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A Review of Thermoelectric MEMS Devices for Micro-power Generation, Heating and Cooling Applications

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1. Introduction

Thermoelectric technology can be used to generate a small amount of electrical power, typically in the µW or mW range, if a temperature difference is maintained between two terminals of a thermoelectric module. Alternatively, a thermoelectric module can operate as a heat pump, providing heating or cooling of an object connected to one side of a thermoelectric module if a DC current is applied to the module's input terminals. This chapter reviews the development of microelectromechanical systems (MEMS) based thermoelectric devices suitable for micro-power generation, heating and cooling applications. The chapter begins with a brief overview of thermoelectric technology, macro-thermoelectric module construction and operation. Micro-thermoelectric modules are introduced, and a review of recent developments in research, commercial development, and typical application of MEMS based micro-thermoelectric devices is made. The chapter draws conclusions on the development and potential application of MEMS based thermoelectric devices suitable for thermoelectric cooling, heating and micro-power generation.

2. Overview of thermoelectric technology, module construction and operation

2.1 Overview of thermoelectric technology

Thermoelectricity utilises the Seebeck, Peltier and Thomson effects that were first observed between 1821 and 1851 (Nolas et al, 2001). Practical thermoelectric devices emerged in the 1960's and have developed significantly since then with a number of manufacturers now marketing thermoelectric modules for cooling, heating and power generation applications. Thermoelectric power generation is mainly influenced by the Seebeck effect, with thermoelectric cooling and heating influenced predominantly by the Peltier effect. The Thomson effect does not have a major influence although it should always be included in detailed calculations (Rowe, 2006). For power generation applications, a small amount of electrical power, typically in the µW or mW range, can be generated by a thermoelectric module if a temperature difference is maintained between two terminals of a thermoelectric module. Alternatively, a thermoelectric module can operate as a heat pump, providing

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heating or cooling of an object connected to one side of a thermoelectric module if a DC current is applied to the module's input terminals. The technology has achieved commercial success in mini-refrigeration, cooling and space-craft power applications, with the consumer market for mini-refrigerators and coolers currently the most successful commercial application (Hachiuma and Fukuda, 2007). Future developments in thermoelectric technology will include the need to reduce the size, and improve the performance, of current thermoelectric devices in order to address thermal problems in microelectronics, and create localised low-power energy sources for electronic systems.

2.2 Standard thermoelectric module construction

Standard thermoelectric modules are constructed from P-type and N-type thermo-elements, often referred to as thermoelectric couples, connected electrically in series and thermally in parallel. Each couple is constructed from two 'pellets' of semiconductor material usually made from Bismuth Telluride. One of these pellets is doped to create a P-type pellet, the other is doped to produce an N-type pellet. The two pellets are physically linked together on one side, usually with a small strip of copper, and placed between two ceramic plates. The ceramic plates perform two functions; they serve as a foundation on which to mount the thermo-element; and also electrically insulate the thermo-element (Riffat and Ma, 2003). A single couple of a thermoelectric module is shown below in Fig. 1.

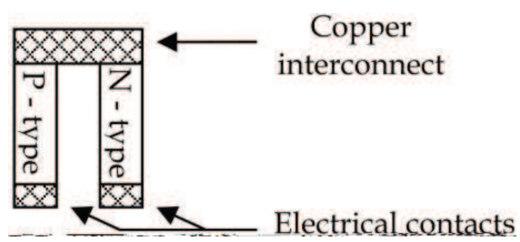

Fig. 1. A single couple of a thermoelectric module

The thermo-element, or couple, is then connected electrically in series and thermally in parallel to other couples. Standard thermoelectric modules typically contain a minimum of 3 couples, rising to 127 couples for larger devices. A schematic diagram of a thermoelectric module is shown in Fig. 2.

