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Communication

Pulse mode of operation – A new booster of TEG, improving power up to X2.7 – to better fit IoT requirements

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A R T I C L E I N F O

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A B S T R A C T

Internet ***of*** ***T***hings (***IoT***) is becoming the new driver for semiconductor industry and the largest electronic market ever seen. The number of ***IoT*** nodes is already many times larger than the human population and is continuously growing. It is thus mandatory that ***IoT*** nodes become self-supplying with energy harvested from environment since periodic exchange of batteries in such a huge number of units (often located in inaccessible places e.g. industrial environment or elements of constructions) is impractical and soon will be simply impossible. Photovoltaic generators may easily harvest energy where light is available, but the ***IoT*** nodes often work in dark, hidden locations where the only available energy sources are heat losses. There, ***T***hermo***E***lectric ***G***enerators (***TEG***s) could be the best candidate, if not that if we speak of exploiting heat losses it often means very low temperature differences. This means conditions where ***TEG***s power production drops down dramatically. In this paper we put forward a new idea of ***TEG***'s pulse operation that boosts the power production up to X2.7. This extends the domain of applicability of ***TEG***s to lower temperature differences, where conventional ***TEG***s are out of the game. Next, we show that the improvement X2.7 maintains also at larger temperature differences that presents obvious advantages.

1. Introduction

Semiconductor industry is currently under huge influence of the ***I***nternet ***of*** ***T***hings (***IoT***) [1,2] technologies. Emerging market of ***IoT*** (*see black line in* Fig. 1) outnumbers ~ X7 human population [3]. Additionally, the aforementioned quantity growth is accompanied by the miniaturization and densification trend that continues over several decades [4–6]! In light of omnipresence, quantity and availability of electronic devices, supplying them becomes a difficult challenge, even though their power consumption per operation has been largely reduced over past years [7,8]. The challenge is not only with battery lifetime but also with renewing (*exchanging*) them in trillions of places. Being aware that the quantity of *Things* is ~X7 higher than human population and considering that usually ***IoT*** nodes are installed in harsh and difficult to reach locations, maintaining them is difficult. Despite that the energy needed for ***IoT*** node to operate is very small (~100 μJ/*cycle* [9]), each *Thing* in ***IoT*** system has to be supplied. Grid supply requires wiring each element in the system making it costly, unreliable and difficult to modify. Battery-fed sensors are also problematic in the context of their quantity, portability, working environment and installation points, making maintenance more-and-more time consuming and expensive, not forgetting about bad influence of used batteries on the natural environment.

Therefore, searching for alternatives for battery or grid supply is an urgency. The ***IoT*** systems consist of large number of miniature sensors (*Things*) providing measured information (e.g. *temperature, air pressure, person presence etc.*) to controlling unit.

The rapid device's performance boost is not followed by the supply techniques. It can be said that the growth of the semiconductor market could be even faster and bigger when finding reliable alternatives for

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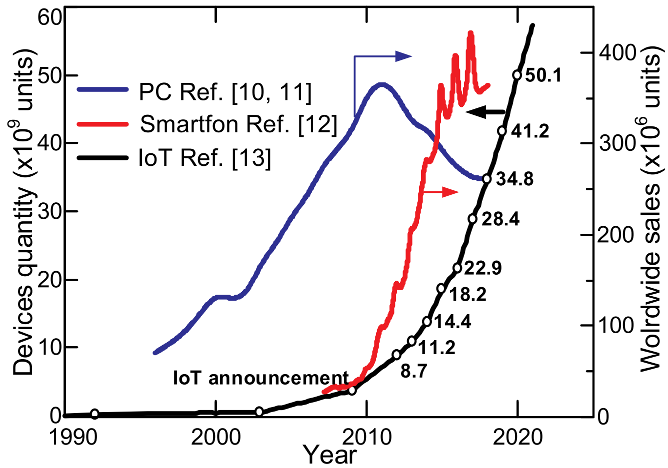

Fig. 1. Historical number of personal computers [10,11] and smartfons [12] benchmarked with the number of ***IoT*** nodes [13].

battery or wire supply. In that context the ***E***nergy ***H***arvesting (***EH***) [14,15] – energy production from waste or naturally provided energies (e.g. *heat, light, mechanical energy - vibrations, electromagnetic radiation etc.*)- could respond ideally to the current needs of the ***IoT*** market unlocking its further expansion.

