TITLE

Design of a Thermoelectric Generator with Fast Transient Response

ABSTRACT

Thermoelectric modules are currently used both in Peltier cooling and in Seebeck mode for electricity generation. The developments experienced in both cases depend essentially on two factors: the thermoelectric properties of the materials that form these elements (mainly semiconductors), and the external structure of the semiconductors. Figure of Merit *Z* is currently the best way of measuring the efficiency of semiconductors, as it relates to the intrinsic parameters of the semiconductor: Seebeck coefficient, thermal resistance, and thermal conductivity. When it comes to evaluating the complete structure, the Coefficient of Performance (COP) is used, relating the electrical power to the thermal power of the module. This paper develops a Thermoelectric Generator (TEG) structure which allows minimising the response time of the thermoelectric device, obtaining short working cycles and, therefore, a higher working frequency.

KEYWORDS

Thermoelectric Generator; High Dynamic Response; Geometry Design; Thermoelectric Model

AUTHOR'S INFORMATION

First Author–Corresponding Author:

First Name: Miguel

Last Name: Fisac

Academic Degree: PhD Candidate

Affiliation: Universitat Politècnica de Catalunya

E–mail Address: miguel.fisac@upc.edu

Primary Phone: +34 93 8967728

Fax Number: +34 93 8967700

Address: EPSEVG, Avda. Víctor Balaguer s/n, 08800 Vilanova i la Geltrú (Barcelona)–Spain

Second Author:

First Name: Francesc

Middle Initial: X

Last Name: Villasevil

Academic Degree: PhD

Affiliation: Universitat Politècnica de Catalunya

E–mail Address: francisco.javier.villasevil@upc.edu

Primary Phone: +34 93 8967728

Fax Number: +34 93 8967700

Address: EPSEVG, Avda. Víctor Balaguer s/n, 08800 Vilanova i la Geltrú (Barcelona)–Spain

Third Author:

First Name: Antonio

Middle Initial: M

Last Name: López

Academic Degree: PhD

Affiliation: Universitat Politècnica de Catalunya

E–mail Address: lopezm@eel.upc.edu

Primary Phone: +34 93 8967728

Fax Number: +34 93 8967700

Address: EPSEVG, Avda. Víctor Balaguer s/n, 08800 Vilanova i la Geltrú (Barcelona)–Spain

HIGHLIGHTS

- Development of a thermoelectric structure which verifies the model used.
- Design and manufacture of a thermoelectric module with a short response time.
- Relationship between geometry of the thermoelectric system and its performance.
- Experimental testing of time to change of state on the thermoelectric module.

NOMENCLATURE

Q_H	Dissipated heat flow (W)
Q_C	Absorbed heat flow (W)
I	Electrical current (A)
Z	Figure of merit (K^{-1})
R	Electrical resistance (Ω)
R_s	Semiconductor's electrical resistance (Ω)
R_m	Electrical resistance of the junction metal in the semiconductors (Ω)
ℓ	Length of a semiconductor and pellet (m)
C	Equivalent electrical capacity (F)
T_c	Cold side temperature (°C)
T_h	Hot side temperature (°C)
T_0	Room temperature that surrounds the thermal structure (°C)
$T_{1,2,3,4,5,6}$	Temperatures in the different structure interfaces (°C)
n	Total number of pellets in the thermoelectric structure
P_E	Electrical power (W)

GREEK SYMBOLS:

∇	Three–dimensional partial derivative
α	Seebeck coefficient ($\mu V \cdot K^{-1}$)
β	Thermal diffusivity ($m^2 \cdot s^{-1}$)
σ	Electrical conductivity ($\Omega \cdot m^{-1}$)
ρ	Electrical resistivity ($\Omega \cdot m$)
κ	Thermal conductivity ($mW \cdot cm^{-1} \cdot K^{-1}$)
κ_0	Thermal conductivity of material in contact with air ($mW \cdot cm^{-1} \cdot K^{-1}$)
κ_{cc}	Thermal conductivity of the ceramic cold plate ($mW \cdot cm^{-1} \cdot K^{-1}$)

κ_{ch} Thermal conductivity of the ceramic hot plate ($mW \cdot cm^{-1} \cdot K^{-1}$)

κ_{m} Thermal conductivity of the metal contacts between semiconductors ($mW \cdot cm^{-1} \cdot K^{-1}$)

κ_{s} Thermal conductivity of the semiconductor used ($mW \cdot cm^{-1} \cdot K^{-1}$)

1 INTRODUCTION

Cooling devices are very important in everyday life. For example, a patient with diabetes should always travel with their insulin to a certain temperature level. Another example is the application of thermoelectricity in cryogenic surgery in oncology. Therefore, thermoelectric devices should be compact, easily portable and flexible. Moreover, it would be very interesting that these devices were long-lasting and maintenance free.