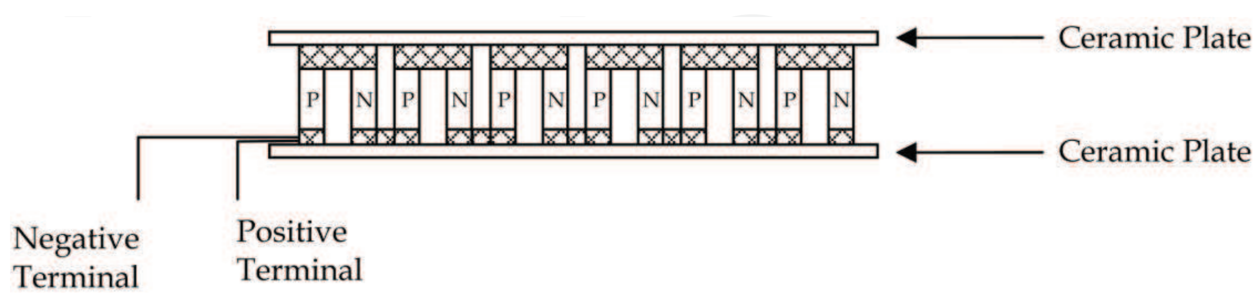

Fig. 2. A schematic diagram of a thermoelectric module

2.3 Thermoelectric module configuration

A thermoelectric module can cool or lower the temperature of an object, if the object is attached to the 'cold' side of the module, often referred to as 'TC', and DC electrical power is applied to the module's terminals. Heat from the object will be absorbed by the 'cold' side of the thermoelectric module, and transferred or 'pumped' through to the 'hot' side of the module 'TH' due to the Peltier effect. Normally, the hot side of the module will be attached to a heat sink in order to reject this heat into the atmosphere. A thermoelectric module operating as a thermoelectric cooler or heat-pump is shown below in Fig. 3. If the polarity of the DC current applied to the thermoelectric module terminals is now reversed, the module will heat the object connected to the cold side of the module, with the other side of the module now cooling down. In this condition, the thermoelectric module is referred to as a thermoelectric heater.

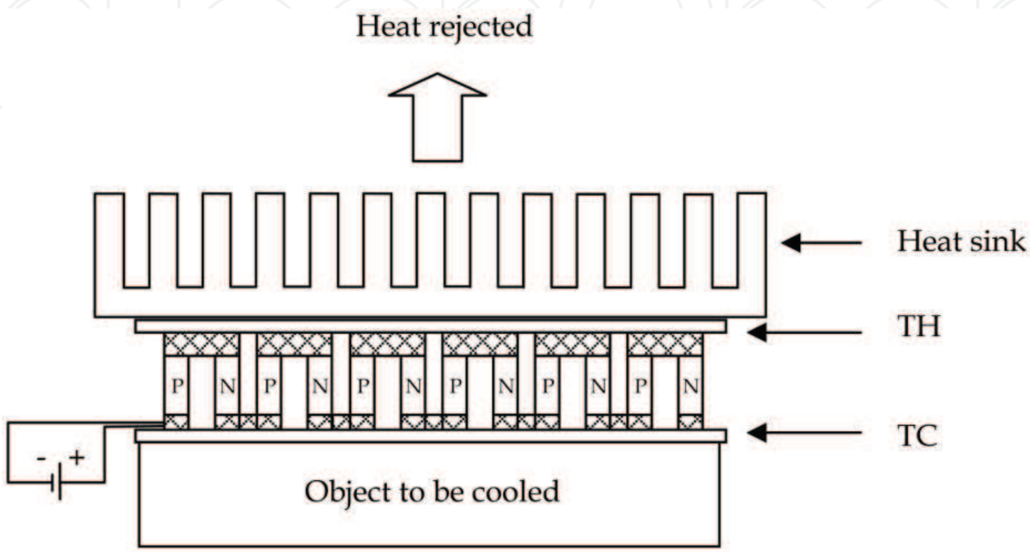

Fig. 3. A thermoelectric module operating as a thermoelectric cooler or heat-pump

A thermoelectric module can also be used to generate a small amount of electrical power, typically in the µW or mW range, if a temperature difference is maintained between both sides of the module. Normally, one side of the module is attached to a heat source and is referred to as the 'hot' side or 'TH'. The other side of the module is usually attached to a heat sink and is called the 'cold' side or 'TC'. The heat sink is used to create a temperature difference between the cold and hot sides of the module. If a resistive load (RL) is connected across the module's output terminals, electrical power will be generated in the resistive load when a temperature difference exists between the hot and cold sides of the module, due to the Seebeck effect. A thermoelectric module, operating as a thermoelectric power generator, is shown below in Fig. 4.

