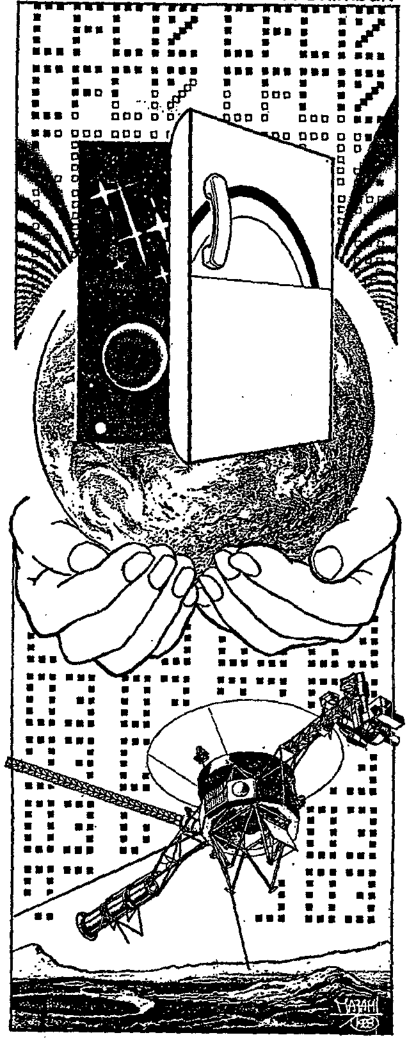
The International Thermoelectric Society

SCT- 93

SHORT COURSE ON THERMOELECTRICS

1993-8-1 The Nihon Keizai Shimbun



Illustrate by Masami Ishii

FOR THE GREEN
21st CENTURY

Pacific Convention Plaza Yokohama
Japan

8th November 1993

Sponsored by the International Thermoelectric Society

Organized by ITS Japan Branch

Editted by: The International Thermoelectric Society

Short Course on Thermoelectrics - 1993 (SCT-93)

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THERMOELECTRIC MODULES
FOR
POWER GENERATION AND COOLING

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LECTURE 5

THERMOELECTRIC MODULES FOR POWER GENERATION & COOLING

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1. INTRODUCTION

This portion of the course describes the configurations of the thermoelectric (abbreviated TE) modules which may have a practical application in a number of areas, particularly in power generation and cooling. Before mentioning a few of TE modules, it is necessary to talk about how the electrical and thermal contacts are made to the materials that are used in TE p-n couples (elements).

1.1 Electrical and Thermal Contacts

Even if materials have excellent TE properties, i. e.

- high Seebeck coefficient, α(V/K)
- low electrical resistivity, ρ (Ω-m)
- low thermal conductivity, κ (W/m-K)
- high figure of merit, $z = \alpha^2/(\rho\kappa)$ (K^{-1})

these TE materials can not be used without joining them to metal conductors or to other components consisting legs to form a p-n couple. The electrical and thermal resistance at each contact must be as low as possible because Joule heat losses and temperature drops across the contact will reduce the performance of the TE couple. It is very important that this joining contact exhibits long time stability at the operating temperatures. As the temperature increases the mechanical, chemical and electrical properties of the contact may be adversely affected by;

- thermal shock and cycling
- mechanical shock
- diffusion
- oxidation
- sublimation, etc.

It is desirable that the coefficients of thermal expansion of the components at the contact interface be the same. Otherwise, the contacting (junction) materials, must have good shear and tensile strength, and maintain as high a ductility as possible.

1. 2. Making Contacts

The contact is obtained by the techniques described below which should be selected depending on the TE or bridging materials (straps or shoes), operating temperatures, atmosphere etc. A contact with low electrical resistance can be made by first etching the contact area. Care must be taken to avoid the use of any contact material that could deteriorate the TE properties of the legs.

1. 2. 1 Solid State Diffusion Bonding

If metals or TE materials are in close contact under pressure, and are heated at their re-crystallization temperature, the atoms at interfaces move into each other's surface and solid-phase diffusion bonding is formed. When bonding materials of different re-crystallization temperatures A and B, a thin film of a third material C of lower re-crystallization temperature is inserted between A and B. The third material C may be a foil, plated or a sprayed material. Diffusion bonding is used to form TE couples of SiGe, Selenides, or Fe-Si TE legs.

1. 2. 2 Pressure Contact

To prevent any trouble arising from direct bonding or diffusion bonding at high operating temperatures, a pressure contact is formed using a spring or a bolt. PbTe legs are usually coupled with hot and cold shoes.

Large scale cooling systems using bismuth telluride alloys can be also built under pressure with bolts. These systems were designed by J. G. Stockholm. When the pressure is below 0.5 MPa, the dispersion of the resistance values can be several fold. In practice it is necessary to have interface pressures in excess of 1 MPa, but the interface resistance is 10 times greater with pressure contact than with bonded or soldered interface[1].

1. 2. 3 Vapor Deposition

Vacuum evaporation, sputter, ion plating, ICB (Ion cluster beam) etc are widely applied to the contact surfaces to make easy bonding or soldering. The deposited films are useful as a barrier layer preventing impurities from the bridging metals or soldering materials from contaminating the TE material.

The p- and n-type TE materials or the bridges between them can be formed using these vapor deposition methods.

1. 2. 4 Flame or Plasma-jet Spray

The bridging between p- and n-type legs can be obtained by spraying the fine molten particles or vapor of the bridging material, using a high temperature plasma furnace or flame, on the contact surfaces.

1. 2. 5 Brazing or Soft Soldering

First the flux displaces the atmospheric gas layer on the contact surfaces between the base materials and the solder alloy. Then on heating the flux removes the tarnish films from these fluxed surfaces and wetting occurs when the solder alloy melts. Figure 1 shows the common alloy families for soldering and brazing[2].

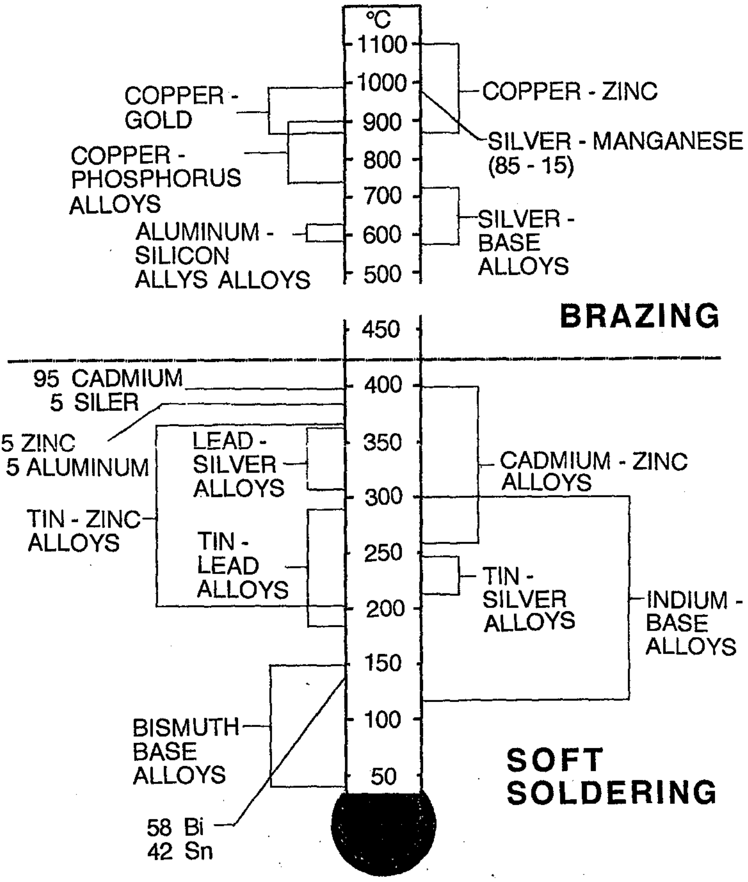

Fig. 1 Common Alloy Families for Soldering and Brazing
(after Manko, H. H., 1964, Reference 2)

1. 3 Example of SiGe TE Uni-couple

The Radioisotope TE Generators (RTGs) for the LES 8 & 9 (MHW : Multi-Hundred Watt), Voyager 1 and 2 (MHW), Galileo (GPHS: General Purpose Heat Source) and Ulyses (GPHS) enabled the exploration of the moon, the sun and the planetary system. Voyager carries three MHWs.

The TE couples are made in uni-couple assemblies as shown in Figure 2 and are individually bolted to the beryllium outer case which is the main support structure for the uni-couples as well as the heat source. The legs of the uni-couple are silicon germanium (SiGe) alloys and the hot shoe (bridge or strap) contains a silicon molybdenum alloy. Three hundred and twelve couples arranged in 24 circumferential assemblies of 13 couples. A two string, series-parallel electrical circuit is used to enhance reliability. The hot junction temperature averages about 1273 K and the cold junction about 573 K during space operation. The overall mass of the RTG is 38.5 kg with a BOL (beginning of life) power of at least 150 We[3]. Each uni-couple produce approximately 0.5 watts.

The spacecraft Cassini powered by two GPHS-RTGs will be launched in 1996 to conduct a detailed, four-year study of the Saturnian system when it reaches Saturn in 2002.

The uni-couple will be composed of a first bond assembly brazed to a cold stack assembly for heat rejection as shown Figure 3. The first bond assembly, composed of a pair of n- and p-type 78% SiGe legs (pellets) diffusion bonded to a SiMo hot shoe, is coated with silicon nitride (Si_3N_4) to prevent sublimation of silicon from the hot shoe and the legs which in turn could lead to electrical shorts throughout the generator[4].