Literature on ***EH*** reports huge variety of approaches to convert loss energy into useful energy. In addition to very well-known and reported methods as photovoltaic [16–19], piezoelectric [20–26], electromagnetic [27–30], radio-frequency [19,31,32] or thermoelectric [33–36], there are numerous emerging techniques including hybrid solutions e.g. pyroelectric [37–40] or triboelectric [41–47].

Despite that the thermoelectric effect (*direct, silent, vibrationless and reliable conversion of heat into electric energy*) is well known since its discovery in 1823 by T. Seebeck [48], it has never been popularized on the market and remains limited to applications such as spatial [49], medical [50–54], automotive [55–57] or sophisticated industrial [58]. The main raison for that is unattractively low ***T***hermo***E***lectric ***G***enerators (***TEG***) efficiencies (η, (1)) [59] resulting from thermoelectric figure-of-merit (zT, (2)) [60] at the material level:

$$\eta = \frac{T_{HOT} - T_{COLD}}{T_{HOT}} \cdot \frac{\sqrt{1+zT}-1}{\sqrt{1+zT}+\frac{T_{COLD}}{T_{HOT}}} \tag{1}$$

$$zT = \frac{S^2 \cdot \sigma}{\kappa} \cdot T \tag{2}$$

Where: S is thermoelectric thermopower, and σ and κ state for electrical and thermal conductivities, respectively. ***TEG*** thermal operating conditions are described by the temperature drop ($\Delta T = T_{HOT}$-T_{COLD}) across the generator. Increasing η requires boosting the zT which is an extremely challenging task since S, σ, κ are interdependent. Therefore, it took more than 30 years to find a material exhibiting $zT > 1$ [35,61]. Currently, maximal zT oscillates around 2.5 for ***n***-SnSe 2%Bi [62] and ***p***-SnSe [63] which is still not enough to be named the "Holy Grail" [64] material that will kick-off thermoelectricity on the market (*it should be n- and p-type cheap bulk materials with* $zT > 3$). Knowing that zT improvement is very difficult, scientific community reported also alternative approaches to boost ***TEG*** performance proposing unconventional topologies: (i) lateral [36,65–71], (ii) large area pn junction [72–76] or (iii) flexible [77,78]. However, their unconventionality results more in fabrication cost reduction rather than in performance enhancement.

Closer look at the ***TEG*** output power (P) [79,80] reveals another possibility to improve generator's performance by manipulation of the temperature difference. If T_{HOT} and T_{COLD} denote temperatures of the reservoirs, it does not mean that such a temperature difference (T_{HOT}-T_{COLD}) is seen at the extremities of the Seebeck device itself. Actually, due to the so-called thermalization effect caused by non-zero thermal contact resistances between Seebeck device extremities and the reservoirs, the Seebeck device may be powered by a much smaller temperature difference ΔT_{eff}, see Fig. 2.

Eq. (3) indicates three possible paths to increase P: (i) rising S_{TEG} (S_{TEG}=$S_n + S_p$, *sum of n- and p-pillars thermoelectric power*); (ii) working under load matched condition $R_{TEG} = R_{Load}$ [53,81–85] or (iii) increasing effective ΔT_{eff} across the ***TEG***.

$$P = \left[\frac{S_{TEG} \cdot \Delta T_{eff}}{R_{TEG} + R_{Load}}\right]^2 \cdot R_{Load} \tag{3}$$

where: S_{TEG}, R_{TEG} state or the total thermopower and internal resistance for a given ***TEG***, R_{Load} denotes the load resistance, while ΔT_{eff} is the effective temperature difference across ***TEG*** itself.