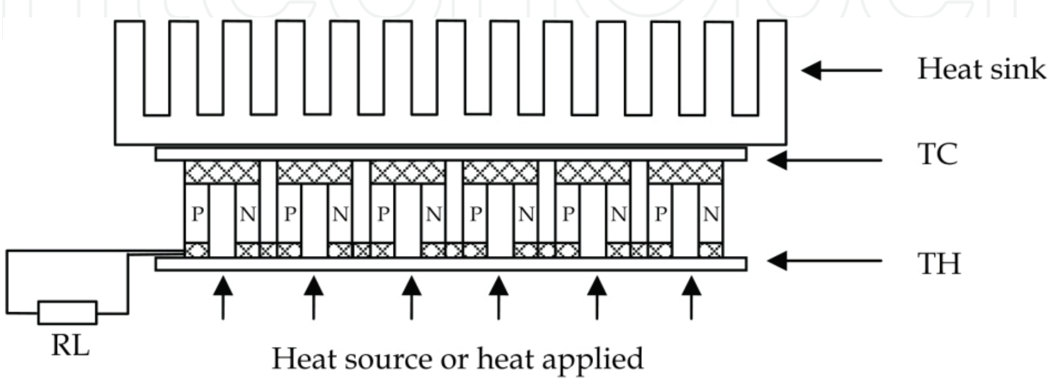

Fig. 4. A thermoelectric module operating as a thermoelectric power generator

2.4 Operation of standard thermoelectric modules

Semiconductor theory can be used to describe the operation of thermoelectric devices. In Fig. 5, a single thermoelectric couple is connected to operate as a heat pump.

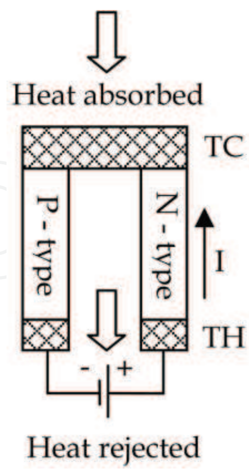

Fig. 5. A single thermoelectric couple connected as a heat pump

When a DC voltage is applied to the module terminals, electrical current flows from the positive terminal of the supply voltage to the negative terminal. This is shown as an anti-clockwise current flow in the configuration shown in Fig. 5. The negative charge carriers, i.e. the electrons, in the n-type bismuth telluride pellet are attracted by the positive pole of the supply voltage, and repelled by the negative potential. Similarly, the positive charge carriers, i.e. the holes, in the p-type material are attracted by the negative potential of the supply voltage, and repelled by the positive potential, and move in an opposite direction to the electron flow. It is these charge carriers that actually transfer the heat from one side of the thermoelectric couple to the other side in the direction of charge carrier movement. In the n-type pellet, the negatively charged electrons are the charge carriers and absorb heat from the 'cold' side of the thermoelectric couple and transfer or 'pump' this heat to the 'hot' side of the couple in a clock-wise direction. Similarly, the positively charged carriers in the p-type pellet, the holes, absorb heat from the cold side of the couple and transfer this heat to the hot side of the couple in an anti-clockwise direction. Practical thermoelectric modules are manufactured with several of these thermoelectric couples connected electrically in series and thermally in parallel. Arranging the thermoelectric couples in this way allows the heat to be pumped in the same direction.
According to (Rowe, 2006), the energy efficiency of a thermoelectric device, operating in a cooling or refrigeration mode, is measured by its Coefficient of Performance (COP), found by:

$$\text{COP} = \frac{\text{Heat absorbed}}{\text{Electrical power input}} \tag{1}$$

For thermoelectric power generation, if a temperature difference is maintained between two sides of the module, thermal energy is moving through the n-type and p-type pellets. As these pellets are electrically conductive, charge carries are transported by this heat. This movement of heat and charge carriers creates an electrical voltage, called the Seebeck voltage. If a resistive load is connected across the module's output terminals, current will flow in the load and an electrical voltage will be generated. A thermoelectric couple connected as a thermoelectric power generator is shown in Fig. 6.

