Complex Method to Control the Quality of Construction and Performance Reliability of Thermoelectric Modules in Optoelectronic Devices

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Introduction

Thermoelectric (TE) modules are components in many optoelectronic devices (photodetectors, charge-coupled devices, semiconductor lasers, etc.). International and national standards impose stringent requirements on quality and reliability of TE modules applied in optoelectronics.

According to Standards (e.g., Telcordia, MIL Standards), an increase of electrical resistance R is a single failure criterion that can be used universally for express reliability testing of TE modules and TE modules assembled with a device. Besides, TE modules manufacturing companies have the screening procedure of measuring TE modules Figure-of-Merit – the so-called parameter Z.

In our previous paper [1] it was shown that that this approach is not sufficient for detailed TE modules quality express control: it is not possible to analyze the reasons of a product fault and in a number of cases it is not even possible to identify a faulty TE module. It was suggested that a complex method of TE module quality and reliability analysis by three parameters should be applied. These parameters are electrical resistance AC R, Figure-of-Merit Z and time constant τ. With the help of this method examples of technological defects were studied and analyzed [1] at the level of TE modules manufacturing and reliability testing.

The given paper studies the applicability of the complex (R, Z, τ) control approach to assess quality and reliability of TE modules integrated into optoelectronic devices, especially when disassembly of the TE module is impossible or undesired.

The method is possible to apply using up to date unique devices Z,R,τ-meters of the series DX4065 and DX4165 developed in RMT (Moscow).

Scopes of the Studies

In the paper experimental and theoretical results are presented. Experiment data was carried out with the help of the DX4065 Z,R,τ-meter. The objects of the analysis are assemblies based on optoelectronic packages (of TO style) and standard TE modules manufactured by RMT.

Let us consider an optoelectronic device construction with a built-in TE module (Fig. 1).

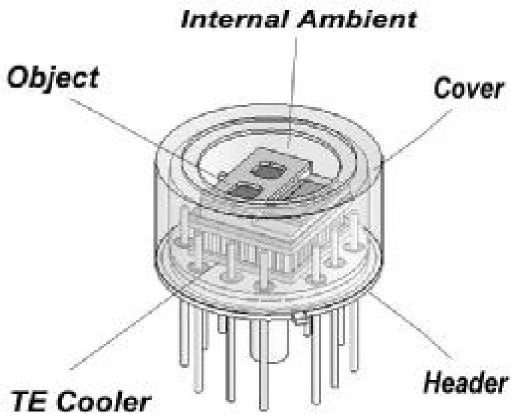


Figure 1. An example of a TE module integrated into the optoelectronic package (TO8)

Commonly a device of this kind is a standard or special package with a TE module mounted inside. On the cold side of the TE module there is an object to be cooled. Usually the package is sealed and the environment (vacuum, gas) is controlled. The TE module is to provide heat removal from the object, cooling it down to the necessary temperature and thermal stabilization of it.

The optoelectronic device performance depends on the efficiency of the above processes; therefore the TE module and the cooling assembly as a whole should evidently be of high reliability.

Thus the analysis can be done according to several most significant aspects as follows:

- TE module performance reliability. There is a regular phenomenon observed during a TE module operation. The reliability is assessed in correspondence with the Standards (Telcordia) by the results of accelerated tests simulating various factors that the module is exposed to, while operating (mechanical, thermal, etc.).

- Integrating of a TE module into the package. The integration method and contact quality can greatly influence the system operation.

- Mounting of an object onto the TE module. It is also should be studied in detail, as reliability and efficiency of the object location on the module determine performance of the whole optoelectronic device.

- Control of environment. It should be managed as the medium in the cooling volume is meant to minimize thermal losses (ideally, in vacuum) or provide stable operational conditions. So, environmental changes and violations can result in degrading the efficiency of a TE cooling system.

TE Module Performance Reliability

Accelerated tests are aimed to verify a TE module reliability.

In Fig. 2 and 3 one can see the results of reliability tests of standard RMT TE modules. The testing methods are temperature cycling (Fig. 2) and power cycling, or burn-in (Fig. 3).