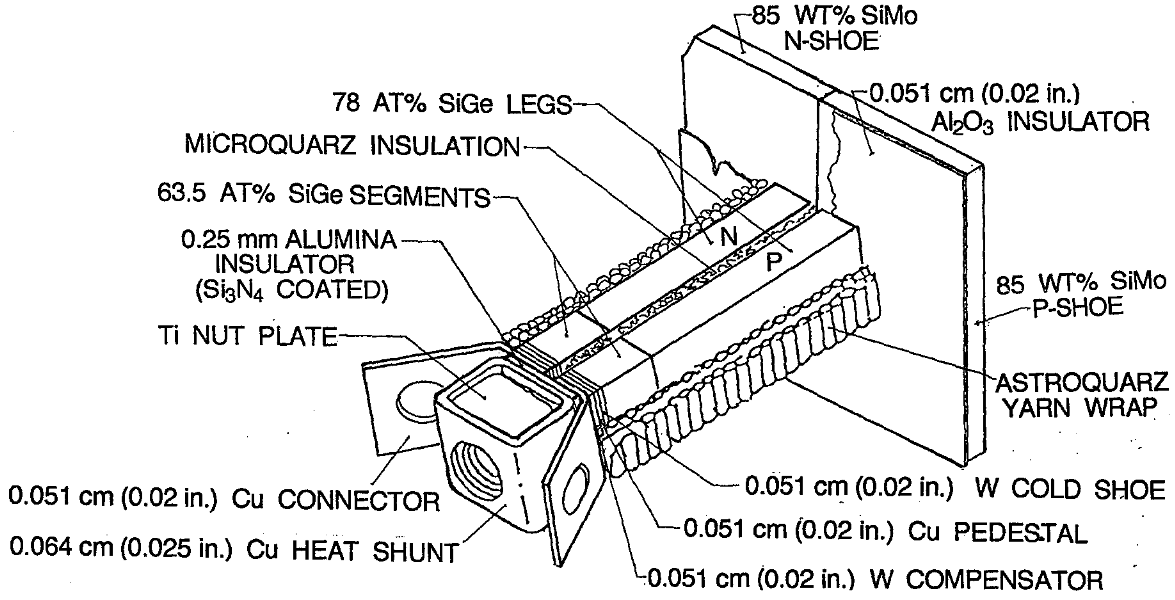

Fig. 2 MHW Silicon Germanium Uni-couple
(after O'Riordan, P. A., 1982, Reference 3, with Permission)

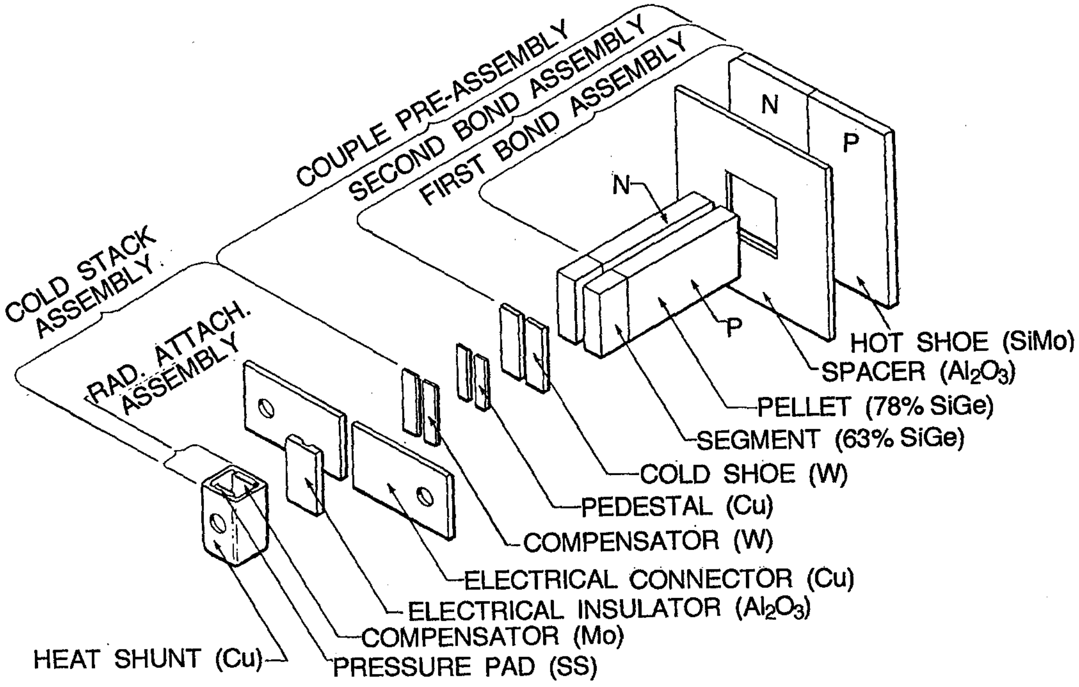

Fig. 3 Schematic of MHW Uni-couple Assembly
(after Nakahara, J. F. and DeFillipo, P. E.,1992, Reference 4, with Permission)

1.4 TE Module

TE module means a standardized unit or component consisting of TE multi-couples, connected electrically in series (or in series-parallel), thermally in parallel and having a defined function when combined with the heat exchangers in a system.

TE modules are available in a great variety of sizes, shapes, operating currents, operating voltages and ranges of generating power or cooling power. The TE legs can be produced for the optional conditions which define the dimensions of the TE legs.

We denote the Geometric Factor G, of the leg as the cross sectional area A (m^2) divided by the length L (m): G=A/L (m). The generating power or cooling power of the module is proportional to Geometric Factor G, and the number of the TE couples N.

Large and complicated systems can be easily designed and formed by assembling various numbers of these modules connected in series or in parallel depending on the desired function. In this lecture I will consider the modules of operating temperatures following range (a) above 500 K (b) below 500 K.

2. TE MODULES FOR POWER GENERATION USING HIGH GRADE HEAT SOURCE (>500 K)

The high grade heat sources include nuclear reactors, radio-isotopes, solar furnaces, fossil fuel, exhaust heat etc. The TE materials for power generation using high grade heat source are silicon germanium (SiGe), lead telluride (PbTe), bismuth terullide (Bi-Te), iron di-siliside (Fe_2Si_3) etc. These generators have highly diversified functions from their use in space, the military, the remote areas, emergency usage to consumer usage.

2.1 SiGe Modular RTG TE Module (Multi-couple) using Radio-isotope Fuel

The modular RTG converts heat from the radio-isotope fuel directly into electrical energy. The isotope is plutonium-238 in the chemical form of the oxide PuO_2 and mechanically pressed into ceramic spheres.

The TE multi-couple (module) consists of 40 TE legs, each coated with a Si_3N_4/SiO_2 barrier coating to suppress migration of the TE materials at operating temperatures. Each leg is separated by a high temperature insulating glass. The TE couples are electrically connected in series through the use of silicon molybdenum hot shoes (bridges or straps) and tungsten cold contacts. Figure 4 shows the modular RTG TE unit design.

SiGe/GaP material is used for the N legs and SiGe material for the P legs. A graphite heat collector, located on the hot end of the module, maintains the heat source at 1373 K and the TE hot/cold junction temperature of the module at 1273 K/573 K. The TE module is designed to produce greater than two watts of electrical power at 3.8 volts DC. The converter efficiency is 7.5 %. Figure 5 shows the configuration of the TE module for the Modular RTG .

Figure 6 illustrates the module fabrication technique. The first step is to cut N- , P-material slices of 0.083 cm and 0.073 cm thickness, respectively. These slices are individually coated with a glass layer coating consisting primarily of silica. Five slices of each type are assembled in an alternating array and are fused together. The fused block is then sliced in a direction perpendicular to the bonded surfaces, to produce four slices of 0.192 cm thickness.

These slices, containing alternating N and P legs, are again coated with silica glass, and four such are assembled into a block joined together by fusing the intervening glass layers.

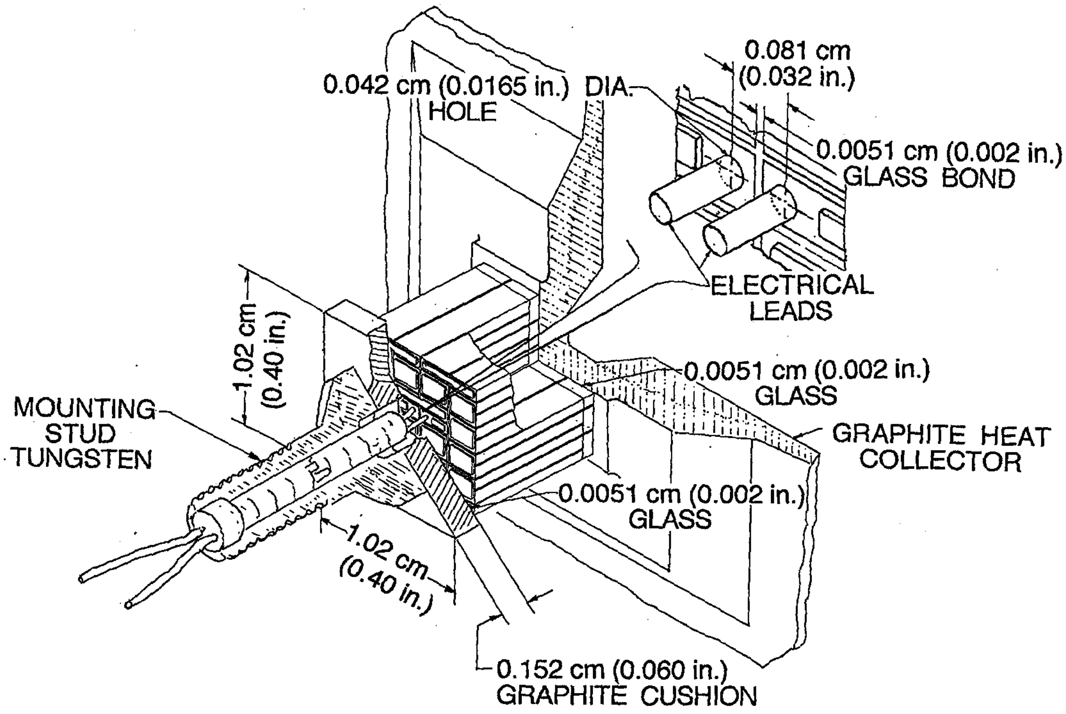

Fig. 4 Modular RTG Module Design
(after Hartman, R. F., 1990, Reference 5, with Permission)