When the application is not related with cooling or heating new needs are created, such as modifying the geometry of the thermoelectric structure and to develop new thermoelectric materials for manufacturing these devices. The creation of these new modules is possible and depends on the design and the development process when thermoelectric modules are being performed.

These thermoelectric structures are usually classified according to its power generation and its cooling temperature range. A thermoelectric structure can perform as a refrigerator of electro–optic components [1], also can be used for turning waste heat into power [2], and it can be applied in several medical areas [3], for example. Due to current market needs, the efficiency of thermoelectric structures is a factor that should be improved. When a thermoelectric device is used as a generator (Seebeck mode), the scope of use is even more restricted [4]. It is highly important to maximize the contribution of each thermo–element; in other words, a high density of thermoelectric generation is needed.

Figure of Merit Z or the dimensionless equivalent ZT is not the only factor that determines the material choice, but it is the most important. Precisely the efficiency of thermoelectric devices is determined by the Figure of Merit, which is defined by the $Z = \alpha^2\, \sigma / \kappa$ ratio. It is common to use the term *Power Factor* to designate $\alpha^2\sigma T$ or $\alpha^2\sigma$, since this term only contains the electronic properties, while κ is always a large contribution of thermal network.

One of the main problems in the conversion of solar energy into thermal or electrical power is the low efficiency of converters based on semiconductors. The reason is that a considerable part of energy flows through phonon subsystem (thermal oscillations of crystal lattice), which are not involved in the power generation.

For obtaining the *COP* (Coefficient of Performance) of a thermoelectric cell working as cooler we should know the absorbed heat by the thermoelectric structure Q_C and the electrical power output of the system P_E.

$$COP = \frac{Q_C}{P_E} \qquad (1)$$

To achieve an increased efficiency, amongst other factors, the geometry of the semiconductor must be taken into account. However, the accurate characterization of a thermoelectric device, either working in Peltier or in Seebeck mode, is rather difficult [5]. When it comes to modelling a semiconductor, the figure of merit is required. There are several methods to obtain this measurement but these should be applied with a degree of caution [6]. Generally speaking, modelling is considered from a point of view in which the properties of materials used in the thermoelectric structure have an average value according to the working conditions –normally the temperature difference between faces–, or also Finite Element Models that lead to the division of the analyzed structure in a number of finite parts, bearing in mind separately that each part has certain specific properties.

At present, frequency behavior is rarely studied in the modelling of thermoelectric structures. However, the importance of the temporal response in the performance of the thermoelectric structures is shown in [7,8], for example. There are applications that are related with cell miniaturization and the inertia in the transient response that require a frequency study.

For all these reasons, in **this paper a discrete model based on electric analogy is used to develop and manufacture a thermoelectric generator with a configurable time response that is hardly expect reached by any commercial thermoelectric module**.

Developed thermoelectric device can be used in an industrial scenario for converting the wasting heat in electrical power, but with the advantage that the transient response can be configured according to the final application. Regarding electric analogy used in this paper, this model has been already tested in conventional structures [9] and its use allows taking into account the time constant of the thermoelectric system.

2 MODEL USED IN THE DESIGN

2.1 BASIC RELATIONS

In general, the heat flow in a semiconductor could be expressed according to the laws of heat for the three dimensions:

$$\nabla(\kappa\nabla T) - T(I\nabla\alpha) + I^2\rho = 0 \qquad (2)$$

In one dimension, this is expressed as:

$$\frac{\partial}{\partial x}\left(\kappa A\frac{\partial T}{\partial x}\right) - IT\frac{\partial\alpha}{\partial x} + I^2\rho = 0 \qquad (3)$$

When considering a steady state system in which the change of internal energy is zero, the model can be determined as a function of the heat absorbed or dissipated in the external faces of the semiconductor [10]:

$$\begin{bmatrix} \alpha I - \kappa & \kappa \\ -\kappa & \alpha I + \kappa \end{bmatrix} \cdot \begin{bmatrix} T_h \\ T_c \end{bmatrix} = \begin{bmatrix} Q_h - \frac{1}{2}I^2R \\ Q_c + \frac{1}{2}I^2R \end{bmatrix} \qquad (4)$$

Although the simple model above does not define other phenomena which take place in the thermoelectric structure – such as the Thomson effect, or the Nerst effect inside a magnetic field –, nor the different phenomena related to the structure set up and used for supporting the semiconductors, it does reveal the high significance of geometry in the evaluation of the model’s coefficients [11].