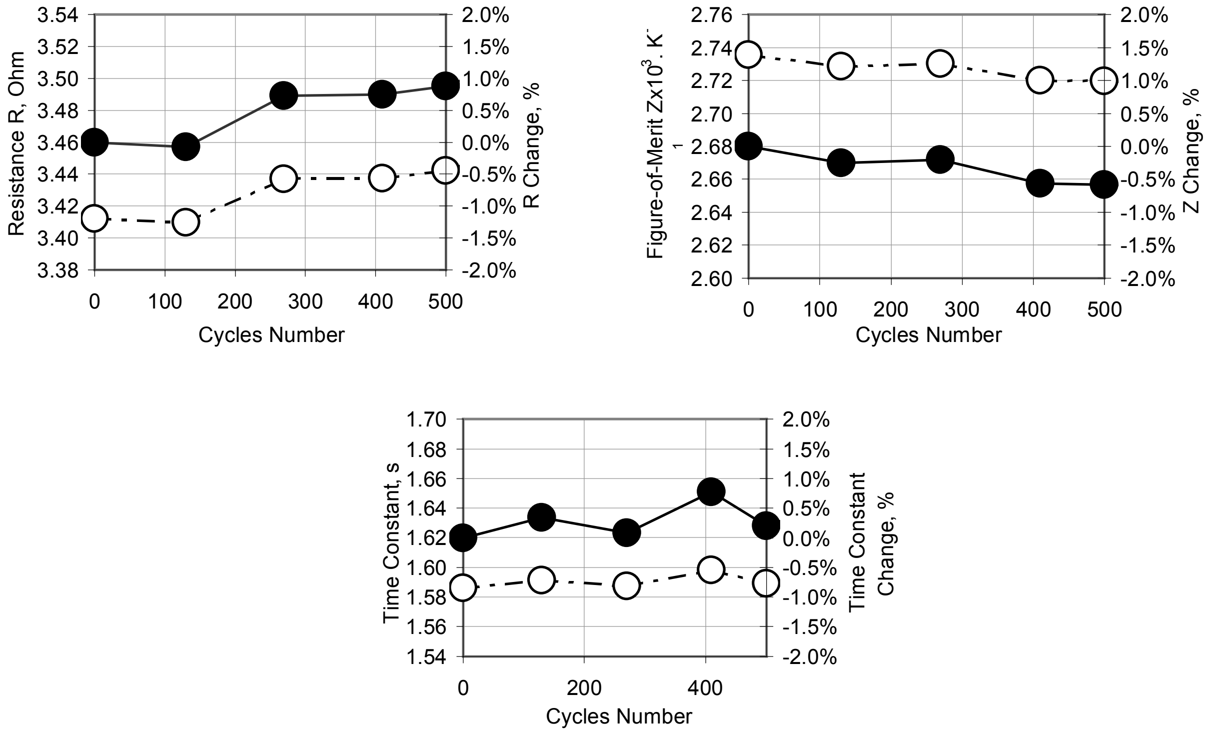
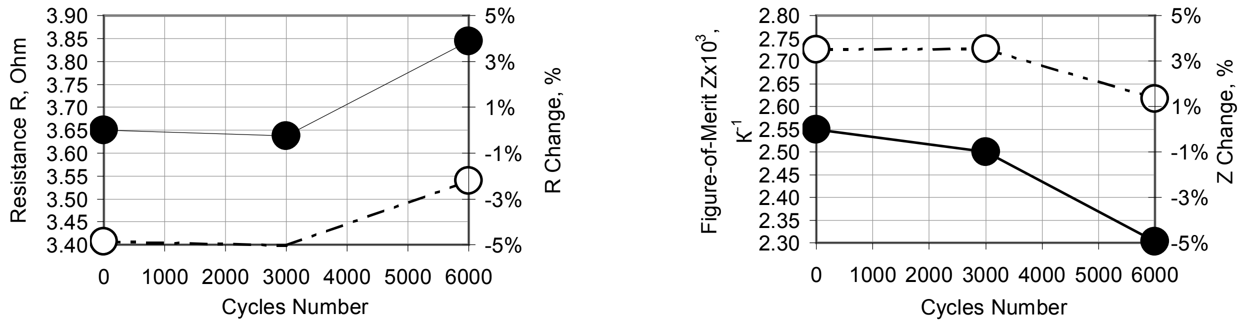


