THERMOELECTRIC COOLING AND TEMPERATURE STABILIZATION OF ELECTRONICS ELEMENTS

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ABSTRACT - All elements and systems of electronics have optimum temperature conditions. A using of the thermoelectric method of cooling is the most approach for the thermal management of power electronics. An analysis of using the thermoelectric cooling and the temperature control is given as an efficient method of ensuring a work of power electronic devices in conditions of micro-miniaturization.

1. INTRODUCTION

Practically all elements and systems of electronics should have optimum temperature conditions [1-3]. Their best parameters can be reached only under this conditions. For example, best features of greater number of *rectifier diodes* are reached under the temperatures $+10^0C \div +30^0C$. An optimum conditions for *stabilitrons* are reached under $-40^0C \div -10^0C$. It is necessary to cool *tunnel diodes* before temperatures in the range of $-40^0C \div -30^0C$, however for *varicap diodes* are reached the best conditions under $-60^0C \div -40^0C$. *Germanium transistors* perfect their own characteristics under the temperatures $-20^0C \div -40^0C$; a cooling of *field-effect transistors* perfects their characteristics under $-60^0C \div -40^0C$. A reducing of working temperatures of *integral schemes* for the computing technique from $+60^0C$ to 0^0C will increases their reliability in over and over again. Consequently, a making of a temperature conditions the most favorable for each element gives a possibility greatly to perfect a quality of electronic systems. As seen however, each of elements has its own best level of temperature stabilization. Moreover, the level is different for different elements in most cases. It is necessary to underline, that most from required conditions are below room temperatures, usually in the interval $-70^0C \div +5^0C$.

Thence appear a problem of develop and design of electronic elements with a local cooling and a problem of the temperature stabilization. A using of the thermoelectric method of refrigeration is the best practical method of cooling electronic components from a cost and efficiency viewpoint. Modern achievements in thermoelectric cooling allow successfully decide such problems.

2. PRINCIPLES OF THERMOELECTRIC COOLING

The thermoelectric cooler does not need CFCs or HCFCs as a compression-type refrigerator, therefore it has principle advantage that it does not harm the ozone layer, and is an environment friendly method of cooling. The compression-type refrigerator requires a working fluid (CFC or HCFS) as a refrigerant, while the thermoelectric coolers use the electron gas as a refrigerant.

The thermoelectric method utilises the Peltier effect. When a DC electric current passes through a junction of two different types of conductors (or semiconductors) it results in a changing of a temperature of the junction, this is the Peltier effect (1834). The temperature is decreased (cooling) or increased (heating) in dependence of the direction of the electric current.

Practically the thermoelectric cooler performs as a thermoelectric module - a small semiconductor device that can operate as a refrigerator component of a unit cooler [4]. It consists of a number of thermoelectric semiconductor branches fabricated from n-type and p-tipe semiconductors (Fig. 1). More popular material for n- and p-branches of the thermoelectric couple for modern coolers are semiconductors on the base of Bi_2Te_3. The semiconductor branches are connected electrically in series and thermally in parallel.

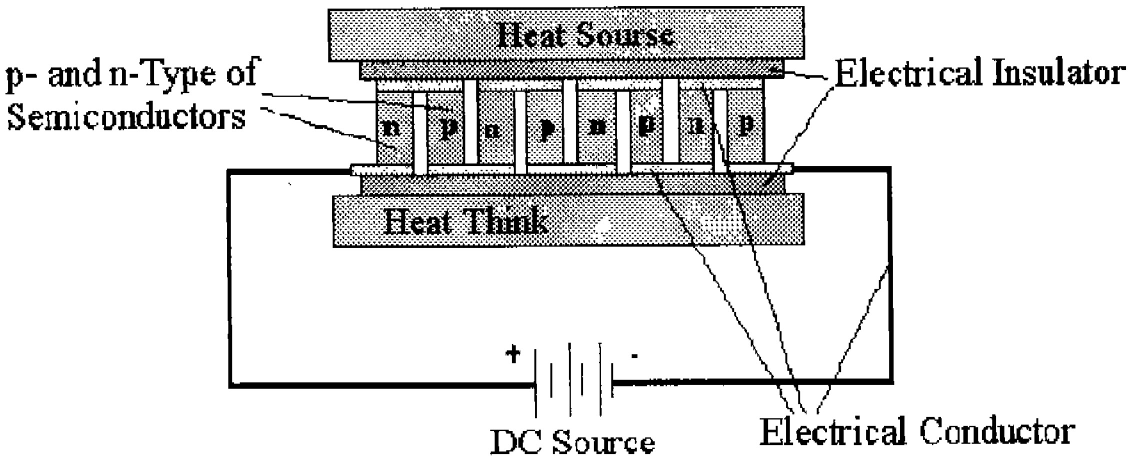

Fig. 1. Thermoelectric Module

Thermoelectric coolers have a number of principal advantages [1-6]. At first they are absolutely clean environmentally and they are very flexible and simple in operation. They have no moving parts so they do not produce any noise or vibration and produced minimum electrical noise. The thermoelectric coolers are exclusively reliable. Their lifetime is comparable with a lifetime of electronic elements. A changing of a direction of the electric current throws the module leads to change of a cooling to a heating. On the other hand, the thermoelectric cooling is capable to function in extreme conditions such as imponderability, vacuum, large mechanical overloads, vibration, etc. Their work does not depend on their orientation in the space. Thermoelectric coolers have a small size and weight; their form, size and parameters can be easily changed, hence, they can be simply combine with the electronic element.