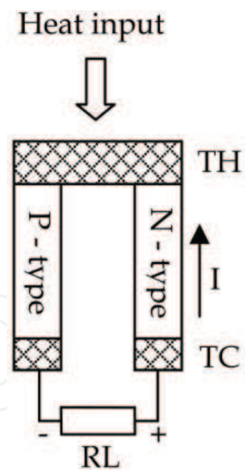

Fig. 6. A single thermoelectric couple connected as a thermoelectric power generator

The efficiency of a thermoelectric module, operating as a power generator, can be found by:

$$\eta = \frac{\text{Energy supplied to the load}}{\text{Heat energy absorbed at the hot junction}} \quad (2)$$

In thermoelectricity, efficiency is normally expressed as a function of the temperature over which the device is operated, referred to as the dimensionless thermoelectric figure-of-merit ZT.

The thermoelectric figure of merit ZT can be found by:

$$ZT = \frac{\alpha^2 \sigma}{\lambda} \quad (3)$$

where α is the Seebeck coefficient, σ is the electrical conductivity, and λ is the total thermal conductivity (Sales, 2007).

Thermoelectric phenomena are exhibited in almost all conducting materials, with the exception of superconductors below specific temperatures. Materials which possess a ZT > 0.5 are usually regarded as thermoelectric materials (Rowe, 2006). The best thermoelectric materials used in commercial macro-thermoelectric devices, Bi_2Te_3-Sb_2Te_3 alloys, operating around room temperature, have typical values of α=225μV/K, σ = 10^5/Ωm, and λ = 1.5 W/mK, which results in ZT ≈ 1 (Sales, 2007). Bismuth Telluride is the most common material used in standard thermoelectric modules, as it exhibits the most pronounced thermoelectric effect around room temperature. Other material combinations are also used including; Alloys based on bismuth in combination with antimony, tellurium and selenium; lead telluride; and silicon germanium alloys (Rowe, 2006).

2.5 Development of micro-thermoelectric modules

Standard thermoelectric modules range in size from 4 x 4 x 3 mm^3 to around 50 x 50 x 50 mm^3. Although, in principle, the dimensions can be reduced further, the fabrication of conventional thermoelectric modules for power generation or heating and cooling applications is a bulk technology, and is incompatible with microelectronic fabrication processes (Volklein & Meier, 2006). The development of micro-thermoelectric devices that are compatible with standard microelectronic technology and manufacturing processes have the potential to enhance the performance of microelectronic systems, achieve significant

reductions in size, improve the performance of thermoelectric devices, and open up new areas of research and commercial application.
Until recently, thermoelectric devices have been confined to niche applications because of their relatively low conversion efficiency and thermoelectric figure-of-merit ZT when compared with other technologies (Riffat & Ma, 2003). For thermoelectric power generation, current thermoelectric efficiencies are between 5% to 10% (Nuwayhid et al, 2005), with a practical thermoelectric figure-of-merit ZT ~ 1. For thermoelectric cooling and refrigeration, a COP of 0.5 is typical, which is lower than that achieved by conventional refrigeration techniques (Bass et al, 2004). According to (Stabler, 2006), since the early 1990's, materials with ZT > 1 have been discovered, and reports of ZT ~ 2 are widely known today with evidence that higher values of ZT are possible (Vining, 2007). Improving the efficiency and thermoelectric figure-of-merit ZT, reducing the cost of thermoelectric devices, and the use of alternative materials that are more widely available are focus areas for current research activity. However, thermoelectric technology does have several advantages over other technologies; For cooling or refrigeration applications, thermoelectric modules do not use any chlorofluorocarbons or other materials that require periodic replenishment; they can achieve precise temperature control to within +/- 0.1°C; the same thermoelectric device can be used for heating or cooling and can cool to temperatures below 0°C (Riffat & Ma, 2003); the modules are electrically quite in operation and are relatively small in size and weight (Alaoui & Salameh, 2001); and do not import dust or any other particles that could cause an electrical short circuit.