Figure 2. The parameters Z, R, τ behavior of the TE module 1MC06-060-10 in temperature cycling tests: 500 cycles from –50 up to +125 °C



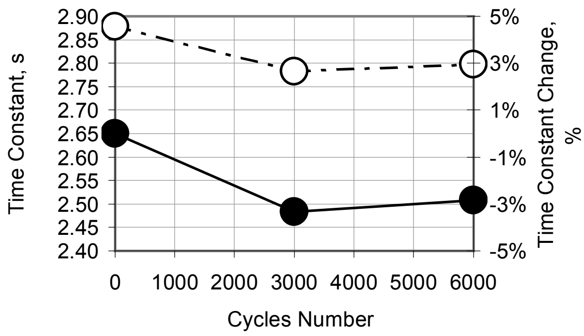


Figure 3. The parameters Z, R, τ behavior of the TE module 1MC06-060-10 in the power cycling tests: 6000 cycles of powering 5 min on and 5 min off at the hot side temperature 85 °C

As was shown in paper [1], due to ageing by various factors, TE modules and, in particular, their TE materials are degraded. Known mechanisms of TE materials degradation cause similar tendencies in the changes of measured parameters for TE modules within a device: an increase of the electrical resistance and decrease of Figure-of-Merit while the time constant keeps nearly constant.

Temperature cycling foremost results in mechanical degradation of a TE module, namely, microcracks in the TE material of the module. This must raise the TE module electrical resistance R and correspondently reduce its Figure-of-Merit Z, as these values are related as an inverse proportion. In the simplest form it may be written as follows:

$$Z \sim \frac{\alpha^2}{k_0}\frac{1}{R_0}, \qquad (1)$$

where α is the Seebeck coefficient, k_0 is the pellet thermal conductance, R_0 is the pellet electrical resistance.

The power cycling (burn-in) is an accelerated test determining operating time to failure at the elevated temperature. Here degradation mechanisms are apparently more complicated (simultaneous effect of high temperature, electric current and thermal strains), but the result is alike: increasing R and decreasing Z.

The time constant turns out more inert than R and Z to such types of exposure as reliability tests but to study its behavior is no less useful. The time constant τ is informative of thermal conductance k of a TE module:

$$\tau \sim \frac{C}{k}, \qquad (2)$$

where C is the heat capacity of all the objects connected to the cold ends of the pellets.

In temperature cycling tests there appear inner strains in the TE material, so its thermal conductance slightly diminishes and, therefore, we observe a small growth of the time constant in the experiment (see Fig. 2).

Power cycling tests involve diffusion mechanisms in pre-junction areas, and, though it may seem paradoxical on the face of it, we obtain some reduction of the time constant (see Fig. 3).

Integrating of a TE Module into the Package

The quality of the TE module mounting on the base of the package is to provide not only a mechanical integration but also a good heat sinking from the TE module hot side. Both in the process of mounting and while a TE module operating, the thermal contact of the TE module with the package basement (header) may degrade or be damaged. For example, in case of a soldering method, there may occur local voids in the solder substance while mounting. And in the process of operation the soldered junction may be chemically or mechanically injured and the thermal contact area may be corrupted or decreased.

Evidently, the TE module electrical resistance R does not depend on the module mounting quality.

Let us simulate degrading of the TE module – header contact as a decrease of this contact area.

The effects of this area change on the values Z and τ are different.

For the Figure-of-Merit this parameter is essential as a characteristic of the contact surface thermal interchange. If finding the Figure-of-Merit Z of a single-stage TE module by the Harman approach [2,3], we can write Z as follows:

$$Z = \frac{\Delta T}{T_{av}} \frac{N\alpha}{IR}, \tag{3}$$

where N is the TE module pellets number, ΔT is the TE module temperature difference and T_{av} is the average temperature of the module.