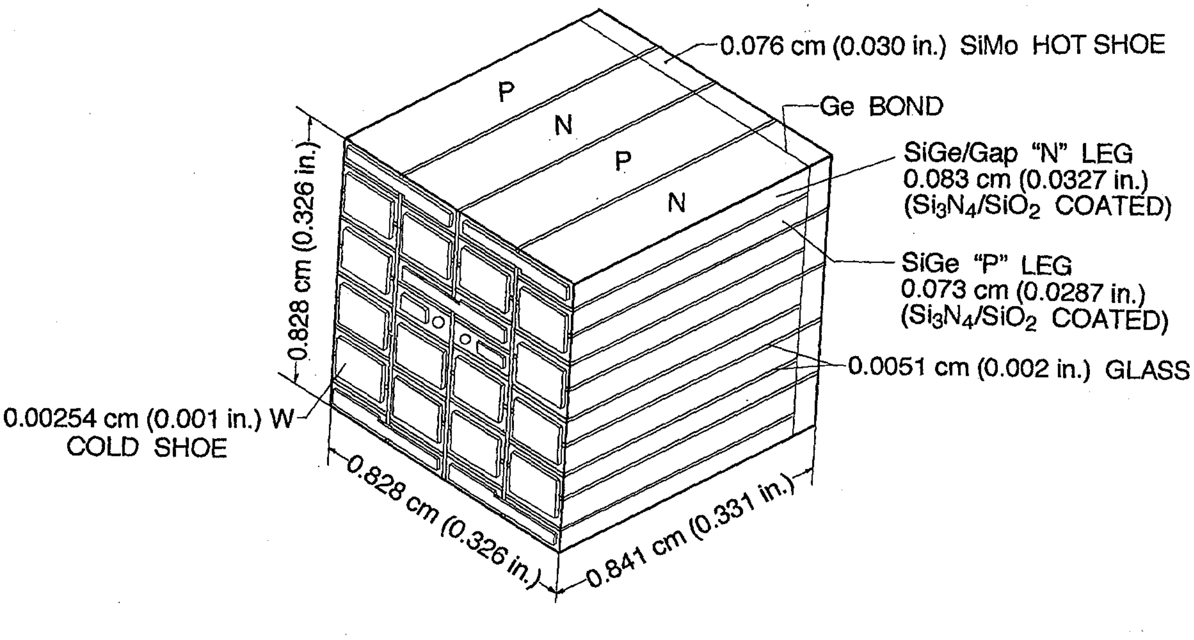

Fig. 5 TE Module for Modular RTG
(after Hartman, R. F., 1990, Reference 5)

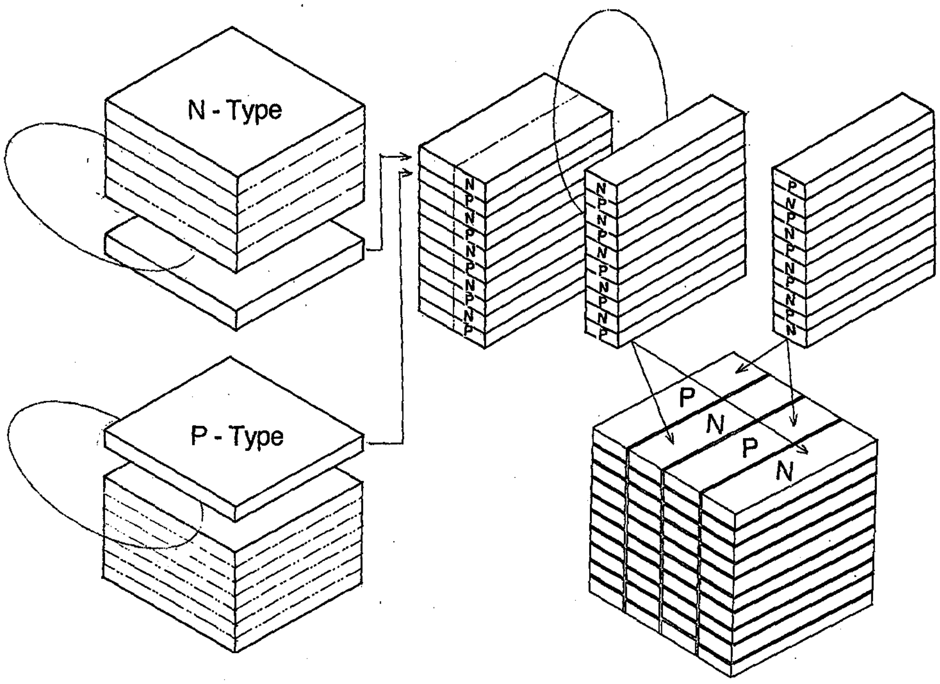

Fig. 6 Fabrication of TE Module for Modular RTG
(after Shock, A. 1981, Reference 6)

The faces of the block are subsequently coated with the same glass material. The glass coating acts both as a bond and as an electrical insulator. In addition, it also serves to suppress the sublimation of silicon from the hot ends of the TE legs[6]. The hot shoes consist of diffusion-bonded doped silicon (SiMo) wafers, and the cold shoes of sputtered tungsten coating.

2. 2 SiGe TE Module for Nuclear Power Converter

The heat generated by the nuclear reactor is converted into electrical energy by the TE modules. The module configuration for the SP-100 program is shown in Figure 7. The TE legs of the module are improved silicon germanium (SiGe) alloys.

The module consists of 64 TE legs (32 couples) which are interconnected to form a four-by-eight matrix, arranged in 4 parallel of 8 series couples, with tungsten/graphite hot and cold shoes. The high temperature glass acts both as a bond and as an electrical insulator between individual TE legs. The module is also insulated from the metallic compliant pad face sheets by a layer of the same glass. The differential thermal expansion between the heat exchangers and the TE modules must be accommodated without inducing large stresses into the TE legs. This is accomplished through the use of compliant pads.

The hot side pads are made of niobium fibers supported between thin face sheets of niobium and tungsten. The cold-side pad is similarly supported, but its fibers are made of niobium-clad copper in order to increase its thermal conductance. Their principal function is to accommodate the heat exchanger differential thermal expansion. The TE power converter for SP-100 consists of twelve identical power converter assemblies (PCAs) and delivers 105.3 KWe at 208.6 V DC. Each PCA is divided into 6 thermoelectric converter assemblies (TCAs) where 120 TE modules are sandwiched between a hot-side and two cold-side heat exchangers. The liquid lithium

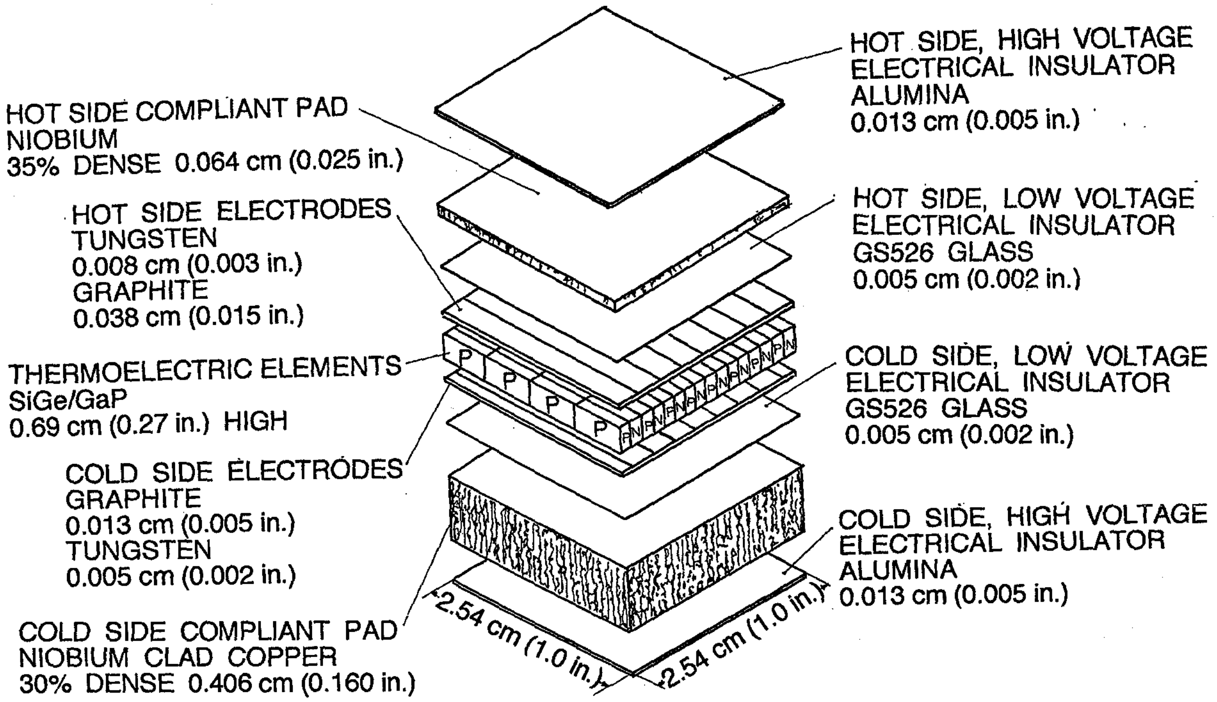

Fig. 7 Module Configuration for SP-100
(after Stapfer, G and Carrol, W., 1989, Reference 7)

from the reactor flows through the hot-side heat exchangers, and returns to the reactor. Similar arrangement removes the heat from the cold-side heat exchangers and transports the waste heat to the radiator panels[7].