When trying to obtain a change of state where there is a high temperature difference, as ΔT, into another state where there is no temperature variation $\Delta T = 0$, a dynamical study of the thermoelectric device must be carried out.

2.2 ELECTRICAL ANALOGY MODEL

The model is considered in one dimension that provides essential information from the thermal structure. The following model is based on temperature increases between interfaces of the different materials that constitute the thermal structure [12]. The thermal parameters are assumed as constant (they actually depend on temperature, geometry, and other factors). Only the thermal conduction phenomenon will be considered, assuming that the structure is immersed in an isotropic medium [13].

In the simple structure it is assumed that there are *n* semiconductors and, therefore, the same number of metallic contacts between the semiconductors [14]. Both ceramic surfaces will support all the structure as shown in Figure 1.

The linear equations that define the thermal structure are:

$$\kappa_0 \left(T_0 - T_1\right) - \kappa_{cc}\left(T_1 - T_2\right) + Q_c = 0 \tag{5}$$

$$\kappa_{cc}\left(T_1 - T_2\right) - \frac{n}{2}\kappa_m\left(T_2 - T_3\right) = 0 \tag{6}$$

$$n\left(-\alpha I T_3 - \frac{1}{2}I^2\left(R_s + \frac{R_m}{2}\right) + \kappa_s\left(T_4 - T_3\right) + \frac{1}{2}\kappa_m\left(T_2 - T_3\right)\right) = 0 \tag{7}$$

$$n\left(\alpha I T_4 + \frac{1}{2}I^2\left(R_s + \frac{R_m}{2}\right) - \kappa_s\left(T_4 - T_3\right) - \frac{1}{2}\kappa_m\left(T_5 - T_4\right)\right) = 0 \tag{8}$$

$$\frac{n}{2}\kappa_m\left(T_4 - T_5\right) - \kappa_{ch}\left(T_5 - T_6\right) = 0 \tag{9}$$

$$\kappa_{ch}\left(T_5 - T_6\right) - \kappa_0\left(T_6 - T_0\right) - Q_h = 0 \tag{10}$$

The analogy between thermal and electrical systems allows us to develop our model as an electrical circuit, in such a way that the heat flow is analogous to an electrical current, and the temperature difference is analogous to a voltage difference [14]. Taking into account the thermal–electrical analogy, the linear equations developed result in the circuit shown in Figure 2.

In any case, the heat flow through a semiconductor element is given by the Laplace operator of the heat flow, as shown in the following equation. If is shown in one dimension, for simplification purposes, it would be [15]:

$$\nabla T = \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \rightarrow \frac{\partial^2 T(x,t)}{\partial x^2} = \frac{1}{\beta} \cdot \frac{\partial T(x,t)}{\partial t} \quad (11)$$

Note that $\beta = \kappa / (\rho \cdot c)$ is the thermal diffusivity.

Based on the previous expression, we can establish an analogy between the time constant of the thermal structure and the time constant of the electrical circuit [16]. In this way geometrical and transient parameters are introduced in the design process, showing its relevancy in the thermoelectric module operation.

The electrical time constant equivalent to the performance described above is:

$$RC = \frac{4\ell^2}{\pi^2 \beta} = \frac{4\ell^2 \rho c}{\pi^2 \kappa} \quad (12)$$

If we multiply and divide by the transversal area of the single module, we will obtain the following expression:

$$RC = \frac{4\ell^2 \rho c}{\pi^2 \kappa} = \frac{4\ell\ell A \rho c}{\pi^2 \kappa A} = \frac{4\ell mc}{\pi^2 \kappa A} \quad (13)$$

We can identify the terms $C = mc$ and $R = \ell / (\kappa A)$ in Equation (14).

3 DEVELOPED SAMPLE DEVICE

A practical thermoelectric structure is developed, which reaches specific change times from one state in which there is a steady operation with a specific temperature difference, to another state with zero temperature difference and low inertia. Figure 3 shows the design of the thermoelectric device, in which pellets of special size have been used to achieve a specific operation. Commercial thermoelectric structures have cubical pellets. In this work we have developed pellets with a non-standard geometry, with a dimension of 1.5 × 1.5 × 6 (width × height × depth, in millimeters). This arrangement of the pellets is aimed for generating electric power [17].