Let the letter A denote thermal exchange coefficient for the whole contact surface. Both the values ΔT and T_{av} depend on A. If the heat sinking from the TE module hot side is embarrassed, the module's average temperature grows. If thermal exchange with air is small, we can express the values T_{av} and ΔT via A [4,5]:

$$\Delta T(A) = \frac{\alpha I}{k_0}\left(T_a + \frac{I^2 N R_0}{A}\right) - \frac{I^2 R_0}{2k_0 A} \quad (4a)$$

$$T_{av}(A) = T_a\left(1 + \frac{\alpha I}{2k_0}\right) + \frac{I^2 R_0 N}{A}\left(1 + \frac{A}{4Nk_0}\right) \quad (4б)$$

We see that both the values discover growth with A decreasing. However ΔT grows more rapidly as the hot side temperature rising rate is higher than that of the cold side temperature. Therefore the Figure-of-Merit Z should increase with degrading of the TE module – header contact (see Fig. 4).

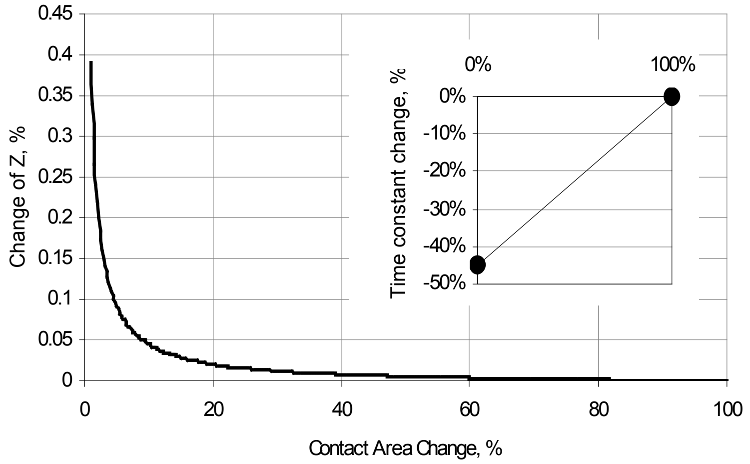


Figure 4. Calculated estimate of a single-stage TE module Z and τ dependence on the contact area of the TE module and the header of the package

The experiment conforms to the theory: the increase of Z was detected - see Fig. 5.

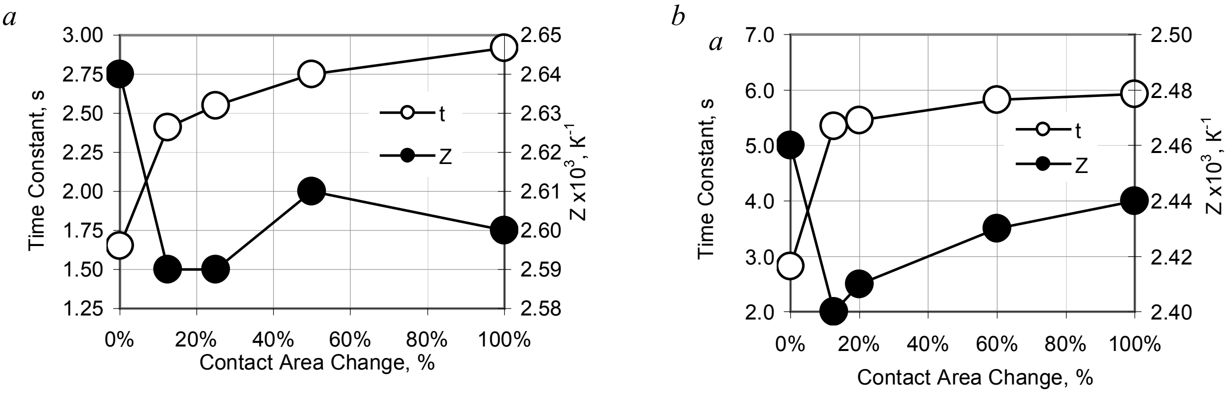


Figure 5. Measured TE modules parameters dependence on the contact area of the module and the header of the package: a) TE module type 1MC06-060-10; b) TE module type 2MC06-041-15. Filled signs – τ, the left axis; empty signs – Z, the right axis

The value of heat capacity of the objects contacting with the TE module is essential for the time constant.