2. 3 PbTe TE Module using Fossil Fuel

Figure 8 shows the assembly of lead-tin-terullide (PbSnTe) couples electrically in series for the TE power generator module shown in Figure 9.

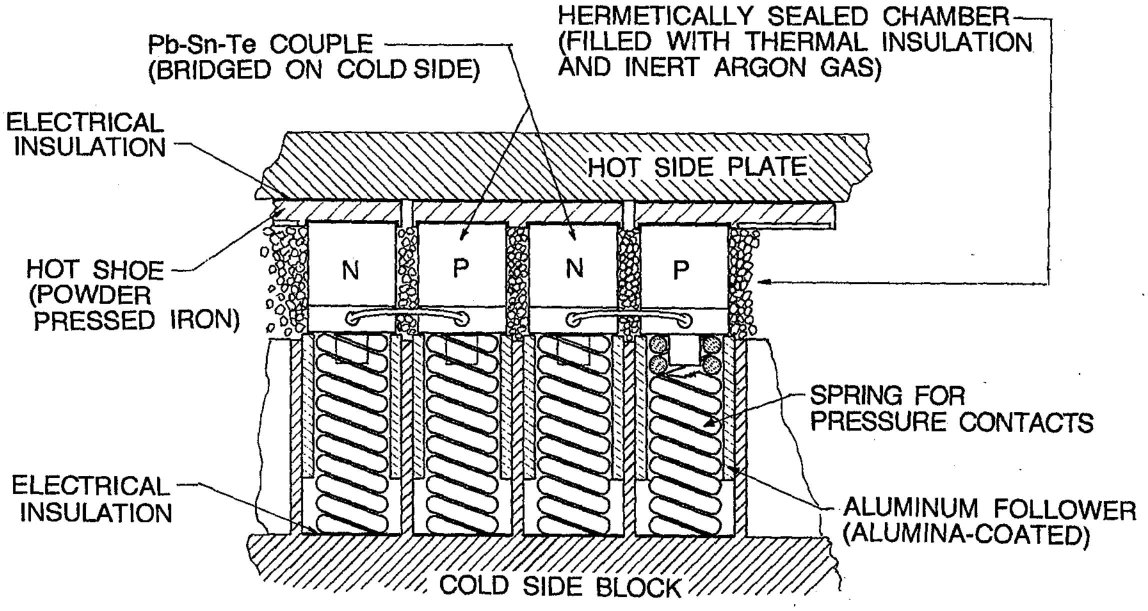

Fig. 8 PbTe TE Couples

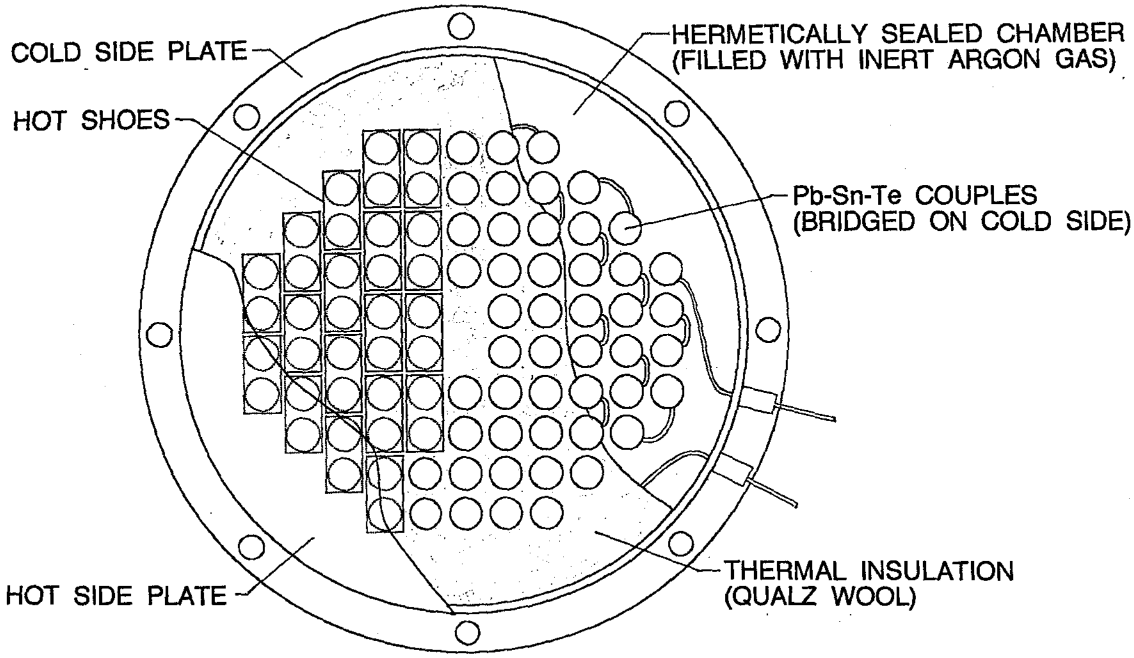

Fig. 9 PbTe TE Module Configuration

The TE legs are protected from the effects of oxidation and sublimation. TE module is hermetically encapsulated and back-filled with argon gas, which is chemically inert. Contact to the hot shoes of powder pressed iron is accomplished by the springs and alumina-coated followers on the cold-side. It is operated by either propane, butane and natural gas. At 297 K(24°C) ambient, TE module cold-side is maintained at 436 K(163°C) by the natural convection of ambient air through aluminum cooling fins when the hot-side is 811 K(538°C).

This type of TE module can be used in conjunction with storage batteries to power a radio, microwave repeater and telemetry systems. The power generators using these TE modules are also useful in providing the negative potential to gas pipe lines and wells for cathodic protection against corrosion[8, 9].

2. 4 Bi-Te TE Module for High Grade Heat source

The Bi-Te compact modules are made into monolithic type structures using an "egg-crate" type of insulator of synthetic mica or fiber glass to separate the legs as shown in Figure 10.

The modules consists of hot pressed or crystal bismuth terullide (Bi-Te) TE legs. The P and N legs are placed in the egg-crate and plasma sprayed or diffusion bonded on each side to form the electrical contacts. When the sprayed or bonded surfaces are ground to the correct thickness, the TE pattern appears as the insulating separators of the egg-crate are uncovered[10]. The sprayed or bonded metal bridges enable the modules to operate continuously at temperatures as high as 573 K and intermittently as high as 673 K without degrading the module.

While the module is well suited for power generation, it can be used for cooling at high temperature applications where sensitive electronic equipment must be cooled to below the ambient temperatures[11].

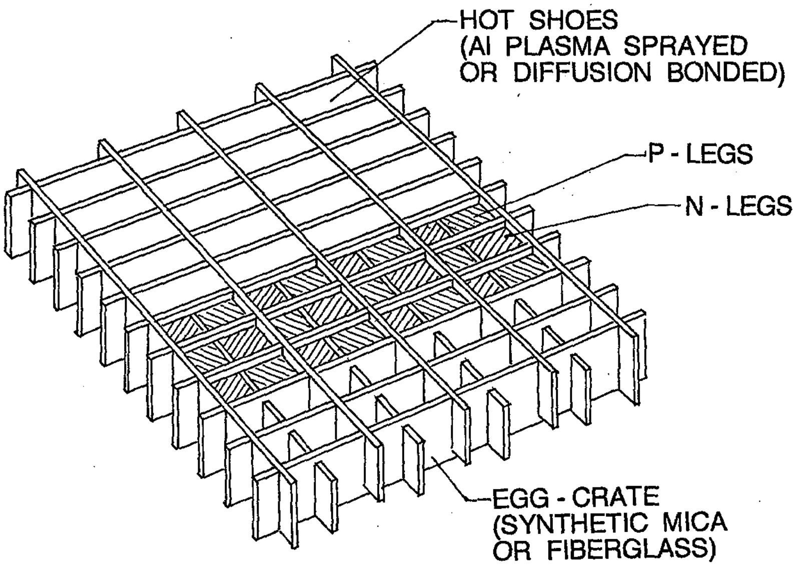

Fig. 10 Fabrication of Bi-Te TE Module for High Grade Heat Source

3. TE MODULES FOR POWER GENERATION USING LOW GRADE HEAT SOURCE (<500 K)

The low grade heat sources include fossil fuel, waste heat, radio-isotopes, solar ponds, geothermal energy etc.The TE materials used for power generation are silicon (Si), lead telluride (PbTe), bismuth telluride (Bi-Te) etc. These generators are used in the remote areas, for waste heat recovery, the military, emergency, medical and consumer usage.

3. 1 Bi-Te Thin Film TE Modules for Power Generation

The thin film TE module vacuum deposited onto 25 μm thick Kapton foil is shown in Figure 12. The TE materials are $Bi_2Te_{2.7}Se_{0.3}$ and $Bi_{0.5}Sb_{1.5}Te_3$ doped with 0.1 wt % Hg_2Cl_2 and 0.2 wt % Pb respectively*. The 32 couples of 0.4 μm thick were deposited onto the 25 cm long Kapton foil substrate. After evaporation they were rolled up and annealed in a pipe furnace at 520 K for 3 hours in a (247°C) purified nitrogen atmosphere.

The module has at 300 K a total resistance of 65 kΩ and a total Seebeck coefficient of 10.4 mV/K after annealing. It may be seen that enlarging the length to 1 m and thickness of the paths to 1 μm, the theoretical power produced may be of 10^{-4} W range with $\Delta T=100K$. These thin film modules can be wound to produce coils as shown in Figure 13 and could be used where constant energy supply but of low grade power is needed e.g. hearing aids, cardiac pacemakers etc[12, 13, 14].