Usually, the user has no influence on the S_{TEG} since this is material parameter that describes entropy per carrier or heat per carrier over temperature [86,87]. Optimization of S_{TEG} requires therefore changes in the thermoelectric material properties and structure. Working under matched load condition is widely used, but requires advanced auxiliary controlling devices able to provide ***M***aximal ***P***ower ***P***oint ***T***racking (***MPPT***) [88–90]. Finally, increasing ΔT_{eff} across the ***TEG*** is also difficult since usually ***TEG***s are subject to the externally imposed thermal conditions. In most cases T_{HOT} and T_{COLD} temperatures are user-independent. However, as we show in this paper, ΔT_{eff} and thus also P can be significantly boosted by providing a discontinuous contact between the Seebeck device and the hot source.

2. The new idea

Conventionally, the generator is permanently mounted on the heat source which results in $\Delta Teff$ decrease because of T_{COLD} parasitic warming by the heat source (*thermalization process*). This is in part due to a disequilibrium between R_{thCOLD} (*that is large*) and R_{thHOT} (*that is small*). The idea is thus to modulate the thermal contact resistance R_{thHOT} by periodic raising the Seebeck device (*due to discontinuity from the hot reservoir* R_{thHOT} *becomes large*) and posing it on the hot reservoir (*due to continuity with the hot reservoir* R_{thHOT} *becomes small*) in order to hinder the thermalization process. Such a pulse way of operation leads to an increase in ΔT_{eff}, during the periods of discontinuity, and even if supposing no increase in ΔT_{eff} in the periods of continuity, the average ΔT_{eff} over long period of time will be improved. Let's emphasize that similar but continuous effect of equalizing the thermal contact resistances (in order to hinder thermalization) is frequently used at the cold side. We mean utilization of a hot sink there, the effect of which is to reduce R_{thCOLD}. Therefore, ***TEG*** practical application is usually accompanied with heat-sinks mounted at the ***TEG*** cold side to maintain satisfactory ΔT_{eff} [54,91,92]. This is, however, undesirable since heat-sinks are costly and cumbersome.

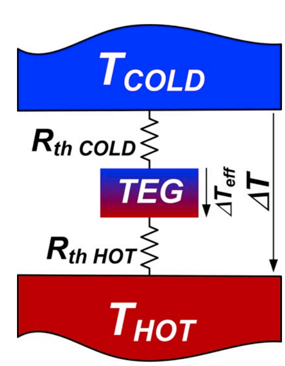

Fig. 2. Illustration of the effective temperature drop ΔT_{eff} over the generator which depends on the thermal resistances $R_{th\ COLD}$ and $R_{th\ HOT}$ between ***TEG*** and cold/hot sources, respectively.

In order to demonstrate the importance of the thermalization process, we have shown in Fig. 3 time dependence of the power production by a ***TEG***. Whereas the initial peak reaches 500 μW, it suffices ~25s to degrade the production down to ~5 μW due to thermalization. The idea is therefore to periodically disconnect the ***TEG*** from the hot source to let it cool down and then produce the next power peak by sticking the ***TEG*** to the heater. We will demonstrate that the integral of such power pulses may largely surpass the continuous power production. Of course, the question is how to produce such a pulse operation without using the ***TEG*** generated power.

We will now give an example of practical realization of the pulse mode, but we wish to emphasize that the realization of the mechanical motion is not in the scope of the paper that is rather dedicated to a demonstration of the fundamental idea of how to enhance Seebeck devices power production by a pulse mode of operation. The mechanical movement we propose here is no more than an example that can do the job and thus shows that the invention is feasible. On the other hand, this realization leads to mechanical and thermal shocks that could better be avoided. Therefore, we hope that the advantages of the pulse mode of operation will inspire researchers in other labs to propose better implementations.

