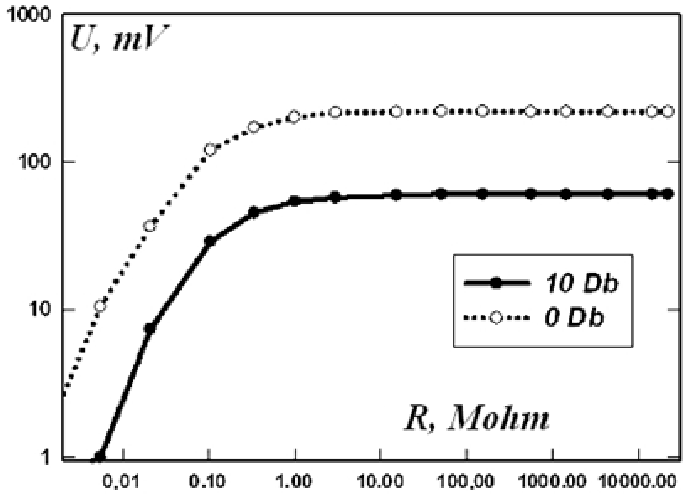

Fig3. *The load characteristics of the detector on the basis of longitudinal local thermo-EMF: the output resistance of the detector is of the order of 200 kOhm*

Large currents of local thermo-EMFs and, accordingly, small output impedances of generators based on them, were explained on the basis of the ballistic model of the motion of electrons above the barrier [5]. The combination of high volt-watt sensitivity with low output impedances of detectors based on local thermo-EMF was consistent with their high detection ability, which exceeds by orders of magnitude the detectability of thermal receivers based on macroscopic effects. This directly indicated that the efficiency of conversion of devices based on local thermo-emf is higher than that of traditional thermoelectric devices, the efficiency of which, as was shown in [4], limits the diffuse character of the macroscopic Seebeck effect.

Thus, the experimental and theoretical confirmation of the possibility of exceeding the efficiency of the traditional thermoelectric conversion made it possible to explain the saturation of its maximum value already 20 years ago.

Any thermal machines have different losses of converted and generated energy. And although the maximum efficiency of thermoelectric conversion $\eta_{ThE}^{\max}$ is limited, like that of any thermal machine, with the Carnot coefficient

$$k^{\text{Carnot cycle}} = \frac{T_{\max} - T_{\min}}{T_{\max}} < 1_{/T_{\min} \neq 0} \tag{1}$$

in real, both thermoelectric and other devices does not $k^{\text{Carnot cycle}}$ give the main contribution to the limitation $\eta^{\max}$

$$\eta^{\max} = Q_{TM}^{\max} \cdot k^{\text{Carnot cycle}} \cdot 100\% \tag{2}$$

and, as shown in Table 1, the main limitation gives the maximum achievable quality factor Q-factor for thermal converters $Q_{TM}^{\max}$, in particular thermoelectric $Q_{TE}^{\max}$. As can be seen from Table 1, the decrease in the efficiency of thermoelectric generators due to the quality factor   is approximately 10 times or more (right column of the table), whereas the Carnot cycle weakens efficiency by several times and by percent.

Table1.

Temperature mode		$k^{\text{Carnot cycle}}$	η^{max}, % реальных устройств	Q_{TM}^{max}
T_{max}, C	T_{min}, C			
Thermoelectric generators				
200	**100**	**0.21**	**2.8÷1.5**	**0.13÷0.07**
150	**50**	**0.24**	**3.2÷2.2**	**0.14÷0.09**
300	**50**	**0.44**	**5.3÷4.1**	**0.12÷0.09**
1000	**50**	**0.75**	**12÷10**	**0.16÷0.13**
The theoretical limit of a thermoelectric generator				
1000	**50**	**0.75**	**12.9**	**0.1716**
Photo detector				
6000	**50**	**~ 1**	**13.6÷6**	**0.136÷0.06**
Internal combustion engine				
2000	**300**	**75**	**36**	**0.48**

The analysis shows that attempts to improve the efficiency of traditional thermoelectric energy transformations on the basis of macroscopic diffuse effects [6, 7, 8] have long been conducted in the illusion area, since the Ioffe ***ZT*** parameter can not be more than one (Fig. 4).