The time constant of a single-stage TE module with a proper contact of the module hot side and the package header can be estimated as:

$$\tau_1 = \frac{LC_1}{s_0 \kappa_0 N} , \tag{5}$$

where C_1 is the heat capacity of the junctions and substrate contingent to the cold ends of the TE module pellets; N is the module pellets number, s_0 is the cross-section of the TE module pellet.

For a one-stage TE module whose substrates are in free heat exchange with the medium ("free TE module"), the time constant can be written as follows:

$$\tau_2 = \frac{C_1 C_2 L}{(C_1 + C_2)\kappa_0 N s_0} , \tag{6}$$

where C_1, C_2, are the heat capacities of all the elements attached to the cold and hot pellets ends of the TE module, correspondingly.

In case $C_1 \approx C_2$, which is quite true for a free TE module, we obtain that the time constant of a single-stage TE module totally detached from the header is approximately twice smaller than that of the TE module mounted properly:

$$\tau_2 \cong \frac{1}{2}\tau_1 \tag{7}$$

The time constant τ changes stepwise due to the criterion: there is a contact – there is no contact with the package. This behavior is in agreement with the experimental data – see Fig. 5: for a single-stage TE module 1MC06-060-10, in the state of no contact with the header, the time constant discovers a 46.6 % decrease. For a two-stage TE module this decrease is pronounced a little less distinctly.

It can be seen that both for a one-stage and a two-stage TEC the Figure-of-Merit Z shows the growth but it is relatively small and not so demonstrative. It is the time constant of the system that is a sensitive criterion of the TE module and package contact reliability.

Mounting of a cooled object onto the TE module

Similarly to the preceding section, the quality and reliability of the mounting of an object to be cooled onto the cold side of a TE module influences the time constant of the construction.

As can be concluded from formulae (2) and (5), the time constant is proportional to the heat capacity (or to the mass) of the cooled object. Fig. 6 presents theoretical curves of the time constant dependences on the cooled object mass.

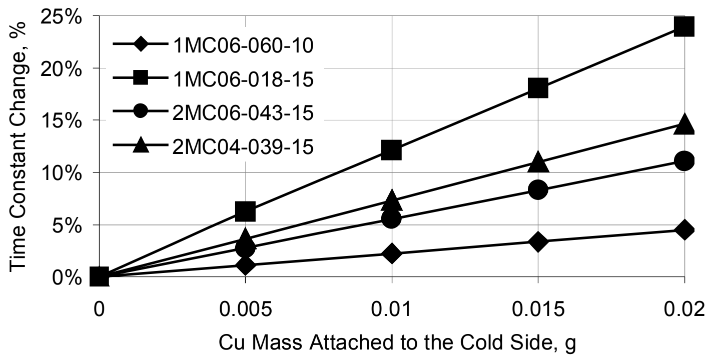


Figure 6. Calculated estimates of the TE modules time constants vs a cooled object mass

Experimental data conform that the time constant exhibits a near-to-linear dependence on the cooled object mass (Fig. 7).

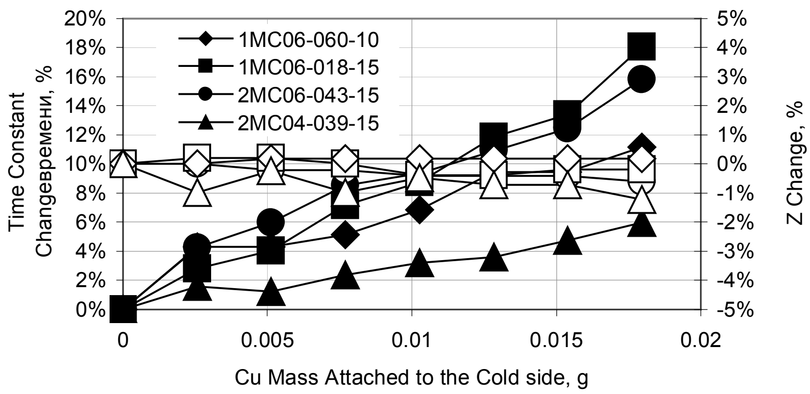


Figure 7. Measured TE modules parameters dependence on the attached to the cold side Cu equivalent mass for several TE modules: filled signs – τ, the left axis; empty signs – Z, the right axis