A simple way to practically realize the pulse operation can be provided by the thermally bi-stable strip (*bimetal*) that was used in the heat-driven piezoelectric generators [93–98]. The difference is that in the present approach the thermoelectric generator replaces the piezoelectric one. The generating device is lifted/lowered over the heat source as illustrated in Fig. 4. As described in Refs. [93–98] the bimetal, bistable strip bends over periodically towards the opposite source with sub-Hz frequencies. In other words, when it touches the hot source during a few seconds, it will bend over and touch the cold source. Then after a few seconds of touching cold source, it will bend over again to touch the hot source, and so on. As schematically shown in Fig. 4, this periodic motion may be used to displace the ***TEG***. This is only an example and we wish to emphasize that the realization of the mechanical motion is not in the scope of the paper. We are convinced that many alternative ways to accomplish such a periodic movement of a ***TEG*** exist. It is only a question of a smart engineering. Therefore, in this paper we are focusing only on demonstration of the more fundamental thesis that with such a periodic, or pulse, mode of operation the produced power is much larger than in a continuous mode. In the following section we present measurement setup and procedures that will be used to demonstrate the validity of the idea.

3. Measurement setup and procedure

The measurement scheme is presented in Fig. 5. Let's note that it does not employ the bi-metal strip described above, since for the sake of reliable demonstration of the idea itself, we preferred to separate the proof from the implementation. The experimental benchmarking of the idea was realized upon commercialized ***TEG*** (*model TG12-4* [99]) in the clean-room (*class 100 ISO 5 cleanness*) using Sawatec HP-200 hot plate as a heat source and a load resistor $R_{Load} = 1\Omega$ for all investigated cases. As an acquisition device, a digital oscilloscope DSOX2024A was used. Clean-room environment for this experiments gave access to the: (i) high-stability heat source, normally used for lithographic resist bake, allowing simple implementation of ***TEG*** cyclic movements, (ii) equal ***TEG***-to-hot plate feed force owing to the soaking system and (iii) ultra-stable and well monitored temperature ($T_{ambient}$) and humidity (***RH***) during experiments ($T_{ambient} = 21.77 \pm 0.09°C$; $RH = 48.74 \pm 3.48\%$).

During the measurements, the ***TEG*** output voltage is measured. Load resistance of $R_{Load} = 1\Omega$ was used for all acquisitions. Selection of R_{Load} value is not random, we wanted to provide the characterization far from load matched condition to check if impulse ***TEG*** operation improves performance even in the disadvantageous conditions.

In order to deliver fair and accurate comparison between conventional and pulse operation a statistical measurement (*with a population of at least four runs*) for each case was done. Knowing that in the real-life situation ***TEG***s operate for years without being serviced, the acquisitions were executed over very long time (*minimal acquisition time 200s*) which was preceded by at least 5 min of preliminary ***TEG*** operation to insure the steady-state conditions.

To give a broad performance evaluation, ***TEG*** was measured under six different operating conditions varying heating (t_H) and cooling ($t_C = t_{C1}+t_{C2}$) duration. This analysis is done at five different $T_{HOT} = \{25; 28; 32; 37; 72\}°C$. Knowing the average Tambient during the measurement, it is possible to calculate the maximal temperature drop (*temperature difference between reservoirs*) over the ***TEG*** $\Delta T_{MAX} = \{3.1 \pm 0.01; \; 6.15 \pm 0.02; \; 10.1 \pm 0.026; \; 15.25 \pm 0.04; \; 50.29 \pm 0.008\}°C$, respectively. It is worth to note that this characterization was performed for the temperatures that are of high interest for ***IoT*** devices since ***IoT*** nodes are usually exposed to similar conditions.

4. Results and discussion

As shown in Fig. 5 the measured signal is the ***TEG*** output voltage. The output power (***P***) is retrieved knowing R_{Load} following formula $P = V^2/R_{Load}$.