3. PARAMETERS OF THE THERMOELECTRIC COOLERS

A thermoelectric cooler can be characterized by the following parameters [1,3,4]:

- I_{max} is a DC current that corresponds to the maximum value of the temperature difference under the cold and hot sides of the module ΔT_{max}; in this case, the cooling power $Q_c = 0$.
- ΔT_{max} the maximum value of the temperature difference ΔT at I_{max} with $Q_c = 0$; $\Delta T = T_h - T_c$ (T_h is the hot side temperature and T_c the cold side temperature). The ΔT_{max} for commercial single stage modules are about $67K$ to $73K$ at the hot side temperature $T_h = 300K$.
- $Q_{c\,max}$ the maximum value of the cooling power Q_c that corresponds to a temperature difference $\Delta T = 0$.
- V_{max} the terminal voltage for I_{max}.

If the ΔT is less than 55^0C, than a single stage thermoelectric module is sufficient. If ΔT is grater than 55^0C, than a multistage thermoelectric module should be considered [7]. A multistage module achives a high ΔT by stacking as many as two to seven single stage modules on top of each other. The limit of ΔT_{max} for multistage module is 160^0C [2].

It is well known that the main energetic characteristic of any refrigerating system is the coefficient of performance (COP). The COP is determined as

$$\varepsilon = \frac{Q_c}{W}, \tag{1}$$

where Q_c is a cooling power and W the corresponding electrical power.

The thermoelectric cooler can operate under different behaviors, but more impor ant of them are: 1) the behavior of maximum COP ε_{max}, and 2) the behavior of maximum cooling power $Q_{c\,max}$.

The maximum COP of a thermoelectric cooler can be written as [1,3]

$$\varepsilon_{max} = \varepsilon_0 \cdot \frac{\sqrt{1+ZT_M} - \frac{T_h}{T_c}}{\sqrt{1+ZT_M}+1}, \qquad (2)$$

where T_M is the average temperature:

$$T_M = \frac{T_h + T_c}{2},$$

and

$$\varepsilon_0 = \frac{T_c}{T_h - T_c} \qquad (3)$$

is the COP of the ideal thermodynamic Carnot cooling machine.

The parameter Z characterizes properties of a material and called "the thermoelectric figure of merit"; which is determined by

$$Z = \frac{\sigma S^2}{\kappa}, \qquad (4)$$

where σ is the electrical conductivity, κ the thermal conductivity and S the thermoelectric power of a semiconductor material.

Under the condition of maximum cooling power the COP becomes [1,3]

$$\varepsilon_q = \frac{1}{2T_h}\left(T_c - \frac{2(T_h - T_c)}{ZT_c}\right). \qquad (5)$$

It is necessary to underline that unlike compressor-type refrigerators, a thermoelectric cooler can maintain their COP down to very low values of Q_c, of the order of milliwatts [3].

It is very simple for a thermoelectric cooler to change an operating regime from the behavior of ε_{max} to the behavior of $Q_{c\,max}$, or to operate in some medium condition by changing the electric current. So, a thermoelectric cooling is very flexible.

4. APPLICATIONS OF THERMOELECTRIC COOLING IN ELECTRONICS

An essential progress in a micro-miniaturization of the thermoelectric coolers was reached in the Institute of Thermoelectricity (Ukraine) and some other institutions (see [2,3,5-11]). A size of the thermoelectric coolers becomes to be comparable with sizes of crystals for electronic scheme elements. Such achievement opens principal new directions of the electronics development, as follow - a creation in one frame an electronic element (chip) and a thermoelectric cooler. Sizes of such hybrid thermoelectric and electronic devices are not distinguish practically from usual non-cooled and non temperature stabilized electronic elements and systems.

A volume of the thermoelectric micro coolers is from $0.5\,mm^3$ to $220\,mm^3$, a value of cooling and temperature stabilization is $-80^0C \div +60^0C$. The micro-coolers use a usual voltage of DC current. Such voltages can be $3V$, $6V$, $12V$, $24V$ or any other depending on request of a special application. The cooling power of micro-coolers is from $0.01\,W$ to $100\,W$. This range can be increased if it is necessary for an application. Thermoelectric micro-coolers have a high speed of operation. They can ensure a needed temperature condition at $0.2\,\sec \div 2.0\,\sec$.

Let us discuss some concrete applications of thermoelectric cooling in electronics.