Pellet geometry should be optimized by considering the interaction of all system elements, that is, between the pellets and the rest of elements of the thermoelectric structure. For this reason is necessary to consider other factors related to pellets geometry that can influence either directly or indirectly on the system efficiency. These factors considered in our product development are as follows:

- *Volume of the pellet*. This value should be reduced.
- *Contact surfaces between electrical connections*. An additional thermal power is generated in the electrical connections due to the Joule effect. These losses may vary depending on the design of the pellet geometry.
- *Mechanical design*. Not all configurations and shapes of the pellets are valid from the mechanical standpoint. To get a robust thermoelectric module that supports mechanical stress is necessary.
- *Cost and ease of manufacture*. Economical cost may be affected by the pellets geometry, although it depends on the size of the manufactured series. A balance between economical cost and design optimization must be taken into account during the product design.

Regarding to the effect in the time domain, in order to obtain a reduction in the transient response between the states, we have added metal conductive elements between the thermoelectric faces [18] in the system. Furthermore, to quickly drive the heat flow between the heat source and the thermoelectric structure, a heat pipe is placed on one side of the structure, as shown in Figure 4. On the other hand, the deactivation time tends to get higher, but by introducing a heat sink these losses are balanced.

At a structural level, the greater the distance between the hot face and cold face of the thermoelectric module, the lower the thermal conductance. This increases efficiency (semiconductors with longer length than a conventional device working as a Peltier device) [19], but if the length of the semiconductor is increased too much, the Joule effect is also increased, causing a decrease in the system's efficiency. The heat pipe must be able to dissipate all the heat that reaches the cold face coming from the heat flow of the heat source [20]. This results in a notably reduced time constant equivalent to *RC* with the incorporation of the new elements in the system.

4 RESULTS

The equations shown in this article allow to know the thermal system response in function of frequency. Consequently, this aspect allows us to control and improve the time response of the thermoelectric system as is shown in following figures.

Figure 5 shows the temporal response of output voltage, output current and electrical power supplied by the thermoelectric module when a temperature difference of 35°C is applied between hot and cold faces, and a load of 30Ω is connected to the thermoelectric structure. It should be noted that results are optimal and the system reaches the steady state in the shortest time possible. When temperature increases the thermoelectric module is able to maintain a constant current and voltage and consequently the power delivered to the load. The time spent by the system until steady state is approximately 4 seconds. Disconnection time is slightly higher, although using heat pipe the transient has been improved.

A comparison between the experimental results and theoretical simulation is shown in Figure 6. Note that the theoretical model is consistent with the experimental response. Therefore, the expressions developed make possible to modify the transient response of the thermoelectric system in the design process depending on its final application.

5 CONCLUSIONS

In this work, several design expressions have been developed which provide insight into the system's transient response under conditions of smaller thermal inertia, depending on the structural characteristics of the thermoelectric module. Based on these expressions, it has been possible to reduce the temporal response of the thermoelectric module prior to its manufacturing.

Moreover, the thermoelectric structure has been designed, developed and manufactured which verifies the theoretical expressions presented in this paper. The thermoelectric module achieves shorter times in state changes than a conventional structure, making it suitable for use in applications requiring fast response times.

Comparisons between simulation results and experimental results show a good correlation. In addition to characterising the thermoelectric structure, the reliability of the model used has been verified, since the theoretical values obtained are very similar to the experimental results.

6 REFERENCES

[1] V. A. Semenyuk, Thermoelectric Cooling of Electro–Optic Components, in: D. M. Rowe (Ed.), Thermoelectrics Handbook: Macro to Nano, CRC Press, Boca Ratón, 2006, pp. 58/1–58/21.

[2] T. Kajikawa, Thermoelectric Power Generation System Recovering Industrial Waste Heat, in: D. M. Rowe (Ed.), Thermoelectrics Handbook: Macro to Nano, CRC Press, Boca Ratón, 2006, pp. 50/1–50/28.

[3] D. I. Aronov, M. S. Fee, Analyzing the dynamics of brain circuits with temperature: Design and implementation of a miniature thermoelectric device, J Neurosci Methods. 197 (2011) 32–47.

[4] L. Kornblit, Can thermoelectric generators be significantly improved?, Eng Convers Manag. 32 (1991) 97–99.