Fig. 6 compares the ***TEG*** output power for continuous and pulse ($t_H = 15$ s $t_C = 25$ s) operation for $T_{HOT} = 28$ °C. Fig. 6a shows the harvested output power in a logarithmic scale and indicates pics (that exceed the continuous power by at least one decade) that appear shortly after bringing the ***TEG*** into contact with the hot reservoir. This is caused by the fact that at the beginning of the measurement the temperature of the entire ***TEG*** volume equals $T_{ambient}$. Therefore, it can be noted that the power peaks refer to charging ***TEG*** heat capacitance by the heat source. Focusing on the continuous operation (*see* Fig. 6b), a few observations can be made. First of all, pulse operation produces power peaks with a large amplitude several times higher than the continuous mode power. Despite the fact that ***P*** gradually drops to zero when ***TEG*** is lifted, the average power is higher than in the continuous mode, if only the disconnection does not last for too long (*see summary in* Fig. 7). In other words, the output power ***P*** is dominated by the short generation periods when ***TEG*** is heated, if only they are sufficiently dense. Focusing on the pulse power transient, four consecutive stages can be distinguished. Firstly, (***stage 1*** *in* Fig. 6b), when ***TEG*** is heated, its heat capacitance charging is observed leading to abrupt ***P*** increase. Subsequently (***stage 2***), rapid ***P*** drop occurs despite that ***TEG*** is being heated, this corresponds to the thermalization process (*cold side warming*). Subsequently, ***stage 3*** begins when ***TEG*** is being disconnected from the hot source. Despite absence of supply with heat, ***TEG*** still delivers some power, this can be explained by discharging the ***TEG***'s heat capacitance.

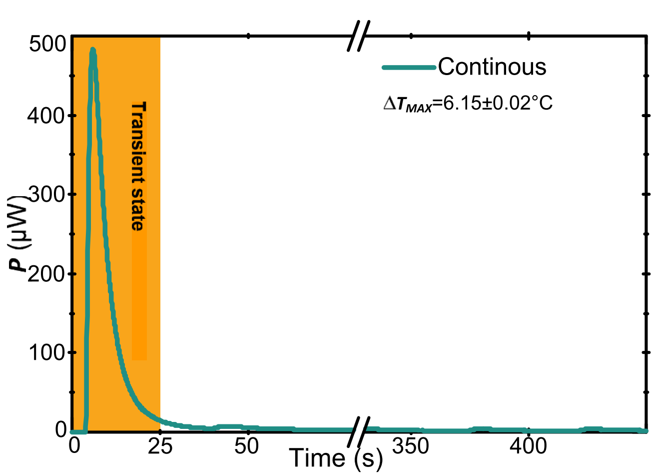

Fig. 3. ***TEG*** output power versus time in the continuous mode operation.

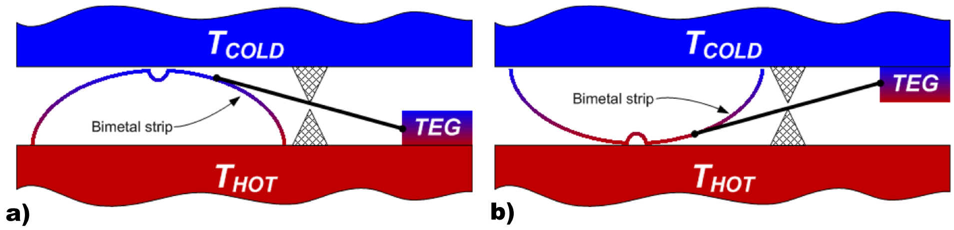

Fig. 4. The idea of ***TEG*** pulse movement realization without consuming ***TEG*** output power; **a)** bimetal strip in up position; **b)** bimetal strip in down position.

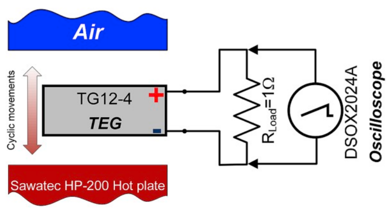

Fig. 5. Measurement setup of pulse fed thermoelectric generator.