Chips spot cooling

The requirement for increasing speeds of integrated circuits and computers is accompanied by higher power output and a higher packaging density. Both of the necessities lead to very high power densities. This problem limits integration of devices and components on the board. For example, a Solid State Power Amplifier (SSPA) for microwave applications expected to go from a current output power of $5\,W$ to $30\,W$ within a few years [8]. That increase will multiply the heat flux that has be removed from $30\,W/cm^2$ to over $100\,W/cm^2$ [8]. This level of heat flux density will result in a major thermal management problem. Moreover, many devices will be operating at or near the edge of reliability, and so they will need to operate at lower temperatures.

The most importent advantage to thermoelectric cooling of power amplifiers and microprocessors is the ability to spot cool decrete or localized devices and also the ability to redice the temperature of the device below ambient. Today certain CPUs are cooled by thermoelectric method. On the heated side of the thermoelectric battery are heat exchanges and generally a small fan. The length of the legs of the thermoelectric coolers for this purposes is between $1.0\ mm$ and $1.5\ mm$. But such type of cooler can not satisfy higher levels of output power.

For more high level of output power as $30\ W/cm^2$ to $100\ W/cm^2$ it is necessary to design new cooling micro devices with thick and thin films [2,8]. As an example, the cooler fabricated on Bi_2Te_3-based thick films, bounding of metallized diamond or AlN substrates to the thermoelectric films [8,9] With a ΔT of $50^0 C$ the cooling power density increases 10 fold each time when the thermoelectric leg length decrease by a factor of 10 from $2\ mm$ to $0{,}2\ mm$ and to $20\ mcm$, and reaches a value of $300\ W/cm^2$ [2].

Radiation detectors

The principal of operation of photoelectric detectors is based on the internal photoelectric effect. The photoelectric detectors can be classified for following types depending upon the mechanism that converts the radiation into electric signal: *photoresistors, photodiods, phototransistors* and *multi-range detectors*. All photoelectric detectors are selective devices. It is necessary to select optimum photoelectric material for each region of the spectrum. In excess of 25 semiconductors are used over the range of $0.4 \div 20.0\ mcm$, that covered by photoelectric detectors [11].

The maximum detectivity of the most photoelectric detectors strongly depends on the operating temperature. For example, the detectivity of *HgCdTe* based photoelectric detectors at $80\ K$ is two orders of magnitude higher than at $200\ K$, while detectors based on *InSb* exhibit a slightly less marked temperature dependence of the detectivity. Hence, the special temperature conditions should be determine for each photoelectric detector separately. The information about the detectors that are cooled by thermoelectric method to operating temperatures is shown at Table 1 [11].

Table 1. Photoelectric detectors that cooled by thermoelectric method.

Basic photoelectric material	Number of stages in TE cooler	Operating temperature, K	Input power TE cooler, W	Spectral range, mcm
PbS	1 - 4	195 - 263	1.53 - 16	1.0 - 3.5
PbSe	1 - 4	193 - 293	0.4 - 16	1.0 - 5.0
HgCdTe	2 - 4	195 - 243	1.0 - 16	3.0 - 5.0
Ge	1 - 4	200 - 258	1.0 - 3.0	0.6 - 1.9
InAs	2 - 4	200 - 250	1.0 - 3.0	1.0 - 3.4

Fiber optic laser packages

The strong increasing of the fiber optic telecommunication networks has created a significant recent upsurge in the demand for thermoelectric coolers. The thermoelectric coolers are used for temperature control of the laser diodes that transmit light pulses down a fiber optic system. It is known that optical telecommunication lines offer increased bandwidth and electrical noise immunity to a user [5,12].

Unfortunately, the laser diodes produce a lot of heat. So a temperature of $40^0 C$ can reduces a lifetime of the laser diode by two orders of magnitude [12]. The thermoelectric coolers are employed in the laser modules to maintain the laser chip at a constant temperature, typically $25^0 C$ over a wide range of ambient temperatures. Careful design enables devices to operate over a temperature range of $-40^0 C$ to $+80^0 C$ [5,12]. The fiber optic laser packages cooling is one of the fastest growth areas for thermoelectric cooling applications.

The typical laser package contains the small laser chip, that is mounted precisely in line with the fiber pigtail, with a *photodiode* behind, and also with a *thermistor* for the laser temperature control [12]. All these components mounted upon the thermoelectric cooler within a rectangular hermetic package.

Electronic systems with very high level of heat production

The thermoelectric cooling for temperature stabilization of powerful electronic devices and systems, which produced a heat power from $0.1\ kW$ to $10\ kW$ also is possible. Schemes of a heat exchange, based on liquid and air heat transportation as the thermoelectric air-conditioners for such systems was designed. The thermoelectric air-conditioners intended for instance for making the necessary temperature conditions for electronic blocks in power supply units, for temperature stabilization of navigational and radio-equipment on boats, in devices of automation in industry and for other purposes.

5. CONCLUSION

A lot of power electronic devices operate at high temperatures close to the edge of their reliability. Then the devices need cooling to improve performance and lifetime. The specific problem of spot cooling of power devices can be very efficiently solved by thermoelectric method of cooling. Especially thermoelectric cooling is effective in temperature management of chips in power amplifiers and microprocessors, in radiation detectors, fiber optic laser packages, etc.

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