[5] R. Venkatasubramanian, E. Siivola, T. Colpitts, B. O'Quinn, Thin–film thermoelectric devices with high room–temperature figures of merit, Nat. 413 (2001) 597–602.

[6] D. Ebling, K. Bartholomé, M. Bartel, M. Jägle, Module Geometry and Contact Resistance of Thermoelectric Generators Analyzed by Multiphysics Simulation, J Elec Mat. 39 (2010) 1376–1380.

[7] L. M. Shen, F. Xiao, H. X. Chen, S. W. Wang, Numerical and experimental analysis of transient supercooling effect of voltage pulse on thermoelectric element, Int J Refrig. 35 (2012) 1156–1165.

[8] N. Q. Nguyen, K. V. Pochiraju, Behavior of thermoelectric generators exposed to transient heat sources, Appl Therm Eng. 51 (2013) 1–9.

[9] G. Fraisse, M. Lazard, C. Goupil, J. Y. Serrat, Study of a thermoelement's behaviour through a modelling based on electrical analogy, Int J Heat Mass Transfer. 53 (2010) 3503–3512.

[10] D. M. Rowe, General Principles and Basic Considerations, in: D. M. Rowe (Ed.), Thermoelectrics Handbook: Macro to Nano, CRC Press, Boca Ratón, 2006, pp. 1/1–1/10.

[11] D. M. Rowe, G. Min G, Design theory of thermoelectric modules for electrical power generation, Science, Measurement and Technology, IEE Proceedings. 143 (1996) 351–356.

[12] F. Meng, L. Chen, F. Sun, A numerical model and comparative investigation of a thermoelectric generator with multi–irreversibilities, Eng. 36 (2011) 3513–3522.

[13] R. Yang, G. Chen, A. R. Kumar, G. J. Snyder, J. P. P. Fleurial, Transient cooling of thermoelectric coolers and its applications for microdevices, Eng Conv Management. 46 (2005) 1407–1421.

[14] D. Astrain, J. G. Vián, J. Albizua, Computational model for refrigerators based on Peltier effect application, Appl Therm Eng. 25 (2005) 3149–3162.

[15] G. N. Logvinov, Y. V. Drogobitskiy, Y. G. Gurevich, A. F. C. Cachez, O. Y. Titov, Unsteady–state thermoelectric response for a thermal pulse in semiconductors, Proceedings ICT'97. XVI International Conference on Thermoelectrics 1997, pp. 749–752.

[16] L. Man, E. Man, Electro–thermal analogies for temperature calculation, 34th International Spring Seminar on Electronics Technology (ISSE) 2011, pp. 358–362.

[17] F. X. Villasevil, Desarrollo y caracterización de estructuras termoeléctricas con pellets constituidos por nuevos materiales y geometrías no estándar, Doctoral Thesis, 2006, pp. 91-112.

[18] V. A. Semeniouk, T. V. Pilipenko, Thermoelectric coolers with small response time, Fifteenth International Conference on Thermoelectrics 1996, pp. 301–306.

[19] G. Min, D. M. Rowe, Improved model for calculating the coefficient of performance of a Peltier module, Eng Conv Management. 41 (2000) 163–171.

[20] S. B. Riffat, S. A. Omer, X. Ma, A novel thermoelectric refrigeration system employing heat pipes and a phase change material: an experimental investigation, Renewe Eng. 23 (2001) 313–323.

FIGURES CAPTION

Figure 1. Thermoelectric structure diagram with different temperatures considered