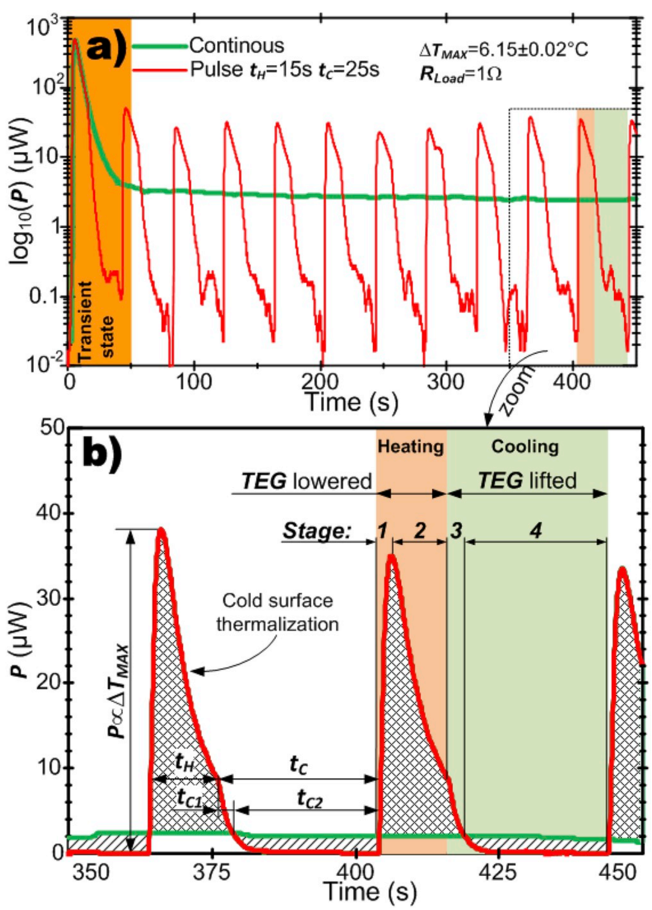

Fig. 6. ***TEG*** output power for continuous and pulse ($t_H = 15$ s $t_C = 25$ s) operation for $T_{HOT} = 28\,^{\circ}$C; **a)** pulse and continuous operation in a logarithmic scale; **b)** zooming on continuous operation emphasizing different stages in pulse operation and highlighting the energies where pulse outperforms continuous (▨) and vice versa (▨).

Stage 3 ends when power from pulsed operation crosses continuous mode power. The duration of ***stage 3*** is marked as t_{C1} in Fig. 6b. Afterwards, the ***stage 4*** starts, this is a period of cooling when the generator tends to complete heat discharge, delivering merely residual power, much smaller than that in the continuous mode. ***Stage 4*** lasts for t_{C2} (*see* Fig. 6b). After time $t_C = t_{C1}+t_{C2}$ the whole process starts again. In terms of optimization it could seem that t_{C2} should be as short as possible since only residual power is generated there. In fact, a minimal duration of ***stage 4*** is important for attaining by the ***TEG*** a thermal equilibrium with ambient. Otherwise, the next power peak may be reduced. On the other hand, if t_{c2} is too long, the gain with pulse operation may be compromised. Therefore, knowing that t_C is significantly influencing on the average harvested power, lets now determine t_C boundary values. Firstly, t_{C2} should be at least larger than zero (or $t_C > t_{C1}$). Typical value of t_{C1} counts in a few seconds. Secondly, the duration (t_{C2}) of cooling ***stage 4*** should not exceed t_{C2MAX}, where t_{C2MAX} is the time needed for the continuous production to equalize the energy of the peak. In order to determine t_{C2MAX} the energy of the pulse (*surface denoted as* ▨ *in* Fig. 6b) has to be set equal to the energy delivered when ***TEG*** is continually heated (*surface denoted as* ▨ *in* Fig. 6b). The time when both energies are equal defines t_{C2MAX}. For the studied cases t_{C2MAX} ranges from almost 40sec to above 100sec. Summarizing, we have to fulfill the following conditions in order to ensure higher power production with the pulse mode, compared with the continuous mode: $t_{C1} < t_C < (t_{C1} + t_{C2MAX})$. As t_{C1} is in the order of a second and t_{C2MAX} in the order of many dozens of seconds, this condition is very easy to satisfy.