* It is assumed that they were not films' composition but mother alloys. (Lecturer's opinion)

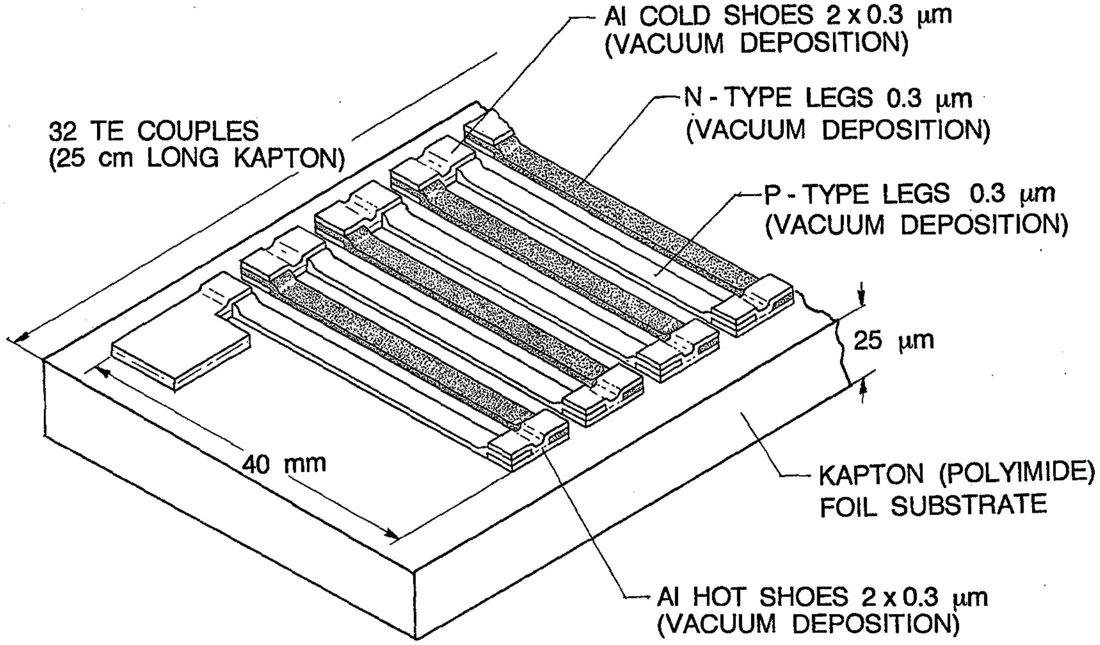

Fig. 11 Bi-Te Thin Film TE Module for Power Generation
(after Przyłuski, J. Reference 12)

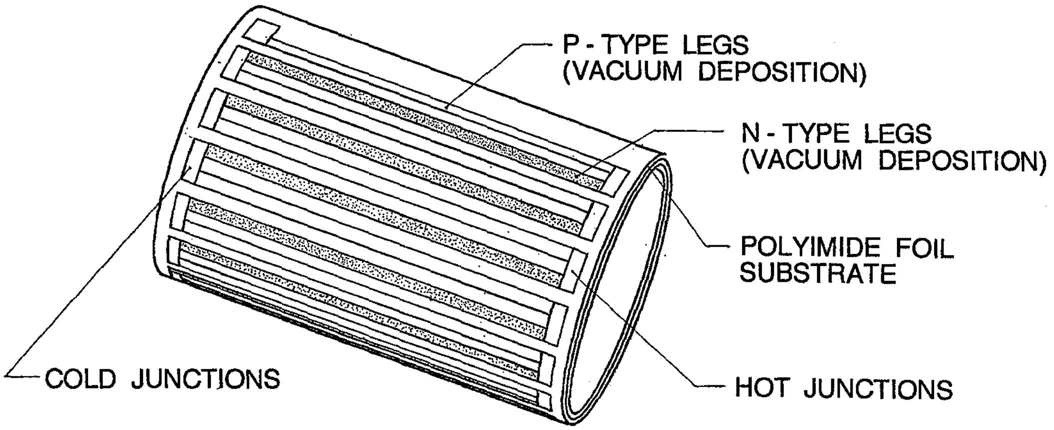

Fig. 12 Thin Film Coiled TE Module for Power Generation
(after Adler, K., Renner, Th., Reference 13, 14, 15)

3. 2 Si Miniature TE Modules for Power Generation

A miniature module for TE generator has been developed by D. M. Rowe et al using silicon integrated circuit technology. Alternate n- and p-type active strips are ion implanted into an undoped silicon substrate. Figure 13 shows a schematic configuration of the module.

The fabrication sequence is schematically illustrated in Figure 14. Wafers of near intrinsic silicon (ρ>100 Ωcm) (100)* which are epitaxially grown on sapphire ($1\bar{1}02$)*

* crystal plane face

are used as the starting material. In the first two stages the technique of ion implantation is used to produce alternate strips of p- and n-type material by implanting boron (B) and phosphorous (P) ions respectively.

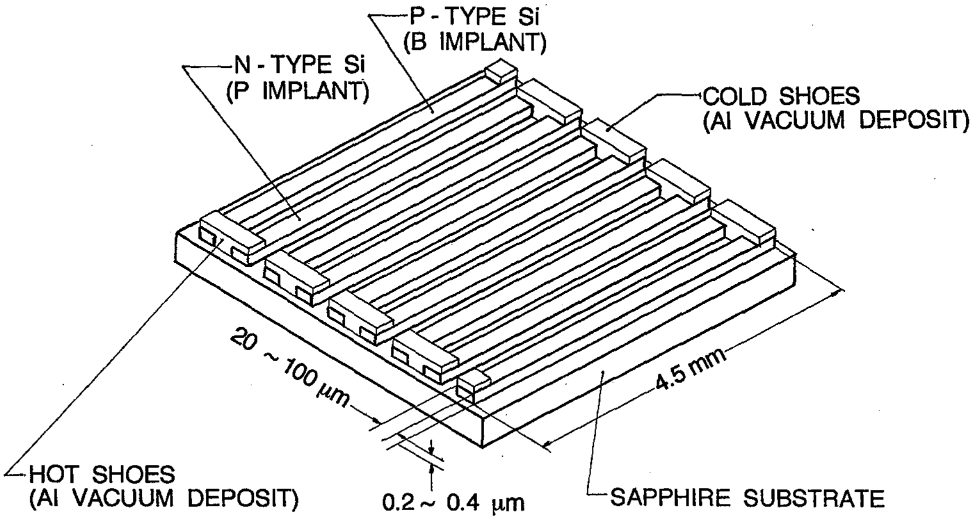

Fig. 13 Miniature TE Module for Power Generation using IC Technology (after Rowe, D. M., Morgan, D. V. and Kiely, J., Reference 16)

To provide electrical isolation (or insulation) between the p- and n-type regions a reactive ion etch is performed. to remove the unimplanted regions of silicon.

Metallization of element connecting strips and output contacts enables several hundred TE couples to be connected electrically in series and occupy an area approximately 25 mm square.

The integrated electronics require the low power level (micro-milliwatt), relatively high voltage (volts) sources that can operate reliably and unattended over long periods of time. The miniature TE generators are a source of electrical power that could meet these requirements in situations where a flux of heat is available[16].

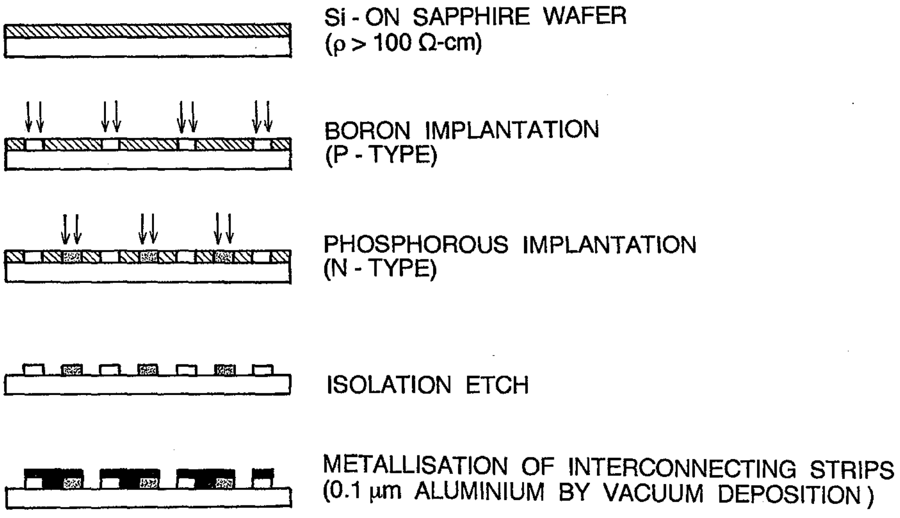

Fig. 14 Process Sequence for Miniature TE Modules (after Rowe, D. M., Morgan, D. V. and Kiely, J. Reference 16, with Permission)

3. 3. Bi-Te TE Modules for Power Generation using Low Grade Heat Source

The Bi-Te commercial TE modules for cooling described in the next paragraph 4 can be used for power generation using low grade heat source.

4. TE MODULES FOR COOLING

For TE cooling a quaternary alloy of bismuth, tellurium, selenium and antimony is used. Its figure of merit is $2.6\sim3.0\times10^{-1}K^{-1}$.

The TE materials based on bismuth telluride cannot be tinned directly using ordinary lead-tin solder. In the production of TE modules, it is a common practice to tin the TE legs using a bismuth-tin solder. It should be noted that such contacts have a relatively low melting temperature and modules made in this way should never be operated above the hot-side temperature of 373 K(100°C). Care must be taken to avoid the use of any contact material such as copper, silver or gold that could deteriorate the bismuth telluride TE properties. Nickel-plated films are useful as a barrier layer preventing impurities from the copper bridging metals or soldering materials from contaminating the TE material.