3. Thermoelectric MEMS devices

3.1 Overview

There is an increasing amount of published research in support of developing MEMS based thermoelectric devices. MEMS technology, combined with microelectronics and micromachining techniques, has been successfully and widely utilised in micro-sensor and micro-actuator applications, and there is significant commercial value in developing next generation thermoelectric devices for applications in power generation and integrated circuit cooling (Huang et al, 2007). Current micro-sensors and micro-actuators may also be based on thermal and thermoelectric principles, and use thin-film technology to achieve sensing and actuator functionality, with micromachining techniques to achieve device optimisation (Volklein & Meier, 2006). According to (Min, 2006), the development of thermoelectric devices compatible with standard semiconductor manufacturing processes has the potential to address many applications in microelectronics, with MEMS technology, along with nanotechnology, of significant interest to thermoelectric manufacturers and researchers. It is anticipated that these technologies can be used to reduce the size, and improve the performance, of thermoelectric devices suitable for micro-power generation, heating and cooling applications. Current MEMS based devices will also benefit from incorporating thermoelectric technology, for example where a MEMS based device has an electrical power consumption in the micro-watt range, this could potentially be supplied by thermoelectric devices (Huesgen et al, 2008), or where there is a need for temperature stabilisation of MEMS based microelectronic components and circuits (Li et al, 2003).

3.2 Emerging thermoelectric MEMS based devices

Research into manufacturing a thermoelectric MEMS based device, using thin-film technology, has resulted in the proposal of different device structures; a vertical device structure; and a horizontal device structure (Min, 2006). Commercially available micro-thermoelectric devices, based on thin-film technology, have also recently started to emerge. According to (Vining, 2007), two start-up companies have started to market thermoelectric devices based on thin-film technology. One company has developed thermoelectric devices based on a MEMS like process that use a sputtering deposition method and Bi_2Te_3 related materials. Another company has developed thermoelectric devices based on Bi_2Te_3-Sb_2Te_3 superlattice technology. (Bottner et al, 2007; 2005; 2004; 2002) describe in some detail the development of thin-film MEMS like thermoelectric devices using a sputtering deposition technique. Similarly, (Venkatsubramanian et al, 2007) and (Koester et al, 2006) describe the development of commercial thermoelectric devices using superlattice nanoscale materials.

The concept of MEMS like thermoelectric devices for cooling and micro-power generation applications, using a thin-film sputtering deposition technique, is to have a common vertical architecture of thermoelectric devices that use standard silicon/silicondioxide wafers as a substrate. One of these wafers is used to create an n-type semiconductor using Bi_2Te_3 related materials, and another, separate wafer is used to create a p-type semiconductor. The Bi_2Te_3 related material is deposited using a sputtering method, and after dry etching to create the device structure, the wafers are then sawn in order to create a single n-type and p-type die. The n-type and p-type die are then soldered together to create a thermoelectric couple (Bottner, 2005).

Another approach to creating micro-thermoelectric devices, that are compatible with modern semiconductor processing techniques, is the development of thin-film thermoelectric devices using nanoscale materials. According to (Venkatsubramanian et al, 2007), significant developments have occurred in the last few years in the area of nanoscale thermoelectric materials using superlattices and self-assembled quantum dots. Thin-film thermoelectric superlattices can be manufactured using Planar semiconductor device technology and are compatible with standard microelectronic processing and packaging tools.

There are a number of other examples of recently published work into MEMS based thermoelectric devices. Although not an exhaustive list, a basic literature search will highlight activity by (Liu et al, 2007) on the integration of micro-thermoelectric devices into a silicon based light-emitting diode (LED) in order to stabilise the LED's temperature; a planar multi-stage micro-thermoelectric device for cooling applications is presented by (Hwang et al, 2008); and the development of two micro-thermoelectric cooling devices, one based on a column-type telluride material, and another using a bridge-type polysilicon material and fabricated using MEMS based techniques by (Huang et al, 2008).

3.3 Future application of MEMS based thermoelectric devices

MEMS based thermoelectric devices can be used in thermoelectric cooling, heating and micro-power generation applications. The miniaturisation of thermoelectric modules, and the potentially higher thermoelectric performance that can be obtained, will also allow the development of new applications to emerge.