As it was described in the previous section, sets of measurements varying heating and cooling durations as well as T_{HOT} were carried out in order to deliver wide perspective on the proposed innovative ***TEG*** operation. Fig. 7 summarizes average output powers for all measurements.

Fig. 7 illustrates substantial outperformance of pulse supplied ***TEG*** over conventional continuous operation. This method can significantly improve the ***TEG*** performance over continuous mode. Depending on the values of t_C, t_H and T_{HOT} the improvement over the continuous operation ranges from X1.28 to X2.7! The highest power gain is observed for very short heating periods ($t_H = 5$ s, $t_C = 25$ s), meaning that the optimal ***P*** production is achieved when the ***TEG***'s cold surface thermalization (***stage 2*** *in* Fig. 6b) is completely eliminated or as short as possible, meaning as short as possible t_H times. That is understandable since stage 2 leads to charging of the ***TEG***'s volume with heat that cancels energy production and is difficult to be extracted.

Pulse operated ***TEG*** is exposed to alternative work conditions regarding mechanical and electrical stresses. The electrical fields that may occur while rapidly forcing diffusive thermally induced movement of carriers from hot towards cold regions are far below the critical value at which carrier multiplication can occur. Focusing on the mechanical shocks arising from periodical impacts of ***TEG*** with the hot source while heating, it is justified to say that such movements should not damage mechanically the system. This conviction is based on the fact that semiconductor devices often work in vibrating or other mechanically harsh conditions without damage for long years. However, in the long-term use (*going up to several decades)* fatigue cracks can occur, therefore further study on ***TEG*** "soft landing" on heat source should be carried out to increase the system robustness. Regarding varying electrical carriers' flows incited by the pulse mode, it must be underlined that electronic devices are certified to withstand much more extreme variations in

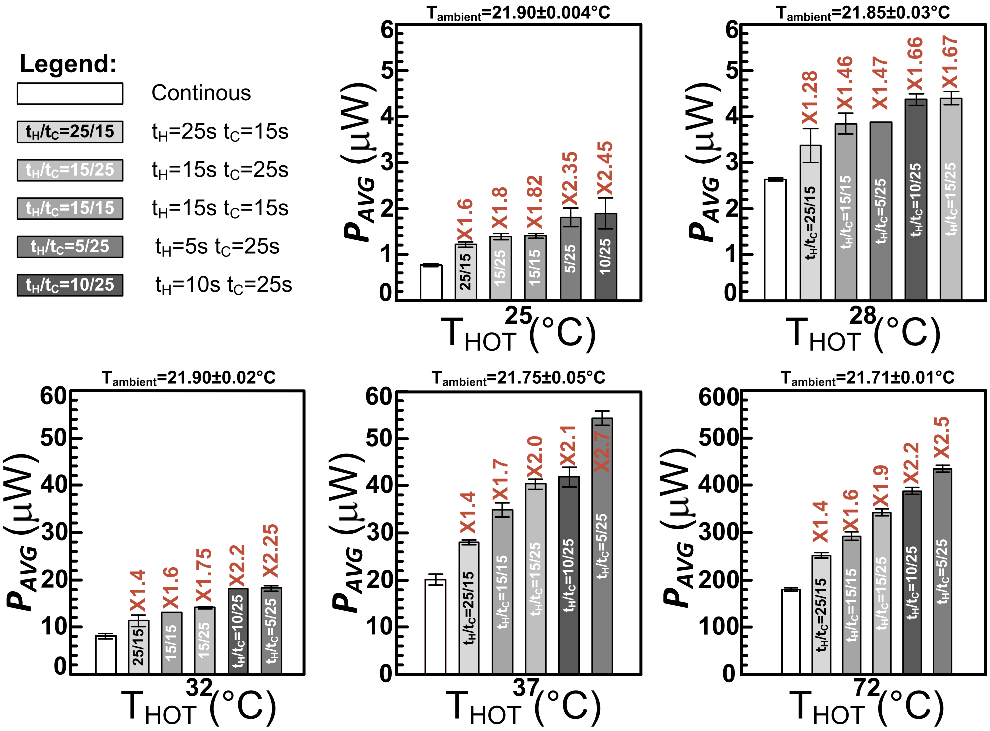

Fig. 7. Statistical summary of the average output power for different operating conditions. Labels above the bars correspond to the improvement ratio over the continuous mode.