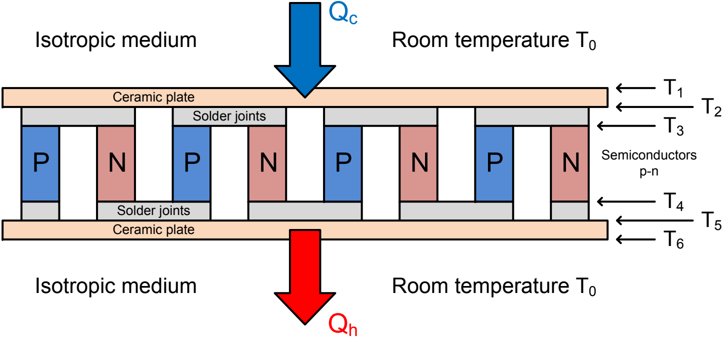
Figure 2. Equivalent electrical circuit

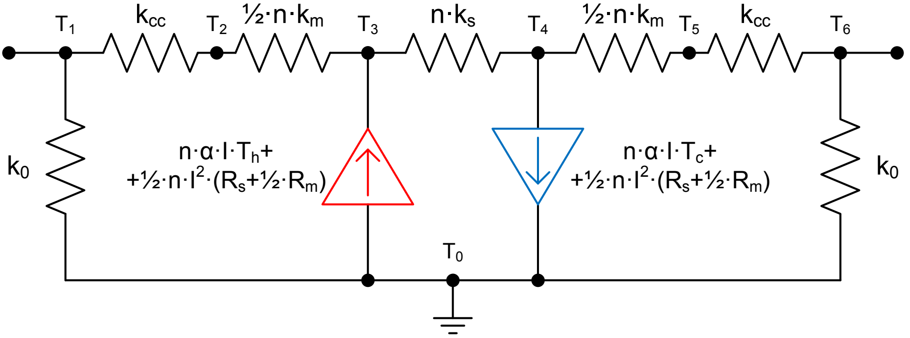
Figure 3. Thermoelectric structure developed

Figure 4. Final thermoelectric generator developed with heat pipe and heat sink

Figure 5. Temporal response of the thermoelectric module

Figure 6. Comparison between the experimental results ($V_{out\ exp}$) and theoretical simulation ($V_{out\ theo}$)


Q_c
Isotropic medium
Room temperature T_0
Ceramic plate
Solder joints
T_1
T_2
T_3
P
N
P
N
P
N
P
N
Semiconductors
p-n
T_4
Solder joints
Ceramic plate
T_5
T_6
Isotropic medium
Room temperature T_0
Q_h


T1
kcc
T2
½·n·km
T3
n·ks
T4
½·n·km
T5
kcc
T6
k0
n·α·I·Th+
+½·n·I2·(Rs+½·Rm)
n·α·I·Tc+
+½·n·I2·(Rs+½·Rm)
k0
T0