Charged by the studied tendency, significant change of the time constant for an integrated TE module with no apparent changes of its Figure-of-Merit and electrical resistance unambiguously shows that the contact with the cooled object is spoilt.

Control of a TE module Environment

In case of a special environment in a cooling TE system, a stringent control should be imposed to keep it unchanged while operating. Three parameters measurement allows managing this control.

- Vacuum environment.

As well known, vacuum is an optimal medium in a TE cooling system for reducing passive heat loads, as gas additional thermal conductance and convection are eliminated.

If the system vacuum tightness is violated, the TE cooling efficiency, and therefore, Figure-of-Merit decreases. Meanwhile the TE module electrical resistance remains constant. Modified thermal conductance has some effect on the time constant and the latter may slightly increase.

- Gas environment

If there appears some uncontrolled gas in the cooled volume (in practice it is likely to be air that interferes), it should also result in the same mechanisms Figure-of-Merit change but quite to a lesser extent than in vacuum. However, the air humidity will be more crucial. In the operating mode in a humid medium, there will occur moisture condensation on the cold side of a TE module. It is certain to cause Figure-of-Merit degrading.

Let us estimate theoretically sensitivity of one-stage TE module Z and τ to violating of vacuum via two aspects:

a) additional thermal conductance between the TE module pellets (tells upon both Z and τ);

б) more intensive thermal exchange from the exterior of the module (tells upon Z).

Suppose air penetrates into the vacuum volume. Let us study the change of the TE construction Figure-of-Merit. Besides radiation mechanisms of heat transfer there are conducting and convectional ones in the air. We take into account additional thermal conductance between pellets by the following equation:

$$k_0' = k_0\left(1+\frac{\kappa_{air}}{\kappa_{mater}}\left(\frac{1}{\beta}-1\right)\right), \tag{8}$$

where k_0 is the TE pellet thermal conductance, k'_0 – increased TE pellet thermal conductance due to air between pellets; κ_{air} is thermal conductivity of air, κ – is thermal conductivity of TE material, β is the so-called TE module filling coefficient equal to the ratio between the cross-section of all the pellets and the whole area of the thermal junction surface.

If the TE material thermal conductivity $k_0 = 1.45$ W/mK, for the modules 1MC06-060 and 1MC06-018 (β=0.36) at 293K $k_0' = 1.49$ W/mK.

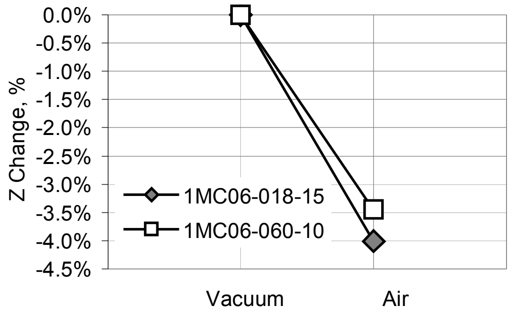
In Table 1 we give calculated results for the modules heat radiation and convection heat exchange coefficients per surface unity. TE modules types are 1MC06-060-xx and 1MC06-018-xx. The measuring approach is the Harman method. The ambient temperature is 293K. The temperature difference at the modules is 3K.

Table 1

TE module Type	α_{rad}, W/m^{2}K	α_{conv}, W/m^{2}K	α_{sum}, W/m^{2}K
1MC06-060	1.61	8.17	9.78
1MC06-018	2.93	9.29	12.22

In Fig. 8a one can see examples of theoretical results (see Eqs. (3), (4a,b)), conforming to the TE construction Figure-of-Merit fall when vacuum tightness is broken.