carriers flows, comparing to the studied ones. In spite of much larger electric fields and/or mechanical stresses, modern semiconductor devices are certified for at least 10–20 years, of lifetime.

It has also to be underlined that in the case of very high ΔT, the pulse operation may lead to destructive thermal shocks. Abrupt ***TEG*** connection with hot source with very high T_{HOT} may release thermally induced expansion/compression forces that may lead to fatigue cracks formation significantly limiting the system lifetime. This needs a further study and optimization if considering high temperature applications".

5. Suitability of the idea to IoT

Wireless ***S***ensor ***N***etworks (***WSN***) are the material realization of the ***IoT*** idea, and are among the most natural applications of energy harvesting [100]. The general hardware architecture of a ***WSN*** node can be divided into four subsystems [101,102]: (i) communication for wireless data transmission, (ii) computing for data processing and managing, (iii) sensing for acquiring data and (iv) power for providing and regulating power supply voltage.

Power subsystems of ***WSN*** nodes consist of three elements: energy harvester, power management unit and energy storage [102]. The power provided by the energy harvester and efficiency of the power management unit determine the duty cycle of a ***WSN*** node, i.e. the proportion of time the node is sensing data, performs data processing and radio activity to the time it spends in a low power mode. Any increase in power production leads to greater autonomy of a ***WSN*** node and enables higher frequency of sensing events.

As part of the ***PRIME*** project (Ultra-Low Power Technologies and Memory Architectures for IoT) we developed hardware and firmware architecture of an ultra-low power ***WSN*** node with embedded sensors, which could be powered from a thermoelectric generator. Average power consumption of those nodes varies with duty cycle, which is a function of the energy supply from one hand and wireless network parameters from the other. Well-designed wireless node should spend about 99% of the time in sleep mode [102]. During inactivity period, the node consumes μA of current. When activated supply current rises to tens of mA.

In this paper, we present a solution how to increase the efficiency of the power subsystem that would lead to greater autonomy of the ***WSN*** nodes, while keeping unchanged the requirements regarding temperature gradient necessary to proper work of a thermoelectric generator used for thermal energy harvesting.

6. Conclusions

In this communication we have reported on a novel approach to significantly boost thermoelectric generators performance. Novelty of this work consists in pulse mode of operation of the ***T***hermo***E***lectric ***G***enerator (***TEG***) realized by periodic connection/disconnection of the generator with the heat source. Additionally, the proposed boosting method can be miniaturized and allows integration with ***IoT*** nodes. We report up to X2.7 increase in average power over conventional continuous operation. This improvement has been observed with very low temperature differences across the generator therefore being of major interest for ***IoT*** devices.

Traditionally, progress in the thermoelectricity is realized rather at topological or material engineering level. This approach opens a new improvement trend which optimizes ***TEG*** operating conditions rather than the generator itself.

IoT market expansion is significantly slowed down by the lack of cheap and reliable alternatives for battery/wire supply. This approach can unlock further ***IoT*** expansion enabling reliable and miniaturizable energy harvesting booster which can be implemented using commercialized and easily available ***TEG***s.

Authors involvement description

TS invented and patented the idea of pulse thermoelectric generator harvesting booster. ***MH*** along with ***TS*** wrote this communication. ***MH*** performed the measurements and retrieved the data. ***MM*** wrote the section about the Wireless Sensors Network. ***SM*** along with ***TS*** published and invented the bistable strip operation and the thermally-driven piezoelectric generator.

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