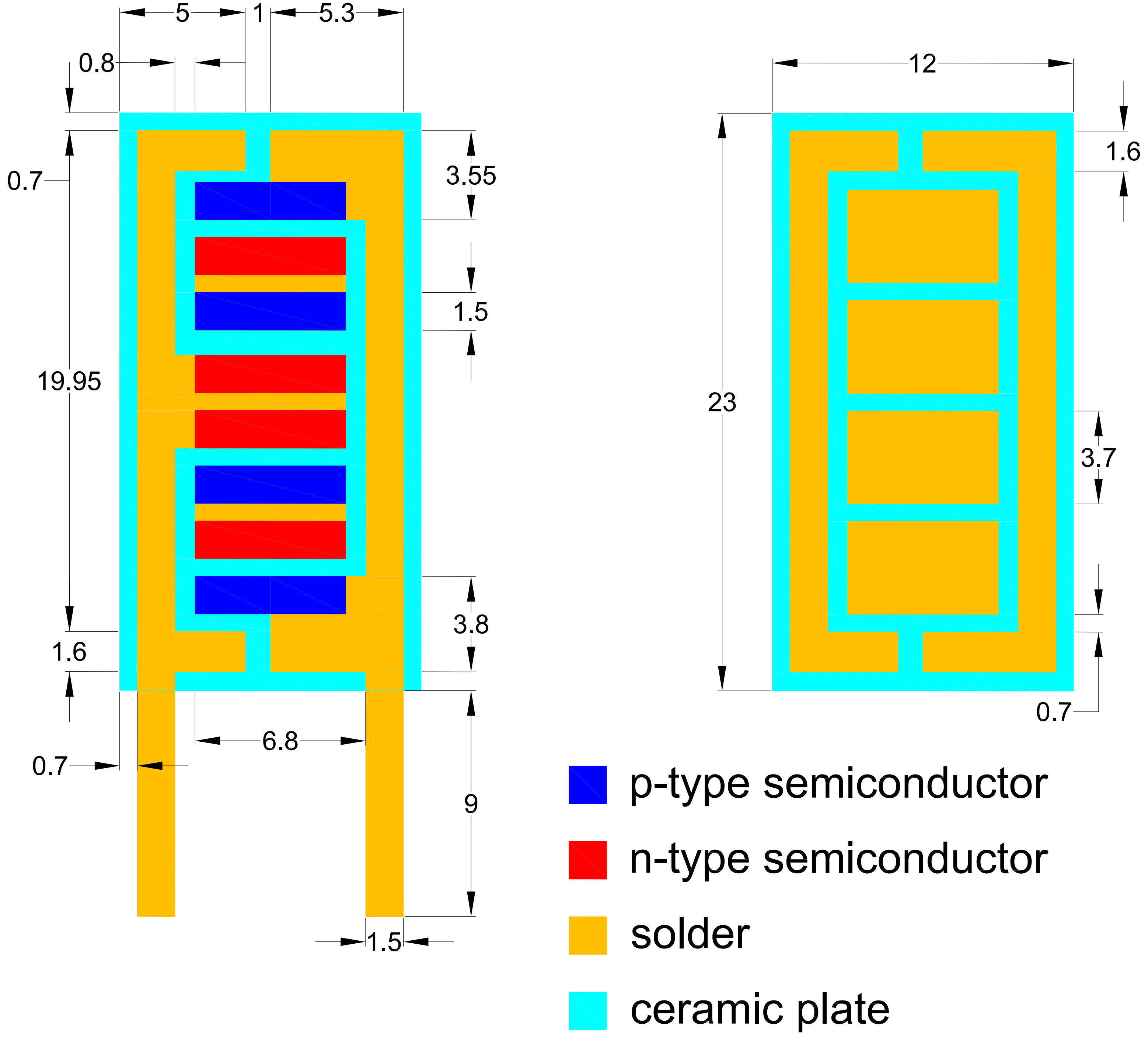
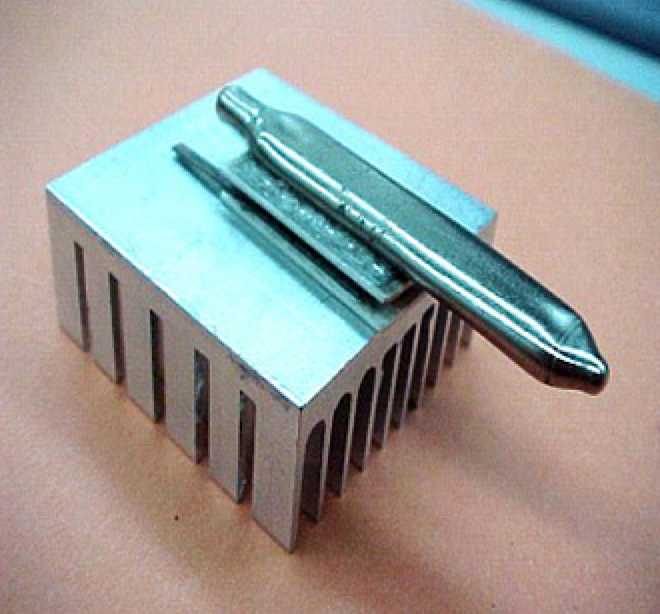
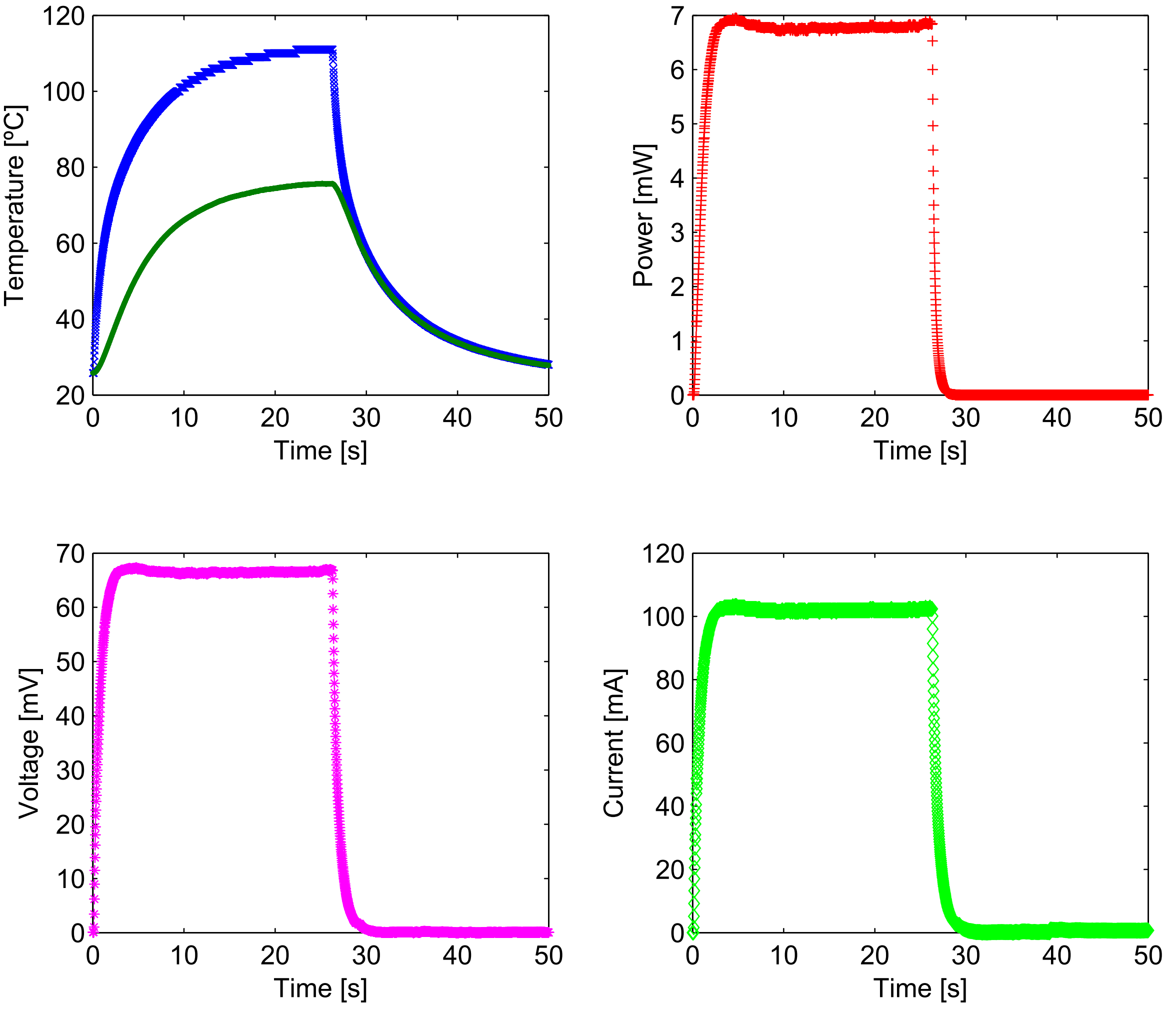
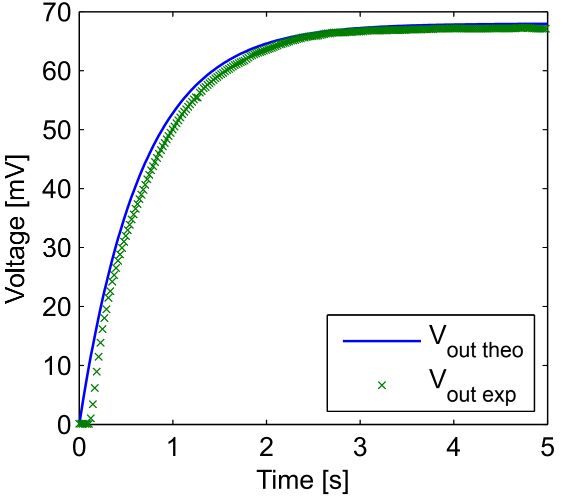