These TE modules can not only be used for cooling but also for power generation using low grade heat source.

4. 1 Commercial Single-stage TE Modules for Cooling

The couples in the commercialized TE cooling modules are integrated between two ceramic plates. These plates form the cold and hot surfaces of the module and provide sound mechanical integrity and high electrical insulation from, as well as thermal conduction, to the heat sink and body to be cooled. Figure 15 shows the configuration of a single-stage TE module. There are modules without ceramic plates. On the one hand, they have the advantage of eliminating thermal resistance of ceramic plates, on the other hand however, they also have the disadvantages of mechanical fragility and require electrical insulation.

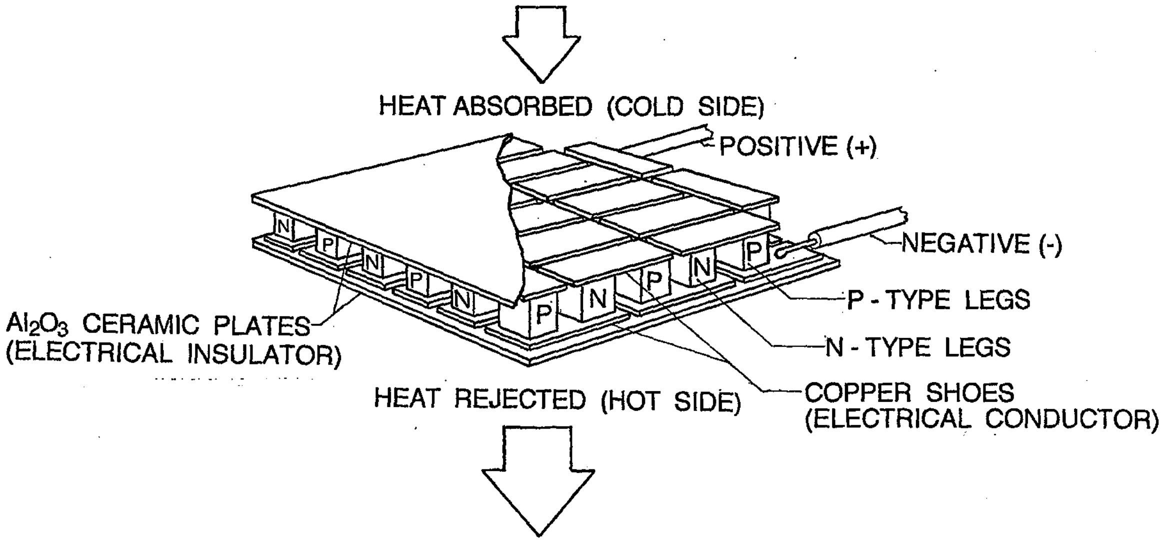

Fig. 15 Bi-Te Single-stage TE Module

4. 1. 1. Maximum Performance Parameters

Four maximum performance parameters with hot junction temperature fixed at 300 K(27°C) are provided on the tables and graphs for commercial single-stage TE modules;

I_{MAX}(A): DC current which yields the maximum junction temperature difference ΔT_{MAX}, the cooling power is equal to zero, which means that there is no heat load on the cooled side. I_{MAX} is not a maximum value of I, but corresponds to the value of current that gives ΔT_{MAX} and $Q_c=0$ as shown in Figure 16.

ΔT_{MAX} (K): The maximum junction temperature difference across the module at I_{MAX} with no heat load. The ΔT_{MAX} of commercial single-stage modules is about 65~75 K with the hot junction temperature at 300 K(27°C).

$Q_{C\text{-}MAX}$ (W): The cooling power which corresponds to a temperature difference across the module of $\Delta T=0$ with current I_{MAX}.

V_{MAX} (V): The terminal voltage for I_{MAX} with no heat load.

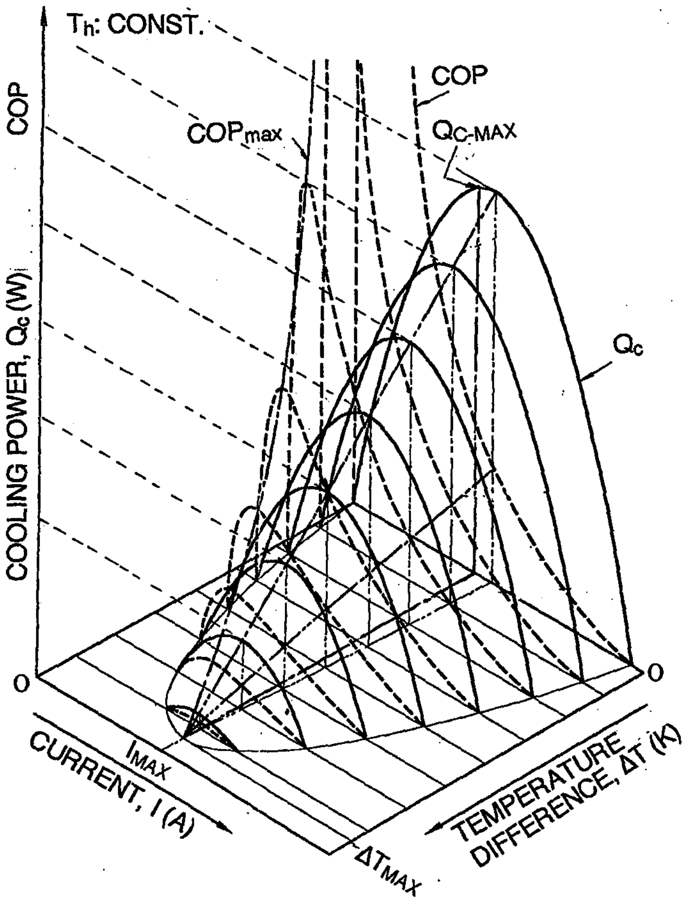

Fig. 16 I_{MAX} corresponds to the Value of Current that gives ΔT_{MAX} when $Q_c=0$

As all the physical properties of the thermoelectric material are dependent on temperature, the module's performance is temperature dependent and for commercial Bi-Te this increases with increasing temperature of the operating hot junction temperature range.

The commercial single-stage TE modules cover a wide range of ceramic face sizes from 1.8x3.4 mm^2 to 62x62 mm^2 and heights from 2.45 mm to 5.8 mm with,

$Q_{C\text{-}MAX}$: from 0.2 to 125 Watts
I_{MAX}: from 0.8 to 60 Amps
V_{MAX}: from 0.4 to 15.4 Volts
Number of couples: from 4 to 127 couples
(refer to page Uemura- 5, paragraph 1.4)

4. 1. 2. Universal Characteristics

In practice, the modules are operated under conditions that satisfy the particular requirements of the application;

T_c (K): The temperature of the cold junctions
T_h (K): The temperature of the hot junctions
ΔT (K)=T_h-T_c: The junction temperature difference
Q_c (W): The cooling power i.e. the amount of heat load to be absorbed by the cold junctions
Q_h (W): The amount of heat dissipated at the hot junctions
I (A): The applied current
V (V): The terminal voltage
P (W): The electrical input power, equals to I·V

And the Coefficient of Performance COP is defined as the cooling power Q_c divided by the input electrical power P; Q_c/P. All these values have an interdependent relationship with each other which are specific to each module. These Universal characteristics are a non-dimensional presentation of the parameters: $\Delta T/\Delta T_{MAX}$, I/I_{MAX}, $Q_c/Q_{C\text{-}MAX}$, V/V_{MAX}, available for a wide range of hot junction temperatures[17].

Figure 17 shows the universal relationship (Chart I) between - the operating current ratio I/I_{MAX}- the cooling power ratio $Q_c/Q_{C\text{-}MAX}$ - the Coefficient of Performance COP, as a function of the junction temperature difference ratio $\Delta T/\Delta T_{MAX}$.

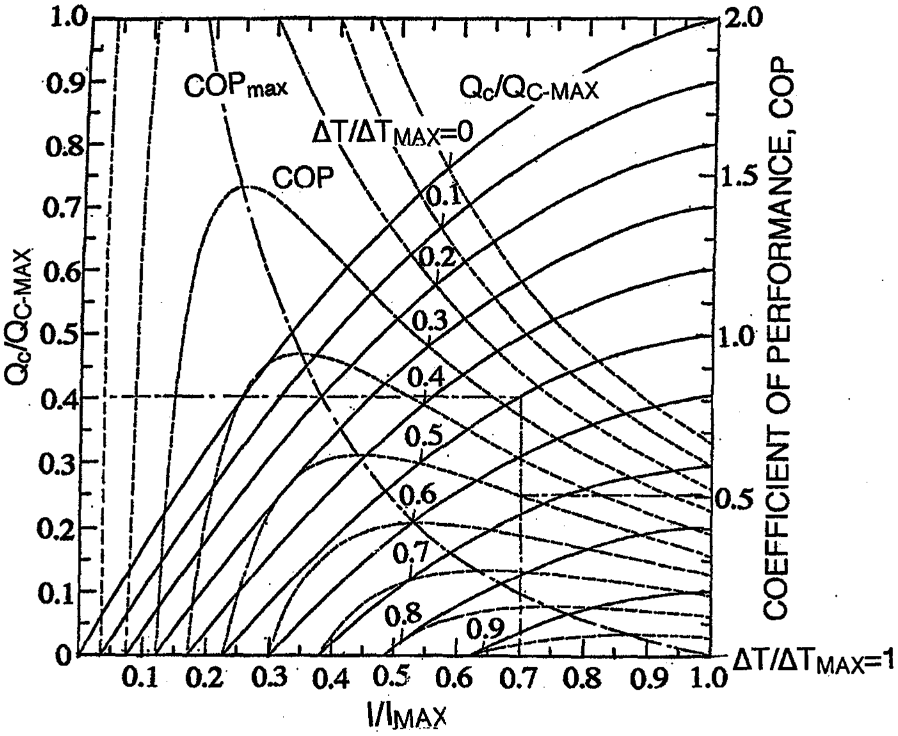

Fig. 17 Universal Chart 1 for Commercial Single-stage TE Modules

The higher the operating current ratio I/I_{MAX}, the greater the cooling power ratio $Q_c/Q_{C\text{-}MAX}$. As the current ratio $I/I_{MAX}$is decreased, the COP increases to the COP_{max} and then decreases. The higher the COP for a given cooling power, the lower the ratio of electrical input power/cooling power and also lesser is the heat generated at the hot junctions that must be dissipated by the heat dissipating exchanger. A suitable operating current is between the value corresponding to COP_{max} and I_{MAX}.