For the TE construction time constant it is only the growth of the effective pellets thermal conductance that is an important factor. Taking into account Eqs. (5), (8) we obtain the decrease of the tir *a* constant in air – see Fig. 8b.



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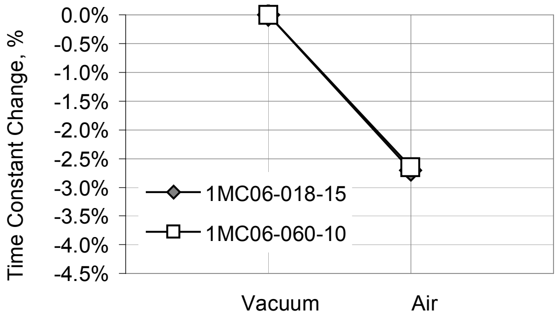

Figure 8. Calculated estimates of a) Figure-of-Merit Z and b) time constant τ of a TE module construction depending on the environment

Conclusion

In Table 2 a diagnostic matrix from our previous paper [1] is given. With its help reasons of TE modules faults can be identified by measuring three parameters (Z, R, τ).

Table 2

Defect	R	Z	τ
1. Metal junctions detachment	~const	~const	↑
2. Confused p-n pellets polarity	~const	↓	↑ *
3a. Thermal Contact of Pellet Wall and Solder Meniscus	~const	↓	↓
3b. Thermal and Electric Contact of Pellet Wall and Solder Meniscus	↓	~const	↓
4. TEC Pellets Short Circuit	↓	↓	↓
5. Two-stage TEC: confused stage polarity.	~const	~const	↓**
6. TE material Degradation	↑	↓	~const
**- ~const @ low current; **- ~ twice lower to nominal value*			

Table 3 presents a continuation of this diagnostic matrix for a number of faults of TE module applications in optoelectronic devices.

Table 3

Defect	R	Z	τ
1) Operational Degrading of a TE module	↑	↓	↑ or ↓
2) Poor integrating of a TE Module into the Package	~const	↑	↓*
3) Faulty mounting of a cooled object onto the TE module	~const	~const	↓
4) Environment violation in a TE module construction	~const	↓	↓
*- *for the total detachment appr. twice lower*			

Table 3 shows that the suggested method of analyzing faulty states by three parameters allows making a diagnosis of the reasons of degrading of the TE cooling systems quality and reliability in optoelectronic devices. Moreover, this reference of a fault to its cause is possible without demounting of a TE module from the device.

By one of the studied parameters, for example by R, as commonly used, in the three out of the four cases considered (Table 3) it is impossible not only to identify the reason of a fault but detect the fact of a failure itself. By one parameter it is not possible to assess the responsibility of a TE module for an optoelectronic device failure either. And, vice versa, the last but not the least: in case reasons of a fault have nothing to do with a TE module, this method can definitely prove it, if all the measured parameters keep within their nominal values.

Literature

1. L.B. Yershova, G.G. Gromov, I.A. Drabkin. Complex Express TEC Testing. Proc. of XXII Int. Conf. on Thermoelectrics, August 17-21, La Grande Motte, France, 2003. P. 504

2. T.C. Harman Measurement of Pertinent thermoelectric Properties. //Thermoelectric Materials and Devices. Cadoff I.B., Miller E., Reinhold, 1967, chap.6.

3. V.P. Babin,S.M. Gorodetskiy. Thermoelectric modules quality testing by a manufacturer. Proc. XIV Int. Conf. on Thermoelectrics, June 27-30, St. Petersburg, Russia, 1995. P. 338.

4. I.A. Drabkin. TE modules Characteristics. TE cooling. /Edited by L.P. Bulat. – Saint-Petersburg, 2002, P. 99.

5. G.G. Gromov, D.A. Kondratiev, A.U. Rogov, L.B. Yershova. Z-Meter: Easy-to-use Application and Theory. Proc. of VI European Workshop on Thermoelectrics, Freiburg, 2001.