5
1
5.3
0.8
0.7
3.55
1.5
19.95
3.8
1.6
6.8
0.7
9
1.5
12
1.6
23
3.7
0.7
p-type semiconductor
n-type semiconductor
solder
ceramic plate

Figure 4

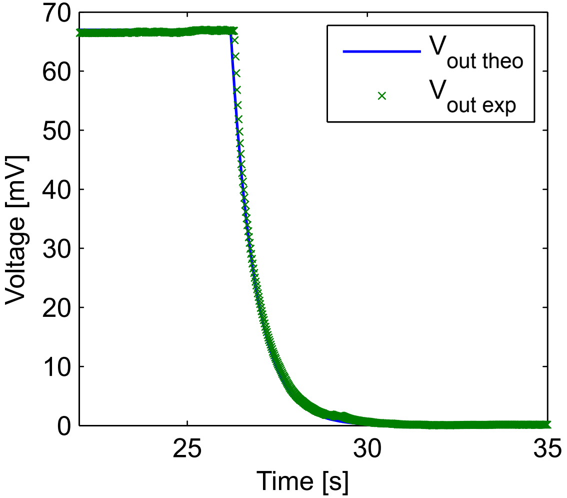




Temperature [ºC]
Time [s]
Power [mW]
Time [s]
Voltage [mV]
Time [s]
Current [mA]
Time [s]



Voltage [mV]
Time [s]
V out theo
V out exp



Voltage [mV]
Time [s]
V out theo
V out exp