Micro-thermoelectric devices, fabricated in thin-film technology, have achieved sufficient miniaturisation to be integrated inside semiconductor packaged devices, rather than having to be mounted onto the outside of a semiconductor device, as is normal with a macro-thermoelectric module. As the semiconductor industry further reduces the size of transistors in integrated circuits, a trend is to fabricate more of the external circuitry inside the semiconductor packaging. Removing the heat within these integrated circuits is becoming more of a design challenge, and the miniaturisation of cooling devices can be used to solve these problems (Baliga, 2005). Historically, the motivation for using thermoelectric technology to cool microelectronic integrated circuits in the computer industry has been to increase their clock speed below ambient temperatures. Increasing microprocessor performance has usually been accompanied by an increase in power and on-chip power density. Both of these present a challenge in cooling microelectric devices (Mahajan et al, 2006). The computer industry may begin to approach the limit of forced-air cooled systems and will need to find alternative solutions (Sharp et al, 2006).

Localised areas of high heat flux on microprocessors can produce 'hot spots' that limit their reliability and performance, and are becoming more severe as local power density and overall die power consumption increase. Although a macro-thermoelectric module can be used in this application to provide cooling of the entire integrated circuit, micro-thermoelectric cooling of these localised regions of higher temperature or 'hot spots' may provide a better alternative. According to (Snyder et al, 2006), embedded thin-film micro-thermoelectric devices is a promising approach to reduce the temperature of localised, high heat flux hot spots generated by modern microprocessors. Micro-thermoelectric devices are also suitable for addressing other thermal management problems in microelectronics, and could be used to cool or stabilise the temperature of laser diodes, and provide a faster response time than conventional cooling techniques. It may also be possible to integrate a micro-thermoelectric device inside the laser diode packaging (Baliga, 2005). Infra-red detectors, charge coupled devices (CCD), light-emitting diodes (LED) and other opto-electronic devices may also benefit from micro-thermoelectric cooling.

Thermoelectric micro-power generation and energy harvesting is also a target market for micro-thermoelectric devices. (Bottner et al, 2007) believes that self-powered electronic sensor systems will require MEMS like manufacturing of micro-thermoelectric devices to meet the high volume requirements of this market. Energy harvesting or scavenging systems can be designed to replace batteries in autonomous sensor and wireless systems, and it has been shown that body heat can be used as an energy source to power low-energy devices, including a wrist watch or hearing-aid (Weber at al, 2006). Micro-thermoelectric power generators could also be used to supply power to electronic devices for wearable electronics applications (Bottner, 2002).

4. Conclusion

Thermoelectric technology can be used in cooling, heating and micro-power generation applications. Macro-thermoelectric devices have developed significantly since their introduction in the 1960's, and have achieved commercial success in mini-refrigeration, cooling and space-craft power applications. There is a requirement to reduce the size, and improve the performance, of current thermoelectric devices in order to address the need to solve thermal problems in microelectronics, and create localised low-power energy sources for electronic systems.

The miniaturisation and development of MEMS based thermoelectric devices has the potential to improve the performance of thermoelectric devices, and create new applications for the technology. Thermoelectric MEMS based devices, based on thin-film technology, that are compatible with modern semiconductor processing techniques have now started to enter the market place. Thermoelectric devices based on a MEMS like process that use a sputtering deposition method and Bi_2Te_3 related materials, and thermoelectric devices manufactured using Bi_2Te_3-Sb_2Te_3 superlattice technology are two recent entries into the thermoelectric market place.

It is anticipated that MEMS based thermoelectric devices can address the need to solve thermal problems in microelectronics, including the cooling of integrated circuits in the computer industry, and the cooling of optoelectronic and telecommunication devices. Micro-thermoelectric power generation is also expected to supply low-level localised power to other electronic components and systems, and provide a power source for energy harvesting systems.

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This book discusses key aspects of MEMS technology areas, organized in twenty-seven chapters that present the latest research developments in micro electronic and mechanical systems. The book addresses a wide range of fundamental and practical issues related to MEMS, advanced metal-oxide-semiconductor (MOS) and complementary MOS (CMOS) devices, SoC technology, integrated circuit testing and verification, and other important topics in the field. Several chapters cover state-of-the-art microfabrication techniques and materials as enabling technologies for the microsystems. Reliability issues concerning both electronic and mechanical aspects of these devices and systems are also addressed in various chapters.

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