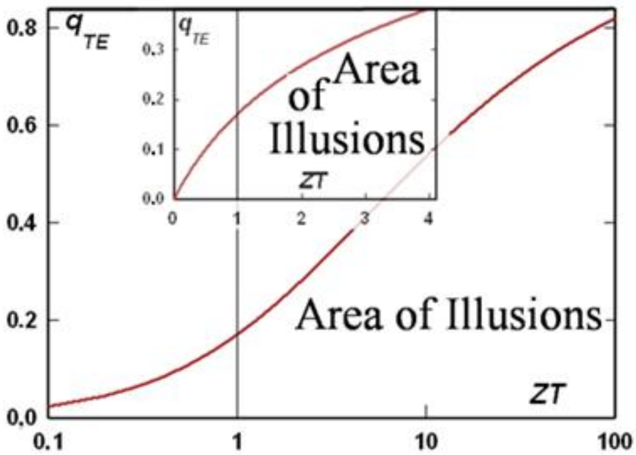

Fig4. *Dependence of the thermoelectric figure of merit on the Ioffe parameter* ***ZT***

Whereas, the ballistic nature of local thermo-EMF removes the diffuse limitation on the efficiency of the thermoelectric conversion. Thus, the efficiency of thermoelectric conversion can not only reach the practical value of the photodetector efficiency [9], but also the declared maximum for photodetectors 32%, and even the efficiency of the internal combustion engine is 36%.

Above, we presented the results of measurements of the characteristics of detectors based on local thermo-EMFs in a purely oscillator mode. The purely generator characteristics of the detectors made it possible to make estimates of the efficiency of generator thermoelements based on local thermo-EMF in the silicon p-n junctions used.

Table2.

	Available on the basis of macroscopic Seebeck effect	Designed on the basis of local thermo-EMFs
EMF	2÷12 %	12 ÷30 %
Specific (per unit mass) power	3÷300 W/kg	not less than 3 kW/kg
Specific (per unit volume) power	0,2 ÷1,5 W/cm3	not less than 200 W/cm3
Operating voltage	0,5 ÷5 V	12 V and more

As can be seen from Table 2, the obtained characteristics of detectors based on local thermo-EMF provide the possibility of manufacturing light, small-sized, high-voltage and high-efficiency thermoelectric generators.

Considering that the work of thermoelectric detectors depends little on many factors, in particular dust, they can be more practical in solar batteries than photodetectors. In addition, detectors based on local thermo-EMFs have no fundamental limitations on the wavelength range of the detected radiation, which additionally increases the efficiency of their use in solar batteries, especially in space.

The speed of detectors based on local thermo-EMF is slightly higher than for photo-detectors at equivalent p-n junctions, and their volt-watt sensitivity in the initial section increases with increasing modulation frequency of the heat flux. In this case, the dynamic range of the linear conversion of the signal increases (Fig. 5).

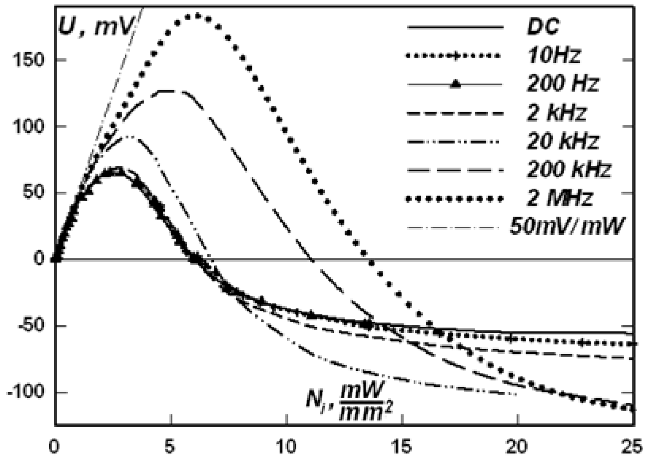

Fig5. *Reduction of the saturation of the longitudinal local thermo-EMF as the duration of the heating pulse decreases (increasing the modulation frequency of the signal)*

An additional increase in the volt-watt sensitivity on short pulses (checked up to nanosecond fractions) indicates that the temperature of hot electrons is higher than the equilibrium one. In combination with additional noise suppression due to the detected resonance in longitudinal local thermo-EMF [10], these thermal detectors at room temperature are comparable in detectability with cooled thermal detectors.

However, for silicon p-n junctions on the longitudinal local thermoelectric effect, power limitations are observed (Fig. 1, 5), which was the reason for additional [11] studies of local thermo-EMF in wide-gap semiconductors [12] and multilayer structures.

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