Figure 18 shows the universal relationship (Chart II) between the three parameters - operating junction temperature difference ratio $\Delta T/\Delta T_{MAX}$ - the terminal voltage ratio V/V_{MAX} - the cooling power ratio $Q_c,/Q_{C\text{-}MAX}$, as a function of the operating current ratio I/I_{MAX}.

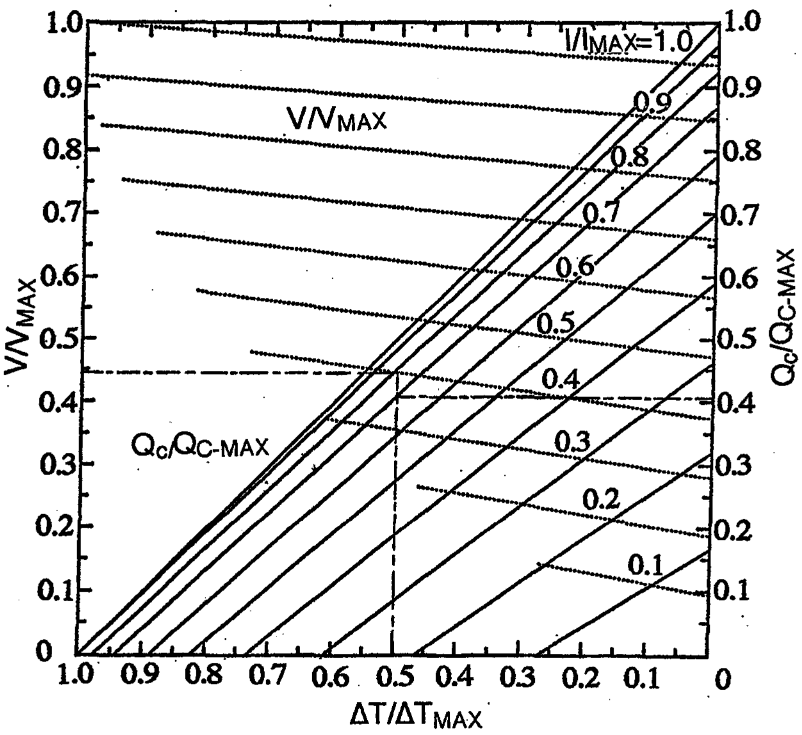

Fig. 18 Universal Chart II for Commercial Single-stage TE Modules

4.2. Multi-Stage TE Modules for Cooling

The junction temperature difference ΔT of a single-stage TE module cannot exceed the maximum value ΔT_{MAX} , when the cooling power Q_c and the COP are both zero for the single-stage TE modules. However, this limitation can be overcome by using several stages.

A multi-stage TE module is essentially two or more single-stage modules stacked on top of each other when the top stage is used for cooling then the bottom stage requires greater cooling power to pump the heat dissipated by the top stages. Therefore, when the module of each stage has the same thermoelectric element (leg) with the same Geometric Factor G, all connected electrically in series, a bottom stage requires more couples than a top one.

Figure 19 shows the configuration of a typical pyramid-shaped three-stage TE module. Figure 20 shows a configuration of a two-stage Peltier module in which the top module consists of the same number of couples as the bottom but the Geometric

Factor G is one half of the bottom. The top module is divided into halves that are connected in parallel. (G: refer to page Uemura- 5, paragraph 1.4)

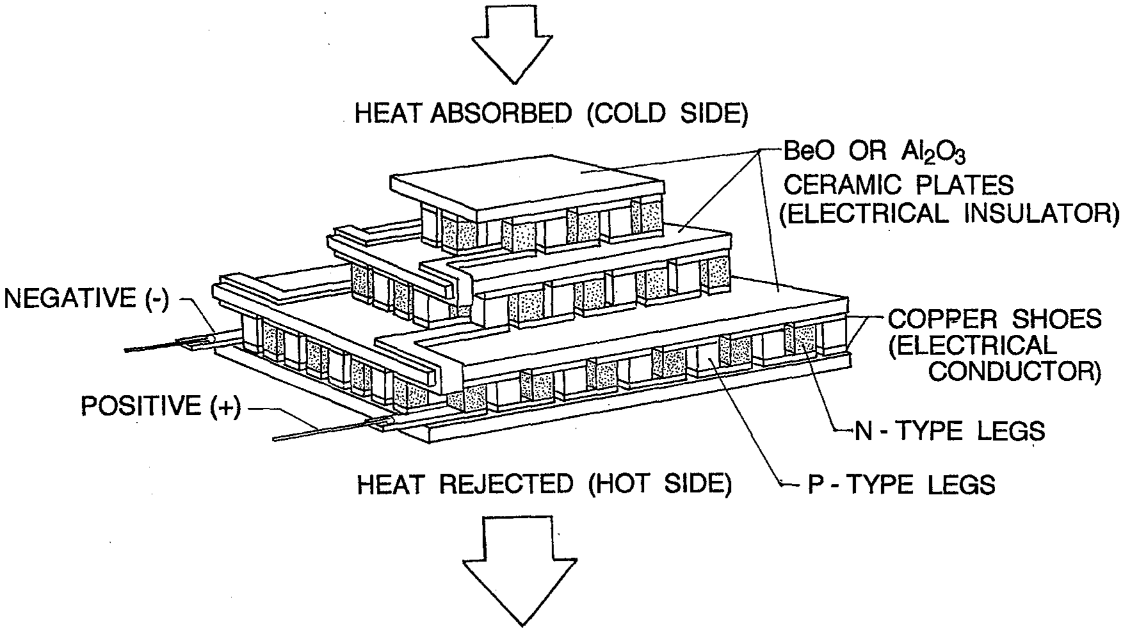

Fig. 19 Three-stage TE Module

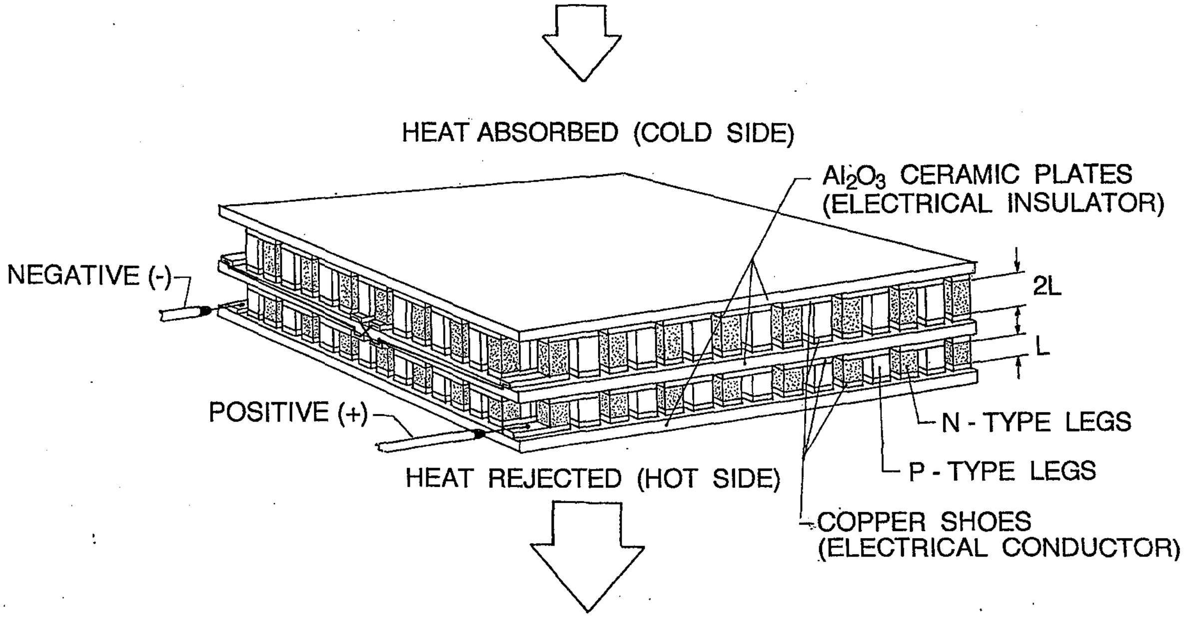

Fig. 20 Two-stage TE Module

4. 2. 1. Performance

The four maximum performance parameters I_{MAX}, ΔT_{MAX}, $Q_{C\text{-}MAX}$ and V_{MAX}, with a hot junction temperature of the bottom module fixed at 300K(27°C) are given for the multi-stage commercial TE modules. Their definitions are the same as those for single-stage modules. However the maximum temperature difference ΔT_{MAX} of multi-stage is determind by the number of stages. Figure 21 shows the ΔT_{MAX} of multi-stage TE modules as a function of the bottom stage hot junction temperature T_h for the constant current I_{MAX}.

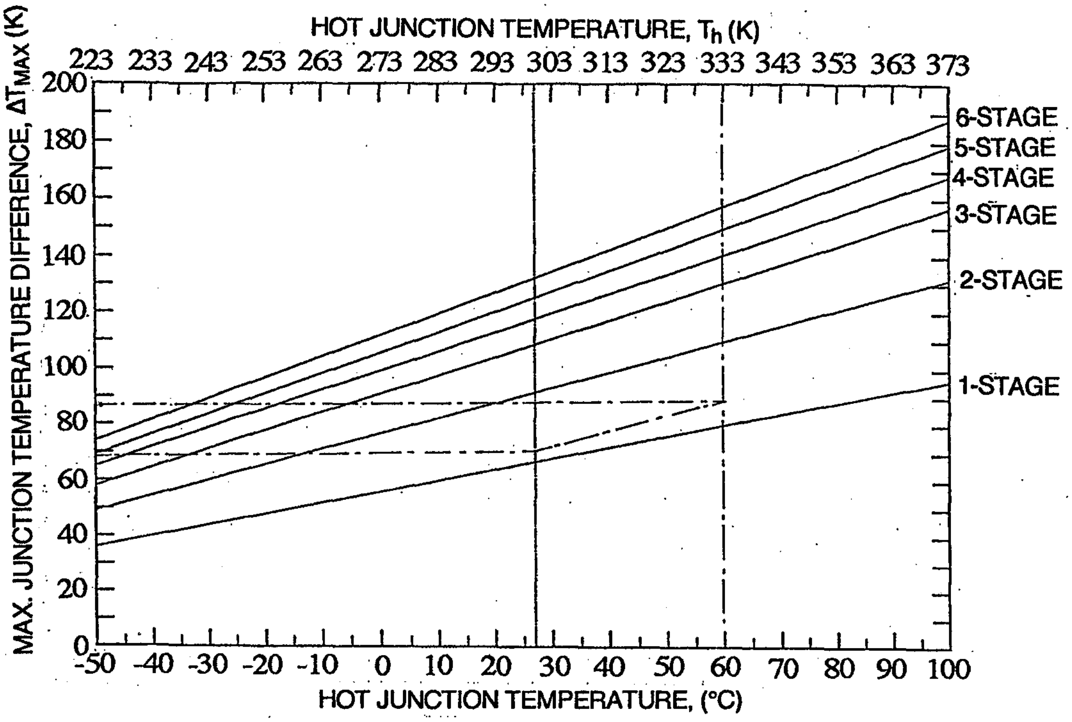

Fig. 21 ΔT_{MAX} of Multi-stage TE Module, with Bottom Stage Hot Junction Temperature T_h, for Constant Current=I_{MAX}

4. 2. 2. Commercial Multi-stage TE Modules

Commercial multi-stage TE modules cover a range of ceramic face sizes from 3.2 x 3.2 mm^2 to 62 x 62 mm^2 at the top (cooling side), from 3.8 x 3.8 mm^2 to 62 x 62 mm^2 at the bottom (heated side), and heights from 3.8 mm to 21.4 mm with,

I_{MAX} (A) : from 0.7 to 9.5 Amps
$Q_{C\text{-}MAX}$ (W): from 0.39 to 59 Watts
V_{MAX} (V): from 0.8 to 14 Volts
Number of stages: from two-stages to six-stages

5. TE MODULES FOR OTHER APPLICATIONS

The Seebeck coefficient of TE materials is about 10 times greater than that of metals. TE couple or modules can be used for temperature sensors, pyrometers, IR detectors and for other applications. They can be small, light and have a small heat capacity. High signal response and figure of merit are essential. Thin film TE modules using ferro sillicide (Fe-Si), bismuth antimony (Bi-Sb), bismuth telluride (Bi-Te) materials are good for such applications.

5. 1. Bi-Te Thin Film TE Module for Pyrometers

The Bi-Te thin film TE modules manufactured using photolithographic technology have been developed by L. I. Anatychuk et al[18]. TE modules were designed especially for pyrometers - signal output, time constant and detectivity. The schematic structure of the TE module is shown in Figure 22. The following specifications are required for pyrometers i.e.

length of TE leg: 500 µm
thickness of TE leg: 1 µm
thickness of insulating substrate: 0.5 µm
width of TE leg: 30 µm
separation of the legs: 2~3 µm

The TE module was designed with the above basic values. It consists of more than 100 couples in 1 mm^2 of active area.

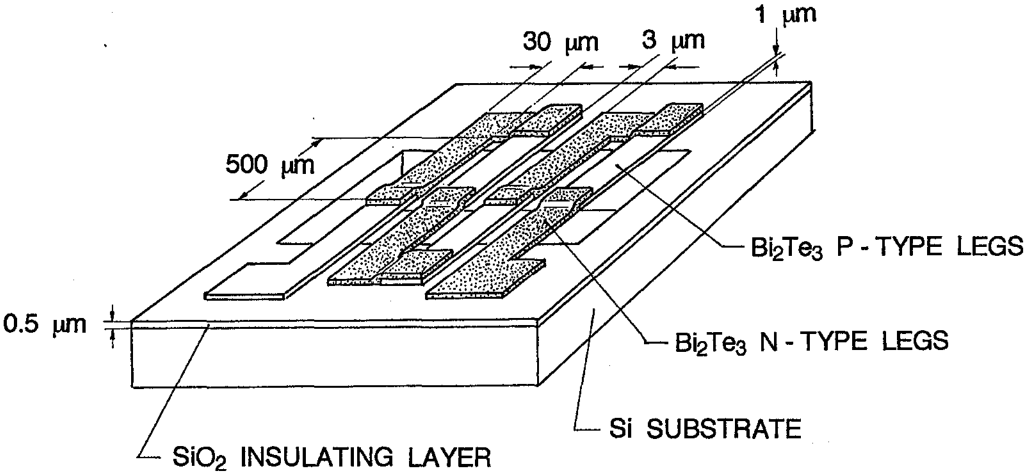

Fig. 22 Bi-Te Thin Film TE Module for Pyrometers
(after Anatychuk, L. I., Moldavasky, M. S., Rasincov, V. V. and Tsipko, N. K., 1991, Reference 18, with Permission)

The manufacturing sequence is schematically illustrated in Figure 23.

In the first step - the silicon dioxide (SiO_2) layer of thickness of 1~2 µm is formed on the monocrystalline silicon substrate.

In the second step - the Bi-Te p-type material film of thickness of about 1 µm is deposited on the silicon dioxcide surface using the magnetron sputtering method.

In the third step - to provide the P-type legs, a photolithgraphic process - (a) photo-resistant coating (b) masking (c) exposure (d) developing (e) etching - are used to isolate* the p-legs.

In the fourth step - the Bi-Te n-type material film of thickness of about 1 µm is formed onto the surface with deposited p-type legs.

In the fifth stage - to provide the n-type legs, the same process as the third step is used to isolate the n-legs. The hot and cold side contacts are formed by deposition of the n-type material onto the p-type material.

* isolate: to obtain as a separate substance or to cut off from all contact with others in order to povide electrical insulation.

In the sixth step - the silicon substrate under the TE couples is removed by anisotropic etching so as to eliminate the thermal shunting among the legs. In addition it provides the window for receiving the radiant energy.

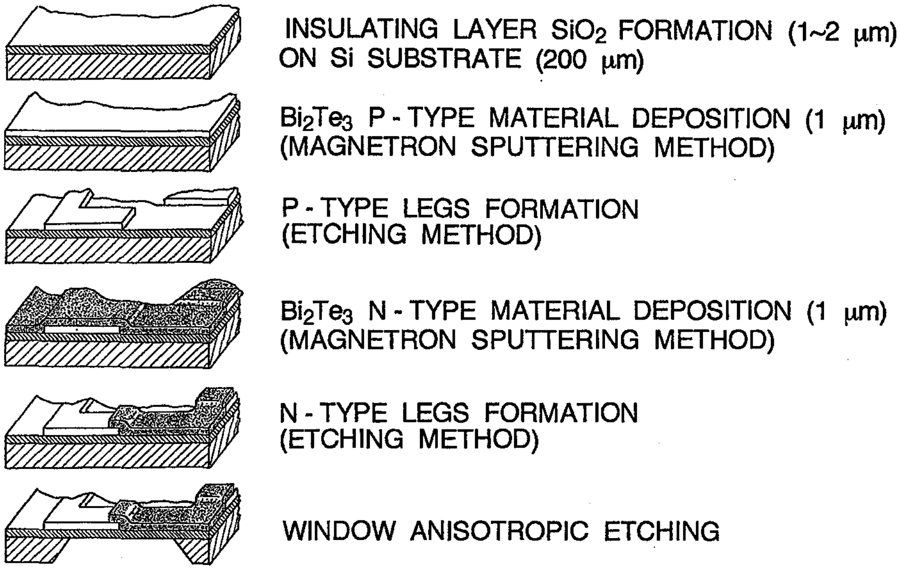

Fig. 23 Manufacturing Process for Thin Film TE Radiation Detector (after Anatychuk, L. I., Moldavasky, M. S., Rasincov, V. V. and Tsipko, N. K., 1991, Reference 18, with Permission)

6. CONCLUSION

Since a fully comprehensive account of all available thermoelectric modules is beyond the scope of this lecture. The final paragraph 7. REFERENCES is available for further details of the thermoelectric modules. The Bi-Te TE modules are manufactured commercially by many manufacturers in the world. To obtain the reference and details of the Bi-Te TE module, the catalogues and technical sheets of manufacturers' should be consulted.

7. ACKNOWLEDGEMENTS

The contents of this lecture are much indebted to the proceedings of the ICTEC and ICT conferences. I would like to thank to the authors of the papers. Specifically I would like to acknowledge Dr. P. A. O'Riordan (U. S. Department of Energy, USA), Dr. J. F. Nakahara (Martin Marietta Astro Space, USA), Dr. R. F. Hartman (Martin Marietta Astro Space, USA), Dr. D. M. Rowe (Univ. of Wales College of Cardiff, UK), Dr. L. I. Anatychuk (Institute of Thermoelectricity, Ukreine) who kindly gave me their permission to include the figures in their papers in this text of the Short Course on Thermoelectrics.

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